Biologically Inspired Multi-Scale Image Analysis

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TU/e, Department of Biomedical Engineering

Medical imaging is big business:

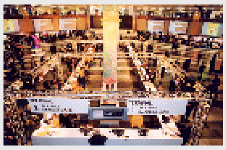
- 1/3 of hospital's equipment is for medical imaging
- 80% of all diagnoses are done on images
- 800 bed hospital: 10 Terabyte/year, stored 10 yrs
- Sector grows steadily by 10% per year
- GE, Philips, Siemens: billions of dollars markets
- Philips Medical Systems: 22% of company turnover

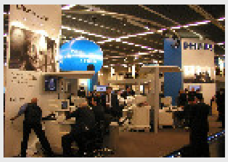
Trend: Higher resolution (space & time), more slices

Philips Medical Systems

Vital Images

Radiological Society of North America: 65.000 participants
European Congress of Radiology: 13.000 participants

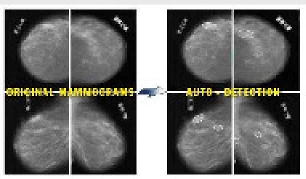




"Imagine" exhibit

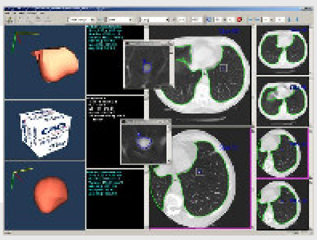
Computer-aided diagnosis

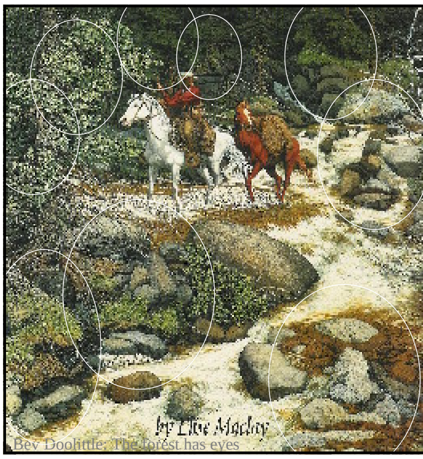
Mammography:



CADx

X-Thorax:





Bev Doolittle: The forest has eyes

Computer-Aided Diagnosis

The challenge

How do we do it?

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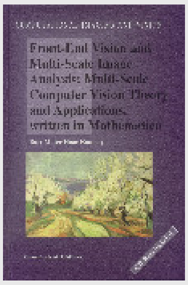
Multi-Scale Image Analysis



Biologically inspired computer vision
→ **bio-mimicking**

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"Scale-Space Theory in Computer Vision" Conference Series

Utrecht, 1997

Corfu, 1999

Vancouver, 2001

Isle of Skye, 2003

Hofgeismar, 6-10 April 2005
www.scalespace.org

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Focus:

- Model: simple cells in V1:
  Regularized spatio-temporal differential operators
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  Geometry-driven diffusion, edge preserving smoothing
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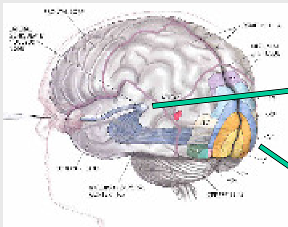
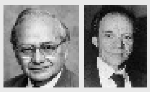
The first stages of our visual system





David Huvel
Torsten Wiesel

Visual cortex : Accurate map

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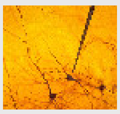
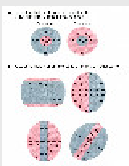
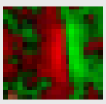
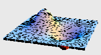
Bio-mimicking visual perception



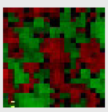


In the visual cortex the first analysis takes place





Model: several orders Gaussian derivatives



Receptive fields measure spatio-temporal structure

differential geometry

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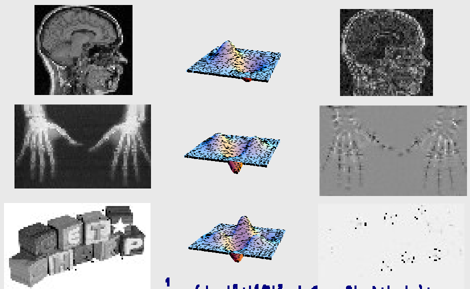
The visual system measures changes in place and time: derivatives



