# Imperial College London

Topic 18

Link

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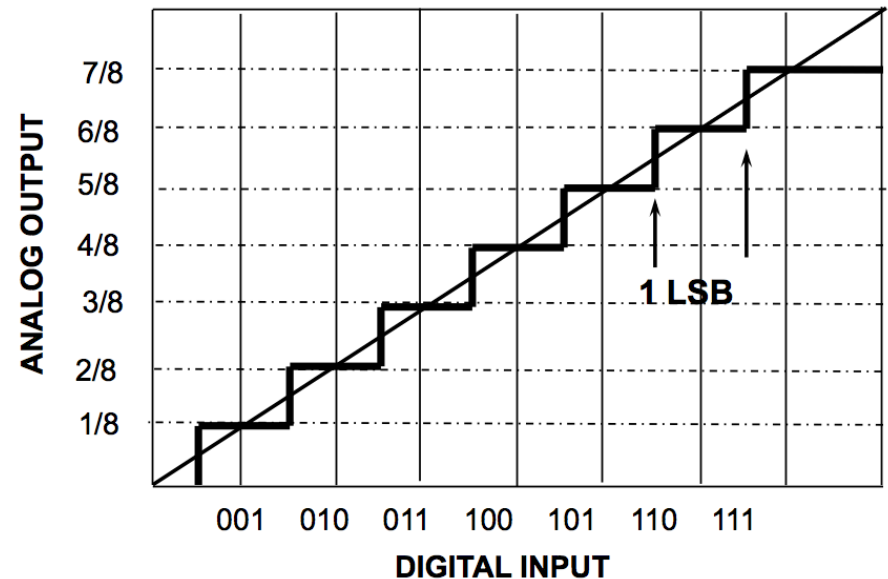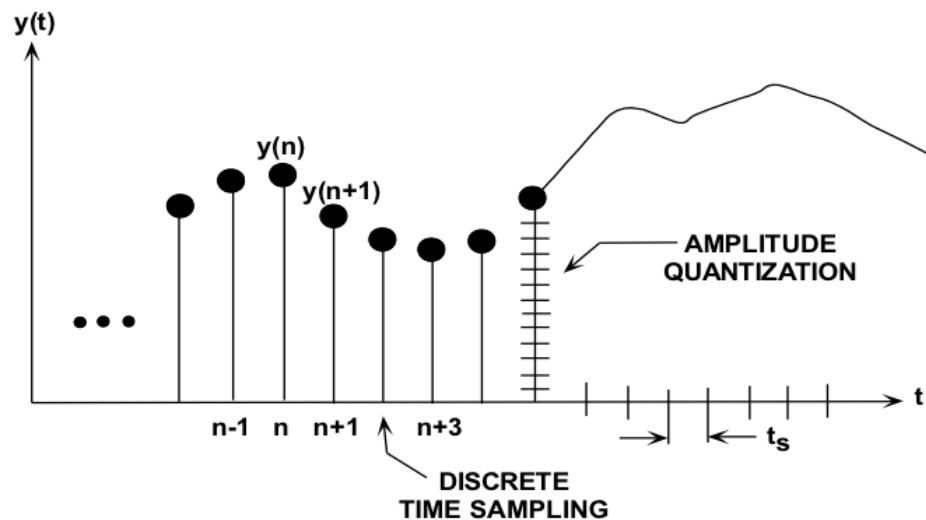URL: www.ee.ic.ac.uk/pcheung/teaching/DE1_EE/
E-mail: p.cheung@imperial.ac.uk

Linking between analogue and digital domains

- Much of the physical world is analogue in nature.

