02502
Image Analysis
Lecture 2: Image acquisition, compression and storage

http://courses.compute.dtu.dk/02502/

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Image Analysis
The amazing adaptive brain

- How much is the brain involved when biking?

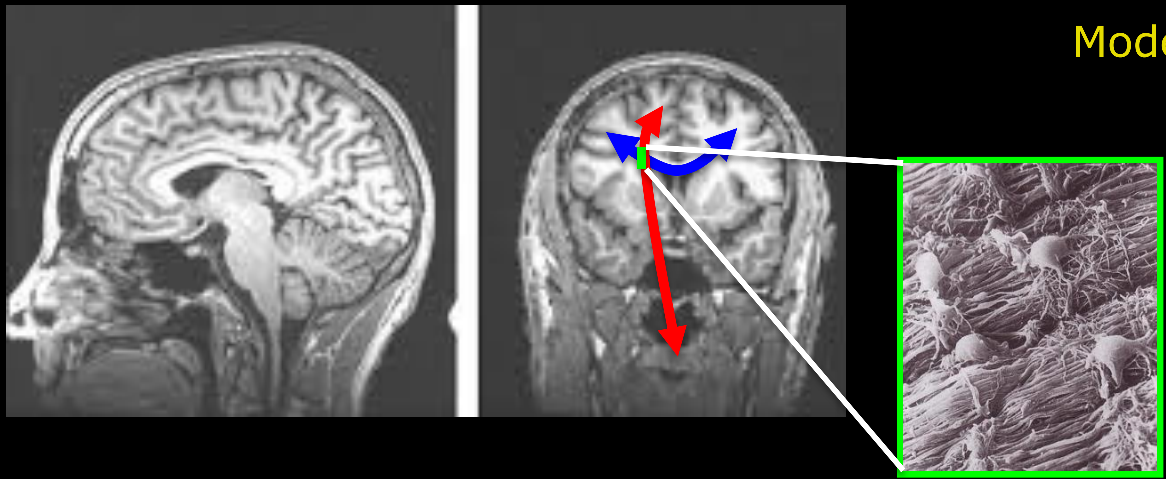
- Aging, dementia and Alzheimer

- Schizophrenia

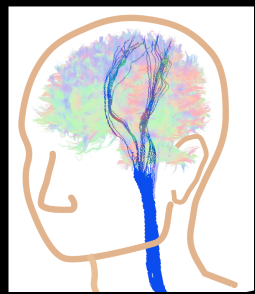
- Multiple sclerosis

Mapping brain network and microstructure using MRI

- Magnetic Resonance Imaging (MRI) of the living brain

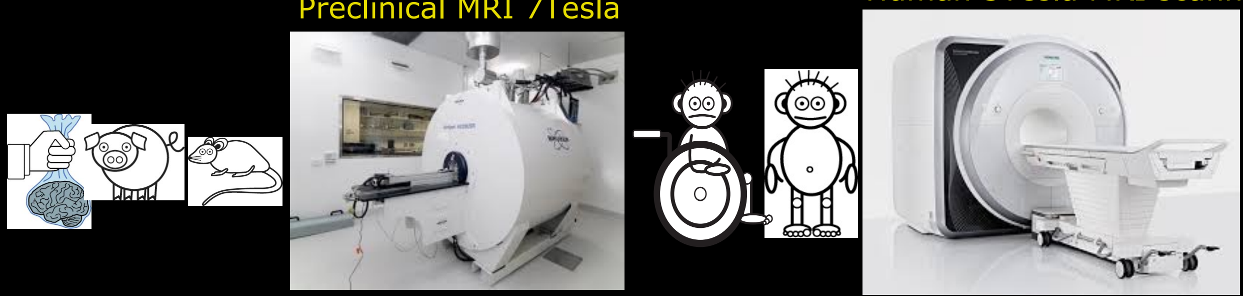


Model of the brain network
From MRI

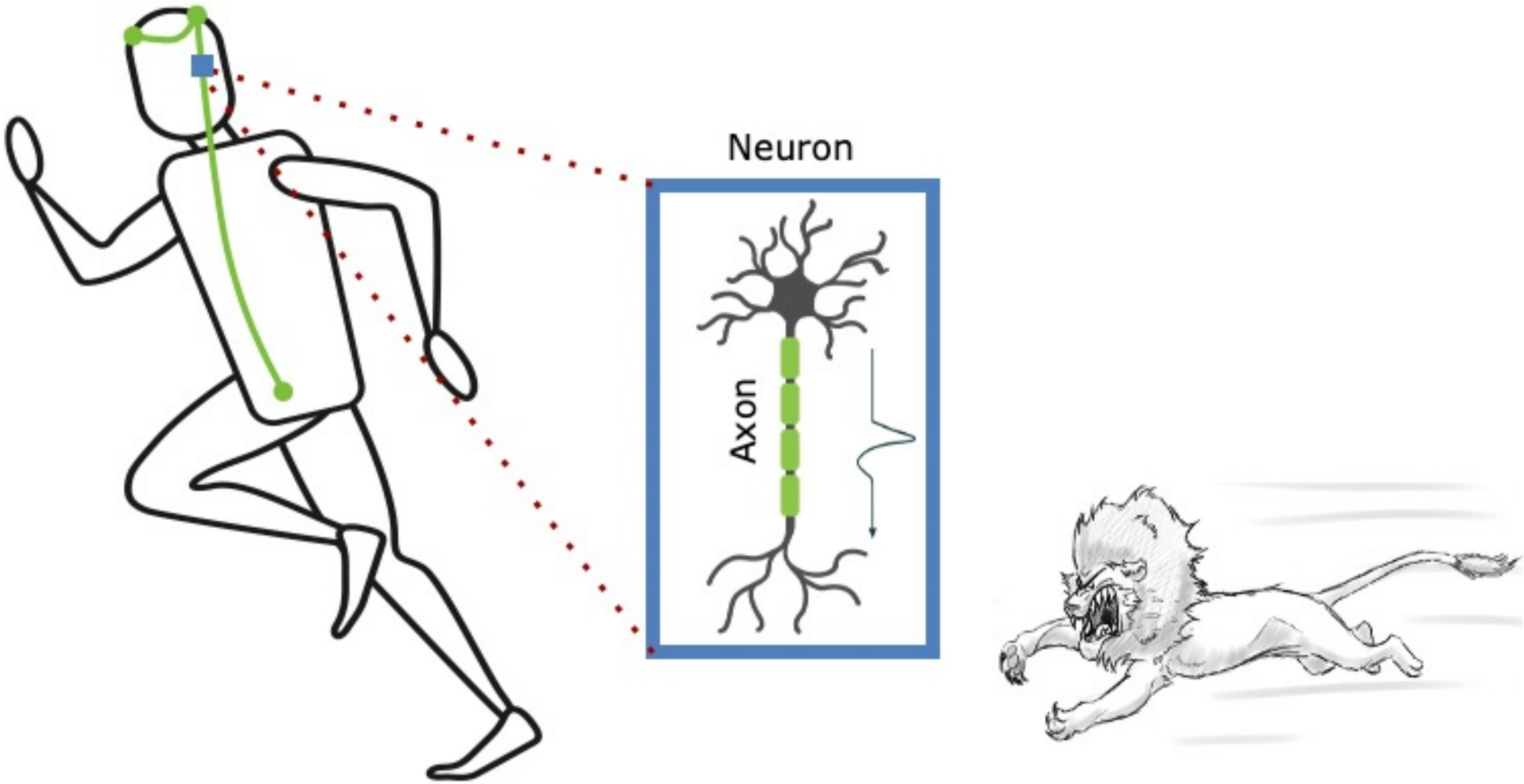


Preclinical MRI 7Tesla

Human 3Tesla MRI scanner

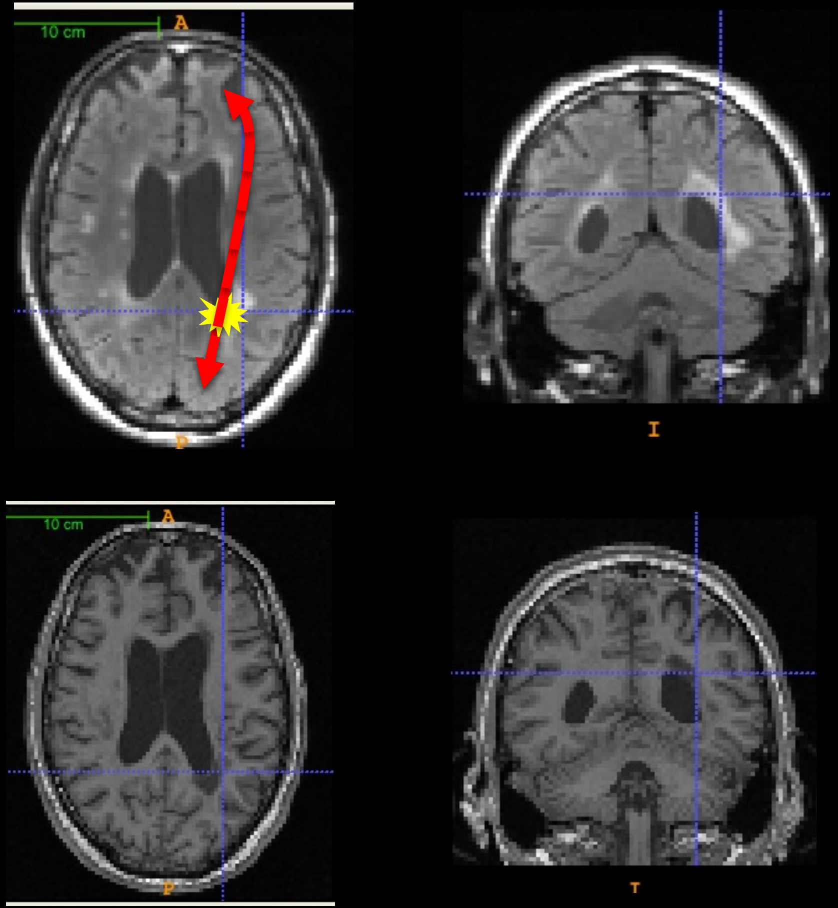


Communication speed in the brain network matters!

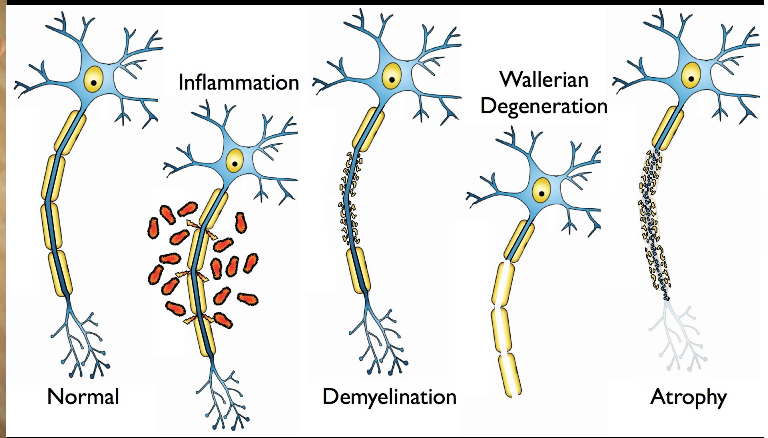


The challenges:

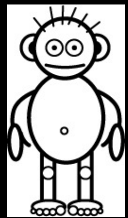
- Weakly correlating with clinical tests
- Clinical MRI is very sensitive to anatomical changes but often lacks specificity

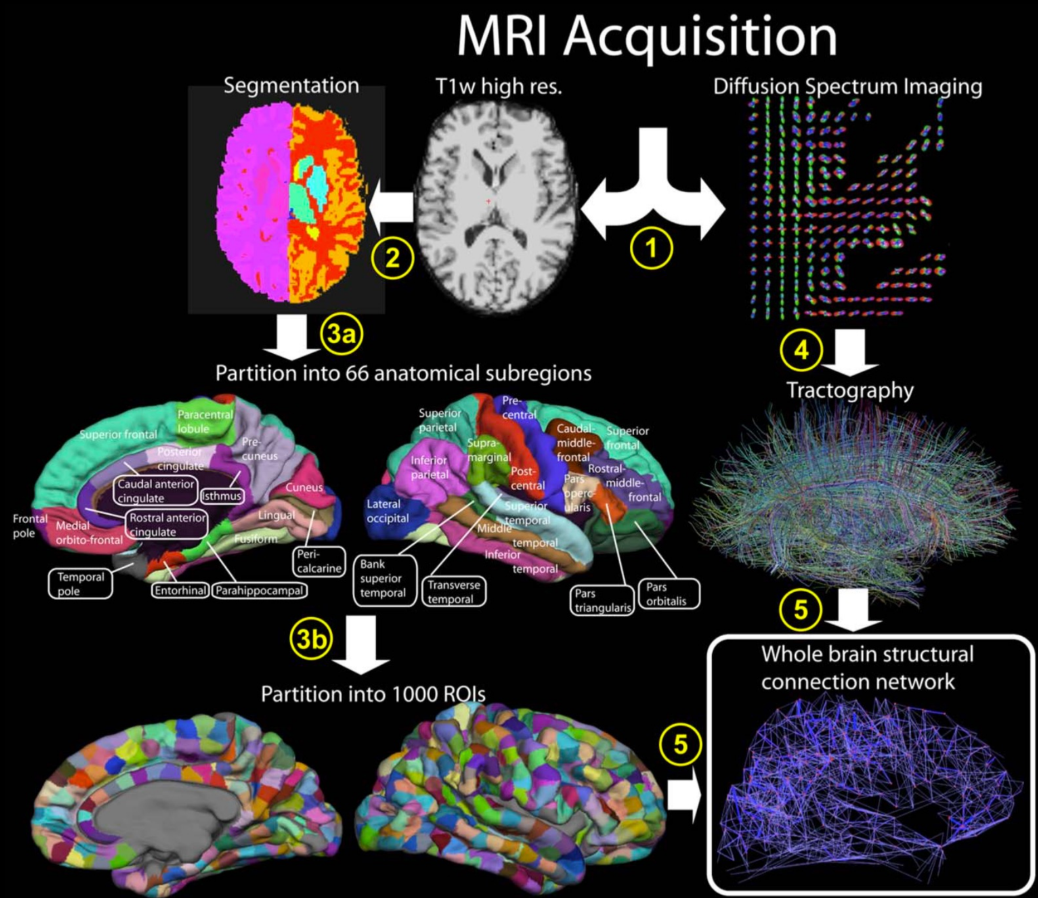


Disease attacks the brain neurons



Human 3T MRI scanner





Hagmann et al., 2008, PloS Biol

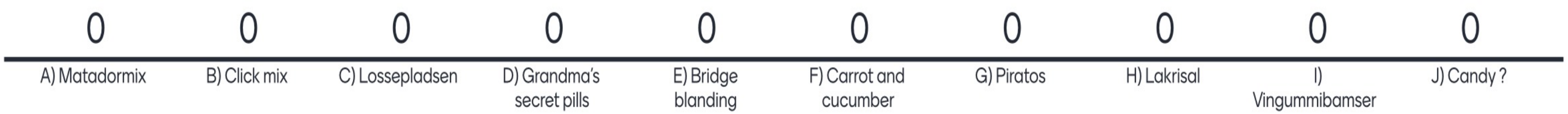
Image analysis:

- Image acquisition
- Data storage
- Point wise operations - Histograms
- Segment anatomical structures
- PCA analysis
- Design biophysical mathematical models of the brain network

Go to **www.menti.com** and use the code **6732 4259**

Mentimeter

Quiz 1: What is your favourite candy

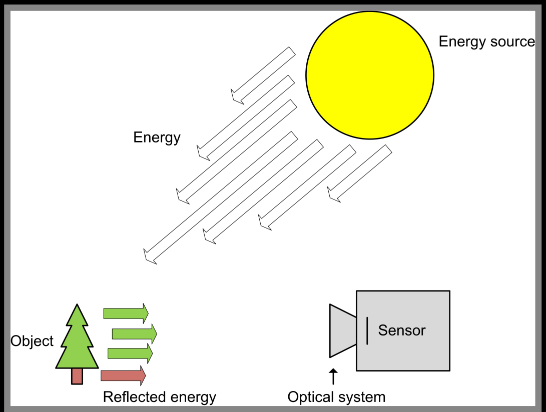


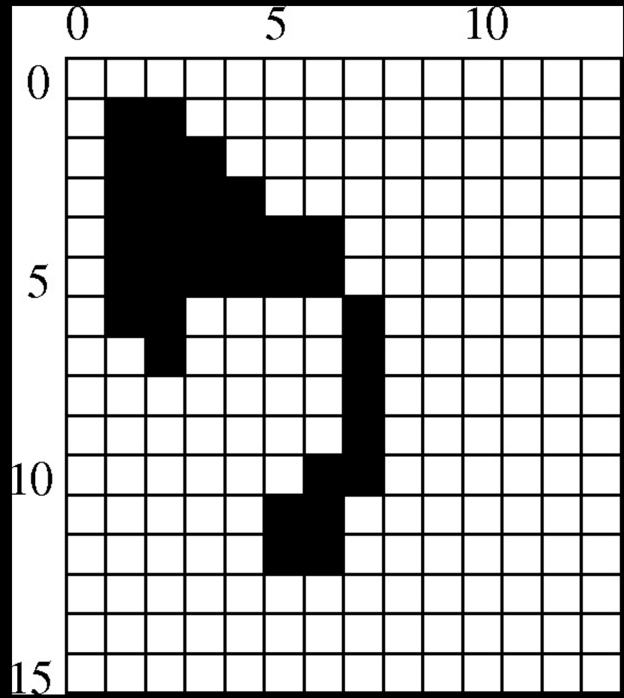
Quiz 1: What is your favourite candy

A) Matadormix
B) Click mix
C) Lossepladsen
D) Grandma's secret pills
E) Bridge blanding
F) Carrot and cucumber
G) Piratos
H) Lakrisal
I) Vingummibamser
J) Candy ?

Lecture 2

- Image acquisition, compression and storage

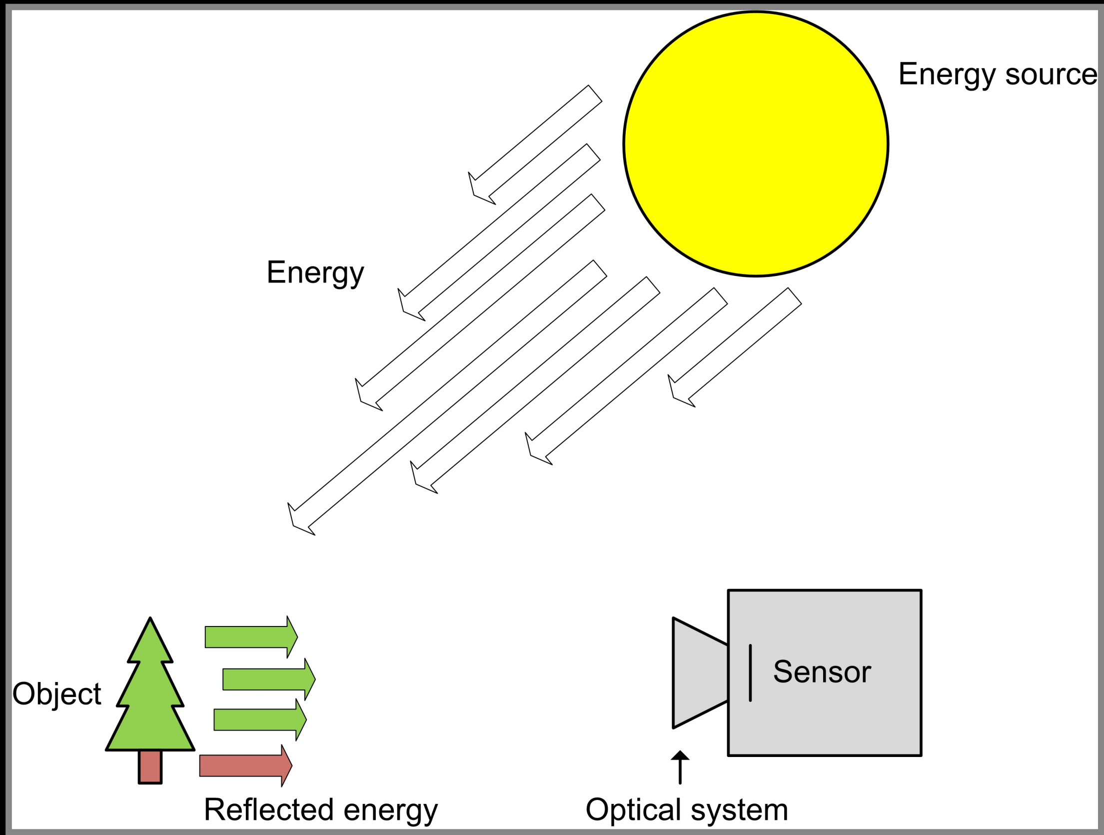




Today – What can you do after today?

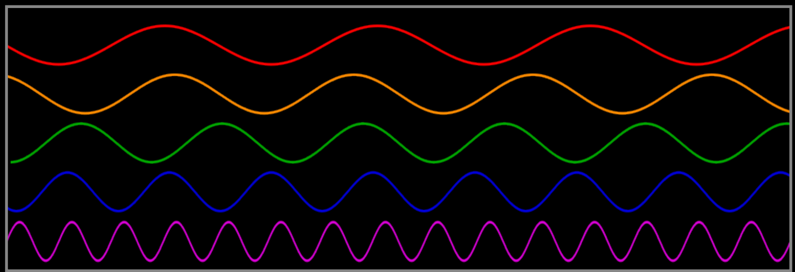
- Explain where visible light is in the electromagnetic spectrum
- Describe the pin hole camera
- Describe the properties of a thin-lens including focal-length, the optical center, and the focal point
- Estimate the focal length of a thin lens
- Compute the optimal placement of a CCD chip using the thin lens equation
- Describe depth-of-field
- Compute the field-of-view of a camera
- Explain the simple CCD model
- Compute the run-length code of a grayscale image
- Compute the chain coding of a binary image
- Compute the run length coding of a binary image
- Compute the compression ratio
- Describe the difference between a lossless and a lossy image format
- Decide if a given image should be stored using a lossless or a lossy image format
- Understand the principle of X-ray and MRI imaging methods

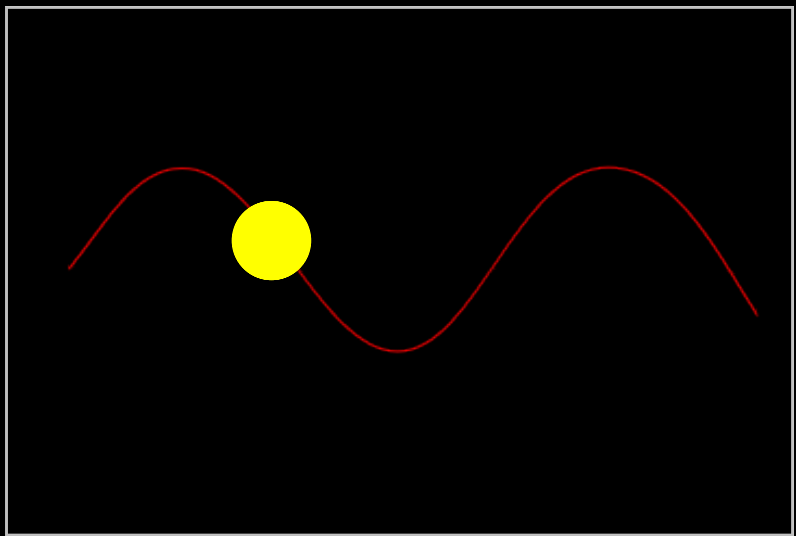
How is an image created?



This is just one way! Other methods will be described later in the course.

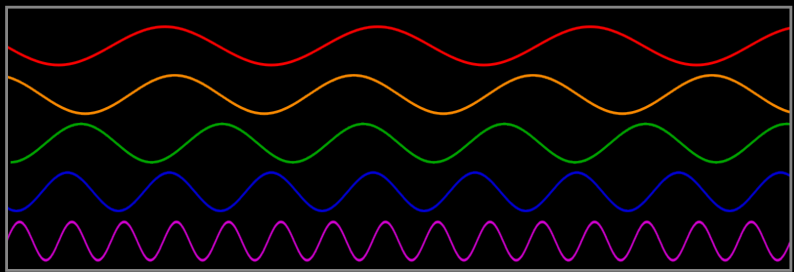
What is light?