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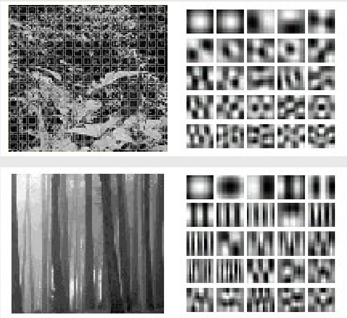
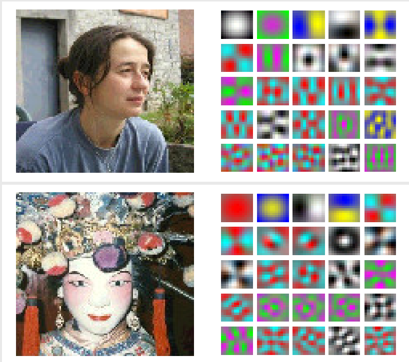


Singular Value Decomposition:

Eigen-patches



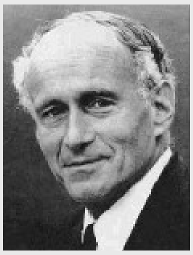
The formal mathematical method to solve the problems of ill-posed differentiation was given by Laurent Schwartz:

A regular tempered distribution associated with an image is defined by the action of a smooth test function on the image.

$$T_L = \int_{-\infty}^{\infty} L(x)\,\phi(x)\,d\,x$$

The derivative is:

$$\partial_{i_1\ldots i_n} T_L = (-1)^n \int_{-\infty}^{\infty} L(x)\ \partial_{i_1\ldots i_n}\phi(x)\ d\,x$$



Laurent Schwartz (1915 -)

Fields Medal 1950 for his work on the theory of distributions.
Schwartz has received a long list of prizes, medals and honours in addition to the Fields Medal. He received prizes from the Paris Academy of Sciences in 1955, 1964 and 1972. In 1972 he was elected a member of the Academy. He has been awarded honorary doctorates from many universities including Humboldt (1960), Brussels (1962), Lund (1981), Tel-Aviv (1981), Montreal (1985) and Athens (1993).

Mathematics	$\Leftrightarrow$	Smooth test function
Computer vision	$\Leftrightarrow$	Kernel, filter
Biological vision	$\Leftrightarrow$	Receptive field

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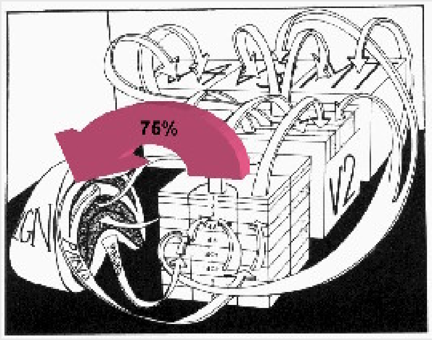
Very extensive feedback from primary visual cortex to LGN: RF tuning



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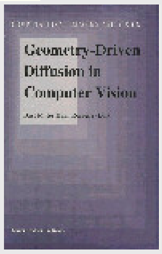
A *conductivity coefficient* (c) is introduced in the diffusion equation:

$$\frac{\partial L}{\partial s} = \vec{\nabla}.c\vec{\nabla}L \qquad c = c\left(L, \frac{\partial L}{\partial x}, \frac{\partial^2 L}{\partial x^2}, \ldots\right)$$

It is a *divergence* of a *flow*. We also call $c\,\vec{\nabla}\,L$ the *flux function*. With c = 1 we have normal linear, isotropic diffusion: the divergence of the gradient flow is the Laplacian.



