



Front-End Vision and Multi-Scale Image Analysis

Prof. Bart M. ter Haar Romeny, PhD

Biomedical Image Analysis & Interpretation

TU/e, Department of Biomedical Engineering

B.M.terHaarRomeny@tue.nl

ter Haar Romeny, FEV

**Course:**

- Details: see [website](#)

Book:

- Includes CD
- Download book [here](#)

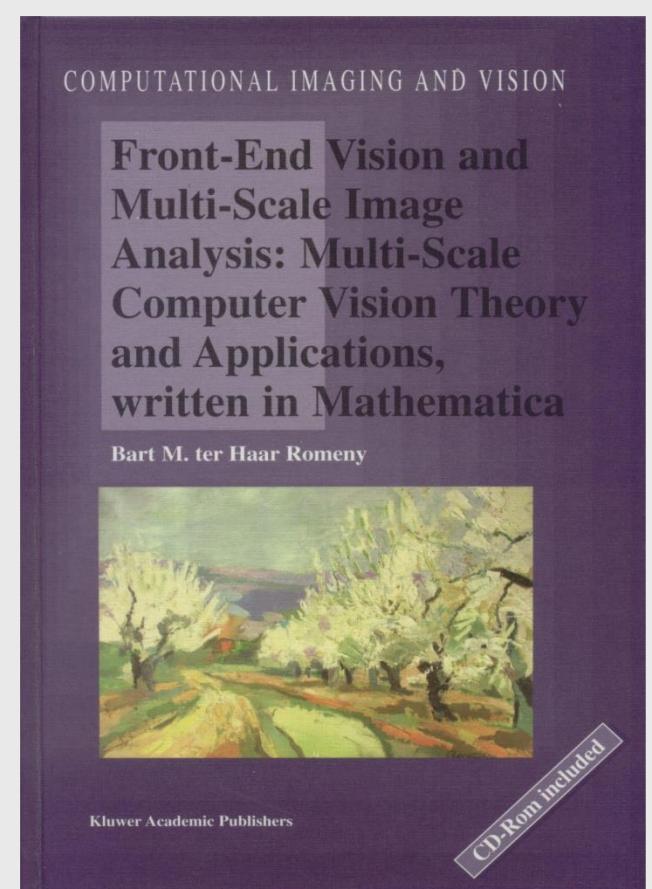
Computer lab:

- *Mathematica* 10
 - Install via [TU/e campus server](#)
 - Home use of Mathematica is allowed
- Introduction to programming
 - Lectures & exercises

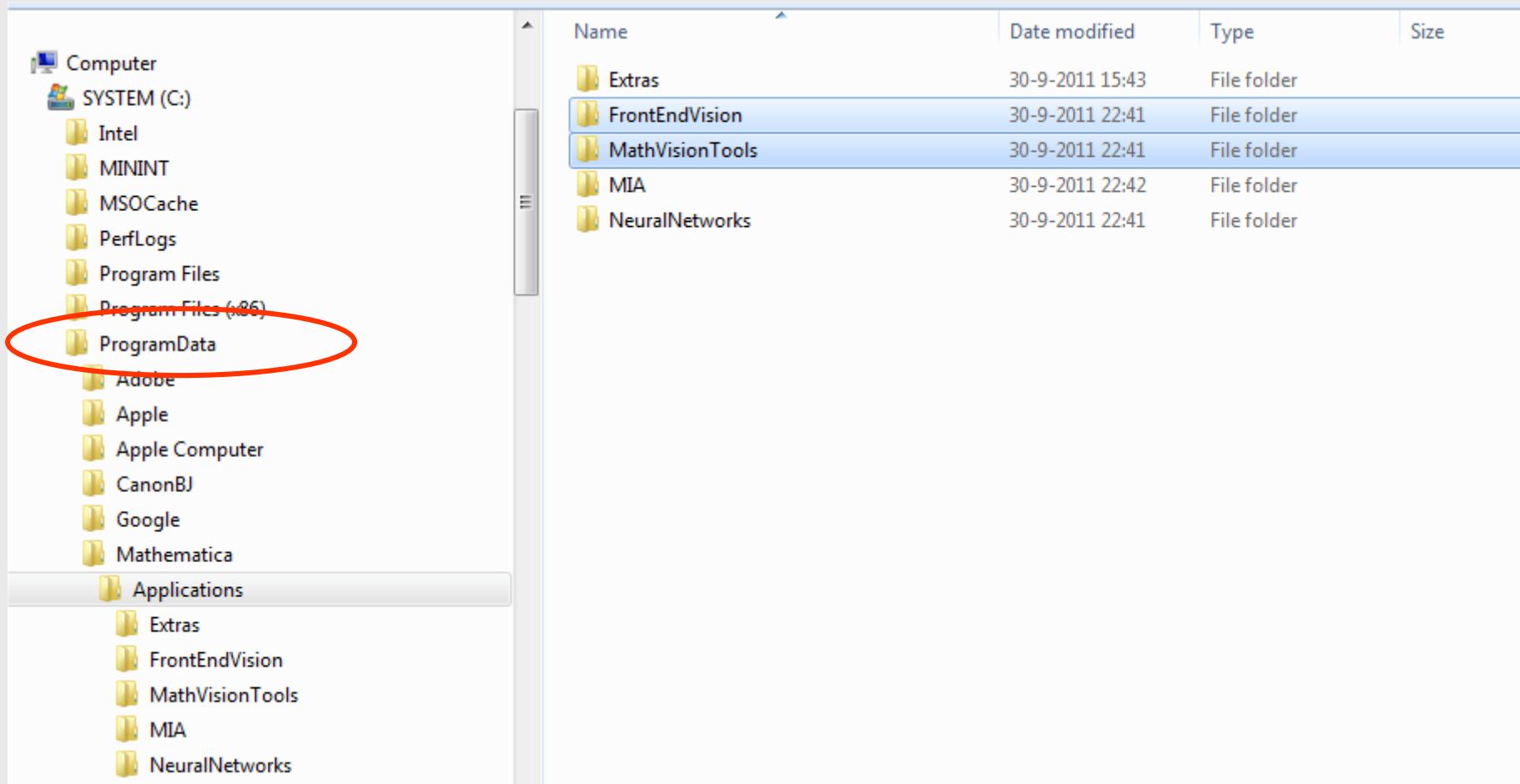
Examination:

- Detailed answers (MMA notebook) of 3 tasks.

Be creative, show new use of the learned methods, stand on your toes!



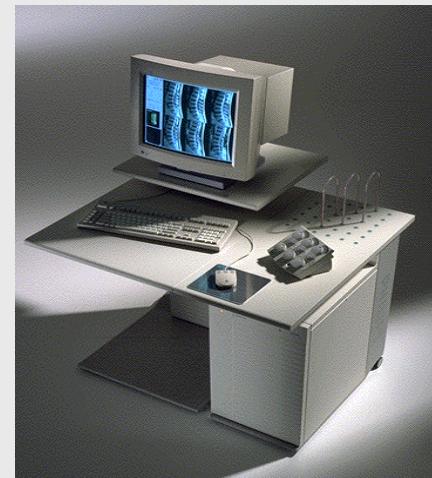
Windows Vista, Windows 7:



Check in *Mathematica*: ?*Directory*

This is an interactive course on brain-inspired image analysis

- Many courses, many computer lab sessions
- Multi-scale differential geometry, 'geometric reasoning'
- Study the notebooks carefully on the computer labs and at home
- Experiment with all examples, own images, vary parameters
- First understand the mathematics, then do the programming
- Use the *Mathematica* Help browser, study tutorials
- Rehearse your mathematics, if necessary
- Interact a lot with your colleagues, 'ask a guru'
- Functional and symbolic programming is very different ...
this takes time!



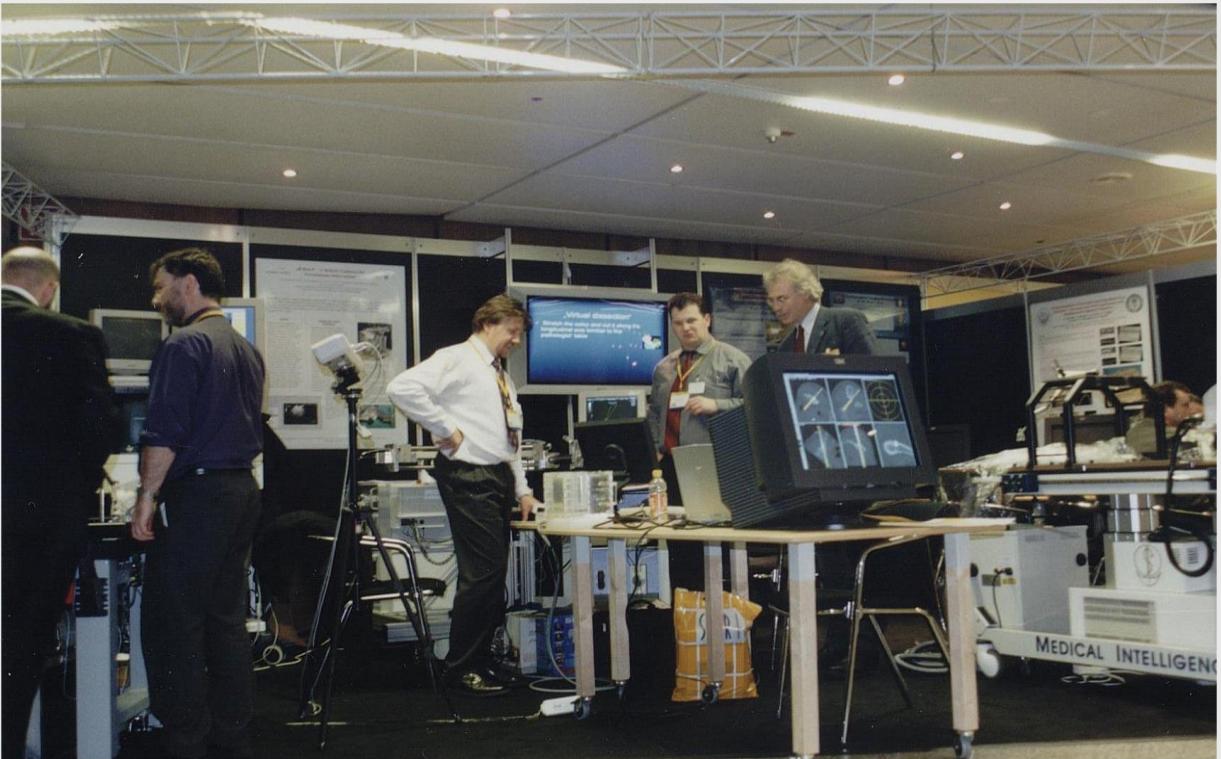


Medical workstations quickly become the super-assistants of radiologists and surgeons

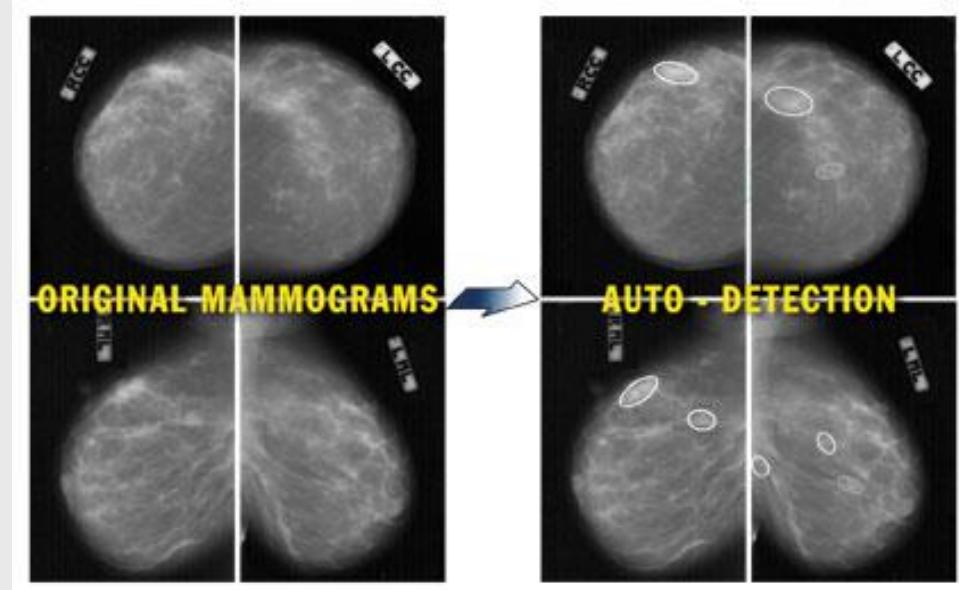
- 3D visualization
- Computer aided diagnosis
- Surgery planning
- Virtual endoscopy
- Tissue classification
- Interactive analysis
- etc.

The lightbox has disappeared, now hundreds of workstations

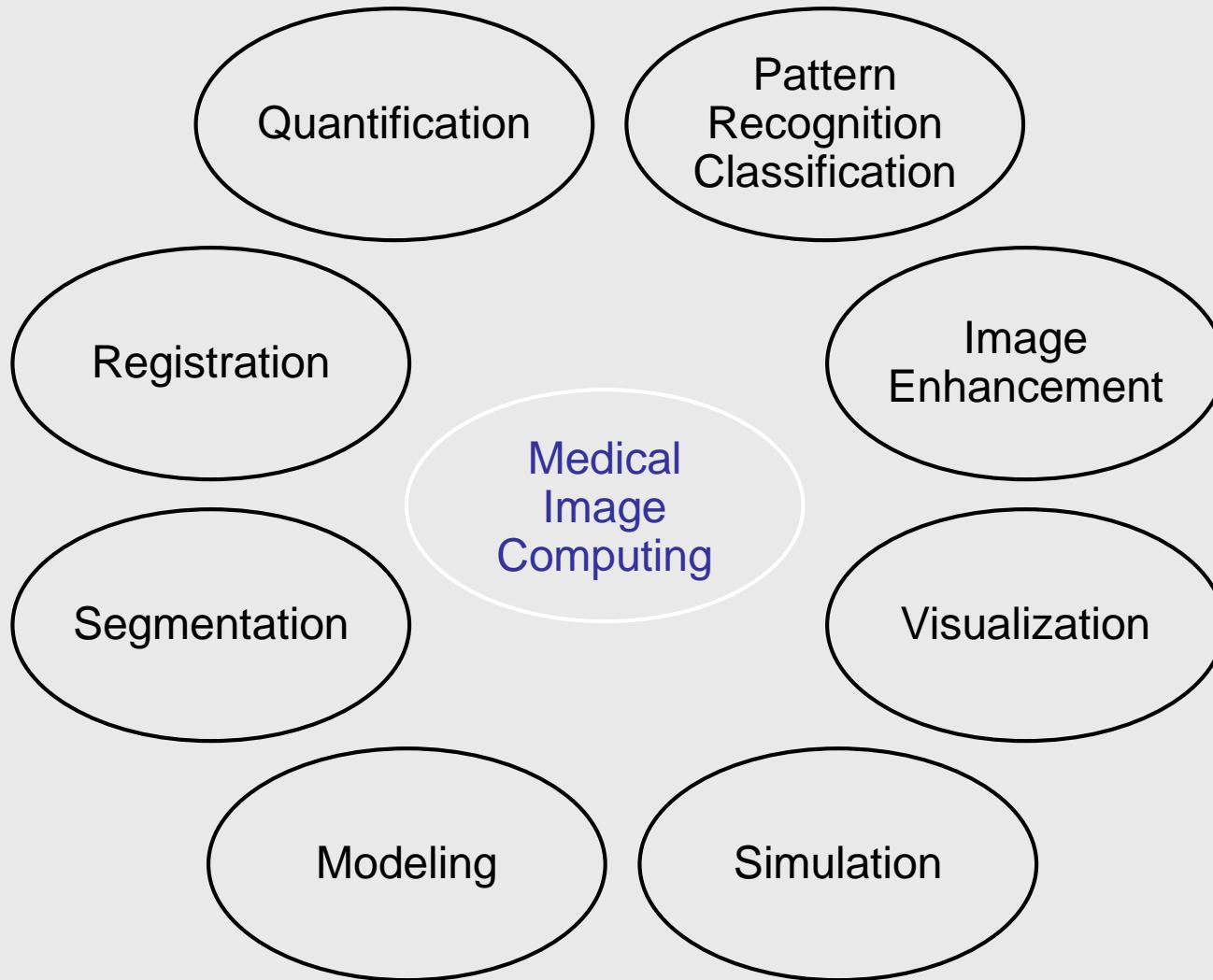
Radiological Society of North America (Chicago): 67.000 participants
European Congress of Radiology (Vienna): 22.000 participants



“Imagine” exhibit

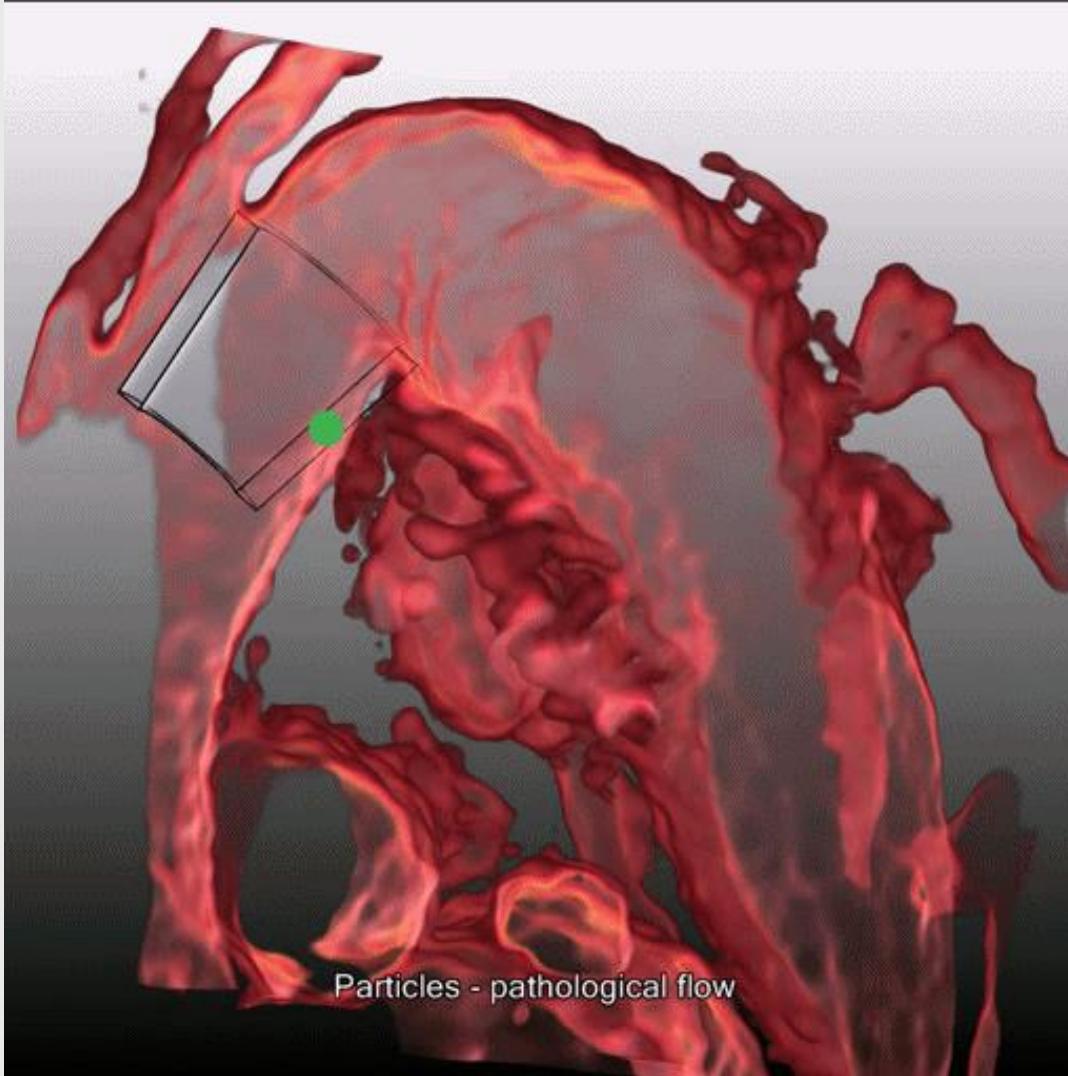


Computer-Aided Detection Computer-Aided Diagnosis



This course: geometry: a language for 'geometric reasoning'

ter Haar Romeny, FEV



Complex visualizations

4D cardiac flow
(van Pelt, Vilanova 2012)

Computer Aided Detection – Definition

The computer *interprets* images, finding abnormalities ...

things that should not be there

tumour, blood clot, polyp ...

