Image Processing - Introduction

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1. Introduction

In this lecture we give an introduction to

- what image processing is.
- what the origins of image processing are.
- what applications image processing has.
- how visual perception works.
- how images are acquired.
- where you can get test images.
- what topics this course contains.

Note

In this lecture we will not go into the mathematical and algorithmic details but mainly aim at providing a motivation for the course.

1.1 Digitization

What we discuss in this lecture is called digital image processing but we omit the term *digital* most of the time. Traditionally signals and images have been processed in an analog fashion, e.g. by using special electronic circuits. Radio and television are the prime examples for this but also in classical photography the images have been processed in an analog fashion.

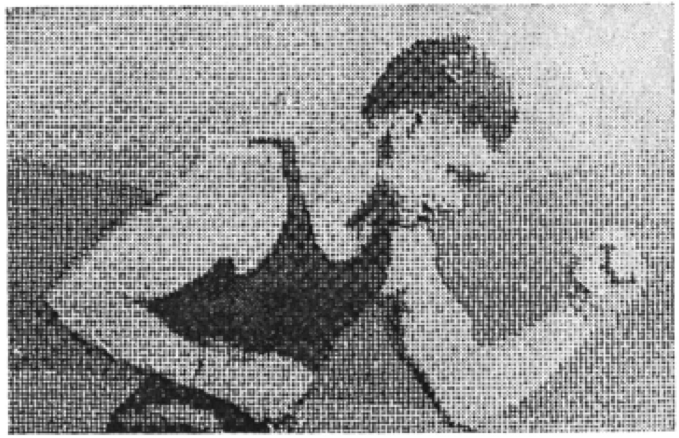
Nowadays (since about 2000) analog signal and image processing has basically been completely overtaken by their digital counterparts and therefore we stick to just the term **image processing**.

Definition

Wikipedia: Digitization is the process of converting information into a digital (i.e. computer-readable) format. The result is the representation of an object, image, sound, document or signal (usually an analog signal) by generating a series of numbers that describe a discrete set of points or samples. The result is called digital representation or, more specifically, a digital image, for the object, and digital form, for the signal.

2. Origins of Image Processing

One of the first applications of digital image processing was the transmission of pictures over a cable in the atlantic ocean from New York to London in the 1920. It allowed to transmit an image in about three hours instead of a week. The bartlane cable picture transmission system used special equipment to encode the picture on the transmitter side and decode it on the receiving side using a special printing equipment. The system initially allowed to encode 5 different gray levels. Here is one of the first pictures:



It is remarkable that this form of digital image processing was already done without the computer being invented in its todays form.

The computer was developed in the years 1940 - 1960 and started with very few circuits that were only capable of doing a minimal number of operations. Starting from the 1960s computers got powerful enough to do meaningful image processing on a low image resolution. One of the first practical applications of computer techniques for image processing was the correction of various types of image distortions captured with an on-board television system on a U.S. spacecraft when landing on the moon:

Ranger 7 took this image, the first picture of the moon by a U.S. spacecraft, on July 31, 1964 at 13:09 UT (9:09 AM EDT), about 17 minutes before impacting the lunar surface.

In parallel with space applications, digital image processing techniques began in the late 1960s and early 1970s to be used in medical imaging, remote earth resources observations, and astronomy.

Within tomographic imaging techniques, such as the computed tomography (CT) one aims to look into patients without slicing them. These techniques inherently required image processing algorithms in order to reconstruct the slices from external measurements. Here is an example of a CT image:

With the introduction of the personal computer in the 1980s, image processing got more accessible to many researchers and in turn many algorithms for

- image enhancement
- image restoration
- image compression
- image segmentation

have been developed. In addition to the personal computer, the digital photography was a main driver for the field.

This picture was taken at the Piazza San Marco after Johannes Paul II. died in 2005:

One can see that almost nobody was taking pictures or videos.

In contrast, the following picture shows the Piazza San Marco after Benedict XVI has resigned in 2013:

This shows that the availability of the smartphone and the associated cloud data, the amount of image data being stored and processed has increased significantly.

It is about to increase even further in the future since the digital revolution is not yet over.

