Introduction to Scientific Visualization

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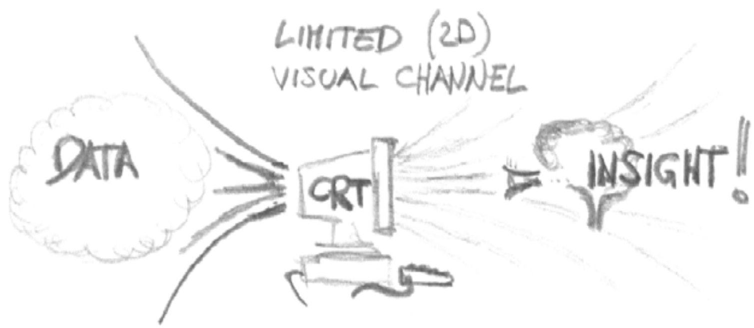
Visualization – Definition

visualization: to form a mental vision, image, or picture of (something not visible or present to the sight, or of an abstraction); to make visible to the mind or imagination

[Oxford Engl. Dict., 1989]



tool to enable a user insight into data

> "The purpose of computing is insight, not numbers."
> **[R. Hamming, 1962]**

Visualization – Goals

- Visualization, …
  - … to explore
    - Nothing is known,
      Vis used for data exploration
  - … to analyze
    - There are hypotheses,
      Vis used for verification or falsification

?!

  - … to present
    - “everything” known about the data,
      Vis used for communication of results

?!

Visualization – Areas

- Three major areas
  - Volume Visualization
  - Flow Visualization
  - Information Visualization

