### Visual Computing - Lecture notes week 1


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# 1. The Digital Image

## 1.1 What is an image?

### Image as a 2D signal

The **signal** is a function depending on some variable with physical meaning. The **image** is a continuous function, where we either have 2 variables `x y` which are the coordinates, or, in case of a video, three variables `x y` and the corresponding time in the video. Usually, the value of the function is the **brightness**.

*Images in Python:*

```
# Load a picture into Python
import cv2
img = cv2.imread('foo.jpg')

# Display the image in Python
cv2.imshow('My image', img)
cv2.waitKey(0)

# Print the image data array
img

# Print the size of the image array and create a subimage
img.shape
subimg = img[72:92, 62:82]
```

```
# Random image in Python
import numpy as np
import cv2
t = np.random.rand(64, 64)
cv2.imshow('Random', t)
cv2.waitKey(0)
```

In summary, an **image** is a picture or pattern of a value varying in space and/or time. It is the representation of a *continuous* function to a *discrete* domain: `f : R^n -> S`.

As an example, for grayscale CCD images, `n = 2` and `S = R^+`.

### What is a pixel?

*A pixel is not a little square!*

**Pixels** are point measurements of a function (of the above described continuous function).

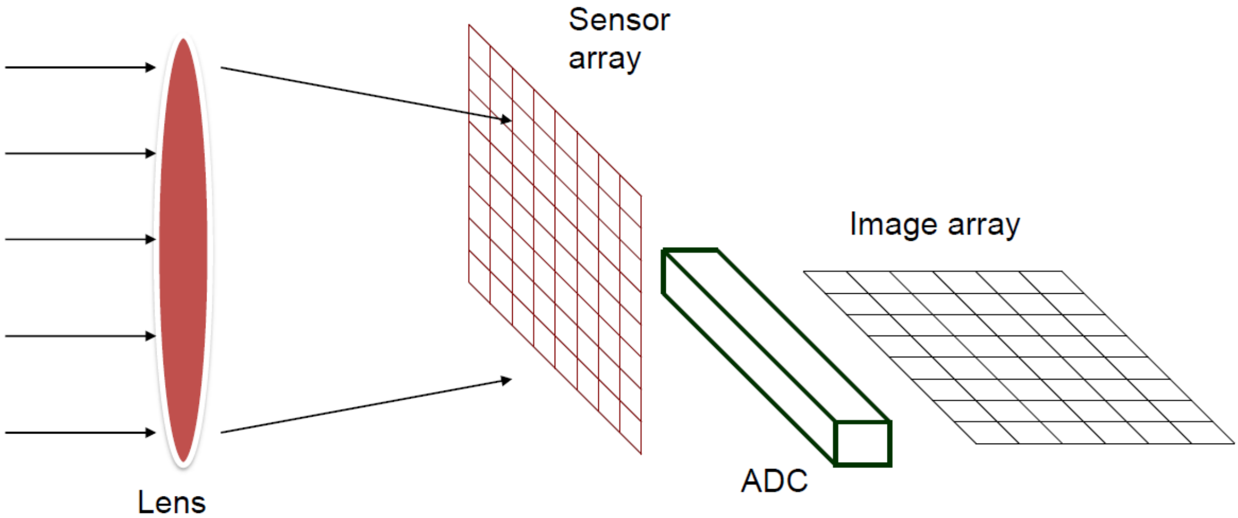
## 1.2 Where do images come from?

There are several things where pictures can come from:

- Digital cameras
- MRI scanners
- Computer graphics packages
- Body scanners
- Many more...

