Karlsruhe Institute of Technology

Automated Analysis of X-ray Data

Alexey Ershov

INSTITUTE FOR PHOTON SCIENCE AND SYNCHROTRON RADIATION (IPS)

Outline

- Automated Analysis of X-ray Data
  - X-ray Imaging
  - Analysis of Dynamical X-ray Data
  - Application Examples
- Collaboration between TPU and KIT
  - Research Directions
  - Possibilities for Students
- Current Topics and Tasks
- Lecture: “Image Acquisition Methods and Image Analysis”

Automated Analysis of X-ray Data

X-Ray Imaging

X-rays are electromagnetic radiation:

- Wavelength in the range 0.01 to 10 nm
- Energies: 100 eV to 100 keV

Interaction of X-rays with the matter:

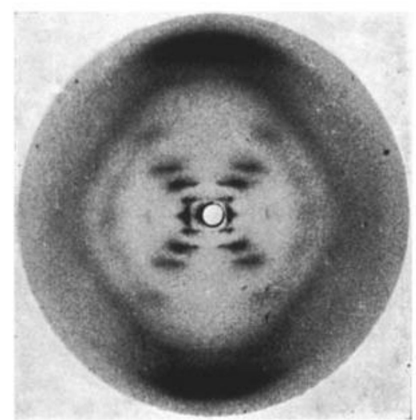
- Photoelectric absorption
- Scattering

More info on the lecture of Prof. Tilo Baumbach „**Modern X-ray Physics**“

X-ray application:

- X-ray crystallography
- X-ray astronomy
- X-ray microscopy
- X-ray fluorescence
- **Radiography**
- **Computed Tomography (CT)**
- Security systems

First X-ray radiograph. *Source:* Wikipedia



DNA structure. *Source:* Wikipedia

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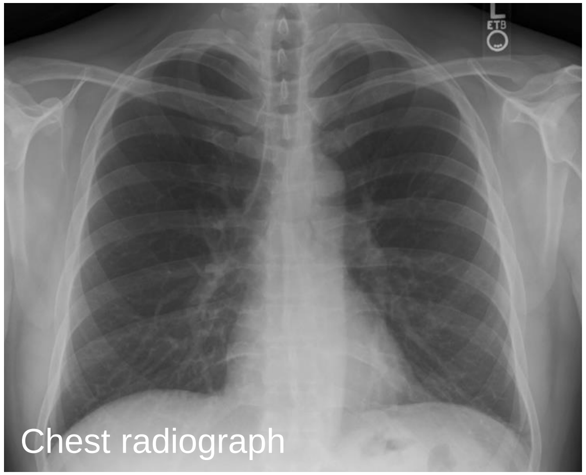
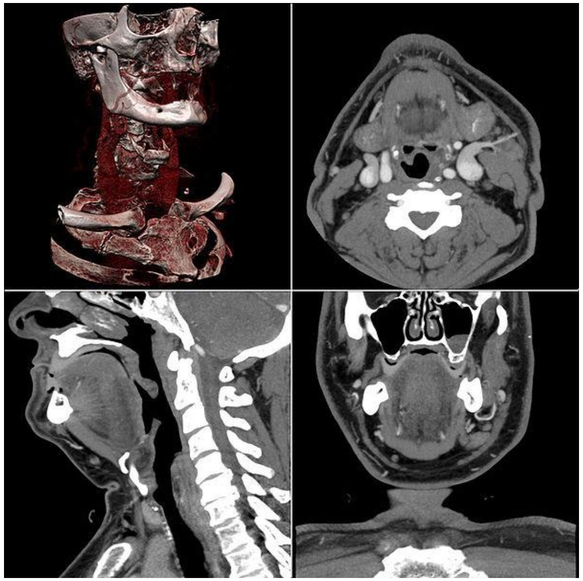

Chest radiograph


CT of the neck region

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ANKA Synchrotron

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Time-resolved X-Ray Imaging

X-ray imaging allow to investigate **internal** structure of **time-varying** processes.

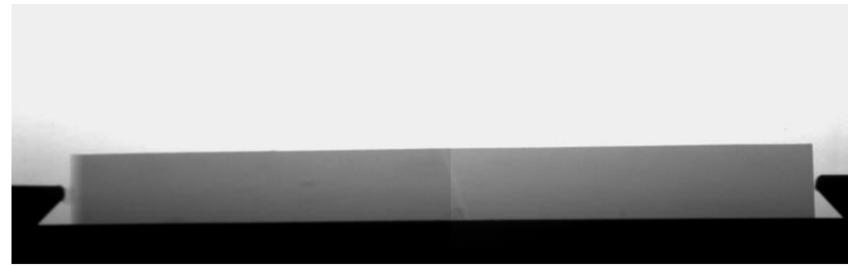
Study examples:

- Evolution of structures
- Fabrication processes
- Living organisms
- Liquid flows, Diffusion processes

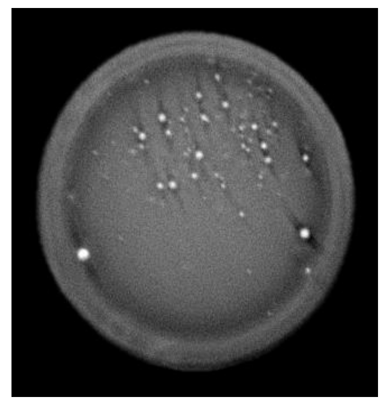
and **many more**…

Time-resolved X-ray data analysis:

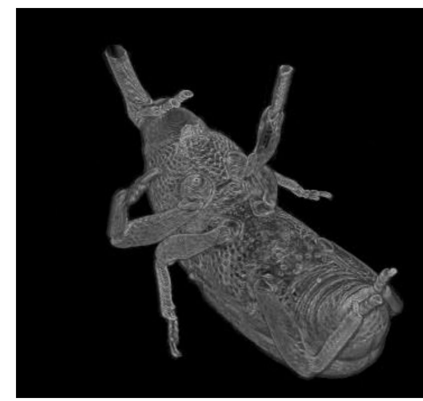
- Study of the dynamics
- Motion analysis and Object tracking
- Motion-based segmentation



Metal foaming process. *Source:* TU Berlin



Crack growth in flip-chips.



Moving bug.
Source: State Museum of National History, Karlsruhe

We aim to extract dynamical information using **optical flow** methods.

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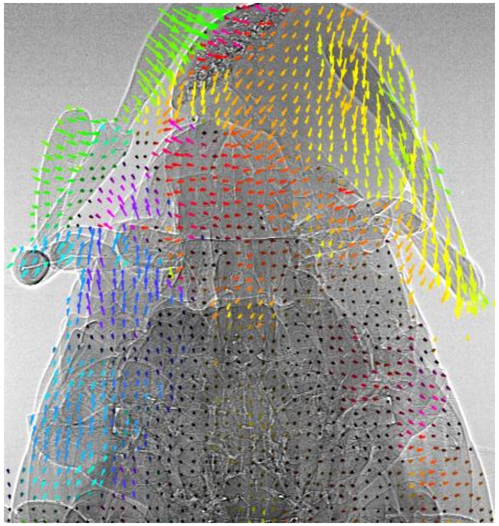
Optical Flow

Optical flow problem is related to the field of **Computer Vision**.

Given: Two images $\mathbf{f} = (f_{1,1}, \ldots, f_{N,M})^\top$ and $\mathbf{g} = (g_{1,1}, \ldots, g_{N,M})^\top$

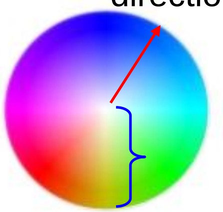
Task: Displacement field $\mathbf{u} = (\mathbf{u}_{1,1}^\top, \ldots, \mathbf{u}_{N,M}^\top)^\top$ which maps all the pixel from the first frame to their new positions on the second frame

chewing cockroach sequence



vector visualization

motion field using **color coding**



A number of well-established optical flow methods exists.

Our choose: **Variational** optical flow methods

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Optical Flow Model

General idea: Use assumptions about image data and motion model.

First idea: brightness constancy assumption

$f(x,y,t)$ - color of a pixel on the first image

$f(x,y,t+1)$ - color of a pixel on the second image

$f(x,y,t) - f(x+u,y+v,t+1)=0$ u,v - unknown displacements

Second idea: Assume the smoothness of the flow field.

$\nabla u = \begin{bmatrix} u_x \\ u_y \end{bmatrix}$ - spatial gradient $|\nabla u| = \sqrt{u_x^2 + u_y^2}$ - magnitude of gradient $|\nabla u|^2 \rightarrow 0$

The variational methods compute the **displacement field** as a minimiser of the energy functional:

$$E(u,v) = \int_\Omega \underbrace{\left(f(x,y,t) - f(x+u,y+v,t+1)\right)^2}_{\text{data term}} + \alpha \underbrace{\left(|\nabla u|^2 + |\nabla v|^2\right)}_{\text{smoothness term}} \, dx\, dy\ .$$

Many advanced models and model assumptions are developed for state-of-the-art optical flow methods…

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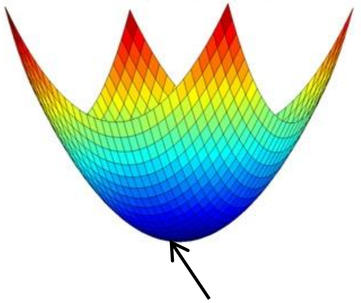
Solution

How to find the minimizer for the constructed energy functional?

$$F(u,v) = \int_\Omega \underbrace{\left(f(x,y,t) - f(x+u, y+v, t+1)\right)^2}_{\text{data term}} + \alpha \underbrace{\left(|\nabla u|^2 + |\nabla v|^2\right)}_{\text{smoothness term}} \; dx\, dy \; .$$



Idea: Use tricks from mathematics

If functional is **convex** ➡ a unique, global minimum exists and can be derived directly using **Euler-Lagrange equations:**

$$0 \overset{!}{=} F_u - \frac{\partial}{\partial x} F_{u_x} - \frac{\partial}{\partial y} F_{u_y} \, ,$$

$$0 \overset{!}{=} F_v - \frac{\partial}{\partial x} F_{v_x} - \frac{\partial}{\partial y} F_{v_y}$$

with (reflecting) Neumann boundary conditions:

$$\mathbf{n}^\top \nabla u = 0$$

$$\mathbf{n}^\top \nabla v = 0.$$

Next step: Discretize the Euler-Lagrange equations on rectangular grid.

Solve system of equations $A\mathbf{x} = \mathbf{b}$, by using an approximation and **iterative** scheme

$$\mathbf{x}^{k+1} = A_1^{-1}(\mathbf{b} - A_2\, \mathbf{x}^k)$$ (Gauss –Seidel method)

We use state-of-the-art, highly accurate and robust optical flow methods.

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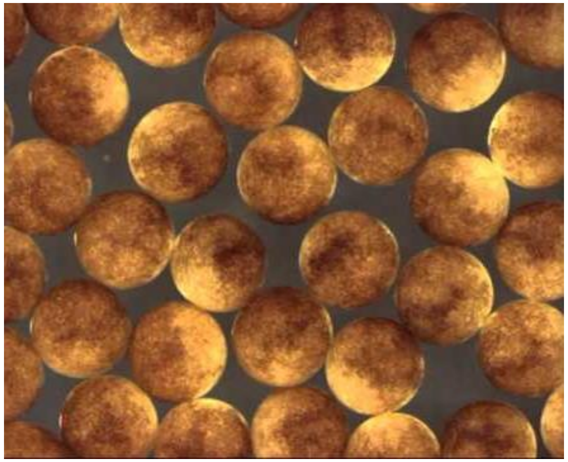
Developmental Biology

African Clawed Frog (*Xenopus laevis)* - Vertebrate model organism


adult African clawed frog

embryo development of *Xenopus laevis*.



- Unlimited availability

→ over 1000 eggs per day

- Homogeneous population

→ no individual factors

- Manipulation

→ injections, transplantations,...