inherent spatial reference

Scientific Visualization

2D/3D

nD

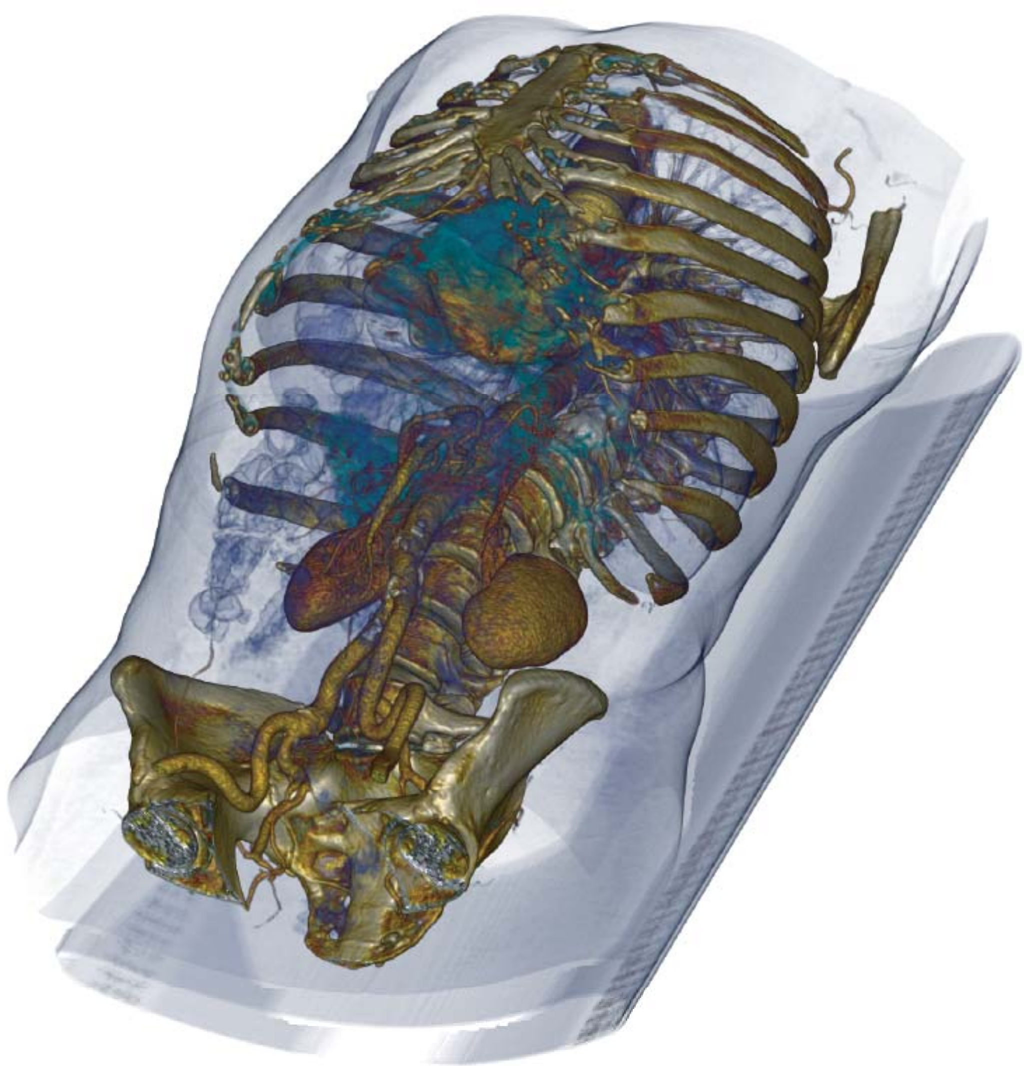
usually no spatial reference

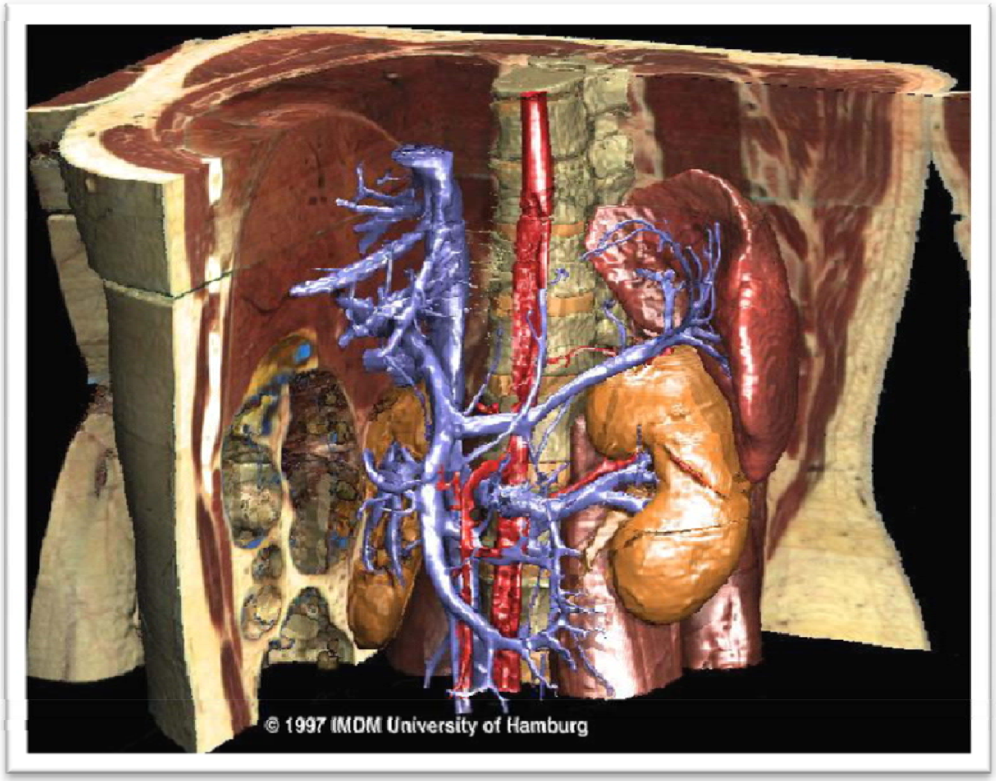
InfoVis vs. SciVis

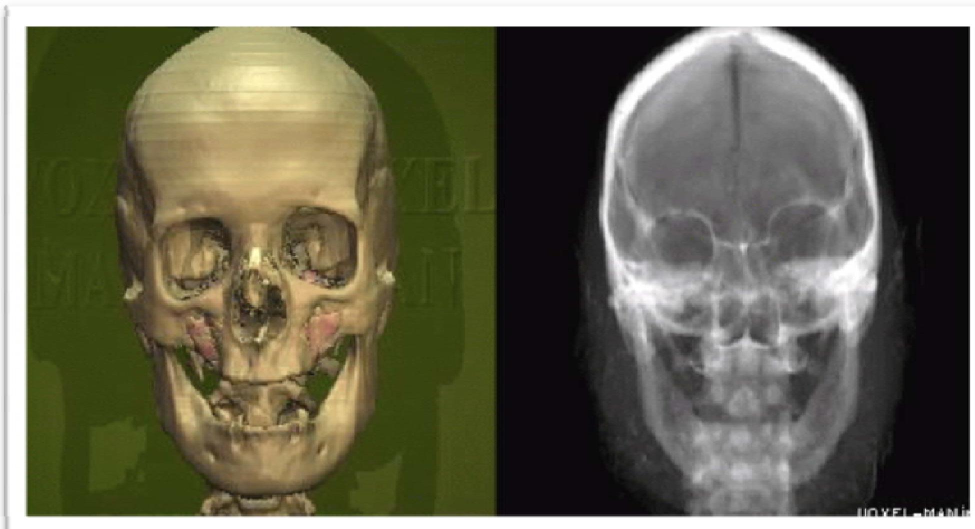
- **N-dimensional** vs. **2/3-dimensional**
  - SciVis can be N-dimensional too (time series, simulation data, …)
- **Abstract data** vs. **spatial data**
  - InfoVis data may also have spatial attributes (country, state, …)
- **Discrete data** vs. **continuous data**
  - InfoVis data may be sampled from a continuous domain

SciVis – Examples (1)