- Can be seen as electromagnetic waves
- Or as a photon (from Greek *phōtos*, “light”)
  - Mass less fundamental particle

Light as a wave

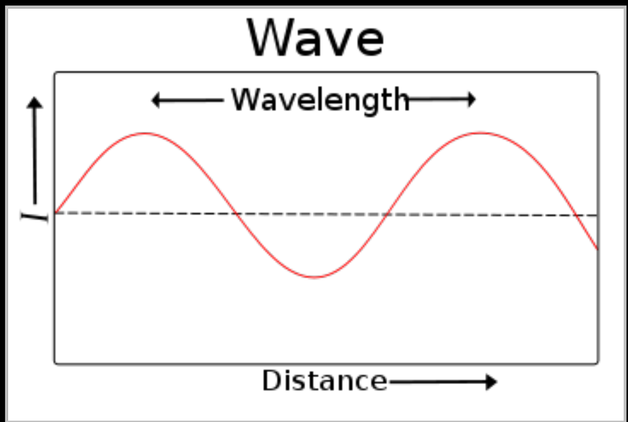


Low

f

High

$$\lambda = \frac{c}{f}$$



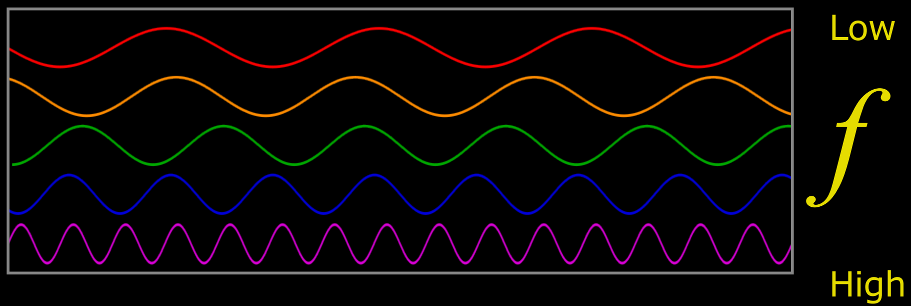
- It has a frequency f
  - Measured in Hertz [Hz]
- It has a wavelength λ (lambda)
  - Measured in meters [m]
- It has a speed
  - "The speed of light" c
  - 299.792 458 [m/s]

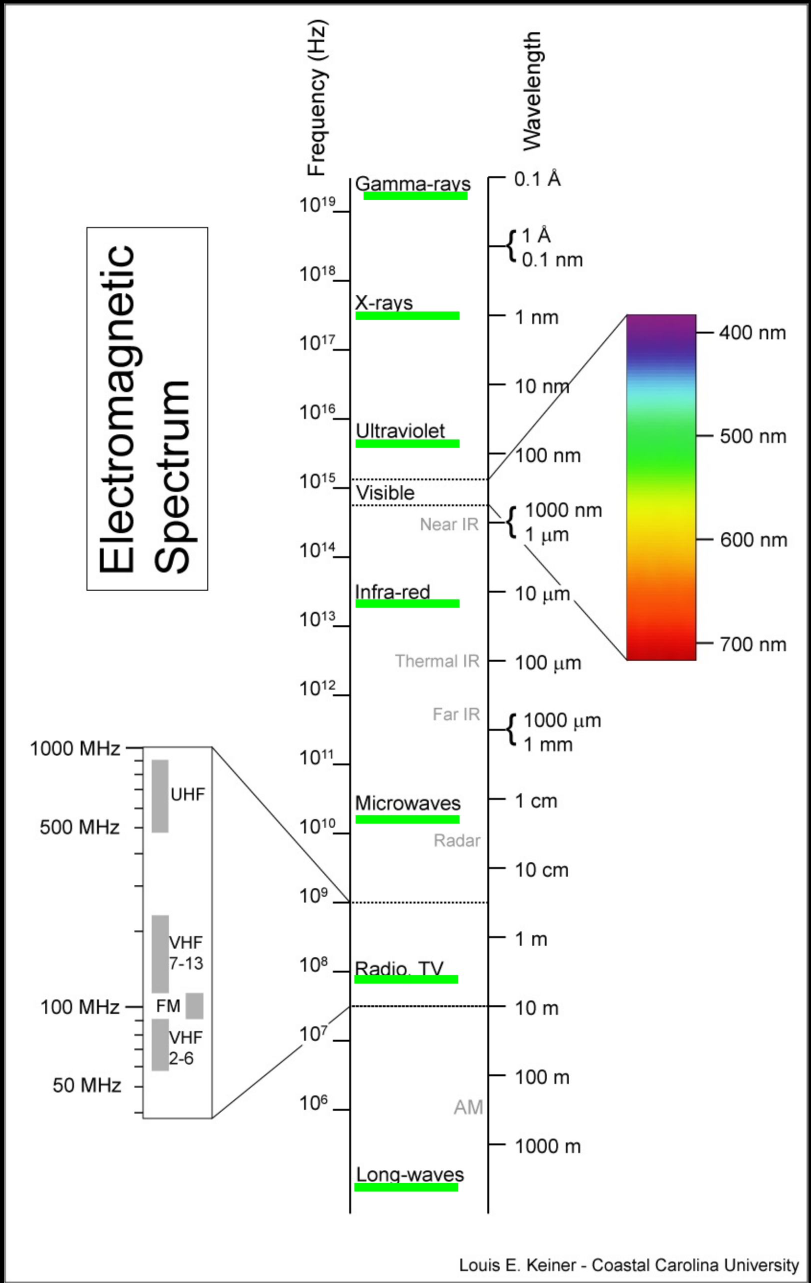
- High frequency -> short waves
- Low frequency -> long waves

Energy of light

$$E = h \cdot f$$

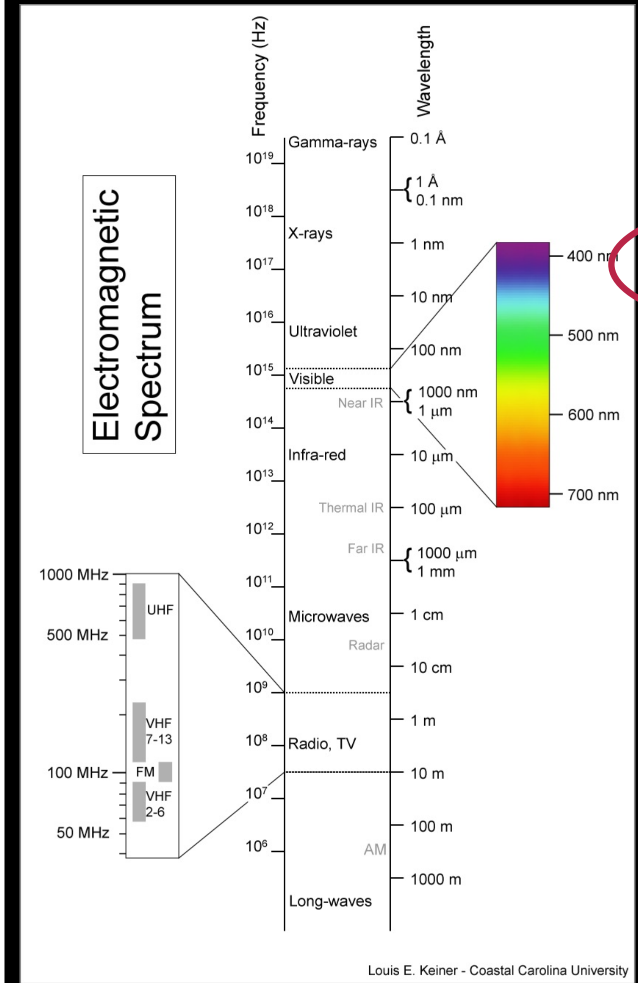
- Light has energy
  - You can feel it in the sun!
- Planck's constant h
- High frequency -> high energy
- Long waves -> low energy





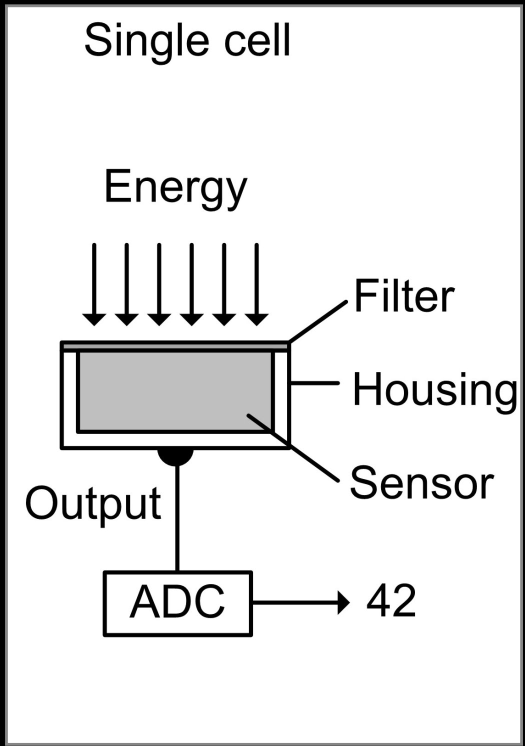
- Electromagnetic spectrum
  - Range of all frequencies
  - Divided into 7 regions
- Wavelengths
  - 1 µm = 1 micrometer = 0.001 mm
  - 1 nm = 1 nanometer = 0.0000001mm

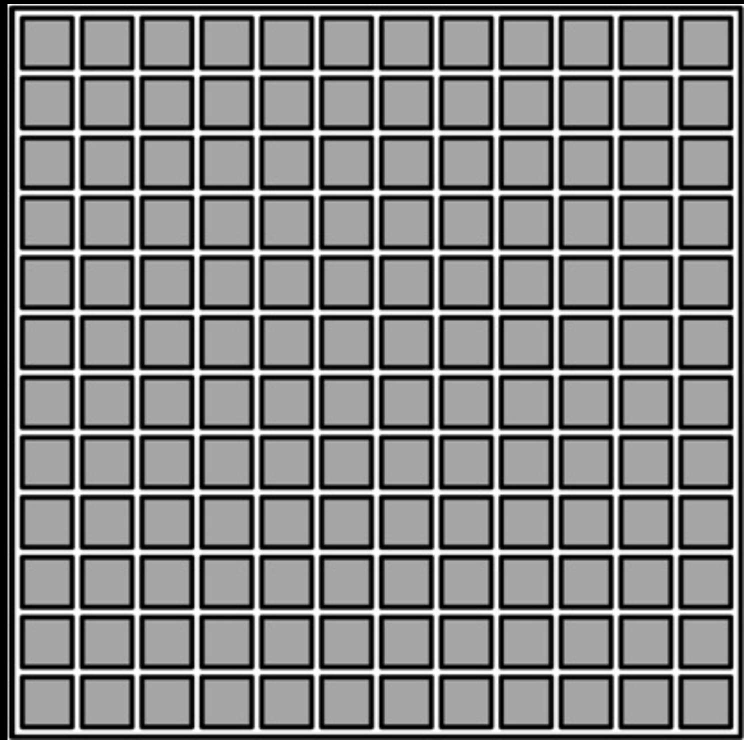
Quiz 2: What has the most energy?



A) Radio
B) X-rays
C) Red light
D) Microwave
E) Ultraviolet

How do light become a digital image?



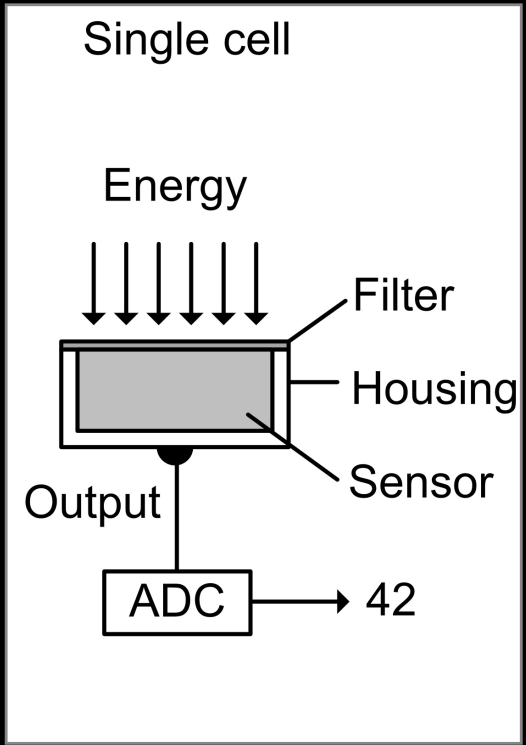


Charged coupled device

(CCD-chip)

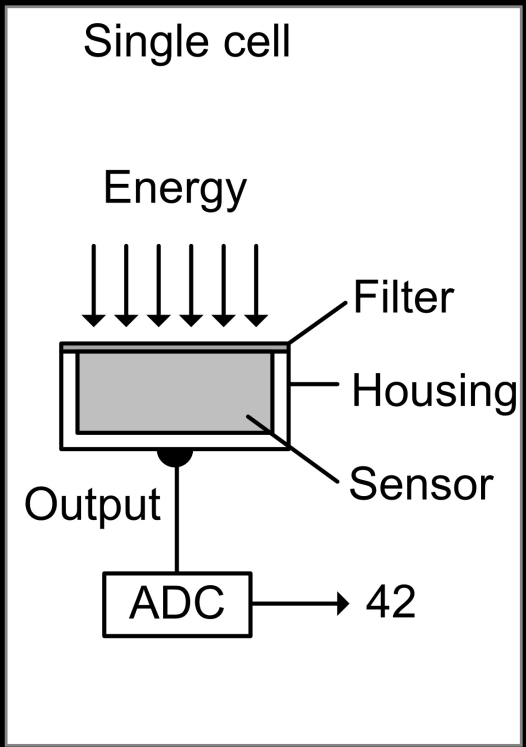
The digital film!

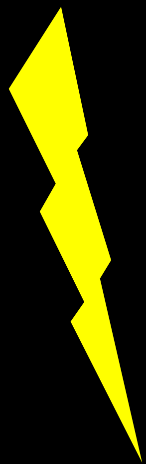
The CCD cell



- The cell can be seen as a well that collects energy
- It collect energy for a limited time (*to be charged*)
  - Exposure time
  - Integration time
  - Shutter

The CCD cell - conversion

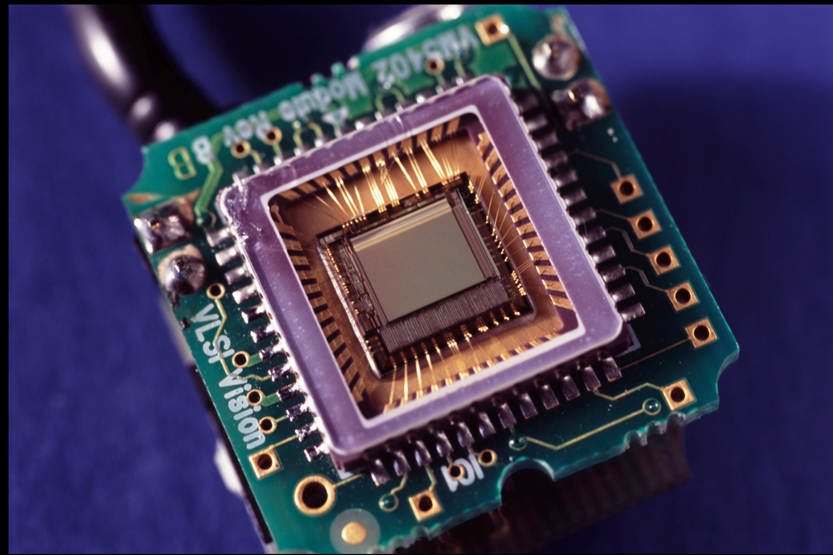




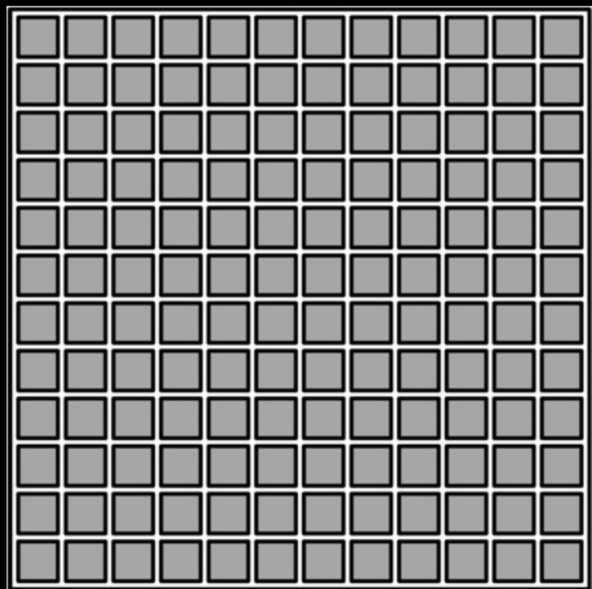
- Energy transformed to a digital number
  - Analog-to-Digital converter (ADC)
- Takes a an "analog signal" and converts it to a digital signal

$(01001001)_2 = (0 \times 2^7) + (1 \times 2^6) + (0 \times 2^5) + (0 \times 2^4) + (1 \times 2^3) + (0 \times 2^2) + (0 \times 2^1) + (1 \times 2^0) = (73)_{10}$

CCD and images

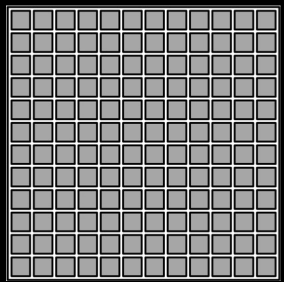


- Surprise! 1 CCD cell = 1 pixel
  - Only for grayscale images
  - More complex for RGB images
- 10 MPixel camera
  - 10 millions analog to digital conversions for one image!



Quiz 3: What is the size of a single CCD cell?

5.3 mm



7.2 mm

2048 x 1536 pixels

Solution:

7.2/2048= 3.5um

5.3/1536= 3.5um

A) 1 x 1 milimeter

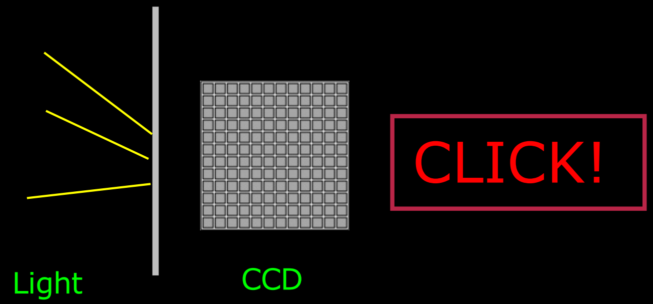
B) 3.5 x 3.5 micrometer

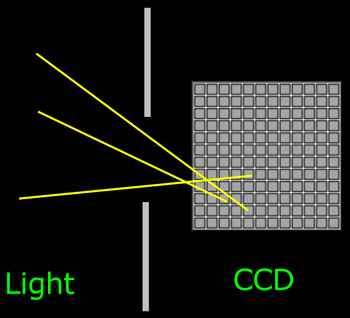
C) 0.002 x 0.002 milimeter

D) 5.6 x 5.6 micrometer

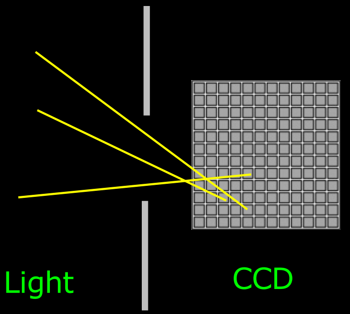
E) 0.4 x 0.4 milimeter

What happens when you press the button?

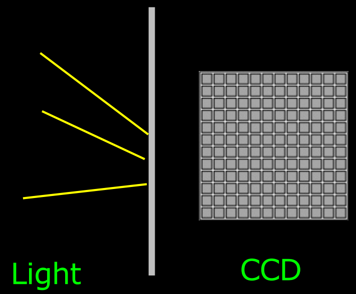




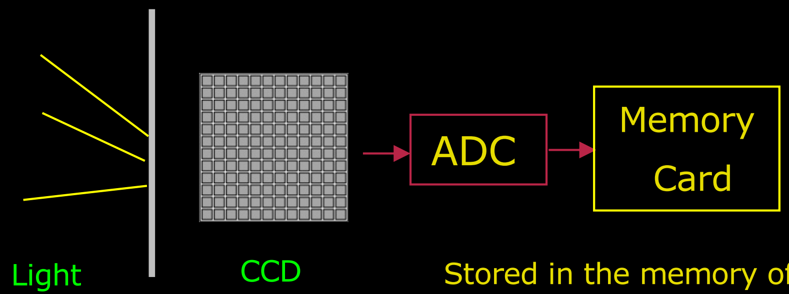
The shutter opens and the CCD is hit by light



CCD is integrating



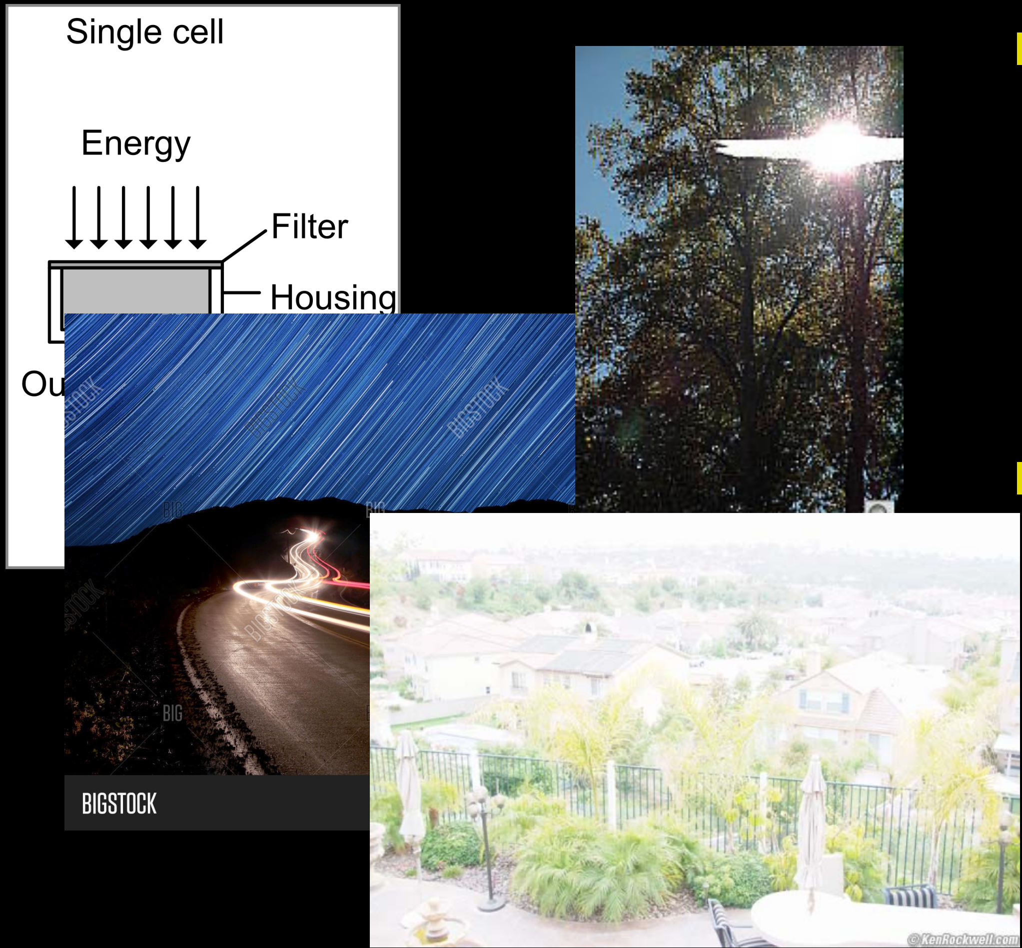
Shutter closes



The collected energies are transferred and converted to digital values

Stored in the memory of the camera

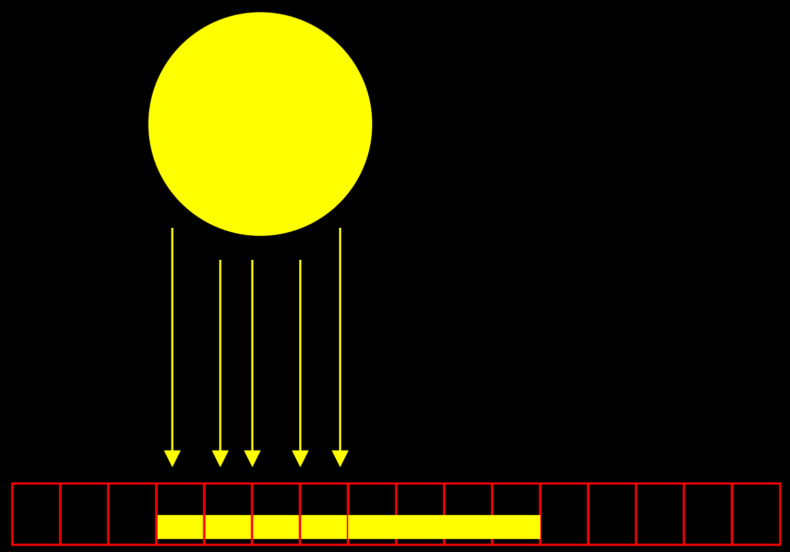
Question: Integration time



- What happens if we integrate over long time?
  - Motion blur
  - Over-exposure (the well is overrunning)
  - Blooming
- Short integration time
  - Noise
  - Lack of contrast

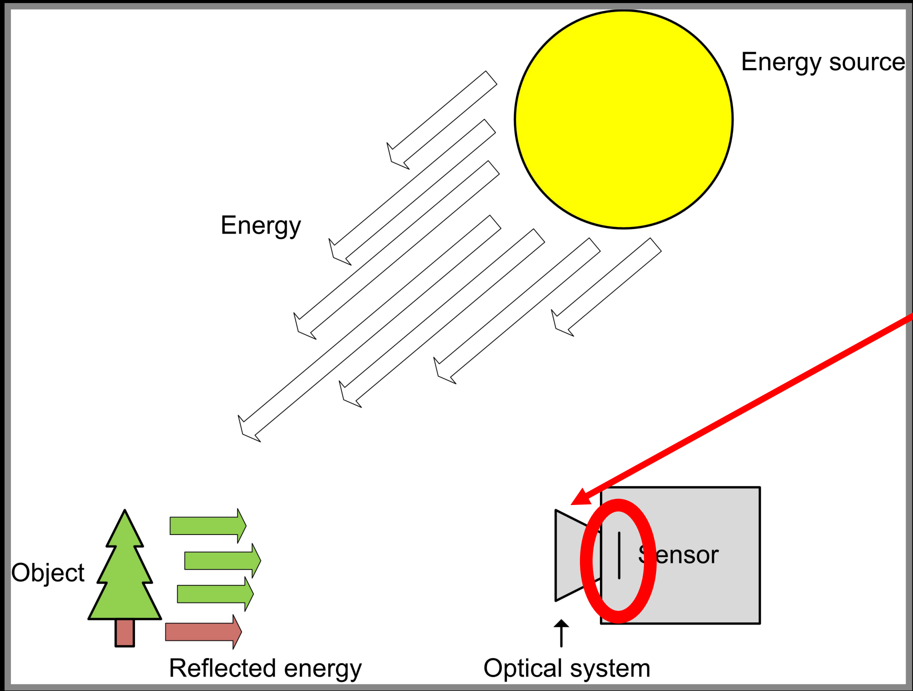
Motion blur

- Causes blurring of the moving object



The bigger picture

- A camera is more than a CCD!
- The CCD is the sensor!
- There is also "an optical system"