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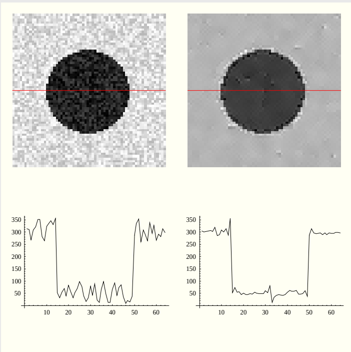
Test on a small test image:



Note the preserved steepness of the edges with the strongly reduced noise.

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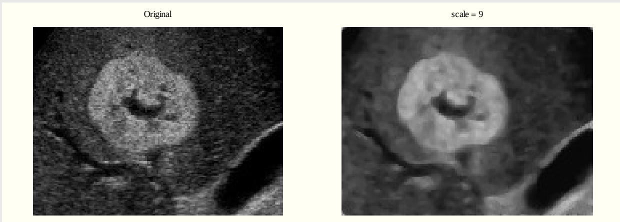
Geometry-driven diffusion:
nonlinear scale-space



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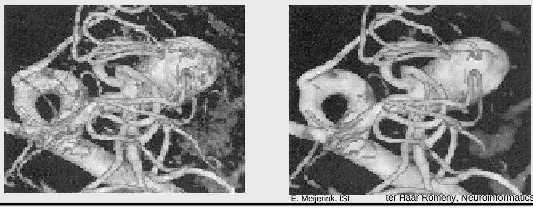
In 3D:

$$\frac{\partial L}{\partial t} = \vec{\nabla}.c^{-\frac{|\nabla L|^2}{k^2}}\vec{\nabla}L =$$
$$\frac{1}{k^2} e^{-\frac{L_x^2+L_y^2+L_z^2}{k^2}} \left((k^2 (L_{xx}+L_{yy}+L_{zz}) - 2(L_x^2 L_{xx} + L_y^2 L_{yy} + L_z^2 L_{zz}) \right.$$
$$\left. -4(L_x L_y L_{xy} - L_x L_z L_{xz} + L_y L_z L_{yz}) \right)$$



E. Meijering, ISI

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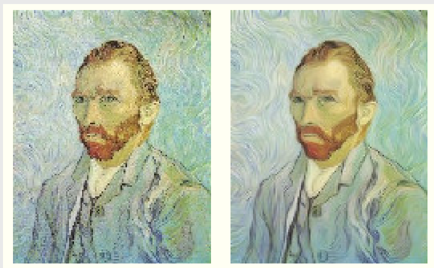
Coherence enhancing diffusion



J. Weickert, 2001

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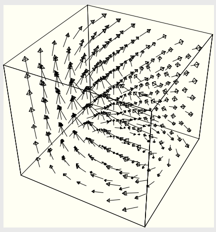
Multi-scale optic flow



How can we find a dense optic flow field from a motion sequence in 2D and 3D?

Many approaches are taken:

- gradient based (differential);
- phase-based (frequency domain);
- correlation-based (area);
- feature-point (sparse data) tracking.

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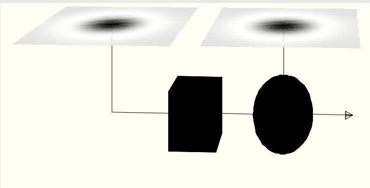

Neurons act as temporal coincidence detectors

This leads to a redundant representation, all velocities and directions are measured at all scales.

Reichardt detector

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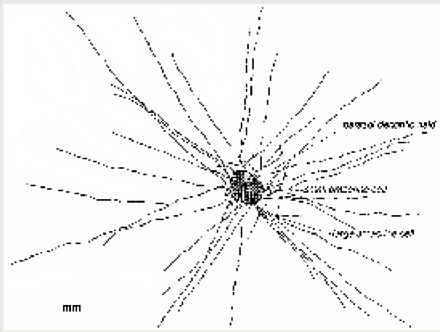
Amacrine cells are found next to ganglion cell bodies

Similar RF pairs are present in both eyes for disparity detection



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Multi-scale optic flow constraint equation:

For scalar images: $\mathcal{L}_{\vec{v}}\, F(g) = \vec{\nabla} F . \vec{v}$

For density images: $\mathcal{L}_{\vec{v}}\, \rho = \rho\, \mathrm{Div}\, \vec{v} + \vec{v} . \vec{\nabla} \rho = 0$

The velocity field is unknown, and this is what we want to recover from the data. We like to retrieve the velocity and its derivatives with respect to x, y, z and t.

