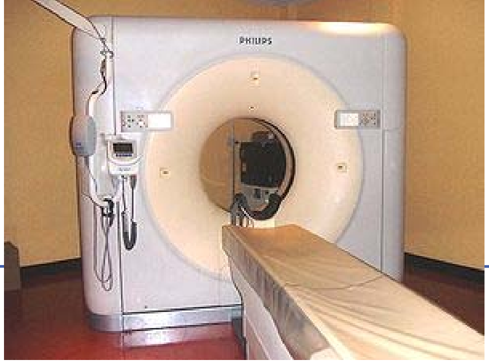


Digital Imaging Systems

Digitala Bildalstrande System

PhD course Nov 2008-Feb 2009

Introduction och background

Ewert Bengtsson, ewert@cb.uu.se

Course web: http://www.cb.uu.se/~ewert/kurs.html/

Aim of the course

- To give a unified perspective on the great variety of imaging technologies that have been developed the last decades.
- The imaging technologies will be discussed based on
  - what they are imaging,
  - how
  - with what quality
  - for which applications

Target group

- Graduate students from different subjects where imaging and images are being or could be used as tools.
  - material physics, biology, geosciences, medicine...
- Graduate students interested in methods development in the area
  - signal processing, scientific computing, image processing…

Participants, preliminary list

- Amin Allalo
- Maria Axelsson
- Milan Gavrilovic
- Gustaf Kylberg
- Patrik Malm
- Filip Malmberg
- Khalid Khan Niazi
- Kristin Norell
- Amalka Pinidiyaarachchi
- Hamid Sarve
- Bettina Selig
- Lennart Svensson
- Erik Wernersson
- Monica Llano Diez
- Rizwan Qaisar
- Vladimir Curic
- Lucas Nilsson
- Sudhakar Aare

SLU

Expected pre-knowledge

- Basic mathematics and physics
  - Some parts may be more advanced, but it should not be necessary to follow the course as a whole
- Some understanding of digital images
- Focus more on pragmatic understanding than theory
  - Some taxonomi
  - An overview of state of the art technology
  - Several examples of actual applications

After the course the participants will:

- Have a better understanding of the
  - possibilities and
  - limitations
  - of different imaging systems
- Be able to evaluate the suitability of a particular technology for a particular task.

Imaging is interdisciplinary

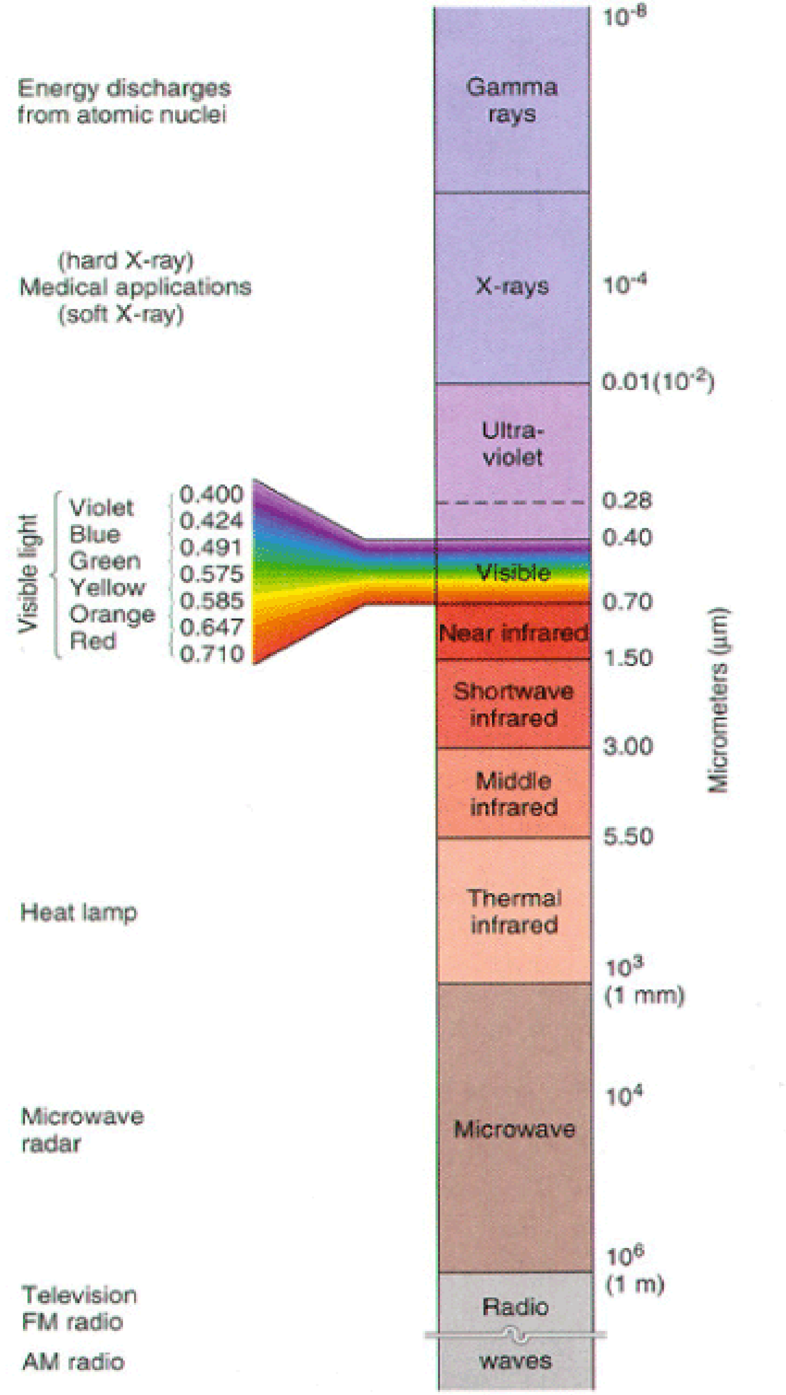
- Physics
  - Optics, wave propagation
  - Solid state
- Electronics
  - Circuit design
  - Sensor technology
  - Signal processing
- Mathematics
  - Geometry
  - Fourier analysis
- Computer science