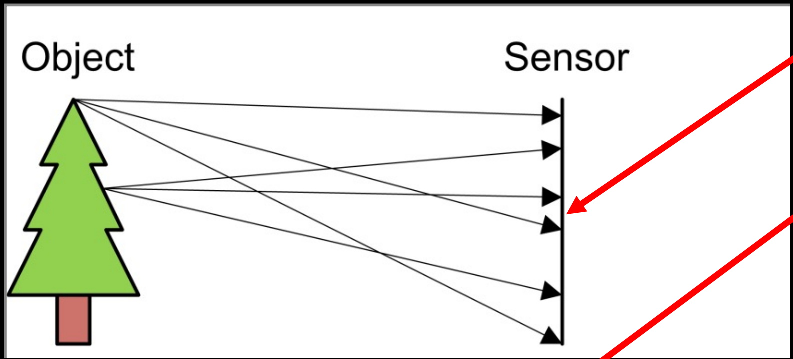
Optical system (lenses)

Optical system

- How do we get an image on the CCD?
- Light follows a straight line
- Light that hit one spot reflects in many directions

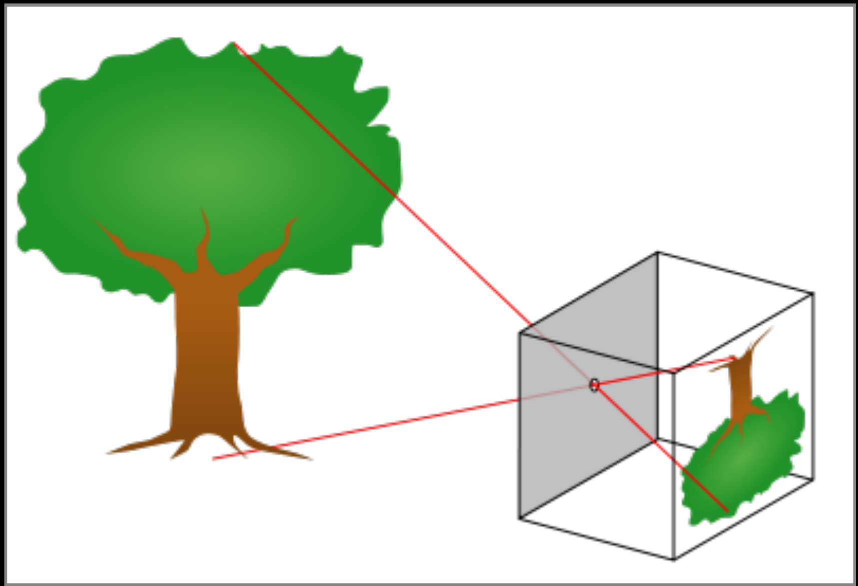
Same point hit by rays from
all over the object

Barrier with tiny hole

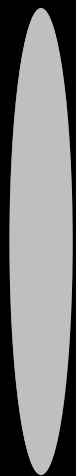


nera

Pinhole camera



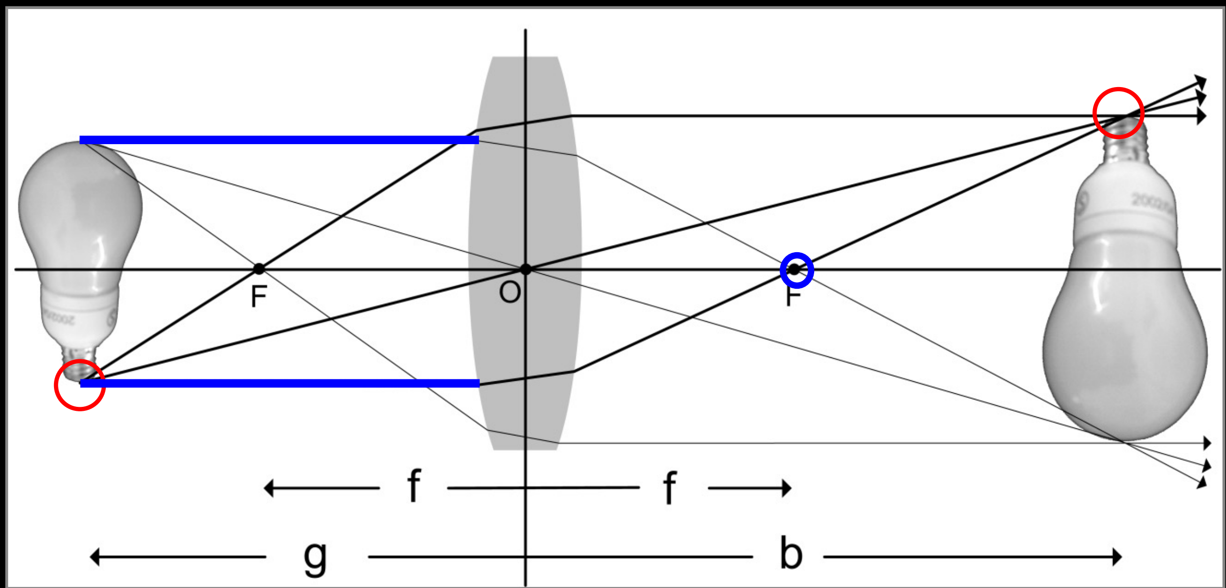
- Light coming through the tiny hole – any problems?
  - Very little light!
- How do we get more light inside the camera?
  - While keeping the focus?



A lens!

The lens

- A lens focuses a bundle of rays to one point
- Parallel rays pass through a focal point **F** at a distance f beyond the plane of the lens. f is the focal length
- O is the optical centre. F and O span the optical axis

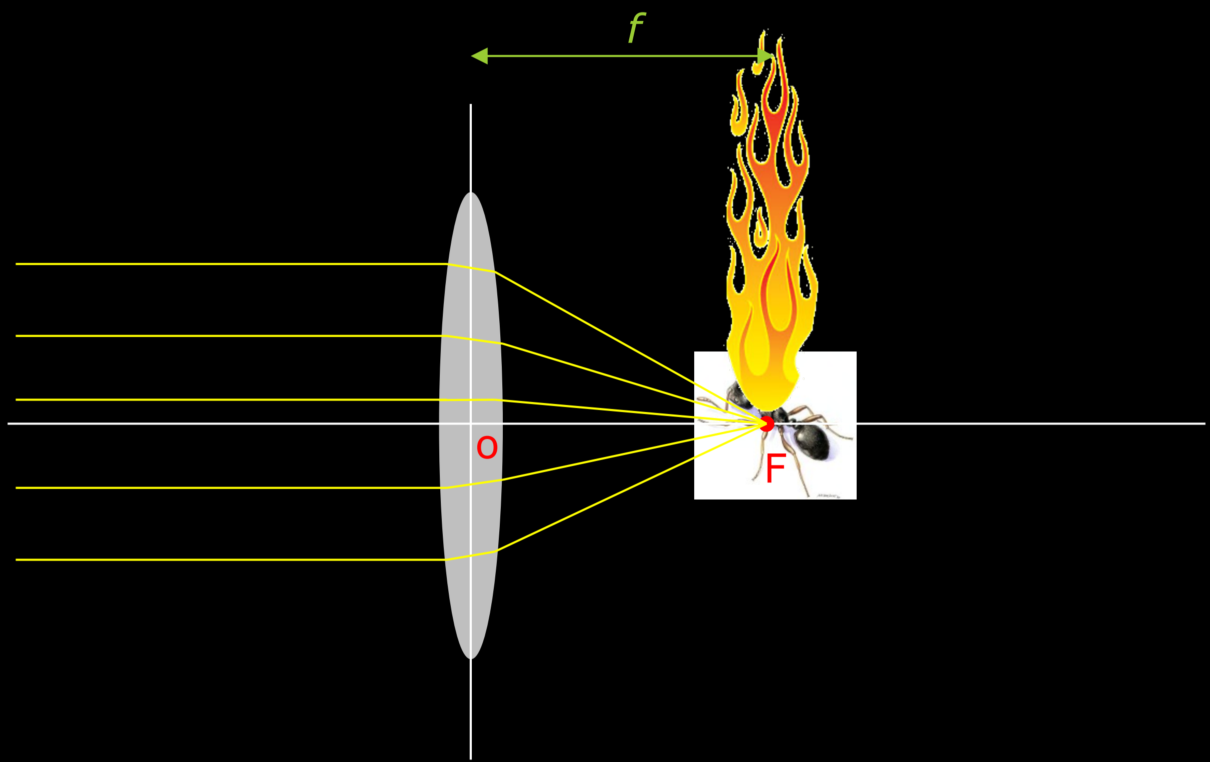


World

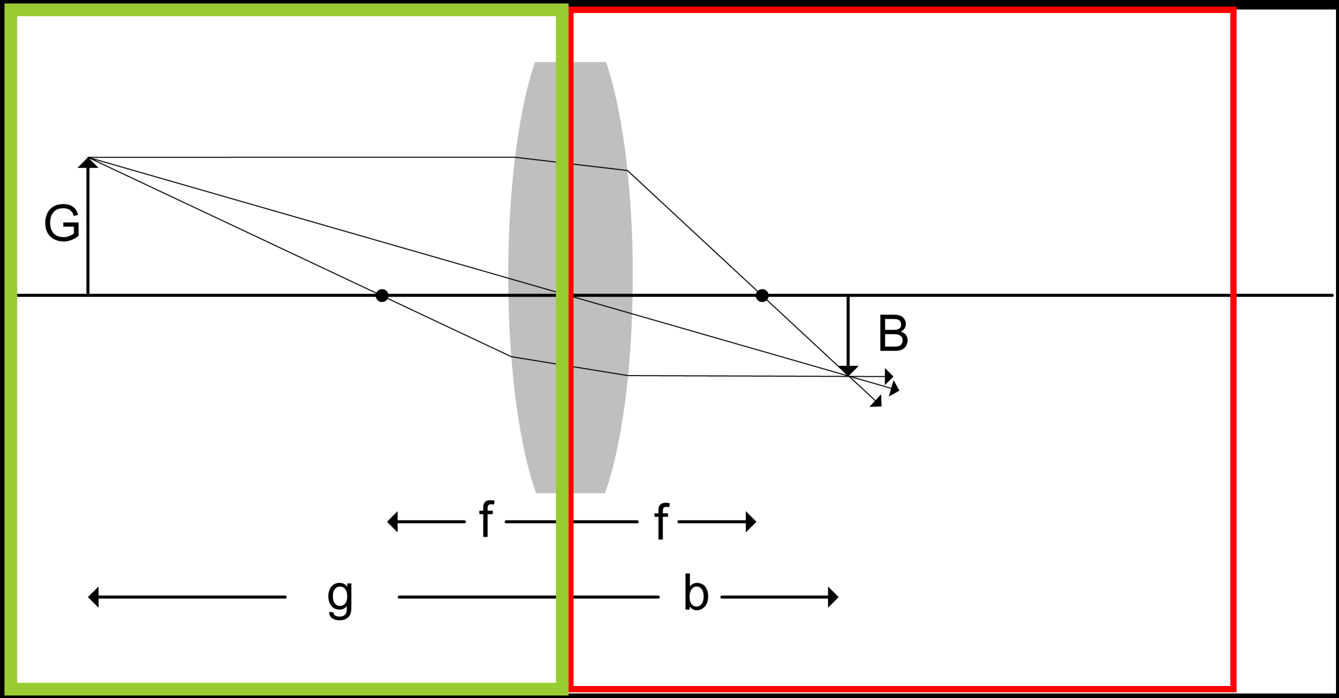
Inside camera

Focal point – focal length

- Light coming from "really far away" can be seen as parallel rays
- Rays intersect at the focal point
- Distance from optical centre O to focal point F is called *focal length f*



Where do non-parallel rays meet?



World

Camera

$$\frac{1}{g} + \frac{1}{b} = \frac{1}{f}$$

Thin lens equation

or

Gauss' lens equation

g – distance to object

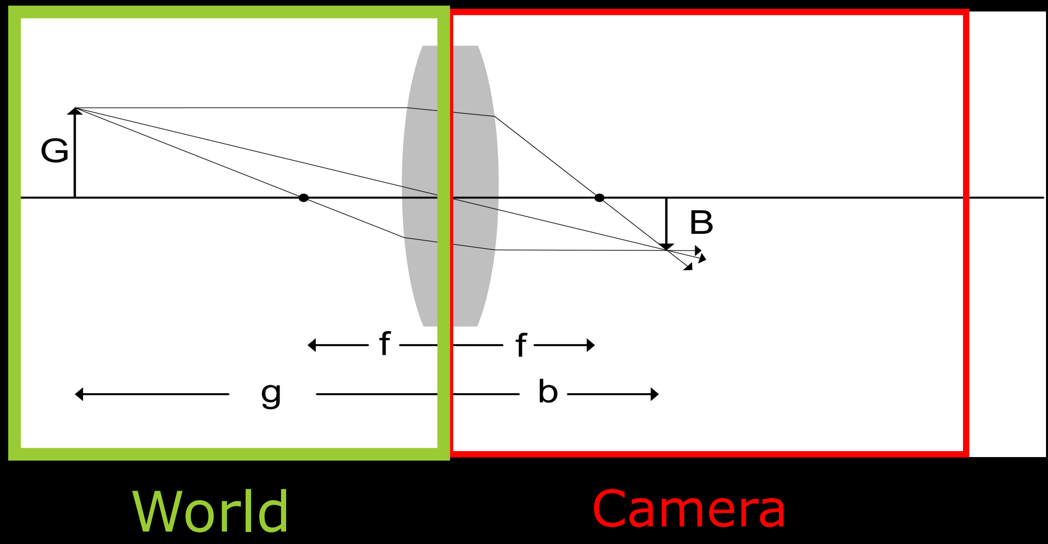
b – distance to intersection

Quiz 4: Where do the rays meet

- Camera with focal length of 5 mm
- Rasmus is standing 3 meters away
- Where do the rays meet in the camera? (b)

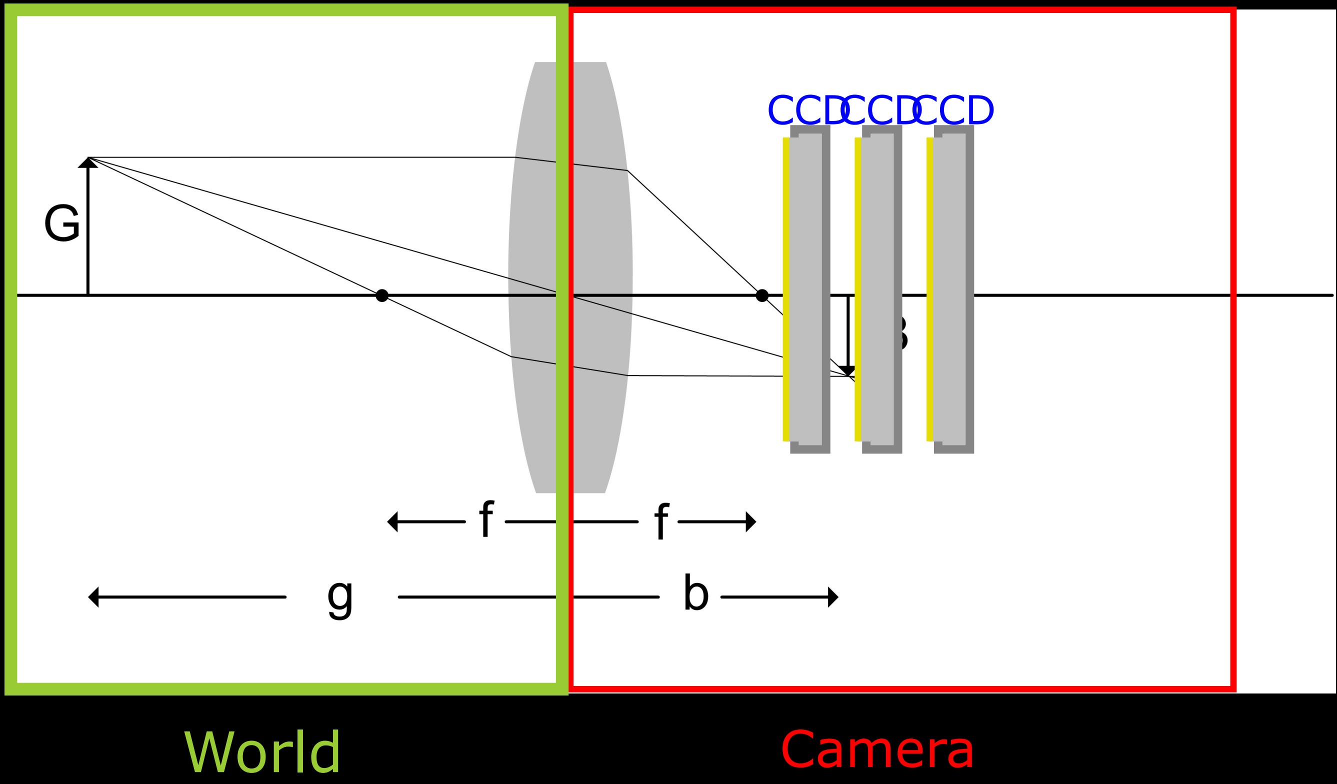
$$\frac{1}{g} + \frac{1}{b} = \frac{1}{f}$$

A) b = 1 mm
B) b = 4 mm
C) b = 5 mm
D) b= 6 mm
E) b = 7 mm



Focus or not to focus?

How do we make focused images? Placing the CCD right

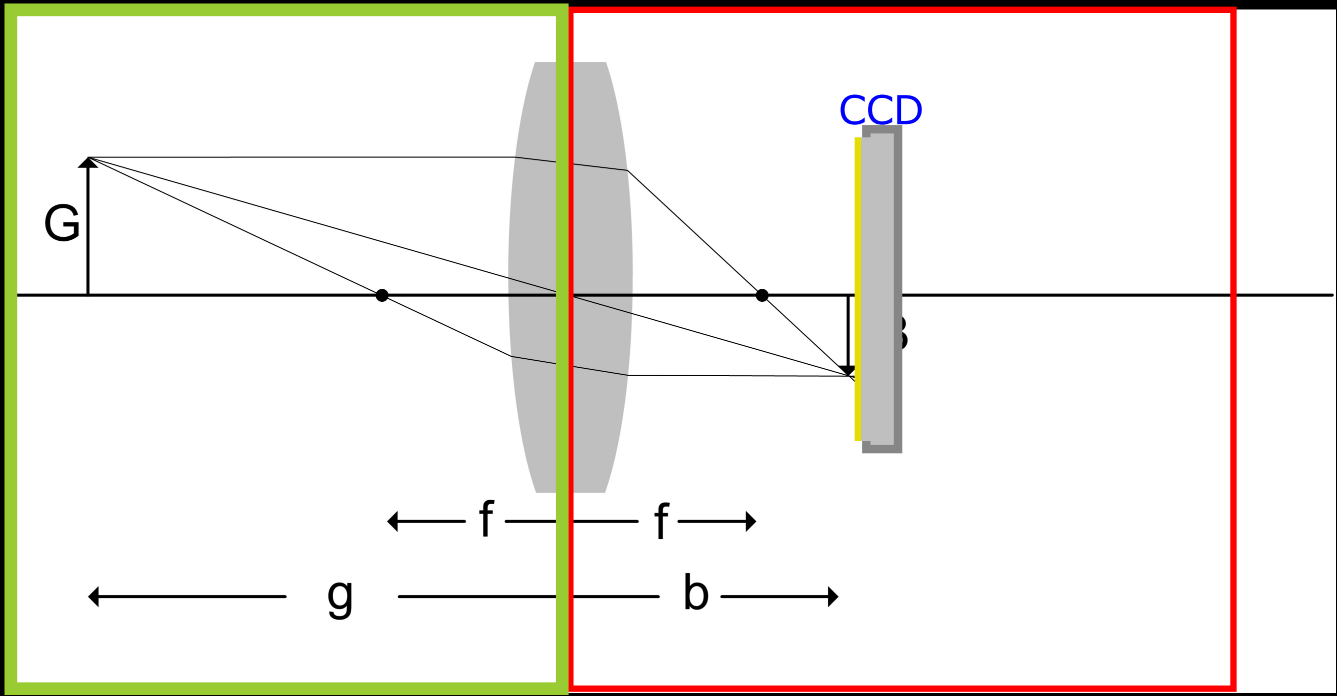


CCD should be placed at b!

g – distance to object

b – distance to intersection

Focusing



World

Camera

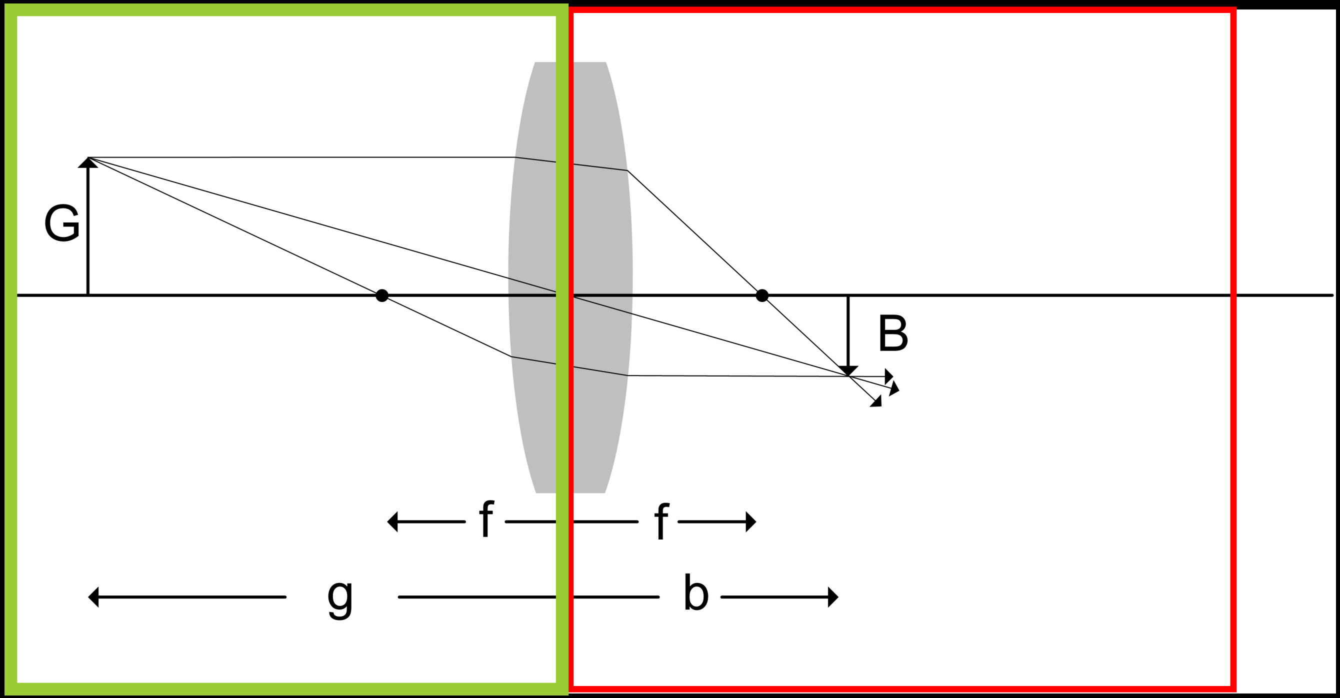
g – distance to object

b – distance to intersection

- We move the camera
- Distance to object (g) changes
- f is fixed
- b changes
- Move CCD to b
  - Focusing

$$\frac{1}{g} + \frac{1}{b} = \frac{1}{f}$$

Object size



World

Camera

What is the size of an object on the CCD?