- Volume data

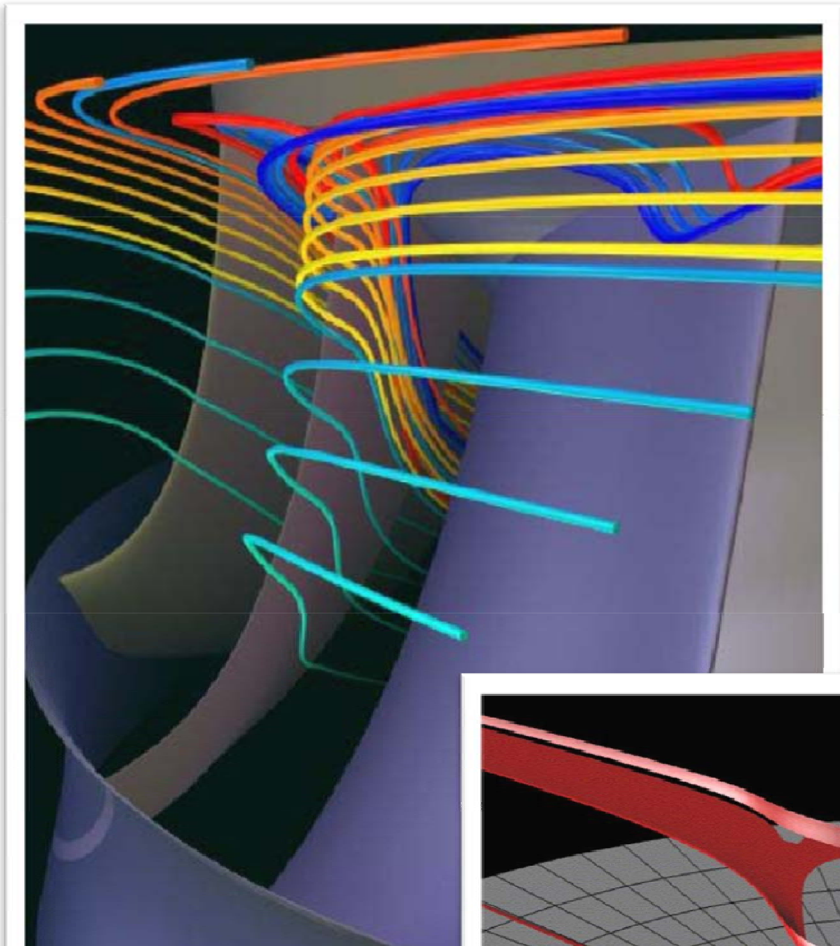


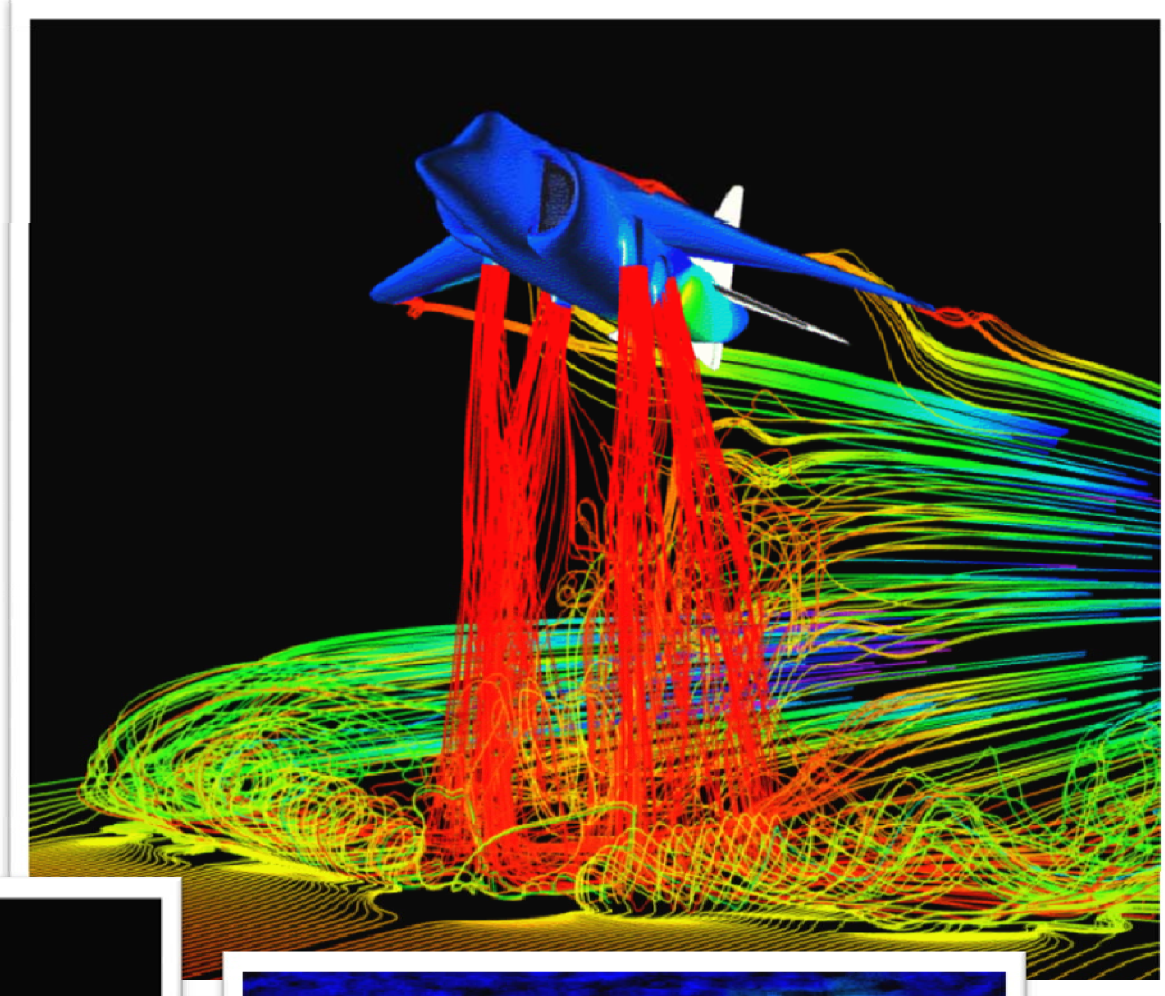


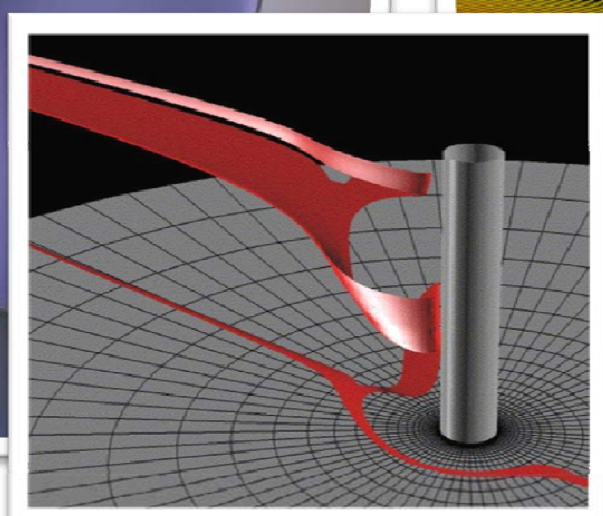


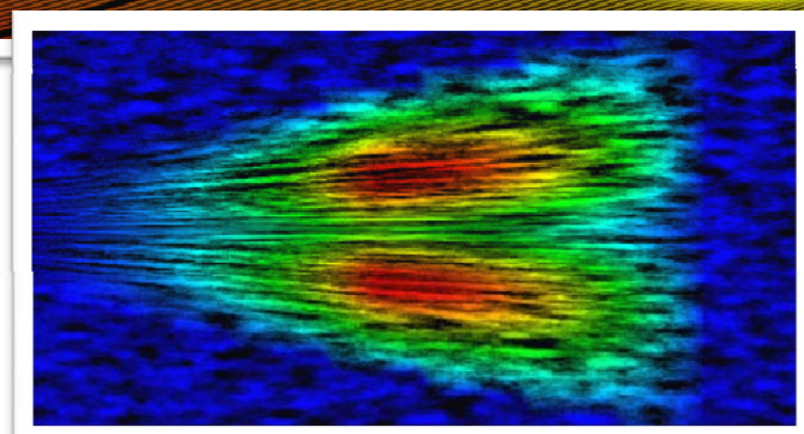
SciVis – Examples (2)