things that should be there but look strange (shape, size)

emphysema in lung tissue, stenosis in vessels

things that look normal but behave strangely (dynamics)

limited blood uptake by infarct tissue in heart or brain

insufficient mobility of diseased heart wall

Computer Aided Detection – Applications

Breast cancer – X-ray mammography

Lung cancer (nodules) – CT

Lung emphysema – CT

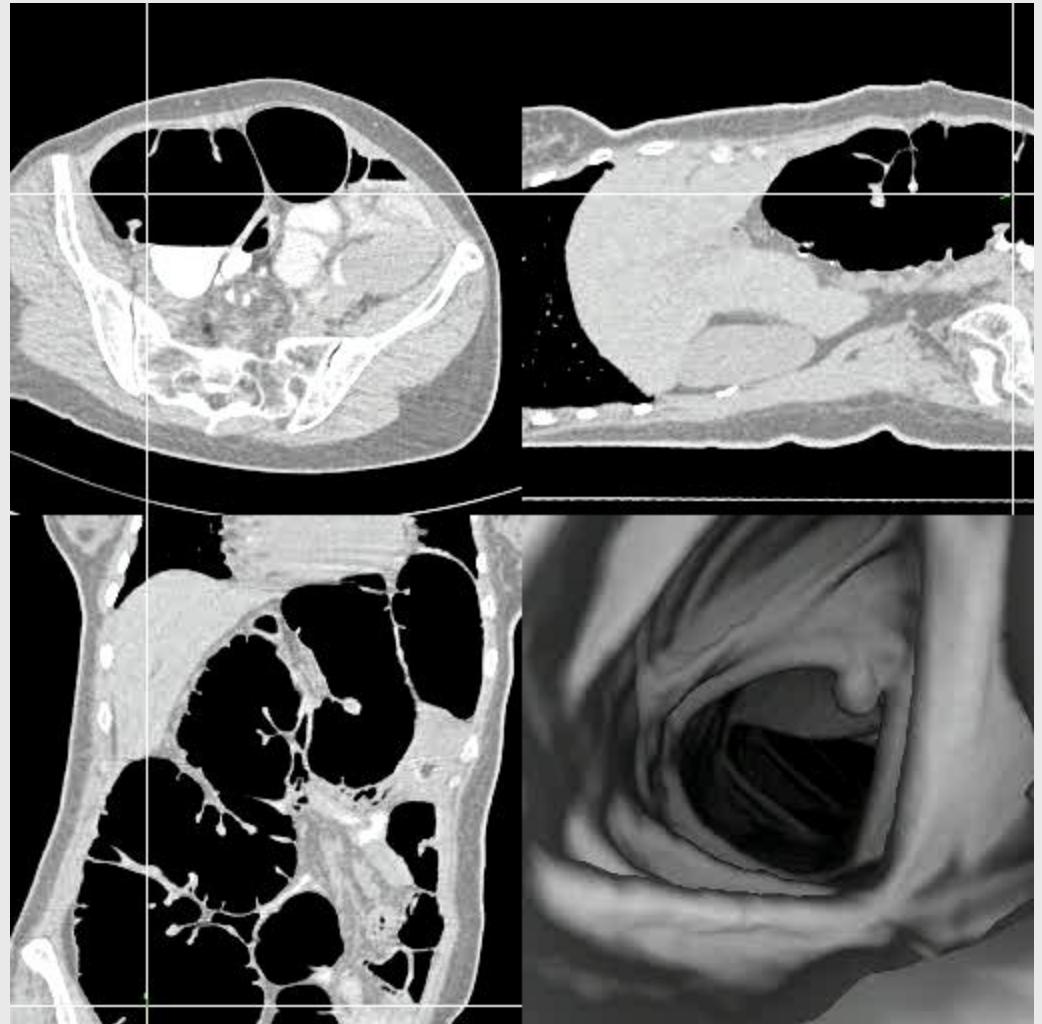
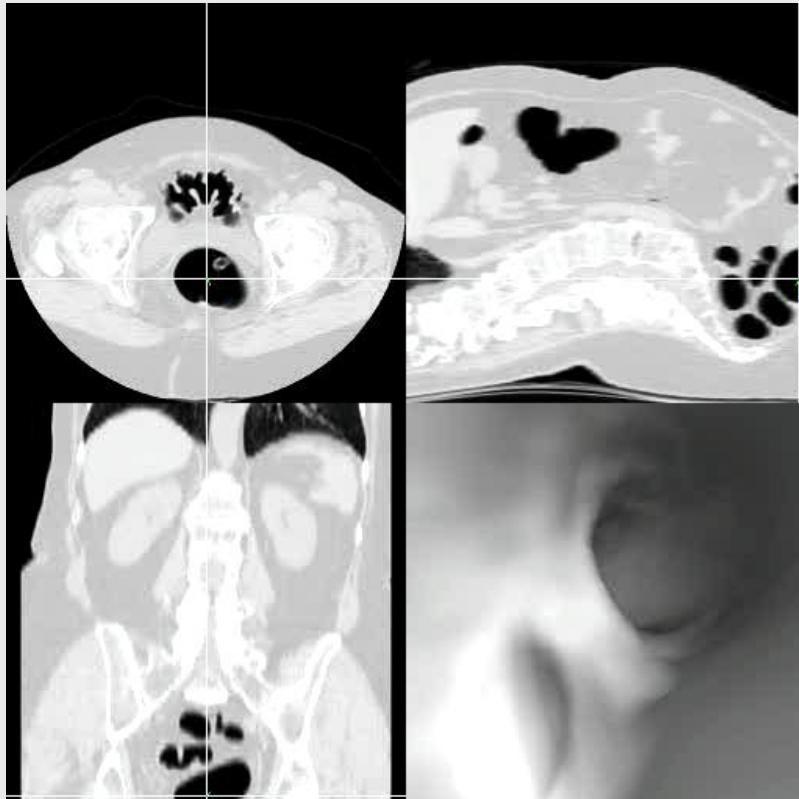
Colorectal cancer (polyps) – Colon CT

Acute pulmonary embolism – Lung CT

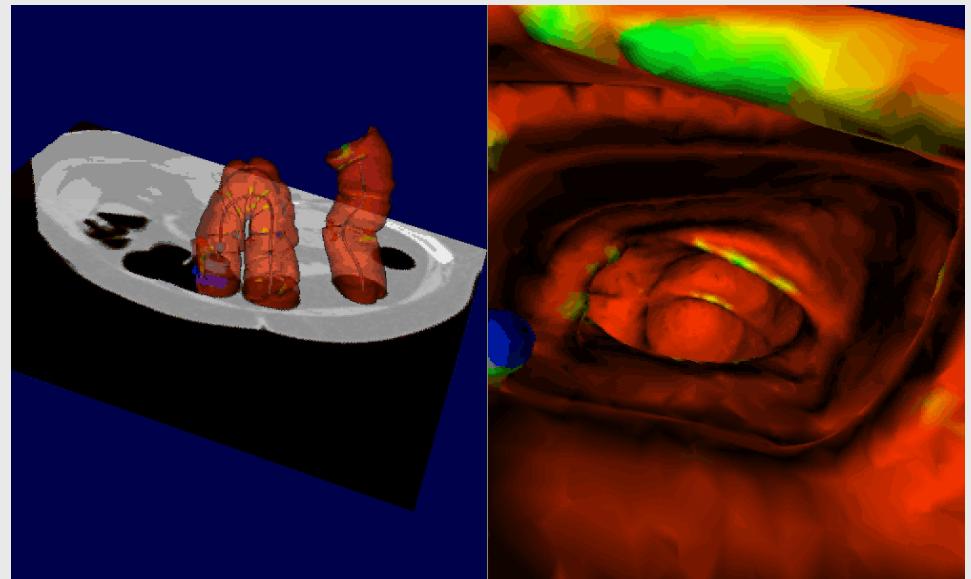
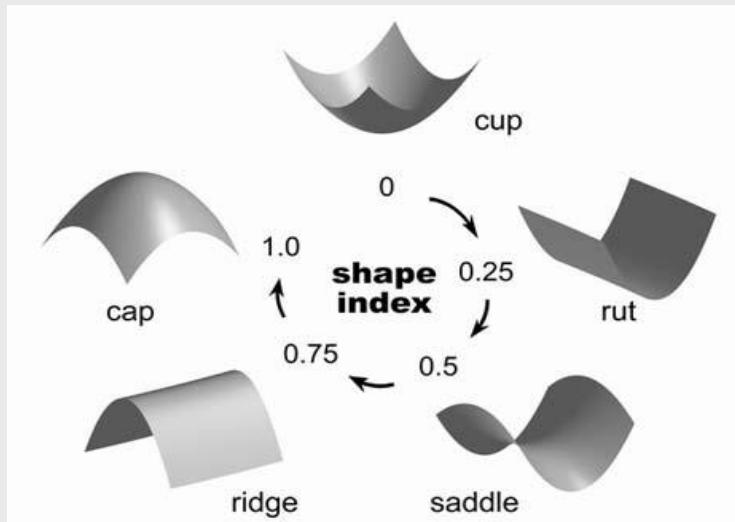
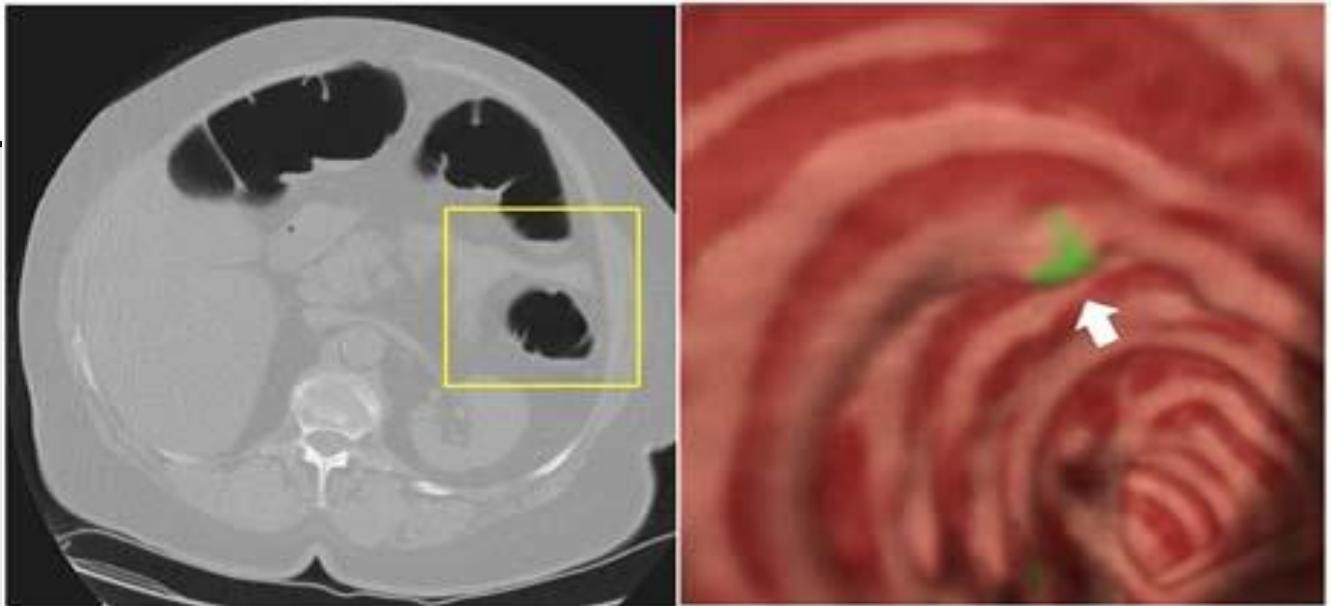
Breast cancer – MR “mammography” \Rightarrow Breast MR

Prostate cancer – US and MR

Virtual colonoscopy

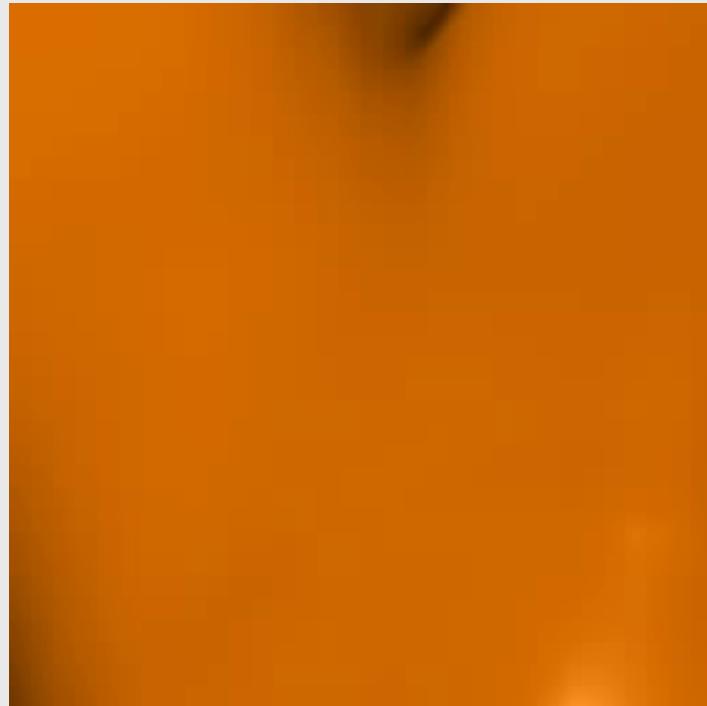


Automatic polyp detection

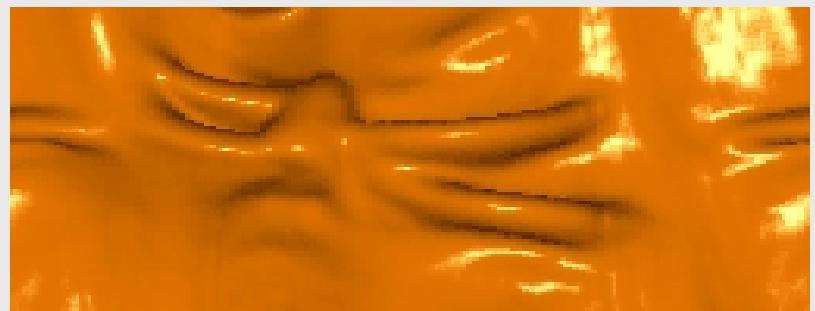


Shape analysis by differential geometry:
Principal curvatures: eigenvectors of Hessian second order structure matrix.

Trend: Versatile 3D visualization



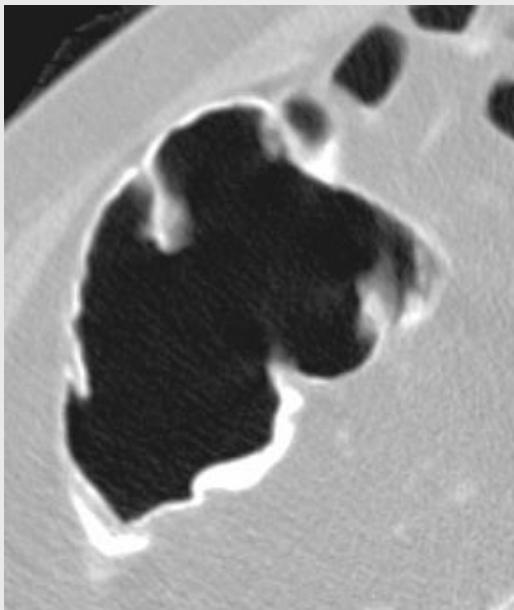
Anna Vilanova, TU Vienna / TU Eindhoven - BMT



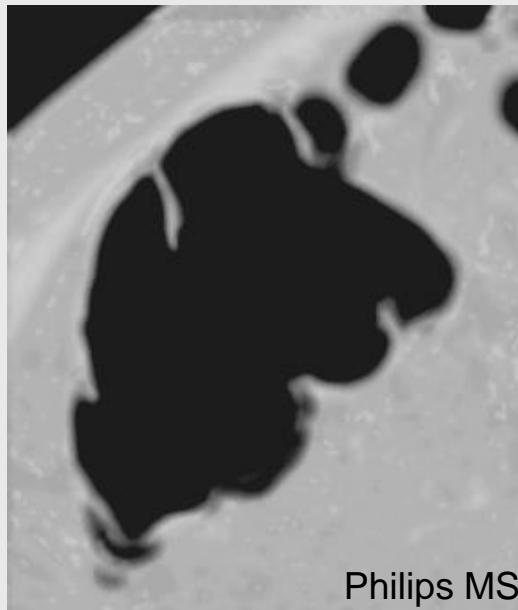
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Virtual
endoscopy

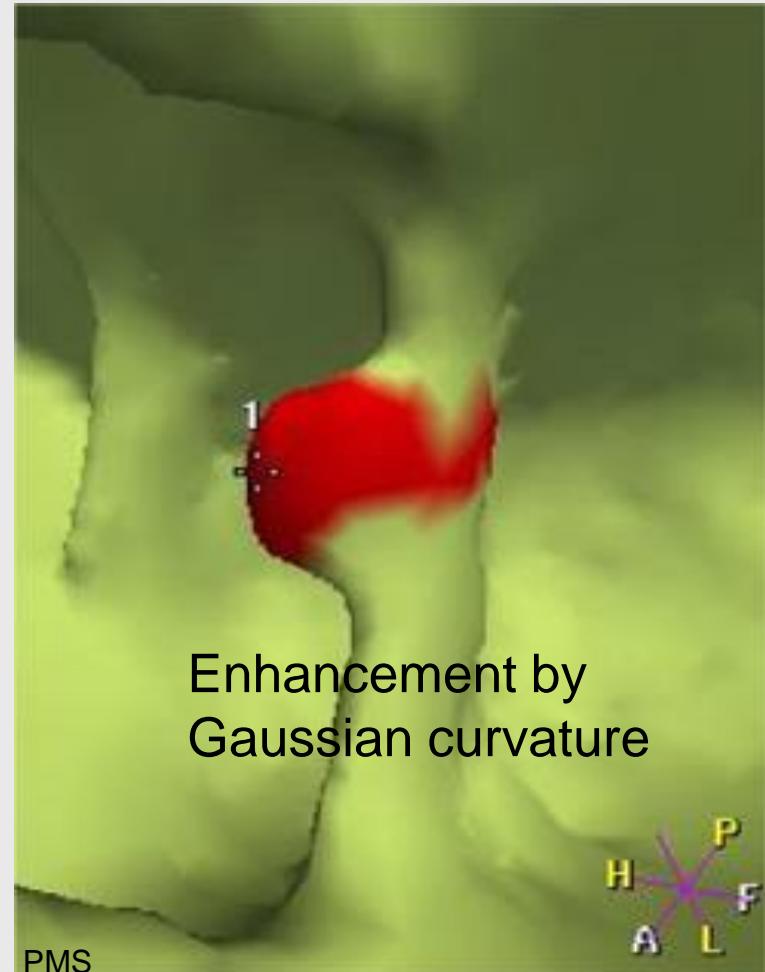
Electronic colon cleansing



CT slice with tagged residual sticking to the wall



Same slice after electronic cleansing



Colon polyps

"Tissue bulging from the surface of an organ"

50 % of population have polyps at ages 50+

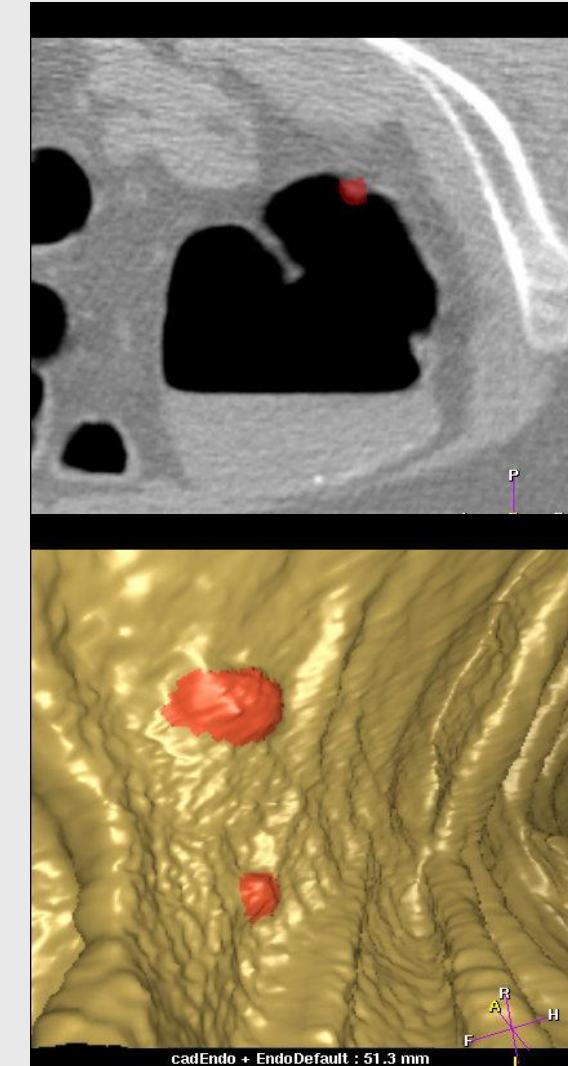
10-20% of larger polyps develop into cancer
over time (5-10 years)

Slow development of disease ⇒ early detection helps!