- Linking digital electronics as used in microprocessors and the physical world is three digital-to-analogue and analogue-to-digital converters. (It is common that DACs and ADCs use the American spelling of analog.)
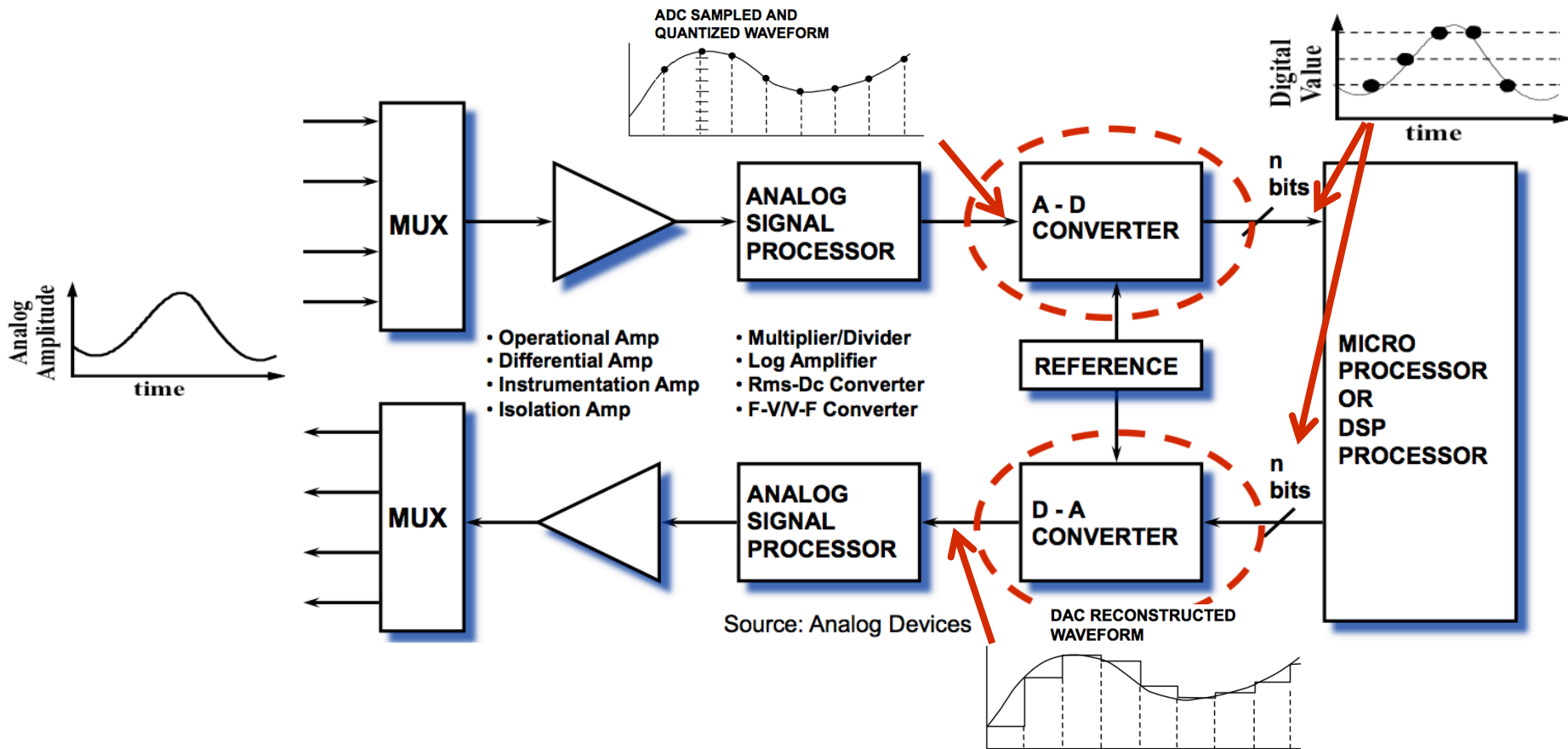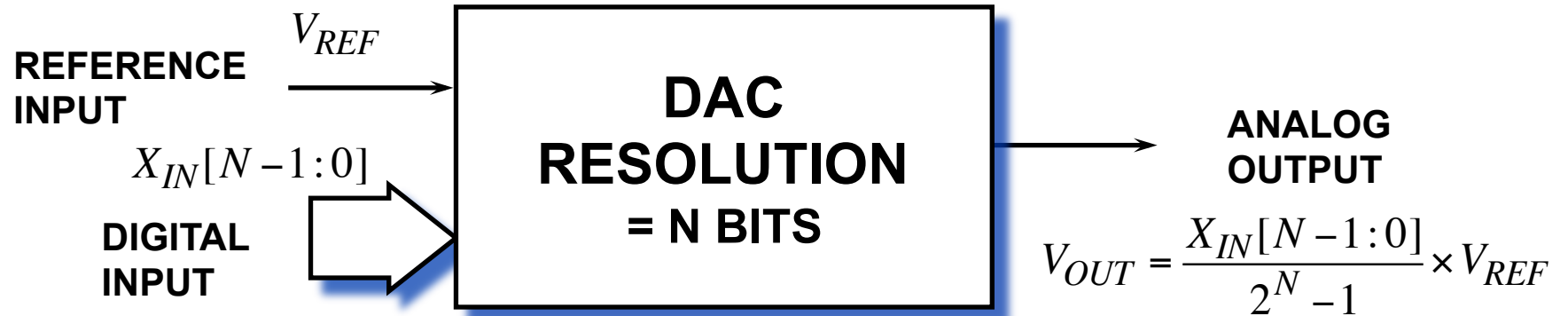
Sampling and Quantization

◆ **Sampling Process**: convert a <u>continuous time domain</u> signal at <u>discrete and uniform</u> time intervals.

◆ Determines <u>maximum bandwidth</u> of sampled (ADC) or reconstructed (DAC) signal (**Nyquist Sampling Theorem**: sampling frequency must be at least twice that of maximum signal frequency)

◆ Frequency Domain- "<u>Aliasing</u>" for an ADC and "<u>Images</u>" for a DAC

◆ **Quantization Process**: convert an <u>analogue signal</u> with <u>infinite</u> resolution with a digital word having <u>finite</u> resolution and an analogue output which only exists in discrete levels