We insert this unknown velocity field as a truncated Taylor series, truncated at first order.

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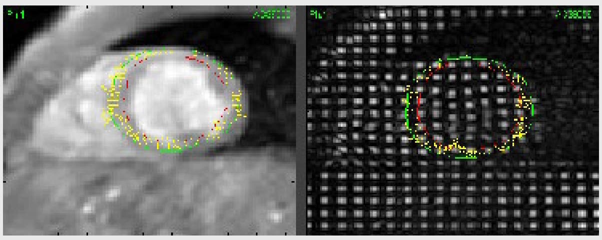
Exact quantitative analysis.

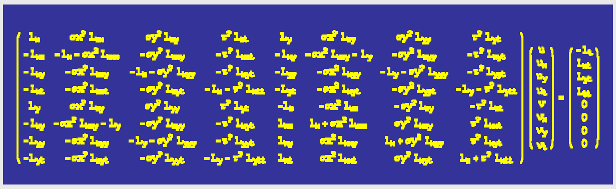
Optic flow: detailed motion analysis of the ventricular wall



A. Suinesiaputra, UMCL / TUE, MICCAI 2002

ter Haar Romeny, Neuroinformatics 2004

Multi-scale density flow: in each pixel 8 equations of third order and 8 unknowns:



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Collaboration
Prof. David Fitzpatrick

Neurobiology,
Duke University

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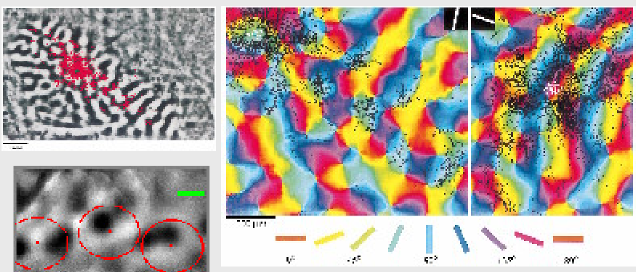
Math: New wavelet class of orientation adaptive context filters inspired by neurophysiology, voltage sensitive dyes



Fitzpatrick, Duke University, J Neuroscience, 1997, 17(6):2112–2127

ter Haar Romeny, Neuroinformatics 2004

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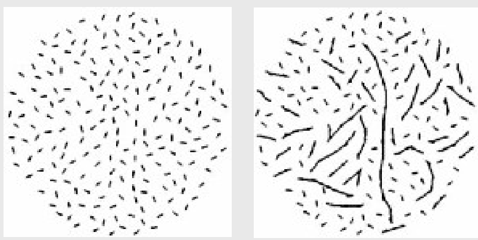
Perceptual grouping (Gestalt)
from orientations: robust detection