3. What is Digital Image Processing?

Let us start by defining what a digital image is:

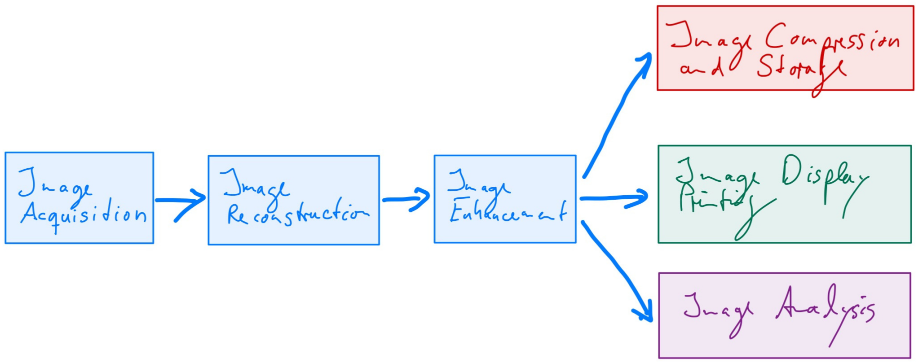
Definition

Wikipedia: A digital image is an array composed of picture elements, also known as pixels, each with finite, discrete quantities of numeric representation for its intensity or gray level that is an output from its two-dimensional functions fed as input by its spatial coordinates denoted with x, y on the x-axis and y-axis, respectively.

The field of image processing is not sharply defined but overlaps with some related fields such as signal processing, image analysis, and computer vision.

The best way to illustrate what image processing involves is to look at the following pipeline:

3.1 Image Processing Pipeline



Let us next look at each step individually:

- **Image Acquisition:** The image data needs to be acquired somehow and we use a *sensor* for that. The sensor can be some CCD or CMOS chip in a digital camera but also be some radar system, or electromagnetic coils in a medical imaging device.
- **Image Reconstruction:** In many cases the image first needs to be reconstructed from the *raw data* acquired at the sensor. This can be some element-wise corrections, or some correction involving the application of a digital filter, or an entire solution of an inverse problem (see tomography).
- **Image Enhancement:** The image then often needs to be enhanced, e.g. the colors need to be optimized to correct for suboptimal lighting, noise needs to be suppressed, blurred images need to be sharpened.
- **Image Compression and Storage**: The acquired and processed images need to be stored for later consumption. In order to do so it needs dedicated file formats and these often involve some form of image compression to reduce the file size.
- **Image Display / Printing**: A variety of images is meant to be consumed by the human eyes. Thus they need to be visualized either by displaying them on a screen or printing them on a sheet of paper.
- **Image Analysis:** Quite often one is not interested in the actual gray values of the picture but in the semantic meaning of them. Using *image analysis* algorithms such as segmentation, feature extraction and object classification it is possible to derive such semantic high-level information in an automated way.

Note

Image processing does not necessary involve all steps in the pipeline. For instance the image reconstruction step can often be skipped.

Based on this pipeline one can classify image processing algorithms into three layers.

- **Low-level**: In this layer some raw data is pre-processed, often pixelwise, to correct for distortions of the acquisition tool. This can be algorithms for noise reduction, contrast enhancement, and image sharpening. Input and output are usually images.
- **Mid-level**: In the middle layer the image itself is enhanced in order to make the high-level algorithms more applicable. This can be tasks such as
    - Segmentation (partitioning an image into regions or objects),
    - Description of those objects to reduce them to a form suitable for computer processing,
    - Classification (recognition) of individual objects.

  A mid-level algorithms usually gets an image as input and outputs attributes extracted from those images (e.g., edges, contours, ...)
- **High-level**: In this layer algorithms are summarized that aim for extracting semantic meaning within an image, i.e. cognitive functions normally associated with human vision are applied.

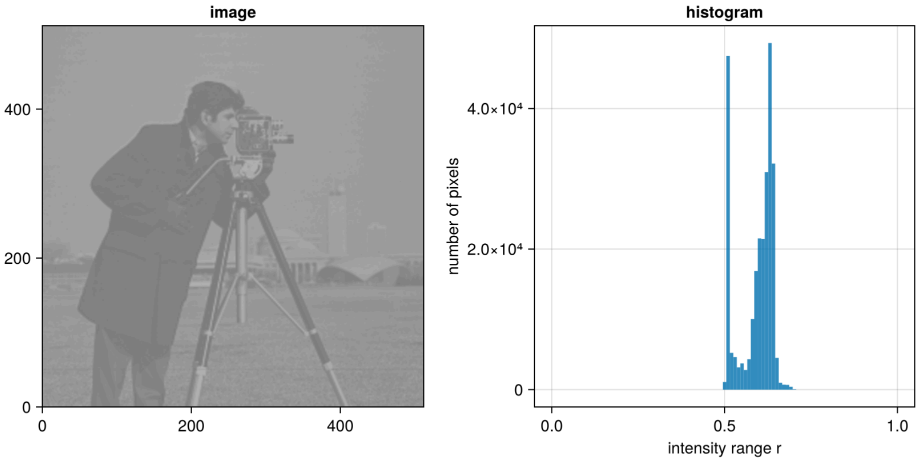
4. Examples and Applications

Next we summarize some examples and applications for image processing.

