

In [111]:

```
from IPython.display import HTML, Image, SVG, YouTubeVideo
```

## Image sources

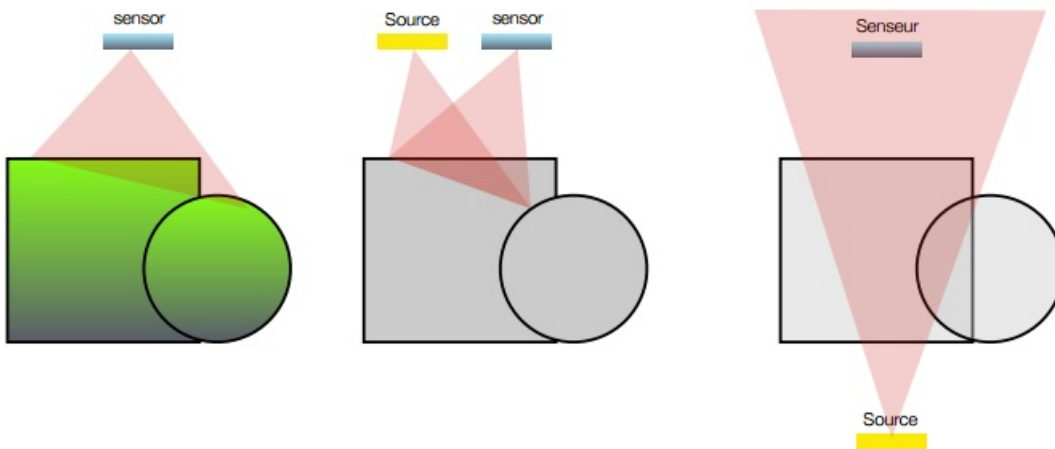
### Passive vs active imaging

- the object is the source of photon (SPECT, stars,...)
- the object reflects/react to light given by a external source (flash, fluorescence)
- the object is traversed by the ligh and diffuses/asborbes it (X-ray)

In [112]:

```
Image('http://homepages.ulb.ac.be/~odebeir/data/trans_reflect.png')
```

Out[112]:



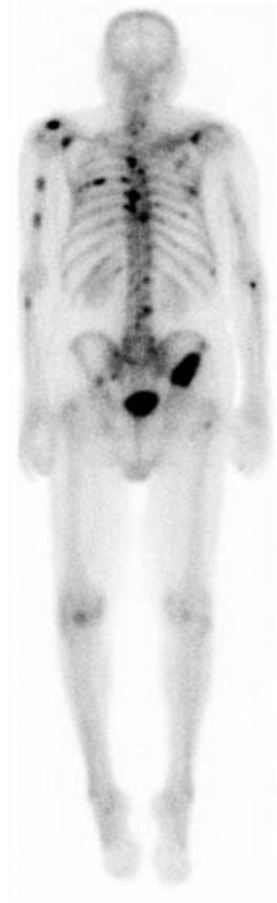
### Object as a source

Nuclear imaging is a good example of the first setup, here an injection of radio-tracer will accumulates to some region of interest (due to specific biochemical affinity). The following example shows how the radio-tracer identifies bone metastasis of a prostate cancer using a gamma camera.

In [113]:

```
Image('https://upload.wikimedia.org/wikipedia/commons/a/ae/Prostate-mets-102.jpg')
```

Out[113]:



[wikimedia commons \(https://commons.wikimedia.org/wiki/File:Prostate-mets-102.jpg\)](https://commons.wikimedia.org/wiki/File:Prostate-mets-102.jpg)

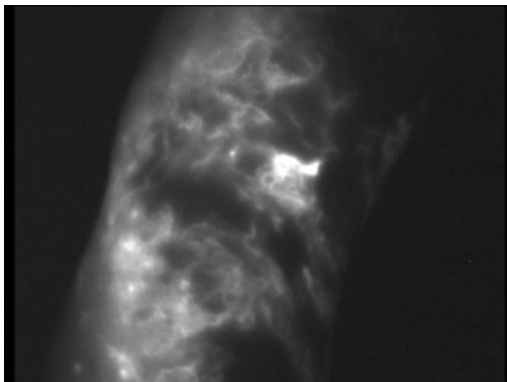
The source can also be the result of an external excitation i.e. an absorption and a re-emission of another photon (fluorescence).

Fluorescence lymphography is an example of imaging using an external excitation, here, infrared light is used to excite fluorophore injected in the lymph system. Fluorophore can in turn re-emit infrared (at a longer wavelength). By using adapted filter, one can observe the lymph displacement inside the lymph network (close to the skin surface).

In [114]:

```
Image('http://homepages.ulb.ac.be/~odebeir/data/fluoroscopy.png')
```

Out[114]:



J.P.Belgrado

An other example, where fluorescence is used: the fluorescence microscopy.

In [115]:

```
#add example
```

## Object reflects / diffuses the light from an external source

This is the more common acquisition setup, external light source flood the scene with visible photons that are reflected by the objects, these photons are then acquired by a sensor.