- Flow data

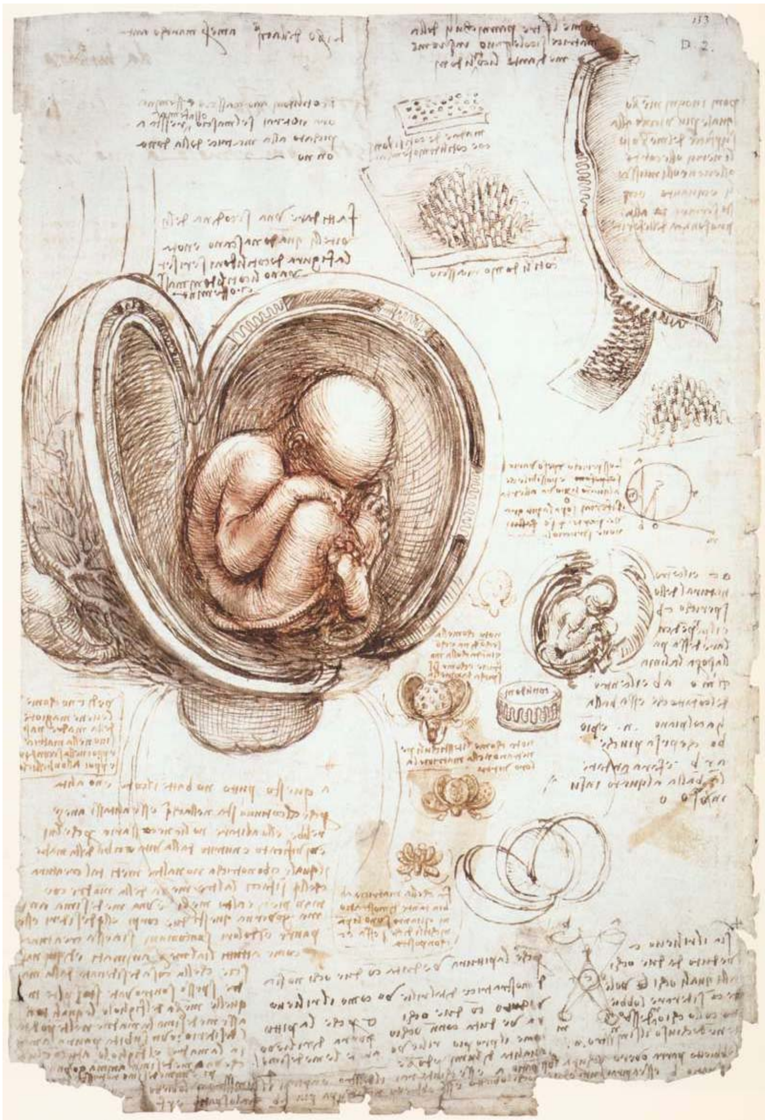




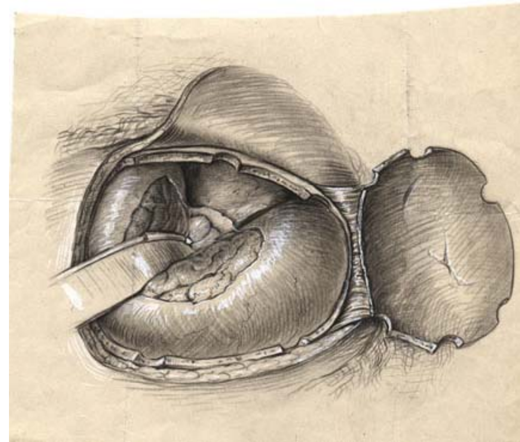


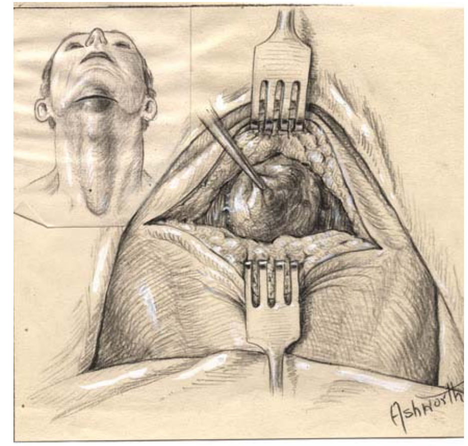


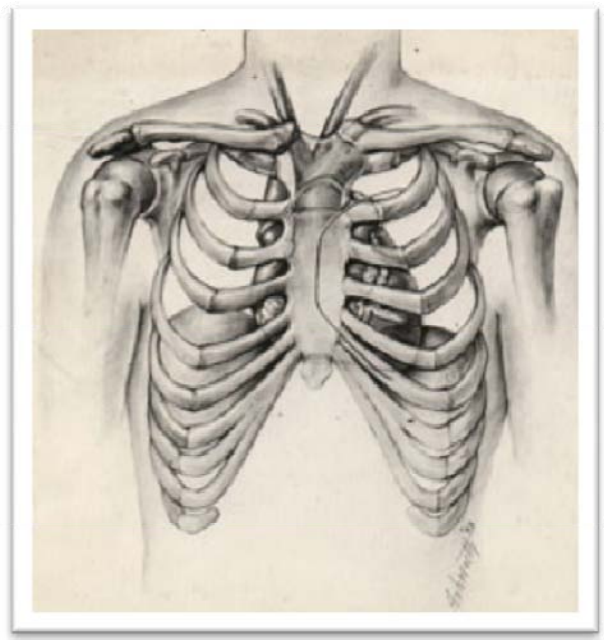
Medicine



sketch from Leonardo Da Vinci's anatomical notebooks

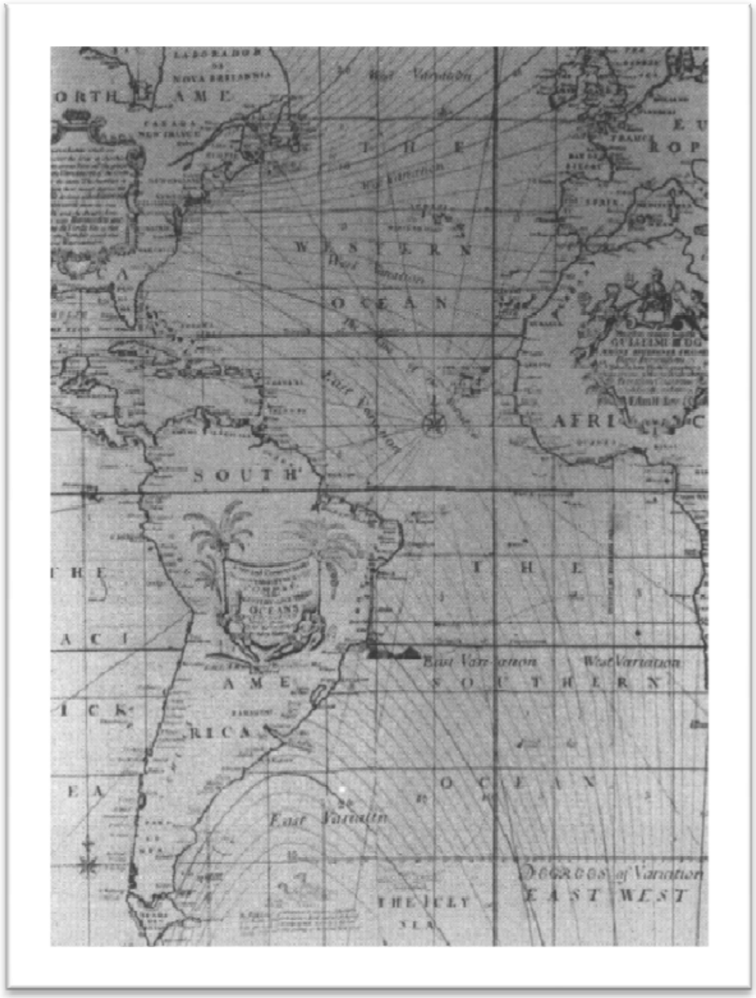




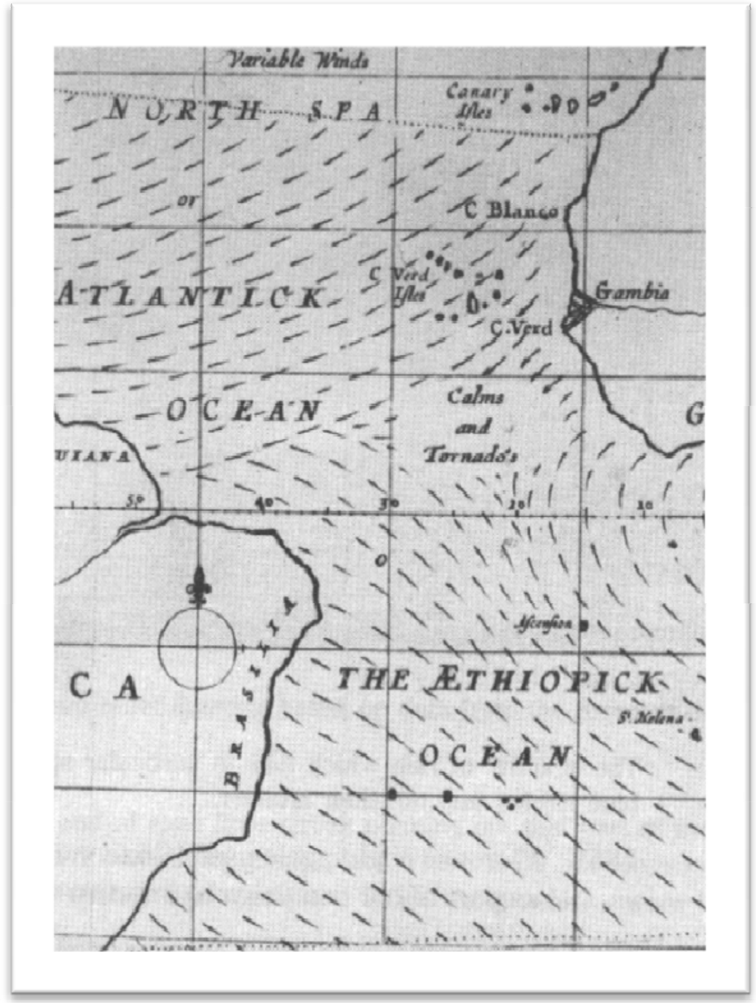


medical illustrations by Clarice Ashworth Francone

Cartography

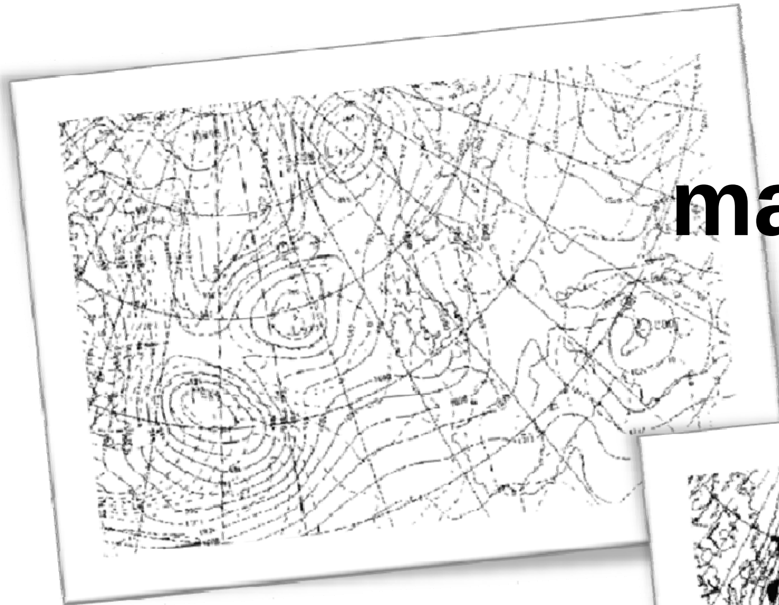


isolines to visualize compass deviations