Images are created from signals

- Electromagnetic waves
- Sound
- Mechanical contact forces

Electromagnetic spectrum

- All parts of the electromagnetic spectrum are used:
  - PET – hard gamma rays, 511keV
  - X-rays, CT
  - Visible light, photography
  - Infrared, Thermography
  - Radio waves, MRT
  - Imaging body electric or magnetic activity, EEG, EMG, MEG



source: Christopherson (2000) *Geosystems*

Imaging is interdisciplinary

- No single person is an expert on all imaging technologies
- The course is based on a whole dozen lecturers, each a leading expert in his imaging field
- All lecturers have been asked to as far as possible relate the description to the general questions discussed in this presentation

No	Date and time	Title	Lecturer
1	18 nov 13.15-15.00	Introduction	Ewert Bengtsson
2	20 nov 13.15-15.00	Ultrasound	Tomas Jansson
3	25 nov 13.15-15.00	Digital cameras, CMOS and CCD	Ewert Bengtsson
4	27 nov 10.15-12.00	Light microscopy	Cris Luengo
5	28 nov 10.15-12.00	Confocal microscopy	Cris Luengo
6	4 dec 13.15-15.00	Electron tomography	Ulf Skoglund
7	9 dec 13.15-15.00	Computer tomography, X-rays, CT & SPECT	Hans Lundqvist
8	11 dec 10.15-12.00	Electron and atomic force microscopy	Åsa Kassman Rudolphi
9	12 dec 13.15-15.00	Magnetic resonance imaging, MRI	Hans Lundqvist
10	16 dec 13.15-15.00	Positron emission tomography, PET	Pasha Razifar
11	19 dec 13.15-15.00	Functional Magnetic Resonance Imaging fMRI	Magnus Borga
12	13 jan 10.15-12.00	Radiointerferometric imaging	Lars Bååth
13	15 jan 10.15-12.00	Radar, SAR and CARABAS	Lars Ulander
14	20 jan 13.15-15.00	Laser radar and gated imaging	Ove Steinvall
15	22 jan 10.15-12.00	Infrared Imaging	Malin Ingerhed
16	29 jan 10.15-12.00	Concluding discussion about digital imaging	Ewert Bengtsson
Ex	11 feb 9.15-13.00	Written exam	Course participants

The different dimensions of imaging

Lecture 1:
Digital Imaging Systems
November 18, 2008
Ewert Bengtsson

B = F(x,y,z,w,t)

- An image can be described as a 5D function
  - x,y,z – 3 spatial dimensions
  - w – wavelength, spectral dimension
    - can be generalized when not dealing with electromagnetic signals
  - t – time - temporal dimension
    - exposure time and repetition frequency
- Each dimension and the function value must be quantized into a limited range of discrete values

The different dimensions of imaging

- ***The densitometry***
  - What property is being imaged, how well
- ***The spatial dimension***
  - ***Projection, distance image or tomographic reconstruction***
  - ***Light emission, transmission or reflection***
  - ***Light sensing: Active or passive sensor system***
- ***The spectral dimension***
  - ***Spectral selection and multiplexing***
- ***The temporal dimension***
  - ***Integration: point, line, area, volume***
  - ***Direct digitalisation or intermediate image (photo)***
- ***Volume imaging***

Densitometric aspects

- What physical property is being imaged?
  - The light reflection of a surface
  - The light transmission
  - The density distribution of a certain molecule, atom or elementary particle
  - The surface topology
  - The elastic properties of the object
- How well can this property be described?

Imaged physical property, examples

- Emission
  - Astronomy
  - Autoradiography
- Exited emission
  - Fluorescense
- Transmission
  - Light microscopy
  - Transmission electronmicroscopy
  - Film scanning
  - Classical X-rays
- Reflection
  - Normal photography
  - Document scanning
  - Fax
  - Scanning electronmicroscopy
  - Satellite sensors

Densitometric aspects; resolution

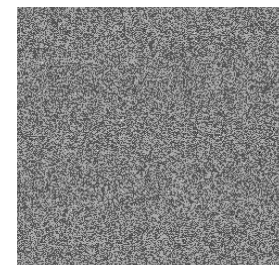
- What is the densitometric resolution
- What is the signal to noise ratio?
- How many greylevels do we get?
  - Are all these meaningful?
- What is the property that is measured, i.e. mapped into greyscale?
  - Intensity
  - Energy
  - Photon count

Densitometric aspects; linearity

- Is the greyvalue linearly or logarithmically related to the physical property of interest?
  - Is the linearity good?
- Can the densitometry of the image be calibrated in absolute terms?
  - Is this calibration stable over time?
  - Is it difficult to perform?

Contrast resolution

- The image should have the correct exposure time to use the dynamic range of the sensor
  - The histogram is the best tool
- The number of bits should be related to the signal/noise ratio
  - Ideally about 1 bit noise
  - Look at bitplane images



- Shading correction is often necessary
- When the imaging conditions are stationary, averaging improves S/N
  - according to $\sqrt{\text{number of exposures}}$