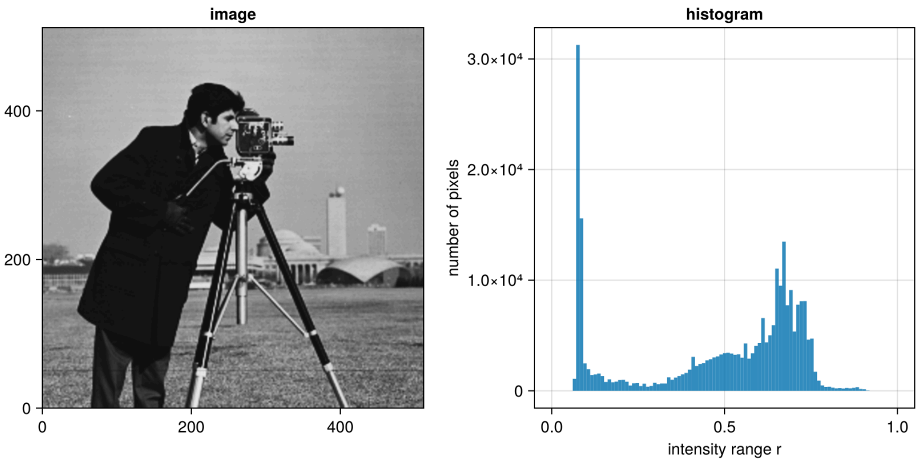
The first two examples *intensity correction* and *denoising* are part of the class of *image enhancement* algorithms that aim to fix certain issues present in raw images.

4.1 Intensity Correction

Take a look at the following image having a very low contrast. This means that the differences in the image gray values are quite low. This visual impression can be verified in the histogram, which confirms that only gray values between 0.5 and 0.7 are present in the image, while the full range would be $[0, 1]$.



In order to fix this we can *stretch* the histogram leading to the following image:

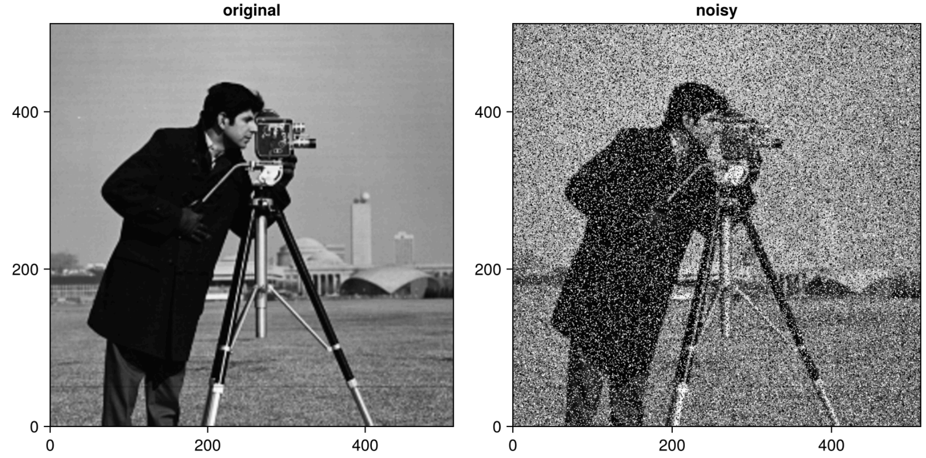


One can see that the image looks better and the details can be seen much more clearly now. In the histogram one can see the stretching effect.

Denoising

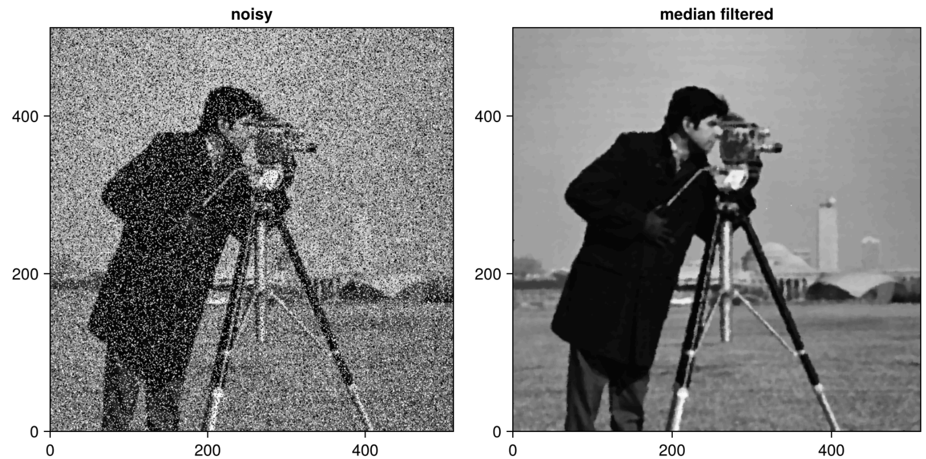
Quite often images are affected by noise. This can happen even with the best cameras since the detector has only a limited number of bits and the amount of light reaching the detector is often very low (e.g. in a dark environment).