  • Determines <u>Maximum Achievable Dynamic Range</u>

  • Results in <u>Quantization Error/Noise</u>

A simplified view of a DAC

REFERENCE INPUT V_{REF}

$X_{IN}[N-1:0]$

DIGITAL INPUT

DAC RESOLUTION = N BITS

ANALOG OUTPUT

$$V_{OUT} = \frac{X_{IN}[N-1:0]}{2^N - 1} \times V_{REF}$$

- A digital-to-analog converter (DAC) produces a quantized (discrete step) analogue output (voltage or current) in response to binary digital input.
- A reference quantity (either voltage or current) is accurately divided into binary and/or linear segments.
- The digital input drives transistor switches that connect an appropriate number of segments to the output.
- 2^N discrete values resulting in quantization errors.
- Sampling and quantization impose fundamental but predictable limitations in the system.
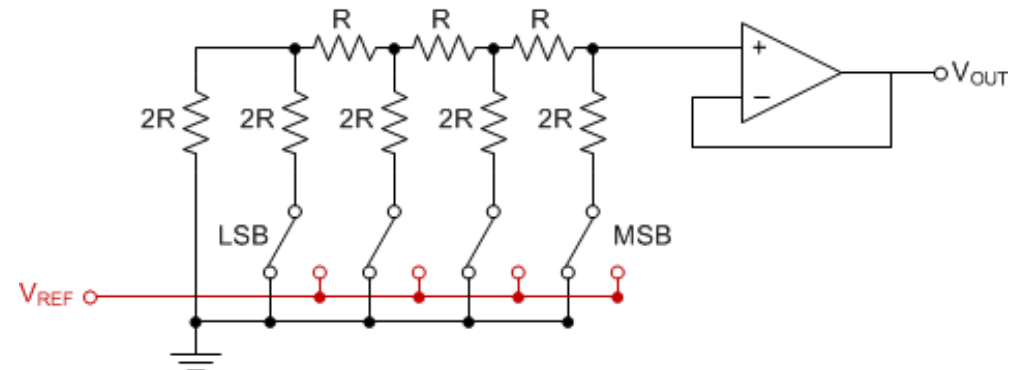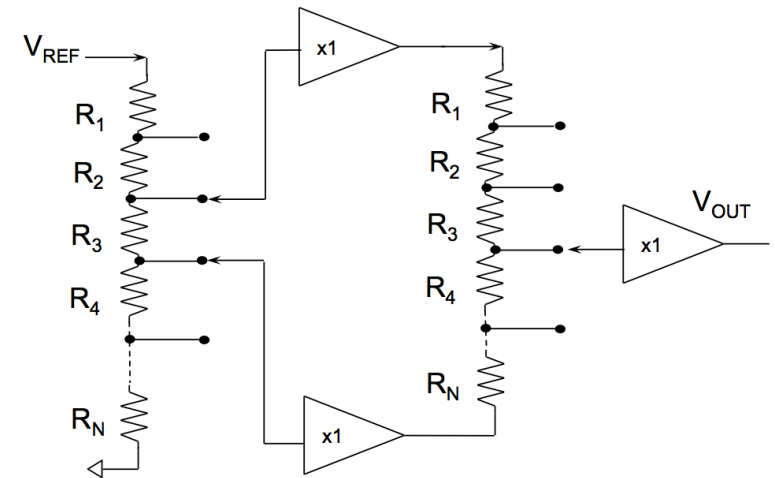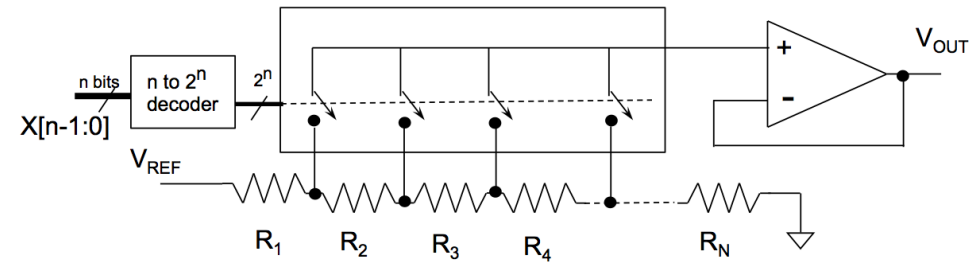- The microcontroller on the Pyboard has 2 x 12 bit DAC converters.

Resolution in various forms

- **Resolution** of a ADC or DAC is dependent on the number of input data bits.
- This defines the quantization step, which is expressed as LSB voltage (least significant bit).
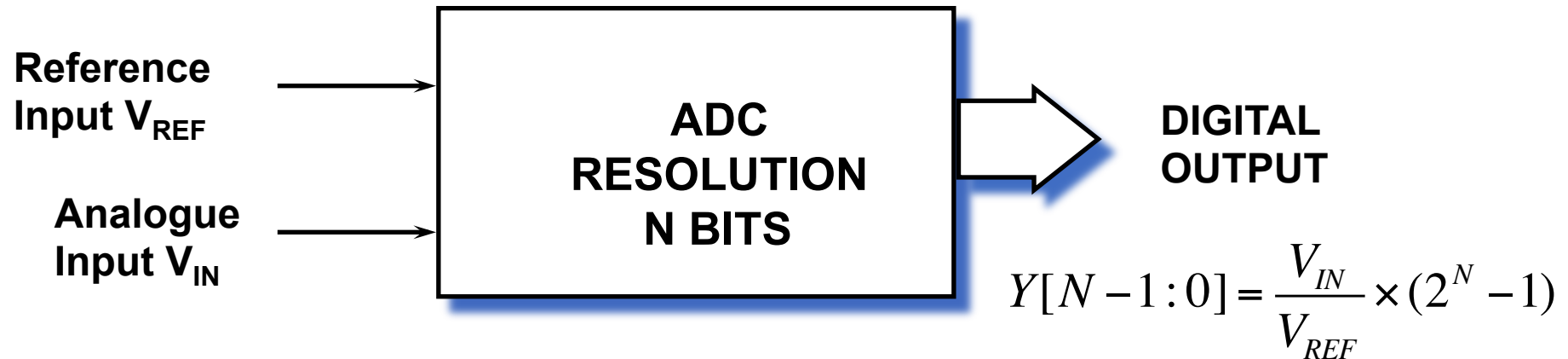- Resolution can also be expressed as %, parts per million (ppm), or dB relative to full scale (FS).