## Digital cameras

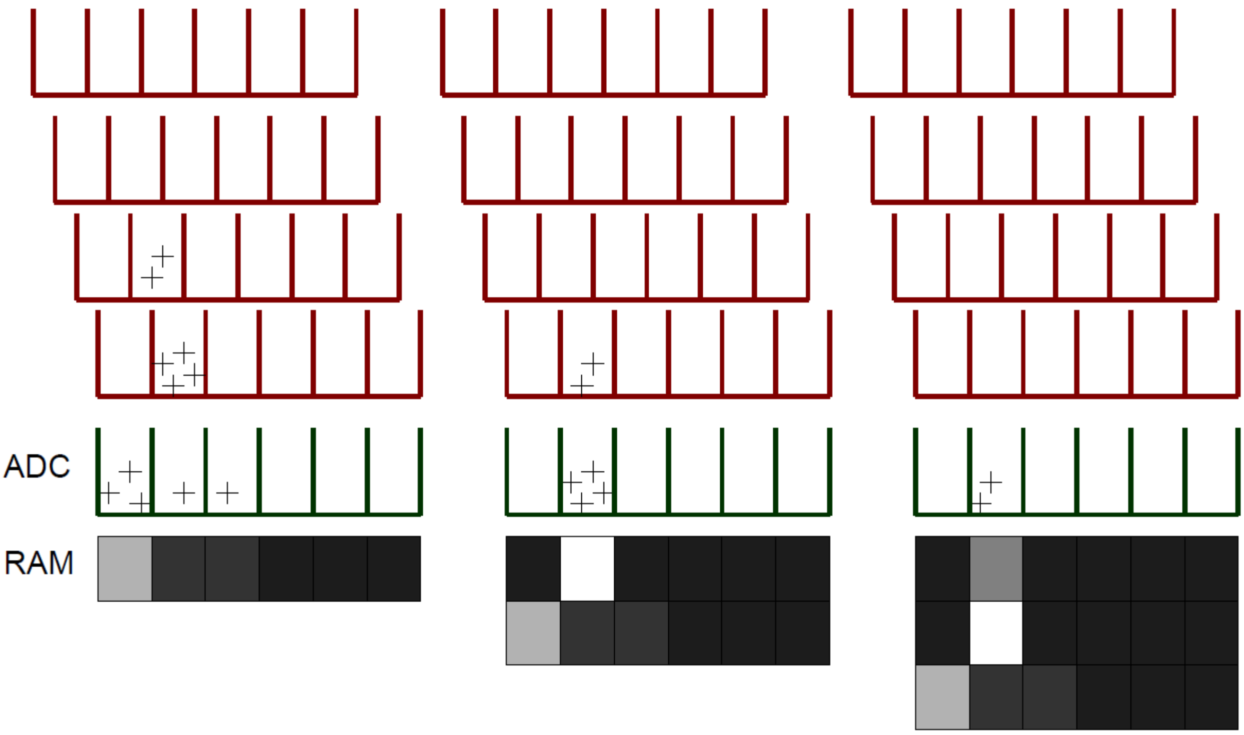
Simplified, the **digital camera** consists of the following parts and is said to be a *Charge Coupled Device (CCD)*:




The **sensor array** can be < 1 cm^2 and is an array of *photosites*. Each photosite is a bucket of electrical charge, and this charge is proportional to the incident light intensity during the exposure.

The **analog to digital conversion (ADC)** measure the charge and digitizes the result. The conversion happens line by line in that charges in each photosite move down through the sensor array.

Example:



Because each bucket has a finite capacity, if a photosite bucket is full, it can overflow to other buckets, which leads to **blooming**.

Even without any light, there will still be some current which can degrade the quality of a picture. CCD's produce thermally-generated charge, which results in a *non-zero output* even in darkness. This effect is called the **dark current**.

# 1.3 CMOS

**CMOS** sensors have the same sensor elements as CCD. Each photo sensor has its own amplifier, which results in more noise and a lower sensitivity. However, since CMOS photo sensor use standard CMOS technology, we might put other components on the chip (such as "smart pixels").

## CCD vs. CMOS

*CCD*

- Mature technology
- Specific technology
- High production cost
- High power consumption
- Blooming
- Sequential readout

*CMOS*

- More recent technology
- Cheap
- Lower power consumption
- Less sensitive
- Per pixel amplification
- Random pixel access
- On chip integration with other components

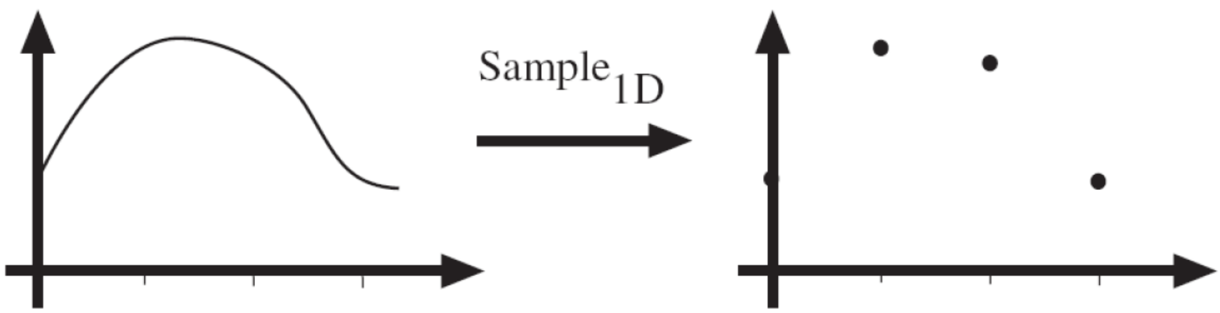
## Rolling shutter

By resetting each line in the sensor line by line (the "shutter"), each line will start capturing light a little before the line below and so on. Each line in the picture is therefore a little behind in time as the line above.