## Object attenuates the source

Source and sensor can be placed on both side of the object being imaged, a good example is the X-Ray imaging, where a X-Ray source project photon through a patient, these photon interact with the matter in such a way that tissue density and composition (bones vs soft tissues) can give a contrast variation at the sensor level.

[image source \(https://www.flickr.com/photos/tracemeek/5327224133/\)](https://www.flickr.com/photos/tracemeek/5327224133/)

## Direct image acquisition

### CCD - coupled charge device

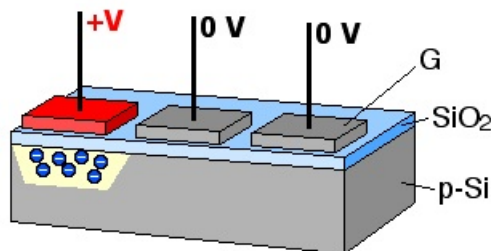
Charges are liberated by light interaction with the semiconductor inside photoactive region, for each pixel of the sensor grid. In order to digitize the amount of charges (proportional to light captured, CCD devices will move the charges along the substrate up to a charge to voltage converter.

Coupled Charge Device uses electrode potentials to move charges inside silicium substrate as illustrated bellow.

In [116]:

```
Image(url='https://upload.wikimedia.org/wikipedia/commons/6/66/CCD_charge_transfer_animation.gif')
```

Out[116]:



[wikimedia commons \(https://commons.wikimedia.org/wiki/File:CCD\\_charge\\_transfer\\_animation.gif\)](https://commons.wikimedia.org/wiki/File:CCD_charge_transfer_animation.gif)

Image sensor can have essentially two types of geometry:

- linear: typically used when the sensor is translated (flatbed scanner, but also bank note scanner, satellite, photo finish)
- rectangular: almost every other camera

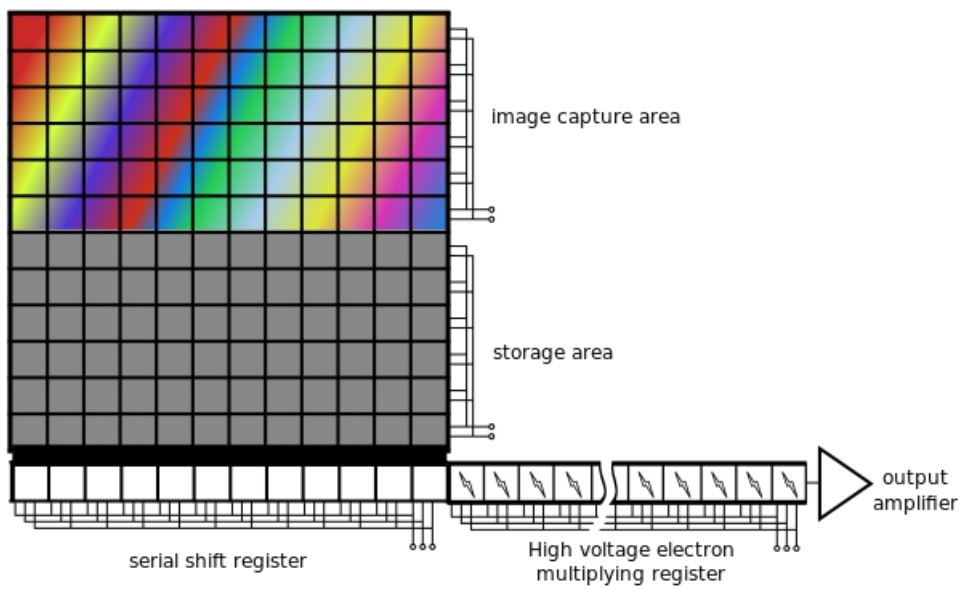
In order to move charges along the dimensions of the CCD sensor, charges are moved along each image line, a perpendicular buffer is used to discharge all these pixels in column into an amplifier that transform each charge into a voltage. The voltage is then converted by an ADC circuit.

Because all the pixels charges are compared using the same circuit, the CCD sensor provide a very constant specification on the complete sensor. The other main advantage of the sensor is the coverage factor of the sensor (the ratio between the sensor surface and the total pixel surface), almost the surface is devoted to light acquisition (no extra circuitry needed).

In [117]:

```
Image('https://upload.wikimedia.org/wikipedia/commons/thumb/e/e1/EMCCD2_color_en.svg/640px-EMCCD2_color_en.svg.png')
```

Out[117]:



[wikimedia commons \(https://commons.wikimedia.org/wiki/File%3ACcd\\_schematic.JPG\)](https://commons.wikimedia.org/wiki/File%3ACcd_schematic.JPG)

In [118]:

```
Image('https://upload.wikimedia.org/wikipedia/commons/thumb/3/30/CCD_line_sensor.JPG/320px-CCD_line_sensor.JPG')
```

Out[118]:

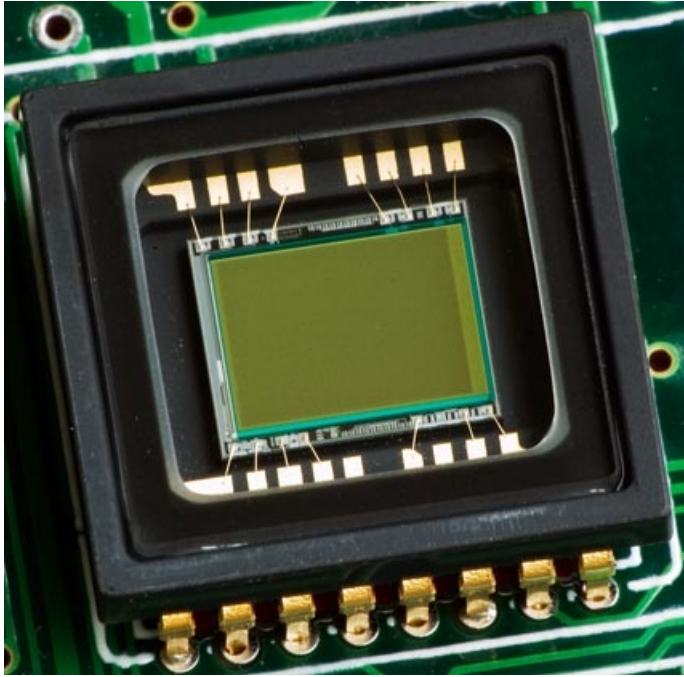


Linear CCD sensor. [wikimedia commons \(https://commons.wikimedia.org/wiki/File:CCD\\_line\\_sensor.JPG\)](https://commons.wikimedia.org/wiki/File:CCD_line_sensor.JPG)

In [119]:

```
Image('https://upload.wikimedia.org/wikipedia/commons/1/17/CCD_in_camera.jpg')
```

Out[119]:



CCD line sensor in a ceramic dual in-line package. [wikimedia commons \(https://commons.wikimedia.org/wiki/File:CCD\\_in\\_camera.jpg\)](https://commons.wikimedia.org/wiki/File:CCD_in_camera.jpg)

## CMOS

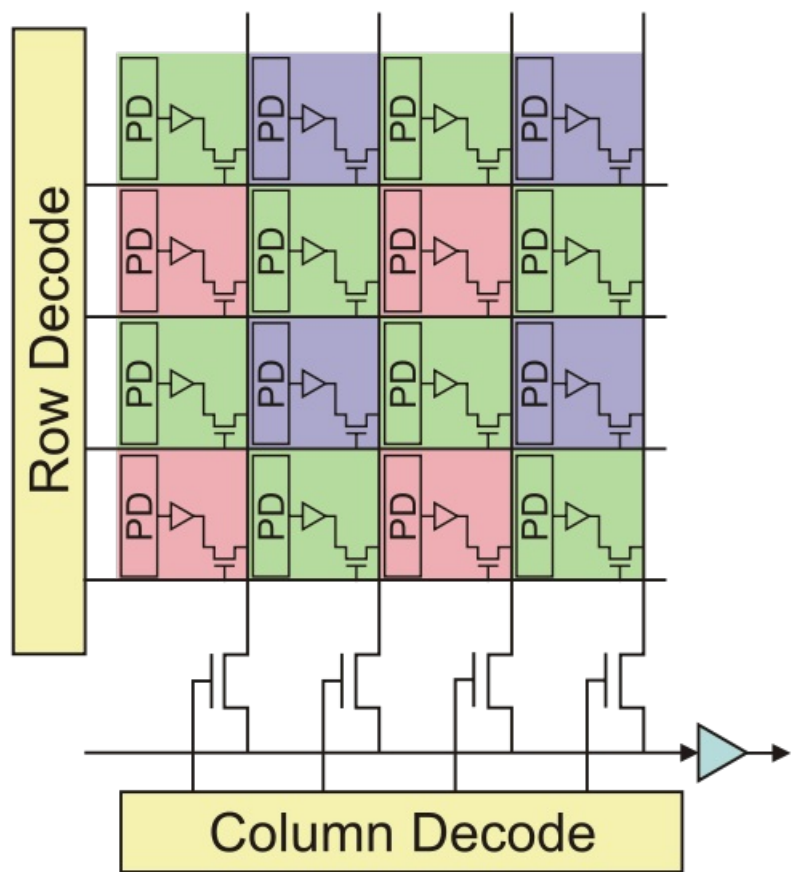
The CMOS technology embeds a photo-detector and a charge amplifier for each sensor pixel, the voltage being then transmitted by electrical conductors.

This strategy enables a greater variety of sensor usage, e.g. addressing a part of the sensor (for low resolution and higher speed).