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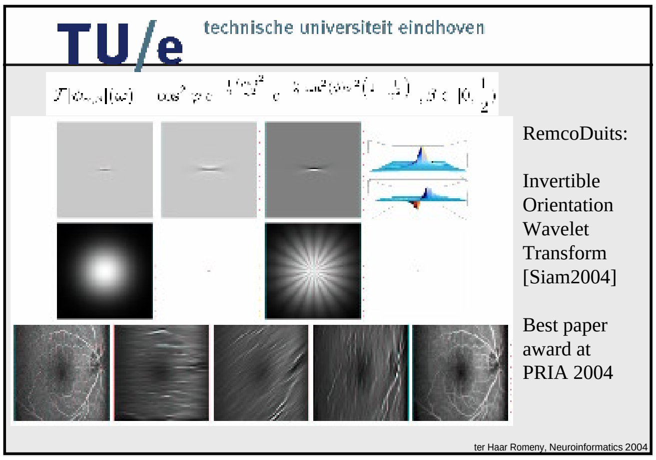
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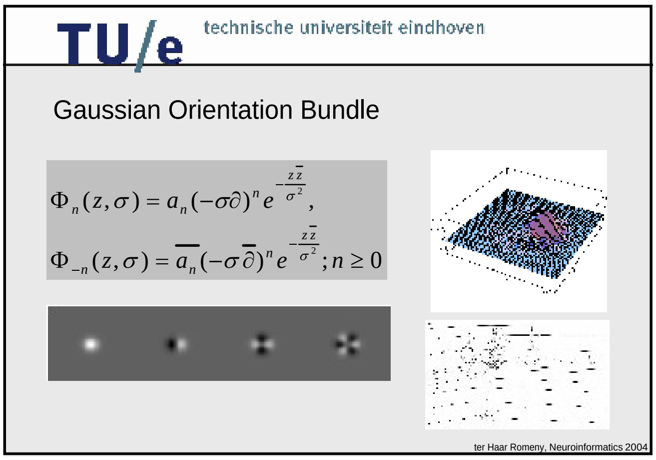
RemcoDuits:
Invertible Orientation Wavelet Transform [Siam2004]
Best paper award at PRIA 2004
ter Haar Romeny, Neuroinformatics 2004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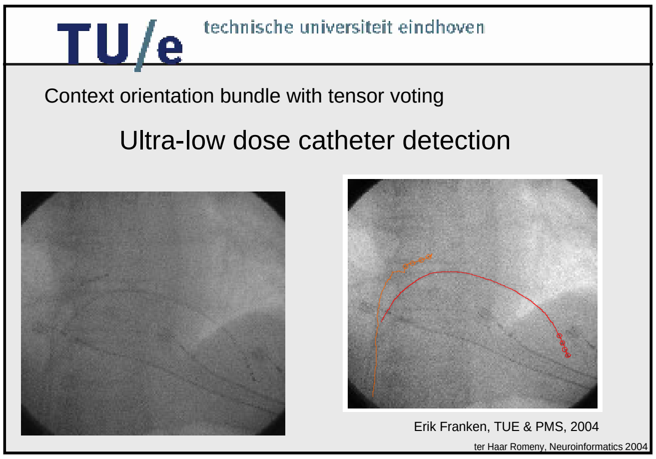
Gaussian Orientation Bundle
$\Phi_n(z,\sigma) = a_n(-\sigma\partial)^n e^{-\frac{z\bar{z}}{\sigma^2}},$
$\Phi_{-n}(z,\sigma) = \overline{a_n}(-\sigma\bar{\partial})^n e^{-\frac{z\bar{z}}{\sigma^2}}; n \geq 0$
ter Haar Romeny, Neuroinformatics 2004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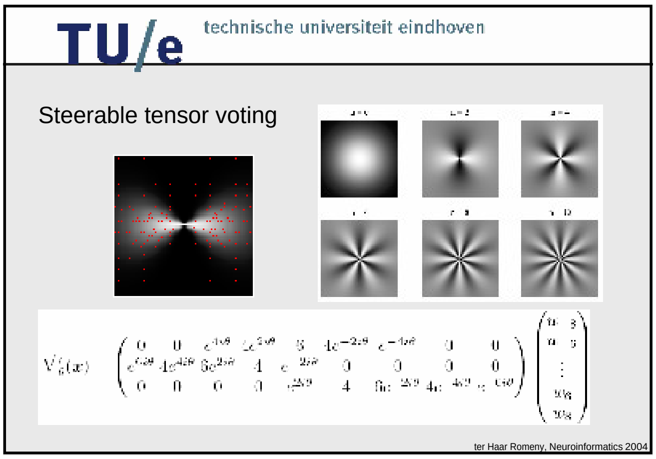
Context orientation bundle with tensor voting
Ultra-low dose catheter detection
Erik Franken, TUE & PMS, 2004
ter Haar Romeny, Neuroinformatics 2004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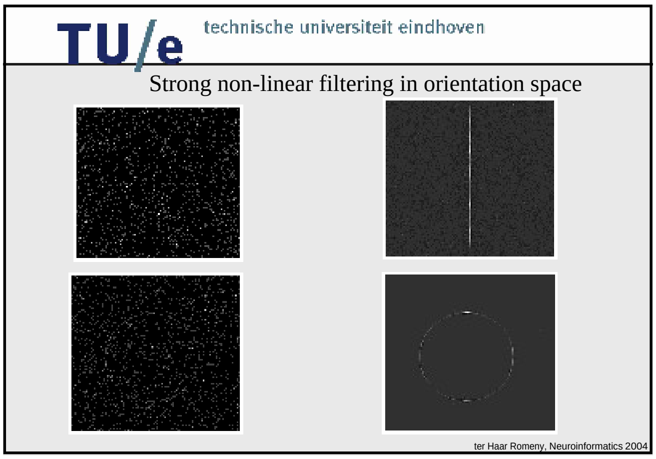
Steerable tensor voting
ter Haar Romeny, Neuroinformatics 2004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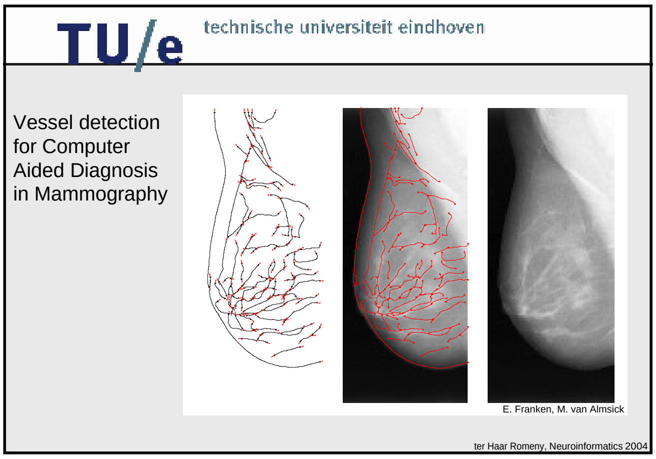
Strong non-linear filtering in orientation space
ter Haar Romeny, Neuroinformatics 2004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Vessel detection for Computer Aided Diagnosis in Mammography
E. Franken, M. van Almsick
ter Haar Romeny, Neuroinformatics 2004