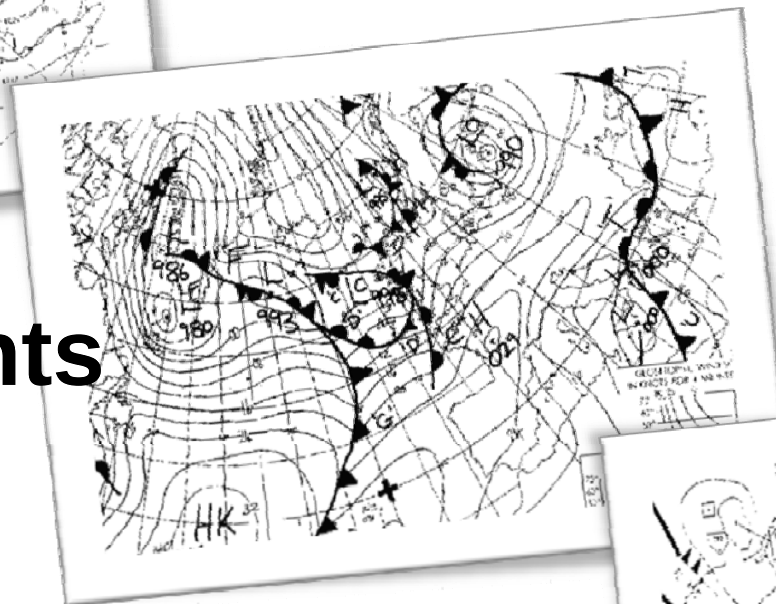


wind flow visualization

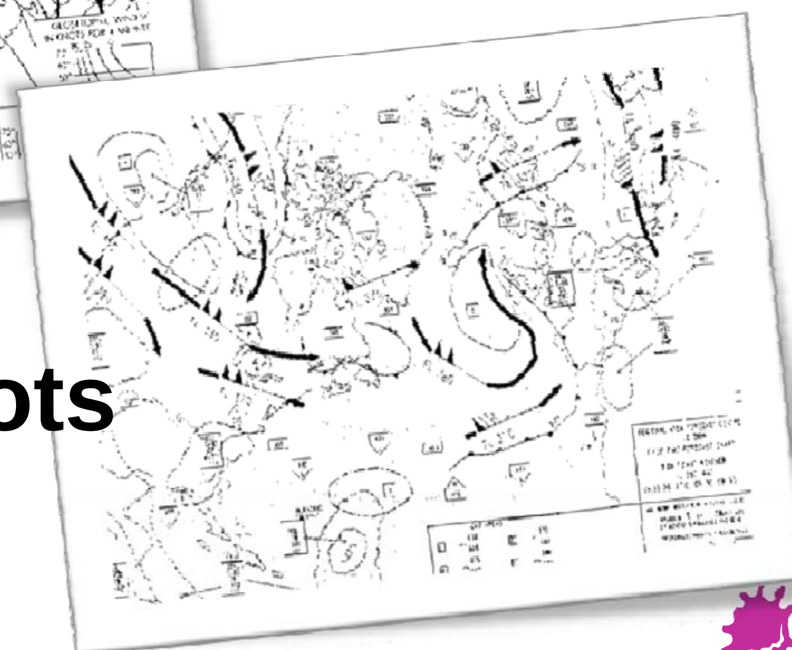
Meteorology



map with iso-pressure lines



weather fronts

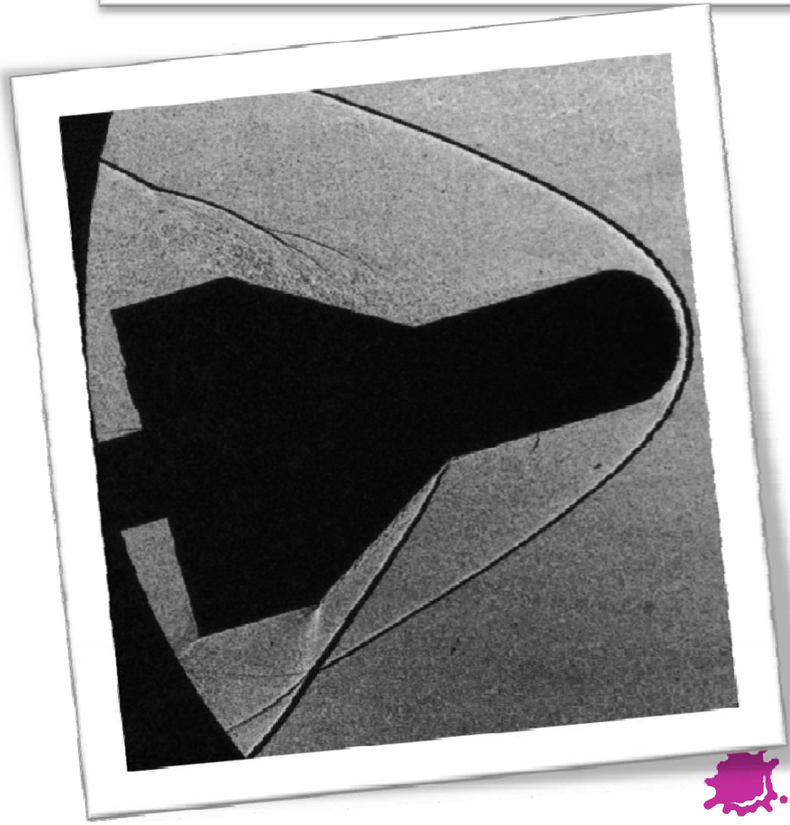


map for pilots

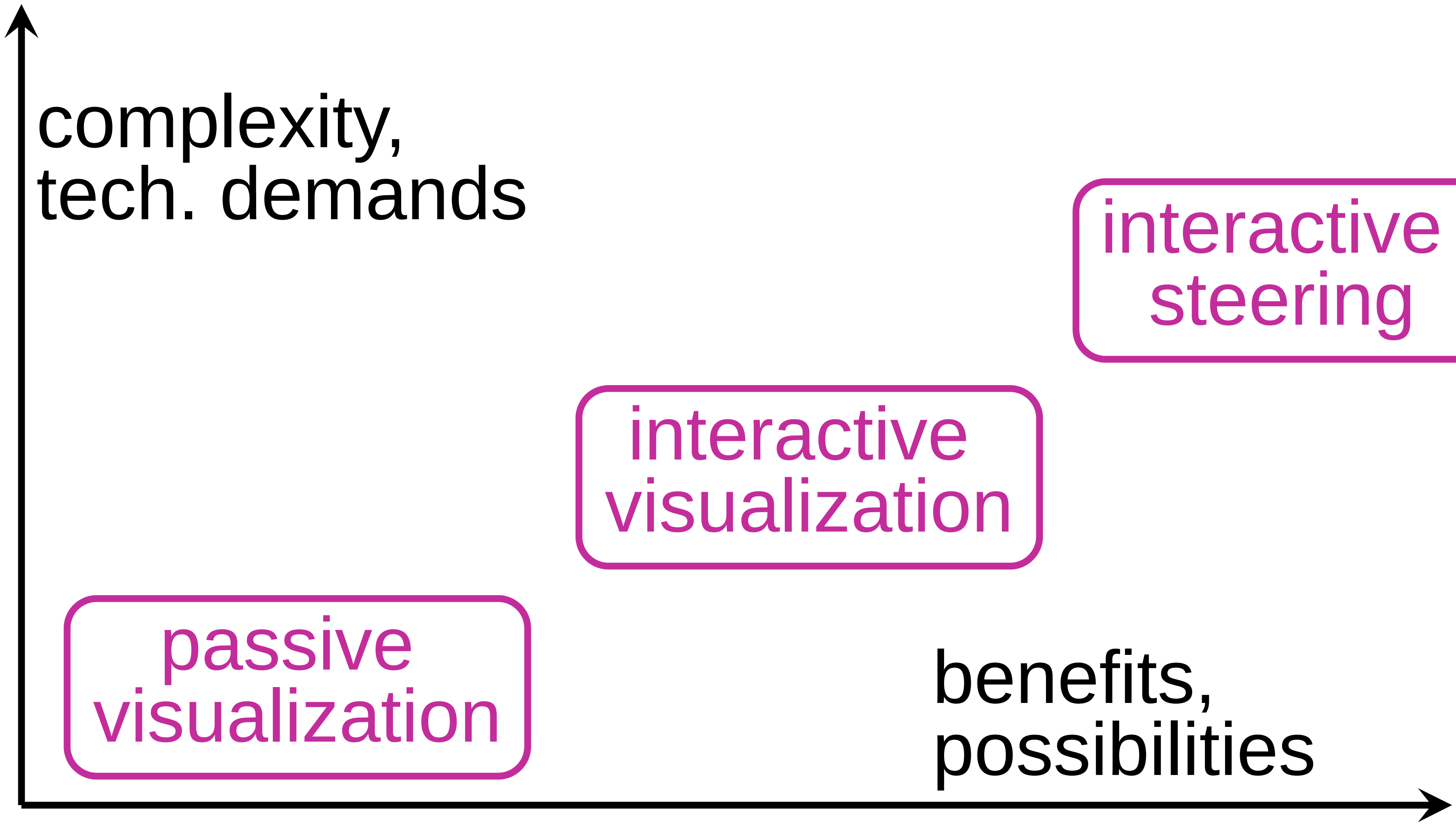
Experimental Flow Investigation

- Fixation of tufts, ribbons on ...
  - aircraft in wind tunnels
  - ship hull in fluid tanks

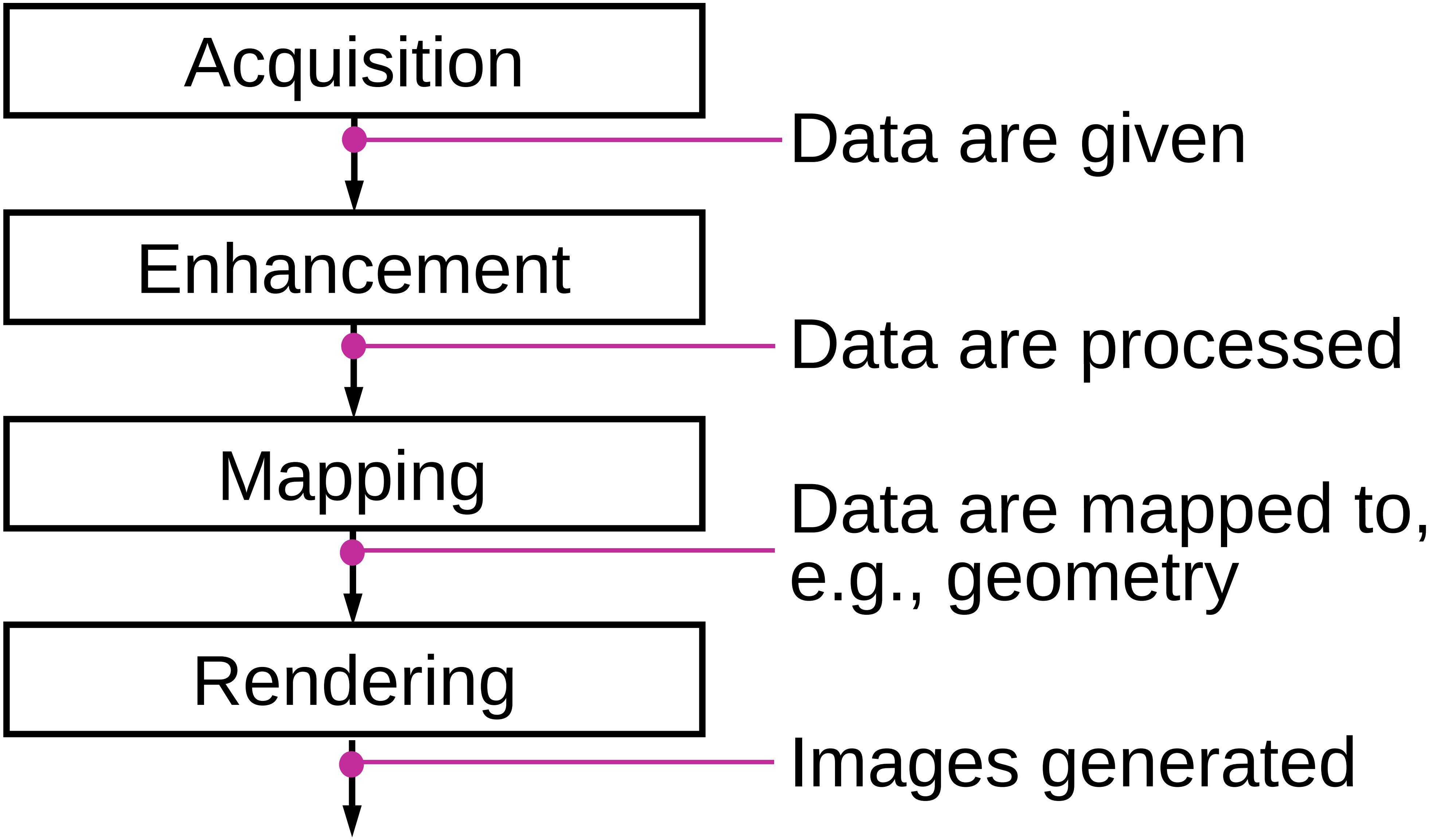
- Introduction of smoke particles (in wind tunnel)
- Introduction of dye (in fluids)



Visualization Scenarios



Visualization Pipeline



Data

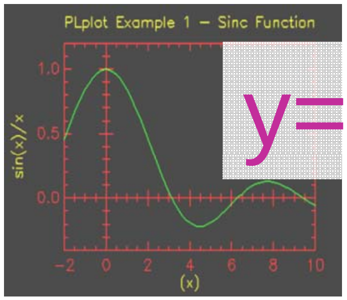
- Focus of visualization,
  everything is centered around the data
- Driving factor (besides user) in choice and attribution of the visualization technique
- Important questions
  - In what domain are the data given?
    (**data space**)
  - What is the type of data?
    (**data characteristics**)
  - Which **representation** makes sense?