Because the conversion is done separately for each pixel, no charge shifting is needed, but discrepancy between charge amplifier may exist, giving unequal pixel sensitivity and noise.

```
In [120]:
Image('https://upload.wikimedia.org/wikipedia/commons/thumb/c/c0/CMOS_Image_Sensor_Mechanism_Illustration.svg/500px-CMOS_Image_Sensor_Mechanism_Illustration.svg.png')

Out[120]:
```



wikimedia commons ([https://commons.wikimedia.org/wiki/File:CMOS\\_Image\\_Sensor\\_Mechanism\\_Illustration.svg](https://commons.wikimedia.org/wiki/File:CMOS_Image_Sensor_Mechanism_Illustration.svg))

CMOS vs CCD

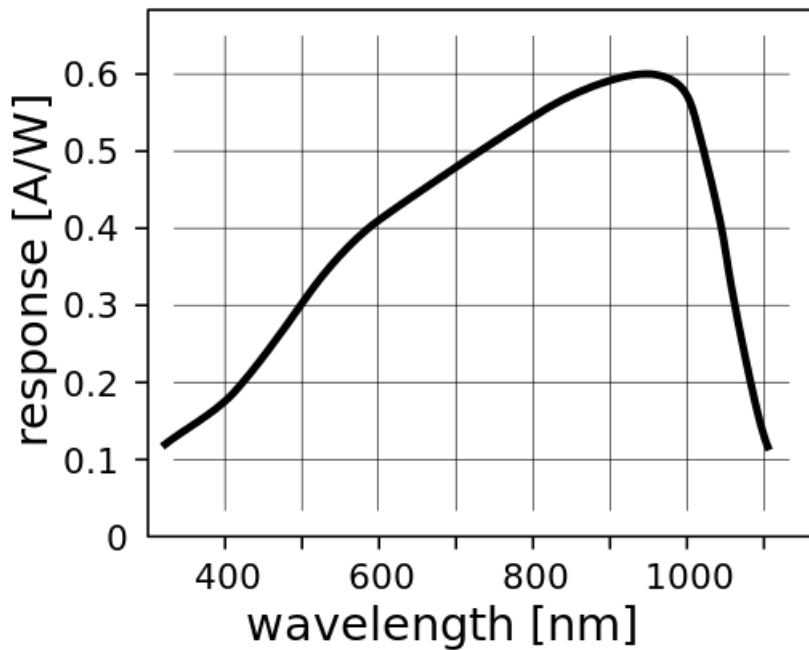
feature	CDD	CMOS
Signal out of pixel	Electron packet	Voltage
Fill factor	high	moderate
Amplifier mismatch	none	moderate
Noise	low	moderate
system complexity	high	low
sensor complexity	low	high
dynamic range	high	moderate
uniformity	high	moderate
speed	moderate	high

CMOS + CDD : high sensitivity to near infrared, therefore, most of the sensors are equipped with a NIR filter.

In [121]:

```
Image(url='https://upload.wikimedia.org/wikipedia/commons/thumb/4/41/Response_silicon_photodiode.svg/544px-Response_silicon_photodiode.svg.png')
```

Out[121]:



[wikimedia commons \(https://upload.wikimedia.org/wikipedia/commons/thumb/4/41/Response\\_silicon\\_photodiode.svg/544px-Response\\_silicon\\_photodiode.svg.png\)](https://upload.wikimedia.org/wikipedia/commons/thumb/4/41/Response_silicon_photodiode.svg/544px-Response_silicon_photodiode.svg.png)

## Multispectral acquisition

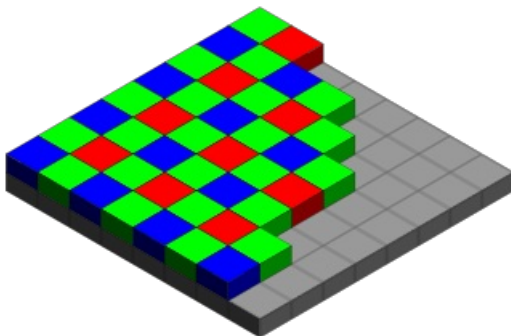
Color acquisition is done by acquiring several images at different wavelength, one common (and cheap) approach is to cover sensors pixels by colored dyes (red, green and blue). The figure above illustrated such filters (bayer), where on each 2x2 pixel square, one pixel is sensitive to the red part of the spectrum, one to the blue part of the spectrum, and finally 2 pixels sensitive to the green part of the spectrum.

The choice of duplicating green is done for symetry purposes and also because the intensity sensitivity of the eye (see rods) is correlated to the green part of the spectrum.

In [122]:

```
Image('https://upload.wikimedia.org/wikipedia/commons/thumb/3/37/Bayer_pattern_on_sensor.svg/320px-Bayer_pattern_on_sensor.svg.png')
```

Out[122]:



[wiki commons \(https://en.wikipedia.org/wiki/Bayer\\_filter#/media/File:Bayer\\_pattern\\_on\\_sensor.svg\)](https://en.wikipedia.org/wiki/Bayer_filter#/media/File:Bayer_pattern_on_sensor.svg)

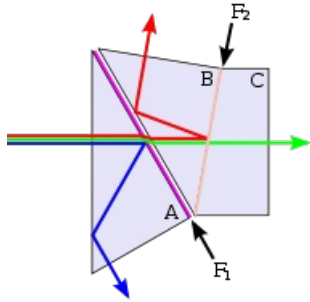
One limitation of the dye approach is the resolution limitation, indeed the image resolution is divided by 4.

The other method used is based on three CCD coupled on the same optical axis and having three different dyes (red, green, blue) as illustrated bellow.