Typical image histogram

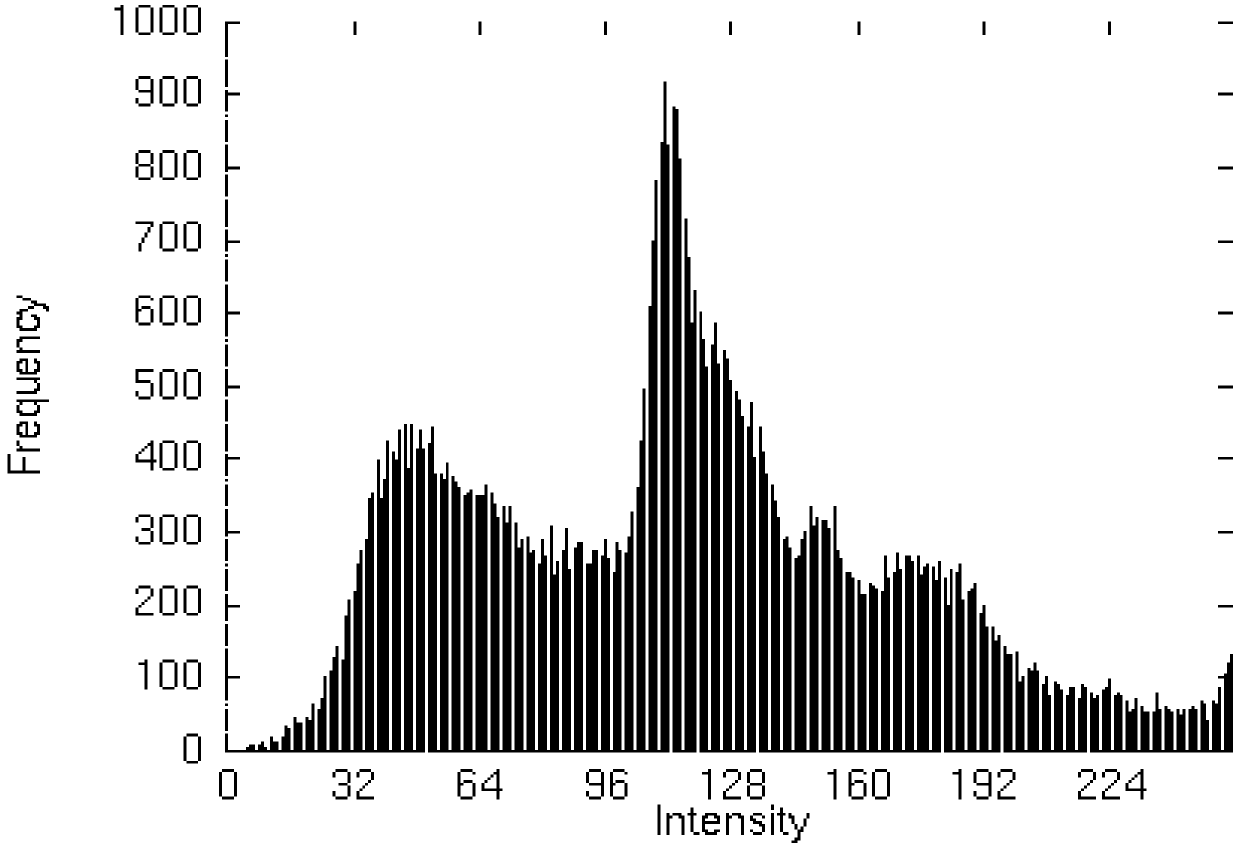


Figure 2.11 *A brightness histogram.*

The spatial dimension

- How are the three spatial dimensions mapped into the image?
- Is the image a slice, a projection, a depth map or what?
- How correct is the image? Distortions?
- What is the geometric resolution?
- Is the technology capable of providing more than 2D?

Spatial resolution

- Analogue, physical image: Limited by physical imaging constraints, aperture and wavelength
- Digital image: Limited by the sampling theorem
  - Which additionally requires perfect samplig
- Aliasing caused by poor sampling is worse than limited resolution

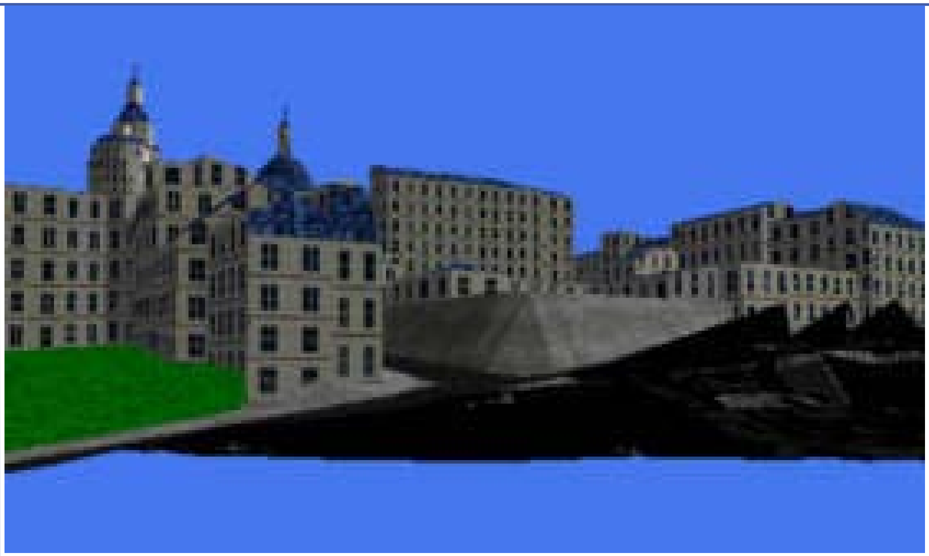
Projection, distance image, slice image or tomographic reconstruction

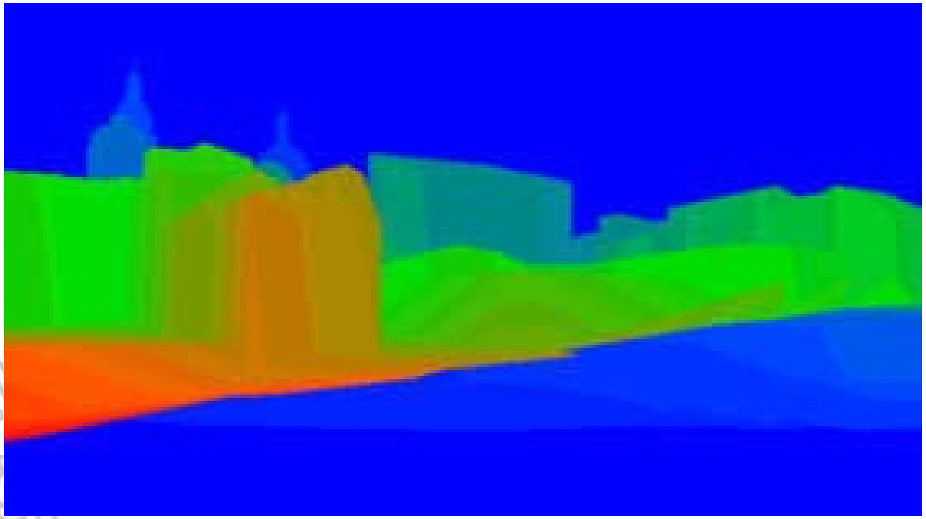
- **Projection** gives a 2D image of visible surfaces in 3D or a transmission through the object
- **Distance images** give explicit depth information as seen from a point i.e. 2½D
- A **slice image** images a selected thin volume
- **Tomographic reconstruction** computes information about internal density structure from measurements of numerous line integrals, gives slice or complete volume images