The following shows an original and a noise affected image:



One can see that the image quality is drastically degraded.

To improve the image we can apply a median filter:



One can see the the result looks much better. Such good results are not always possible but in this case, the noise (salt and pepper noise) can be very effectively removed by applying a median filter.

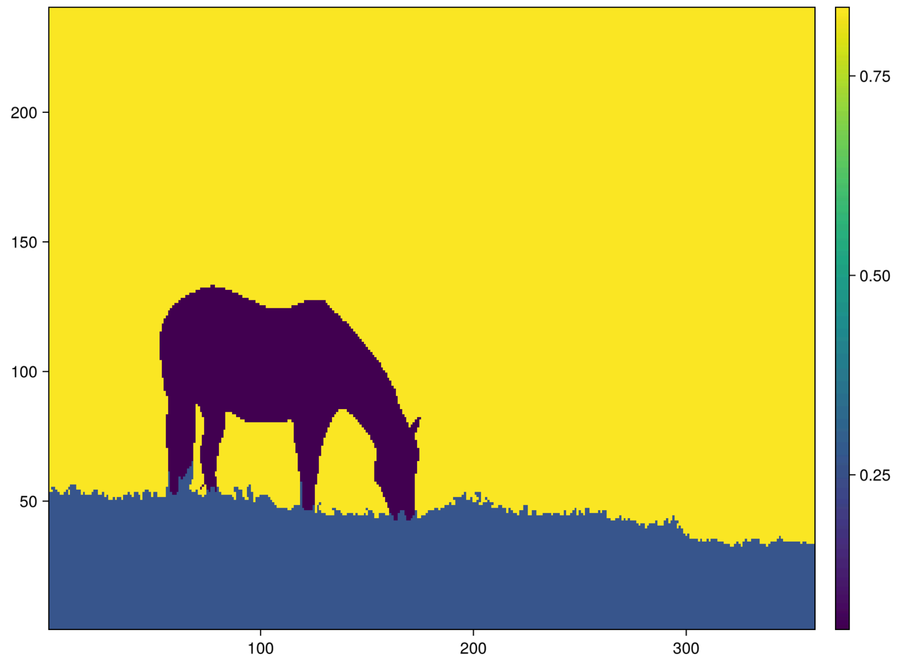
4.2 Image Segmentation

The next example that we look at is image segmentation.

In many cases we are not really interested in the pixel values itself but we want to know what *objects* are within an image. For instance if you are developing an automatic driving car, it would be of interest if a person is infront of the car.

But before recognizing the object to be a person we want to group pixels into regions that can be converted to objects in a later stage. And this is what image segmentation is doing. Let us take a look at the following picture:

We can see that there is a horse on a meadow. And in the background there is sky. When applying an image segmentation algorithm we get the following:



The algorithm successfully identified the three different regions and grouped them together.

The segmented image is more then just a collection of pixels but it preserves some more high-level information:

```
Segmented Image with:
  labels map: 240×360 Matrix{Int64}
  number of labels: 3
```

```
seg
```

The assigned values can be retrieved by:

```
[0.056147, 0.836064, 0.269845]
```

```
[segment_mean(seg, i) for i=1:3]
```

And one can also count the number of pixels in each region.

```
[6095, 63880, 16425]
```

```
[segment_pixel_count(seg, i) for i=1:3]
```

