Digitisation

Digitisation is creating a digital *(bits and bytes)* version of analog signal or physical object (e.g. sound, light, book, temperature …).

Reasons for digitisation:

- **Easier share/distribution** – digital form of information can be easily shared with others.
- **Simple duplication** – creation of copies in the digital form is trivial unlike in case of the real objects/phenomena.
- **Deterioration of original objects** – originals (books, paintings, buildings, analog recordings) may age with irreversible effects, or they can vanish completely. Digital version can be kept relatively safely, as it can be copied and kept in multiple places and on multiple carriers.
- **Mass and rapid processing** – digital version of objects or physical phenomena can be easily processed by computers (statistics, modelling, simulations etc.). Also search is more rapid in the digital form.
- **Reversible modifications** – digital versions can be altered, but the changes can be easily reversed – such changes are impossible in case of real objects.
- **Efficient storage** – keeping real objects takes much more space and time.

Process

The input for digitisation is always an analog signal – light, sound, pressure etc. Analog signals are continuous in both, the possible values the signal may reach at a time, and the moments signal is present. Digital signal (as the data carrier) is discrete in both aspects – the signal values and moments.

If the signal is treated as a function, then digitisation performs a transformation **from (theoretically) infinite domain and range** of the analog signal to **discrete domain and range**.

Phase 1: Level Discretisation

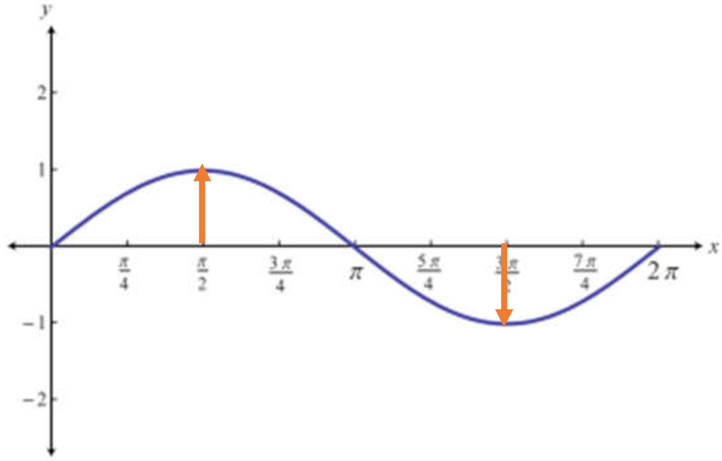
- Sometimes also **sampling**
- Discretisation of the domain
    - Sound, temperature – time
    - Image – space (2D, 3D)
    - Video – both, time and space
- The signal is measured in particular moments of time/space, not continuously
- The measured characteristic is the **signal amplitude** (usually)
- **Nyquist sampling theorem:**

$$f_s = 2f_{max}$$

f_s – sampling frequency

f_{max} – maximum frequency of the signal to be captured reliably

Intuitive reasoning could be illustrated on the sine function:

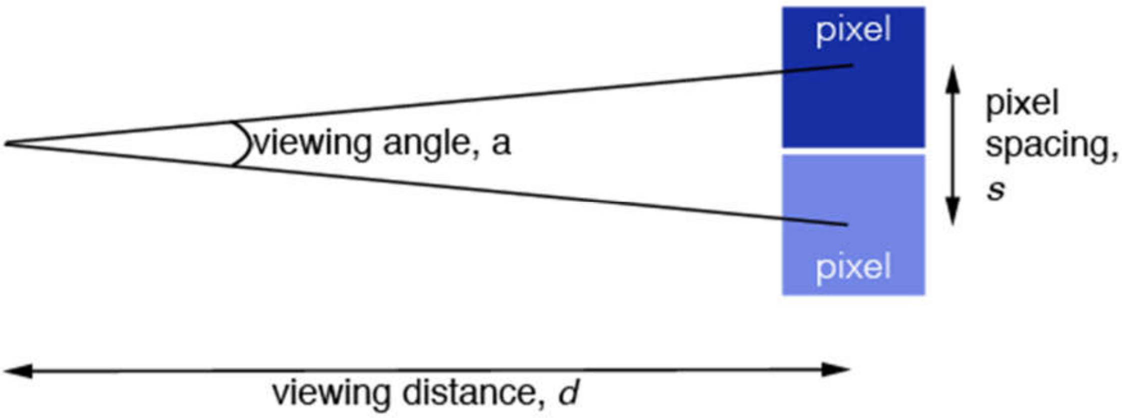


The minimum number of samples per period (if we want to restore something resembling the original signal) is 2 – at the moment of the maximum ($\frac{\pi}{2}$), and minimum ($\frac{3\pi}{2}$). One sample is simply not enough.