Distance images
A way of representing 3D in 2D

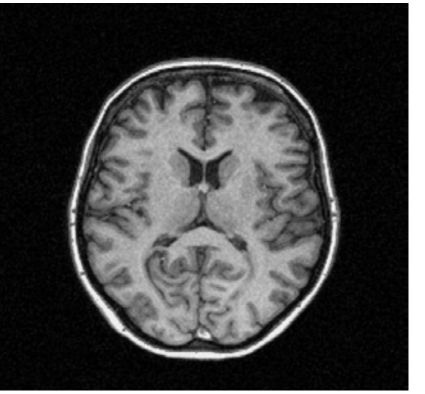
- Measures the distance from the surface of the object to the sensor for each point in the image
- Passive sensor
  - Parallax camera – light source
  - Stereo images
- Active sensor
  - Time of flight (radar, ultrasound, laser)
  - Triangulation, structured light

A normal image and a distance image





Reconstructed images



- Tomography
  - Transmitted X-rays, Computer Tomography
  - Radioactive decay, Emission Tomography
    - PET
    - SPECT
  - MRI, emitted excited radio frequency
- SAR (synthetic aperture radar)
  - CARABAS – long wave, incoherent

Emission, excited emission transmission or reflection

Where / what is the light source?

- Emission gives well defined spectral properties
- Transmitted light is exponentially absorbed, logarithmic intensity is directly proportional to absorbing matter
- In reflection the surface orientation as well as the material properties and the direction and spectral characteristics of the illumination determines the signal
  - Need to differentiate between diffuse and specular reflection

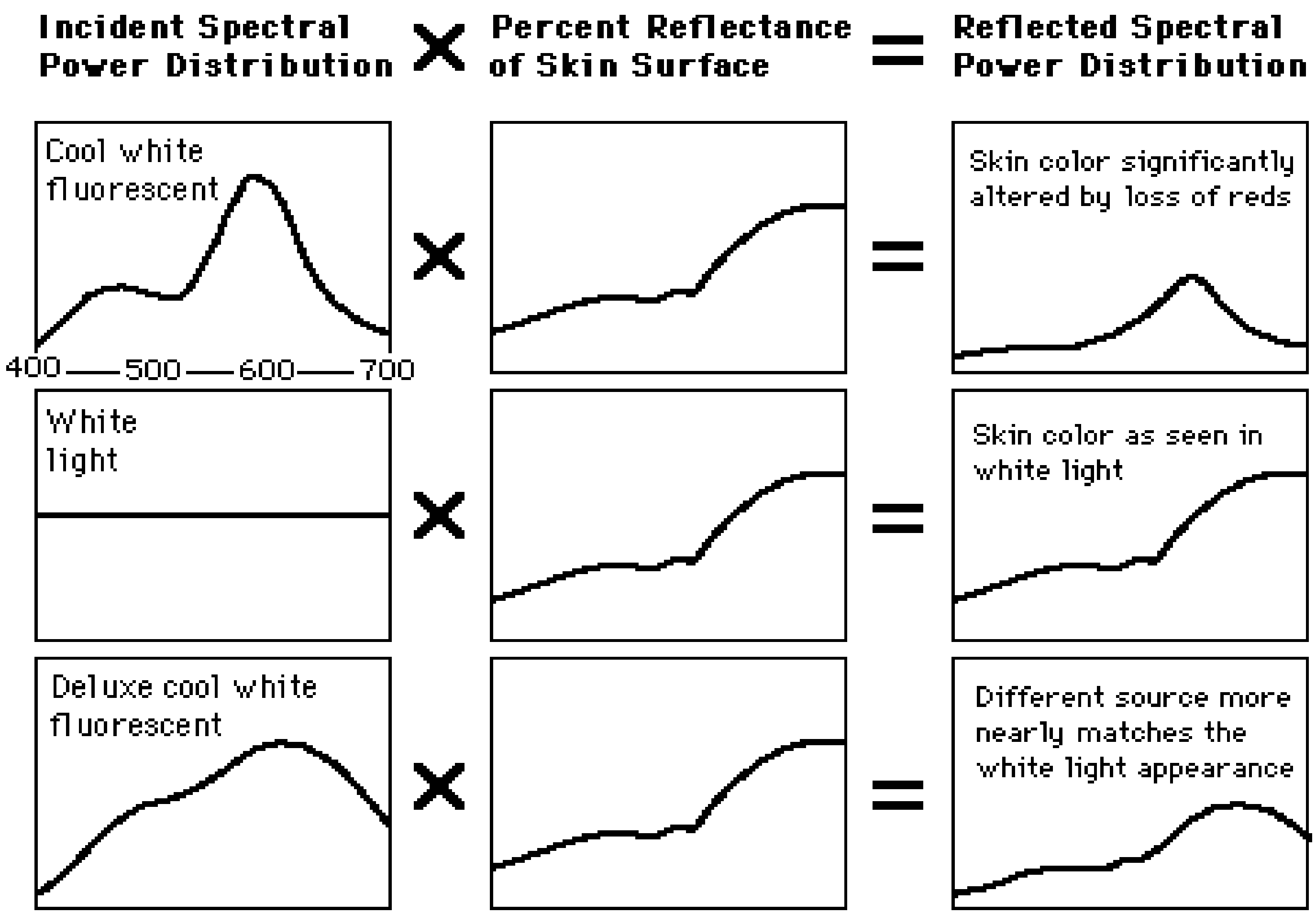
Active or passive sensor system
Can we control the illumination?