150,000 new cases / year (USA)

60,000 deaths / year (USA)

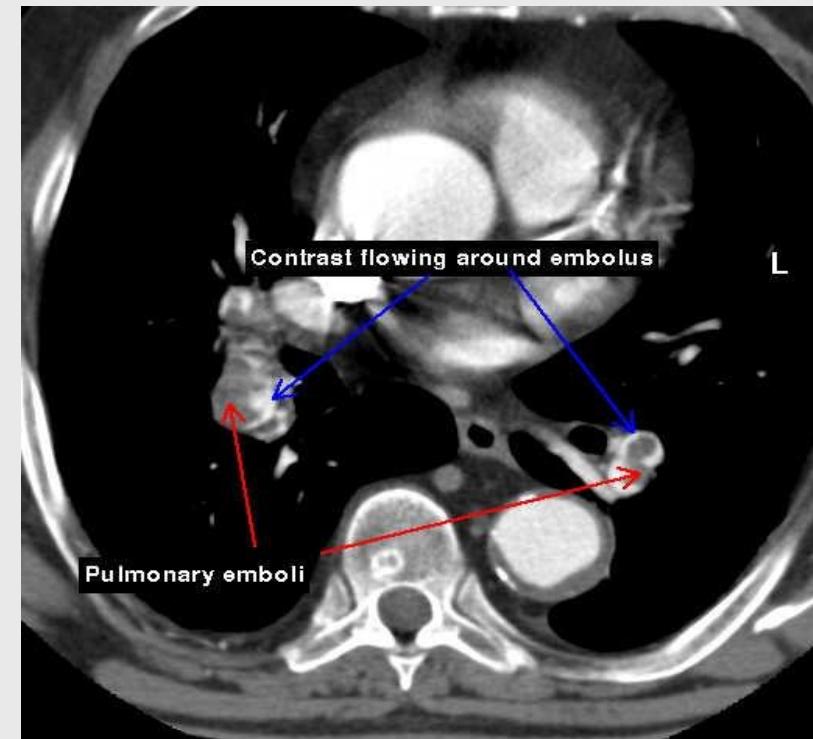
*"Screening for polyps will reduce mortality
from colon cancer"*



Pulmonary Embolism

Obstruction of blood vessels in the lungs – acute

- “Over 500,000 patients experience a pulmonary embolism each year and over 50,000 will die from it.”
- CT has become standard for assessing cardiac / pulmonary state
- Multiple stack-traversals down / up / down needed to assess all arterial branches
- Easy to spot large PE in large arteries
- Easy to miss PE in (sub) segmental parts





PHILIPS

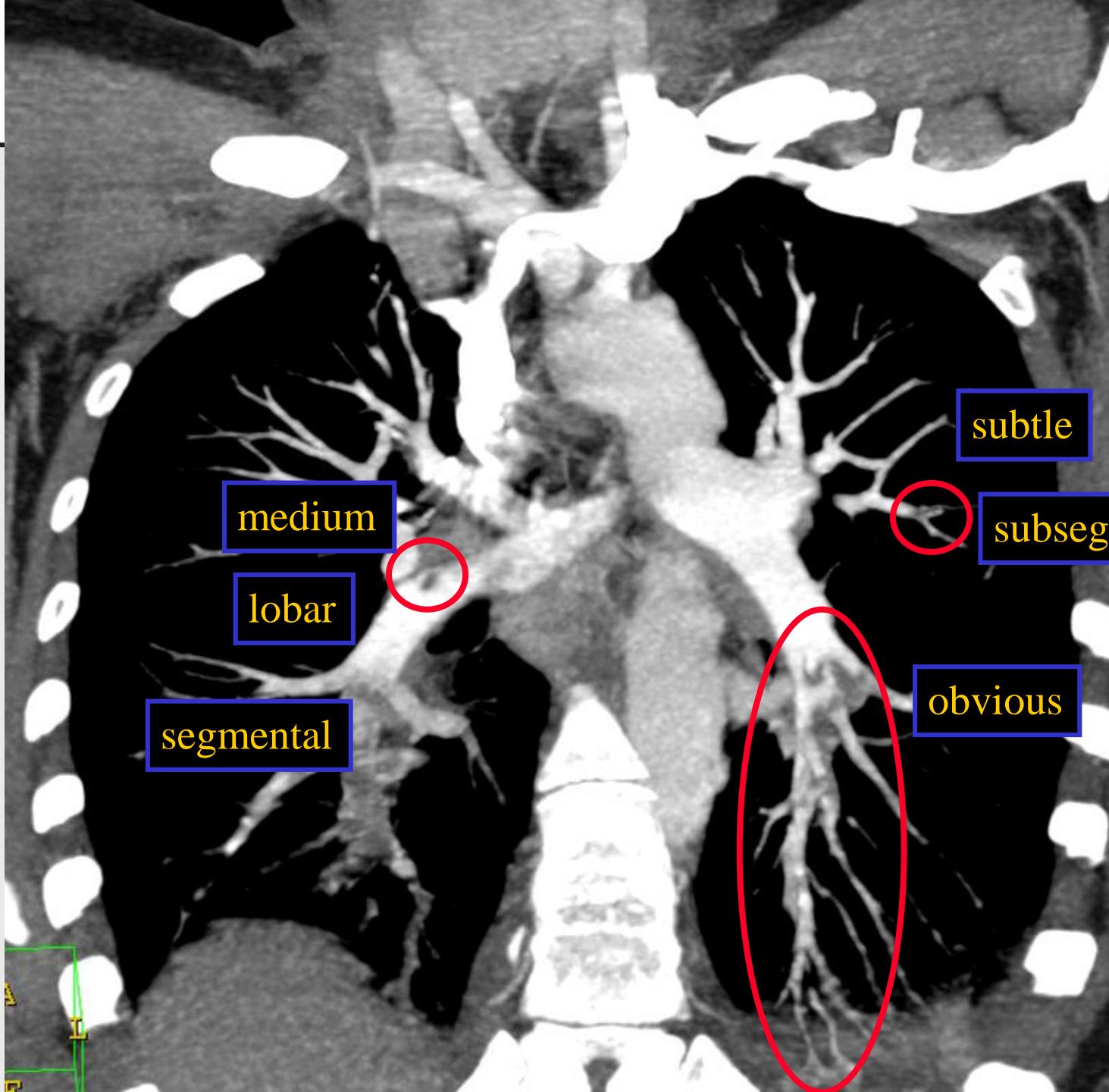
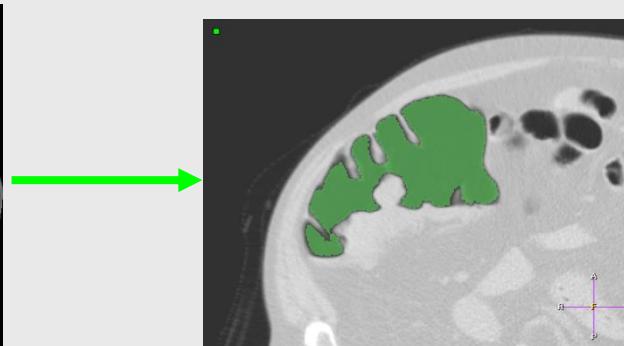


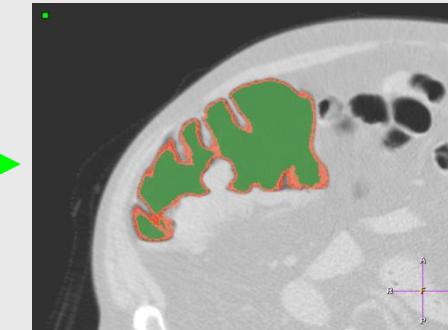
Image Processing – define search area



Colon (CT)



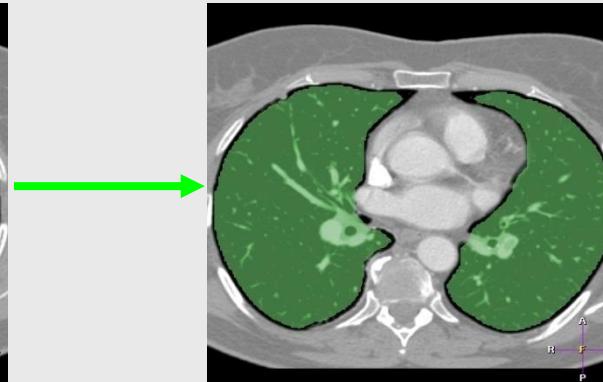
Colon segmentation



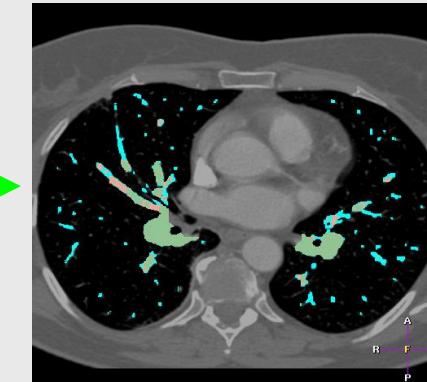
Wall segmentation



Lung (CTA)

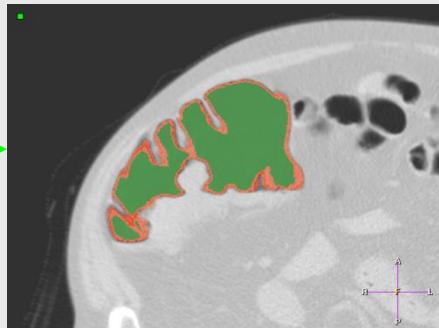


Lung segmentation

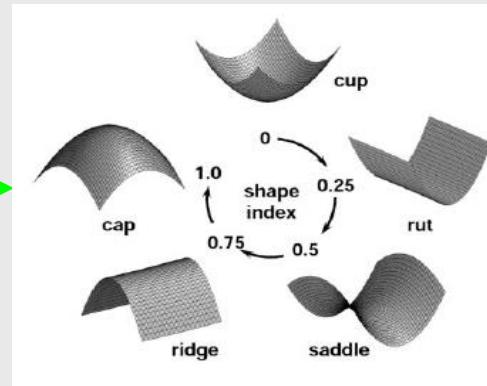


Vessel segmentation

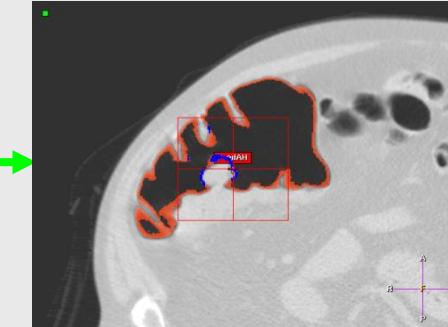
Image Processing – voxel features



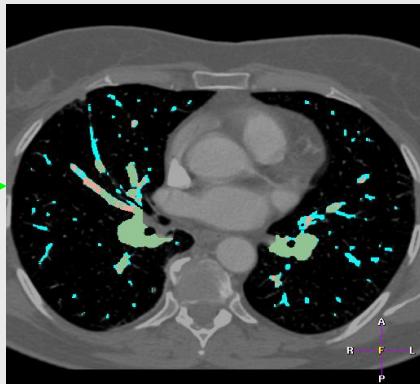
Wall segmentation



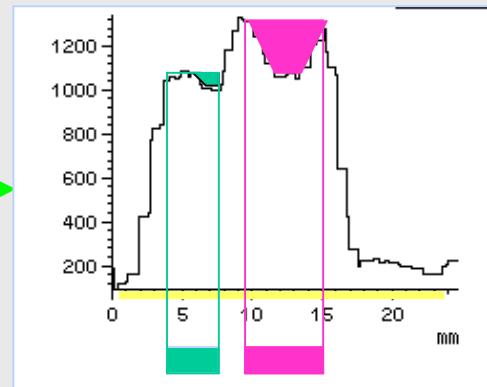
Feature extraction
(shape analysis)



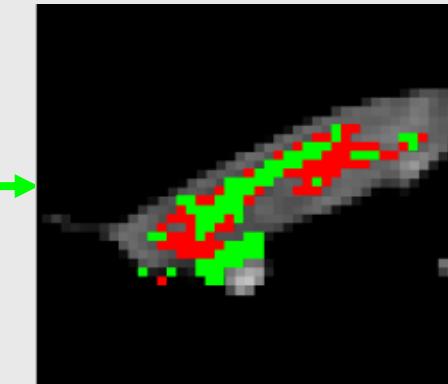
Cap Voxel Areas



Vessel segmentation

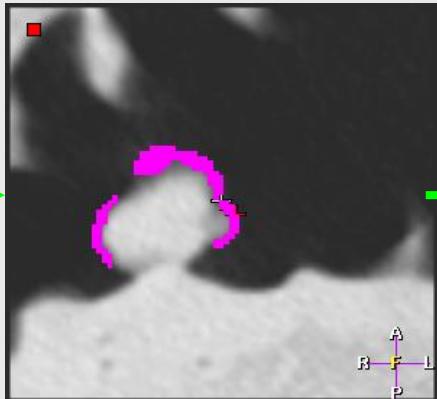


Feature extraction

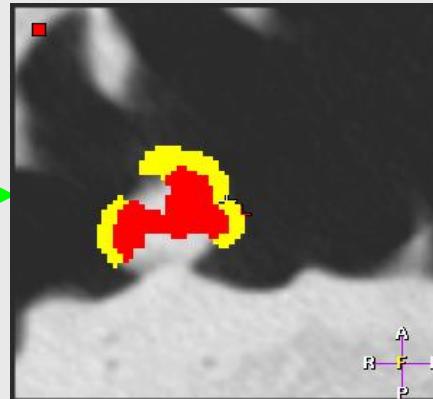


Hessian eigenvalues
Curvature ...

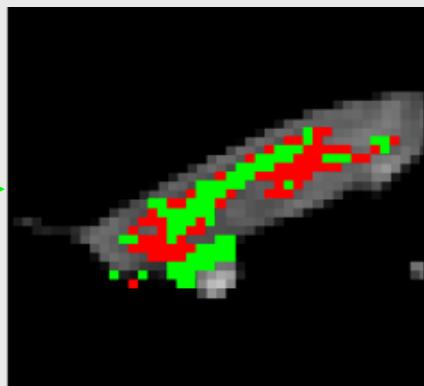
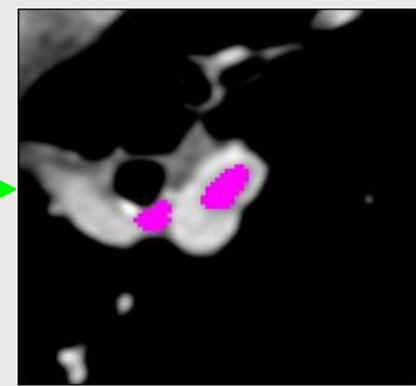
Image Processing – object(s) features



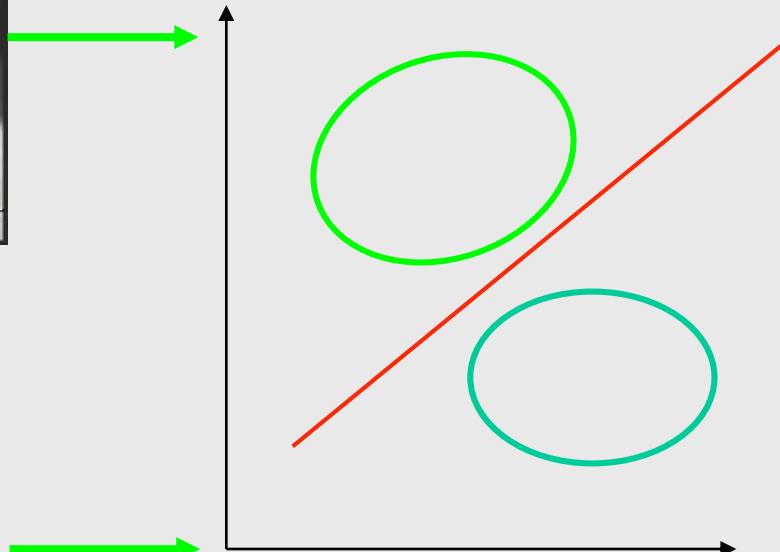
Cap Voxel Areas



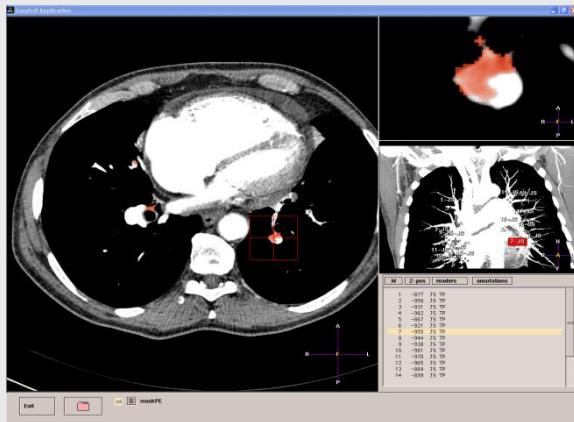
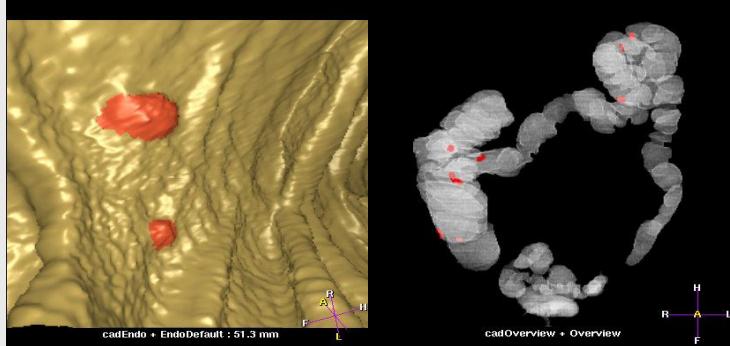
Polyp candidate

Hessian eigenvalues
Curvature ...

Embolus candidate

Classification via
Pattern Recognition

Visualization



Visual Assessment

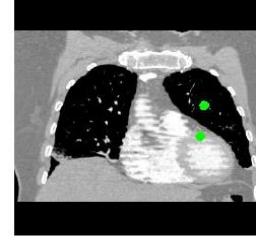
Structured Reporting

Creation date: 22-11-2004 time: 13:58:23
Application information: LungCT

Patient information:
First name:
Last name: PE_AMC_003
Date of birth: 1932-06-16
Sex: O
ID: 8076767

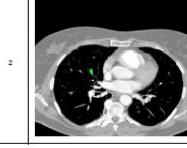
Physician information:
First name: Unknown
Last name: Unknown

Detected nodules:



ID	Size	Completeness	Volume	Avg. diameter	User
1	140	0.885331	460.000000	6.53772	HB
2	140	0.885331	232.395933	6.18622	HB
3	124	0.887894	896.791899	10.42842	HB

Overview images:

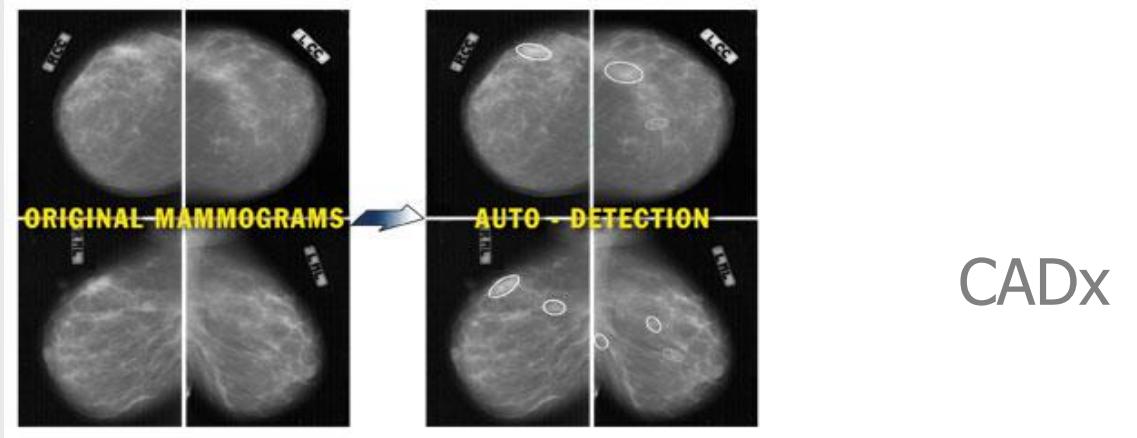
ID	Axis	zoomed*	3D reconstruction
1	Axial		
2	Axial		

page 1

Structured Reporting

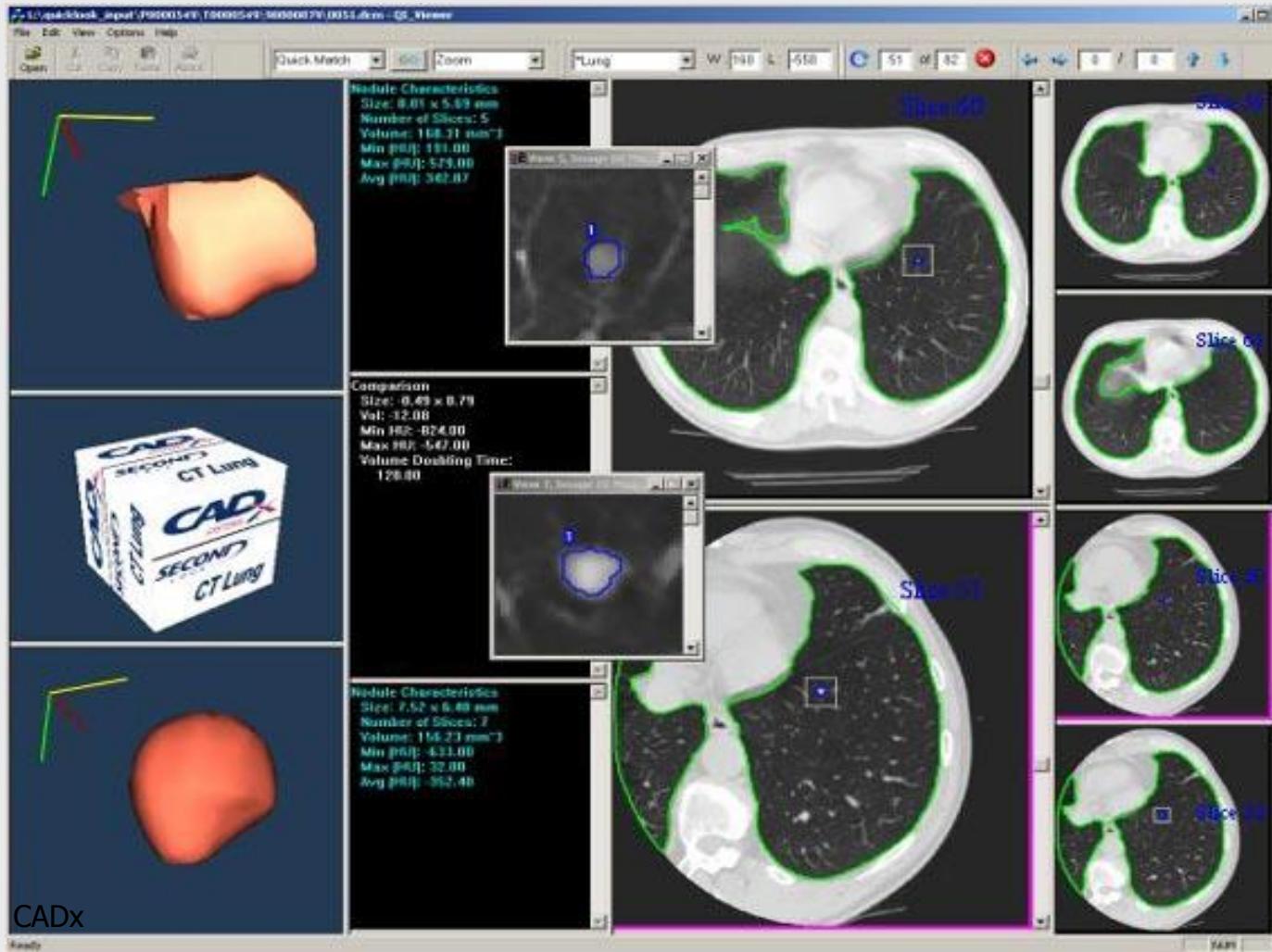
Trend: computer-aided diagnosis

Mammography:



In a prospective study based on screening exams performed on almost 13,000 consecutive women over a one-year period, [Ulissey](#) and colleagues found that CAD increased breast cancer detection by 20% (*Radiology*, September 2001, Vol. 220:3, pp. 781-786).