Example:

Sound → the highest frequency humans can hear is cca 20 kHz. To digitise it, the sampling frequency must be twice as high at least, i.e. 40 kHz.

Another example → human vision, regarding its angular resolution, may recognise details as small as one arc minute.



If we do not want to see individual pixels, we should have a device (distance eye ←→ device 50 cm) with pixels as close as:

pixel spacing < 2d tg(a/2)

pixel spacing < 2 . 0,5 . 1,454.10-4 = 1,454.10-4 m = 0,1454 mm

When recalculated to inches, the density of pixels should be 174 pixels per inch, if viewed from 50 cm.

For smartphone it would be (typical viewing distance is about 28 cm):

pixel spacing < 2 . 0,28 . 1,454.10-4 = 8.145 . 10-5 m = 0,08145 mm

Pixel density: 312 pixels per inch

For the digitised picture it would mean we should set sampling at 312 pixels per inch of the display at least, if viewed on the smartphone with sufficient physical pixels density.

When images are digitised, they are typically sampled in 3 modes – separately for red, green, and blue; forming separate channels, which are then mixed (in digital cameras using Bayer filter).

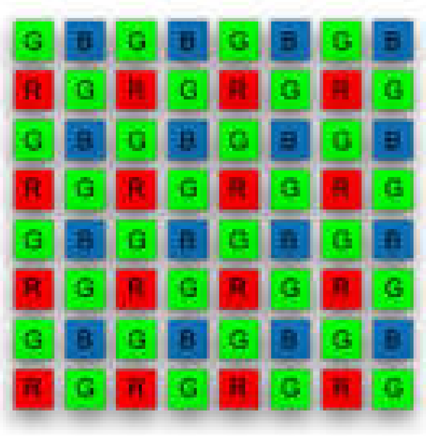
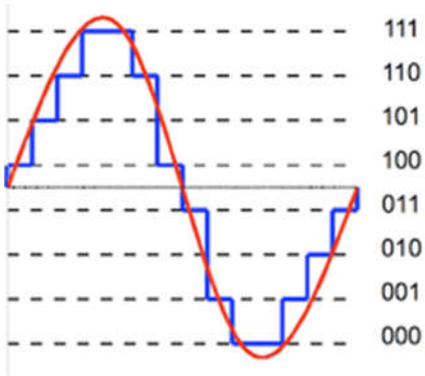


Figure 1: Bayer filter

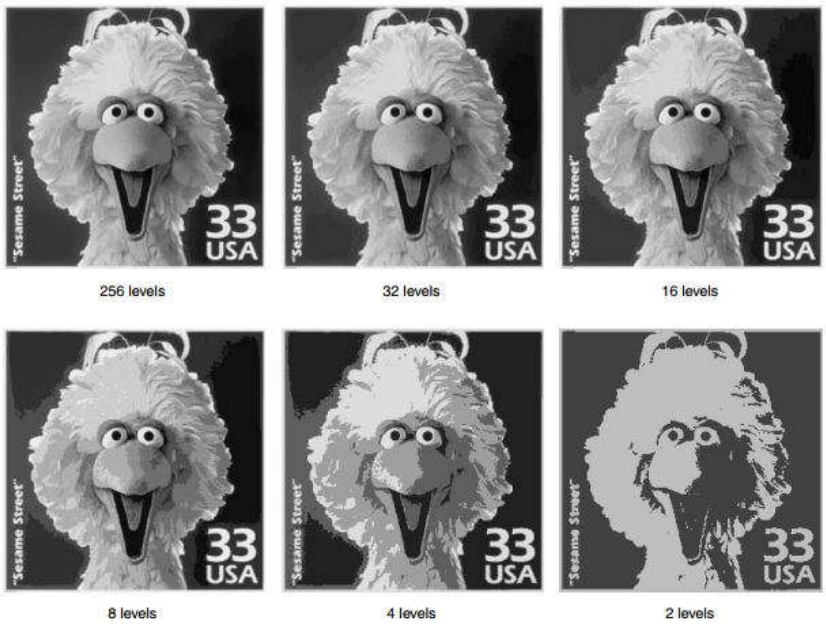
Phase 2: Quantisation

It is the discretisation of the signal intensity. The number of possible levels is limited by the number of bits per sample. The said number of bits is called **bit depth**.