- Active = we can illuminate the scene
  - All at once
  - One or several lines
  - With pixelwise scanning
- Passive = we must cope with existing illumination

The spectral dimension

- All imaging involves a choice of spectral range
- The image is a result of a convolution between
  - The spectral distribution of the illumination
  - The spectral absorption/reflection properties of the object
  - The spectral sensitivity function(s) of the sensor
- Different spectral ranges often give very different image contrast

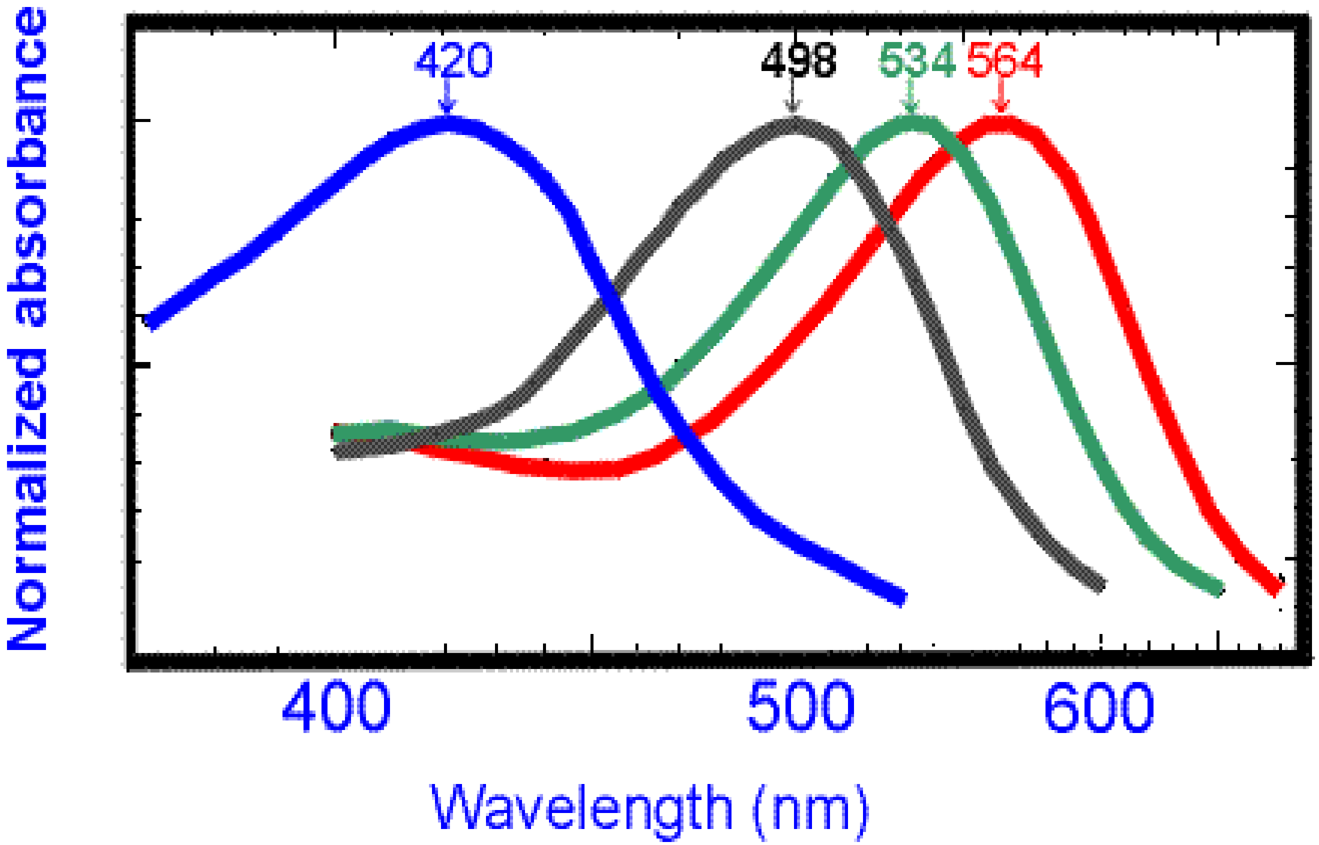
Example of spectral color formation



The spectral dimension
The number of spectral channels

- The visual perception of color is basically a result of the application of the three different spectral sensitivity ranges of the cones in the eye. Many different illumination and reflection functions can give the same color experience
- Most imaging systems are designed to optimize human color reproduction fidelity
- For image analysis we may have completely different number and ranges of spectral channels, the design criterion should be what optimizes the important contrasts or other properties of interest in the image