In [123]:

Image('https://upload.wikimedia.org/wikipedia/commons/thumb/e/ef/Dichroic-prism.svg/200px-Dichroic-prism.svg.png')

Out[123]:



[wikimedia commons \(https://commons.wikimedia.org/wiki/File:Dichroic-prism.svg\)](https://commons.wikimedia.org/wiki/File:Dichroic-prism.svg)

The big advantage of this approach is to keep the sensor native resolution for each color channel.

The number of spectral bands can be higher than three, for example satellite imagery offers many wavelengths inside but also next to it (UV and near-IR).

Quick-bird (environmental imagery, pixel = 0.65m)

- Pan: 450-900 nm
- Blue: 450-520 nm
- Green: 520-600 nm
- Red: 630-690 nm
- Near IR: 760-900 nm

IKONOS (commercial earth observation satellite)

resolution

- 0.8 m panchromatic (1-m PAN)
- 4-meter multispectral (4-m MS)

spectrum

- Blue: 0.445–0.516  $\mu\text{m}$
- Green: 0.506–0.595  $\mu\text{m}$
- Red: 0.632–0.698  $\mu\text{m}$
- Near IR: 0.757–0.853  $\mu\text{m}$

Landsat 8 (American Earth observation satellite)

- Band 1 - Coastal / Aerosol 0.433 - 0.453  $\mu\text{m}$  30 m
- Band 2 - Blue 0.450 - 0.515  $\mu\text{m}$  30 m
- Band 3 - Green 0.525 - 0.600  $\mu\text{m}$  30 m
- Band 4 - Red 0.630 - 0.680  $\mu\text{m}$  30 m
- Band 5 - Near Infrared 0.845 - 0.885  $\mu\text{m}$  30 m
- Band 6 - Short Wavelength Infrared 1.560 - 1.660  $\mu\text{m}$  30 m
- Band 7 - Short Wavelength Infrared 2.100 - 2.300  $\mu\text{m}$  30 m
- Band 8 - Panchromatic 0.500 - 0.680  $\mu\text{m}$  15 m
- Band 9 - Cirrus 1.360 - 1.390  $\mu\text{m}$  30 m

AVIRIS - airborne visible/infrared imaging spectrometer

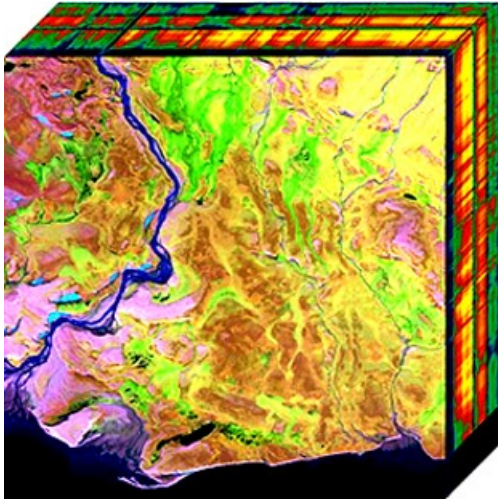
- four linear spectrometers (614-pixel wide) / 224 adjacent spectral bands.



In [124]:

```
Image('https://upload.wikimedia.org/wikipedia/commons/4/48/HyperspectralCube.jpg')
```

Out[124]:



[wikimedia commons \(https://commons.wikimedia.org/wiki/File:HyperspectralCube.jpg\)](https://commons.wikimedia.org/wiki/File:HyperspectralCube.jpg)

## Depth acquisition

Depth imaging is traditionnaly used in stereo application, such for robot vision. Recently depth sensor became widely available thanks to game applications. The main technologies used are:

- stereovision
- laser triangulation
- structured light projection
- Time-Of-Flight (TOF) imaging

The information provided by these sensors is of two types: a rgb image of the scene, and a depth estimation (usually at a coarser resolution).

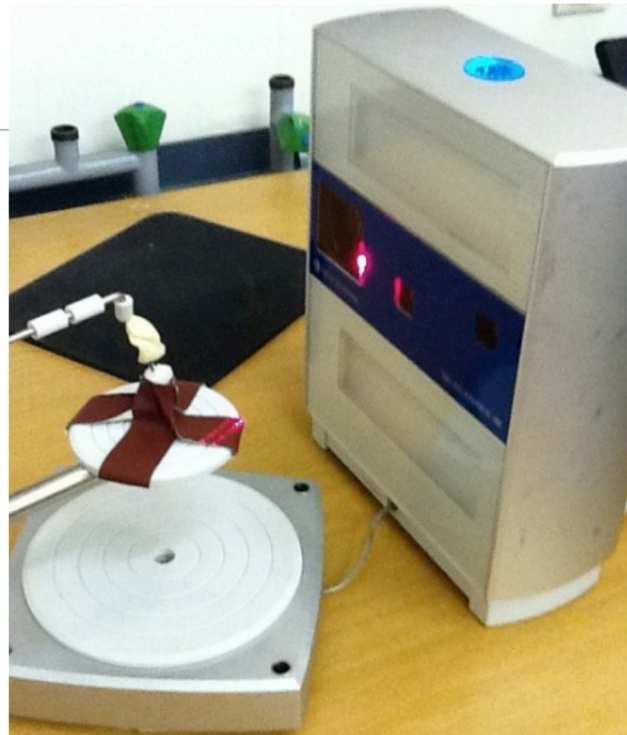
example of a high resolution laser triangulation scanner:

In [125]:

```
Image('http://homepages.ulb.ac.be/~odebeir/data/scanner.png')
```

Out[125]:

## Laser scanner



When high speed is needed, structured light may be a solution.