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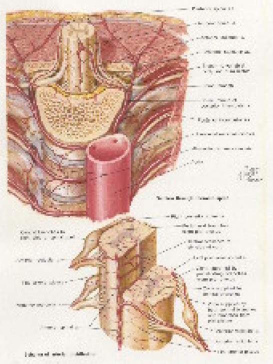
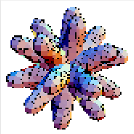
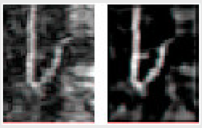
Examples of student projects with Mathematica:



Finding the Adamkiewicz vessel



New wavelet for invertible orientation transform



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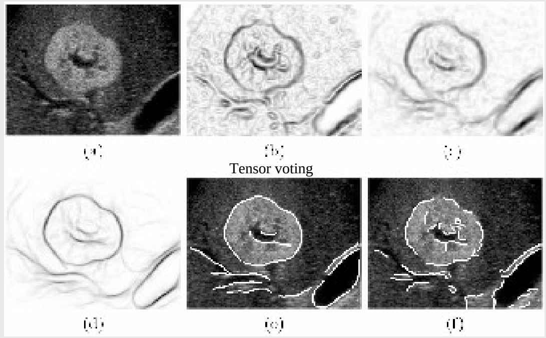

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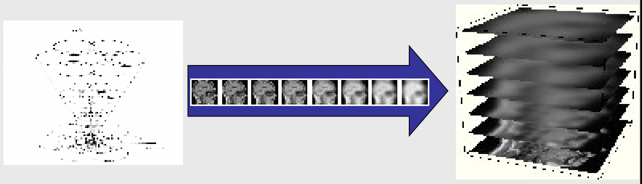
The retina measures on many resolutions simultaneously