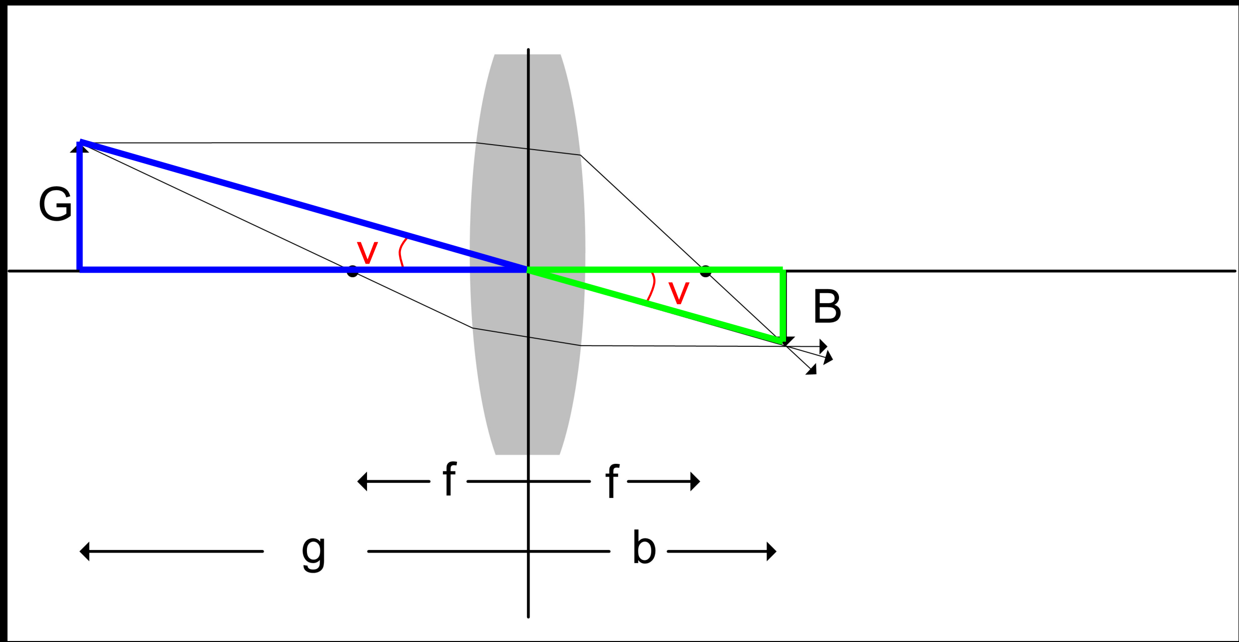
g – distance to object

G – Object height

b – distance to intersection

B – object height on CCD

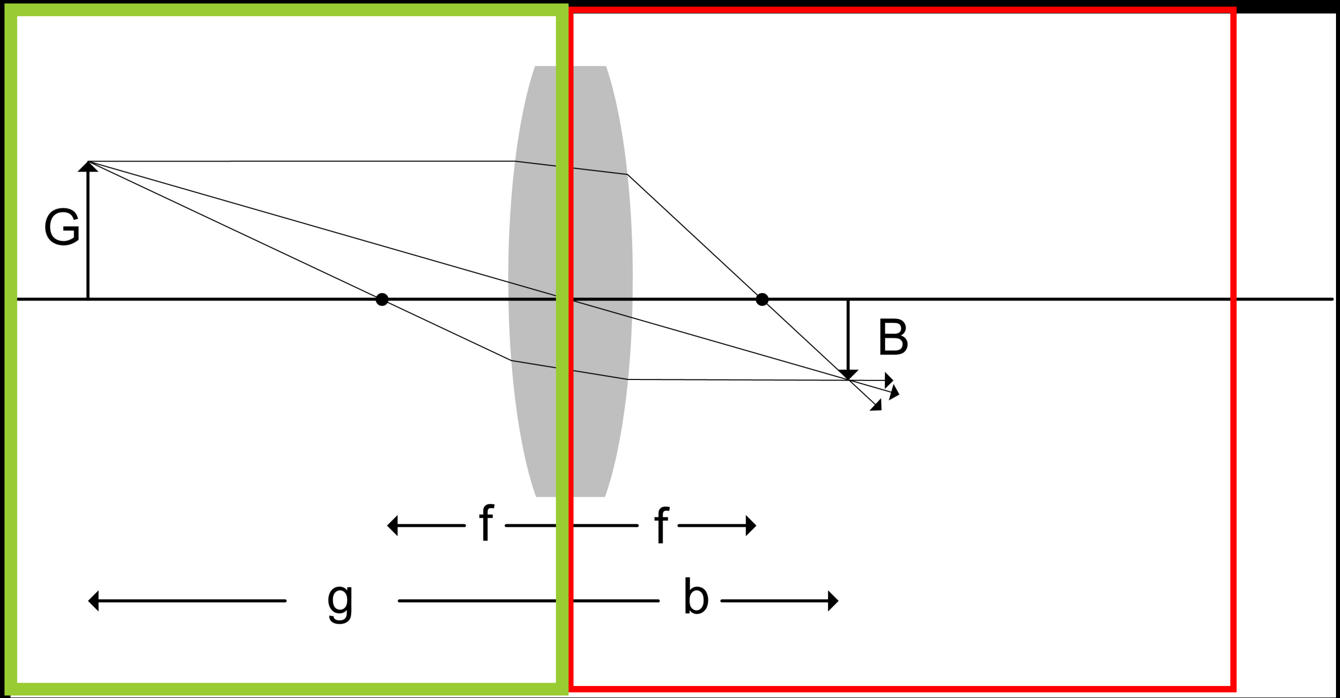
An important relation!



- Two triangles
- One with side length g and one with b
- B and G are related! – how?
- Hint - tangent

$$\frac{b}{B} = \frac{g}{G}$$

An important relation!



$$\frac{b}{B} = \frac{g}{G}$$

World

g – distance to object

G – Object height

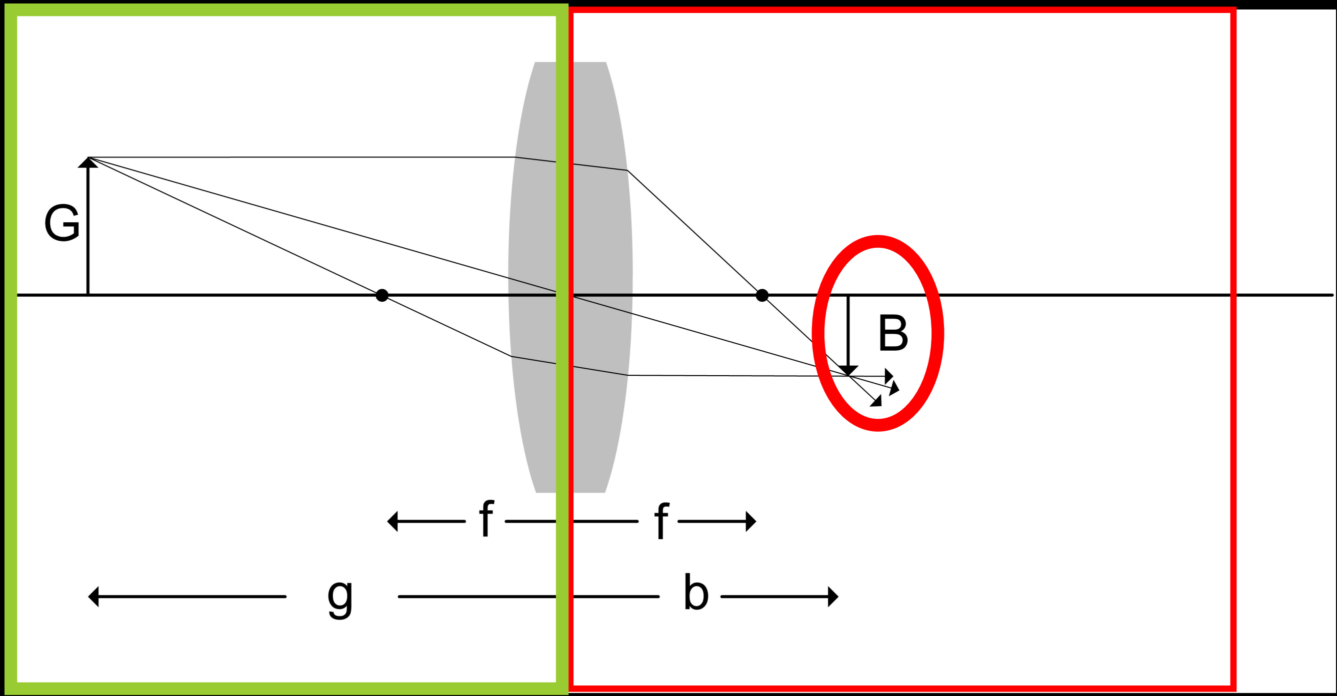
Camera

b – distance to intersection

B – object height on CCD

How do we Zoom ?

We want to make B larger! How?



World

Camera

g – distance to object

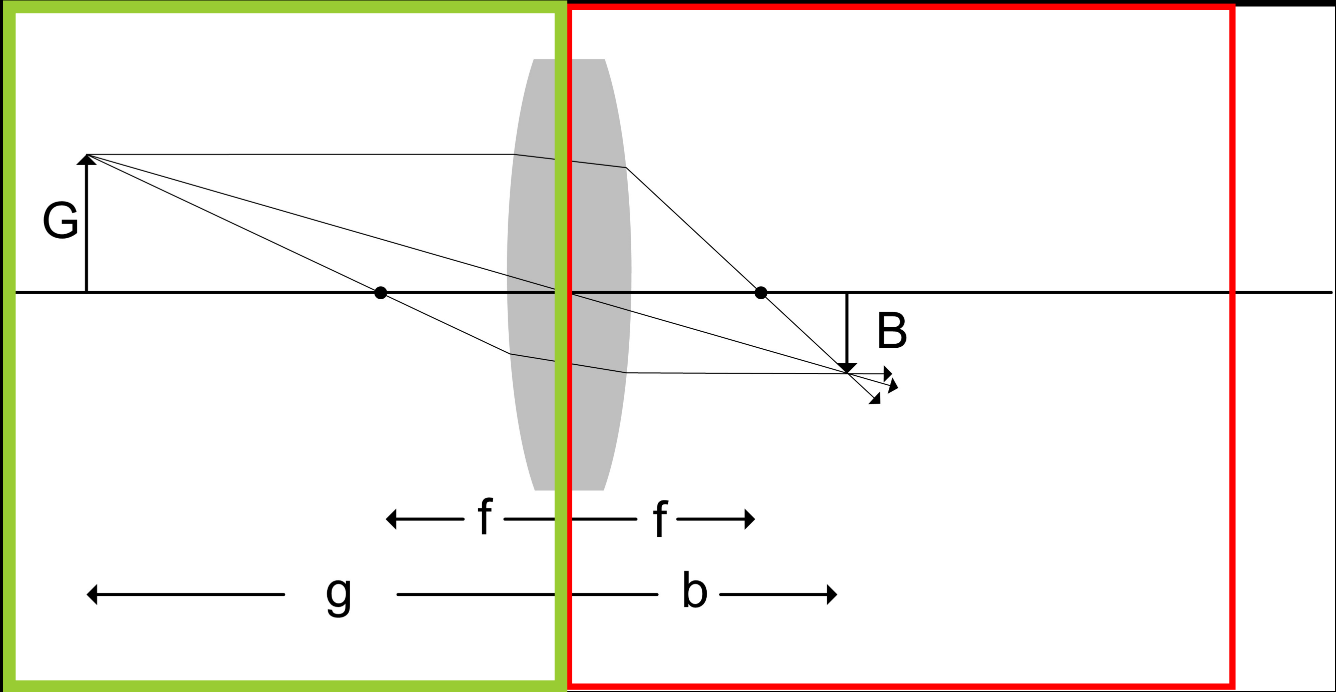
b – distance to intersection

G – Object height

B – object height on CCD

Zoom

We want to make B larger! How?



$$\frac{b}{B} = \frac{g}{G}$$

$$B = b\frac{G}{g}$$

Fixed

World

g – distance to object

G – Object height

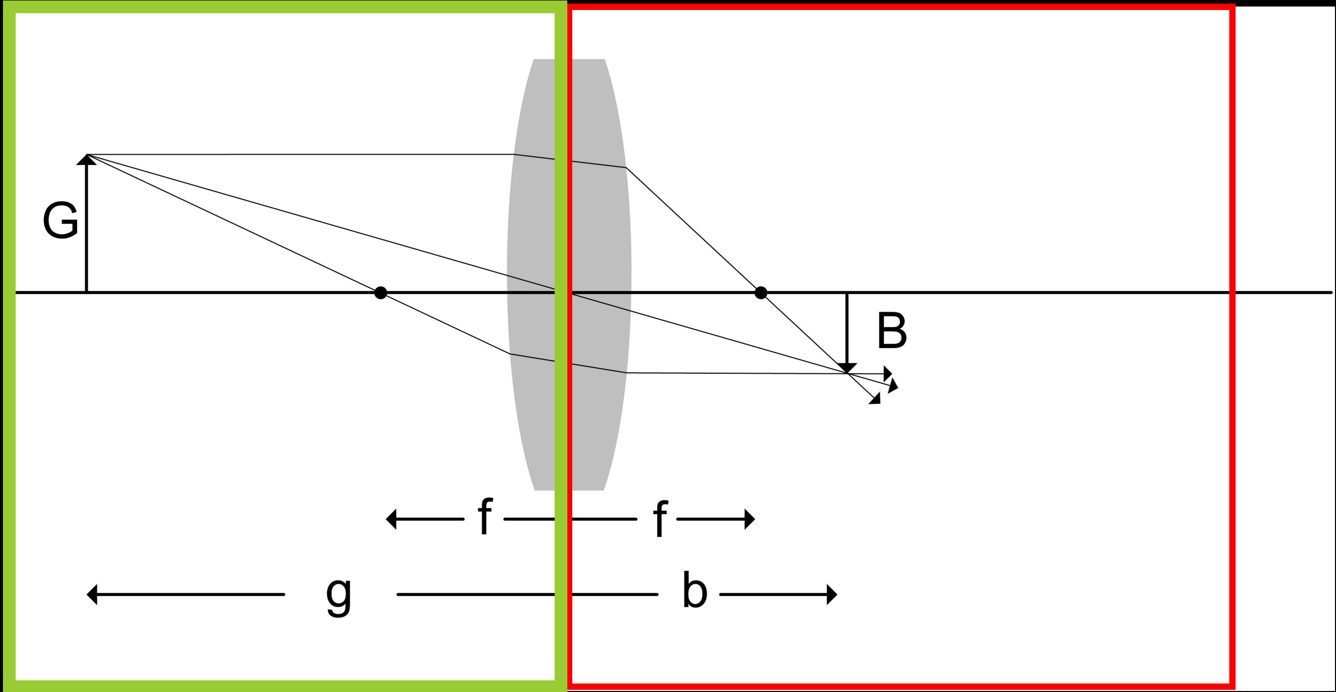
Camera

b – distance to intersection

B – object height on CCD

Zoom

We want to make B larger – changing b!



$$B = b\frac{G}{g}$$

$$\frac{1}{g} + \frac{1}{b} = \frac{1}{f}$$

constant

To change B we change the focal length!

World

g – distance to object

G – Object height

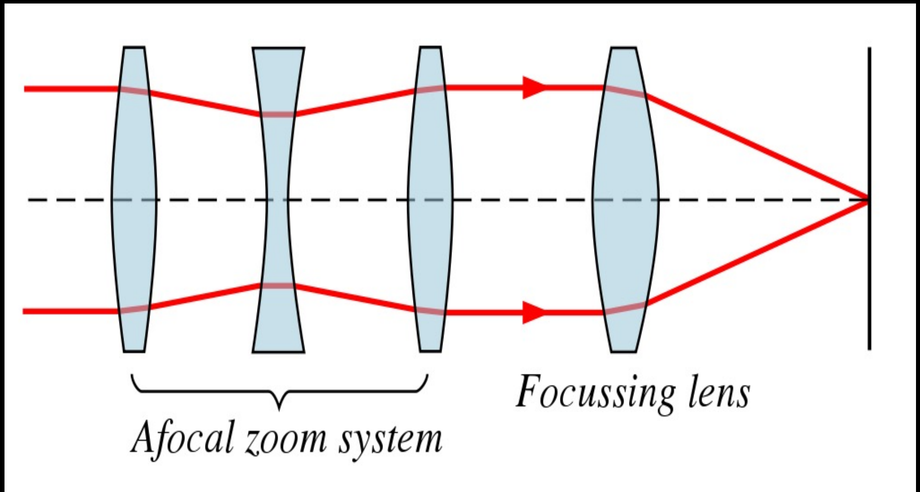
Camera

b – distance to intersection

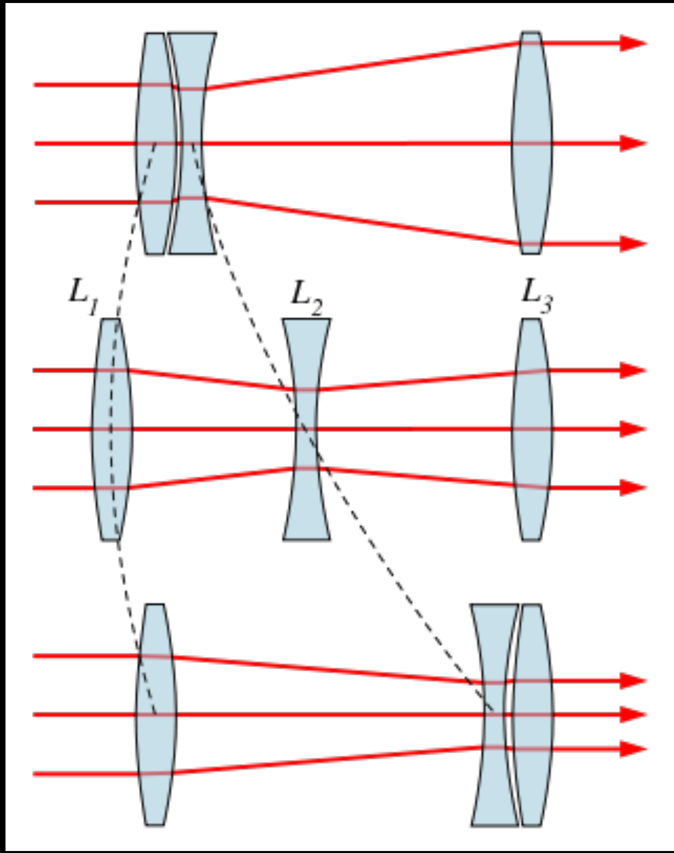
B – object height on CCD

Changing the focal length?

- Not possible on a simple lens
- Need a “zoom lens”
- Several lenses together



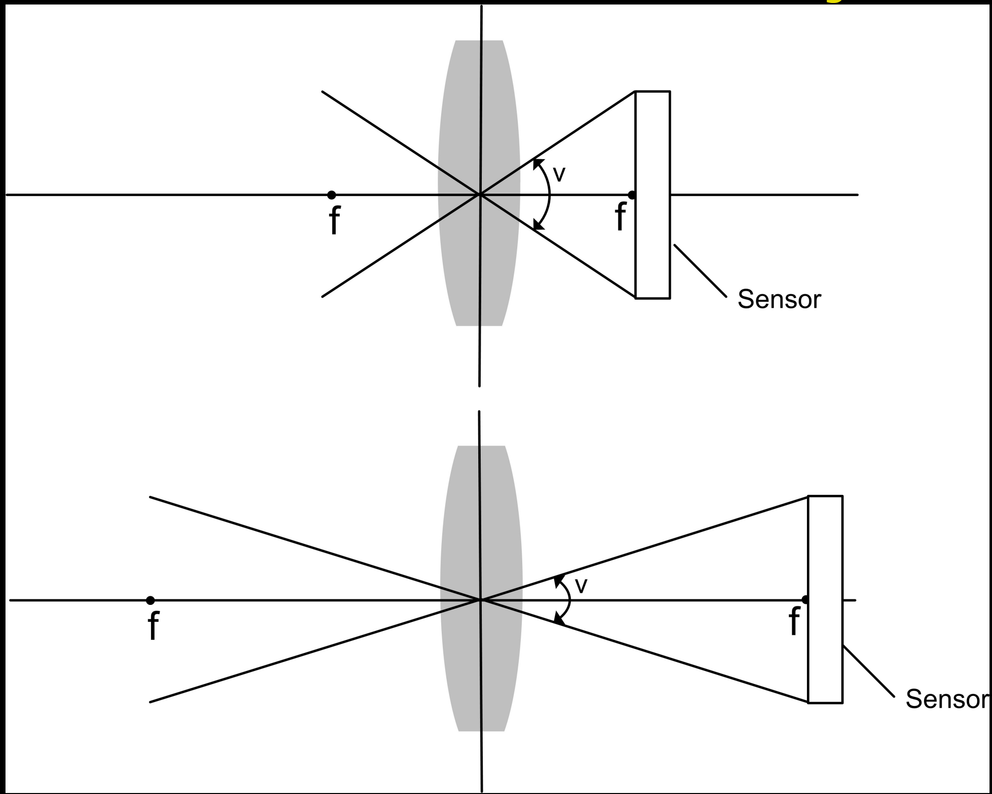
Afocal zoom principle



From WikiPedia: wikipedia.org/wiki/Zoom_lens

Field of view (FOV)

Two cameras with different focal length

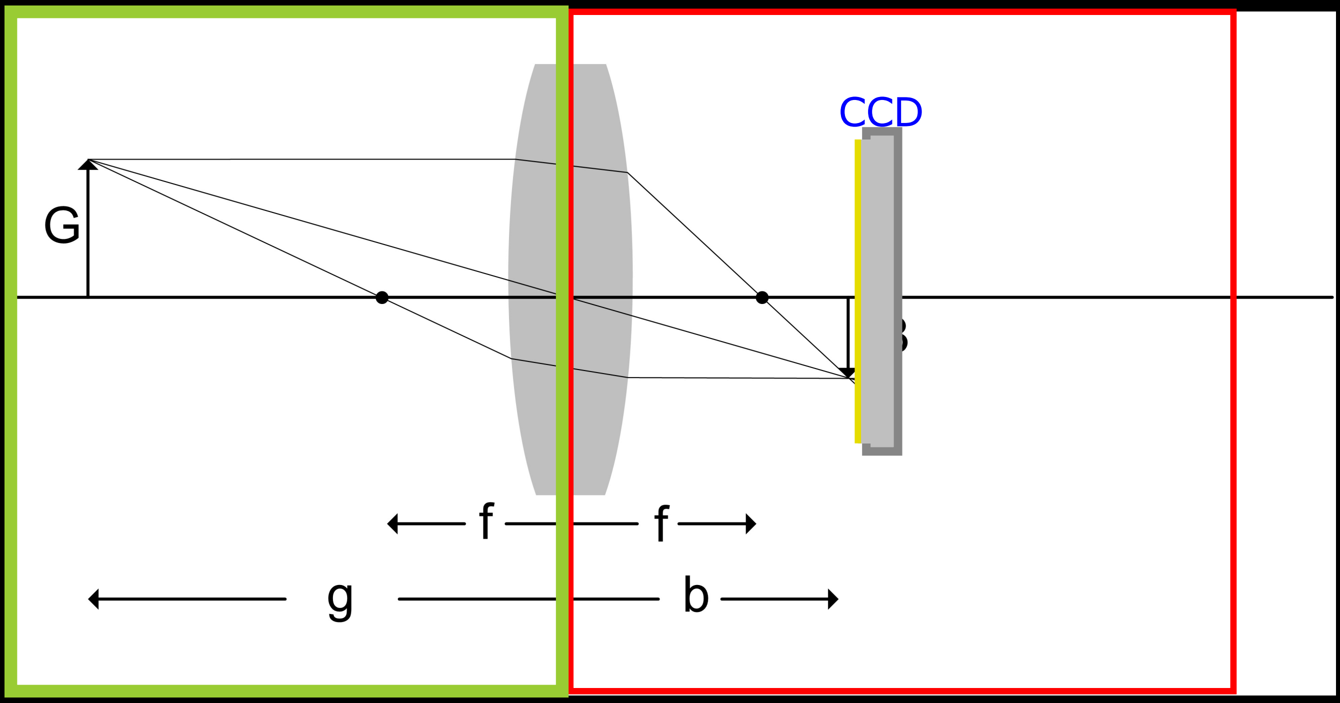


- Described by an angle
  - Large angle the larger FOV
- Depends on
  - CCD size
  - Focal length
- Fisheye lens
  - Small focal length
  - Large field of view

- CCD chip is a rectangle
  - Horizontal field of view
  - Vertical field of view
- Zoom changes field of view
  - Optical zoom
  - Digital zoom

Depth of field - dybdeskarphed

Depth of field



World

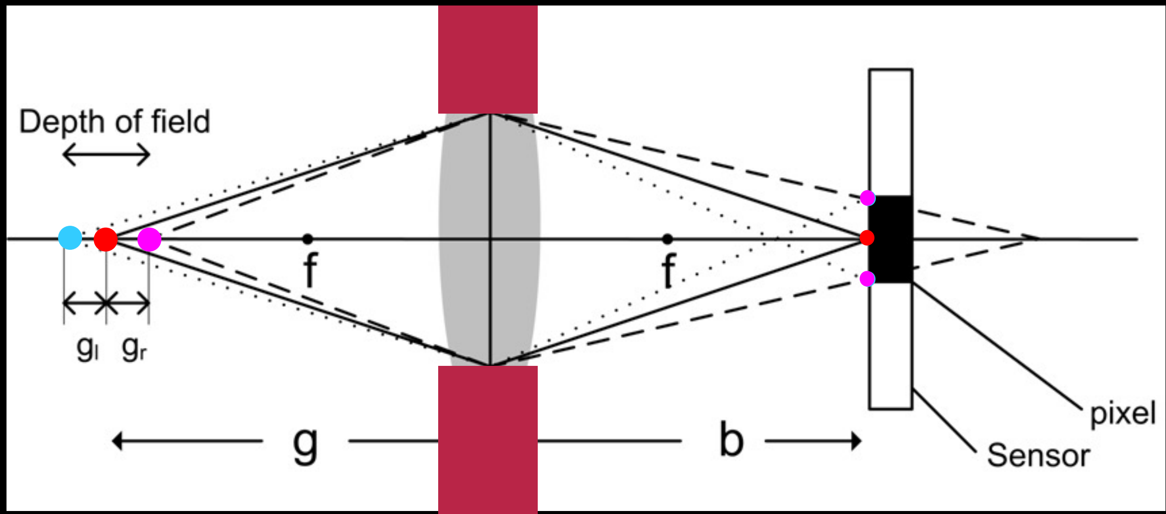
Camera

g – distance to object

b – distance to intersection

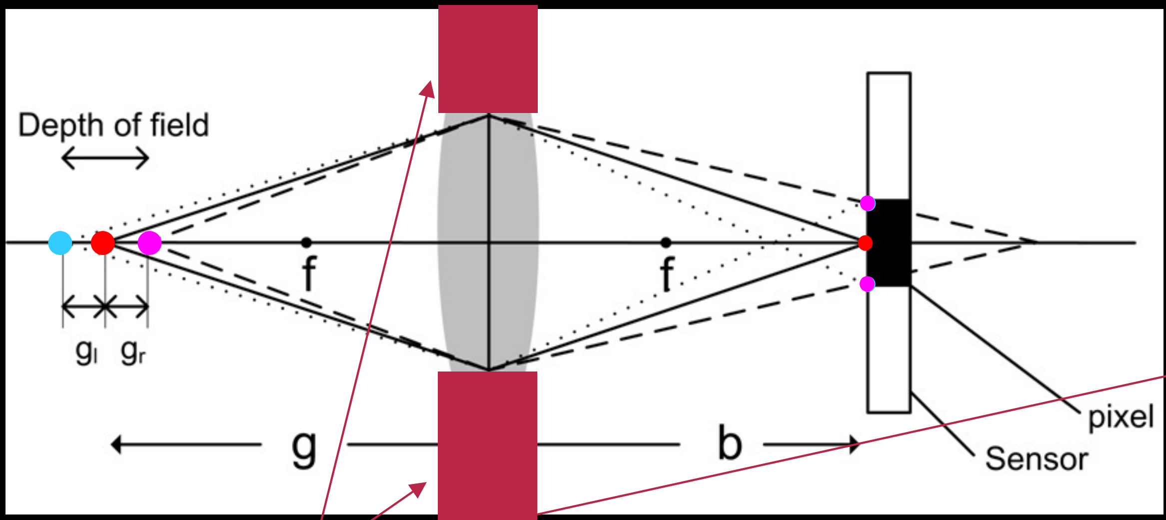
- g is fixed
- CCD should be placed at b
- g is fixed – only focus at one distance!