For example, the first generation of the Kinect sensor uses the principle of structured light projection, a pseudo-random pattern is projected in the near-infrared spectrum (i.e. invisible to human eye) and acquired by an IR sensitive camera. The depth image is produced with a video framerate compatible with gaming.

In [126]:

```
Image('https://upload.wikimedia.org/wikipedia/commons/thumb/6/67/Xbox-360-Kinect-Standalone.png/320px-Xbox-360-Kinect-Standalone.png')
```

Out[126]:



[wikimedia commons \(https://commons.wikimedia.org/wiki/File:Xbox-360-Kinect-Standalone.png\)](https://commons.wikimedia.org/wiki/File:Xbox-360-Kinect-Standalone.png)

In [127]:

```
Image('http://www.mattcutts.com/images/ir-projection.jpg')
```

Out[127]:



image source (<https://www.mattcutts.com/blog/open-kinect-contest/>)

In [128]:

```
Image('http://3.bp.blogspot.com/_PsITwyT0c4Y/T0UvQTQE7WI/AAAAAAAAApg/cGHQtXou2yw/s1600/Kinect+Pattern_IMG_0073.jpg')
```

Out[128]:

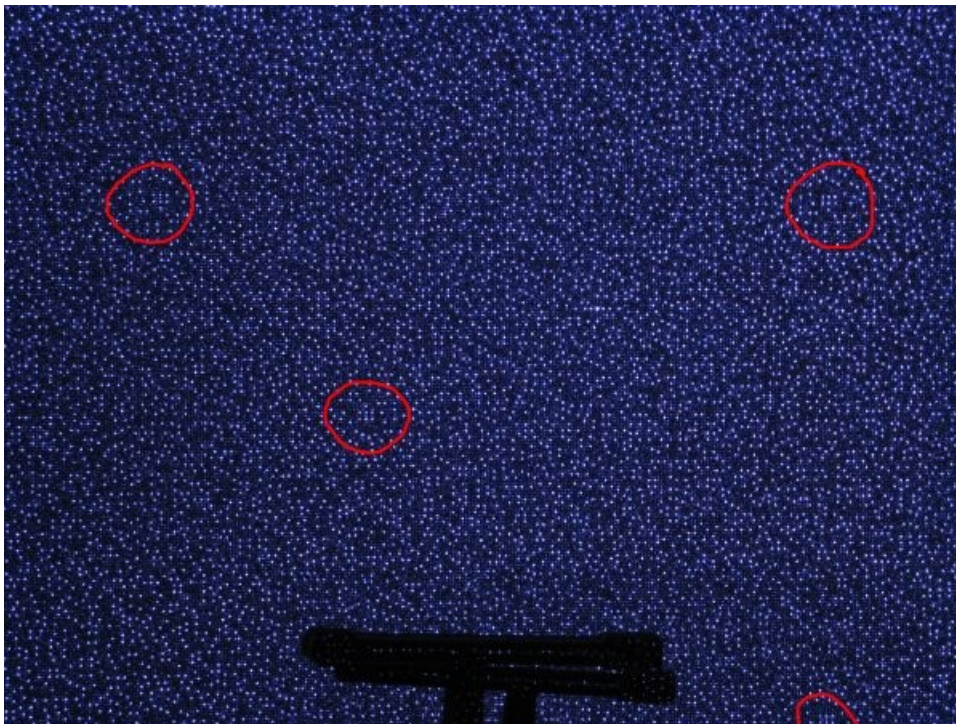


image source ([http://image-sensors-world.blogspot.be/2010\\_11\\_01\\_archive.html](http://image-sensors-world.blogspot.be/2010_11_01_archive.html))