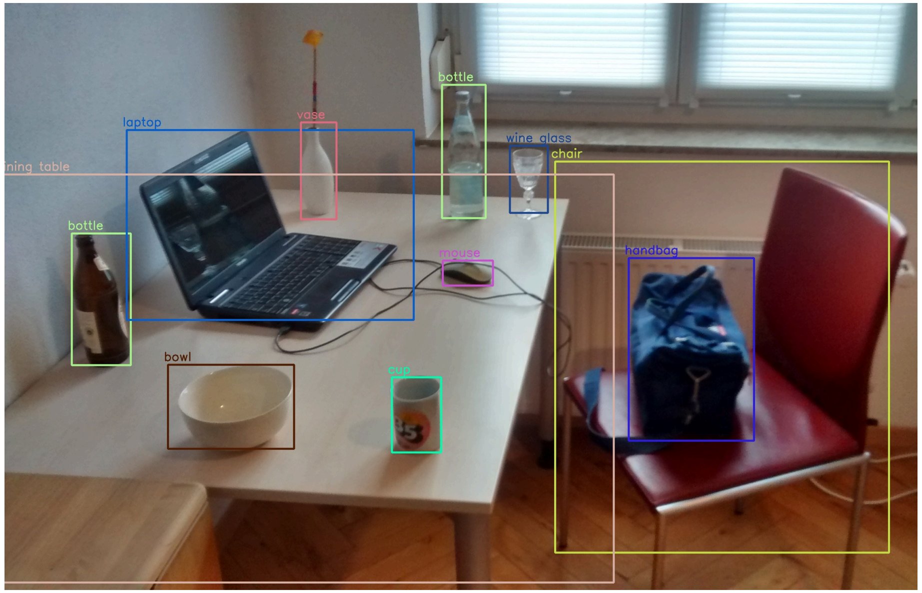
All these are additional *image attributes* we talked about before when introducing middle-layer image processing algorithms.

4.3 Object Detection and Recognition

Once the image is segmented one can perform the following operations to understand what the image actually contains.

1. First, one can do an *object detection*, which only classifies regions into classes: object and non-object. Quite often, the result is a list of bounding boxes.
2. Second, one can take each object and classify it by comparing it with a database of known objects.

The following shows a classification of objects into several object classes:

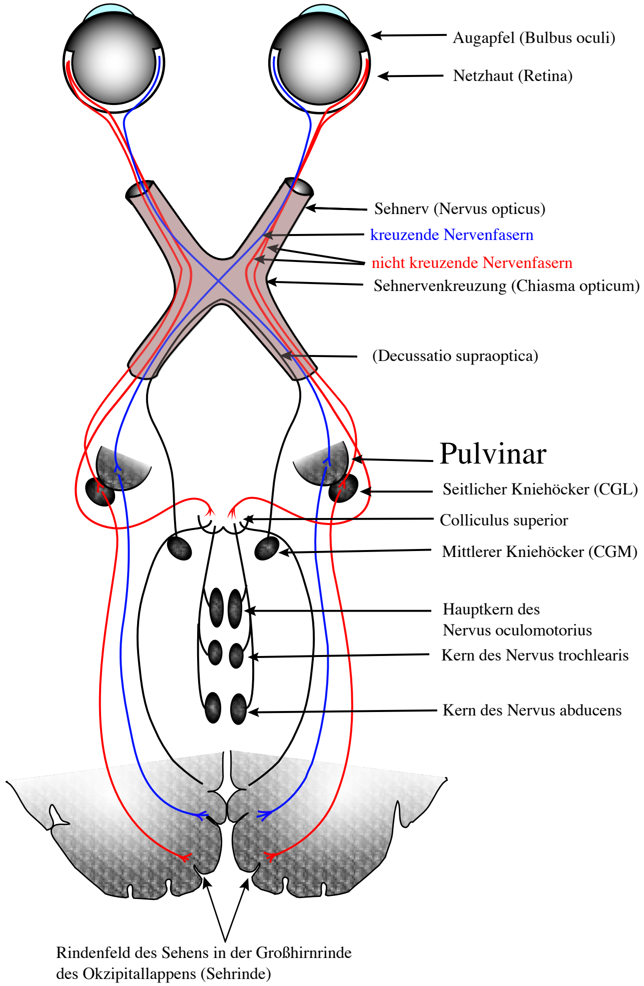


5. Visual Perception

Image processing even when performed entirely in a digital fashion is strongly linked to the visual perception of humans. What basically happens is summarized in the following steps:

1. Light rays are send to the objects reflecting the light.
2. The reflected light enters the human eye.
3. In the optical nerve, the light is converted into electrical signals.
4. These electrical signals are send to the brain, where an 2D image is formed.

The following image shows steps 3. and 4.



There are devices trying to emulate this form of visual perception:

- **cameras:** These are trying to capture what a human would see. The information is stored in a colorful 2D array, i.e. an image.
- **displays:** These are used to to convert the image information into something, which a human can again detect with the visual perception system.