CT lung pathology: automatic nodule finding



Computer Vision techniques:

Image matching

Enhancement

Shape analysis

Motion analysis

Geometric corrections

Colour analysis

Detection and classification

Texture analysis

Segmentation

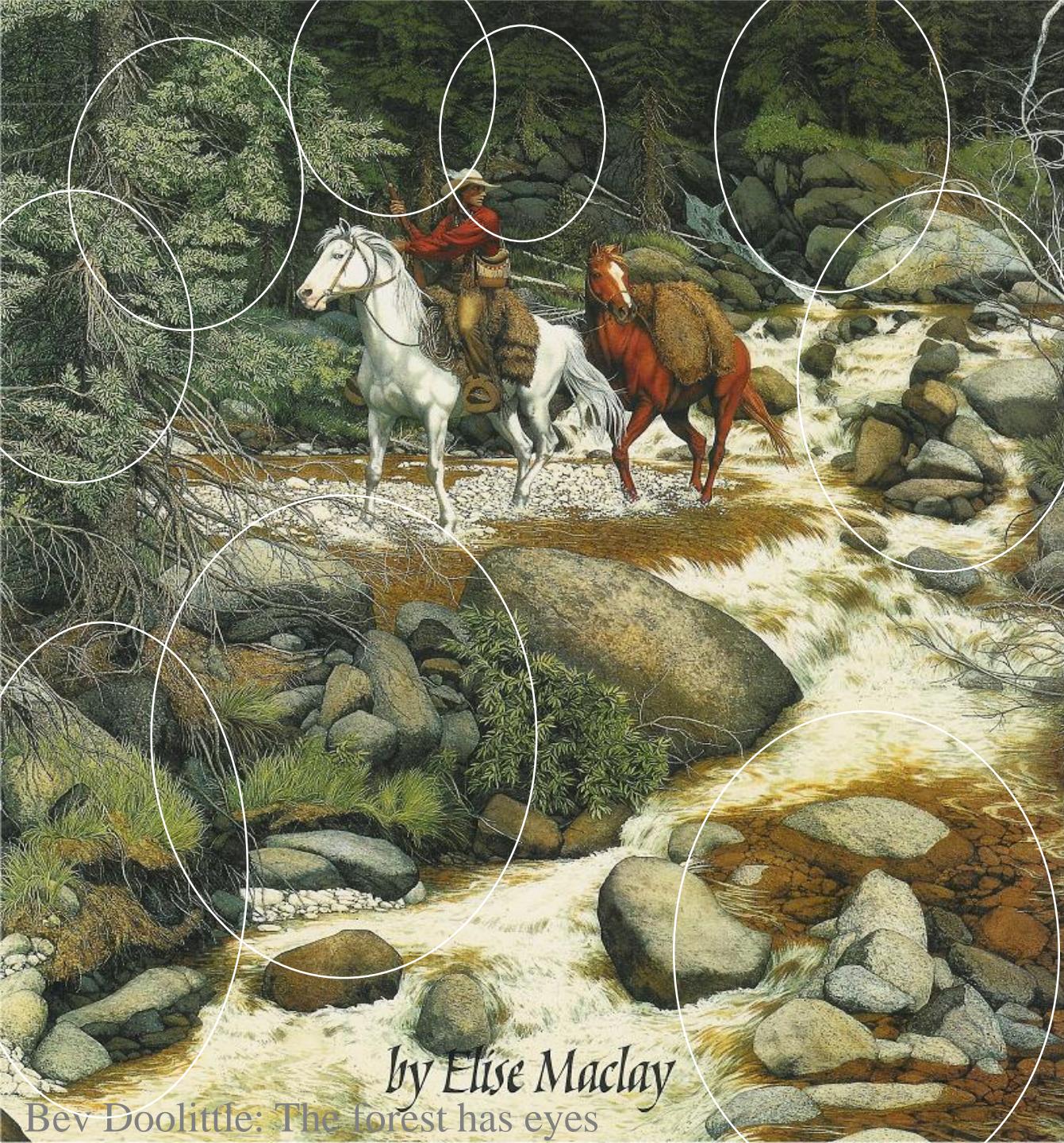
Needed: the differential structure of images

Computer-Aided Diagnosis

The challenge



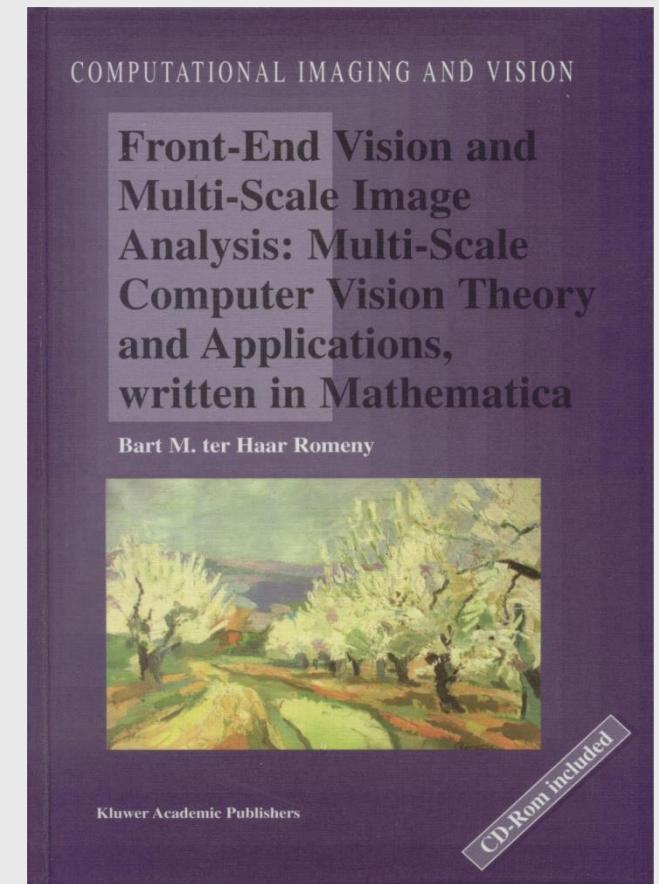
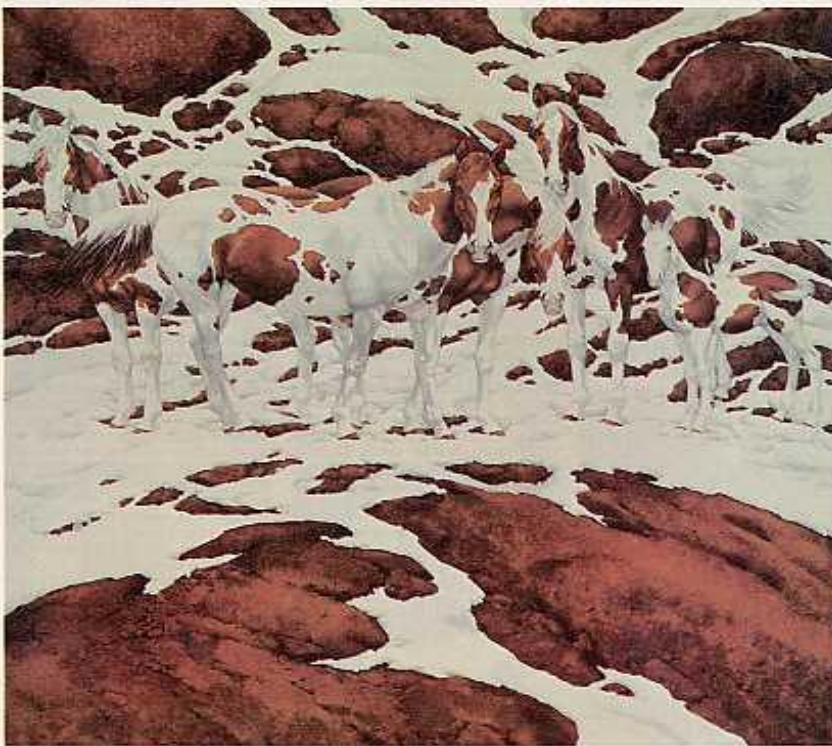
How do *we* do it?



Bev Doolittle: The forest has eyes

ter Haar Romeny, FEV

Multi-Scale Image Analysis



Biologically inspired computer vision

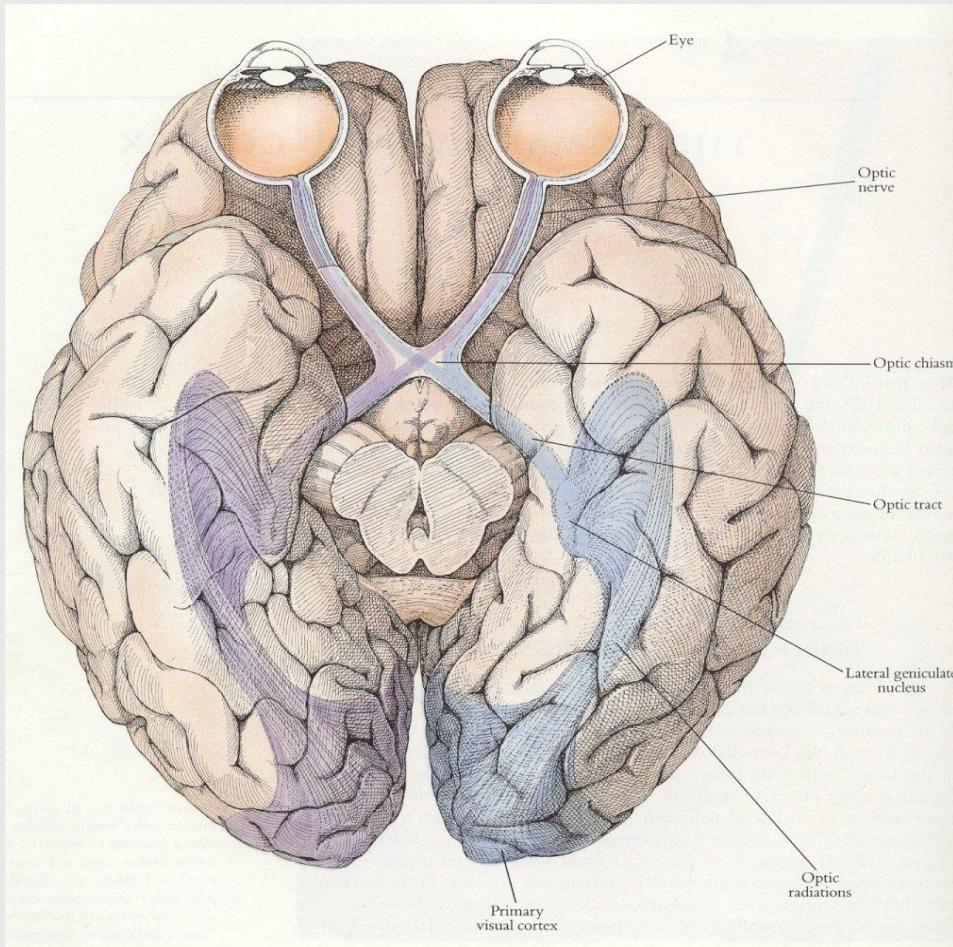
→ bio-mimicking / brain-inspired / neuromathematics, ...

ter Haar Romeny, FEV

Central Visual Pathways

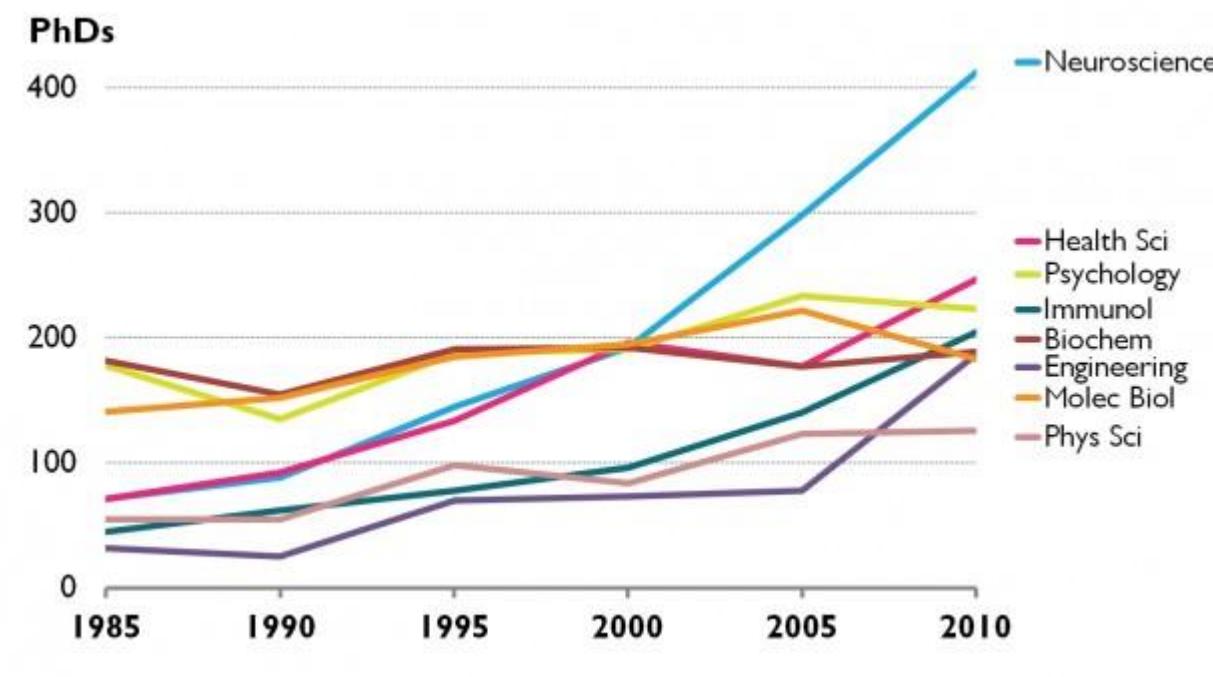


David Hubel
Nobelprize 1981



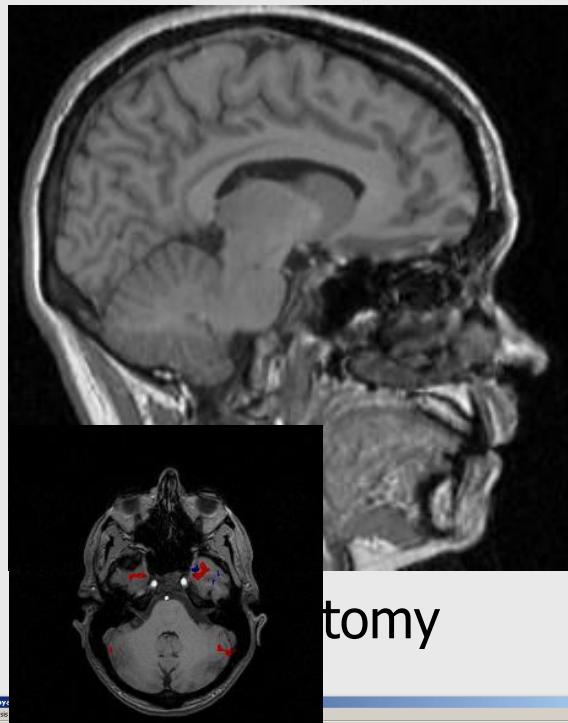
Torsten Wiesel
Nobelprize 1981

We go study
visual perception.

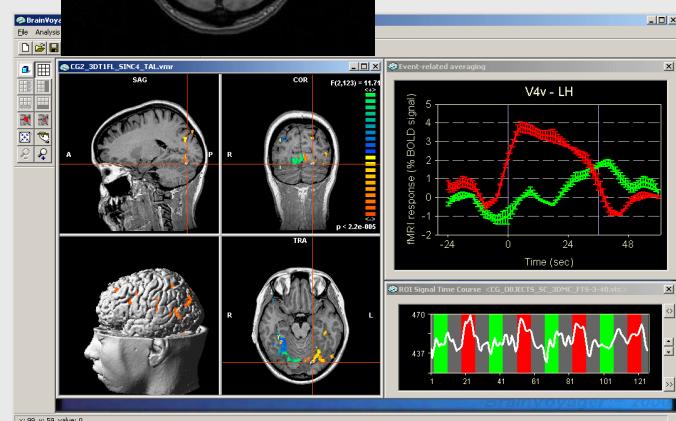


First: the brain - general

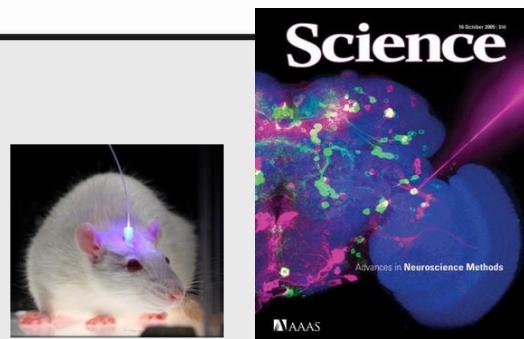
- Brain neurons
- Brain connectivity
- Brain imaging
- Brain plasticity
- Cellular connectivity
- Receptive fields