Depth of field



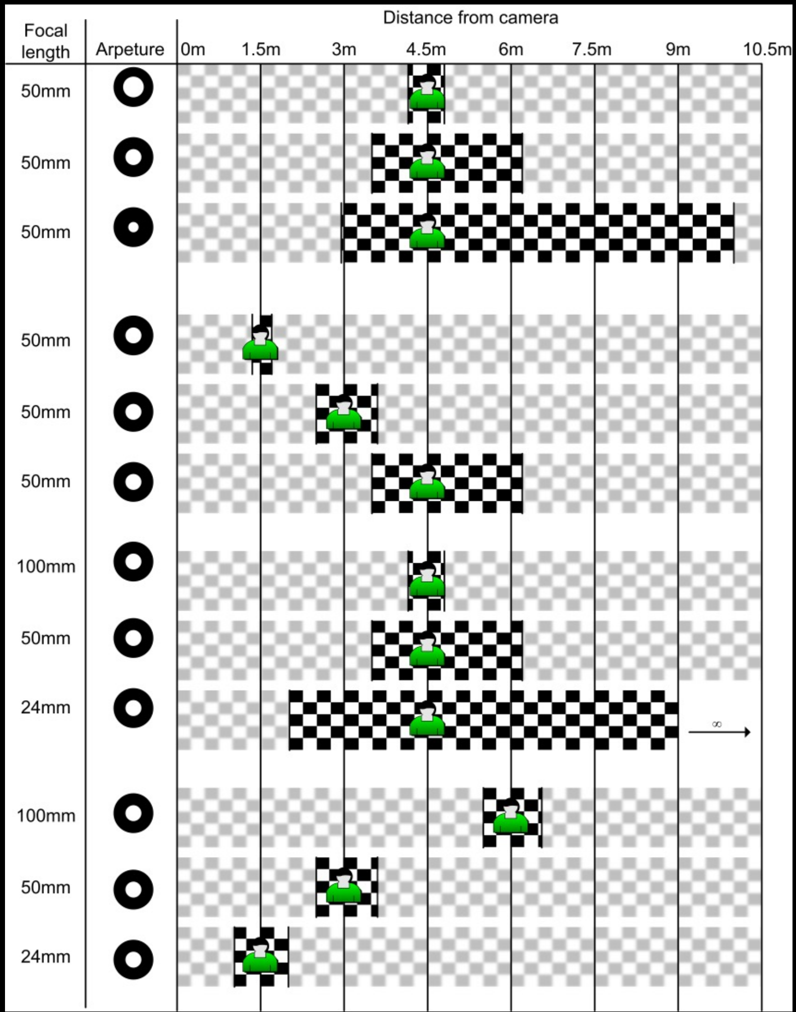
- Look at one pixel in the middle
- The object is placed at distance g
- How much can we move the object?
  - Light has to hit the same pixel
- Move it to the left (g_l)
- move it to the right (g_r) – still hit the same pixel (but twice)

Depth of field – Aperture (blænde)



- The aperture controls the amount of light
- Small aperture
  - large depth of field
  - Less light -> longer exposure

How to acquire a good image?



- Distance to object
- Motion of object
- Zoom
- Focus
- Depth-of-fields
- Focal length
- Shutter
- Field-of-view
- Aperture (DK: blænde)
- Sensor (size and type)

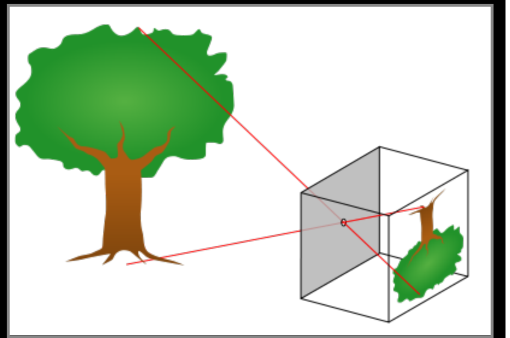
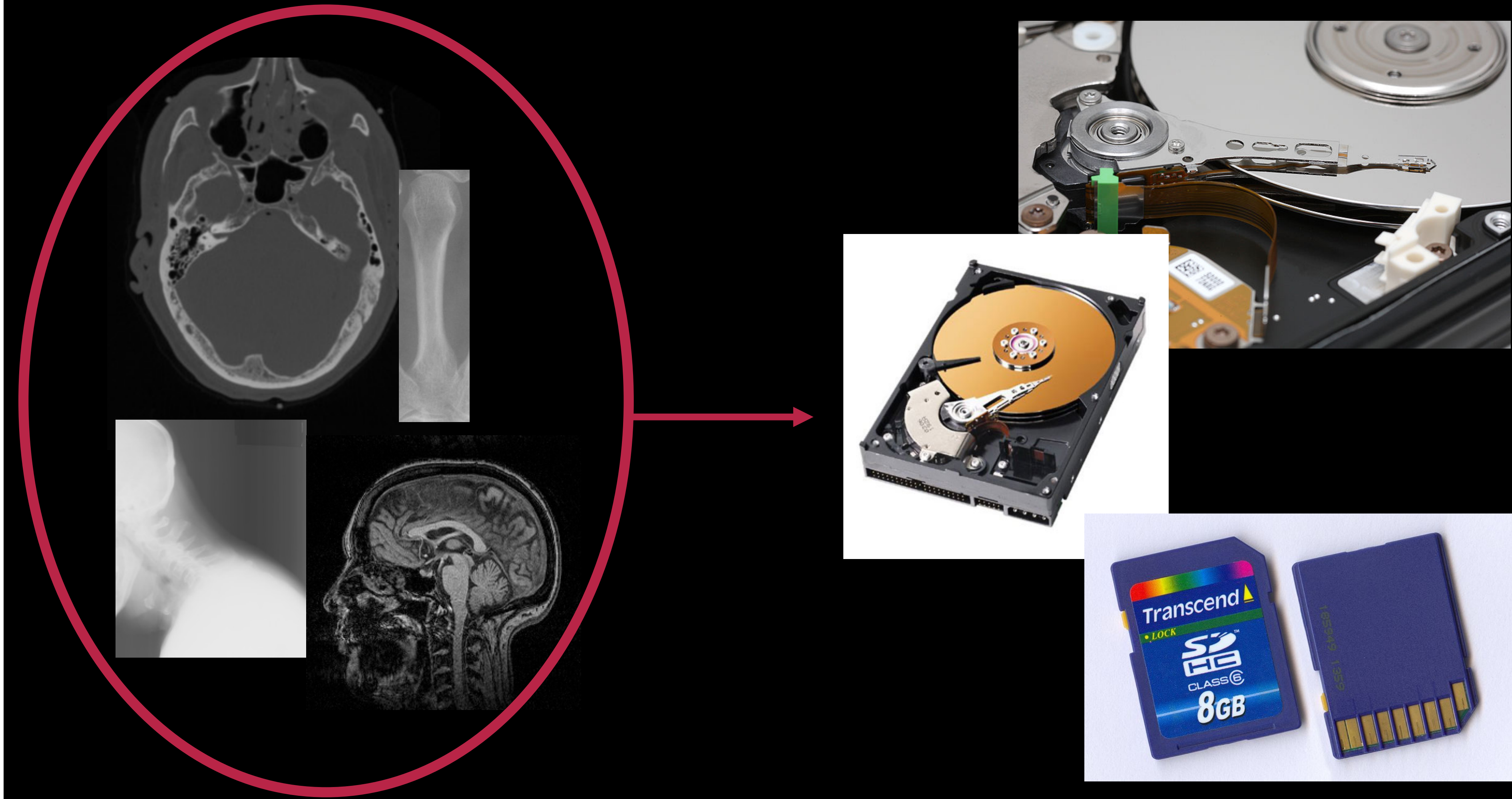


Image storage



Hard disks, memory cards, CDs etc

- Storage for bytes!
  - 500 GB?
  - 500 GigaBytes = 500.000.000.000 bytes!
- A hard disk do not know anything about images
- Stores data as lists of bytes
  - 17, 255, 1, 3, 87, 98, 11, …
- File on a hard disk
  - It has a length (in bytes, MB, GB)
  - Contains numbers! (Bytes)

We want to make an "image file"

Imagine

Size: 200 x 200

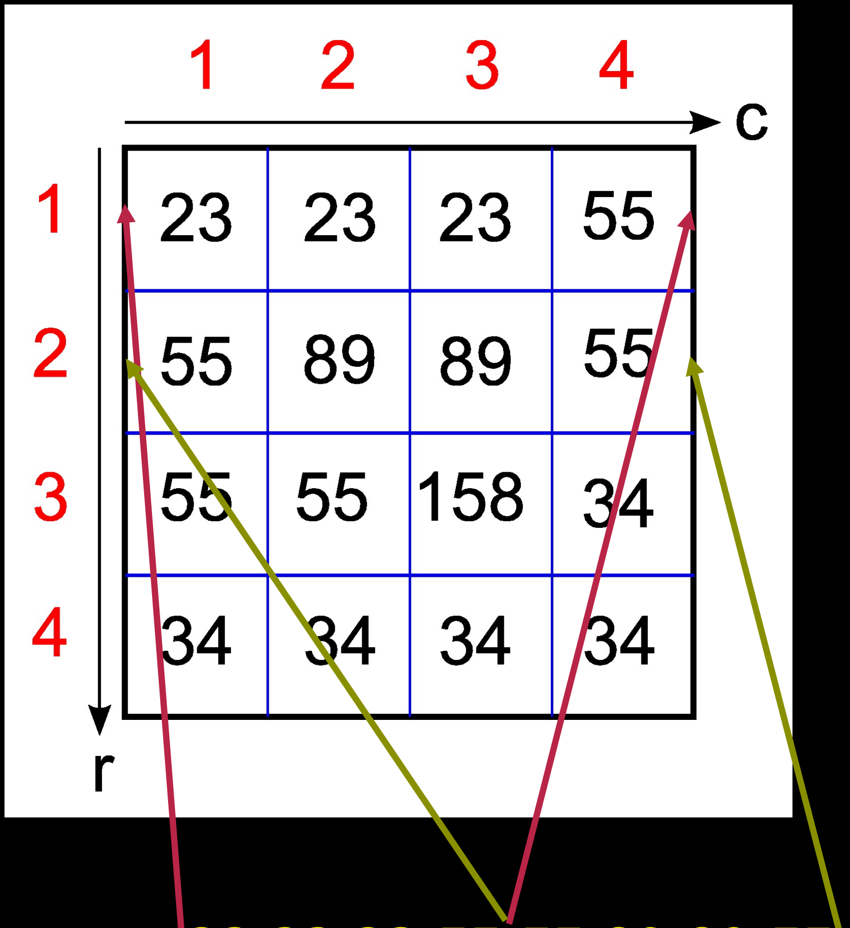
256 grayscales

- You have a telephone. You are only allowed to say no or yes!
- You need to transfer an image to the person in the other end.
- How can we do that?

Remember that each pixel is a byte

A byte is made out of 8 bit

Image as data



- How do we store this image as list of bytes?
- What do we need
  - Size of the image
    - Width as 2 bytes (0-65535)
    - Height as 2 bytes (0-65535)
  - The data

23,23,23,55,55,89,89,55,55,55,158,34,34,34,34,34

Simple image format

- Stores the image as
  - A header with information about size
  - Data with no compression
- Windows Bitmap Format (BMP)

r \ c	1	2	3	4
1	23	23	23	55
2	55	89	89	55
3	55	55	158	34
4	34	34	34	34

Compression - make something smaller

- Is there a more "compact" way to represent the data below?
- Look for patterns
  - A series of numbers can be represented how?
    - The count and the value
- What is the "count and value" code?
  - Reduced from 16 to 12 values

Run length encoding

23,23,23,55,55,89,89,55,55,55,158,34,34,34,34,34

3,23, 2,55, 2,89, 3,55, 1,158, 5,34

Run length encoding

- Simple but useful data compression
- General – not only for images
- Is also used by the Windows Bitmap Format (BMP)

Quiz 5: Run Length coding of image

A) 1 1 3 5 2 3 3 2 2 3 4 201 4 130 0 147 2 88

B) 1 1 2 5 2 3 2 3 3 201 3 19 5 147 4 130 1 147 2 88

C) 1 1 3 5 2 3 1 2 2 3 2 201 3 19 2 147 4 130 3 147 2 88

D) 5 1 1 5 2 3 3 2 2 3 2 201 3 19 2 147 3 130 1 147 5 88

E) 1 1 3 5 3 3 5 2 2 4 2 201 6 19 2 147 4 130 2 88

1	5	5	5	3
3	2	3	3	201
201	19	19	19	147
147	130	130	130	130
147	147	147	88	88

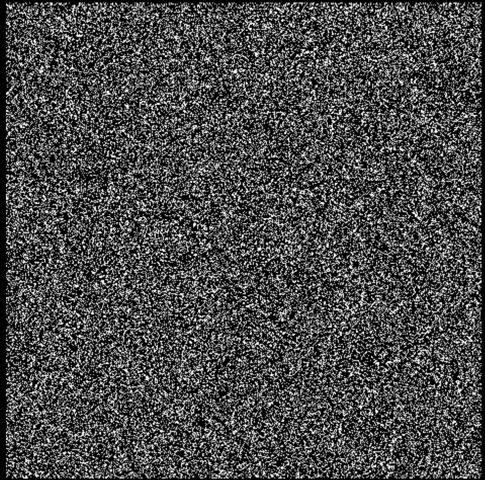
Compression ratio – how compressed?

- Gives a measure for how much data is compressed
- Our example
  - From 16 to 12
  - 16 : 12 = 4 : 3
  - Ratio 1.33

$\boxed{\text{Compression ratio = uncompressed size / compressed size}}$

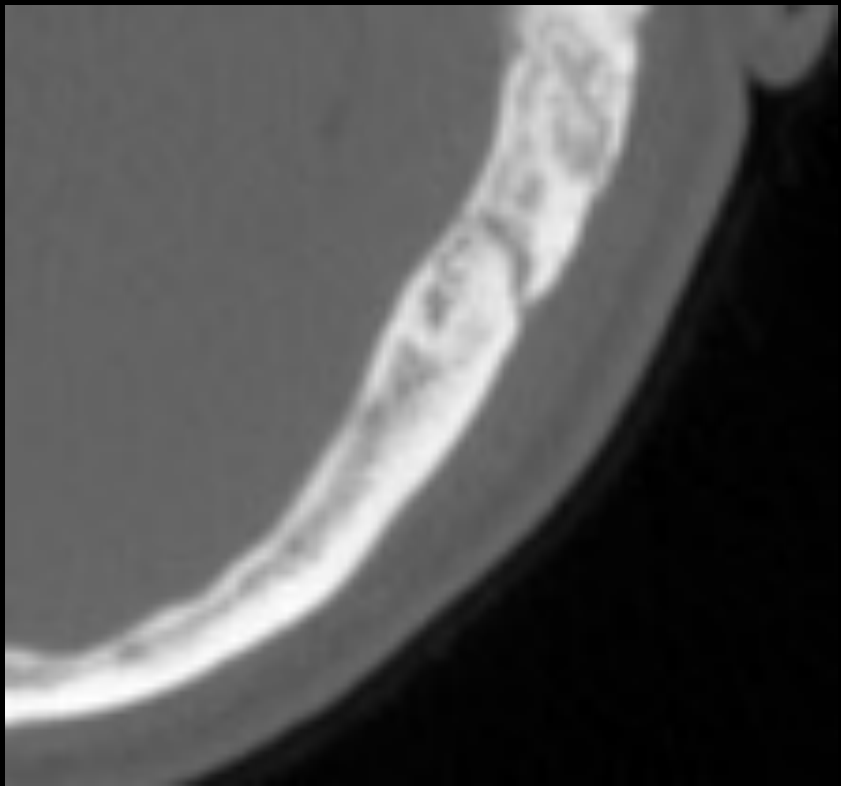
Lossless image formats

Noisy image



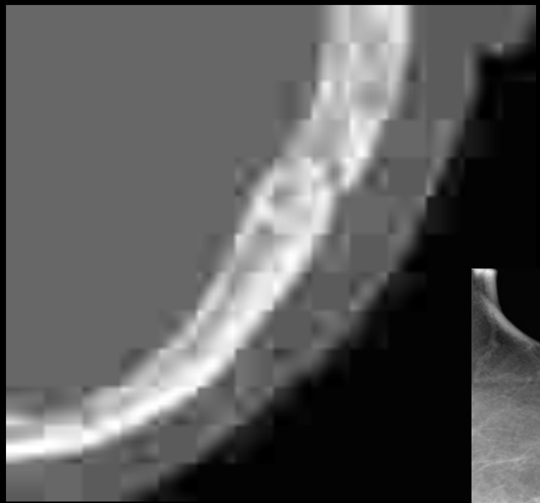
- Do not throw away information
- Good for storing medical images
  - We do not want to destroy any information
- Not very effective for photos. Why?
  - To many changes in the image
- PNG (portable network graphics) is a good format

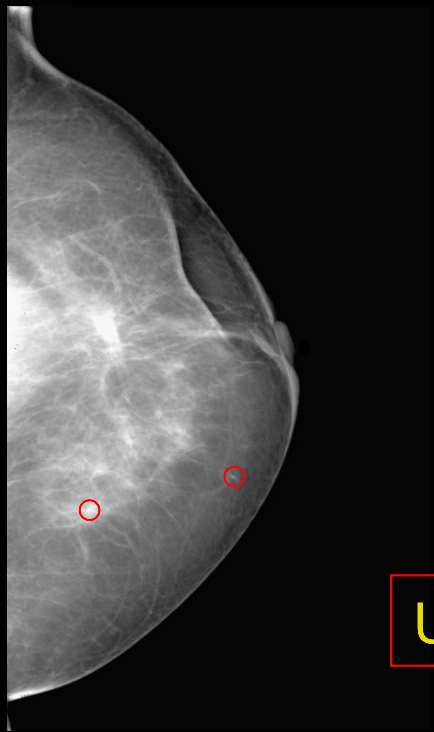
Lossy image formats



- Removes "unimportant" information
- JPEG is an example
- Removes the "high frequencies"
- Similar to the MP3 sound format

Compression artefacts





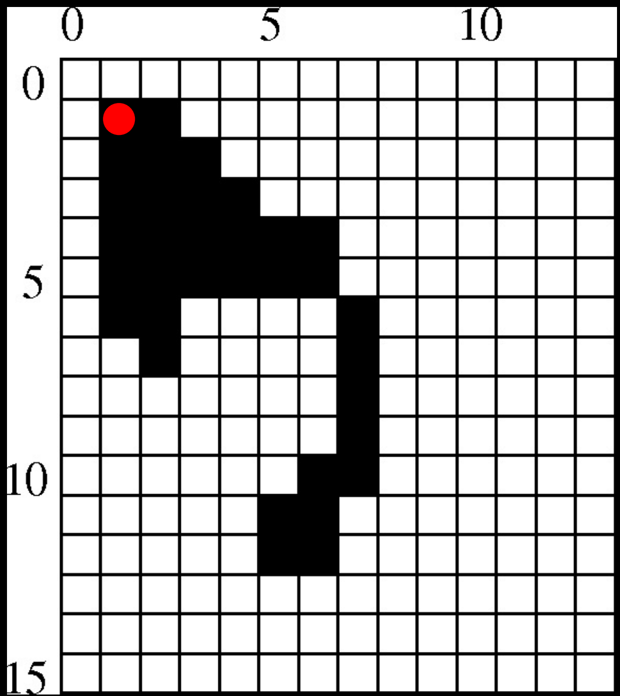
- Lossy compression changes the image
- Normally not a problem for photos
- BIG problem for medical images
- Mammogram
  - Looking for tiny bright spots
  - Would be changed by lossy compression

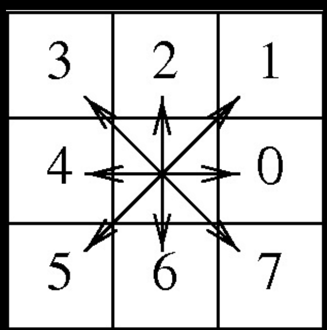
Use JPEG (JPG) for photos only

Binary images

- Binary – means on or off
- Binary image – only two colors
- Background (0 = black)
- Foreground (1 = white)

Chain coding of binary images



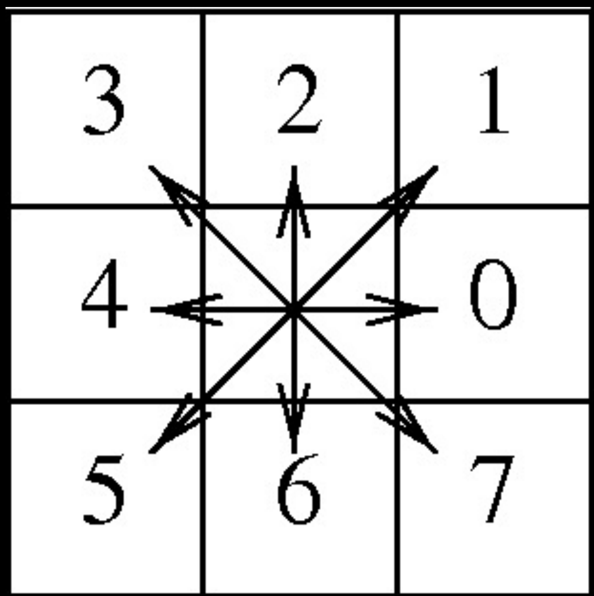


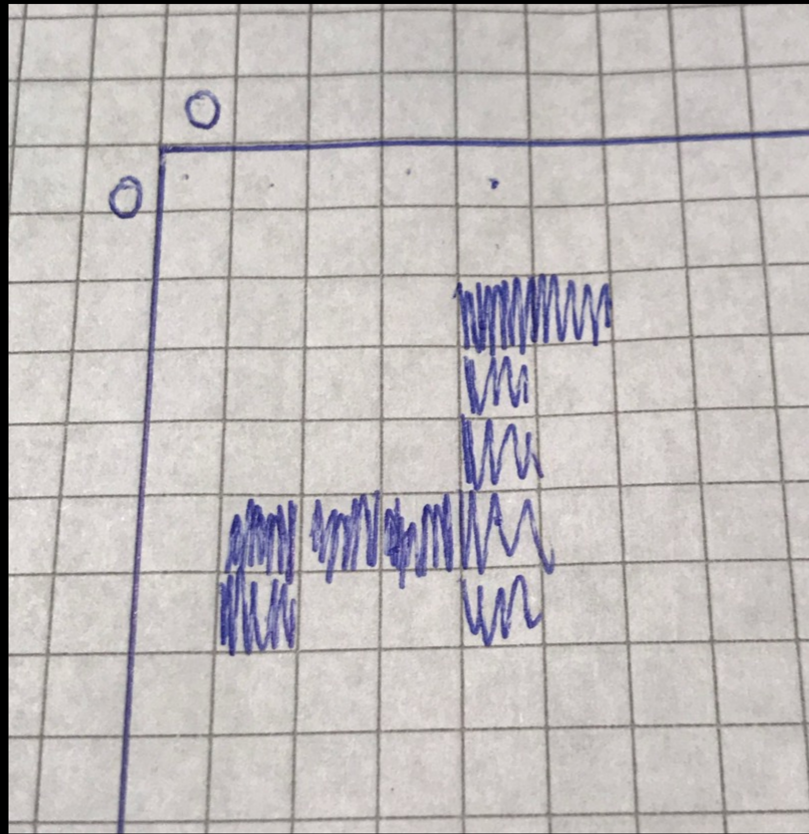
- Sufficient to describe the foreground
- Background given by the foreground
- The coordinates of the starting pixel is stored
- Secondly the sequence of step directions is stored

(1; 1) (07770676666564211222344456322222)

Quiz 6: Chain Coding – what is in the image?