> **Note**
>
> Since visual perception differs from human to human it is quite challenging to standardize these input and output devices. We will investigate this in the lecture on color image processing.

6. Image Sensing and Acquisition

Image sensing and acquisition is the process of determining a digital image. In its core this requires an image sensor, which is usually an abstract thing that converts some physical parameter into a (digital) signal. Let us look at the definition of a sensor:

Definition

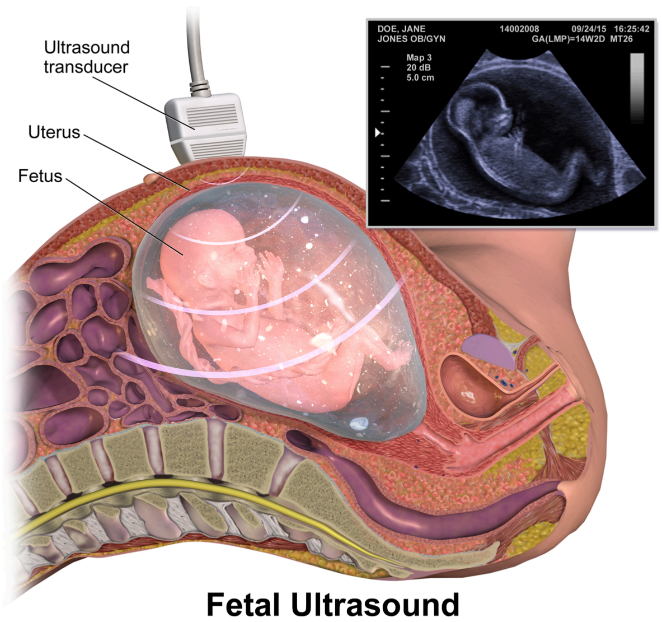
Wikipedia: In the broadest definition, a sensor is a device, module, machine, or subsystem whose purpose is to detect events or changes in its environment and send the information to other electronics, frequently a computer processor. A sensor is always used with other electronics.

In turn an *image sensor* is a sensor that not only generates one signal but an array of signals. This does not necessarily mean that the sensor itself is build in array form but quite often there can be a mix of mechanical, electronical, and computational components that are necessary to form the image.

To make clear that we are not only talking about camera sensors think about the following examples:

Ultrasound

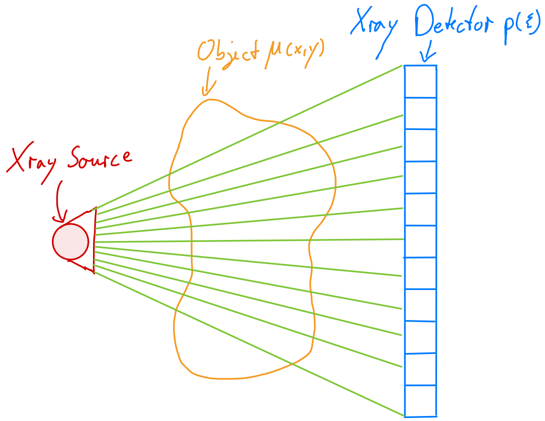
In ultrasound one uses sound waves that are emitted by a transducer into a human subject. Theses waves are reflected when they hit objects and can be recorded in the transducer. To form an image, the sound waves need to be emitted in different directions.



Computed Tomography

Another example from the field of medical imaging is the computed tomography that allows to determine a 3D image of the human body.

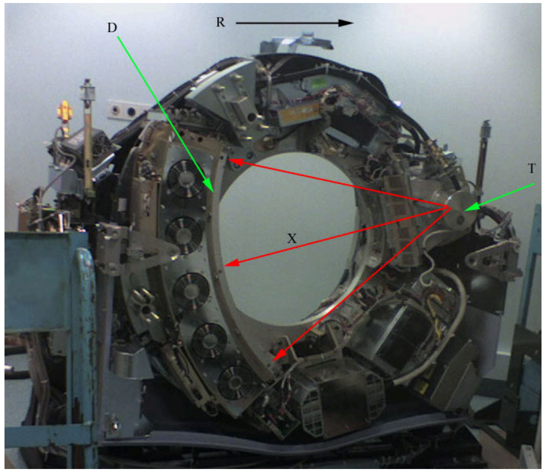
During a CT scan X-rays are passing through the image of interest. This is sketched in the following image:



The sensor in this example is the X-ray detector shown on the right. During the scan, the source and the detector are (mechanically) rotated and the line integrals through the patient are continuously scanned. This implies that:

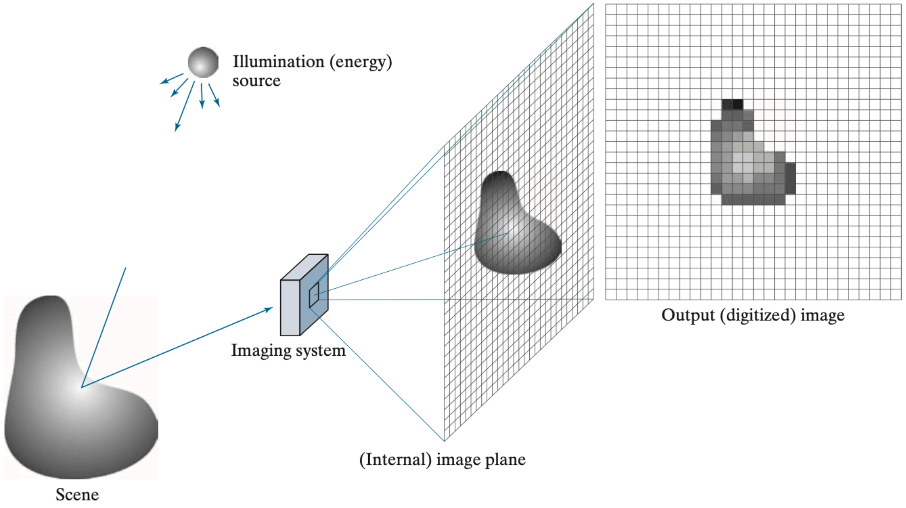
1. We have a combination of electrical and mechanical sensing.
2. A computational step (the so-called image reconstruction) is necessary to convert the raw data signals into an image.

Here is a picture of a real CT imager:

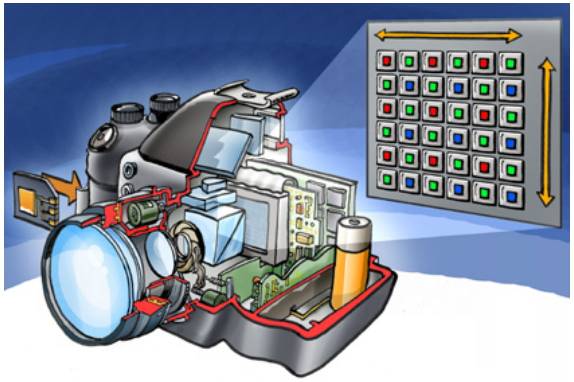


6.1 Image Sensors

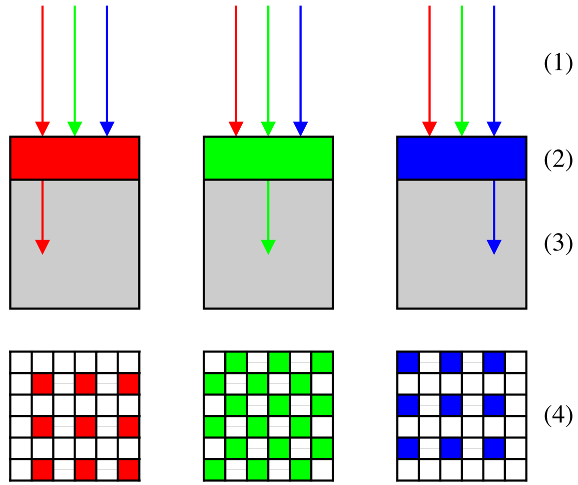
Our previous definition of a sensor that generates an image was a little bit more generic than what you find in some literature. Quite often an image sensor is restricted to those sensors that directly detect some electromagnetic wave and are constructed as an array of individual (scalar) sensor elements. These devices conceptually work like this:



For instance if you open your digital camera it looks like this:



One can see the an array of in this case 6×6 sensor elements. Since each element can only detect a single color one uses a so-called Bayer filter that arranges the red (R), green (G) and blue (B) channels into a certain mosaic pattern:



The filter only lets light of a certain wavelength pass to the photo sensor. Other wavelengths are blocked.

One can observe that there are much more green than red and blue sensor elements. The reason is that the human eye also is most sensitive to green light and this model thus mimics the physiology of the human eye.

In order to obtain a full-resolution image one needs to apply image interpolation techniques. All this is usually done directly in the sensor and can be considered to be *low-level image processing*.

6.2 Image Sensor Technology

Image sensors are based on the photoelectric effect, i.e. the conductivity of semiconductors is increased if light hits the semiconductor. Consequently one can read out the change in conductivity using appropriate electronics.