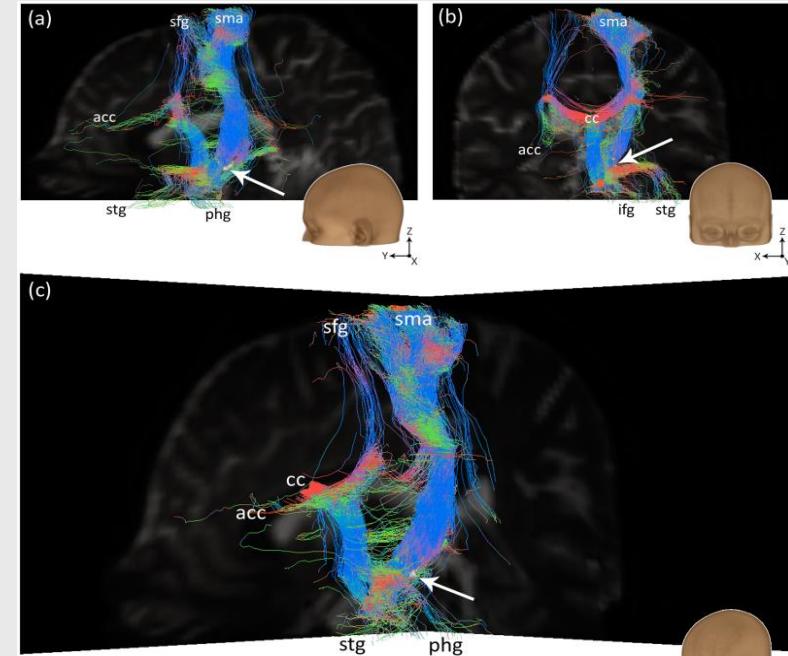
tomy



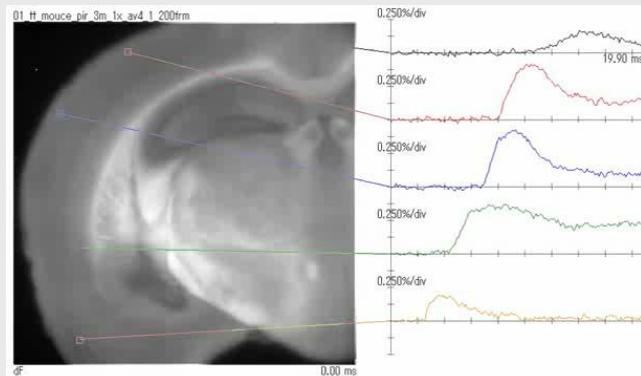
Functional MRI



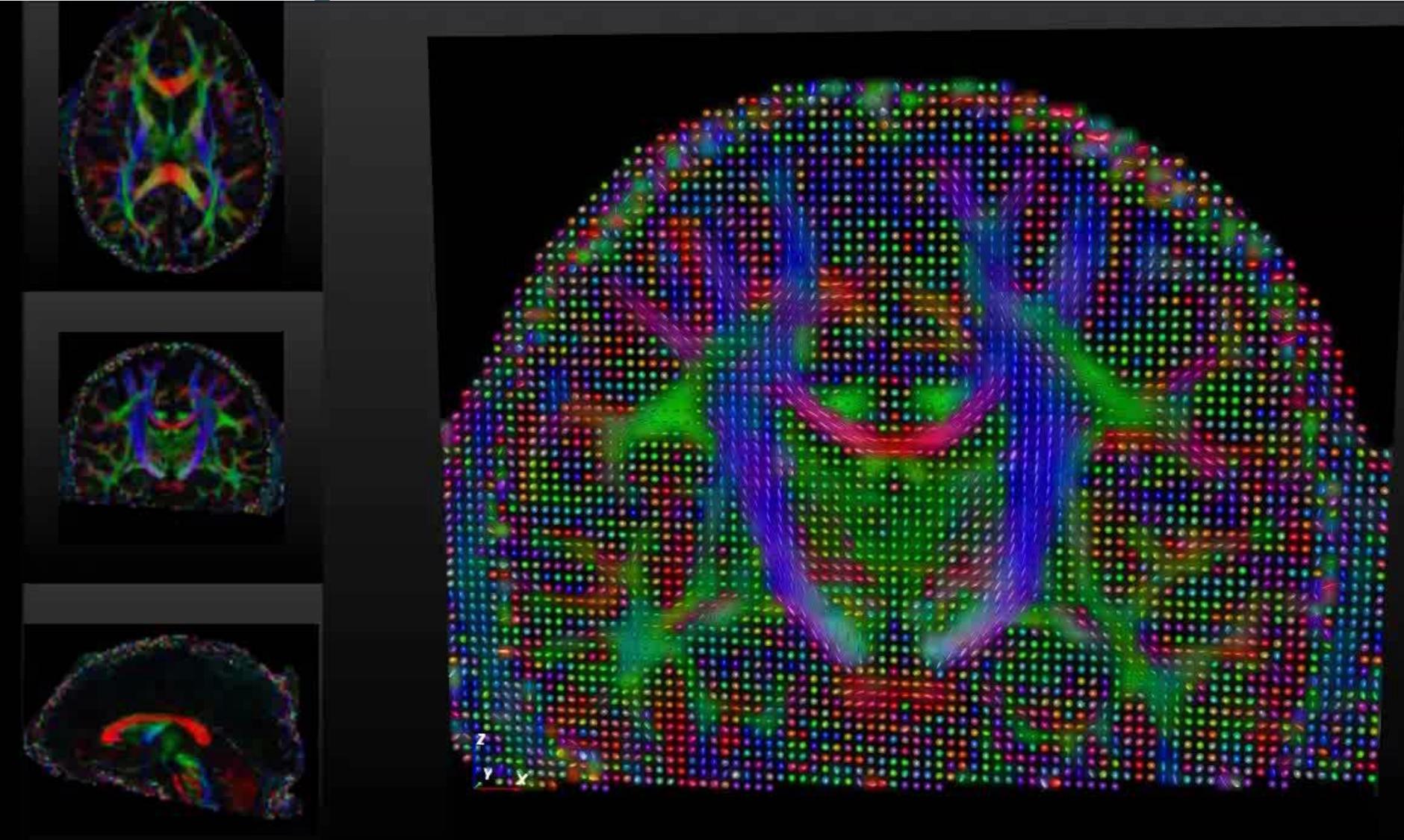
Optogenetics



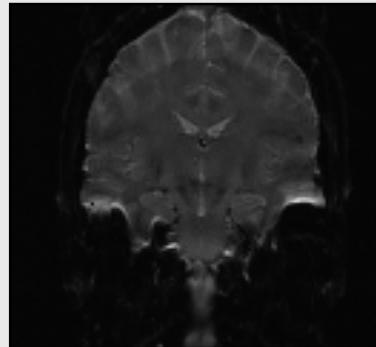
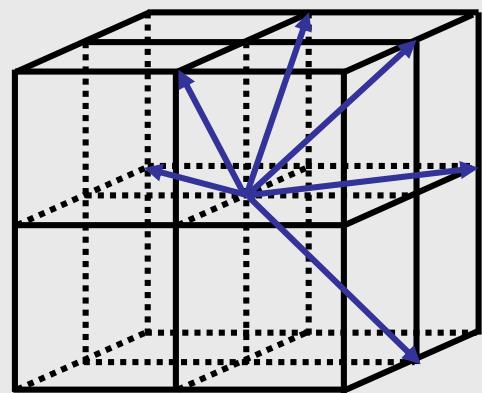
Diffusion tensor imaging



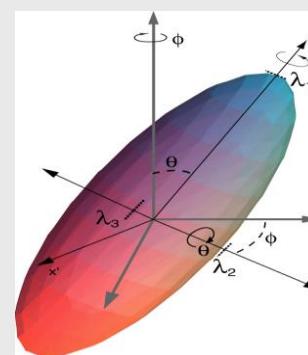
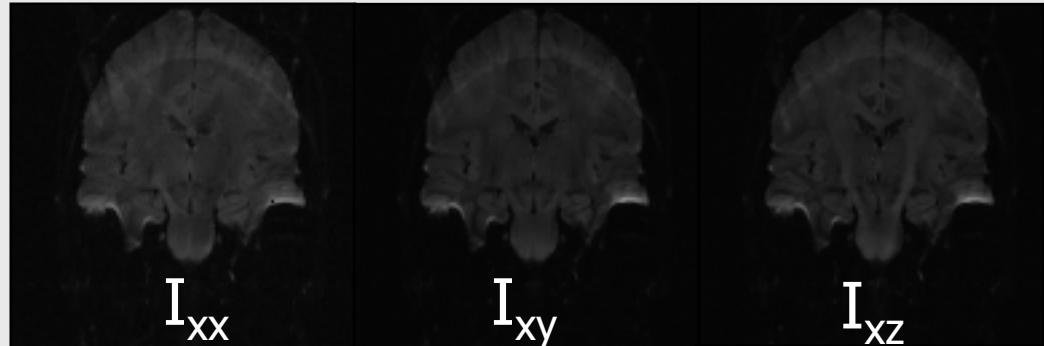
Voltage sensitive dyes



- Seven Images / Slice

 I_0 \vec{G} 

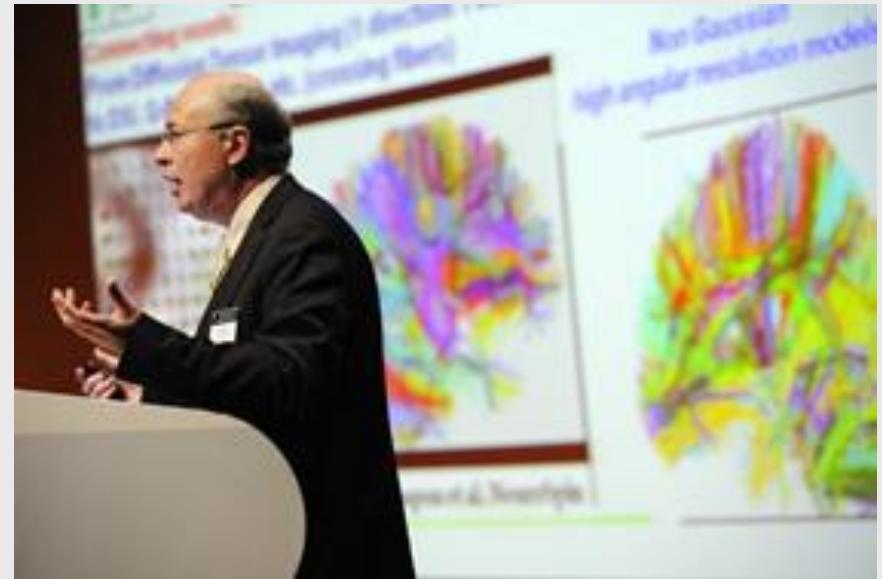
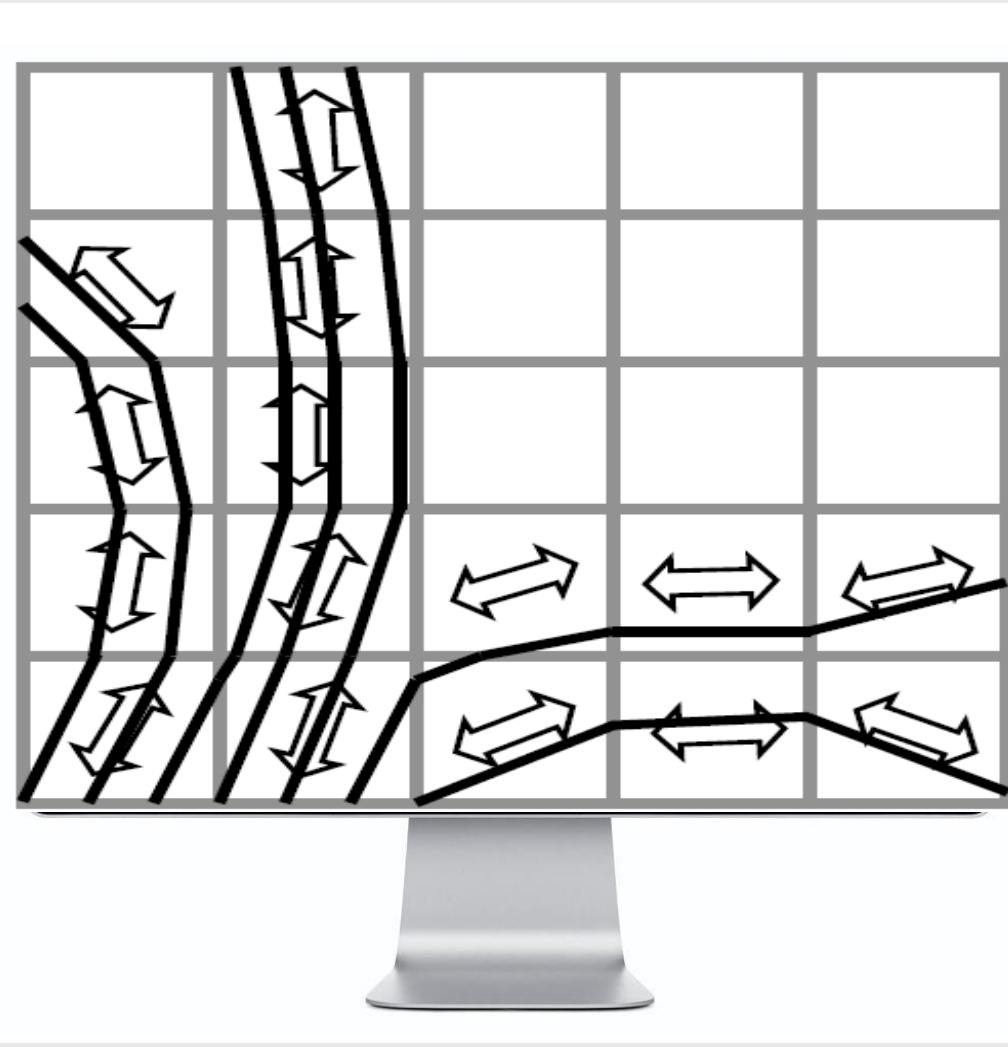
$$\vec{D} = \begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{pmatrix}$$



Basser, PJ. et al., J Magn Reson 1994;103:247–54

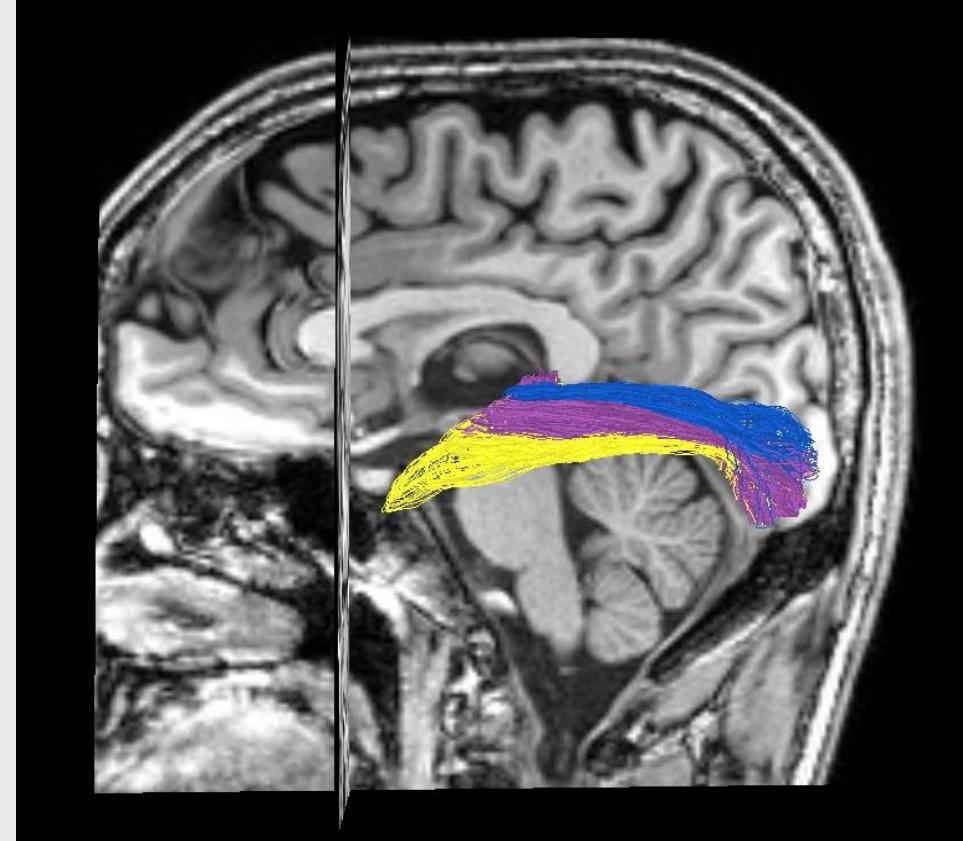
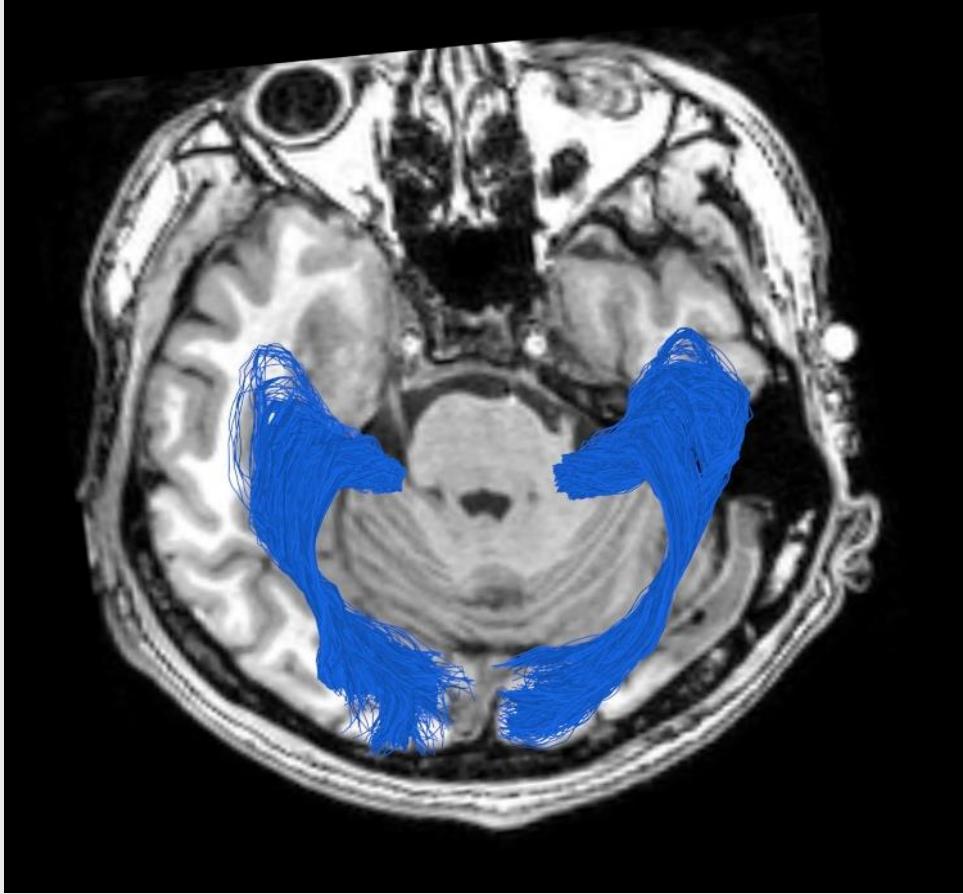
 I_{zz}

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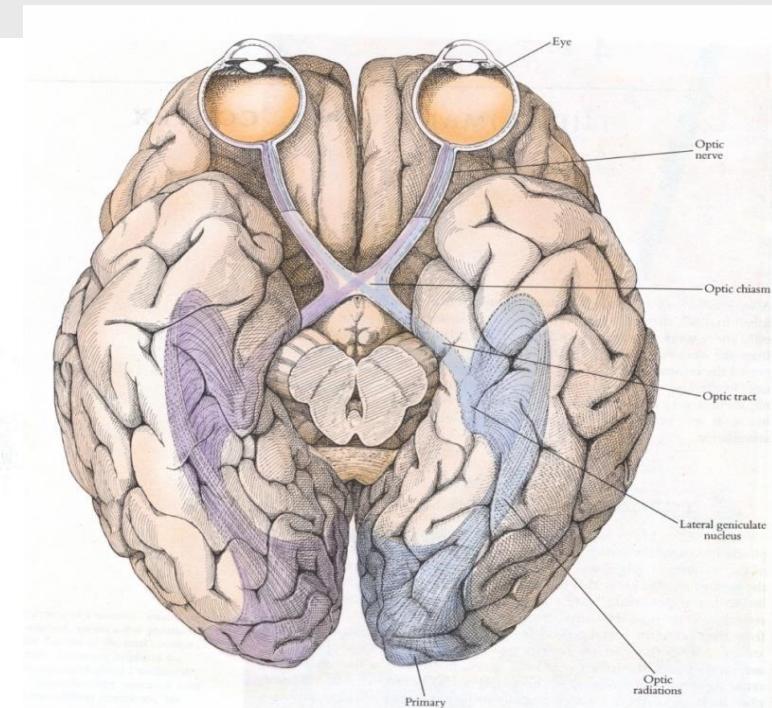
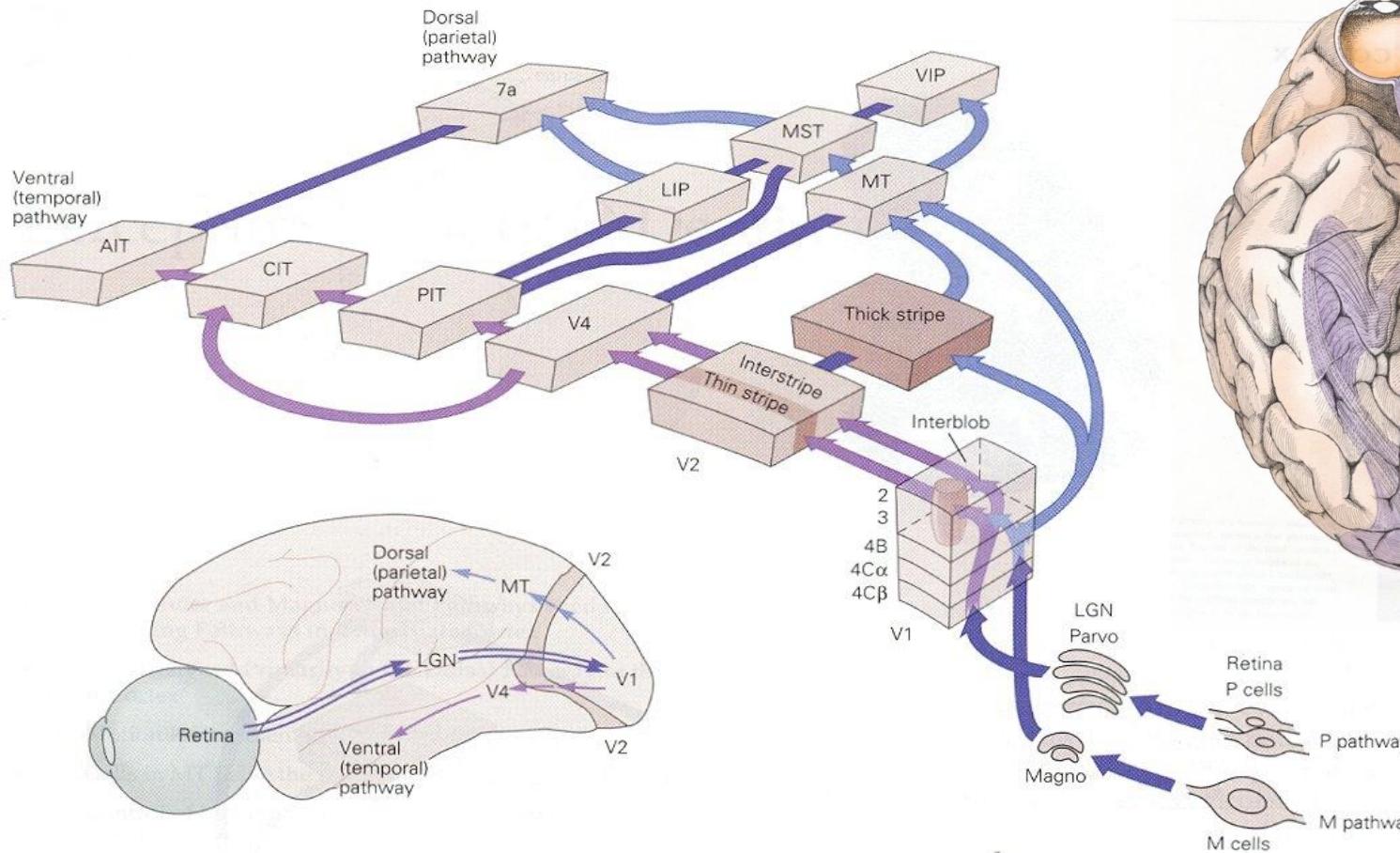
Prof. Denis Le Bihan
TU/e Holst Medal 2010





Central (yellow), upper (blue) and lower (purple)
retinal quadrant tracts of the optic radiation
(Jacobs, Vilanova et al. 2011).