Resolution, Bits (n)	2^n	LSB, mV (10V FS)	% Full Scale	ppm Full Scale	dB Full Scale
8	256	39.1	0.391	3906	-48.0
10	1024	9.77	0.098	977	-60.0
12	4096	2.44	0.024	244	-72.0
14	16,384	0.610	0.006	61	-84.0
16	65,536	0.153	0.0015	15	-96.0
18	262,164	0.038	0.00038	3.8	-108.0
20	1,048,576	0.0095	0.00010	1.0	-120.0

Common DAC architectures

- **Simple voltage divider DAC**: dividing reference voltage into equal steps.
- Output is guaranteed to go up if input goes up – i.e. monotonic.
- Number of taps increases exponentially (2^n) with number of bits.

- **Voltage segment DAC**: use two sets of voltage dividers, one for coarse steps and another for fine steps.
- Number of resistors reduced from 2^n to $2 \times 2^{n/2}$ for two segments.
- Could use three or more segments.

- **R-2R Ladder DAC**: same network as used in Lab 2, Task 3.
- Each stage has a voltage (or current) half that of the previous stage.
- Complexity is **O**rder(n) or **O**(n), where n is the number of input bits.

A simplified view of a ADC

Reference Input V_{REF}

Analogue Input V_{IN}

ADC RESOLUTION N BITS

DIGITAL OUTPUT

$$Y[N-1:0] = \frac{V_{IN}}{V_{REF}} \times (2^N - 1)$$

- ◆ An ADC produces a digital output corresponding to the value of the signal applied to its input relative to a reference voltage.
- ◆ There are 2^N discrete values, therefore introducing error known as quantization noise.
- ◆ Similar effect in sampling and quantization as found in DAC.
- ◆ The microcontroller on the Pyboard has 3 x 12-bit ADC, capable of taking 2.4 Msamples per second.

Video on DAC converter

Parallel Data Links

- The transmission of binary data across a link can be accomplished either in parallel mode or serial mode.
- In parallel mode, multiple bits are sent with each clock period.
- In serial mode, one bit is sent with each clock period.
- There are 2 subclasses of serial transmission: synchronous and asynchronous.
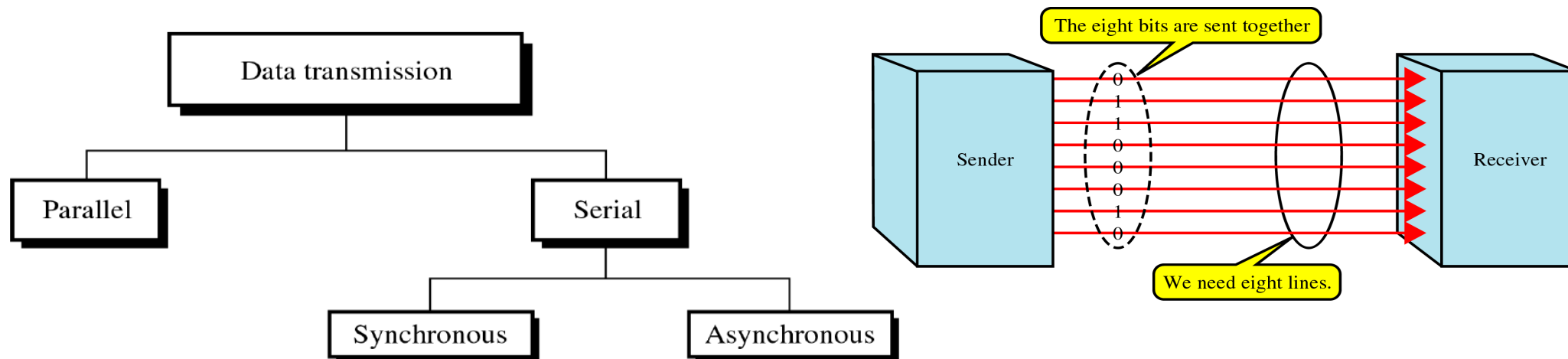
- Binary data may be organized into groups of n bits each.
- By grouping, we can send data n bits at a time instead of one. This is called parallel transmission.
- The advantage of parallel transmission is speed but its disadvantage is cost in interconnect resources.