The spectral sensitivity of rods and cones

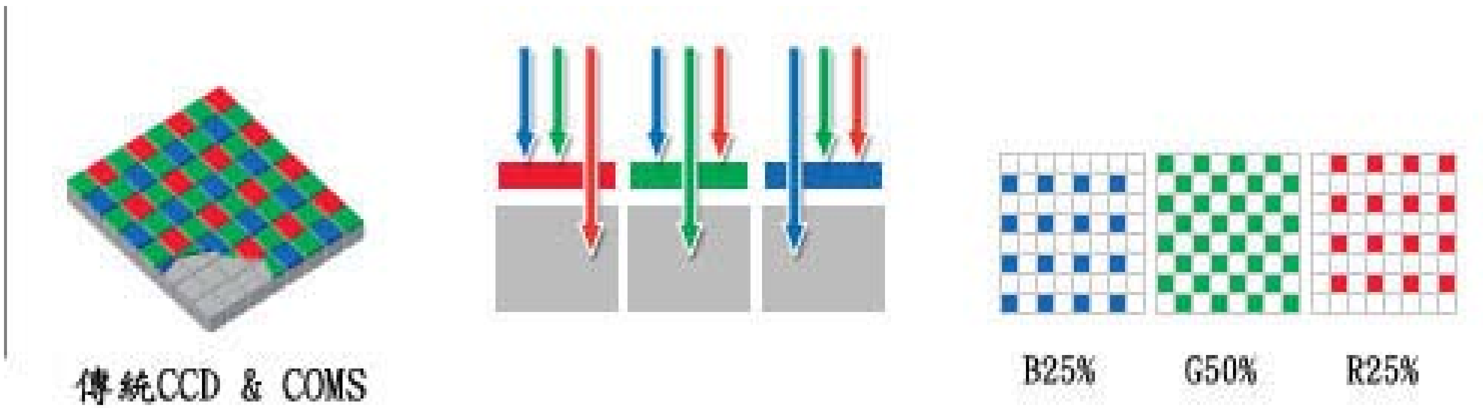


After Bowmaker & Dartnall, 1980

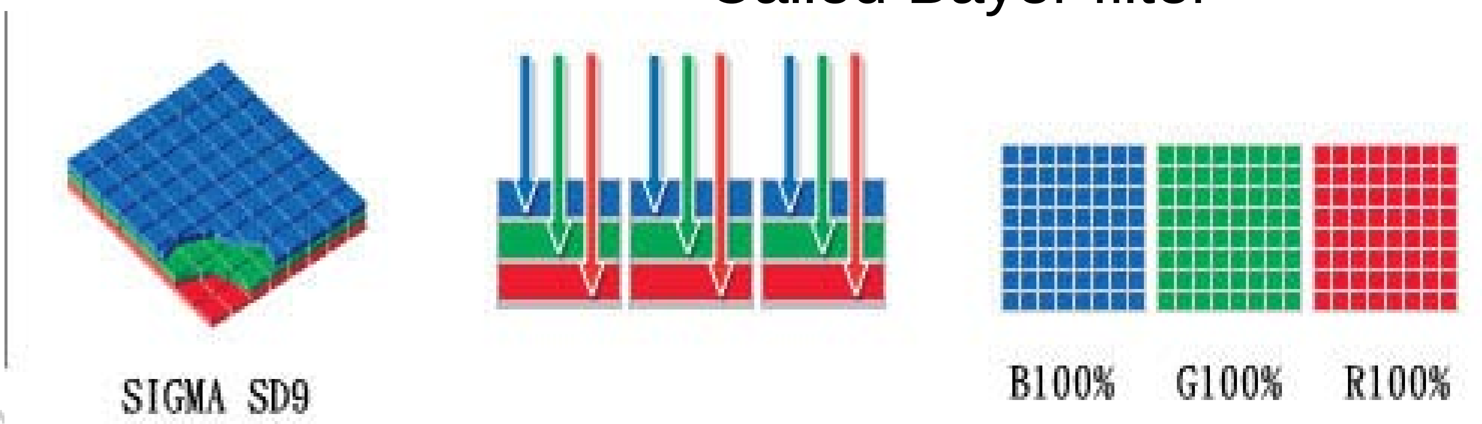
The spectral dimension
Color CCD the most common sensor

- One- or three-chip camera
  - three-chip is usually at least 3 times as expensive
- The color filter matrix for one-chip
  - Reduces color resolution to about half
  - Also reduces light collection efficiency
  - Can be anisotropic in x and y
  - A new method uses “vertical filters” with less resolution loss
- The signal can be digital video, RGB, component, S-video, composite or HF (in order of decreasing quality)

2D Mosaic vs vertical filtering



Called Bayer filter



The spectral dimension
Imaging spectrometry

- The spectral dimension can be spread with a grating orthogonal to a sensor line
  - A 2D sensor will give a line camera with high spectral resolution
  - Motion in the other dimension yields imaging spectrometry
  - Easily leads to lack of sufficient light
  - Gives large amounts of data, needs effective compression
- Can also have a rotating filter wheel and an area sensor

Temporal aspects

- Each image registers something for a defined time interval
  - Single temporal slice – still image
  - Multiple exposures – film, video
  - Continuous recording mode
- For each exposure we need to define the exposure time
  - Does it give motion blur?
  - Can it be varied freely?
  - How are the image quality aspects effected by the exposure time?

The temporal dimension
Exposure time

- Each pixel, line or image is exposed for a certain time
  - Need to consider motion in the scene
  - And of the camera relative to the scene
  - Limited by available light intensity
- Rapid motion can be frozen by short flash illumination
- Or by following the object motion with the camera
  - Special solution: area sensor with electronic object following

The temporal dimension
Image sequences, film and video

- Needed to register and measure motion
- Important timing factors
  - Repetition time
  - Exposure time
  - Data transfer and storage time
  - Influenced by resoloution in all five dimensions
- Stationary or moving camera
- Registration/detection of change
  - subtraction of previous or stored reference image

Integration: point, line, surface, volume

- The signal intensity must be measured for all pixels in order to create an image matrix.
- The degree of parallism in this light collection or integration is an important aspect of an imaging system.
- It can be done pointwise, linewise, for the whole 2D surface, or even for a whole volume at once.
- If we have multiple spectral channels we have an additional dimension to consider in the integration process.
- The integration parallelism strongly influences the light economy of the system

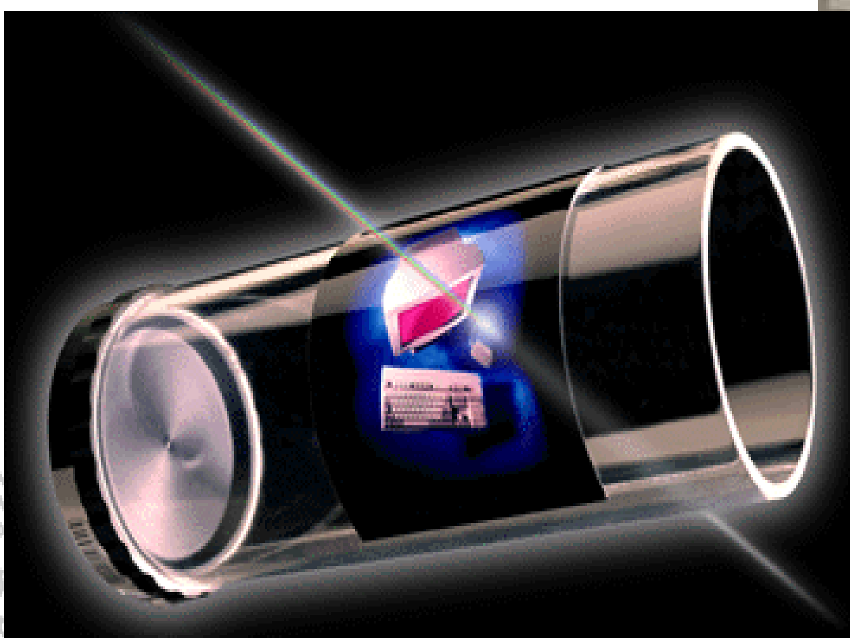
Point-wise integration
Technical aspects

- Distinguish based on what moves
  - The illumination
  - The sensor
  - The object
- Mainly used for stationary conditions e.g. scanning film or paper and in microscopy

Point-wise integration and sensing
Application examples

- Drum scanner
  - For very high quality document or film scanning
- Flying spot scanner
  - With a CRT, cathode ray tube
  - With a laser steered with a galvanometer mirror, or micro mirror device
- Microscopy
  - Fluorescens
  - Confocal
  - Multi-photon
  - Moving stage