- Experiments within the embryo

(*in vivo*) and in petri dish (*in vitro*)

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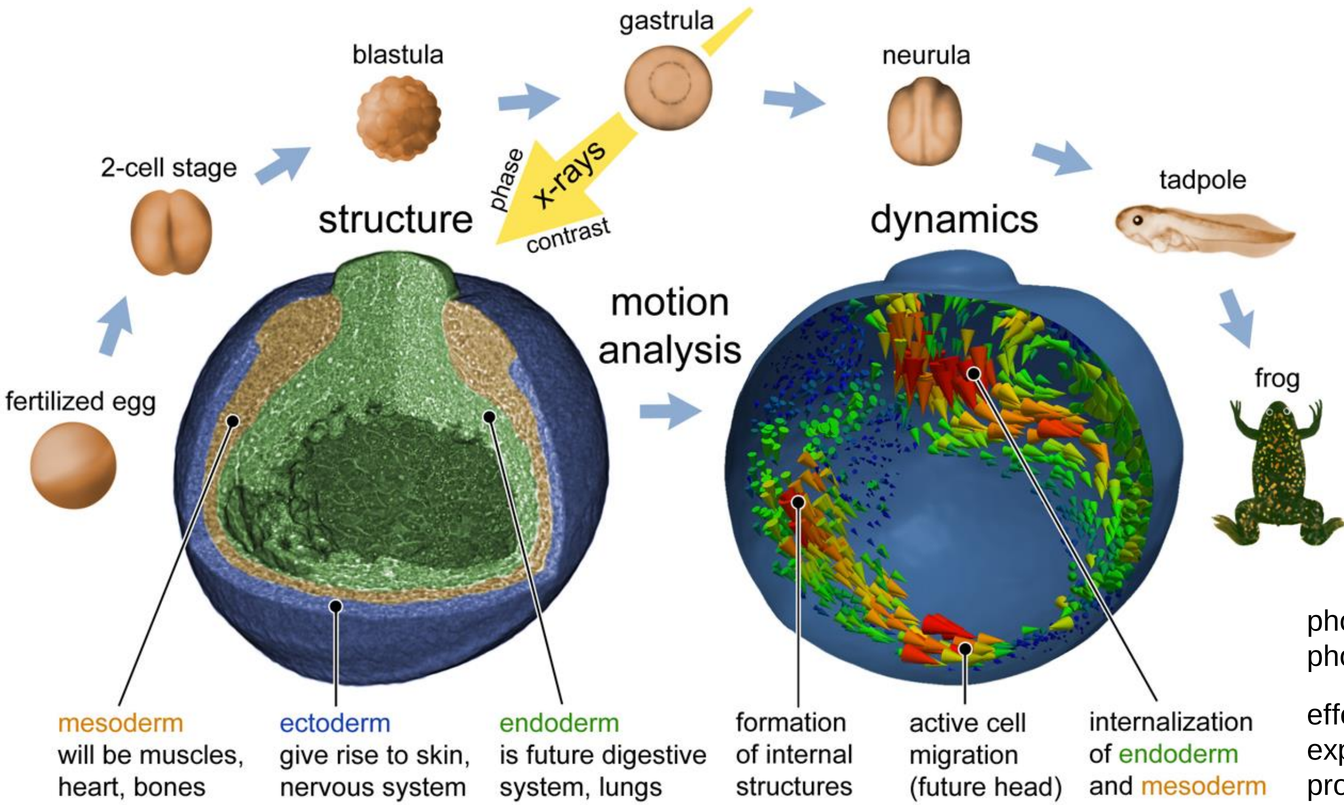
In-vivo X-ray Study of Embryo Development

Application: Analyze morphogenetic movements during embryogenesis.
Imaged by *in-vivo* phase-contrast 4D X-ray microtomography.



photon energy: 30 keV,
photon flux: 10^{12} photons/s/mm^2

effective pixel size: 2.2 µm
exposure time / projection:15 ms
projections / tomogram: 2000

Problem: Complexity of movements and many interconnected events
Solution: Use multi-scale (**hierarchical**) motion analysis approach

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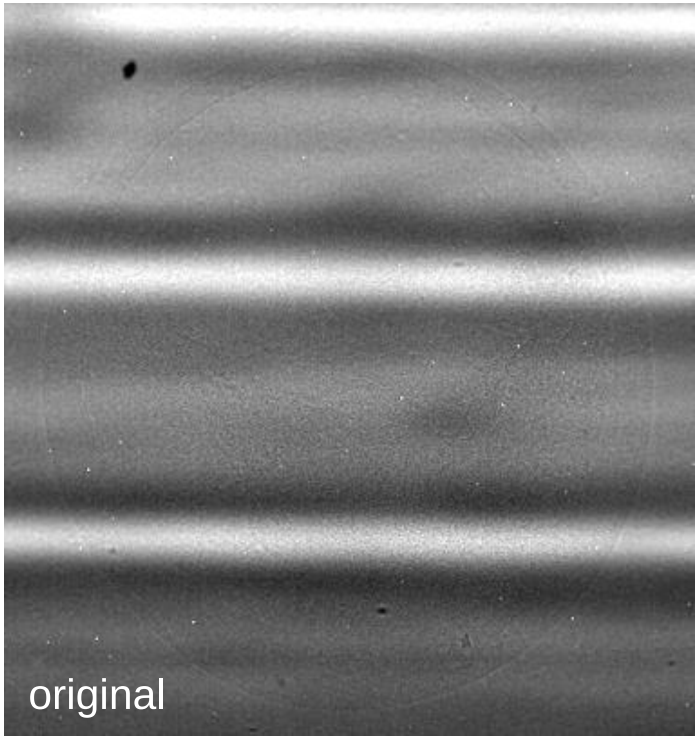
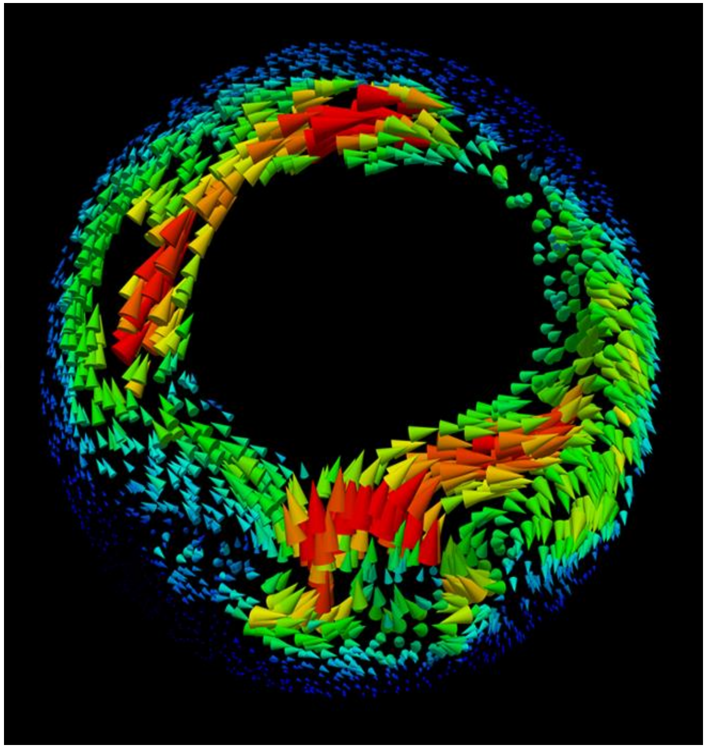
Data Processing Pipeline

Aim: Correct image artifacts and enhance data quality





Data Correction → **Reconstruction** → **Structure** → **Motion**

Data Correction	Reconstruction	Structure	Motion
Flat field correction	Phase retrieval	Segmentation	Optical flow
Noise / artifacts removal	3D reconstruction	3D rendering	
Brightness correction	Background removal	Labeling	

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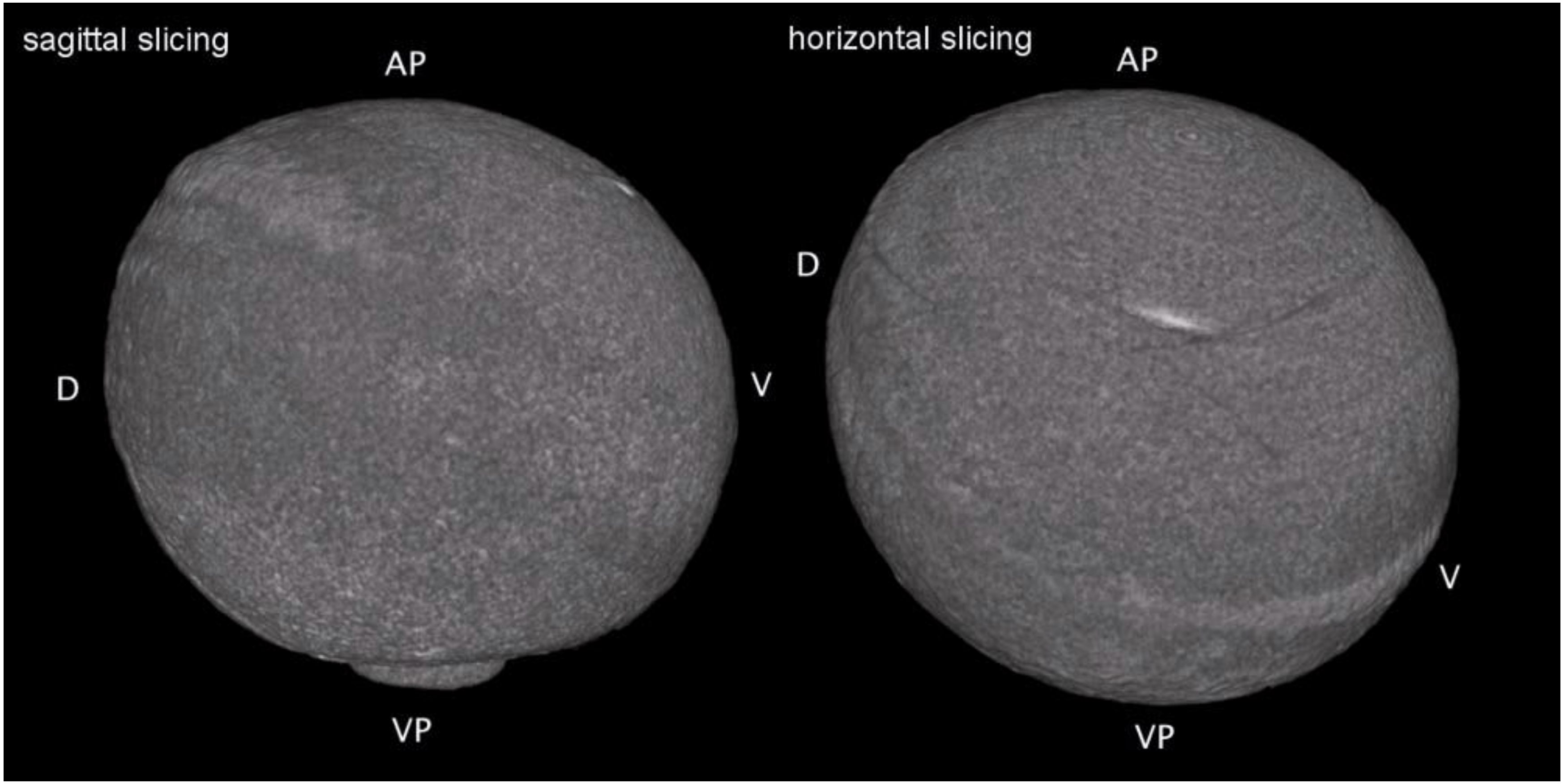
3D Rendering of Entire Embryo