Serial Data Links

- In serial transmission, one bit follows another, so we need only one communicating channel (or wire) to transmit data between 2 communicating modules.
- The advantage of serial transmission is the reduction of interconnect resources, but it takes N times longer to send the information, where N is the number of bits of data.
- Serial transmission occurs in one of 2 ways: **asynchronous** or **synchronous**.
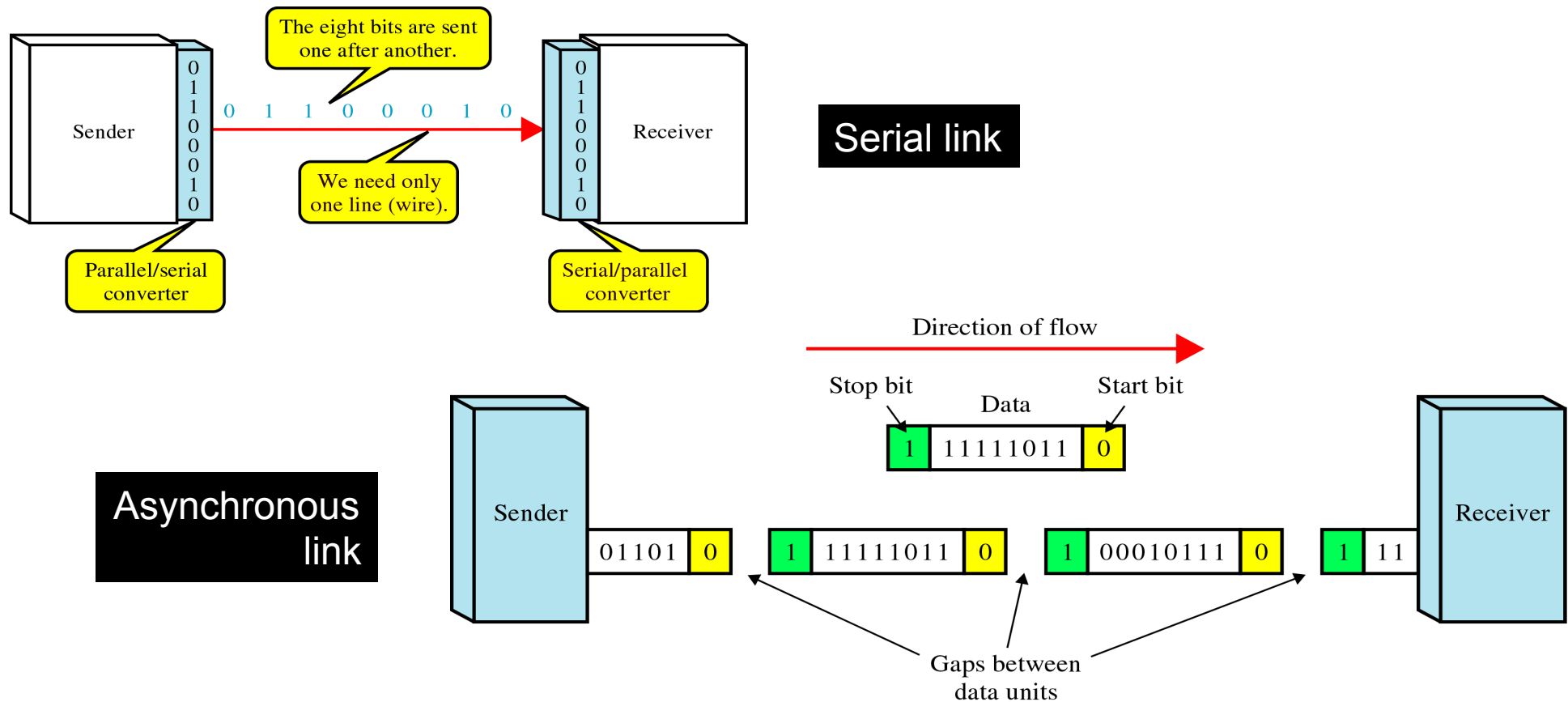
UART and flow control

◆ UART is a module found in many microcontroller that uses an asynchronous serial method for transferring data.

◆ The ESP32 uses UART to talk to your laptop via the USB cable.

◆ The UART signal waveform is shown below. (You have also seen this in Lab 1).

◆ Physical connections between two UARTs consist of four signals:
  • RX – data receive signal (input)
  • TX – data transmit signal (output)
  • CTS – clear to send signal (input)
  • RTS – ready to send signal (output)

◆ Both devices can simultaneously send and receive data. This is known as a full duplex link.

◆ RTS and CTS are active-low signals to indicate when a device is ready to transfer data.