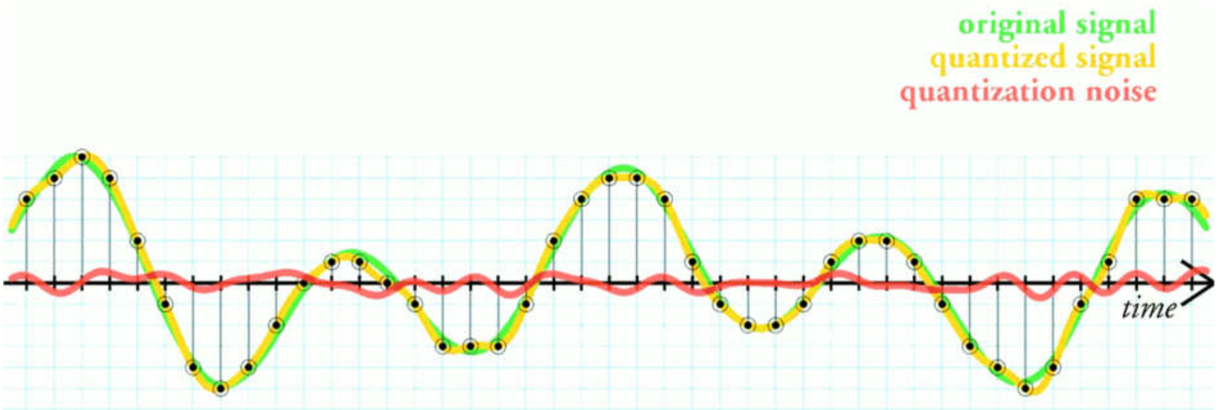
Example: if we use 3 bits for each sample, then we may use $2^3 = 8$ different levels.



Generally speaking, the higher number of bits, the better quality.

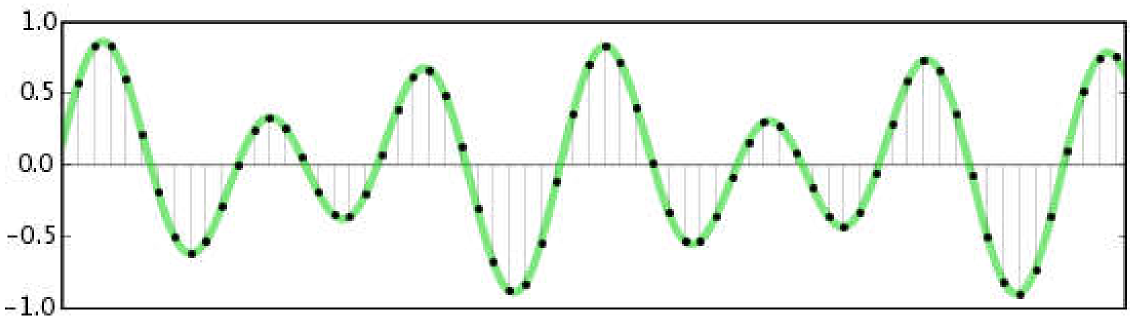


Quantisation is done by rounding to the closest level, which has matching binary representation. This rounding distorts the digital copy of the original. The error is called **quantisation noise**.



Example of the Digitisation Process

- Digitised phenomenon – sound
- Goal: capture human voice – typical frequencies of the human speech are between 300 and 3400 Hz
- **Sampling:** The highest frequency to be digitised – 3400 Hz → the sampling frequency is 6800 Hz, i.e. there will be taken 6800 samples per second.



Sampling (source: http://manual.audacityteam.org/m/images/e/e2/waveform_digital.png)

- **Quantisation:** the amplitude levels will be stored in 4 bits → 16 various levels of the amplitude (*to be honest – not enough for a real situation, but a picture with 256 levels is kind of challenging* ☺).