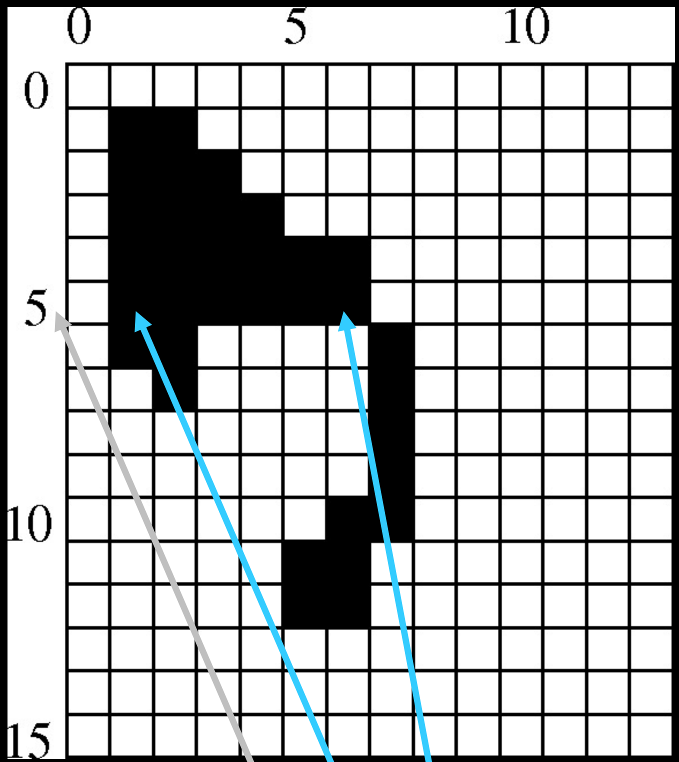
A) House
B) Chain
C) Flower
D) Giraffe
E) Dog
F) Teaport
G) Car
H) Glass
I) Bottle





(4;2)(04666624446)

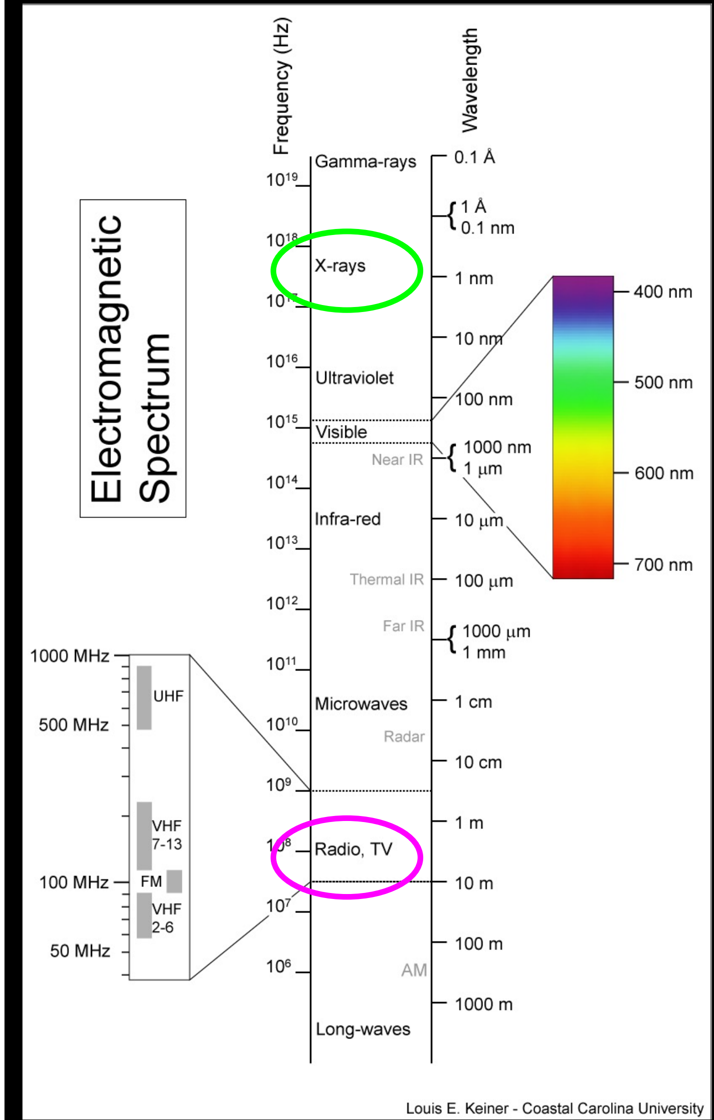
Binary images – Run length coding



- Another way to represent binary images
- Again the foreground is described
- Each line of the image is described
- For each “run” the row number is stored
- Secondly, the start column and the end column is stored

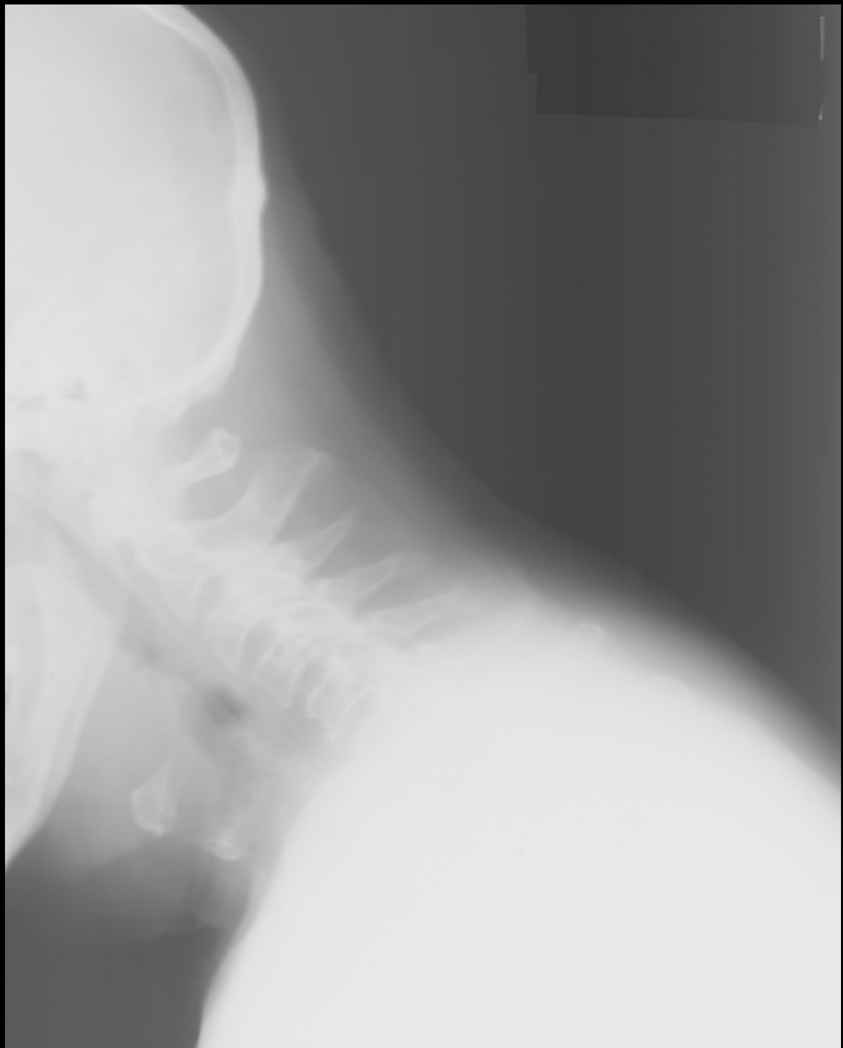
[1; (1; 2)]; [2; (1; 3)]; [3; (1; 4)]; [4; (1; 6)]
[5; (1; 6)]; [6; (1; 2)(7; 7)]; [7; (2; 2)(7; 7)]; [8; (7; 7)]
[9; (7; 7)]; [10; (6; 7)]; [11; (5; 6)]; [12; (5; 6)]

Beyond reflective light - To see the invisible



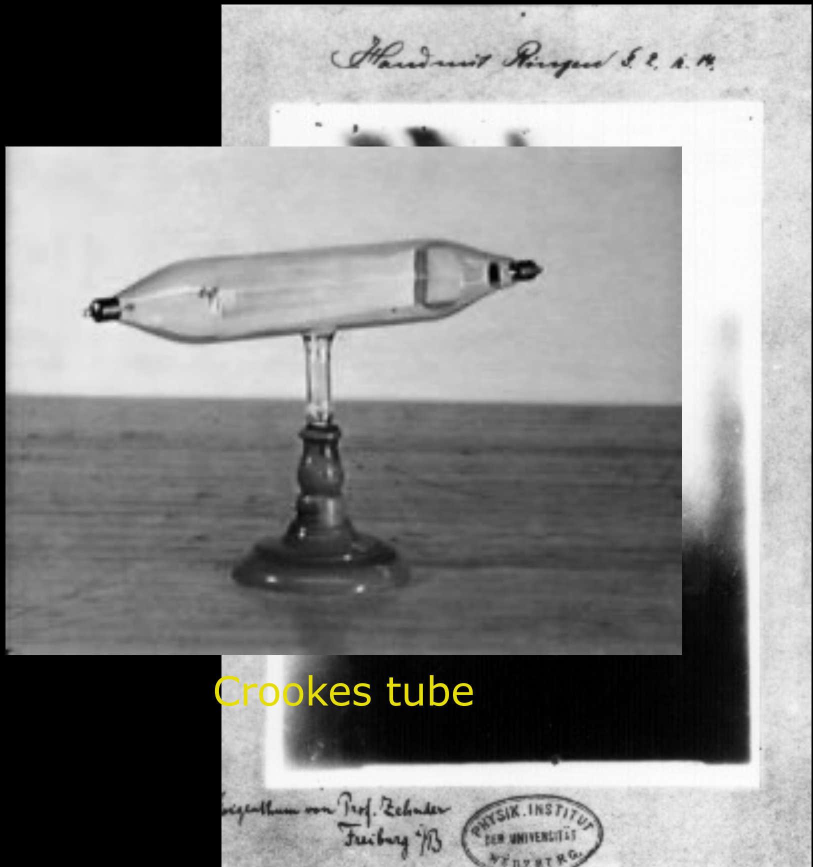
- X-ray imaging
  - High-energy light
  - Computed Tomography (CT) - Medical scanner (Hard tissue)
  - Synchrotron light – high Brilliance x-ray - nano-scope (soft and hard tissue)
- Magnetic Resonance Imaging (MRI)
  - Radio frequency
  - Medical imaging (soft tissue)

X-ray imaging



- The most used form of medical imaging
- Simple
- Cheap
- Fast
- Radiation

Wilhelm Conrad Röntgen

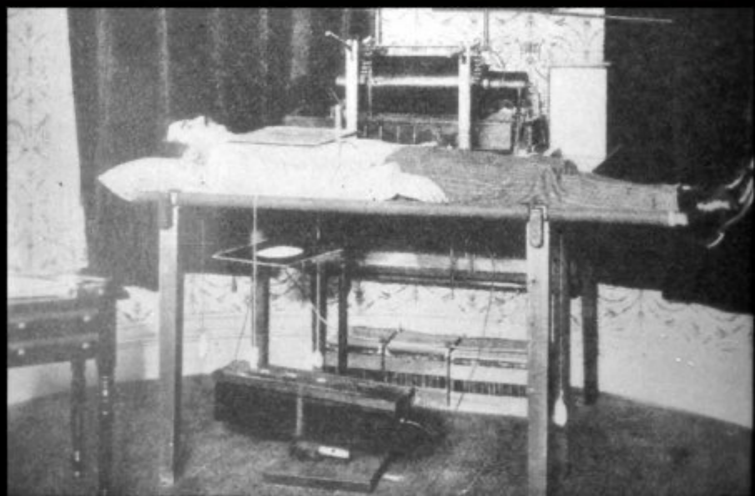


Crookes tube

Wilhelm Röntgen's first *medical* X-ray, of his wife's hand, taken on 22 December 1895

- German physics professor
- Experimented with a *Crookes tube*
- Discovered that an unknown ray could be captured on photographic plates
- Named them X-rays
  - Other call them Röntgen-rays
- Had no idea they were dangerous
- Made an X-ray of his wife's hand
  - First medical X-ray

Quick popularity



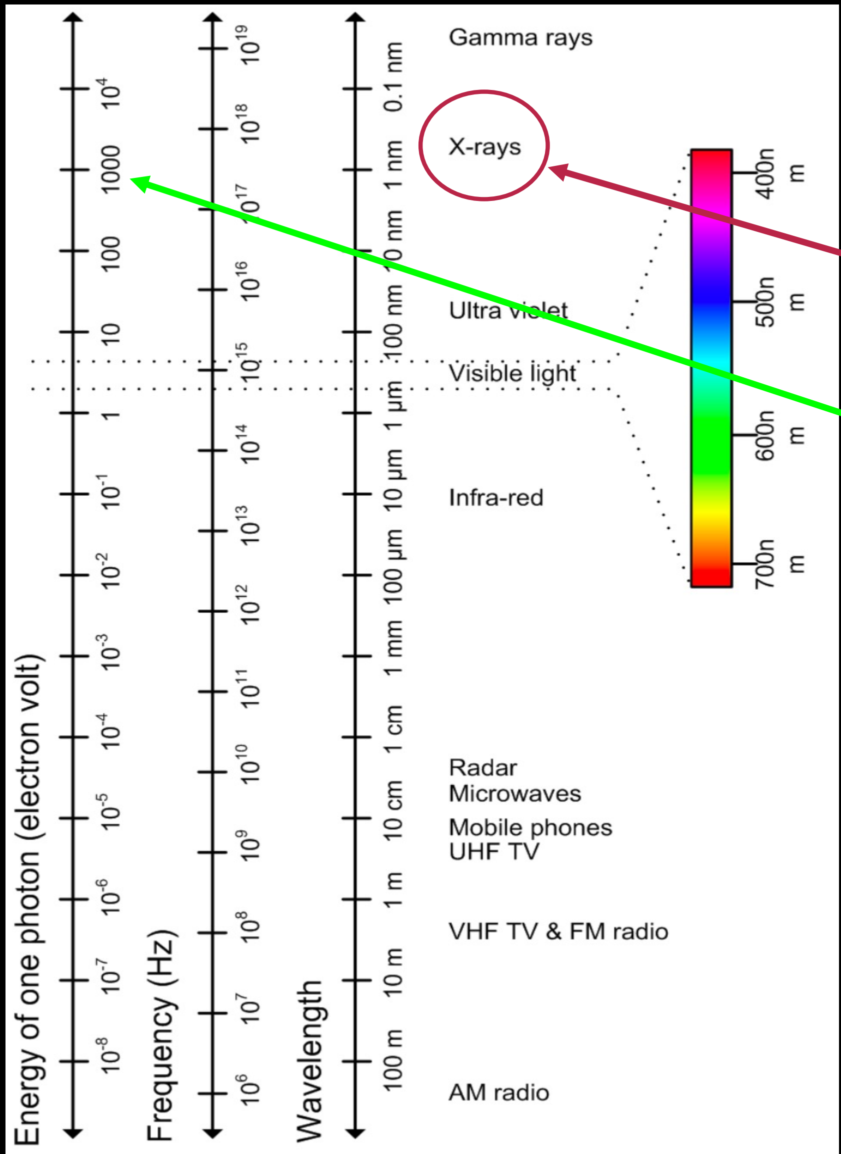
- X-ray became popular extremely fast
  - Shoe fitting
  - Examine your bones in coin machines
  - Wedding pictures
- X-ray clinics in small normal apartments

Dangers

Hands of X-ray pioneer
Mihran Kassabian

- People started to realise that exposure to X-rays could be dangerous

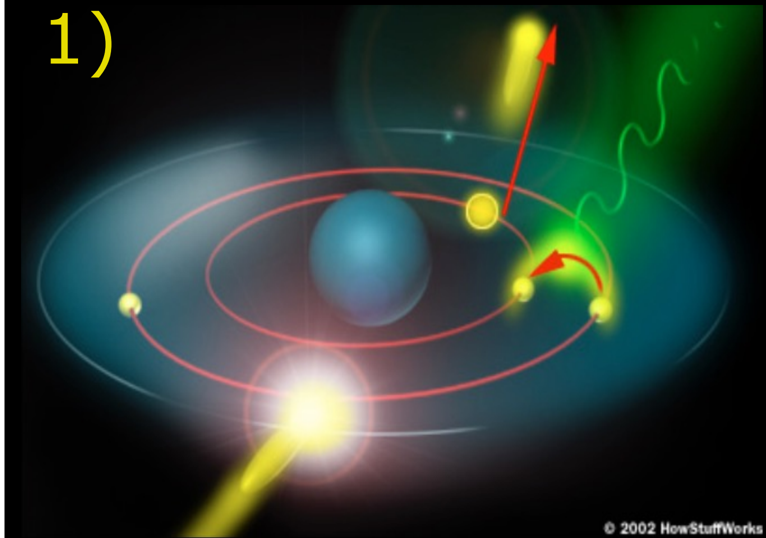
Electromagnetic spectrum



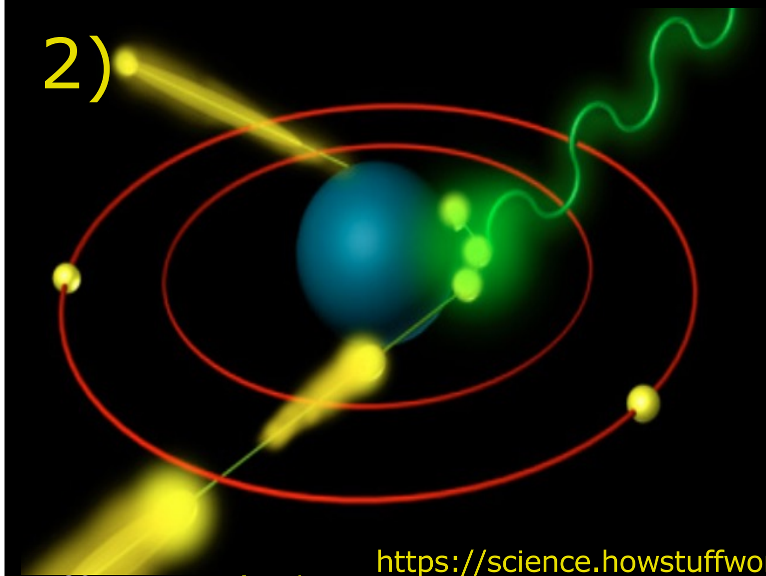
- Wavelength
  - 10 pm < λ < 10 nm
- pm = picometer = 1×10^{-12} m
- nm = nanometer = 1×10^{-9} m
- Small wavelength = high energy

How to generate light – emitting photons

1)



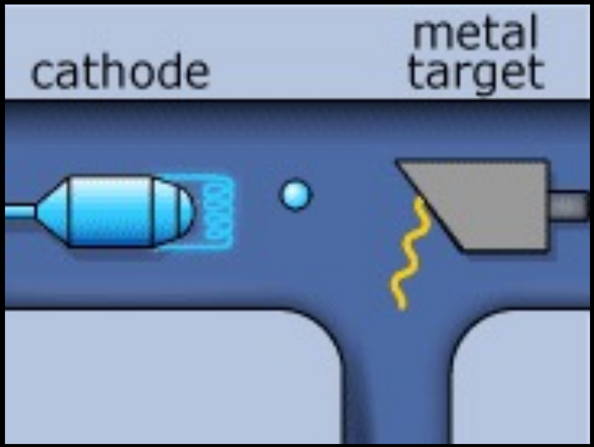
2)

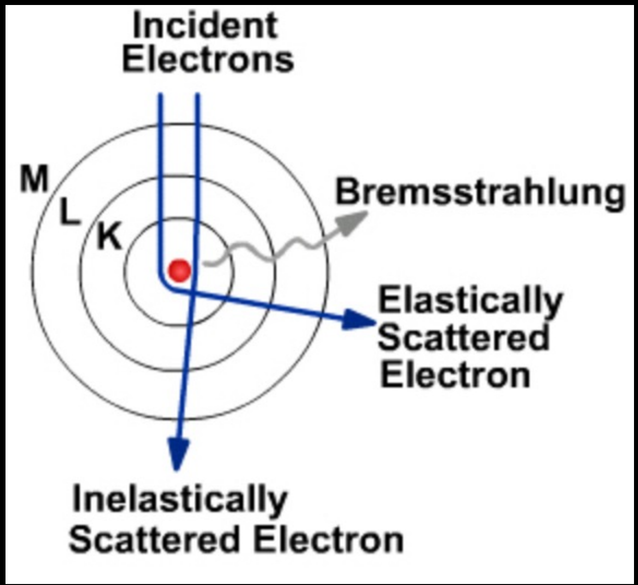


- A) Make a beam of accelerated electrons:
  - Close to the speed of light
  - High energies: kilo electron volts (KeV)
- B) Emitting photons:
  - 1) Incoming electron excite the atom:
    - Electron jump to higher energy level. Fall back to original energy level - release energy→emit a photon
  - 2) De-acceleration of electron → emit a photon

https://science.howstuffworks.com/x-ray2.htm

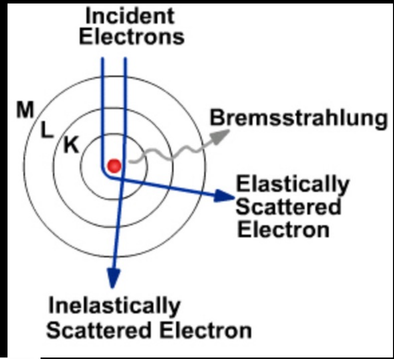
Production of X-rays

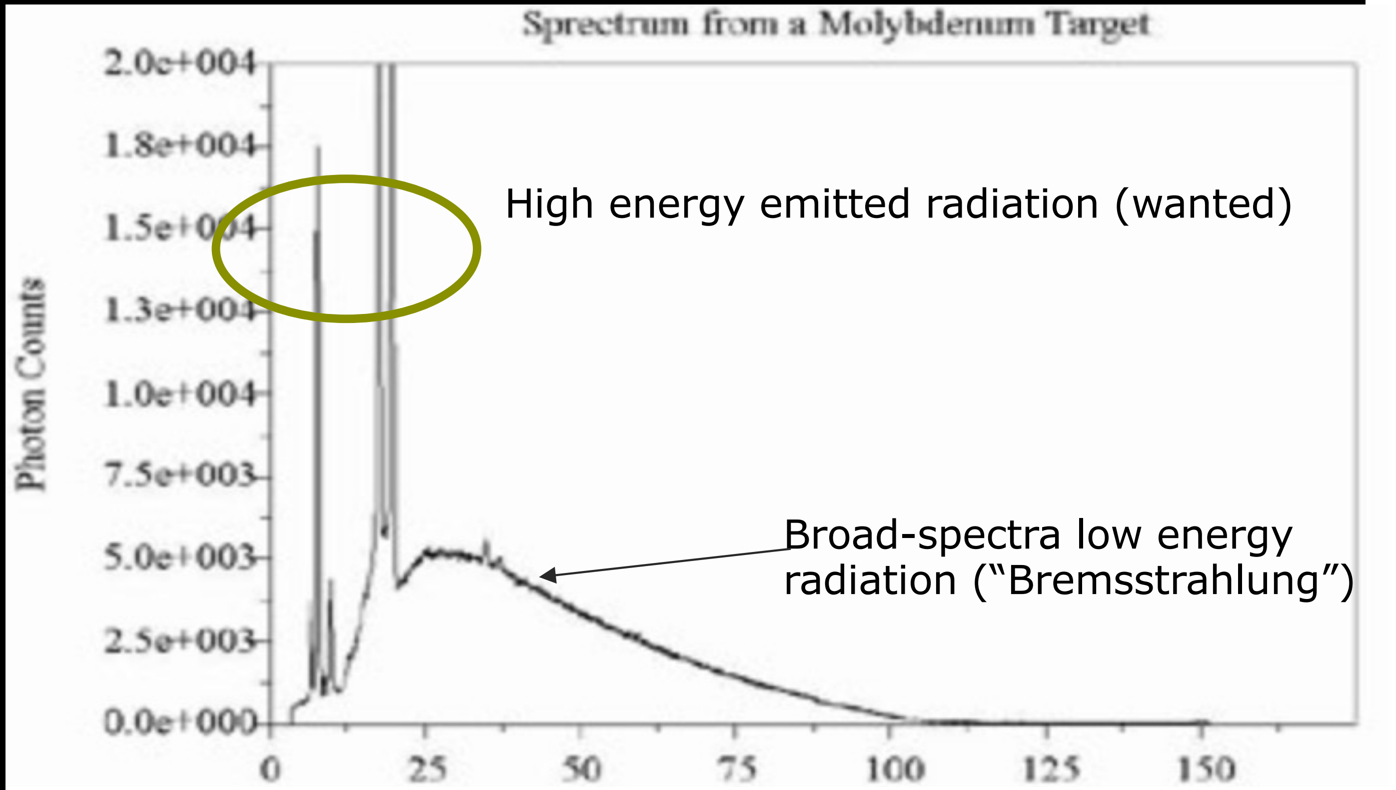




- Electrons are accelerated using a cathode
  - Heating up a filament release more electrons
- Some hit the anode (heavy metal target)
- Slowed down in the anode material
  - Generating heat
  - A small part of the energy is transformed to X-rays
- The electron comes very close to the nucleus
  - Electromagnetic interaction causes a deviation of the trajectory
  - The electron looses energy and an X-ray photon is emitted.