Optical tract: retina – thalamus – cortex



The development language: Mathematica

Mathematica is a high level computer algebra environment
by Wolfram Inc.

- Ideal for algorithm *prototyping*
- Full *symbolic* functionality, complete
- Fast *numerical* functionality
- *Everything* is interactive ('Manipulate')
- A steep learning curve, training < 1 week
- Interpreter, typically very short code
- Integration of code and text in 'notebook' (*.nb)
- Write mathematics as usual (symbols, operators, Greek)
- Functional programming & pattern matching
- Platform independent
- Version 7, 8 faster than Matlab

MathVisionTools

List of currently available functions:

- Differential Geometry
 - Gaussian derivatives
 - for any order
 - for N dimensions
- Import / Export
 - any dialect DICOM
 - high field MRI
 - 3D ultrasound
 - 2-photon microscopy
- Orientation analysis
 - Polar Fourier Transform
 - 2D Hankel Transform

- MIP (perspective and orthogonal)
- Image registration in 2D and 3D
- Mutual entropy & correlation measure
- Stellate tumour detection in mammography
- Catheter detection
- Tensor voting for perceptual grouping
- Dynamic shape Eigen-mode analysis
- Watershed segmentation
- Automatic updating system
- PDE based edge preserving smoothing
- Motion from dense optic flow fields

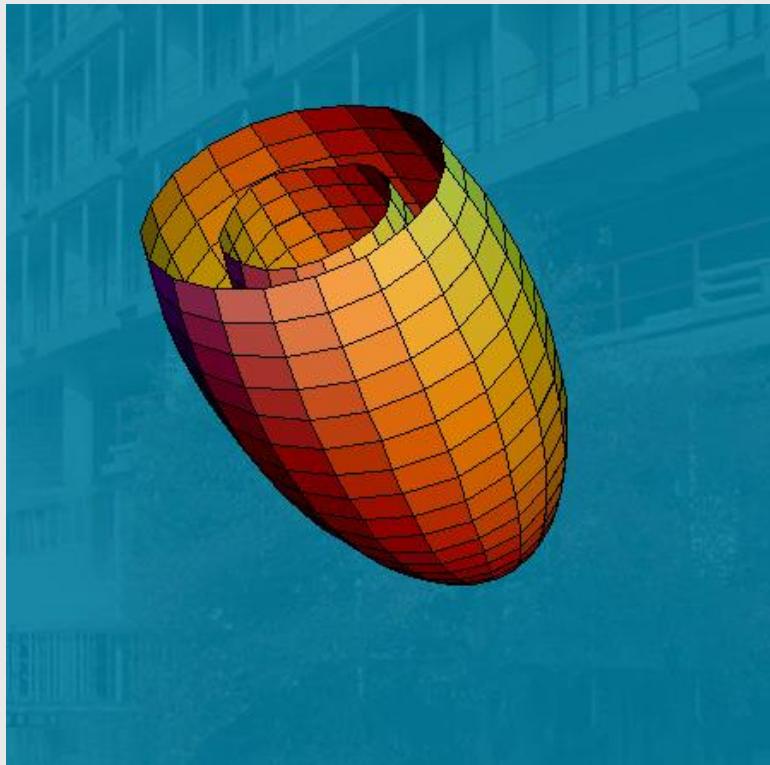
Scheduled:

- Nonlinear image registration
- Active contours atlas mapping
- Snakes and levelsets
- Image retrieval (multi-scale)
- Multi-scale texture classification

The numerical *and* symbolic power of *Mathematica* is used

“Here is a paper: read it, implement it, and understand it”

T. Arts, W. Hunter, A. Douglas, A. Muijtjens, and R. Reneman, "Description of the deformation of the left ventricle by a kinematic model", J. Biomechanics, 25(10), 1992.



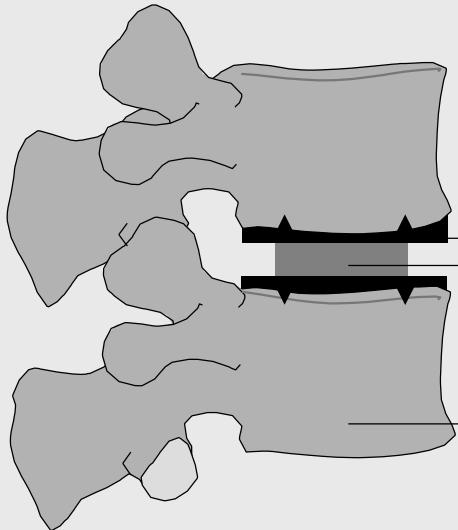
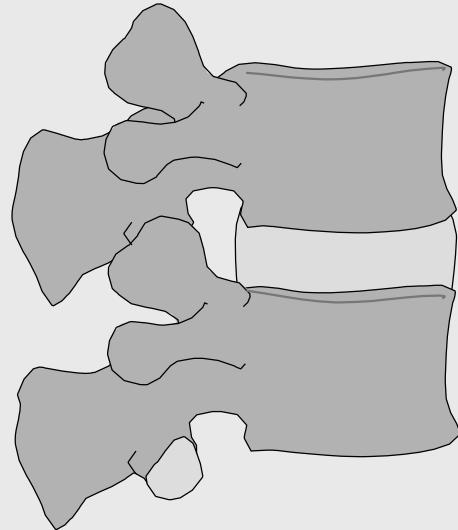
Ventricular heart motion:

- Prolate ellipsoid
- Rotation, scale, shear
- Matrix operations - transforms
- Done in 3 days

Notebook

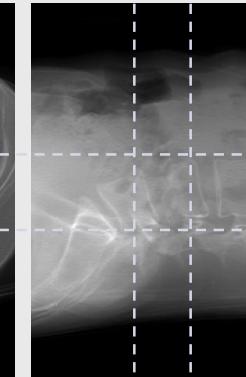
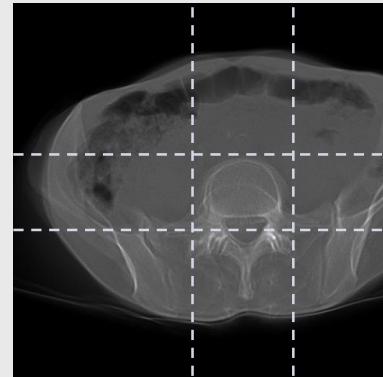
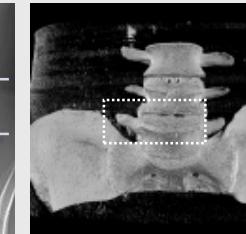
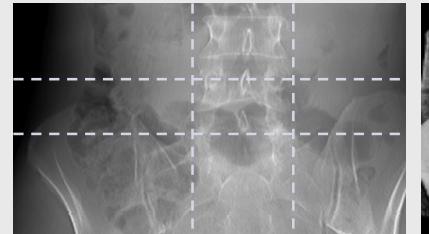
A. Suinesiaputra, TU/e - BME

3D printing of an intervertebral disk



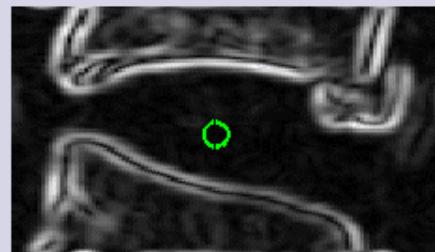
conformal endplate
flexible joint
vertebral body

prosthesis

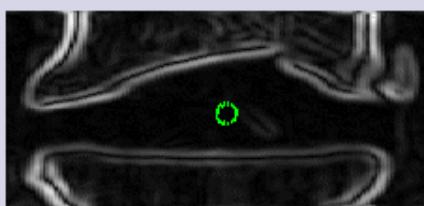


Active contours: balloon with internal (pressure) and external (edges) forces.

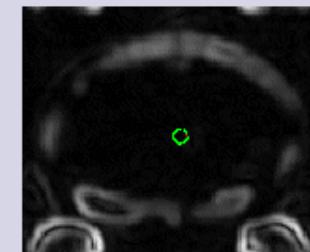
x-direction



y-direction



z-direction

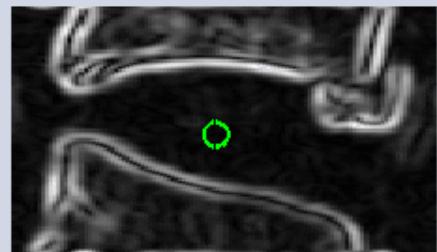


information

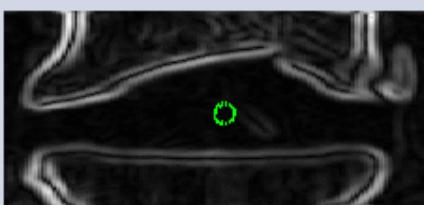
Iteration Number : 2
Elapsed Time : 16 s
Scale: 1.00 mm
Mean displacement: 64 μ m
Max. displacement : 104 μ m
Triangles : 180
Locked: 3 %

Active contours: balloon with internal (pressure) and external (edges) forces.

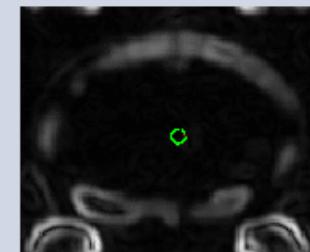
x-direction



y-direction



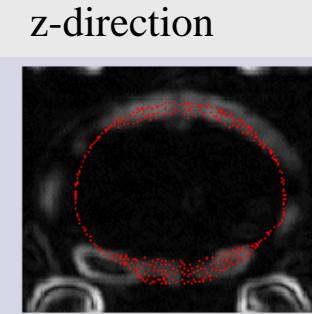
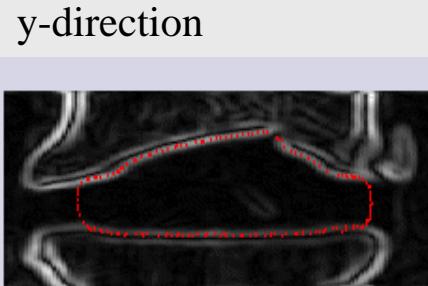
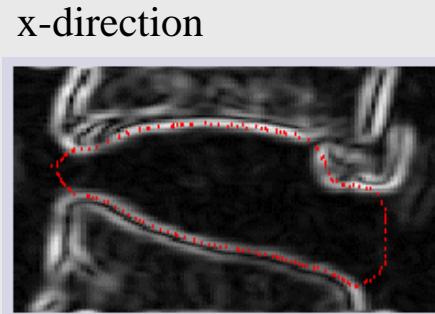
z-direction



information

Iteration Number : 2
Elapsed Time : 16 s
Scale: 1.00 mm
Mean displacement: 64 μ m
Max. displacement : 104 μ m
Triangles : 180
Locked: 3 %

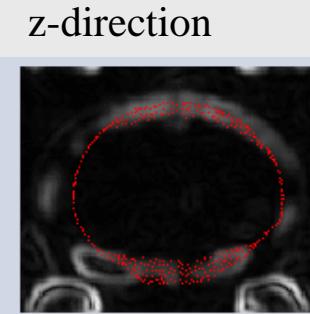
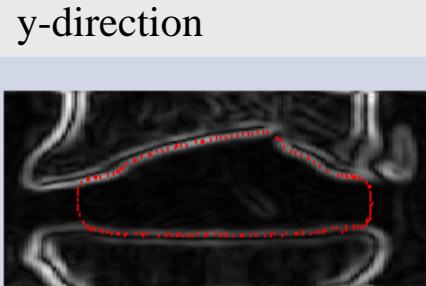
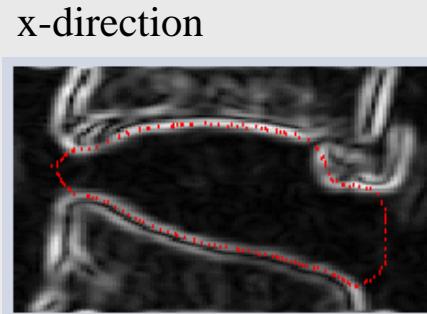
Edge focusing: blur less → finer details



information

Iteration Number : 370
Elapsed Time : 3354 s
Scale: 1.00 mm
Mean displacement: 6 μ m
Max. displacement : 125 μ m
Triangles: 6652
Locked: 100 %

Edge focusing: blur less → finer details



information

Iteration Number : 370
Elapsed Time : 3354 s
Scale: 1.00 mm
Mean displacement: 6 μ m
Max. displacement : 125 μ m
Triangles: 6652
Locked: 100 %

Biomedical Image Analysis

Need for:



- segmentation – **mathematics** of the *task*
- analysis of structure – **mathematics** of *features & invariance*
- analysis of shape – **mathematics** of *robust differential operators*
- recognition – **mathematics** of (statistical) *models*
- Computer aided diagnosis – **mathematics** of *geometric reasoning*
- perceptual grouping - **mathematics** of *non-local descriptors*
- image hierarchy – **mathematics** of *relations between objects*

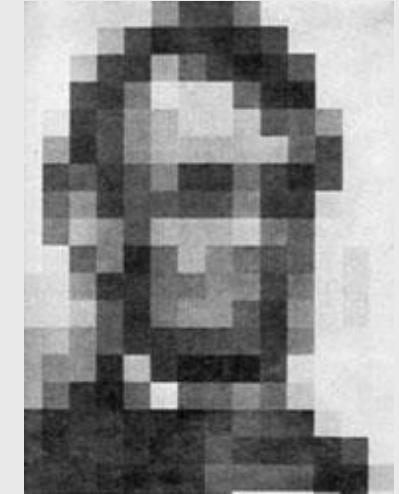
Can a generic theory be designed?

Can we learn from human visual perception mechanisms?

What role plays *scale*?

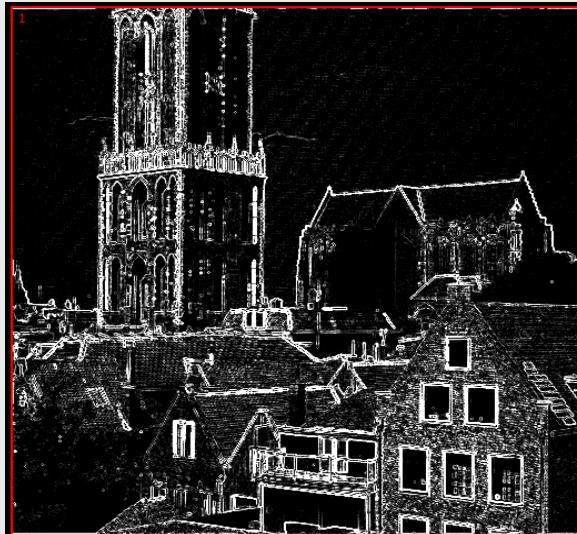
Why multi-scale? Why should you blur?

- Computational efficiency
- Coarse-to-fine
- Extracting hierarchical structure
- First principles of physics of observations
- Visual system is multi-scale





original



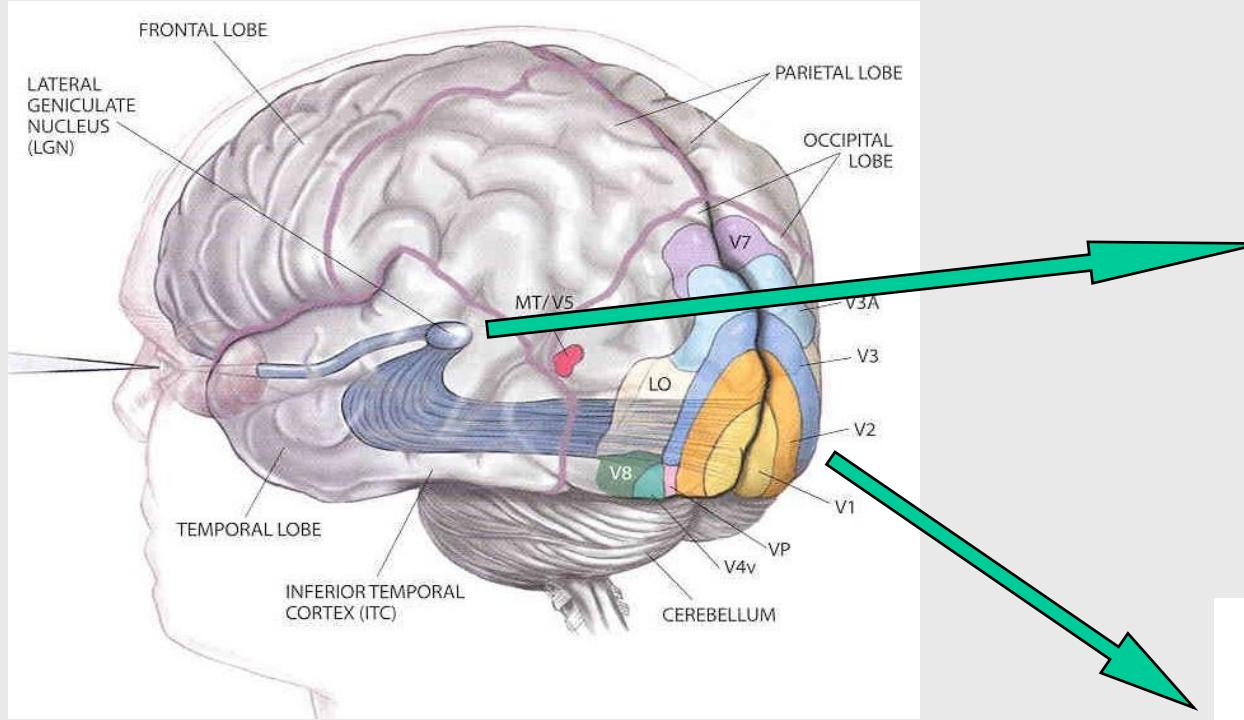
Gradient (scale 1 pixel)



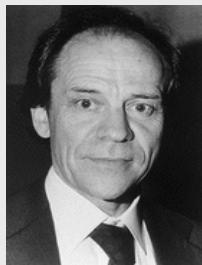
Gradient (scale 4 pixels)

Scale induces an image hierarchy.