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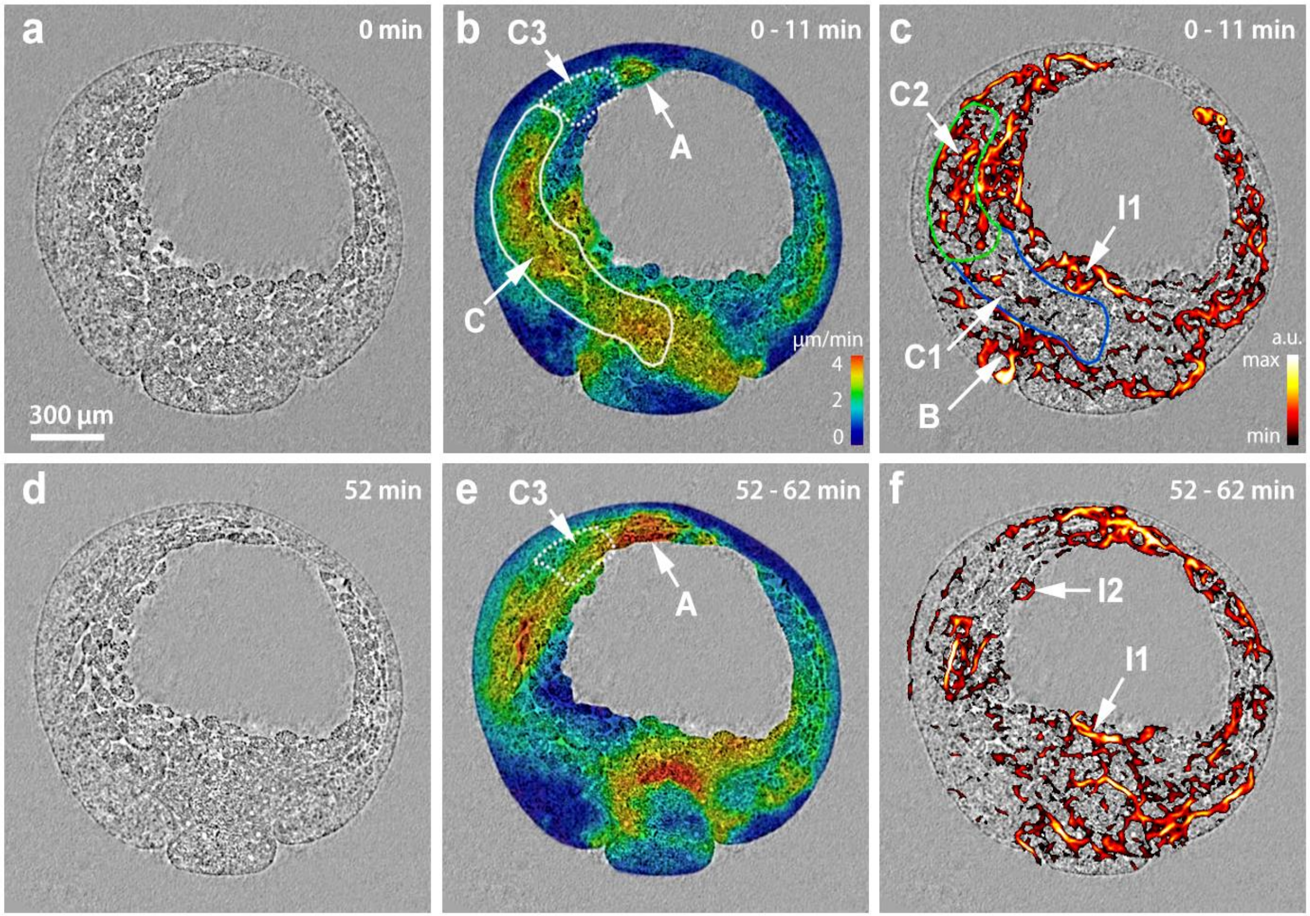
Differential motion

Aim: Distinguish collective and individual cells motion; passive and active movements



tomographic slice | motion magnitude | motion non-uniformity

$\vec{v}$ - motion field

v_x, v_y, v_z - components

$\vec{\nabla}$- spatial gradient

Measures

$|\vec{v}|$- motion magnitude

$G \equiv |\vec{\nabla} v_x| + |\vec{\nabla} v_y| + |\vec{\nabla} v_z|$

- motion non-uniformity

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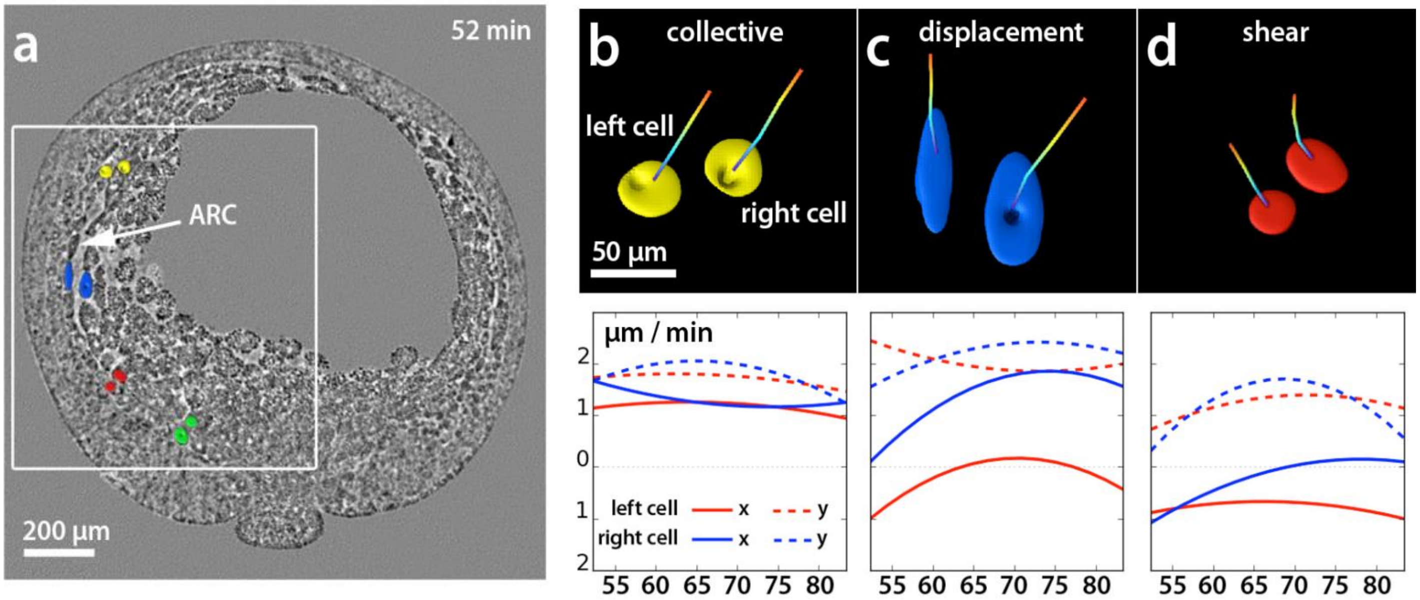
Analyzing individual cells

Aim: Track individual cells, analyze their dynamics to study interaction mechanisms.

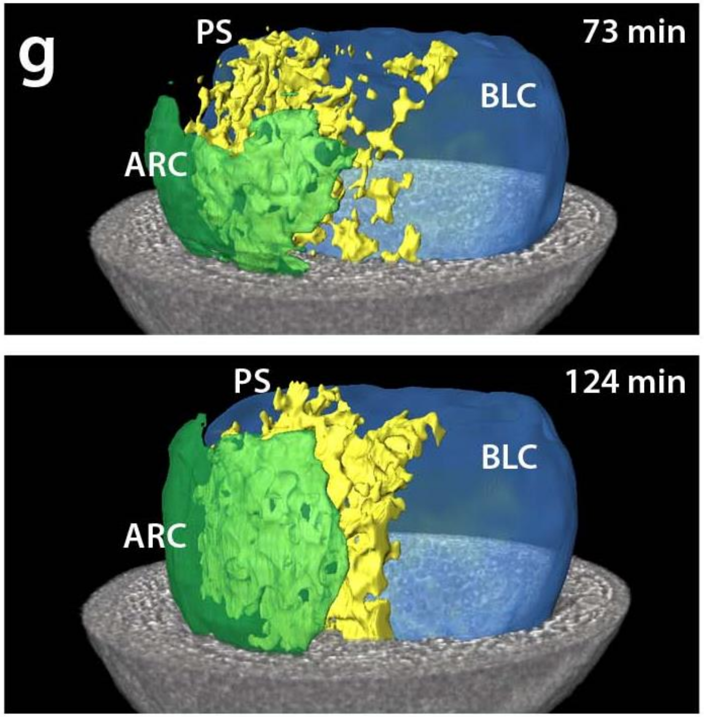


J. Moosmann, A. Ershov, V. Altapova, T. Baumbach, M. Prasad, C. LaBonne, X. Xiao, J. Kashef, and R. Hofmann
X-ray phase-contrast in vivo microtomography probes new aspects of Xenopus gastrulation
Nature 497 (7449) , 374—377 (2013)

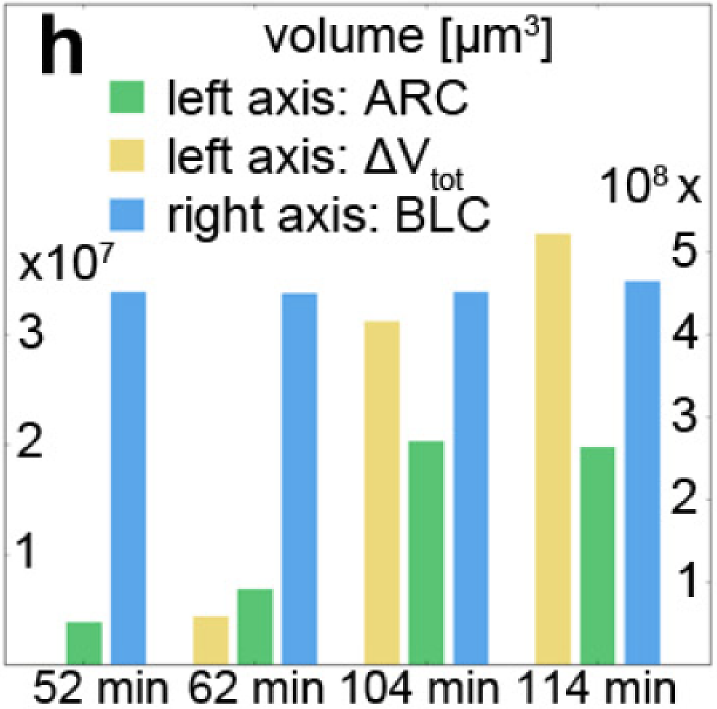
Moosmann, J.; Ershov, A.; Weinhardt, V.; Baumbach, T.; Prasad, M. S.; LaBonne, C.; Xiao, X.; Kashef, J. & Hofmann, R.
Time-lapse X-ray phase-contrast microtomography for in vivo imaging and analysis of morphogenesis,
Nature Protocols 9 (2) , 294—304 (2014)

Changes in internal structures

Aim: Analyze changes in internal structures to get insights about embryo morphogenesis.



changes in internal structures



quantitative characteristics over time

J. Moosmann, A. Ershov, V. Altapova, T. Baumbach, M. Prasad, C. LaBonne, X. Xiao, J. Kashef, and R. Hofmann
X-ray phase-contrast in vivo microtomography probes new aspects of Xenopus gastrulation **Nature** 2013

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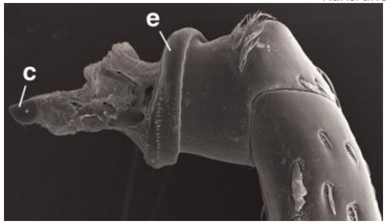
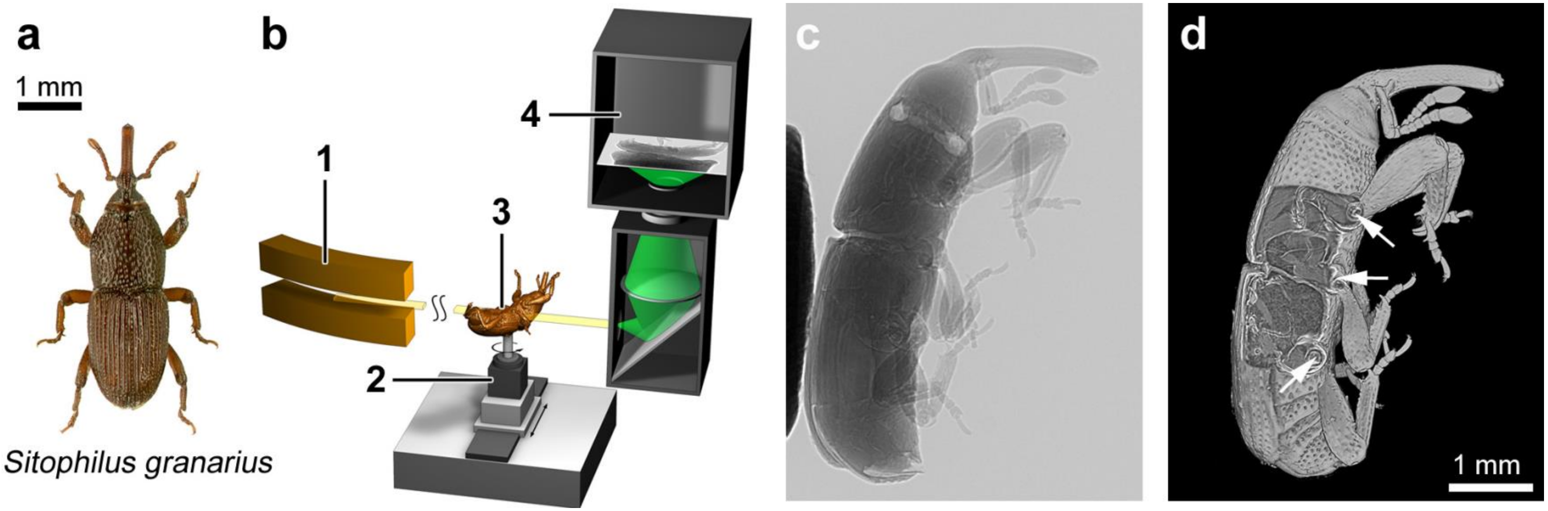
In-vivo X-ray 4D Cinetomography

Application: Analyze function of hip joints in living insect.