These electronics can either use passive or active elements. The first form is used in the charge-coupled device (CCD) sensors, which have been for many years the primary form of detectors being used in consumer electronics. Nowadays, CMOS sensors (that are based on CMOS transistors) have replaced CCD sensors in most applications since they offer various advantages. For details on detector technology we refer to wikipedia.

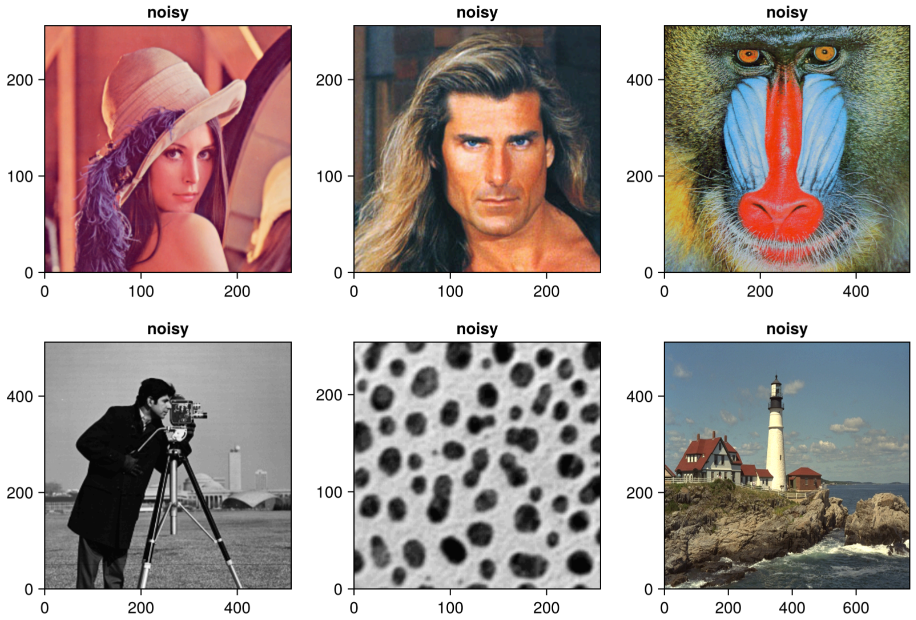
Note

In this course we focus on *computational aspects* of image processing and only roughly sketch the *image sensing* part. If you want to learn about this you need background in electrical engineering and semiconductor technology in particular. There are several courses in the field of microelectronics at TUHH where you can learn more.

7. Test Images

When doing image processing one might wonder what image to use in order to evaluate new algorithms. There is no simple answer to this question since often the answer is application specific.

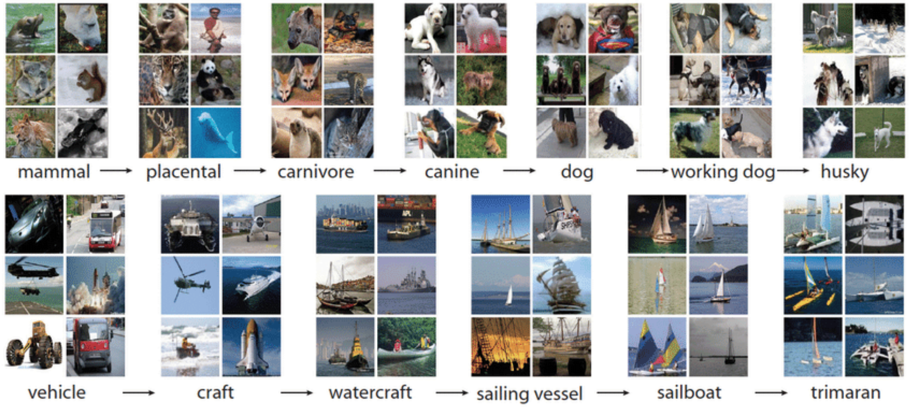
But to benchmark algorithms against each other, researchers have agreed on certain test images. Let us have a look at some of them:



Often these images have a good mix of details, structures, colors and are representative for typical camera pictures.

8. Image Databases

In the field of object recognition, methods usually are trained and evaluated on a large number of datasets. Due to this need large image databases like ImageNet have been created. In addition to the images itself such a database contains also one or several categories in which the image lays.



9. Course Overview

This course will capture the following topics:

1. Organization
2. Introduction ← (you are here)
3. Image Fundamentals
4. Intensity Transformations
5. Filtering in Spatial Domain
6. Filtering in Frequency Domain
7. Image Restoration
8. Color Image Processing
9. Multiresolution Image Processing
10. Morphological Image Processing
11. Image Segmentation