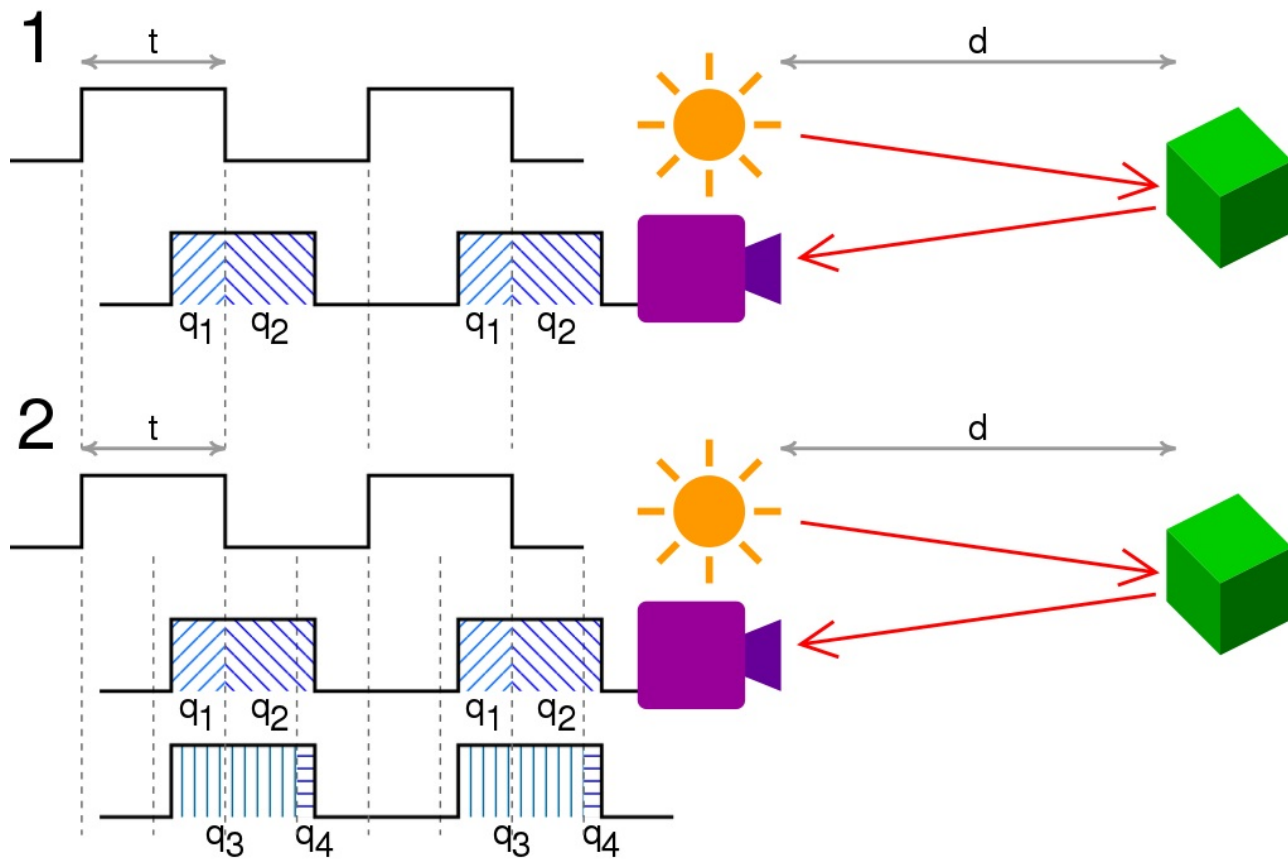
The depth is computed by triangulation thanks to the identification of specific pattern in the image.

The second generation of sensors is based on a completely different technology, the Time-Of-Flight (TOF). To estimate the distance between the sensor and the scene, a light wave is sent and received by the sensor. The phase difference between a modulated light pattern sent by the source and the signal received by the camera gives a measure of the scene depth.

In [129]:

```
Image(url='https://upload.wikimedia.org/wikipedia/commons/thumb/7/79/Time_of_flight_camera_principle.svg/1024px-Time_of_flight_camera_principle.svg.png')
```

Out[129]:



How to measure distance with light ?

Continuous wave demodulation

- retrieve phase shift by demodulation of the received signal
- demodulation by cross-correlation of the received signal with the emitted signal
- emitted signal is

$$g(t) = \cos(\omega t)$$

with  $\omega$  the modulation frequency

- received signal after the return trip to the scene surface:

$$s(t) = b + a \cos(\omega t + \phi)$$

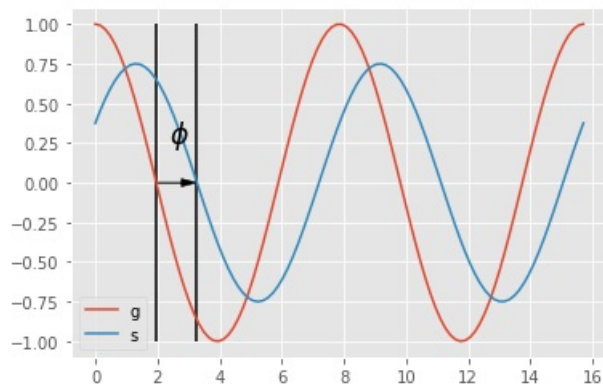
where  $a$  is an unknown attenuation,  $\phi$  the phase shift **i.e. a value proportional to the scene distance** and  $b$  an unknown acquisition noise (neglected here).



In [130]:

```
%matplotlib inline
import numpy as np
import matplotlib.pyplot as plt
from matplotlib import cm
from skimage.data import camera
plt.style.use('ggplot')

plt.figure()
omega = .8
t = np.linspace(0,5*np.pi,100)
g = np.cos(omega*t)
a = .75
phi = -np.pi/3
s = a * np.cos(omega*t+phi)
plt.plot(t,g,label='g')
plt.plot(t,s,label='s')
plt.gca().arrow(np.pi*.5/omega, 0, -phi/omega-.5, 0, head_width=0.05, head_length=0.5, fc='k', ec='k')
plt.vlines([.5*np.pi/omega, (.5*np.pi-phi)/omega],-1,1)
plt.text(.6*np.pi/omega, .25, '$\phi$',size='xx-large')
plt.legend();
```