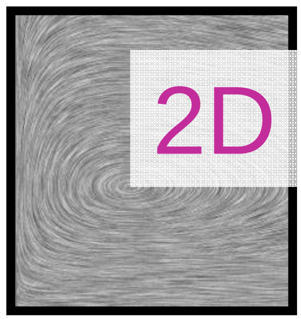
Data Space vs. Data Characteristics

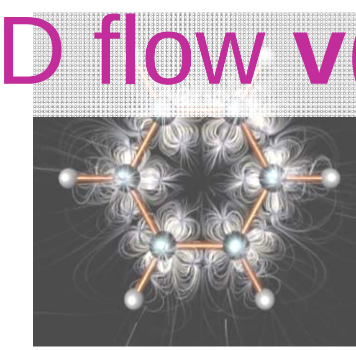
data characteristics

data space

	1D	2D	3D
1D	y=f(x)		spatial curve **x**(t)
2D		2D flow **v**(**x**)	
3D	scalar field d(**x**)		3D flow **v**(**x**)





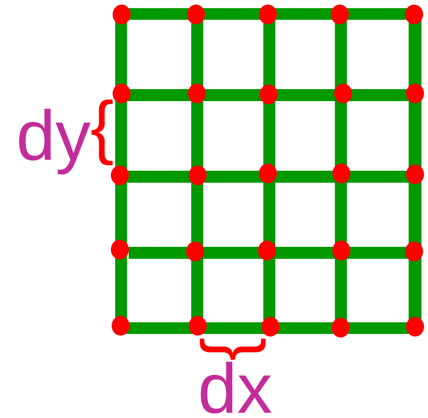


Grids – General Information

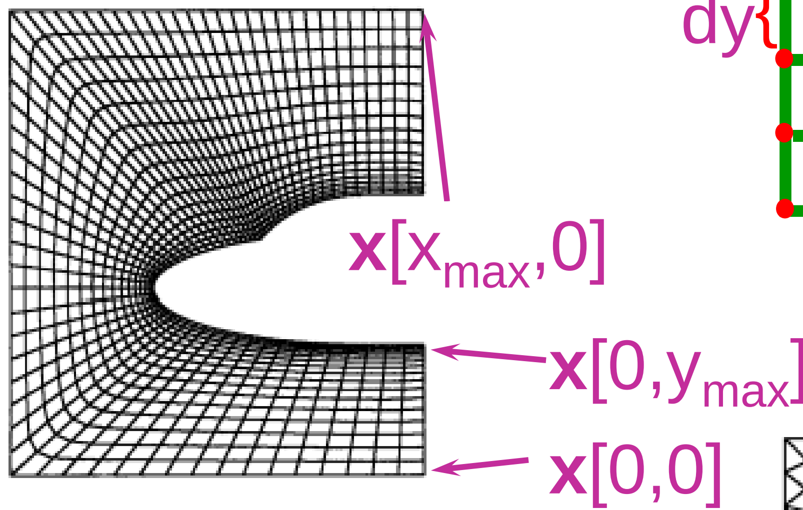
- Important questions
  - Which data organization is optimal?
  - Where do the data come from?
  - Is there a neighborhood relationship?
  - How is the neighborhood information stored?
  - How is navigation within the data possible?
  - Calculations with the data possible ?
  - Are the data structured?