In-vivo X-ray Cinetomography =
Ultra-fast 4D X-ray Imaging + Automated Data Analysis



biological screw



experimental setup

radiographic projection

volume rendering

photon energy: 9.6–24 keV
pixel size: 1.2 µm
imaging rate: 1500 projection / sec
projections / tomogram: 200
tomograms / sec: 7.5 volumes

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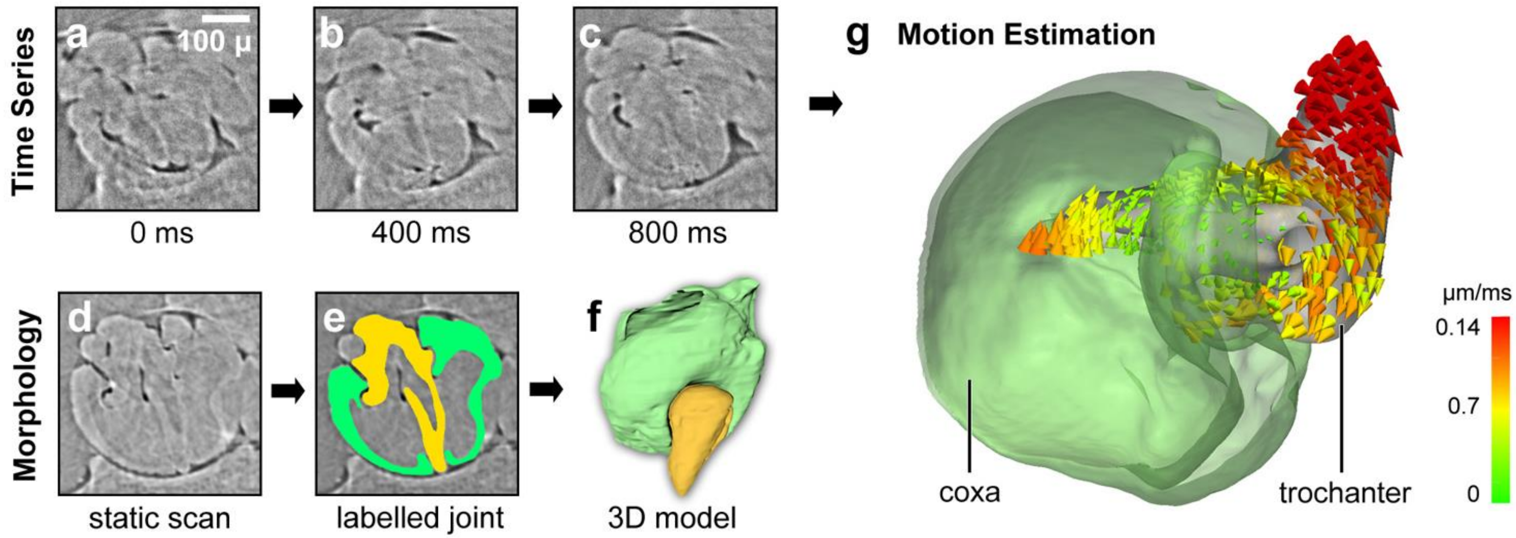
Motion Analysis and Kinematics



Problem: The data quality is **not sufficient** to compute **reliable** motion field

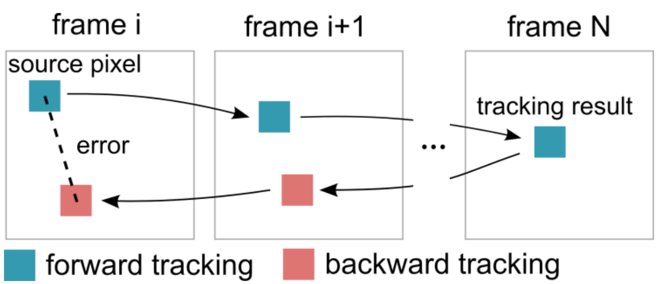
Robust method to extract kinematics:

- Distribute landmarks for both parts
- Track landmarks in forw. and back. directions
- Filter only reliable landmarks
- Register landmarks from frame i and i+1
- Obtain global transformation M_t
- Decompose M_t into

translational and **rotational** components

Confidence measure:

Forward-backward cross-check



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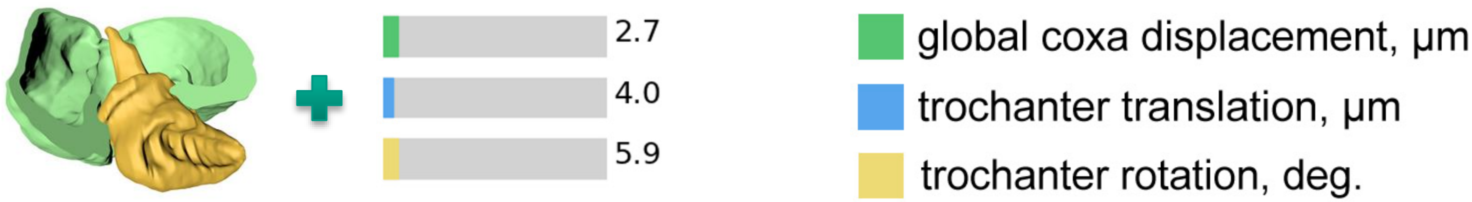
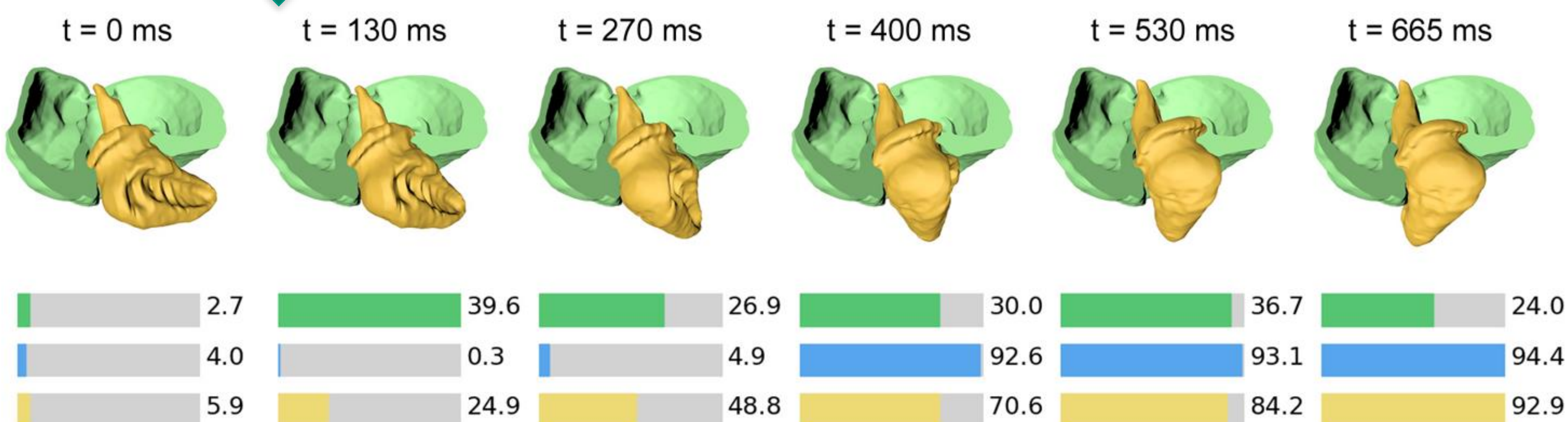
Morphodynamics

Aim: In-vivo study of morphological dynamics of a screw joint system.

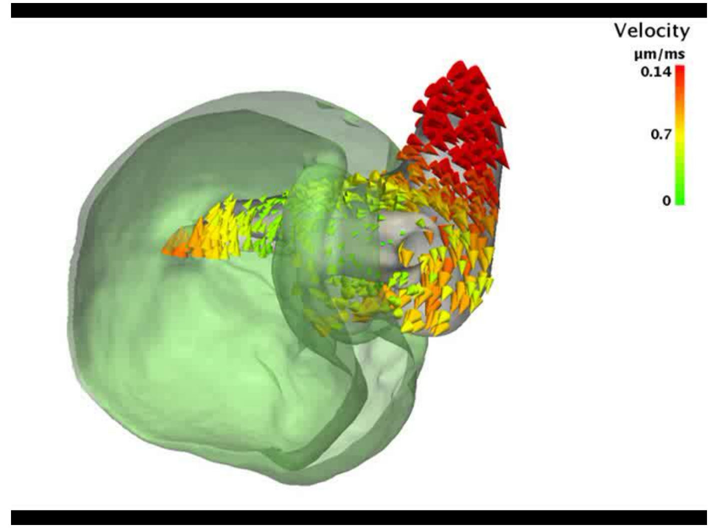


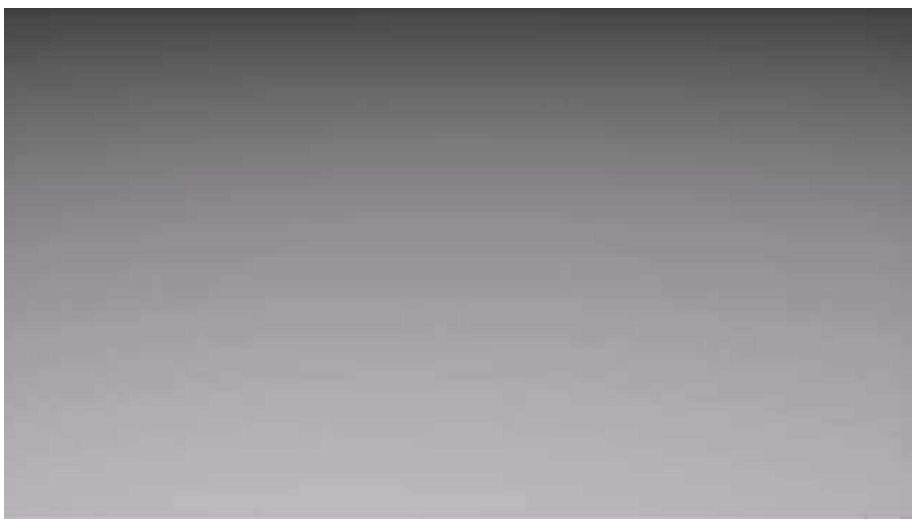
3D model t=0 ms   Motion components



In vivo X-ray 4D Cinetomography for Tracking Morphological Dynamics
T. dos Santos Rolo, A. Ershov, T. van de Kamp, and T. Baumbach
Proceedings of the National Academy of Sciences 2014

In-vivo X-ray 4D Cinetomography





In vivo X-ray 4D Cinetomography for Tracking Morphological Dynamics T. dos Santos Rolo, A. Ershov, T. van de Kamp, and T. Baumbach **PNAS** 2014

Collaboration between TPU and KIT

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TPU & KIT: Current Activities

Main research fields:
- Physics
- Informatics

Visiting students (2011 - 2014):
- 7 Bachelor students
- 5 Master/Specialist students
- 4 Guest scientists (PhD)

Current students and scientists:
- 3 Master/Specialist students
- **2 PhD students at KIT**
- 1 Guest scientist from TPU

Andrey Shkarin
PhD students at KIT

Dr. Sergey Lazarev,
DESY, Hamburg, Germany

Roman Shkarin
PhD student at KIT

Dr. Venera Weinhardt (Altapova),
University of Heidelberg, Germany

Collaboration projects:
- **UFO: U**ltra **f**ast X-ray imaging of scientific processes with **o**n-line assessment and data-driven process control
- **ASTOR: A**rthropod **s**tructure revealed by ultra-fast **t**omography and **o**nline **r**econstruction
- **STROBOS-CODE**: Stroboscopic and correlative diffraction imaging

TPU & KIT: Proposals

To strengthen scientific collaboration between TPU and KIT we propose:

Scientific collaboration in 2 research direction:

- Image Processing and Data Analysis for Medicine and Visual Inspection Systems
- Motion Analysis and Tracking for Video Processing, Monitoring and Intelligent Systems

- Internships / student practice in KIT, Karlsruhe, Germany
- Topics for scientific projects for students
- Topics and co-supervision of Bachelor/Master thesis
- Scientific collaboration with TPU doctorands
- Joint scientific projects with Institute of Cybernetics