◆ By connecting, say, the UART on the ESP32 to the laptop, one can control the flow of data between the two. This is called **flow control** mechanism.
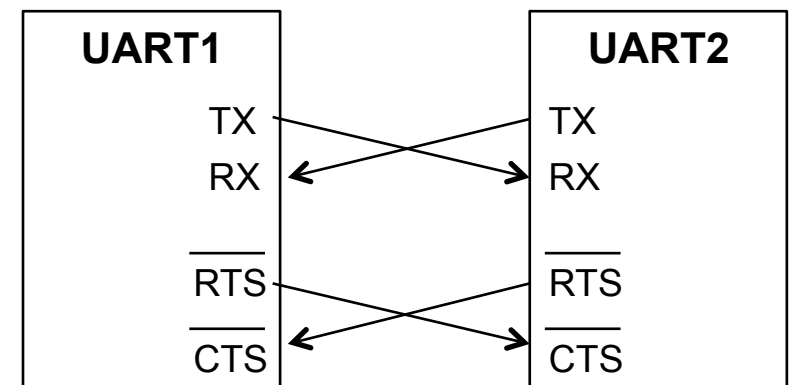
One-wire link - Neopixel
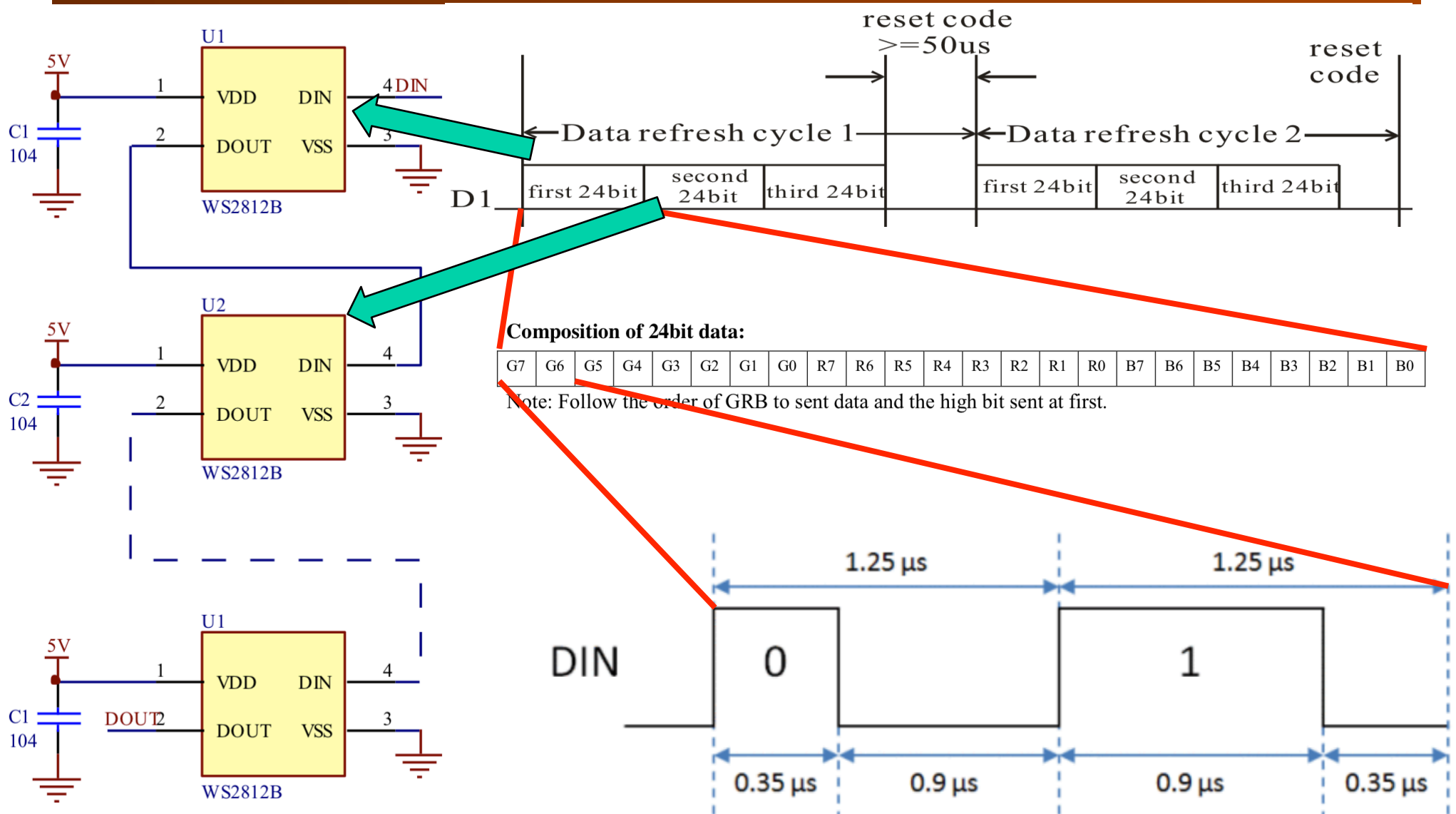
Synchronous Serial Link

◆ In a synchronous link, the bit stream is combined into longer frames which may contains multiple bytes.

◆ Each byte is introduced onto the transmission link without a gap between it and the next one.

◆ It is the responsibility of the receiver to reconstruct the information, usually under the control of a clock signal.

◆ Without gaps and start/stop bits, timing becomes very important therefore the accuracy of the received information is completely dependent on the ability of the receiver to keep an accurate count of the bits as they come in
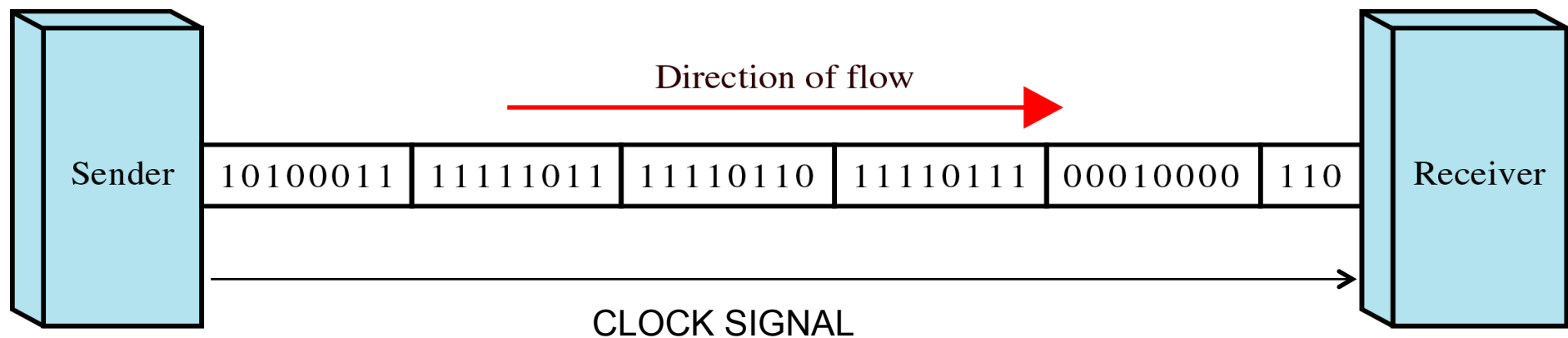
I2C and SPI synchronous serial links

◆ I2C stands for Inter-Integrated Circuit serial protocol. Also known as I^2C or Two Wire Interface (TWI).

◆ Originally from Philips Semiconductor, and it is now an industrial standard.

◆ Allows up to 127 devices to be connected, each having a unique address.