Production of X-rays



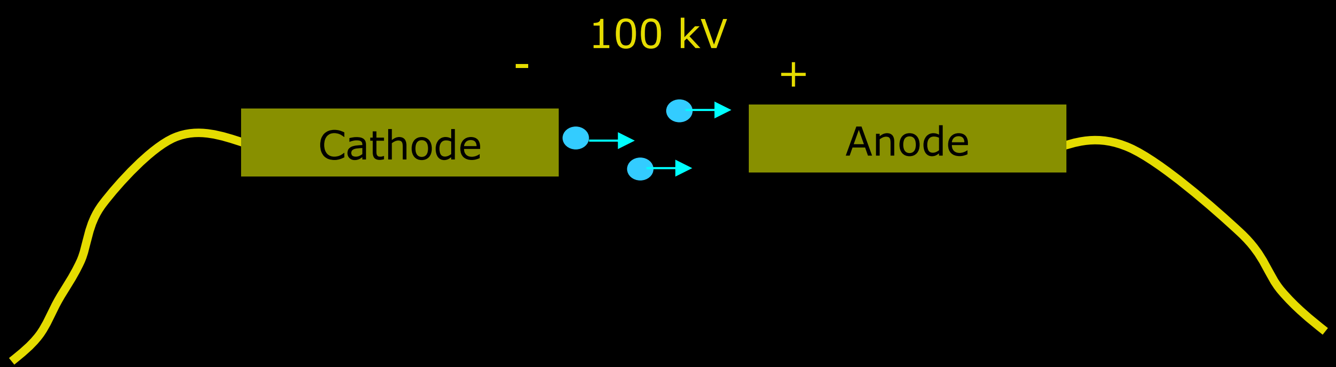


Energy in KeV = wavelength (λ)

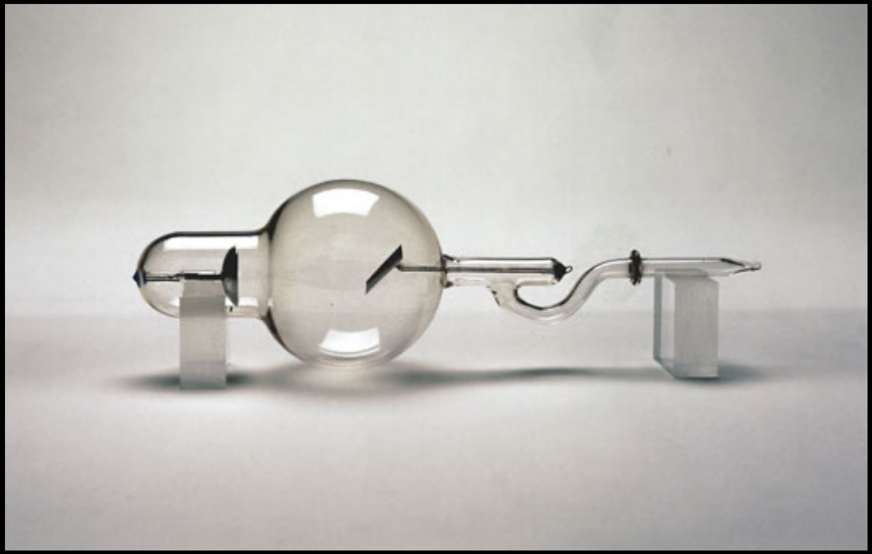
Energy of radiation vs the wavelength: $E = h/\lambda$ [eV]; h: Planck constant

Electron volts

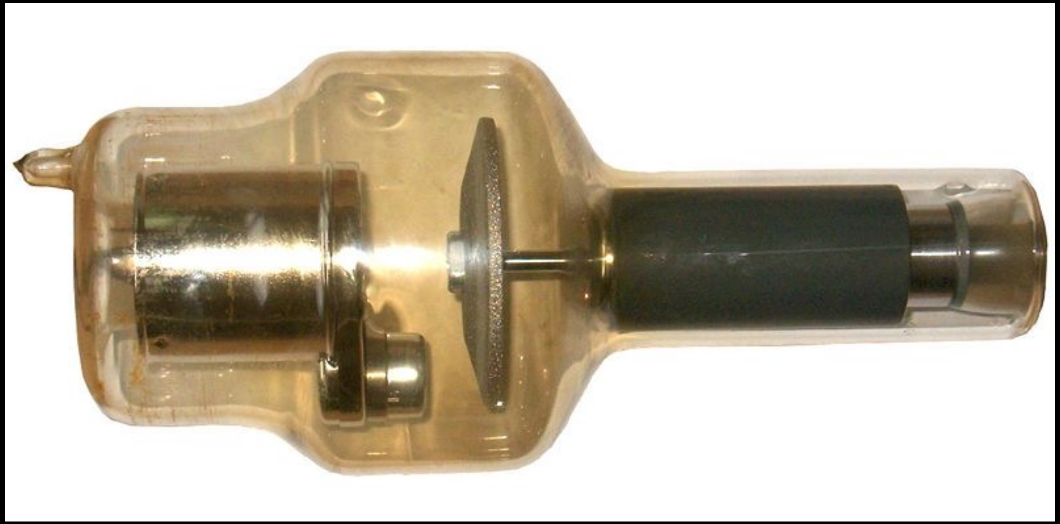
- 1 eV is the energy increase that an electron experiences, when accelerated over a potential difference of 1 V.
- In medical imaging
  - 20 keV < E < 150 keV
- keV = kilo-electron-volts



X-ray tube

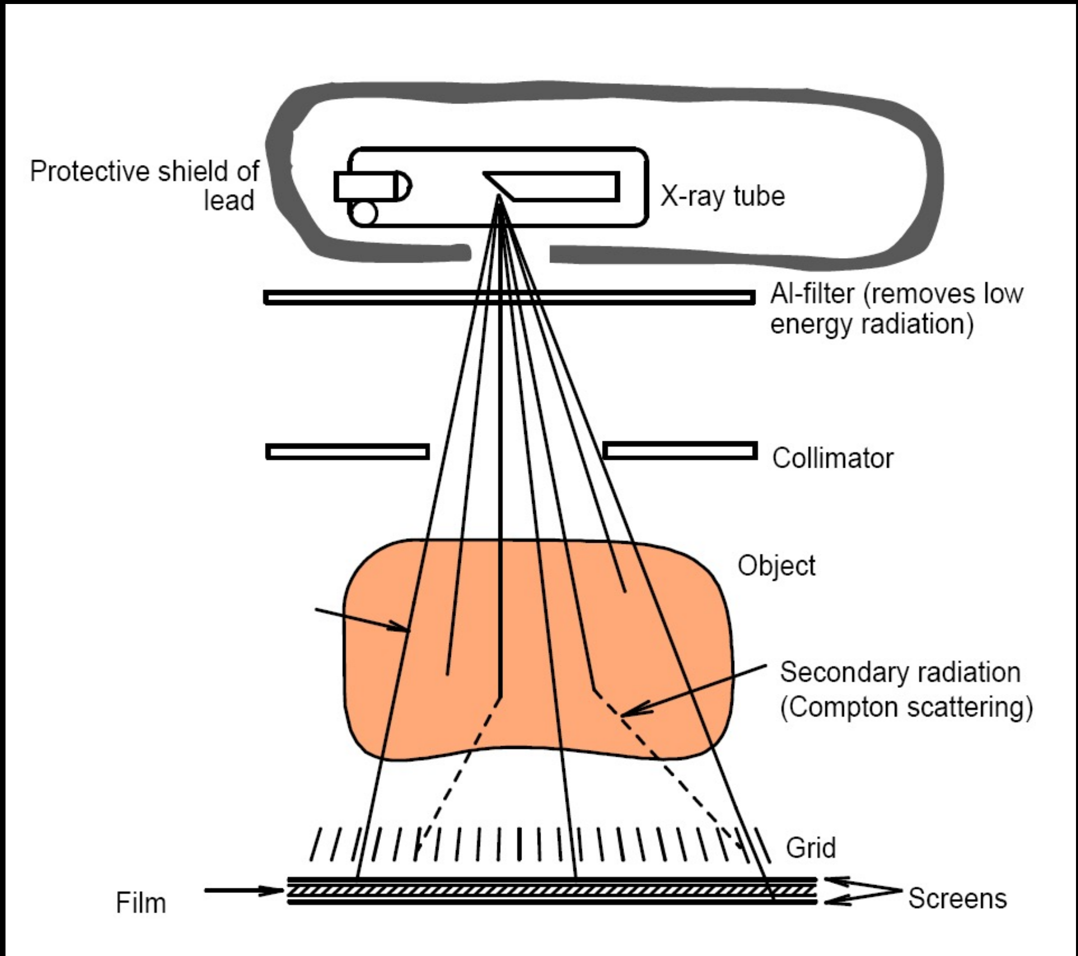


Jackson X-ray tube, 1896.



Modern rotating anode tube

Full X-ray system

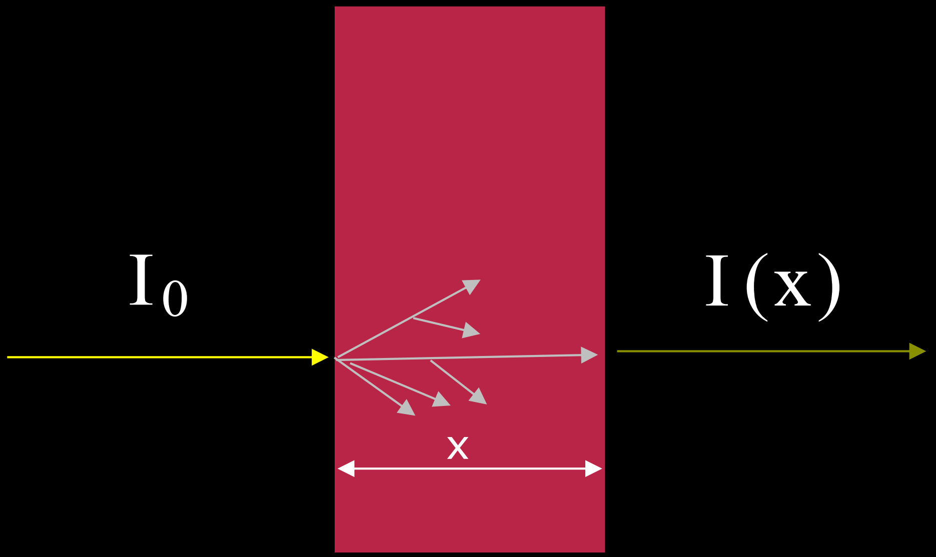


Contrast in X-ray images

Scanned X-ray film

- Some materials absorb more X-rays than others
- We see the X-rays that “got through”
- Dark area – high radiation
  - Air
  - Soft-tissue
  - Fat
- Bright area – low radiation
  - Metals
  - Bone

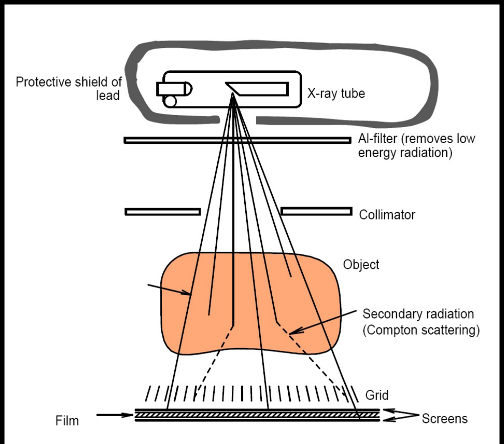
X-ray attenuation



$$I(x) = I_0 \boxed{\exp(-\mu x)}$$

- X-rays hits an object and travels through it
- I_0 is the intensity at the entrance
- $I(x)$ is what is left on the other side
  - after a length of x
- The rest disappears in several different ways
- Computed using Lambert-Beer's law: Different materials have different attenuation coefficients

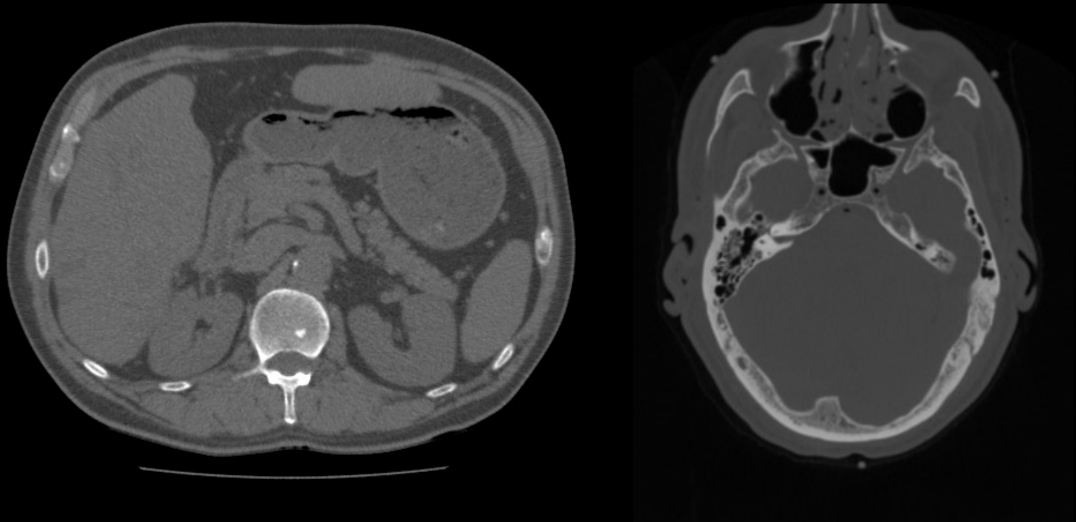
Computed Tomography (CT) scanning



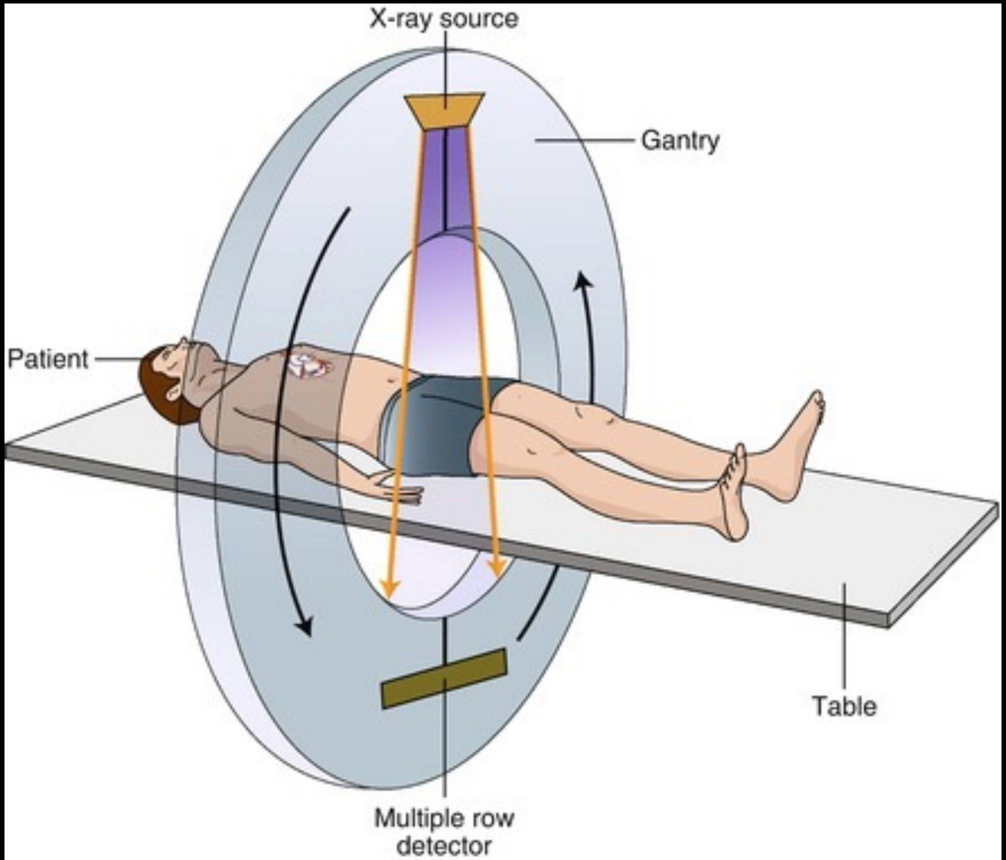
CT scanner (+multi-slice)

Scan single slice of whole object

Scan single slice within an object



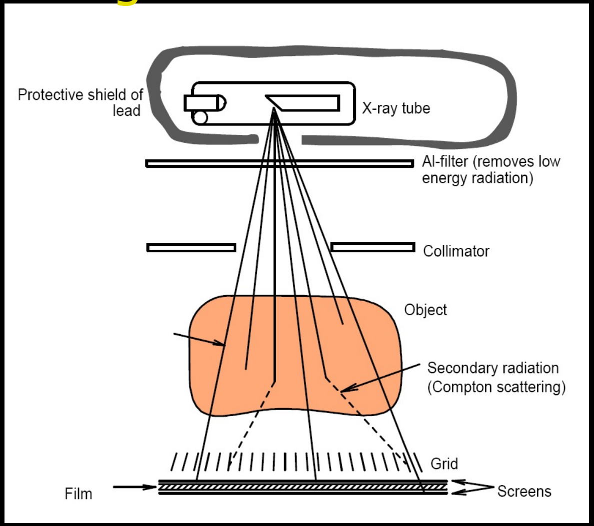
CT scanning - imaging by sections

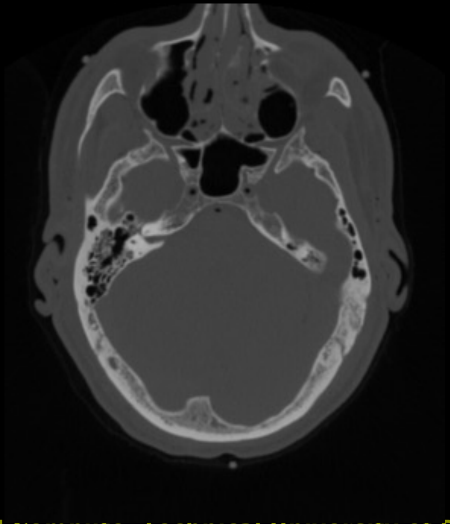


- 512 x 512 pixels per slice
- Many projections
- Image reconstruction
  - Enormous system of equations
  - Find each pixel attenuation coefficient (μ)
  - Hounsfield Units (HU) Calibrate units in medical imaging:
    - Air:1000
    - Water:0
- Not solvable by direct methods

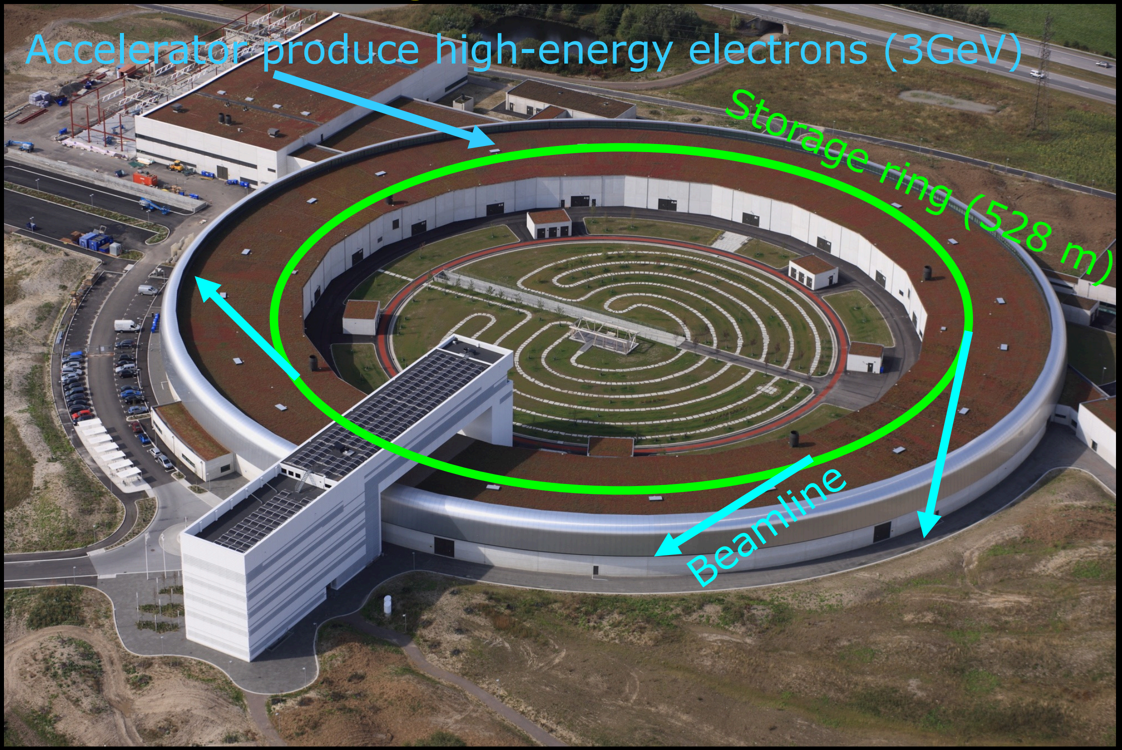
Synchrotron light: The brilliance of x-ray

Inhomogeneous electron beam





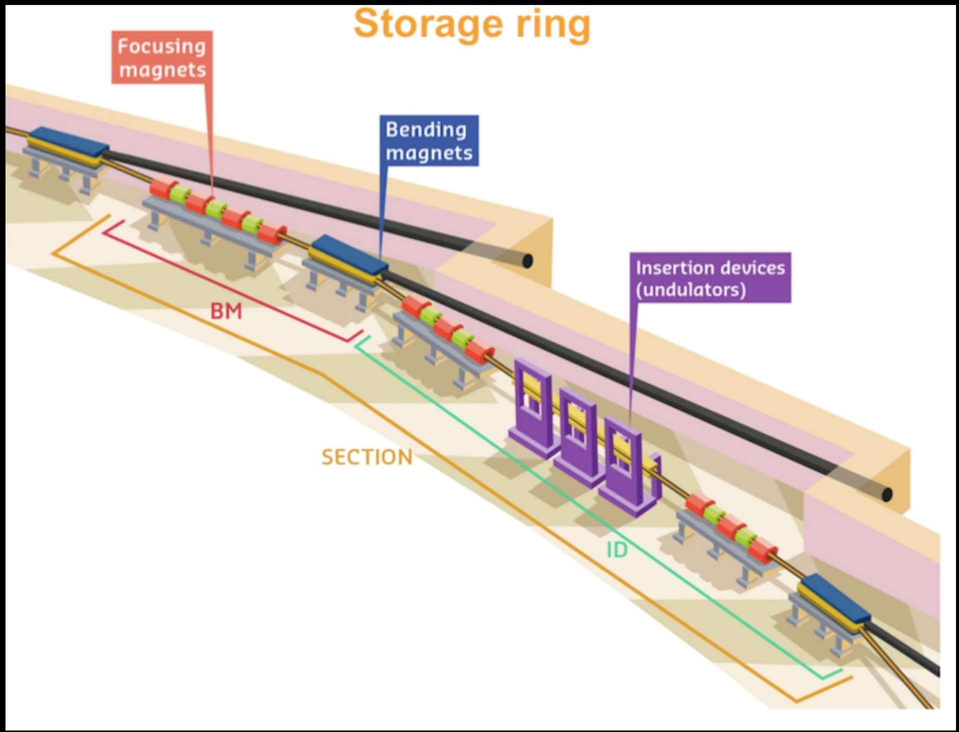
Very homogeneous electron beam

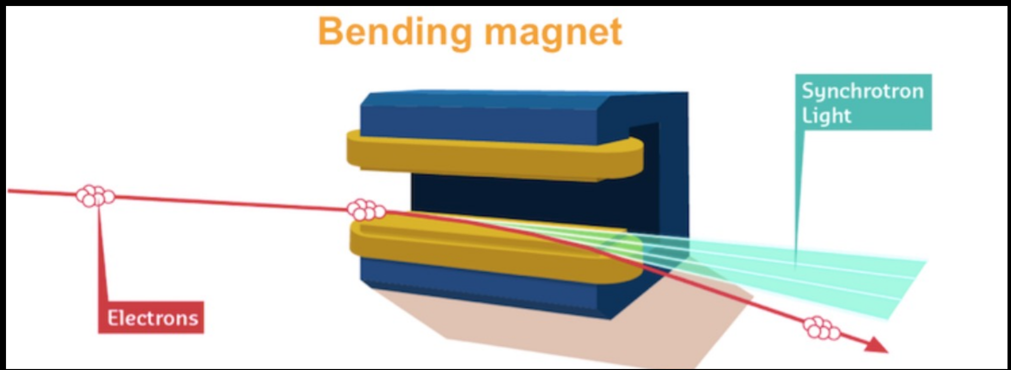


Large scale Research facility:

- MAXIV in Lund, Sweden

Synchrotron radiation: The principle

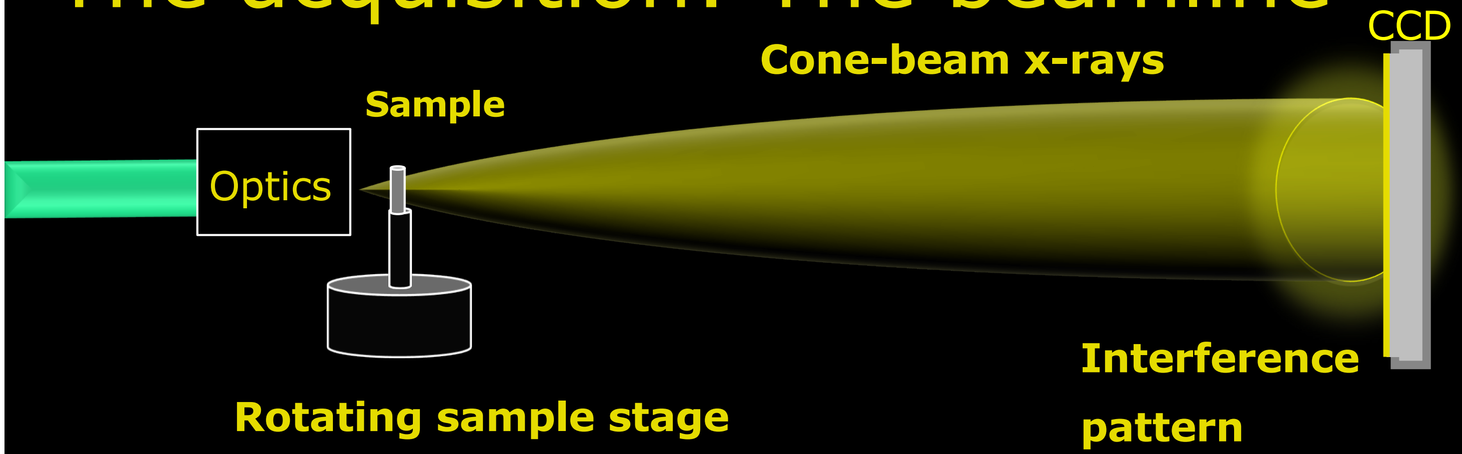


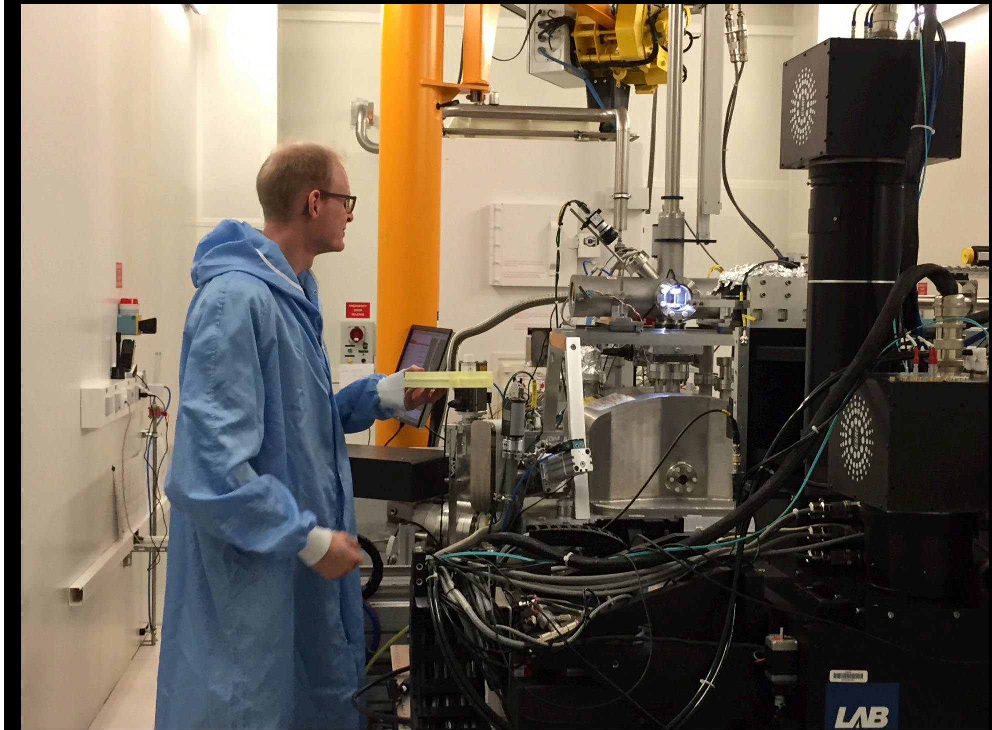


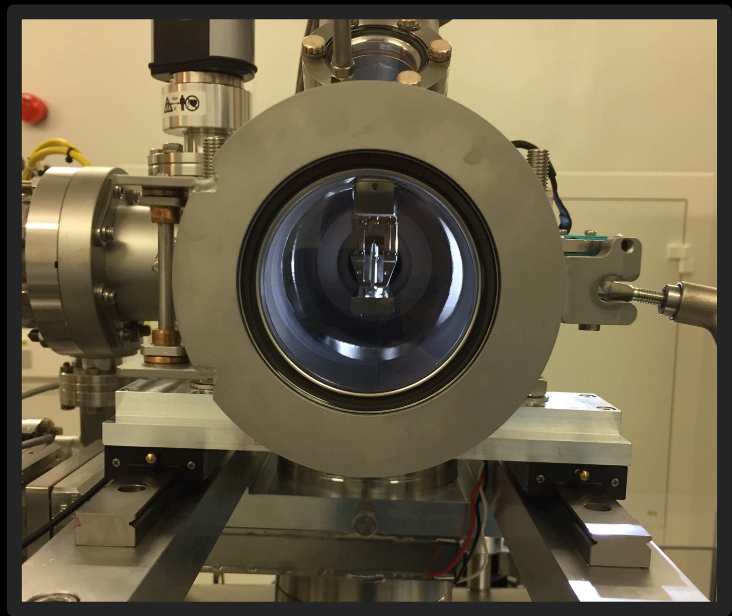
The storage ring

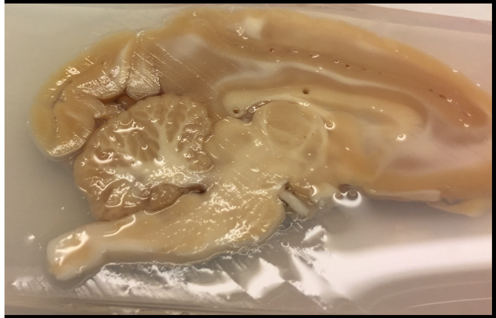
- Segment-wise linear
- Undulators
  - Magnets force electrons to follow a wavy trajectory: Improve the brilliance of the beam
- Bending magnets
  - Electrons deflected from their straight path emit x-ray tangentially (synchrotron light)

The acquisition: The beamline

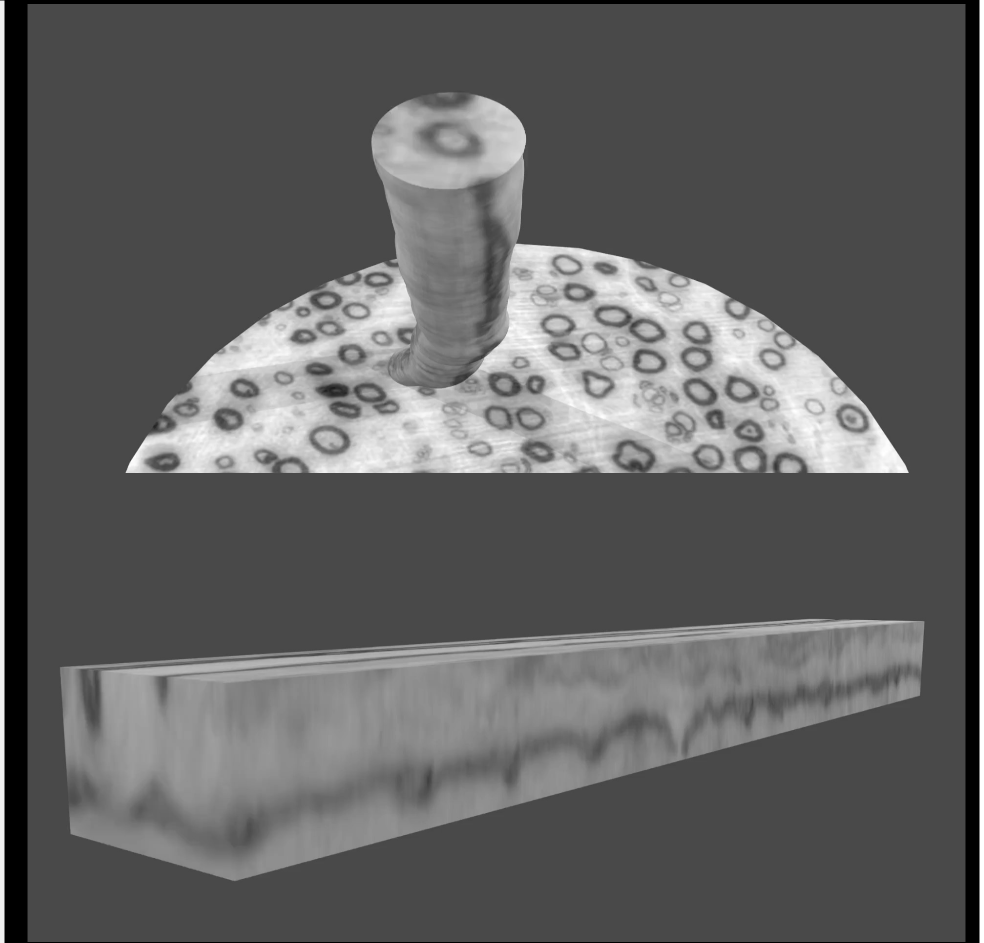








Synchrotron imaging – nano scale image resolution (75 nm)



3D image of nerves fibres in the brain.
(Andersson et al. 2020)

doi: https://doi.org/10.1101/2020.05.29.118737

Layered surface segmentation on human hand nerves (Kjer et al, in prep)

Magnetic Resonance Imaging (MRI)

3D structure of whole body: 10 min

DOI:https://doi.org/10.1016/j.ejrad.2009.09.014

- Magnetic and Radio Frequency in mega Hz
- Soft tissue + brain function
- Expensive compared to CT
- 3D imaging
- No documented danger
- Volume pixel: Voxel
- Clinical voxel sizes 3 to 1 mm^3, but can detect microstructures using biophysical models

Magnetic field

Preclinical MRI 7T

Human 1.5T, 3T, 7T MRI

MAGNETO

0.00005 T

MRI and Safety

You most show respect for the invisible danger!!

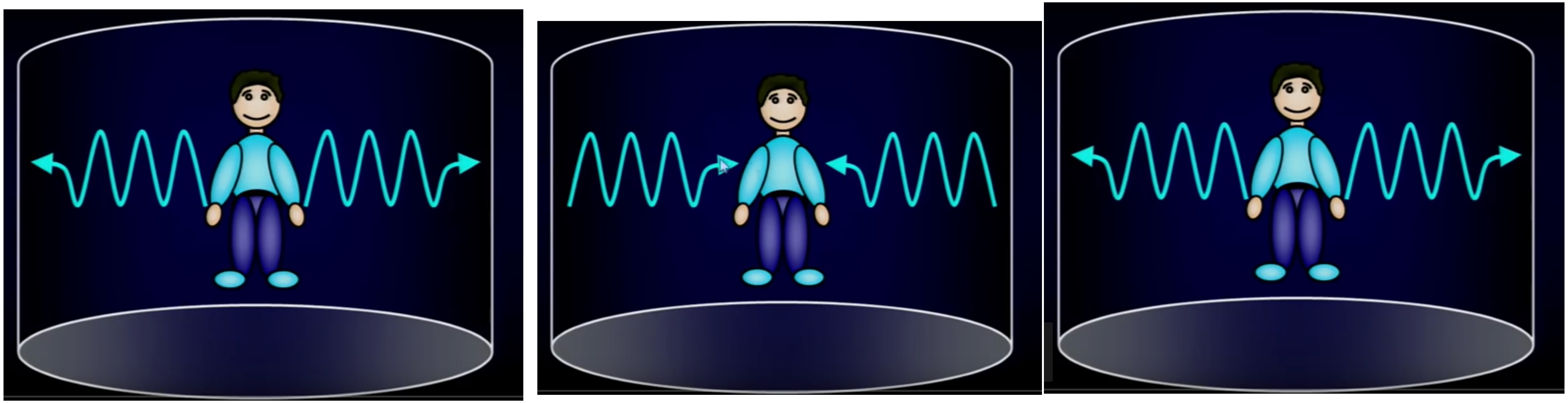
Two hospital workers spent four hours pinned between a highly magnetic MRI machine and a metal oxygen tank.

The 4ft tank was pulled across the room by the machine's magnetic field at Tata Memorial Hospital in New Delhi, India, leaving porter Sunil Jadhav and technician Swami Ramaiah seriously injured.

Hospital authorities launched an investigation into the incident, which was reportedly exacerbated when staff found they were unable to demagnetise the machine.

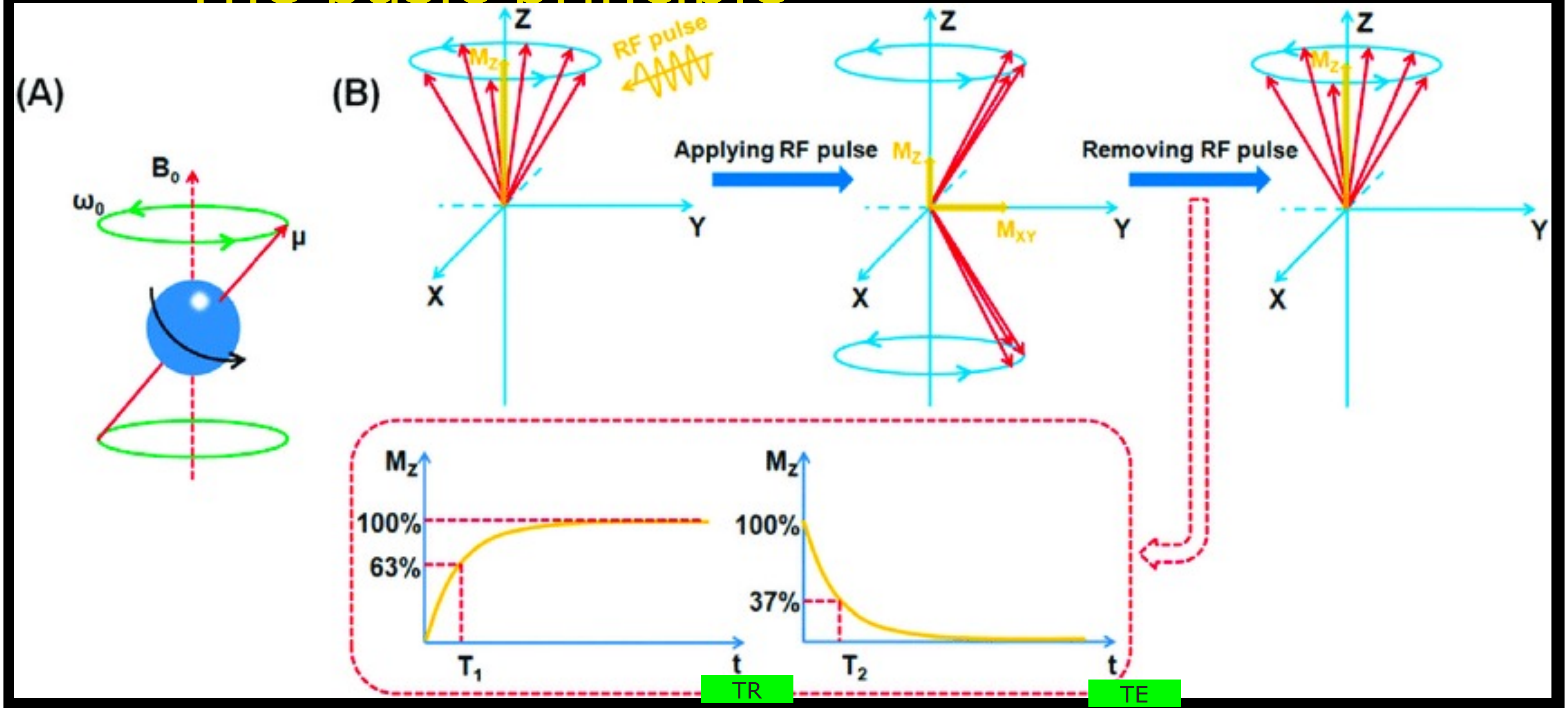
https://www.dailymail.co.uk/news/article-2890088/Two-hospital-workers-spend-FOUR HOURS-pinned-MRI-machine-metal-oxygen-tank-catapulted-room-device-s-giant-magnet-turned-on.html

The MRI overview



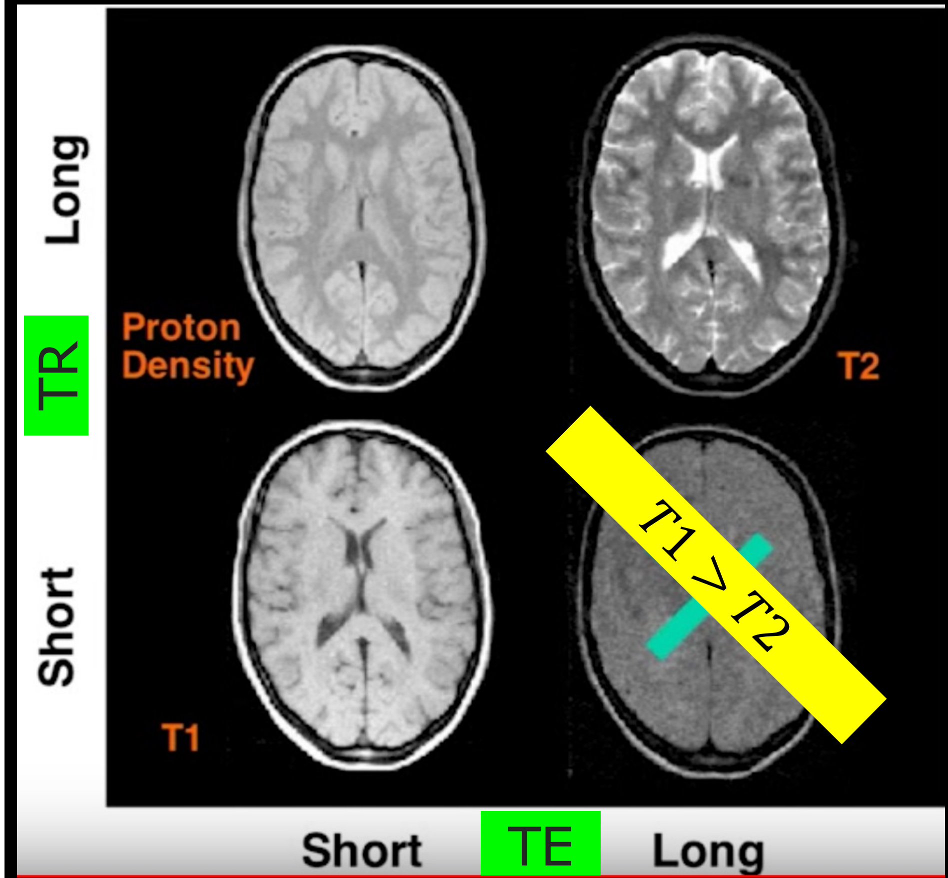
https://www.youtube.com/watch?v=tcGG5njW890

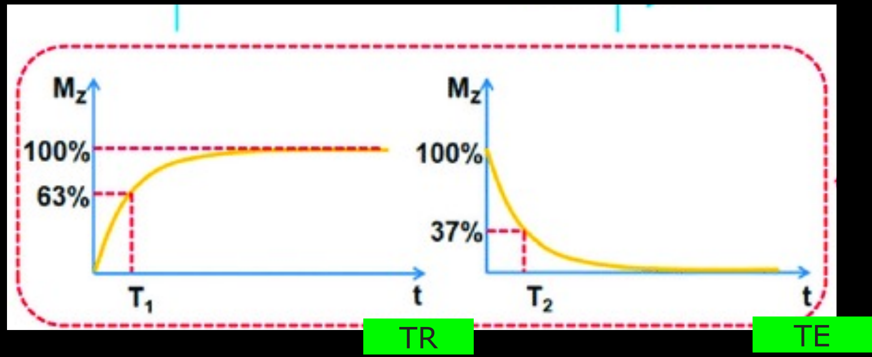
The basic principle



https://www.researchgate.net/figure/Schematic-illustration-of-the-mechanisms-of-MRI-A-Protons-precess-under-an-external_fig1_315899046

The basic principle

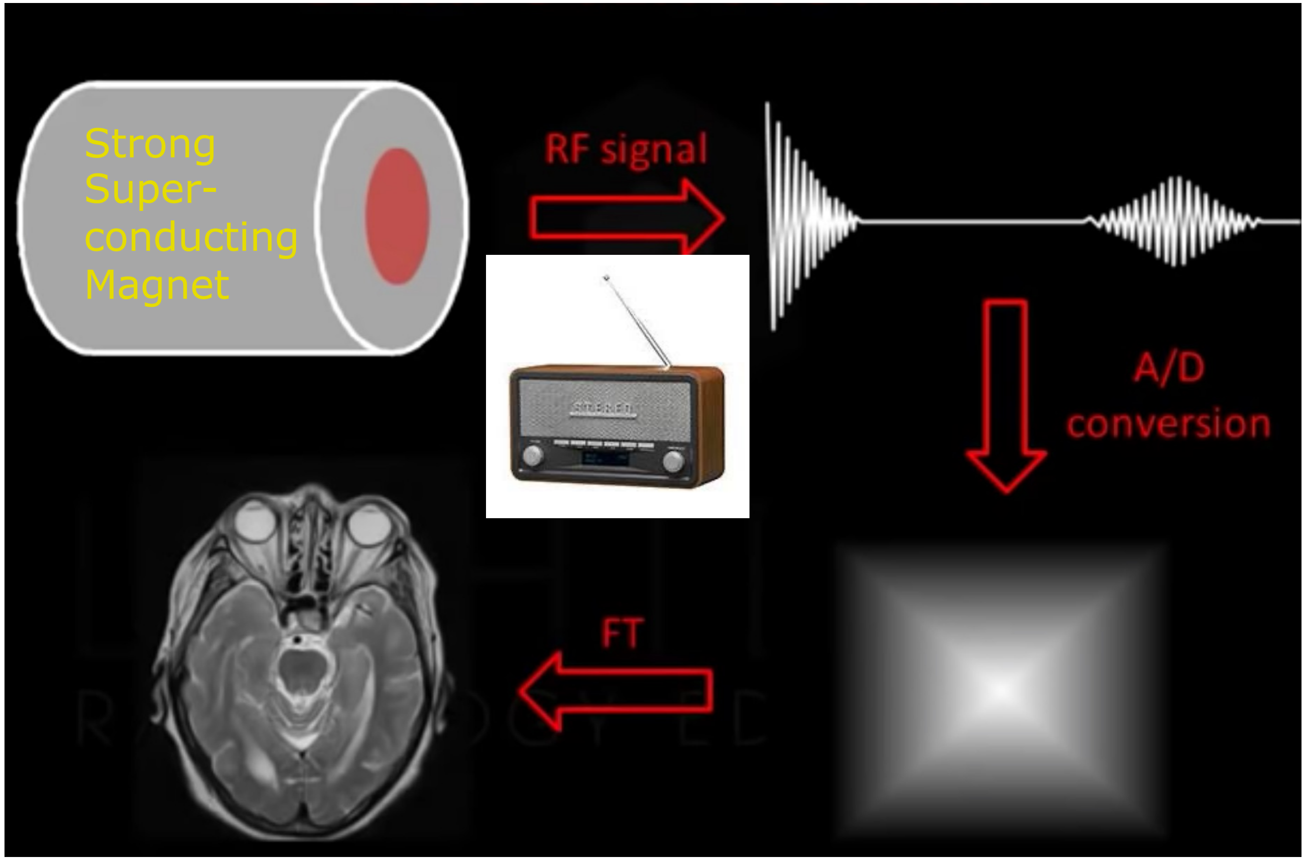




Signal contrast

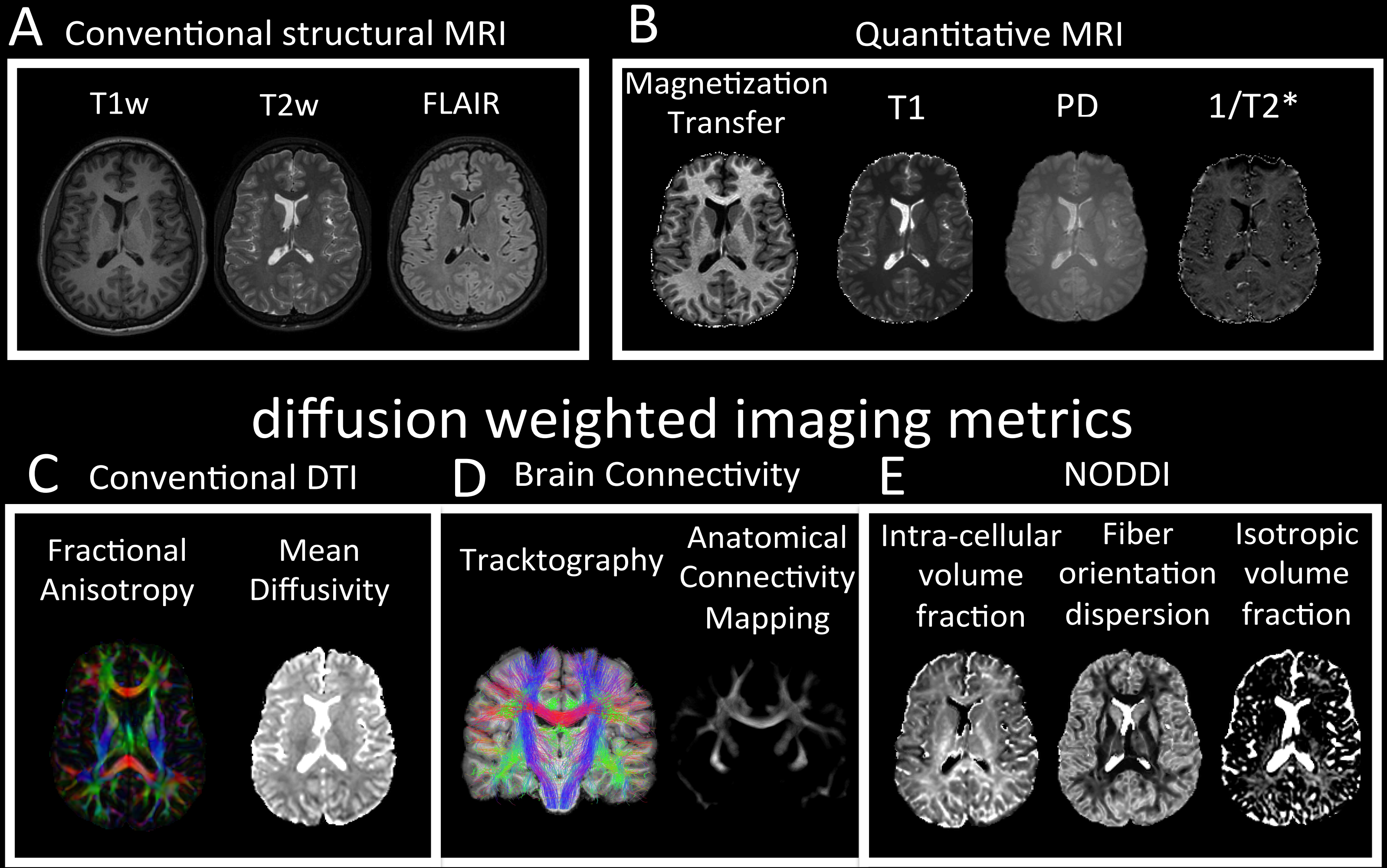
$$Mo = (1 - e^{-\frac{TR}{T1}})e^{-\frac{TE}{T2}}$$

The imaging principle of MRI



Multi-modality of the same subject

- Long scan times: High risk of motion



Today – What did you learn?

- Explain where visible light is in the electromagnetic spectrum
- Describe the pin hole camera
- Describe the properties of a thin-lens including focal-length, the optical center, and the focal point
- Estimate the focal length of a thin lens
- Compute the optimal placement of a CCD chip using the thin lens equation
- Describe depth-of-field
- Compute the field-of-view of a camera
- Explain the simple CCD model
- Compute the run-length code of a gray scale image
- Compute the chain coding of a binary image
- Compute the run length coding of a binary image
- Compute the compression ratio
- Describe the difference between a lossless and a lossy image format
- Decide if a given image should be stored using a lossless or a lossy image format
- Understand the principle of X-ray and MRI imaging methods

Next week

- Pixel wise operations
- Colour images
- MIA chapter 4
- MIA chapter 8