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Current Topics and Tasks

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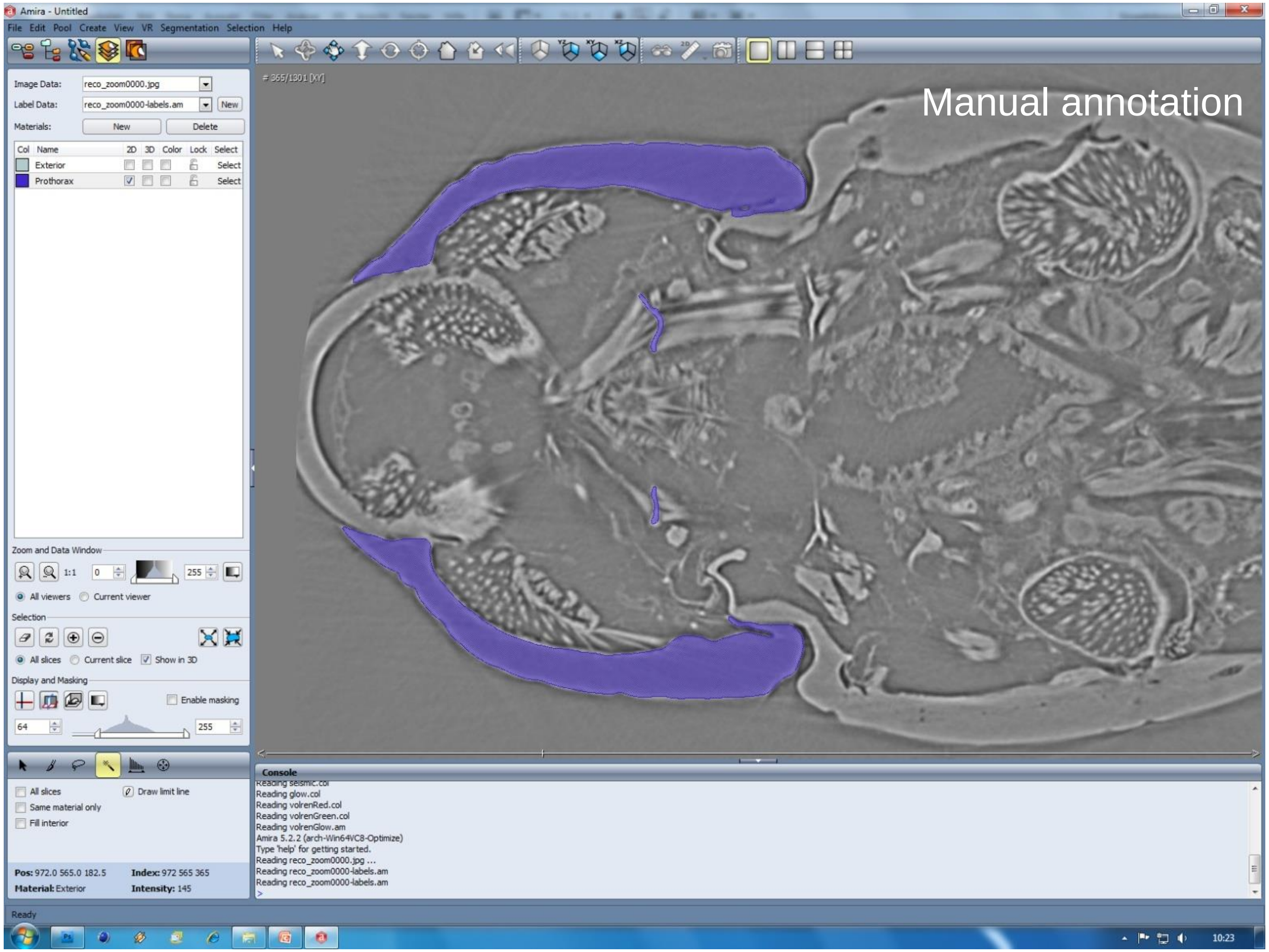
Topic: Image Segmentation

Task: Automated segmentation of structures in materials and biological specimens.



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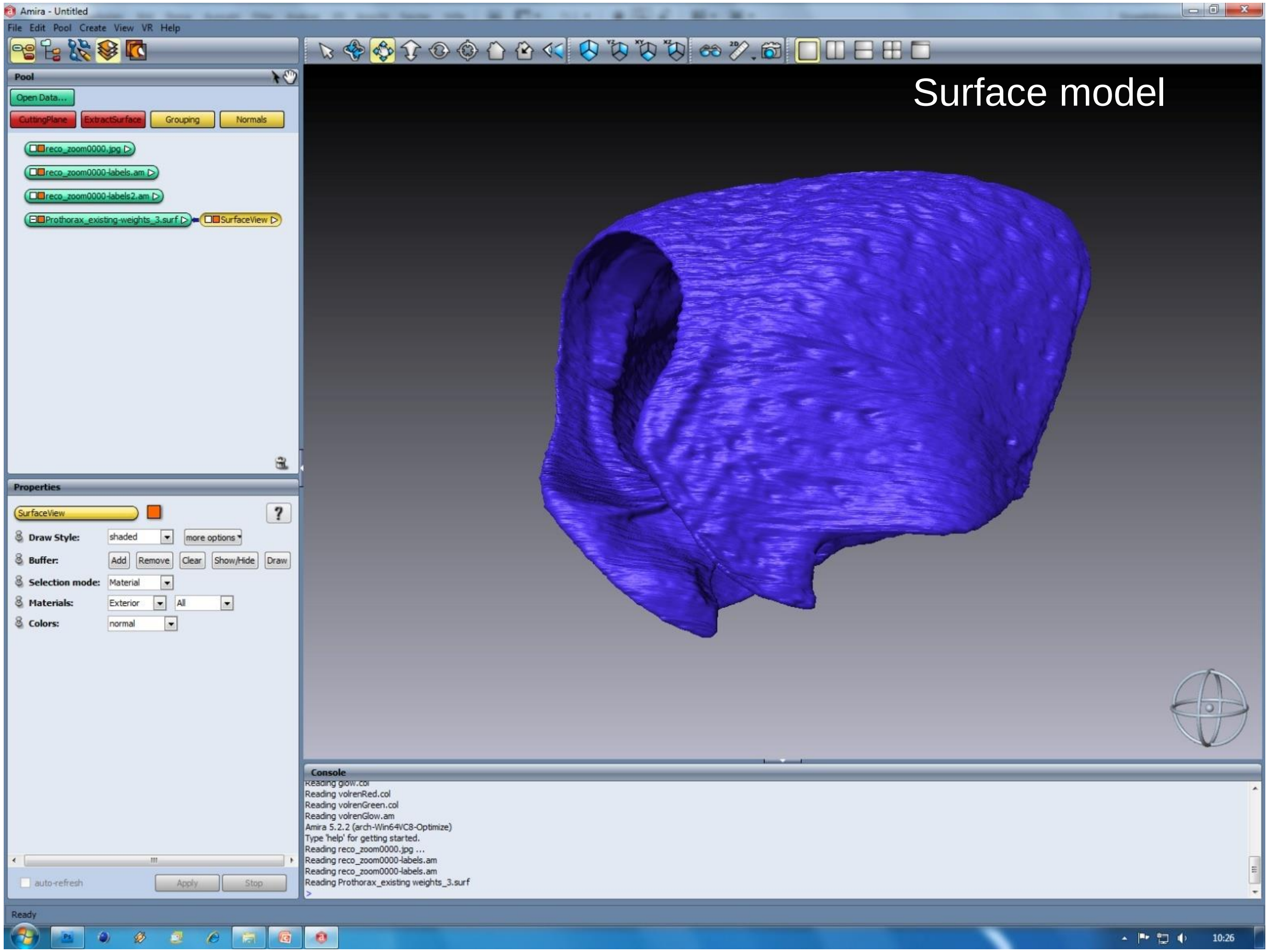

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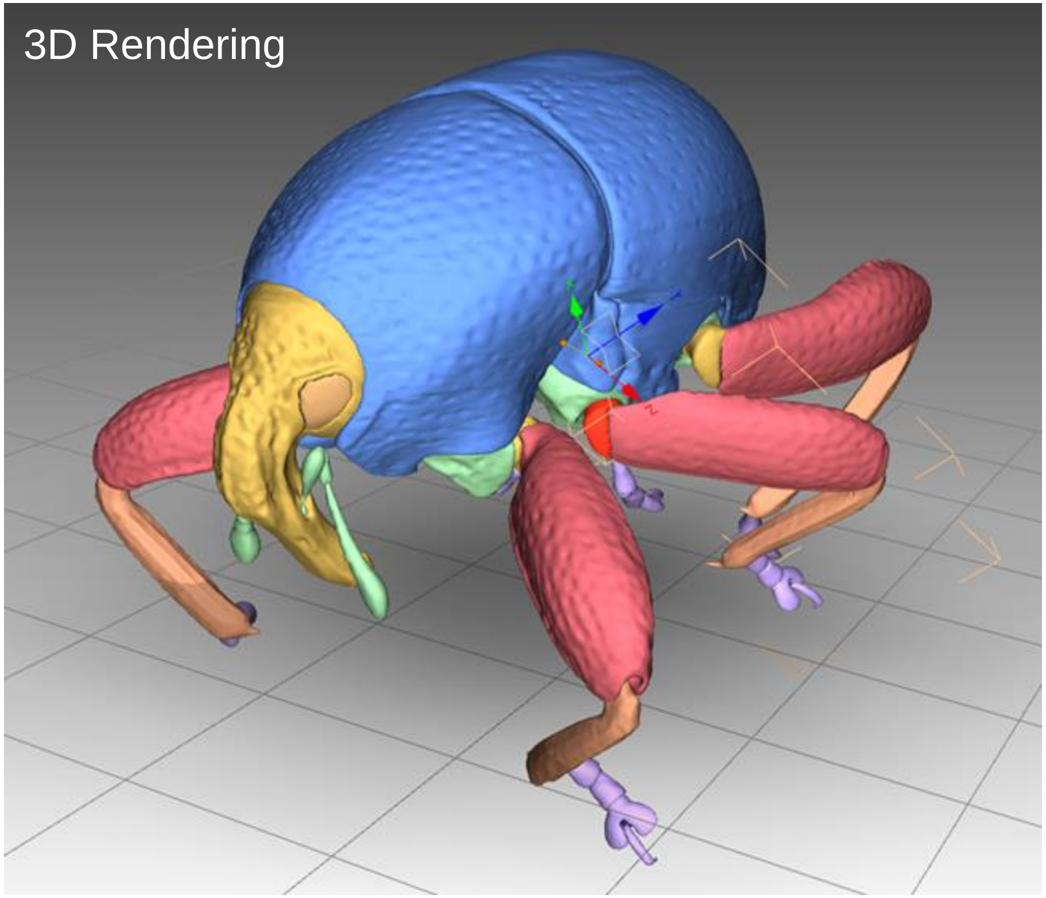

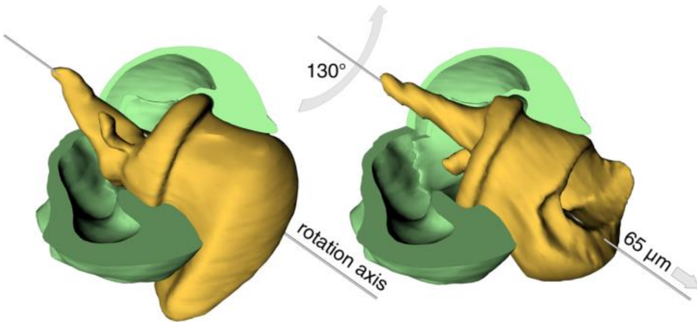

Biological screw joint

Trigonopterus weevils

Automated segmentation is required for high throughput data analysis!