Pointwise scanning: Drum scanner



Point-wise integration
Technical advantages

- Gives maximal possibilities for optimising the measurement of each pixel
- Can have a very highly optimised sensor and optical path
- No differences between the sensor properties of the different pixel sensors
- No limitations in image size

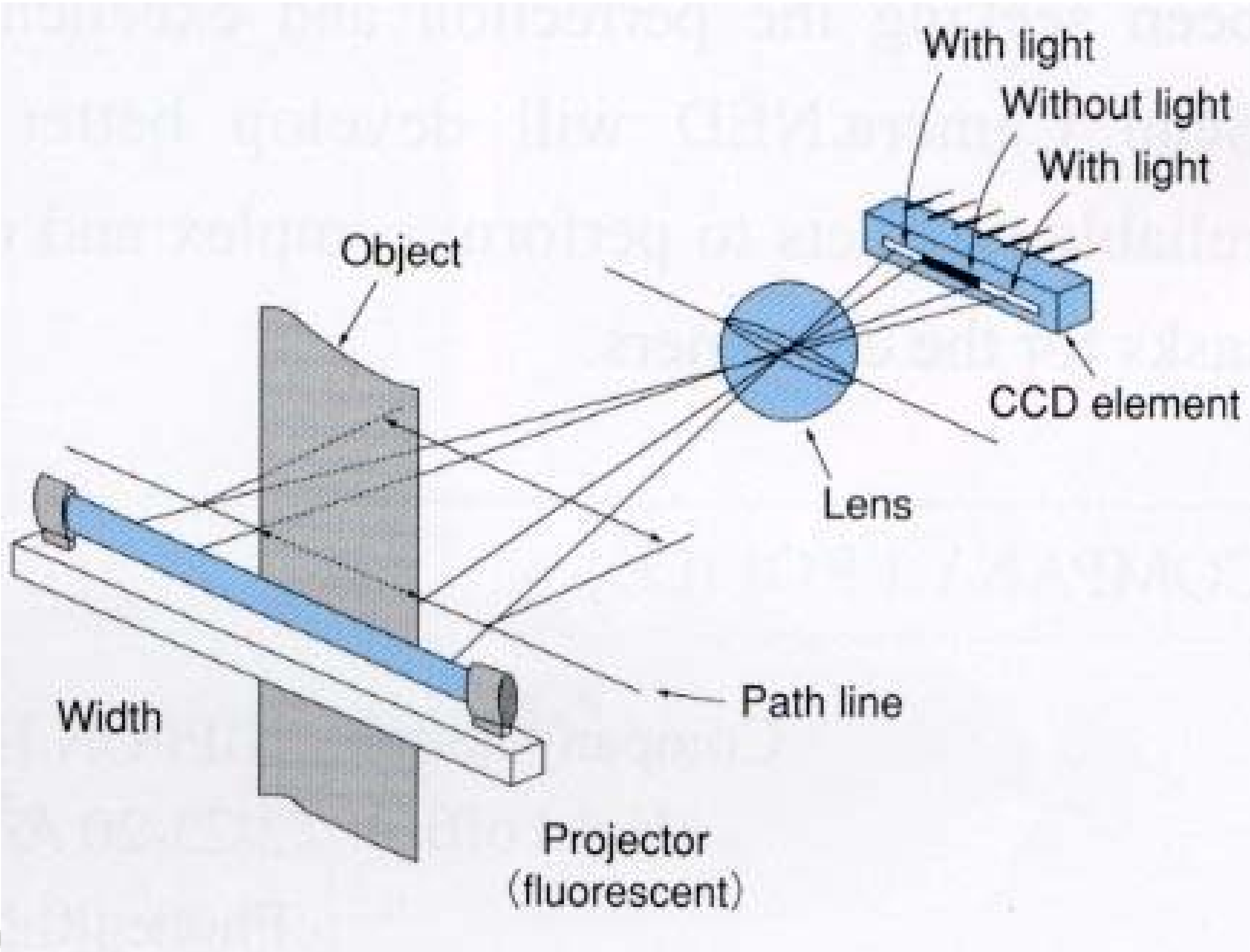
Point-wise integration
Technical disadvantages

- Uses available light poorly
  - can work well anyway if very high light intensity can be used
- Needs separate relatively complex, usually mechanical system, for scanning
- Usually slower than the other approaches

Linewise integration
Technical aspects

- Line sensors are available from 128 through about 10000 pixels
- The sensor elements are typically around 10 microns
- Can be implemented in CCD or CMOS technology
- Can move the scanner or object in the other dimension

Line scanning principle



Linewise integration
Application examples

- Common in scanners, fax and digital copiers
- Practical when there is a natural motion in one direction
  - Inspecting a cable
  - Production line
  - Satellite
  - Scanning the road surface
  - Moving microscopic specimen
- The Uppsala Osiris and Diascanner systems in 1975 and 1985 were early succesful examples of applying this principle in light microscopy

Linewise integration
Technical advantages

- Provides about 1000X better light economy than pointwise integration
- Motion orthogonal to the line will be “frosen”
- Allows using the other dimension in a 2D sensor for the wavelength
  - Used for RGB line scanners
  - And for hyperspectral scanners with up to 200 spectral channels
- Can also easily create ”intelligent sensors” having processor for each pixel