# 1.4 Sampling in 1D

**Sampling** in 1D takes a function, and returns a vector whose elements are values of that function at the sample points.

Example:



Sampling solves one problem with working with continuous functions. How do we store and compute with them? A common scheme for representing continuous functions is with **samples**: we simply write down the function's values as discrete values at many sample points.

## Reconstruction

**Reconstruction** describes the process of making samples back into a continuous function. We might do this for several reasons:

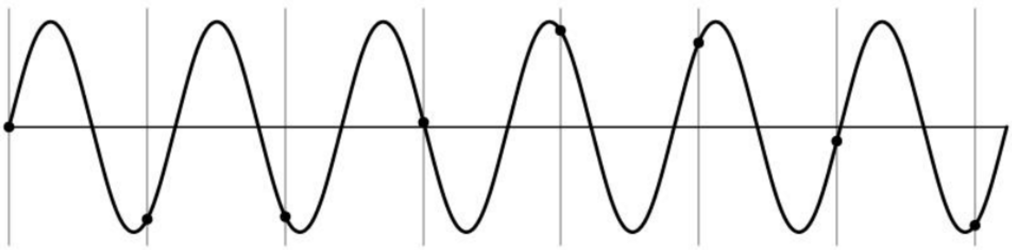
- For output where we need a realizable method
- For analysis or processing, where we need a mathematical method
- Instead of "guessing" what the function did in between sample points

## Undersampling

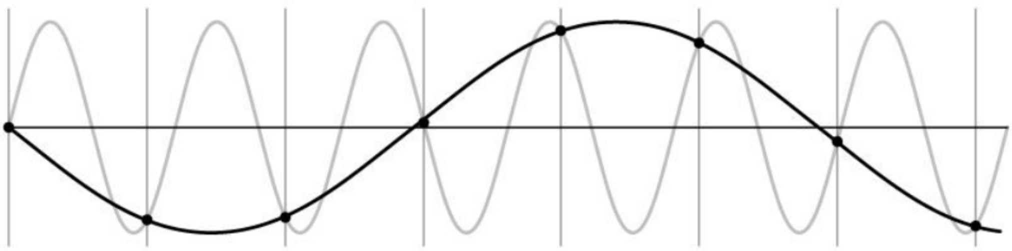
Unsurprisingly, if we undersample some function, we loose information.

Example: If we undersample the following `sin` wave, it gets indistinguishable from lower frequencies:

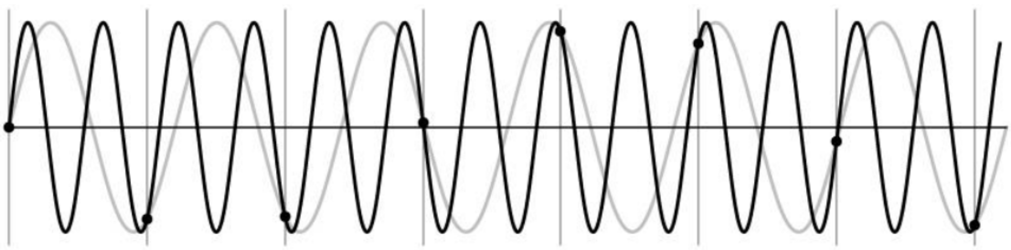
*Sample:*



*Reconstruction 1:*



*Reconstruction 2:*



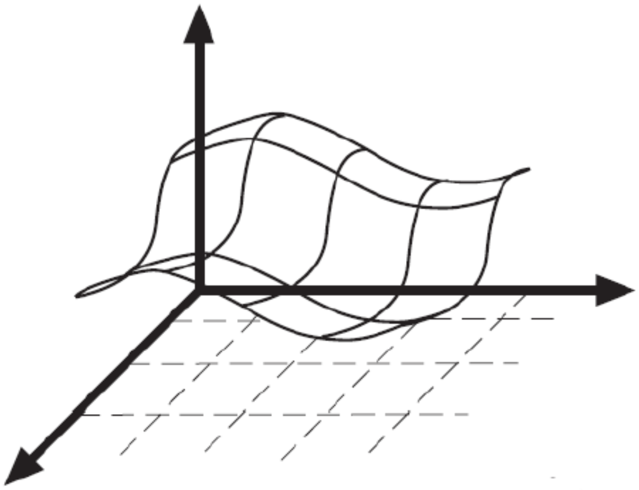
This effect is what we call **aliasing**, i.e. *"Signals travelling in disguise as other frequencies"*.