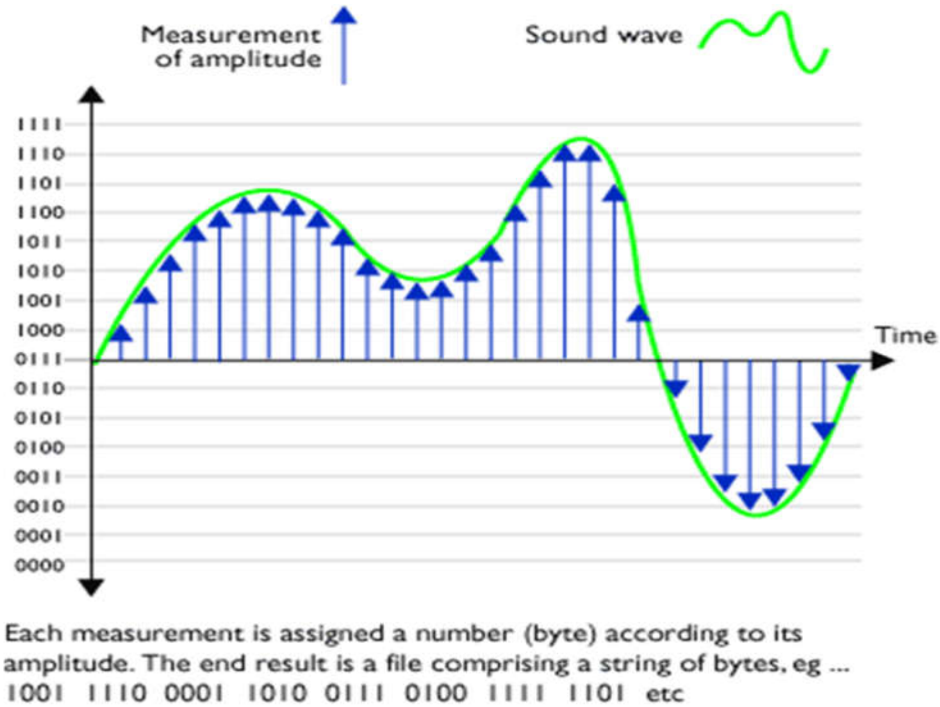


Figure 2: Quantisation - bit depth = 4 b (source: http://www.planetoftunes.com/digital-audio/dig_media/sampling_in_4_bit_convertor.gif)

Analog-to-Digital Converter

Analog-to-digital converter (ADC) is a device (usually a chip), which performs the level discretisation/sampling and quantisation with direct encoding into N bits / the number depends on the ADC properties.

The ADC is usually preceded by an **analog sensor** – a device, which converts observed phenomenon into voltage.

Common Digitisation Devices

- *sound* – microphone + soundcard (which comprises AD/DA converter)
- *image*
  - 2D – (flatbed) scanner, digital camera, X-ray camera
  - 3D – 3D scanner (laser, ultrasound, touch), computer tomography, MRI
- *video* – digital camera, camcorders, IP camera
- *other phenomena* – by related sensors – temperature, humidity, pressure, motion, gravity, gas, magnetic field …

PS: there is also a term **digitalisation**. Sometimes it is used as a synonym for digitisation; however, its more correct meaning is the introduction of digital technologies into process (e.g. *digitalisation of the business*; it would be weird, if you used *digitisation of the business*).

Do you understand this topic? You do, if …

… you can list and clarify 3 reasons for the digitisation,

… you can name the phases of the digitisation,

… you know what sampling is,

… you can explain why the sampling frequency should be twice as high as the top frequency,

… you can clarify the meaning of the term **bit depth**,

… you know how many levels can be recognised for a certain bit depth,

… you can explain why quantisation noise occurs.

Exercises

1. What determines the sampling rate in case of the flat bed scanner?
2. One of the analog sensors is a thermistor. It represents the temperature with voltage levels. A common thermistor, LM35, can represent the values from -40°C to 110°C and matching voltages from -0.4 V to +1 V. If the temperature is then digitized to the bit depth = 10 b, what is the 2^{nd} lowest temperature it can detect?