◆ Up to 400kHz data rate.

◆ SPI stands for Serial Peripheral Interface Bus.

◆ Both of these are common synchronous serial links for connecting to other chips in the systems, such as ADC, DAC and other sensors.
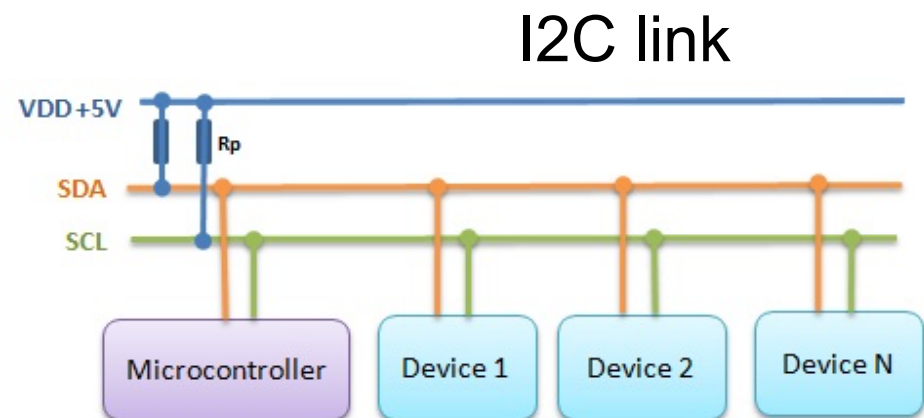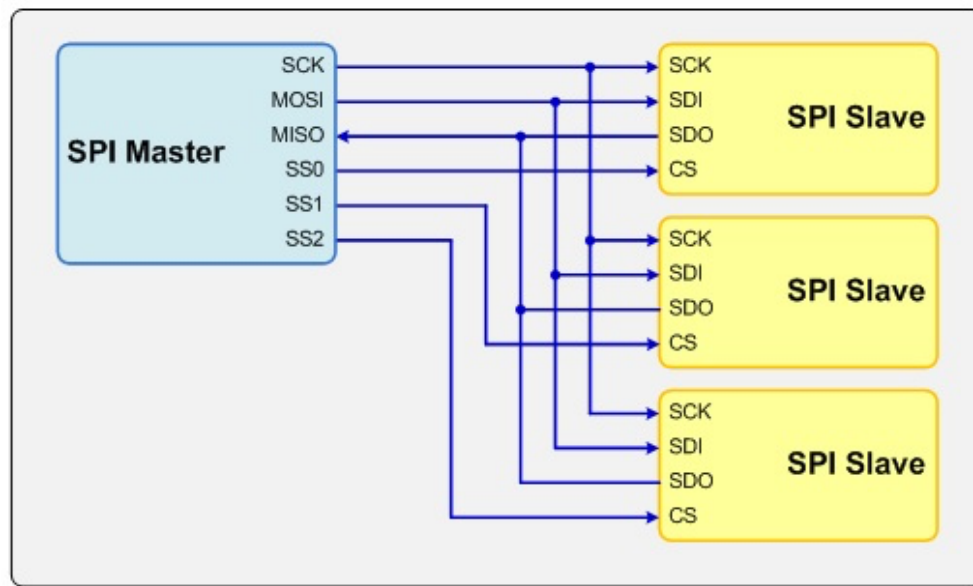

I2C link

Comparison of the three serial links

◆ The Pyboard has 4 UARTs, 2 each of SPI and I2C links.

◆ Micropython provides library functions to drive these interfaces.

◆ We will only use UART on this course.

	Synro nous		Asynchronous
	SPI	I2C	UART
Max Bit Rate	10Mbit/s	1Mbit/s	500kbit/s
Max devices	Limited by pins	127 devices	point to point
No. of pins	3 + n	2	2
Pros	Simple, low cost high speed	Low pin count; allows multiple masters	Long distance, good noise tolerance
Cons	Single master, short distance	Slow, short distance	Only point-to-point, slow
Applications	Connect to peripherals on PCB	Share bus connection with periperals on same PCB	Connect computers to terminals and other slower systems

Bluetooth wireless links

- Bluetooth is a cable replacement technology.
  - 1Mb/s, range ~10m, much lower power than wifi and cheaper
- We use **Bluetooth Low Energy**, a version of Bluetooth that uses much less power, but also has much lower data rate (realistically less than 100kbit/s)
- Bluetooth standard defines a **protocol stack** to enable different types of devices to communicate.