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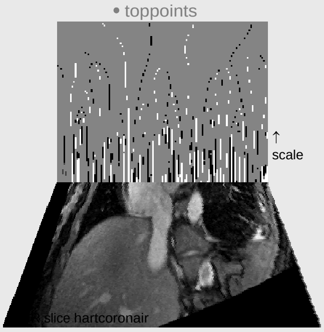

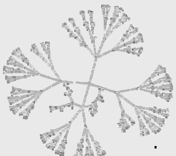

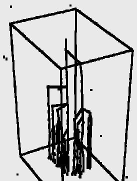

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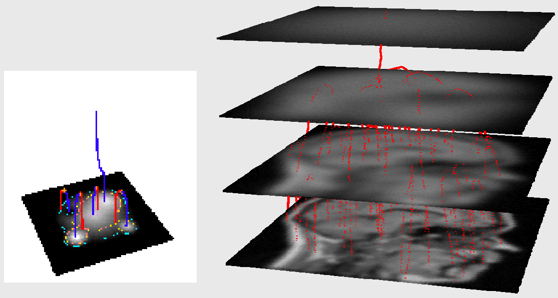
Critical Paths in Scale Space



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The nesting of the iso-intensity manifolds

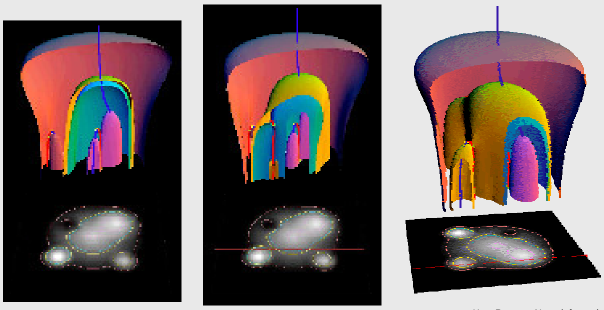

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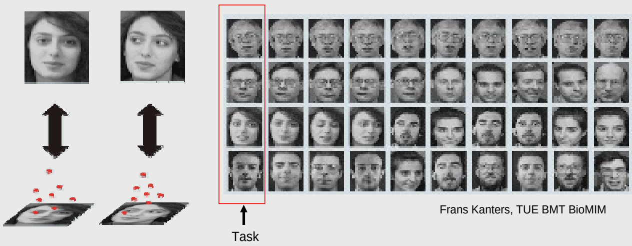
Image guided database retrieval



Point cloud matching
(earth mover distance)

Florack: VICI proposal 2004 (1.2 M€)

ter Haar Romeny, Neuroinformatics 2004

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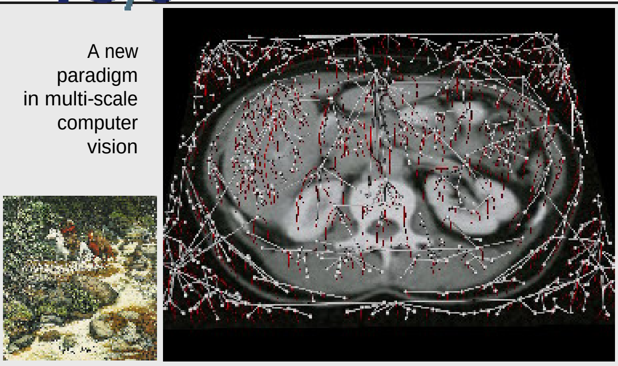
Graph
Theory

A new
paradigm
in multi-scale
computer
vision



ter Haar Romeny, Neuroinformatics 2004

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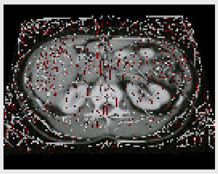
Outlook

- Scale-space: robust mathematical basis
- Regularized differential operators
- Deep structure hierarchical structure
  - graph extraction & reasoning
- Perceptual grouping – Gestalt
  - context operators
- Inspiration from the visual front-end
  - Cortical connections
  - Feedback connections
  - Need to go to higher levels



Mathematics ⇔ Biology

generic analysis algorithms

ter Haar Romeny, Neuroinformatics 2004