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Topic: Image Segmentation

Automated segmentation methods:

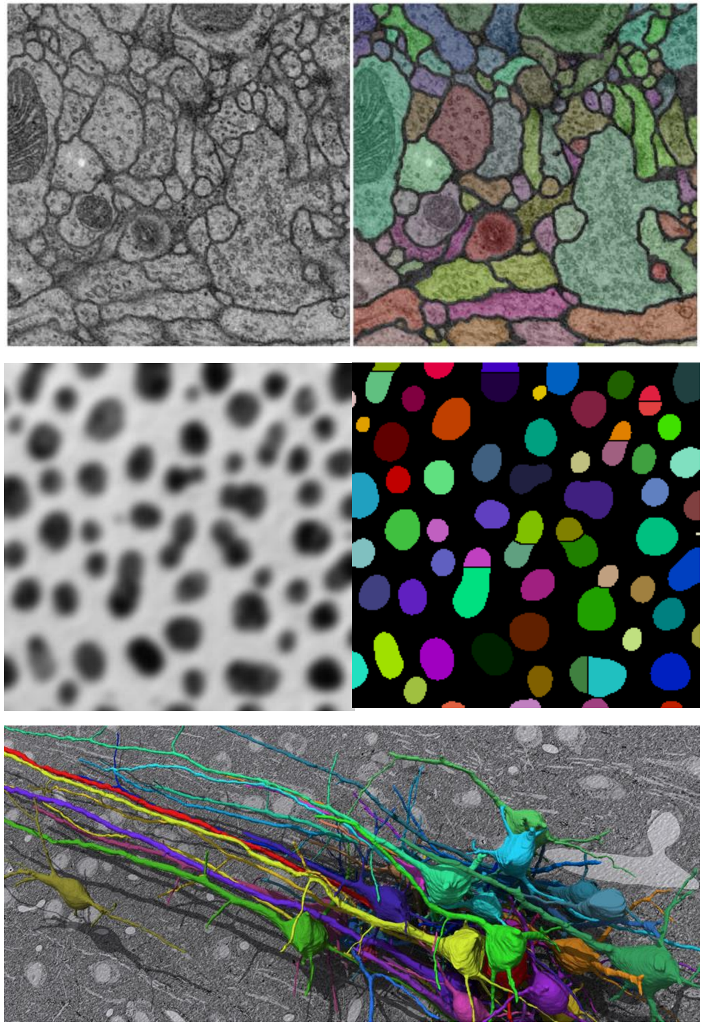
- Grey value thresholding
- Clustering methods
- Edge detection
- Region-growing methods
- Graph partitioning methods
- Watershed segmentation
- Trainable segmentation (NN)

Approaches:

- Automated segmentation
- Semi-automated segmentation
- Multi-level approach

Applications:

- Morphological analysis
- Object detection



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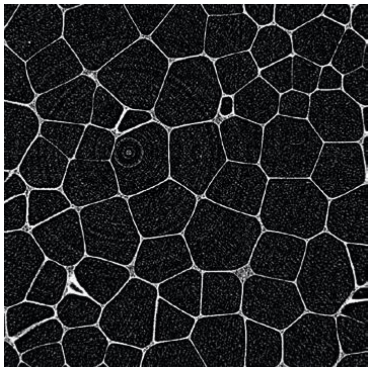
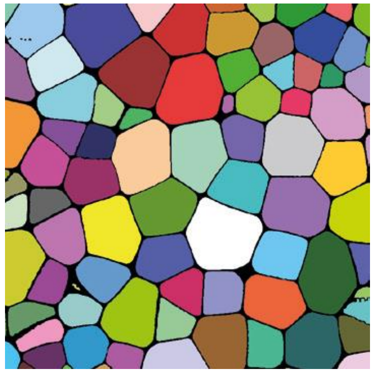
Topic: Morphological Analysis

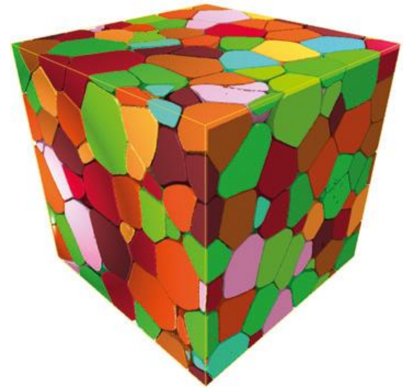
Task: Morphological analysis of porous and fiber materials.



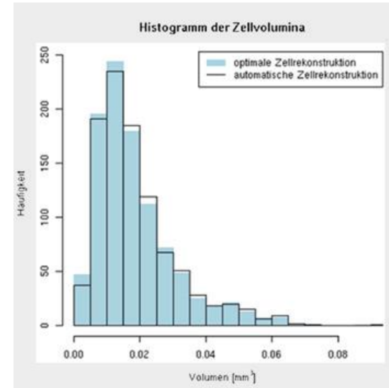
tomographic 2D slice



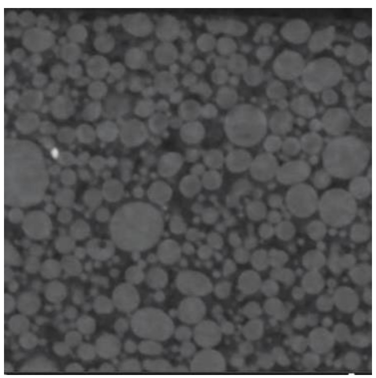
watershed transform



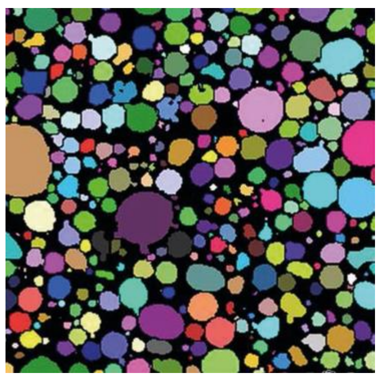
reconstructed cells



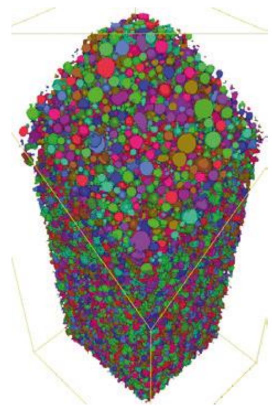
cell volume distribution



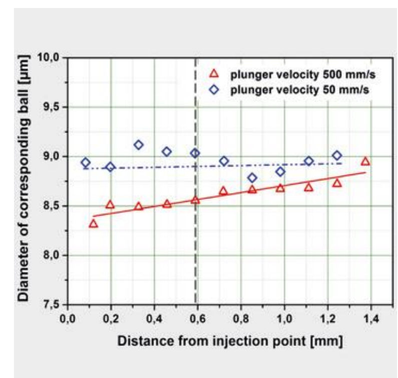
tomographic 2D slice



segmentation



particle system

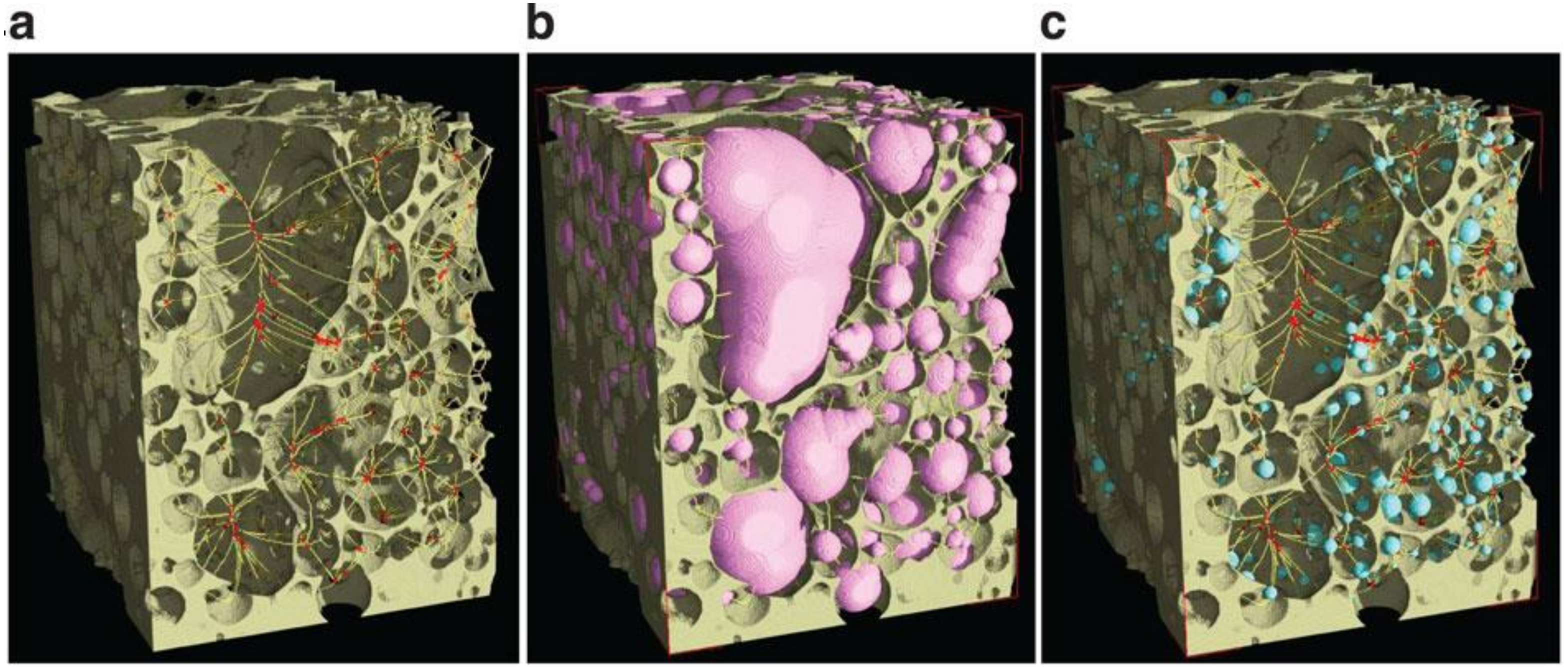


particle size depending on position

MAVI: A modular system for the quantitative analysis of volume images, www.mavi-3d.de
Fraunhofer-Institut für Techno- und Wirtschaftsmathematik ITWM, Kaiserslautern

Topic: Morphological Analysis

Example: Study of bubble growth in basaltic foam



tomographic 2D slice | bubbles volume | pore channel sizes

Baker, D. R.; Brun, F.; O'Shaughnessy, C.; Mancini, L.; Fife, J. L. & Rivers, M. (2012), '*A four-dimensional X-ray tomographic microscopy study of bubble growth in basaltic foam*', Nat Commun 3

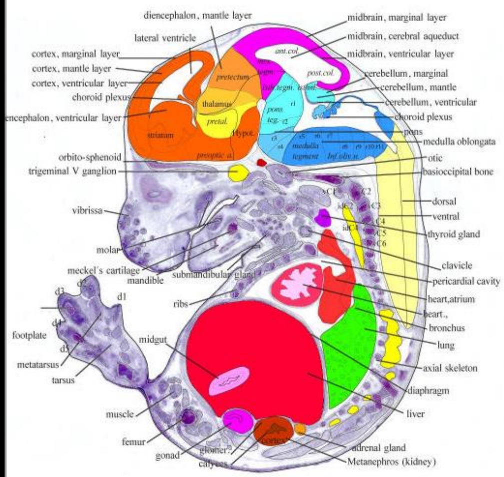
Topic: Digital Atlases

Task: Create digital atlases of model organisms (*Xenopus*, *Medaka*) to study anatomy, pathology, phenotypes and many biological questions.

Examples of successful projects:

Mouse embryo

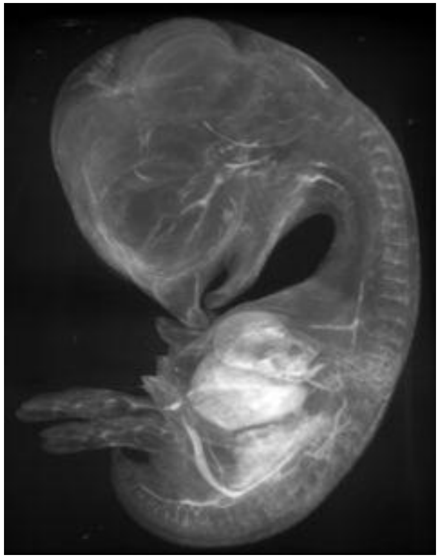
3D surface



anatomical atlas

The e-Mouse Atlas Project

Chicken embryo



2D tomographic slice

3D volume rendering

The e-Chick Atlas of Anatomy

 18.03.15

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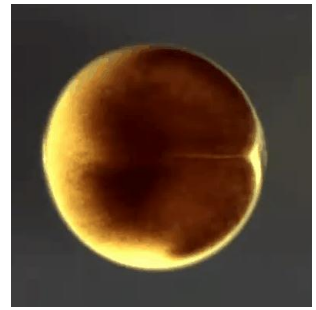
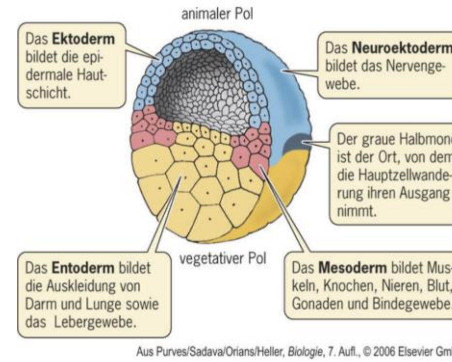
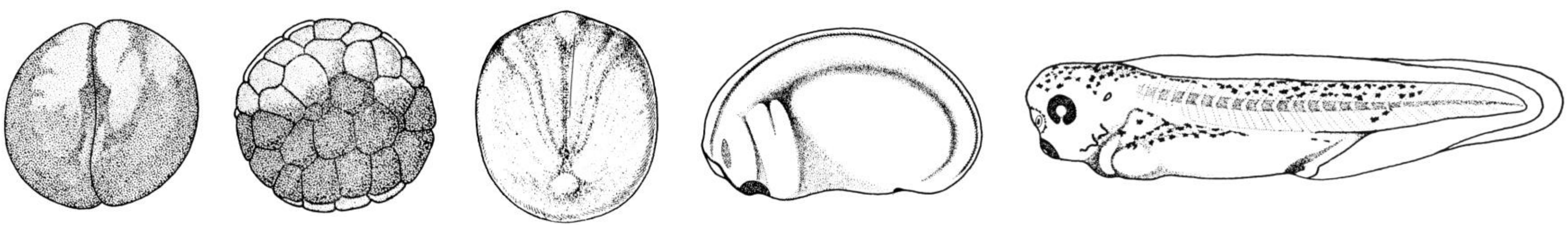
African Clawed Frog (*Xenopus laevis)*



Embryo development of *Xenopus laevis*.