- cross correlation of both emitted and received signal becomes:

$$d(\tau) = s * g = \int_{-\infty}^{+\infty} s(t) \cdot g(t + \tau) dt$$

with  $\tau$  an internal offset

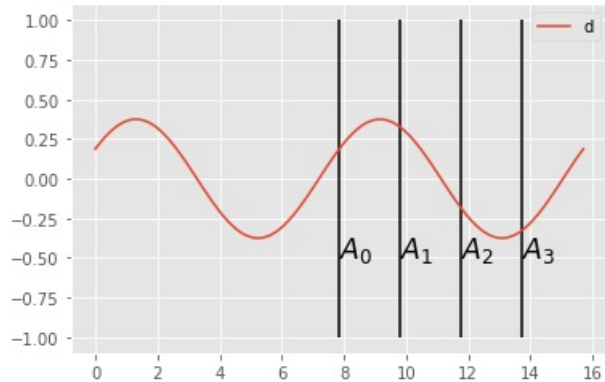
$$d(\tau) = \frac{a}{2} \cos(\omega t + \phi) + b$$

- sample  $d(\tau)$  at 4 distinct moments (phase offsets):

$$A_i = d(i \cdot \frac{\pi}{2}) \text{ with } i = 0, \dots, 3$$

In [131]:

```
plt.figure()
d = a/2 * np.cos(omega*t+phi)
plt.plot(t,d,label='d')
samples = 1/omega * (np.pi*2+np.arange(0,2*np.pi,np.pi/2))
plt.vlines(samples,-1,1)
for i,pos in enumerate(samples):
    plt.text(pos,-.5,'$A_{%d}$'%i,size='xx-large')
plt.legend();
```



- phase and attenuation are then:

$$\phi = \operatorname{arctan}\left(\frac{A_3 - A_1}{A_0 - A_2}\right)$$

and

$$a = \frac{1}{2} \sqrt{(A_3 - A_1)^2 + (A_0 - A_2)^2}$$

- scene distance is then:

$$dist = \frac{c}{4.\pi. \omega} \phi$$

where  $c$  is the speed of light.

What a depth image looks like ?

In [132]:

```
Image('https://upload.wikimedia.org/wikipedia/commons/1/19/T0F_Kamera_3D_Gesicht.jpg')
```

Out[132]:



## Indirect image acquisition

Image can also be the result of a mathematical reconstruction based on an indirect acquisition, the sensor do not acquire an image directly.

For example, computed tomography, uses a series of 1D density profile acquisition enable a 2D reconstruction of the slice.

In [133]:

```
Image('http://130.237.83.53/medicaldevices/album/Ch%207%20Medical%20images/slides/F%207-10%20Computer%20tomography.jpg')
```

Out[133]:

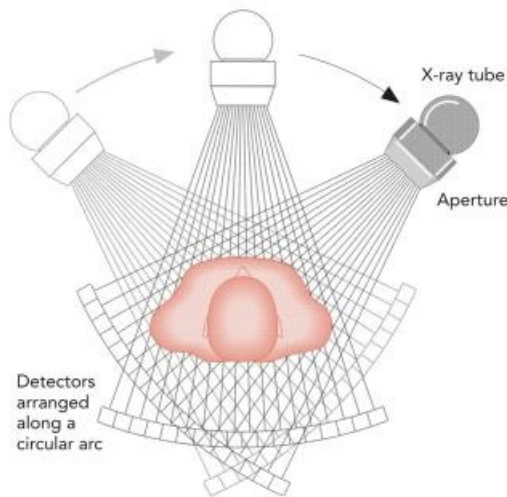


Figure 7-10 Computer tomography

[image source \('http://130.237.83.53/medicaldevices/album/Ch%207%20Medical%20images/slides/F%207-10%20Computer%20tomography.jpg'\)](http://130.237.83.53/medicaldevices/album/Ch%207%20Medical%20images/slides/F%207-10%20Computer%20tomography.jpg)

Echography is an other example of indirect imaging, where mechanical wave propagation are transformed in a 2D image showing the presence of interfaces between tissue of different acoustic impedance.

In [134]:

```
Image('https://upload.wikimedia.org/wikipedia/commons/c/c7/CRL_Crown_rump_length_12_weeks_ecografia_Dr._Wolfgang_Moroder.jpg')
```

Out[134]:



[image source \('https://commons.wikimedia.org/wiki/File:CRL\\_Crown\\_rump\\_lengh\\_12\\_weeks\\_ecografia\\_Dr.\\_Wolfgang\\_Moroder.jpg'\)](https://commons.wikimedia.org/wiki/File:CRL_Crown_rump_lengh_12_weeks_ecografia_Dr._Wolfgang_Moroder.jpg)

other example: MRI image reconstruction

## Synthetic images

Image can also be the result of the grouping of a huge number of localized data, for example, one can imagine a network of temperature sensors spread over a complete contry, then the temperature measurements can be grouped on a 2D map (and interpolated to have a complete coverage).

Visualized data can be from various nature, the common aspect is that these data are placed in a geometric space (usually 2D or 3D).