- The Bluetooth stack includes protocols for the radio layer all the way up to device discovery, service discovery, etc.
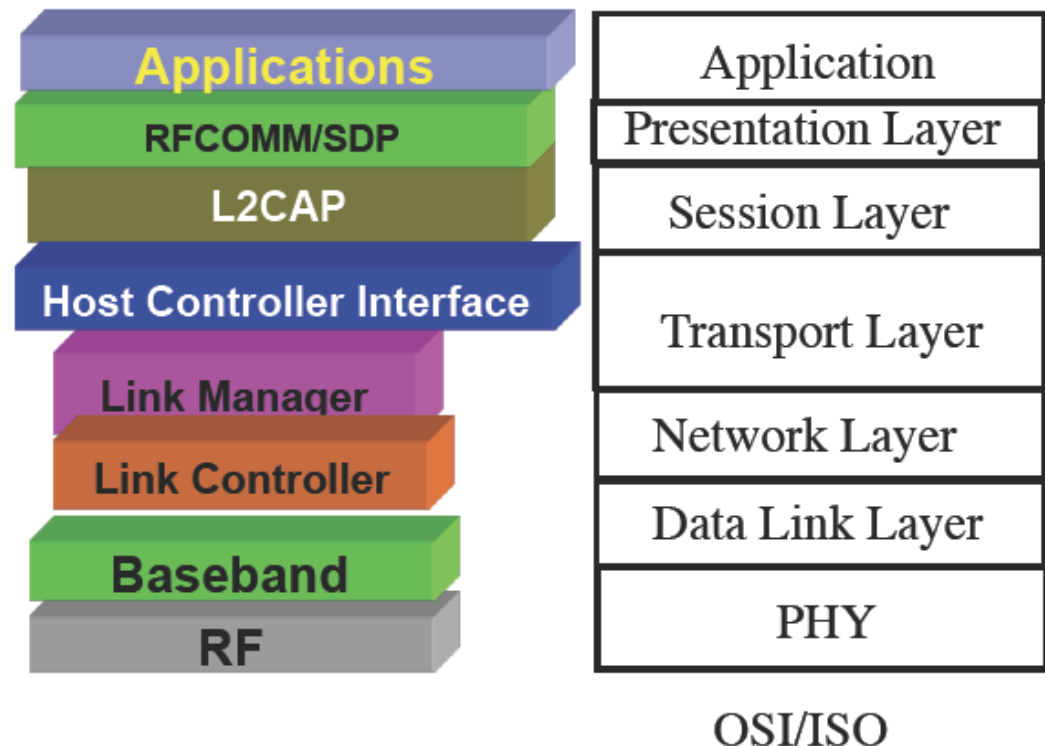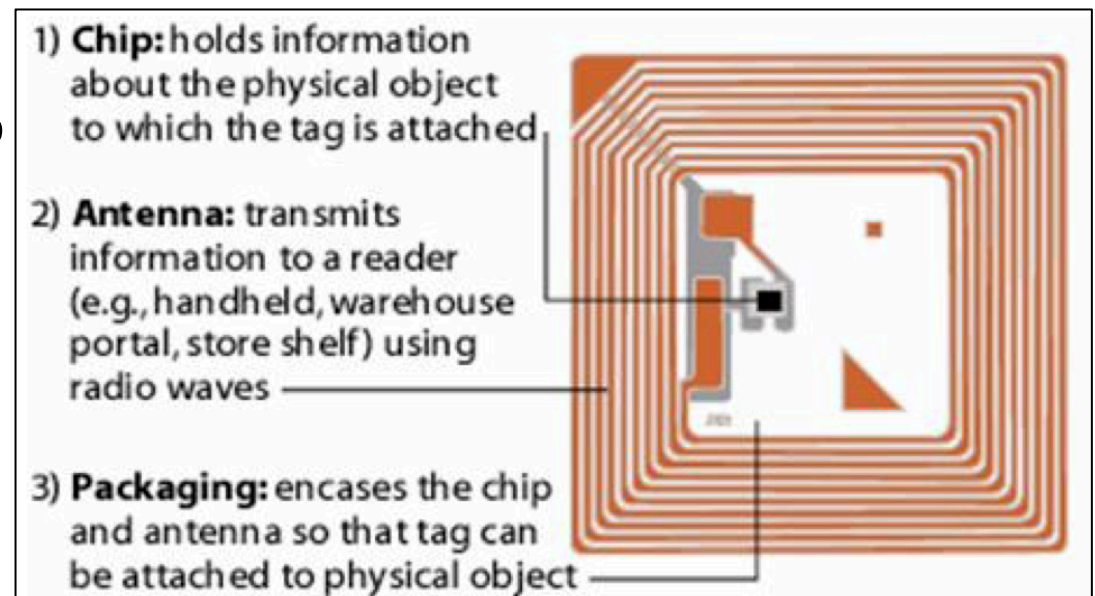
A video on Bluetooth Low Energy (5 min)

What is RFID?

- ◆ Radio Frequency Identification (RFID) is a technology that employs a microchip with an antenna that broadcasts its unique identifier and location to receivers.

- ◆ It employs a microchip called a smart tag, broadcasts unique 96-bit identifier to receiver.

- ◆ The receiver relays the data to a computer.

- ◆ A RFID Tag contains two main parts:
  - • Silicon chips
  - • Antennas
- ◆ These components enable tags to receive and respond to radio frequencies queries from RFID transceivers.
- ◆ Two types of RFIDs:
  - • Passive
  - • Active

1) **Chip:** holds information about the physical object to which the tag is attached

2) **Antenna:** transmits information to a reader (e.g., handheld, warehouse portal, store shelf) using radio waves

3) **Packaging:** encases the chip and antenna so that tag can be attached to physical object

RFID Tags types

◆ **Passive**
- Have no internal power supply
- Electrical current induced in antenna by the incoming signal provides power for integrated circuit in tag to power up and transmit response
- Very Small, Limited Range, Unlimited Life

◆ **Active**
- Have their own internal power source
- Many operate at fixed intervals
- Also called beacons (broadcast own signal)
- Large (coin), Much larger memories, Longer range

Four main frequencies:

	Frequency	Distance	Example Application
LF	125khz	Few cm	Auto-Immobilizer
HF	13.56Mhz	1m	Building Access
UHF	900Mhz	~7m	Supply Chain
µwave	2.4Ghz	10m	Traffic Toll

A video about RFID (4 min)

Chip

Substrate

Antenna coil

Tag-it™

RFID Tag