Current *Xenopus* atlas on the xenbase.org website

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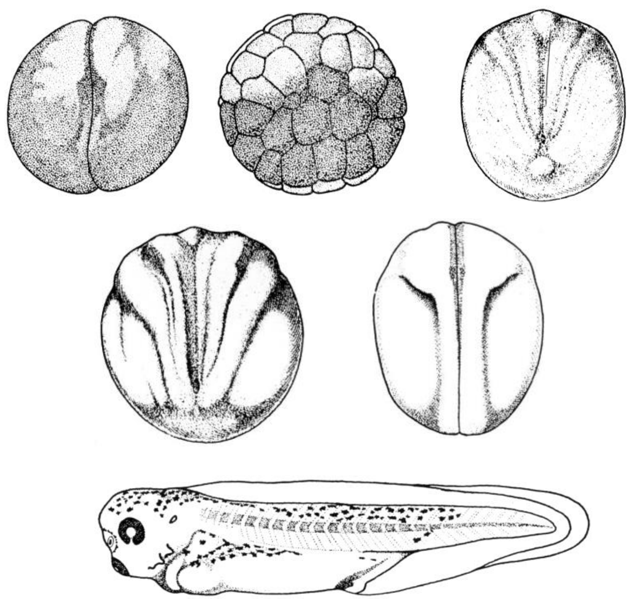
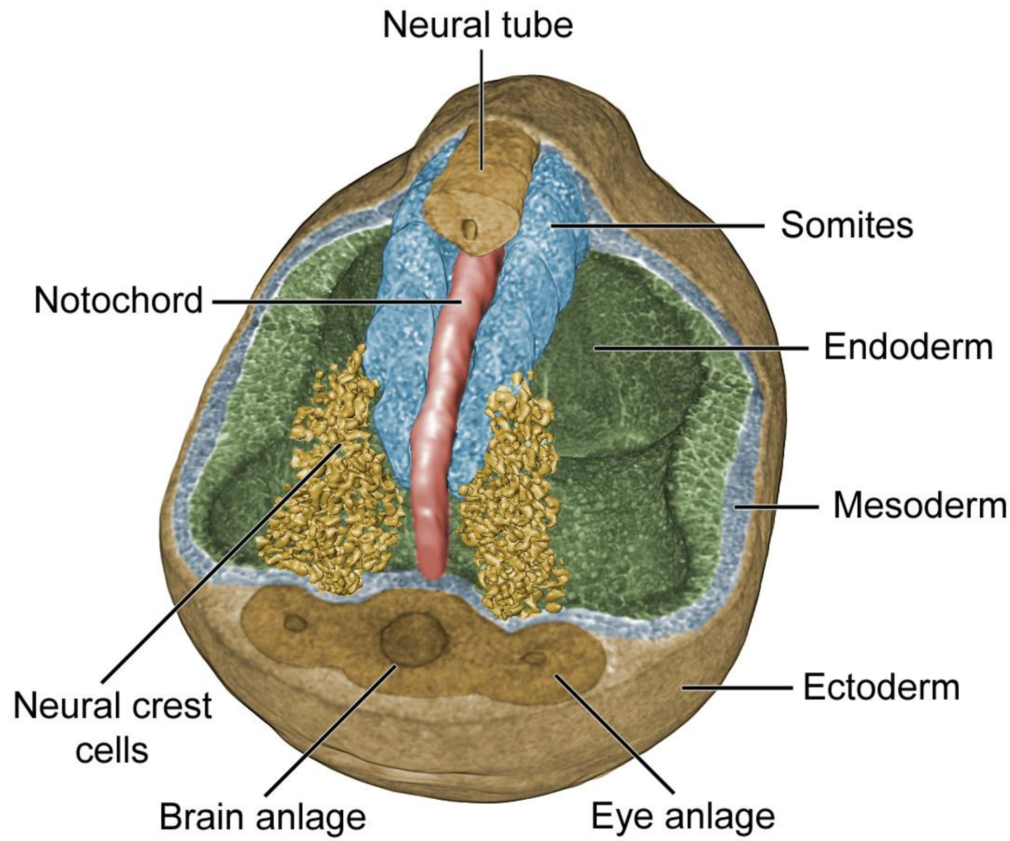


Current *Xenopus* atlas
on the Xenbase website



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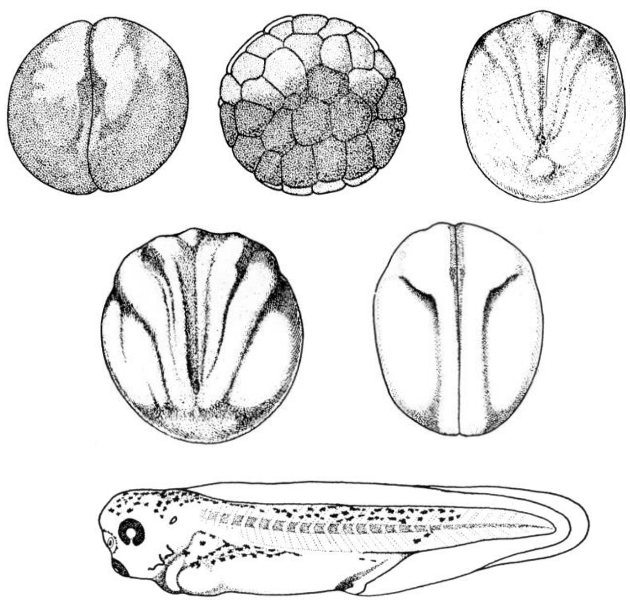

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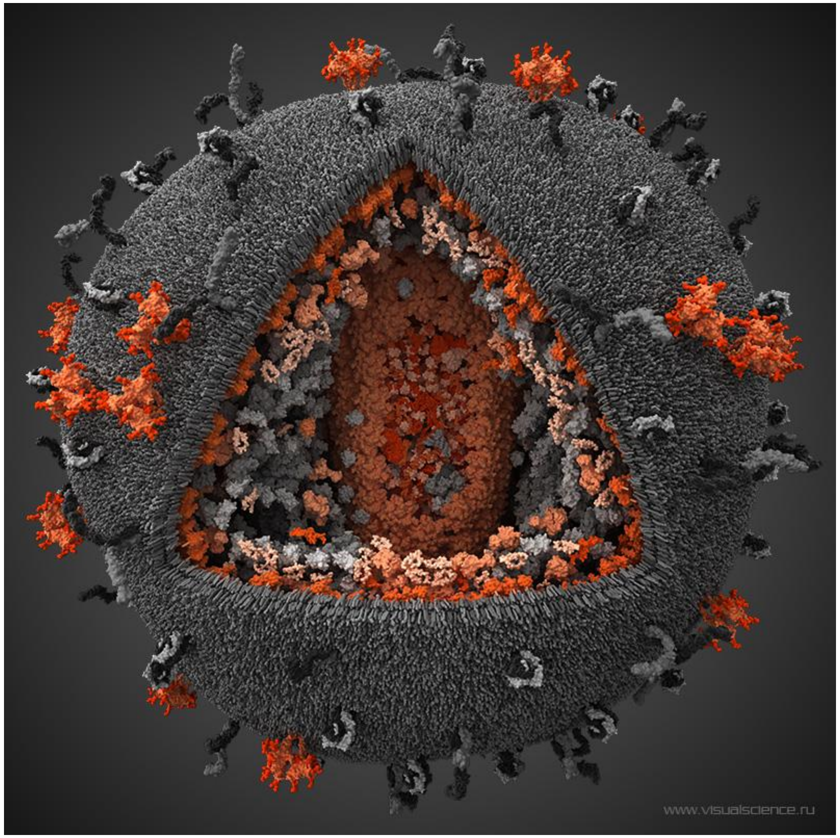

Inspiration: Human Immunodeficiency Virus (HIV) model
visual-science.com, Russia

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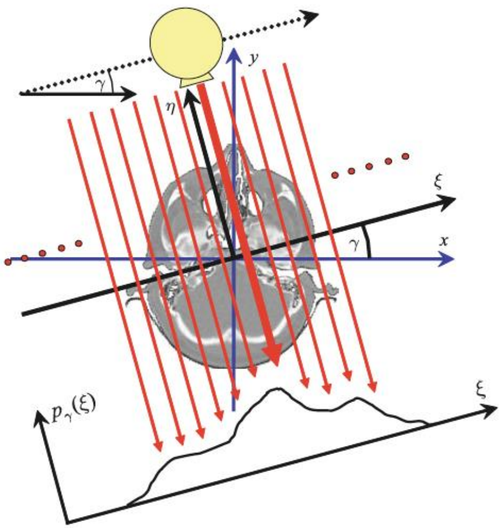
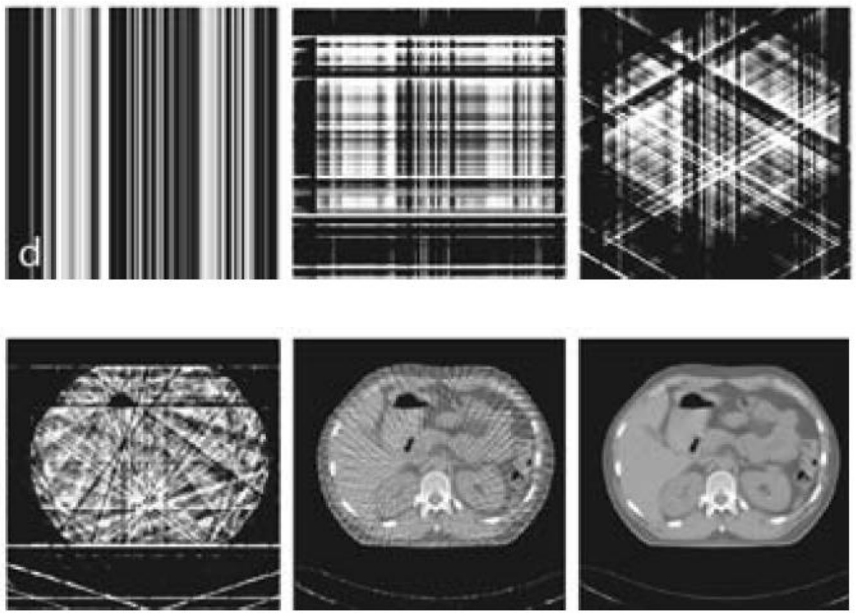
Topic: Tomographic Reconstruction

Task: Reconstruct a 3D object from a series of radiographic images taken at different angles.



parallel beam geometry
line integrals of rays



Example of reconstruction using: 1,2,3,10,45,180 projections

Attenuation: $I = I_0 \exp\left(-\int \mu(x,y)\,ds\right)$

Total attenuation along the ray: $p(r,\theta) = \ln(I/I_0) = -\int \mu(x,y)\,ds$

For coordinate system position is given : $x\cos\theta + y\sin\theta = r$

Radon transform: $p(r,\theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\delta(x\cos\theta + y\sin\theta - r)\,dx\,dy$ Reconstruct original object $f(x,y)$