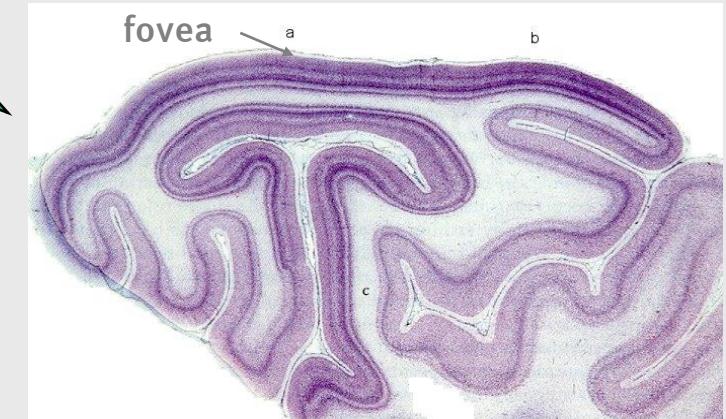
The first stages of our visual system



David
Huelv

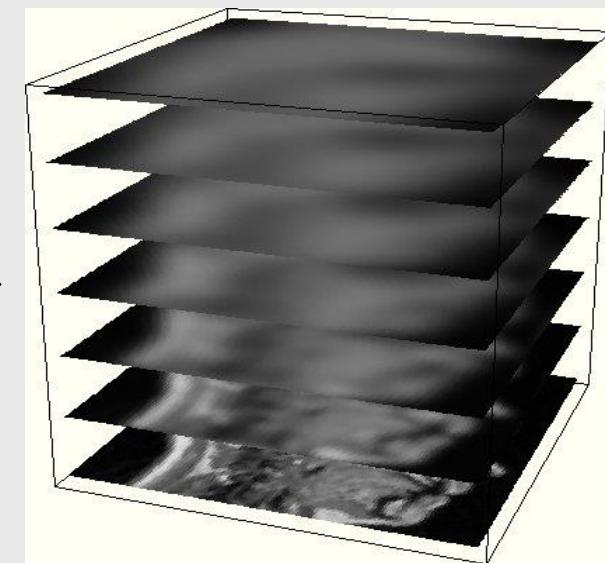
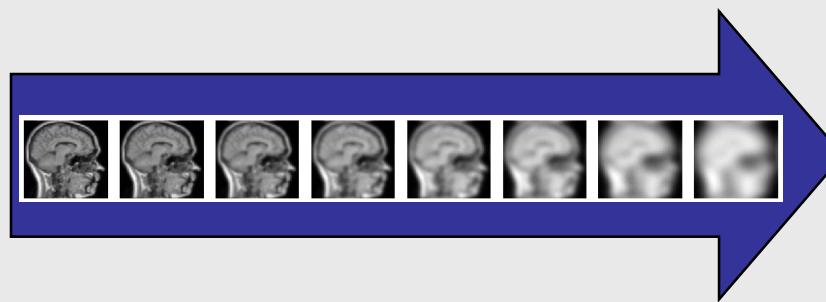
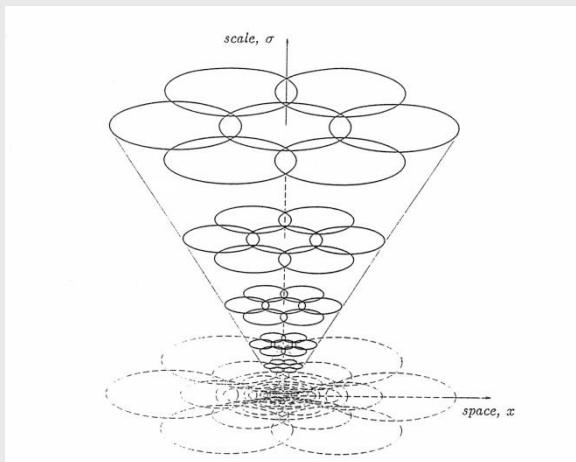


Torsten
Wiesel



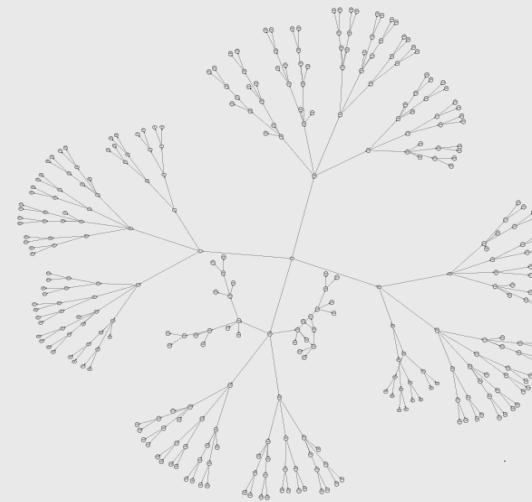
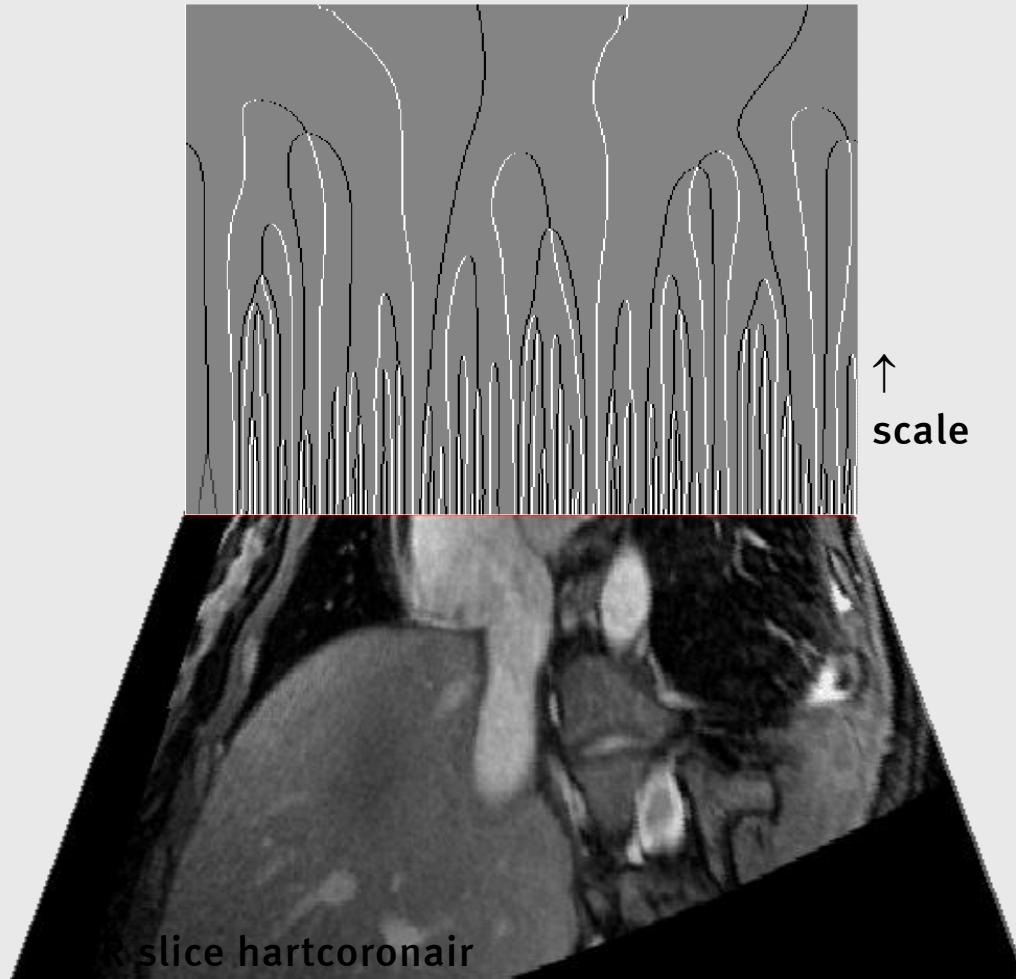
ter Haar Romeny, FEV

The retina measures on many resolutions simultaneously



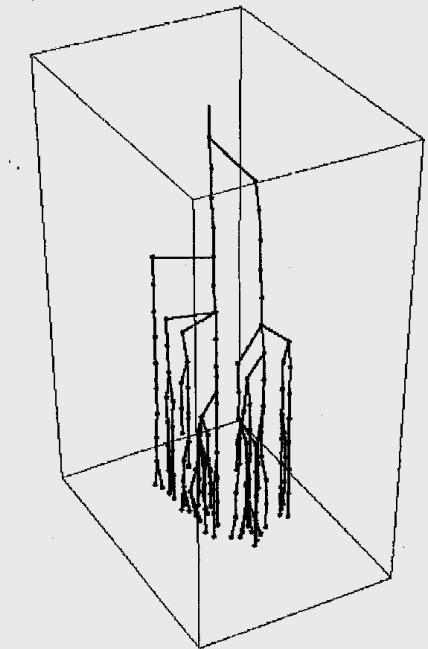
scale-space

- toppoints

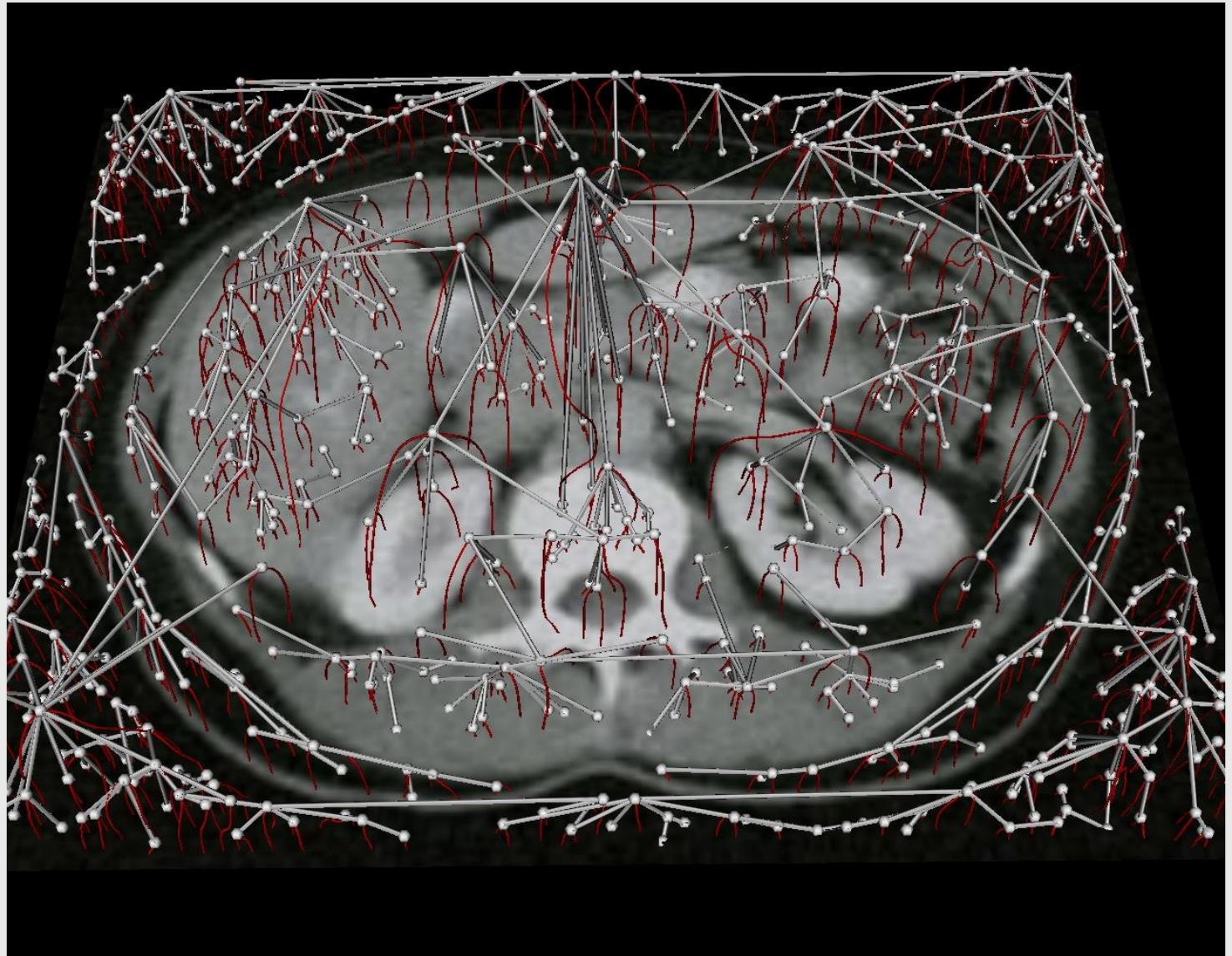


- graph theory

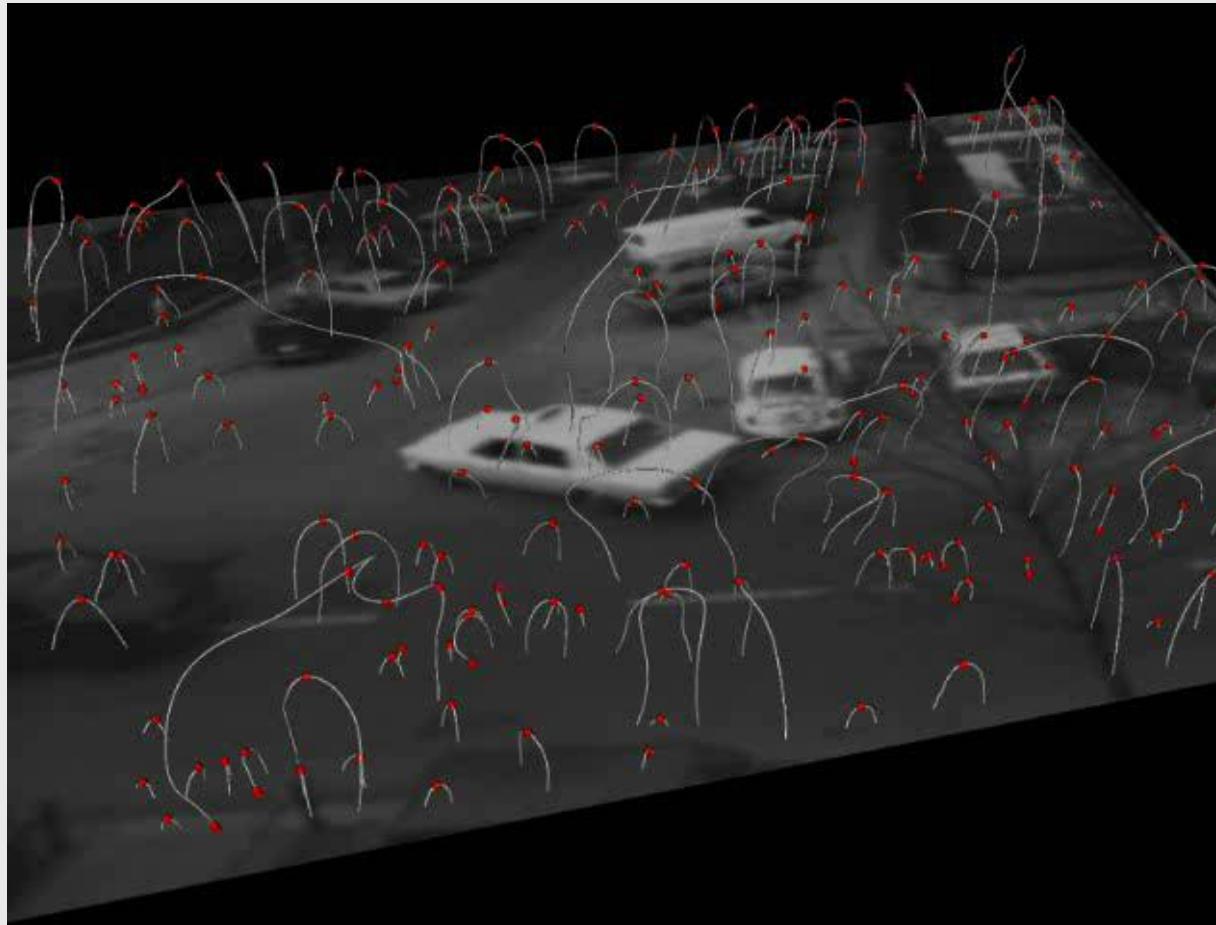
- EC project



A new
paradigm
in multi-scale
computer
vision



Multi-scale motion analysis with toppoints



ir. Pieter van Dorst, TU/e BMT BMIA

ter Haar Romeny, FEV

Image guided database retrieval



Frans Kanters, TUE BMT BMIA

Point cloud matching
(earth mover distance)

“Scale-Space Theory in Computer Vision”

Conference Series



Utrecht, 1997

Corfu, 1999

Vancouver, 2001

Isle of Skye, 2003

Hofgeismar, 2005

Ischia, Italy, 2007

Voss, Norway, 2009

Ein Gedi, Israel, 2011

Graz, Austria, 2013

Bordeaux, France, 2015

The pioneers



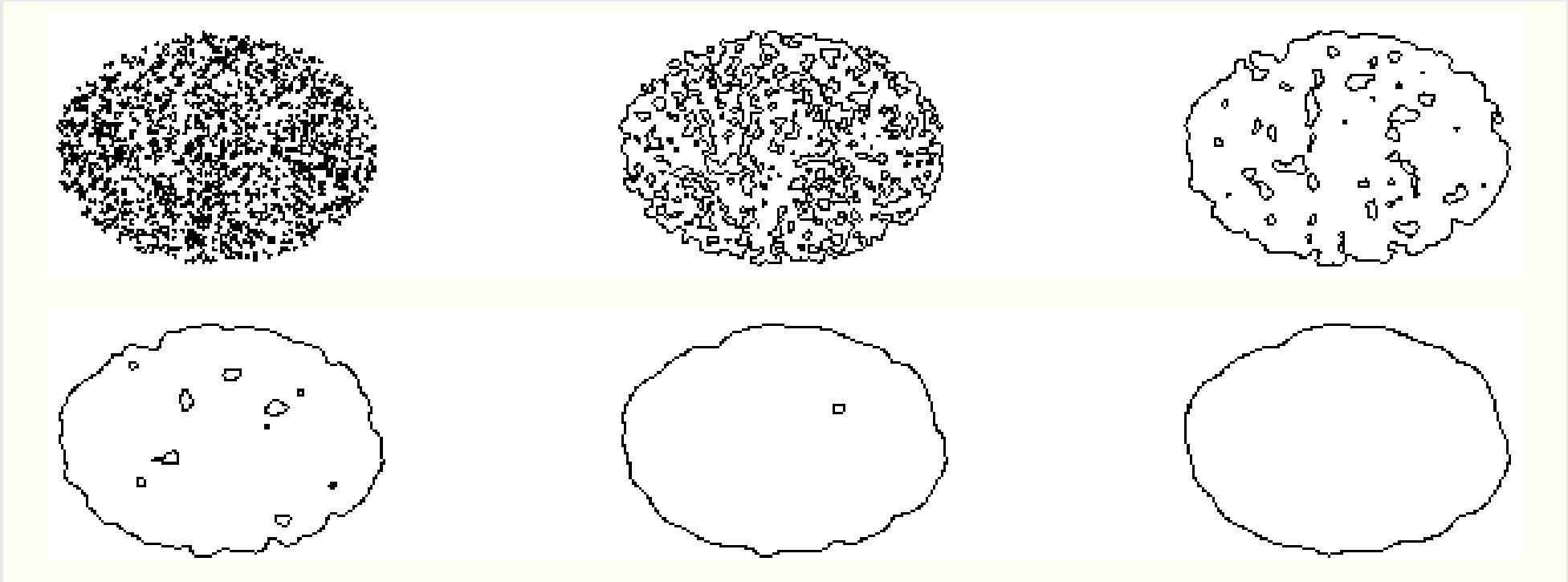
Prof. Jan Koenderink, prof. of
Utrecht University, the Netherlands



Prof. Taizo Iijima, emeritus prof. of
Tokyo Technical University, Japan

How can we fundamentally understand the notion of scale?

- Axiomatics, first principles
- Apertures
- Multi-scale differentiation
- Regularization



What is the size of a cloud?