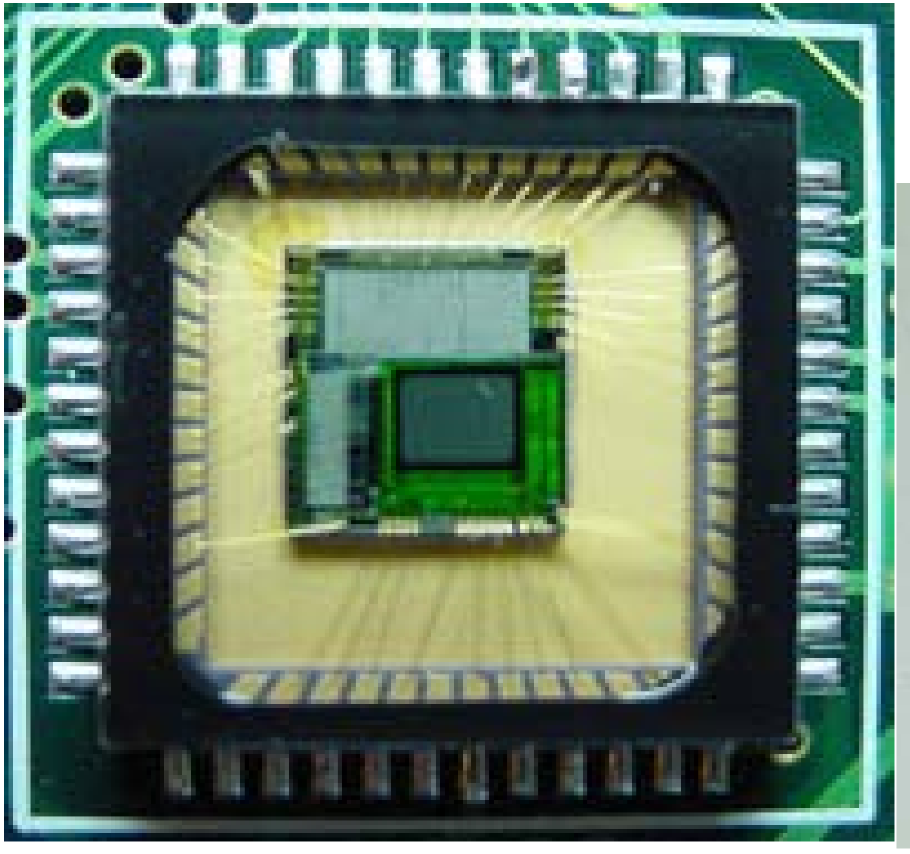
Linewise integration
Technical disadvantages

- Needs even illumination along the scan line
- Needs correction of sensor sensitivity variations along the line (1D) usually has interleaving (2 fold or 4 fold)
- The 1D fill factor is important, but seldom a problem
- There is a risk for x-y inhomogeneity because of the widely different scanning methods

Area integration
Technical aspects

- Historically based on image tubes
  - Vidicon, plumbicon...
- Currently dominated by solid state sensors
  - CCD - Charge Coupled Devices
  - CMOS – Complementary Metal Oxide Semiconductor
- Typical sensor element size 5 – 25 micron
- The area fill factor is an important technical parameter,
  - often lower than one would wish

Typical CCD chip and small camera



Area integration

Application examples: Standard video-sensor

- The basis for the TV and video technology
- CCD matrix with typically ca 480 x 720 element is scanned with line interleaving 25/30 times per second
- Provides an analogue video signal which later is digitized
- Clearly the economically most important and widely spread image sensor technology

Area integration
Application examples: Special sensors

- CCD and CMOS matrices are available in numerous versions with resolutions ranging
  - from around 500x500 e.g. old mobile phones
  - to around 10000x10000 e.g. astronomy
- The “more megapixel the better” sales paradigm has pushed large sensor developments beyond what is optically optimal
- Can be cooled for extremely long integration times allowing very low light levels
- Can have slow, high quality read-out or very high speed readout for capturing rapid events
- Can have different spectral sensitivites

A small CMOS "spy-camera"

Area integration
Technical advantages

- Gives the best light collection efficiency, collects ”all” light
- Rigid geometry (when solid state) gives stable, predictable imaging geometry with low distortion
- Requires no mechanical motion
- Can be mass-produced and become inexpensive

Area integration
Technical disadvantages

- Needs even illumination for the whole image surface
- May have varying sensor sensitivities that need to be corrected for
- Other things than the sensor area competes for space on the 2D surface making it hard to achieve
  - A high fill factor
  - Multispectral scanning
  - Intelligent sensors
- The image size is limited by the sensor size

Volume imaging

- Creating true 3D image volumes
- Rapidly increasing availability and interest
  - medicine has been pioneering field
- These images can not be viewed directly, needs special visualization efforts
- Easily generates large datasets
  - A 1000x1000x1000 image is 1 G pixels

Volume imaging methods

- Physical slicing of the object
  - “destructive imaging”
- Tomograpy
  - X-ray (CT)
  - Magnetic Resonance Imaging (MRI)
  - Emission (SPECT och PET)
  - Elektron microscopic (EMT)
- Confocal microscopy
- Ultrasound

Volume integration

- Only applicable to imaging system that creates volume images
- Most modern tomographic systems collect data from the whole volume, or multiple planes simultaneously creating savings in time and signal economy, examples:
  - Cone and multi slice CT
  - Modern SPECT and PET systems
  - MRI with fast acquisition modes

Stored intermediate analogue image
always involves loss of quality

- Storage medium
  - Photographic film
    - Light sensitivity
    - Grains
    - Spectral properties
  - Polaroids – (rarely used today)
  - Analog magnetic tape (video)
    - bandwidth
    - signal/noise ratio
  - Semiconductor materials (image plates)

Concluding questions: What is important for my image?

- Is geomery or photometry the most important aspect?
- What are the image matrix and resolution needs?
- What are the needs for contrast, dynamic range, signal/noise ratio
- What spectral properties are important?
- Need for speed, temporal resolution?
- Economical constraints?

Summary

- It is important to understand the limitation of the images that are to be anaysed, caused by the imaging system
- This require some understanding of the imaging technology
- This understanding can also be used when selecting an appropriate imaging solution for a particular problem

For further reading

- In scientific literature imaging is mainly discussed in relation to the different application fields e.g. medical imaging
- The web is (as usual) a good source of information, although sometimes biased by sales interests
- There is a number of commercial, free magazines with lots of (biased?) information about new imaging techniques and cameras

Imaging i framtiden

Jan 1999

Prediktion/spekulation - Massprodukter

- Digital video slår ut analog
  - har precis börjat, kommer att gå ganska fort
  - gäller också TV-distribution, politisk strid idag
- Digitalt foto slår ut film i småbildskameror
  - pågår för press och specialändamål
  - börjar komma (begr. uppl.) för amatörer
  - kommer i stor skala om några år
- Inbyggd i telefoner, stationära och mobil
  - Inom ett decennium

Imaging i framtiden

Jan 1999

Prediktion/spekulation - Medicinskt

- Allt bättre tomografiska utrustningar
  - Sann 3D avbildning med CT
  - Realtidsavbildat/rekonstruerat CT
  - Billigare MR med full 3D förmåga
- Ultraljud med 3D i realtid
- Bilder av nya signaler, fält, elasticitet….
- Billigare konfokal mikroskopi