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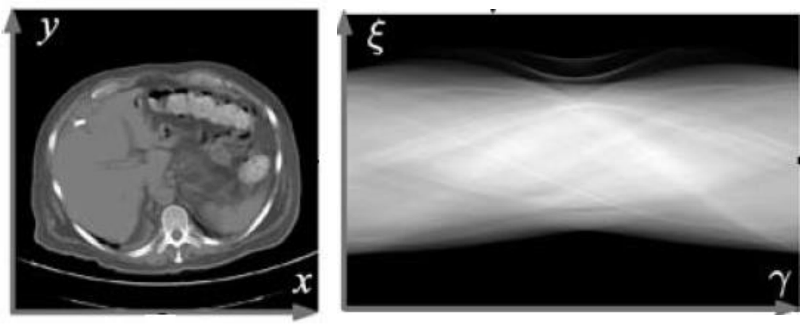
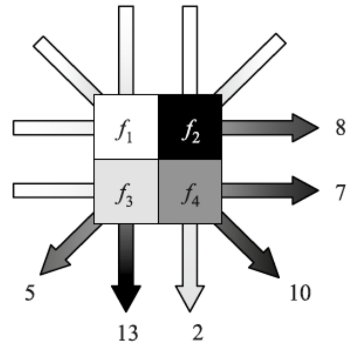


Fourier based methods

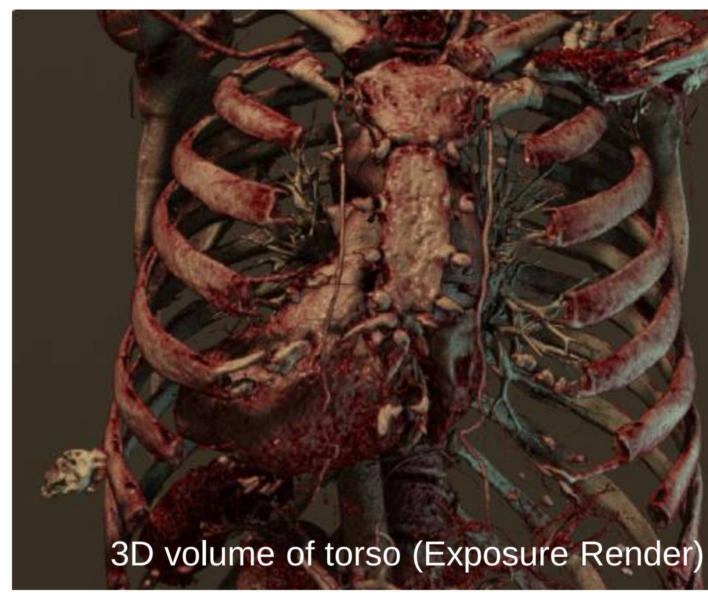


$$\begin{pmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{pmatrix} = \begin{pmatrix} 5 \\ 13 \\ 2 \\ 10 \\ 7 \\ 8 \end{pmatrix}.$$

Algebraic reconstruction techniques (ART)

Aims for reconstruction algorithms:

- Improve quality of reconstruction:
  - Robust to noise and artifacts
  - Take into account additional information
- **Reconstruction of dynamical data**:
  - Reduction of motion artifacts
- **Reduce number of projections**:
  - Reduce dose for biological specimens
  - Decrease acquisition time



3D volume of torso (Exposure Render)

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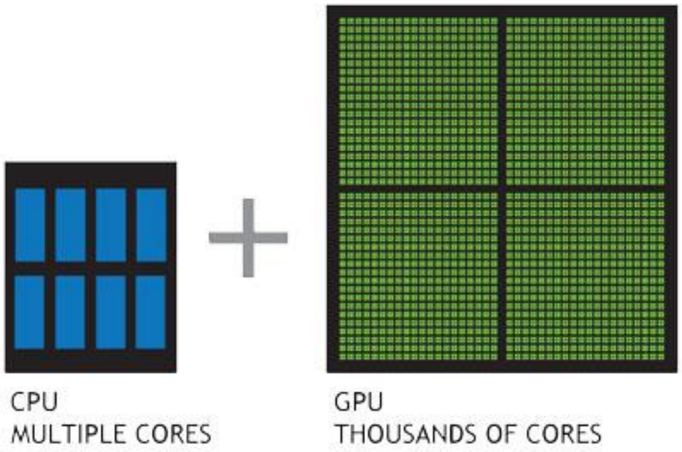
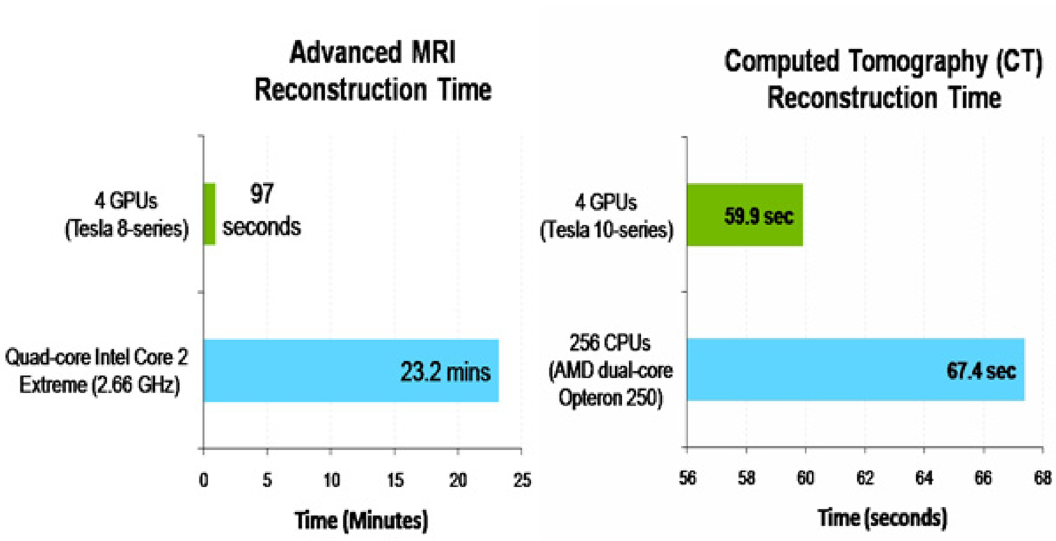
Topic: Computing on GPUs

Task: High-performance image processing algorithms on graphics processing units (GPU).



GeForce® GTX 980 Graphics card



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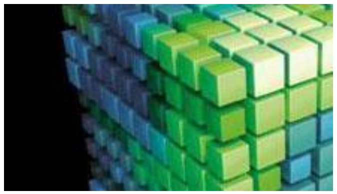
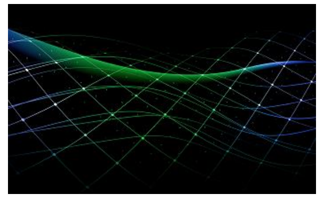
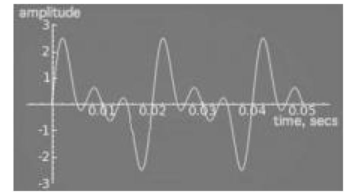


cuBLAS
Linear Algebra



cuSover
Direct Solvers



cuFFT
Fast Fourier Transform

NPP
Image Processing Primitives

OpenCV
Computer Vision

cuDNN
Neural Networks

GPU accelerated software in IPS and IPE:

- UFO framework
- Filtered-back projection
- Laminographic reconstruction
- Simulation of X-ray Data (SYRIS)

Current developments:

- Segmentation algorithms
- ART reconstruction to reduce dose
- 3D Optical flow methods

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Lecture “Image Acquisition Methods and Image Analysis”

"Методы получения и анализа изображений"

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Institute for Photon Science and Synchrotron Radiation, Imaging Group

Image Acquisition Methods and Image Analysis

- For Bachelor students of Institute of Cybernetics (IC)
- As the discipline on student's choice
- **Online** course from KIT (Germany) to TPU
- Language: Russian or English?

- Requirements:
  - Mathematics
  - Programming
  - No previous knowledge of algorithms or image processing is required!
- Practical exercises
- Final exam

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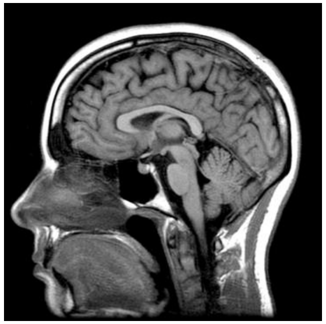
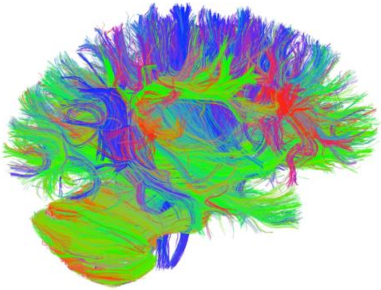
Image Acquisition Methods

- Imaging with Visible Light
  - Electromagnetic Spectrum
  - Optics, Sensors
  - Photography
  - Telescopes, Microscopy
- 2D X-ray and Gamma-ray Imaging
- X-Ray Computed Tomography (CT)
  - Principles
  - Reconstruction: FBP, ART
  - Artifacts
  - Visualization
- Magnetic Resonance Imaging (MRI)
- Electron Microscopy
- Light-sheet Microscopy
- Ultrasound (US)



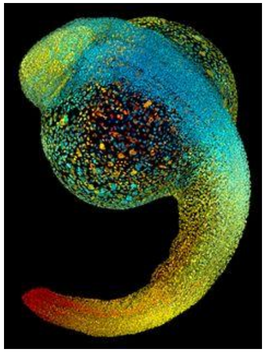


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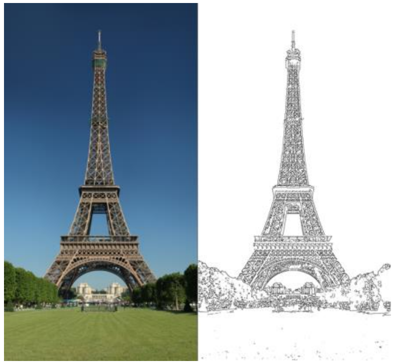
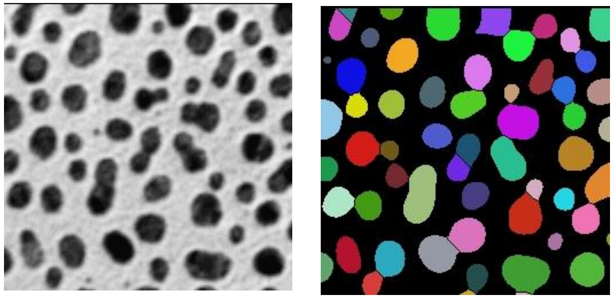
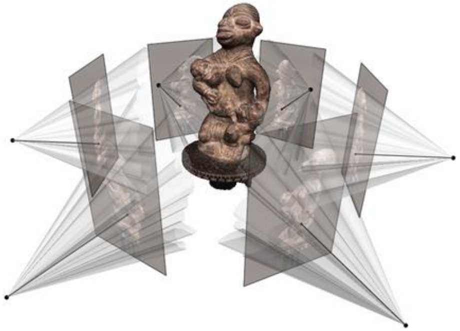
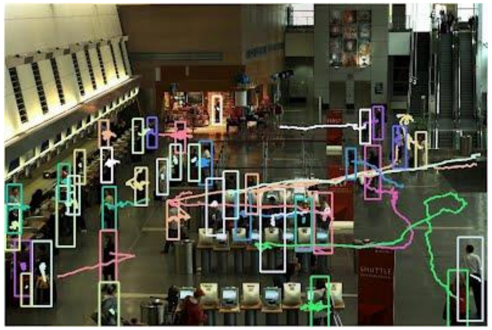
Image Processing and Computer Vision

- Foundations
- Image Transformations
  - Fourier Transform
  - Wavelet Transform
- Image Compression and Interpolation
- Linear Filters
- Non-linear Filters
- Morphological operations
- Image Segmentation
- Sequence Analysis
  - Optical Flow
  - Image registration
  - Object Tracking
- 3D Image Reconstruction
- Object Recognition









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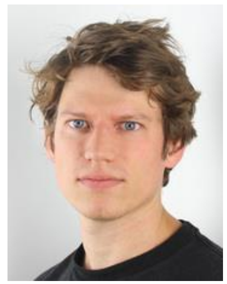
Acknowledgements – The Team

Tilo
Baumbach
Director ANKA
Research supervisor IPS

Ralf
Hofmann



Julian
Moosmann
X-ray Imaging

Phase retrieval

Tomy
dos Santos
Rolo

Fast tomography

Jubin
Kashef
Developmental
biology

Thomas
van de Kamp
Zoology
(arthropods)

Summary

If you are interested in:

- Work on topics of Bachelor/Master thesis (**will be available soon**)
- Make an internships / student practice in KIT, Karlsruhe, Germany
- Participate in lecture: “Image Acquisition Methods and Image Analysis”.
- Scientific collaboration with our group

Lecture will be organized **only** if there will be interest from students!

Take a short poll and give your feedback!
http://simpoll.ru/run/survey/39a97383

Thank you for your attention!

Questions?

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