# 1.5 Sampling in 2D

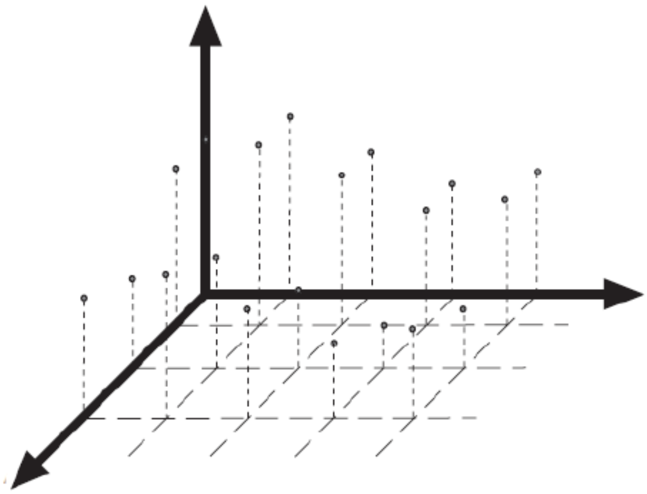
**Sampling** in 2D takes a function and returns an array. We allow the array to be infinite dimensional and to have negative as well as positive indices.

Example:

*Function:*



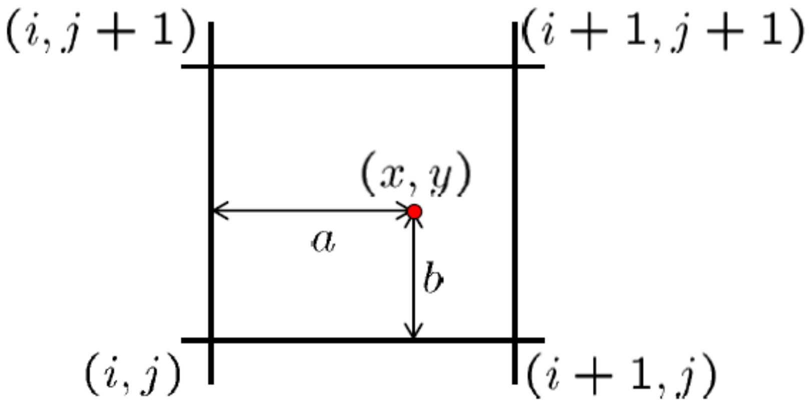
*Sample:*



## Reconstruction

In 2D, a simple way to reconstruct a function from a sample is to use **bilinear interpolation**, which works essentially the same as linear interpolation: we calculate two lines in each direction, and then take the intersection of the two lines.

Example:




$$
\begin{aligned}
f(x,y) = \quad & (1-a)(1-b) && f[i,j] \\
& +a(1-b) && f[i+1,j] \\
& +ab && f[i+1,j+1] \\
& +(1-a)b && f[i,j+1]
\end{aligned}
$$

# 1.6 Nyquist Frequency

We define the **Nyquist Frequency** as half the sampling frequency of a discrete signal processing system. The concept tells us, that if the signal's maximum frequency is at most the Nyquist frequency, then we can reconstruct the signal.

# 1.7 Quantization

When sampling, real valued functions will get digital values, i.e. integer values. This means that **quantization** is lossy: after quantization, the original signal cannot be reconstructed anymore.

This is in contrast to sampling, as a sampled but not quantized signal *can* be reconstructed.

## Usual quantization intervals

The following are the most widely used quantization intervals:

- Grayscale image: `8 bit = 2^8 = 256` gray values
- Color image RGB (3 channels): `8 bit/channel = 2^24 = 16.7M` colors
- 12 bit or 16 bit for some sensors

# 1.8 Image Properties

### Image resolution

Simply tells the amount of pixels our pictures has.

### Geometric resolution

*How many pixels per area?*

Tells us how many pixels we have per a given area (e.g. how many pixels per square centimeter of picture).

### Radiometric resolution

*How many bits per pixel?*

Tells us how much information each pixel can store.

## 1.9 Image Noise

A common model is the **additive Gaussian noise**, which means that we measure some signal with our processor but have some deviation/noise in our measurement:

$$I(x,y) = f(x,y) + c$$

$$\text{where } c \sim N(0,\sigma^2).\ \text{So that } p(c) = (2\pi\sigma^2)^{-1} e^{-c^2/2\sigma^2}$$

One might also use the much more meaningful assumption of **Poisson noise**:

$$p(k) = \frac{\lambda^k e^{-\lambda}}{k!}$$

### SNR

The **signal-to-noise ration (SNR)** `s` is an index of image quality:

$$s = \frac{F}{\sigma},\ \text{where } F = \frac{1}{XY}\sum_{x=1}^{X}\sum_{y=1}^{Y} f(x,y)$$

Often used instead: *Peak Signal to Noise Ratio* (PSNR) $s_{peak} = \frac{F_{\max}}{\sigma}$