Mathematics, Physics, Vision

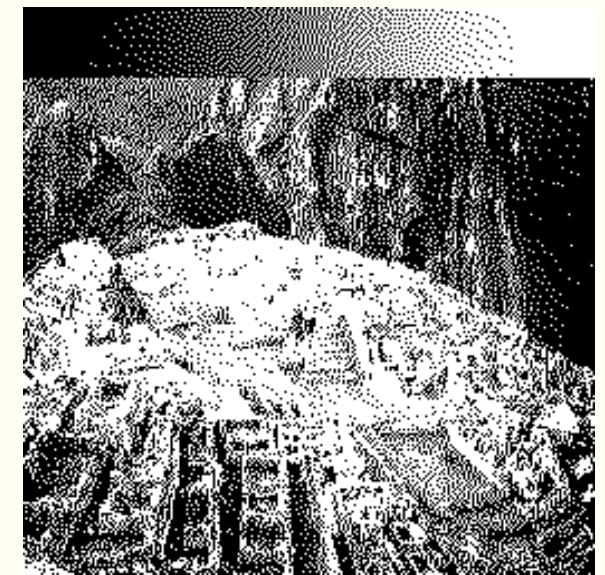
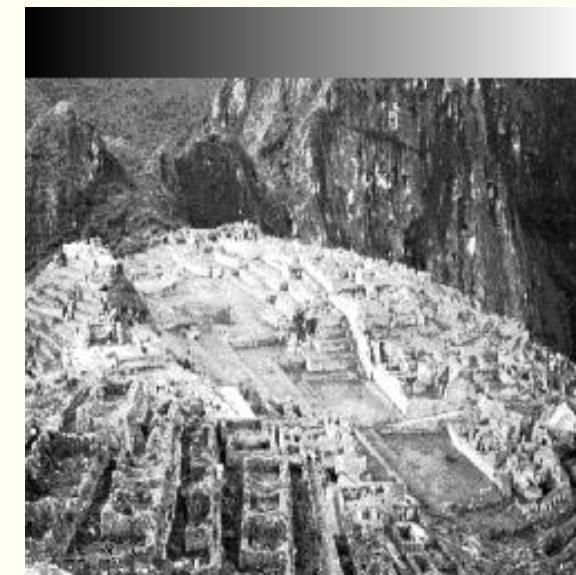
Powers
of 10

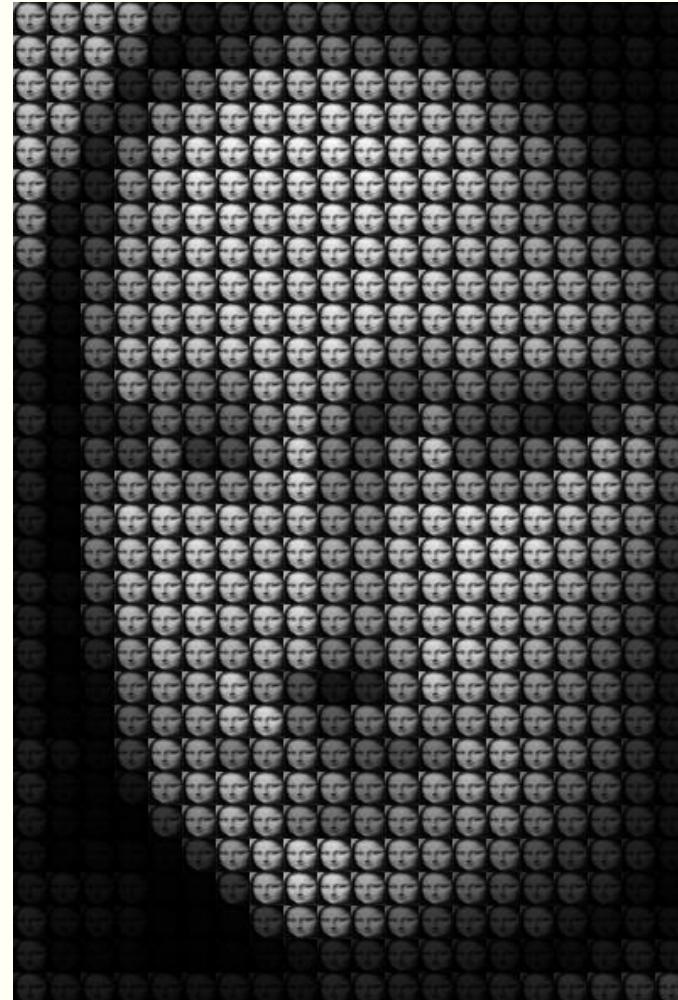
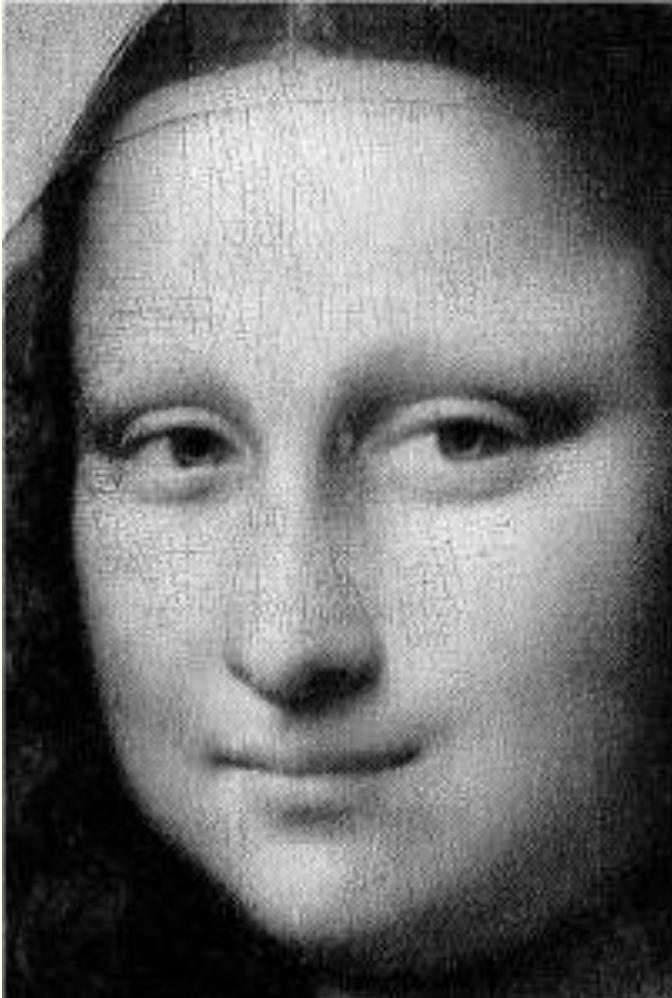
- In mathematics no scale:
 - point, line sizes shrink to zero
 - differential operator: limit of neighbours to zero
- In physics we have dimensional units:
 - everything is a multiple of units
 - instruments determines inner and outer scale
- In vision we have multiple scales receptive fields
 - in retina and cortex
 - for shape, motion, colour, depth

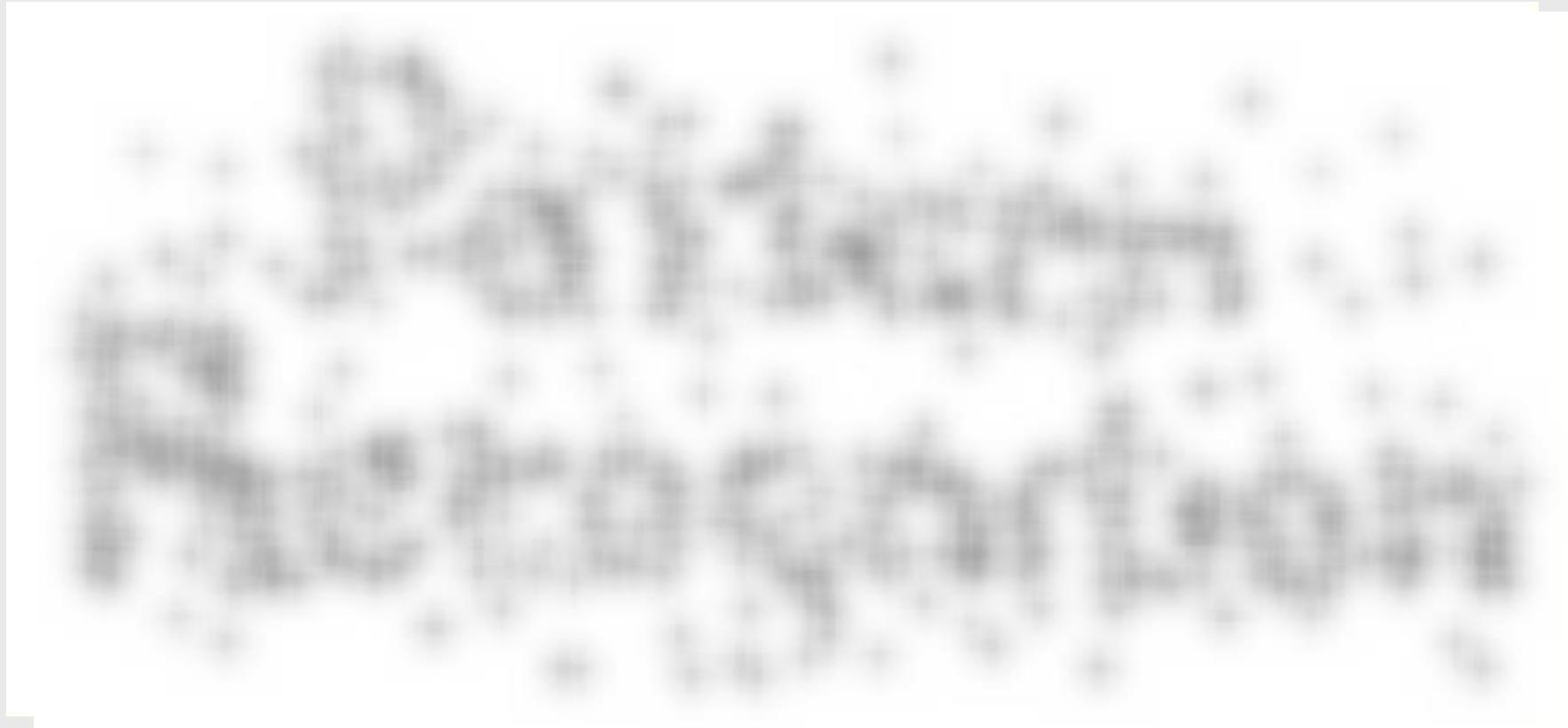


We blur by looking

dithering



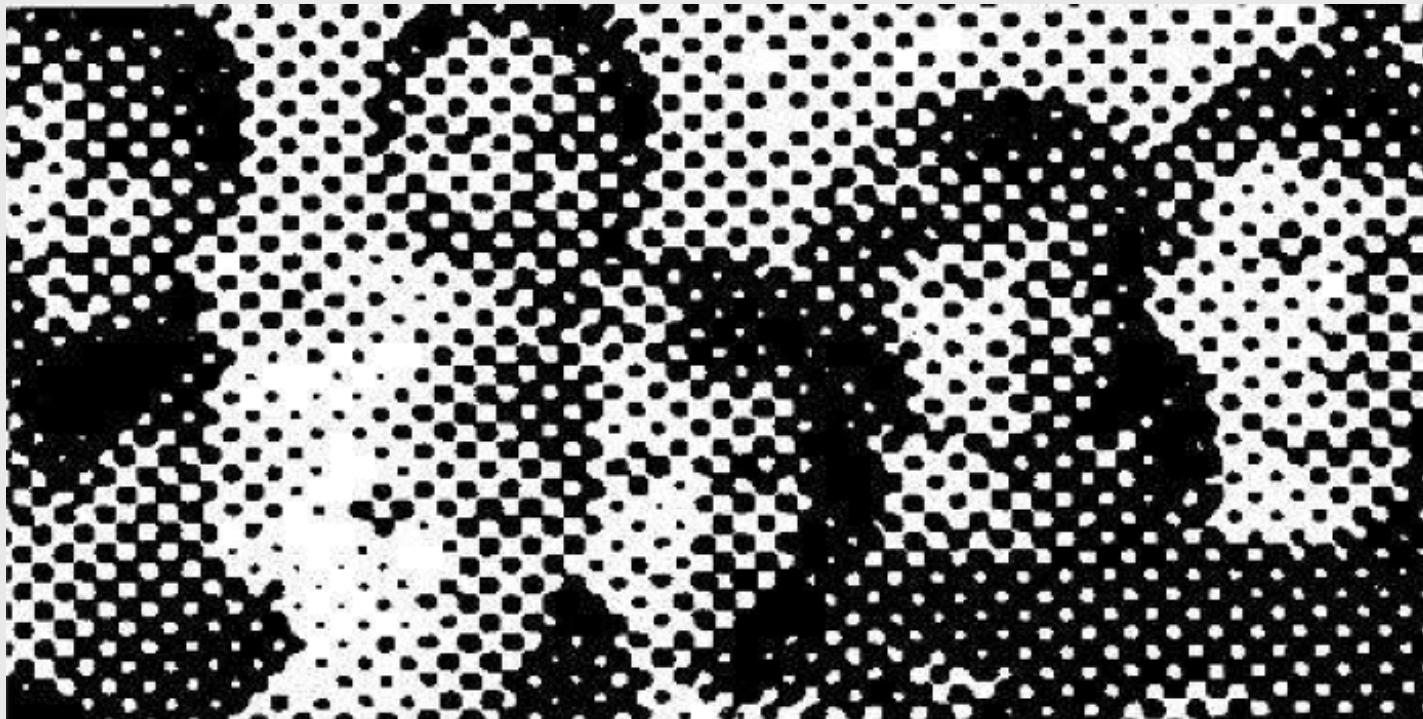




Scale is embedded in the *task*: do you want the leaves or the tree?

The observation scale:







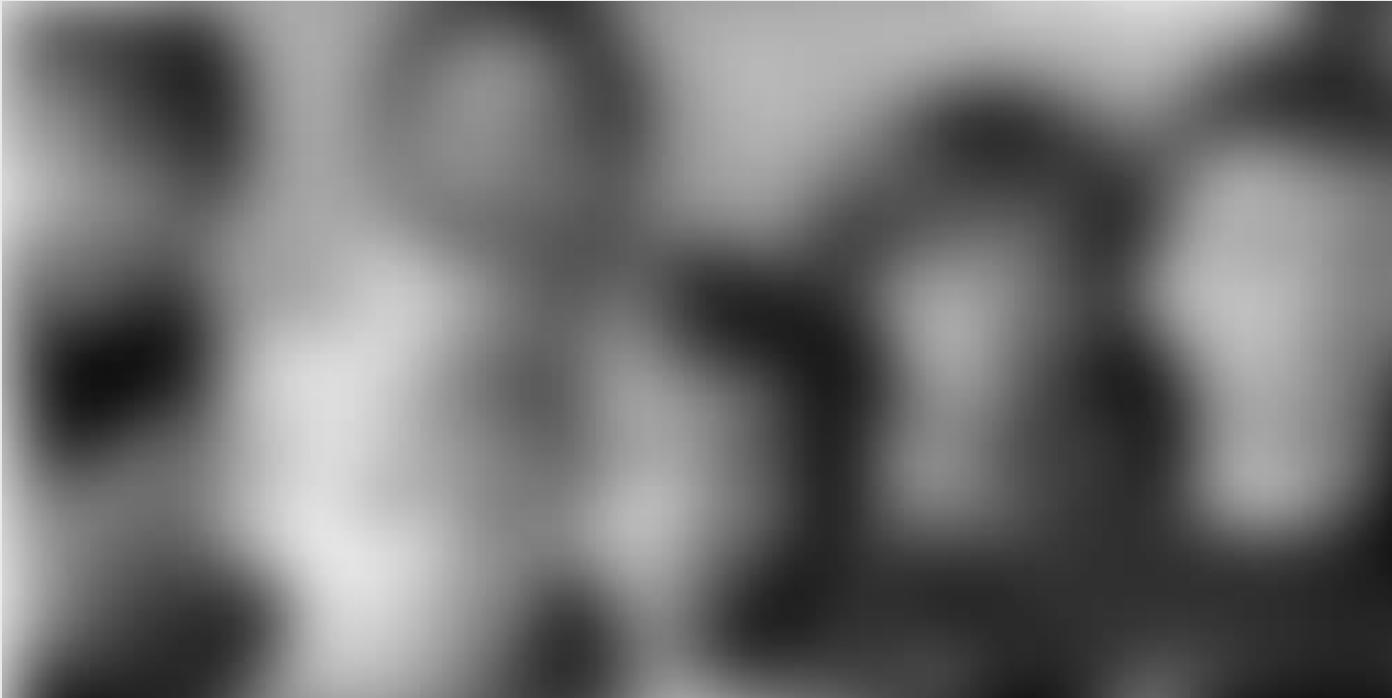


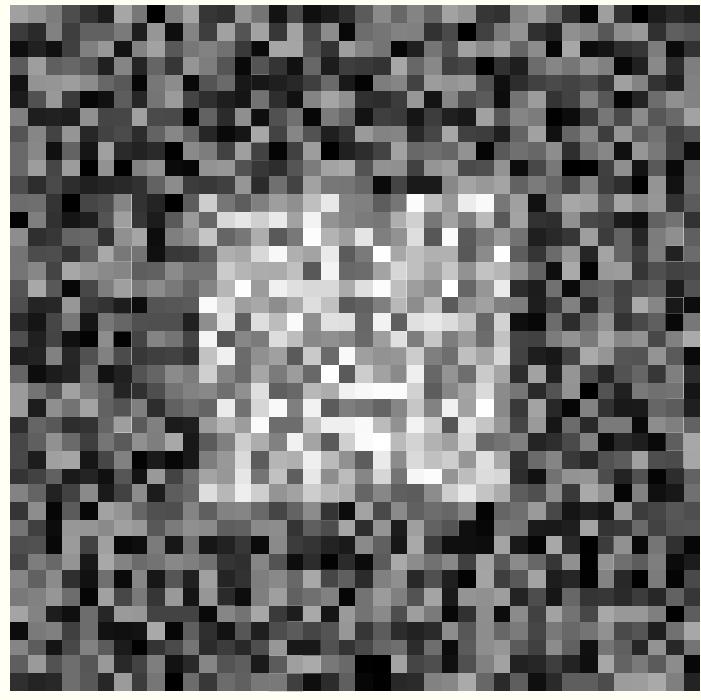












Be careful with the implicit assumption of a model.

- *Is this a square?*
- *This is a square*
- *This is not a square*

Noise is part of the geometry if no info is given of the underlying model or the noise

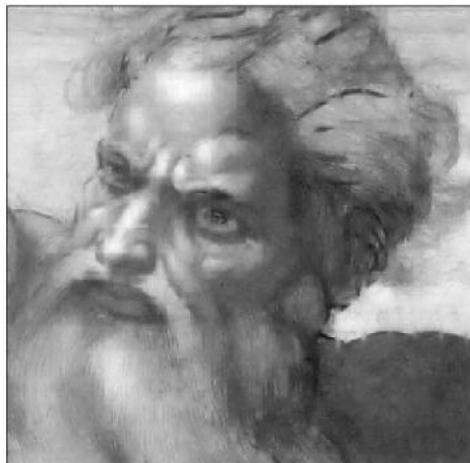
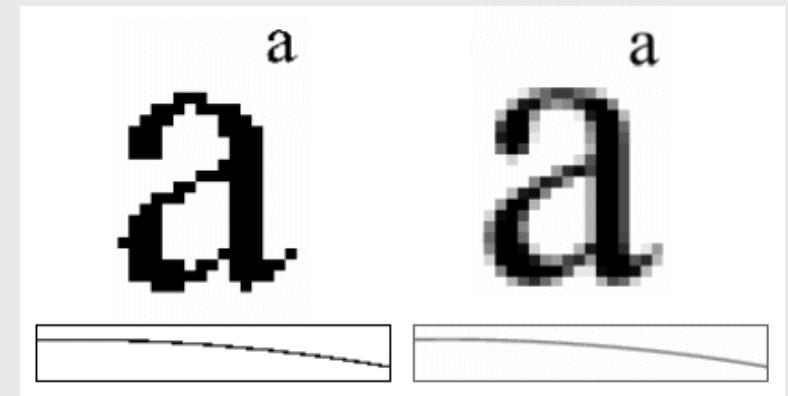
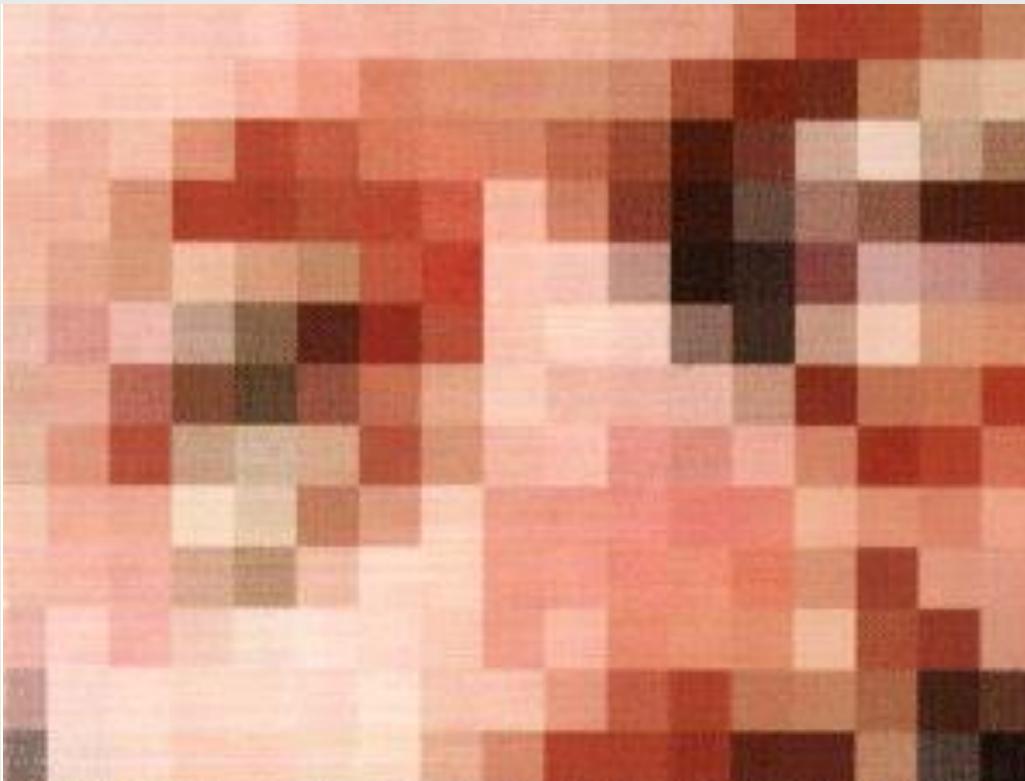


FIGURE 3. The initial corrupted images (left) and the images reconstructed via the hypoelliptic diffusion (2.13) and the SR procedure with parameters from Table 1 (right).

*U. Boscain et al.
Hypo-elliptic diffusion
SIAM J. Imaging Sci., 7(2), 669–695.*



Aliasing,
partial volume effect

‘Spurious resolution’: artefact of the wrong aperture

What is the best aperture?