Grid - Types

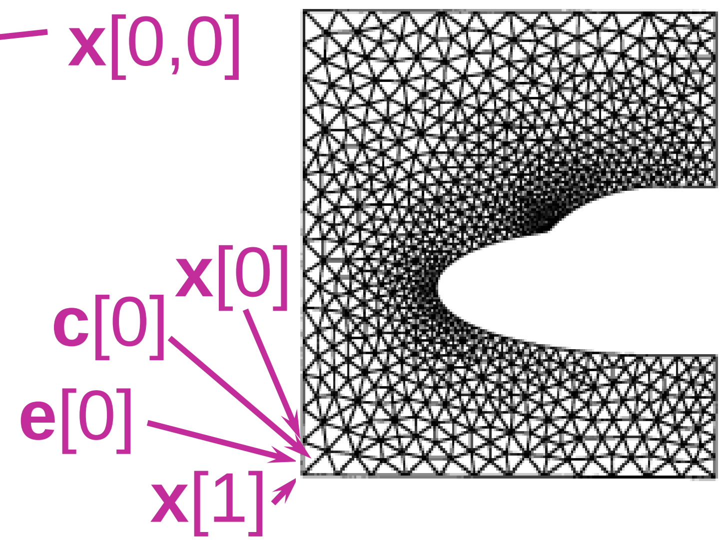
- Cartesian grid



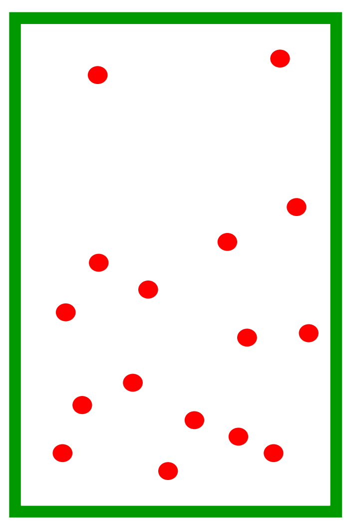
- Curvilinear grid



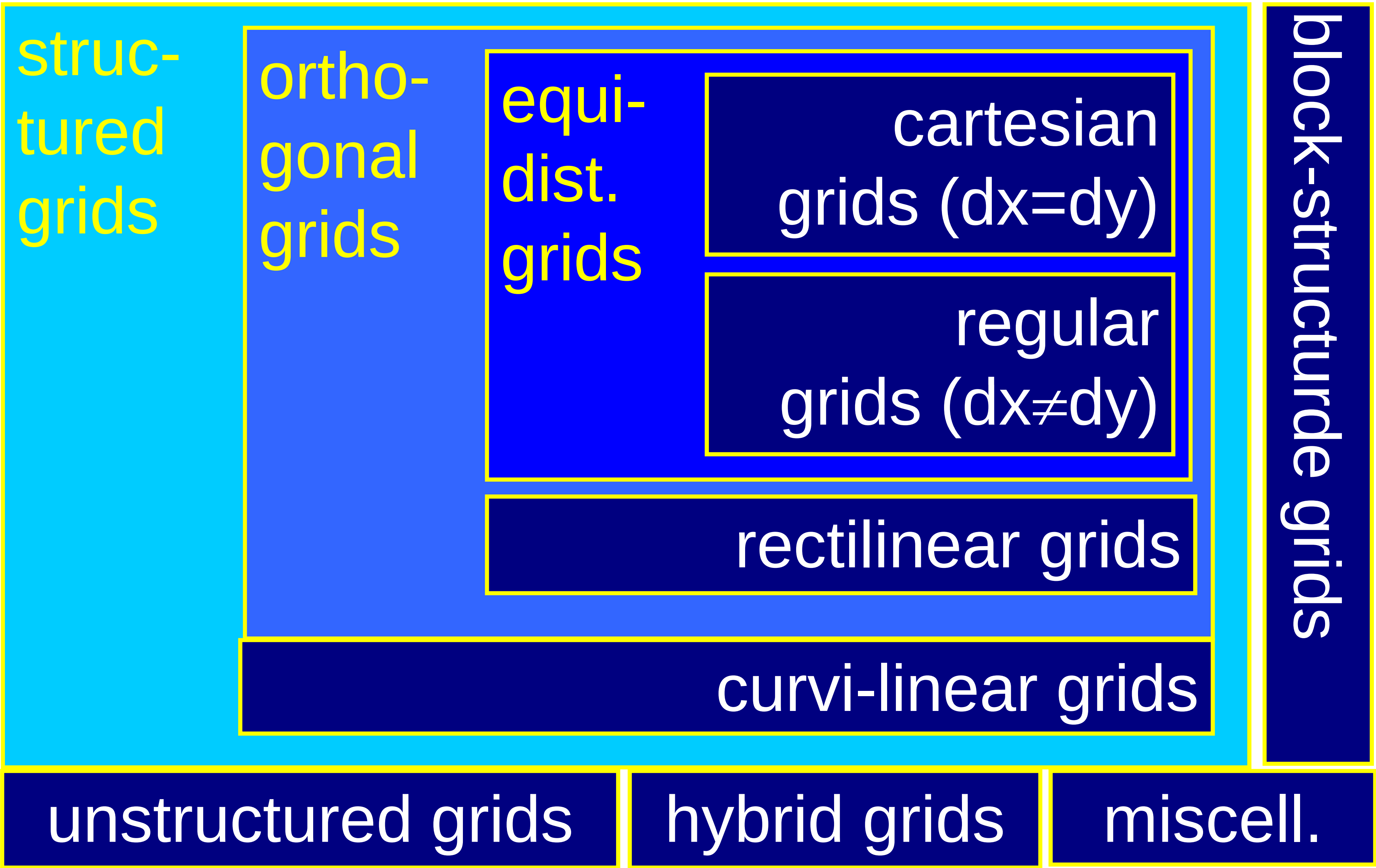
- Unstructured grid



- Scattered data



Grids - Survey

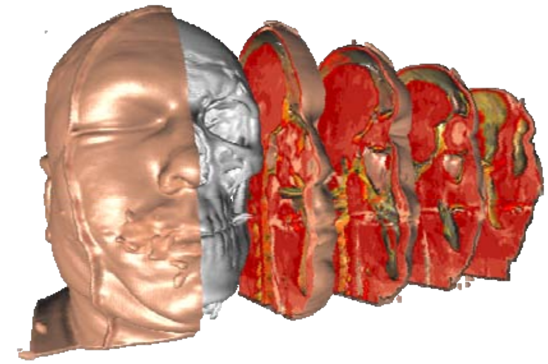


Volume Visualization

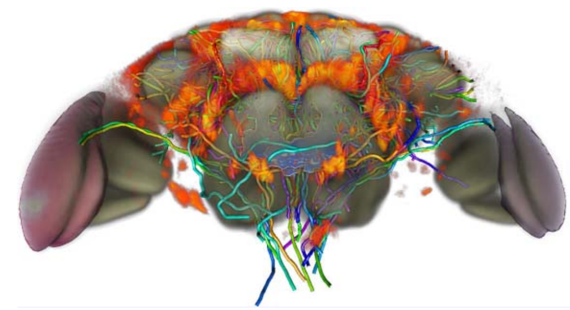
- VolVis = visualization of volume data
  - Mapping 3D→2D
- Volume data
  - 3D×1D data
  - Scalar data, 3D data space, space filling
- User goals
  - Gain insight in 3D data
  - Structures of special interest + context

Volume Data

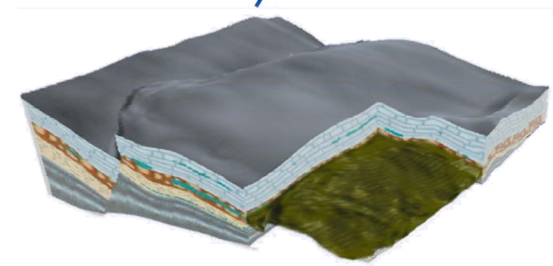
- Medicine
  - CT, MRI, PET, Ultrasound



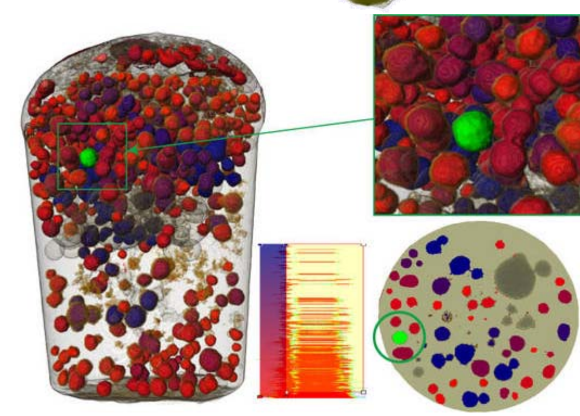
- Biology
  - Confocal microscopy, histological cuts



- Geology
  - Seismic surveys

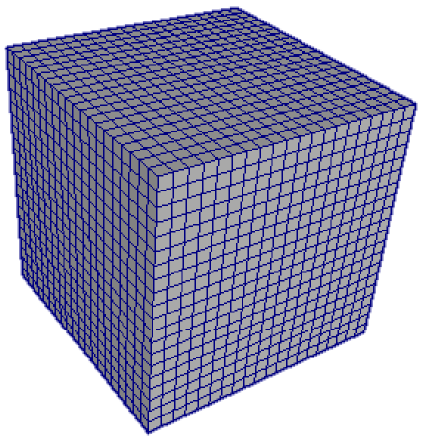


- Material testing
  - Industrial CT

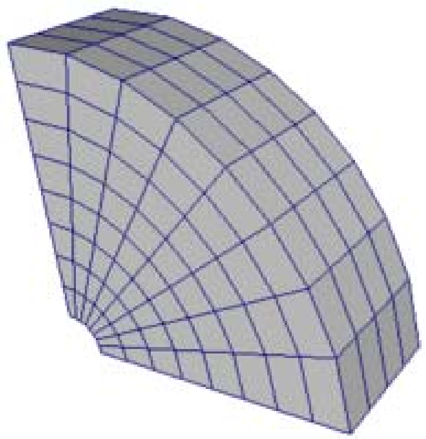


3D Data Space

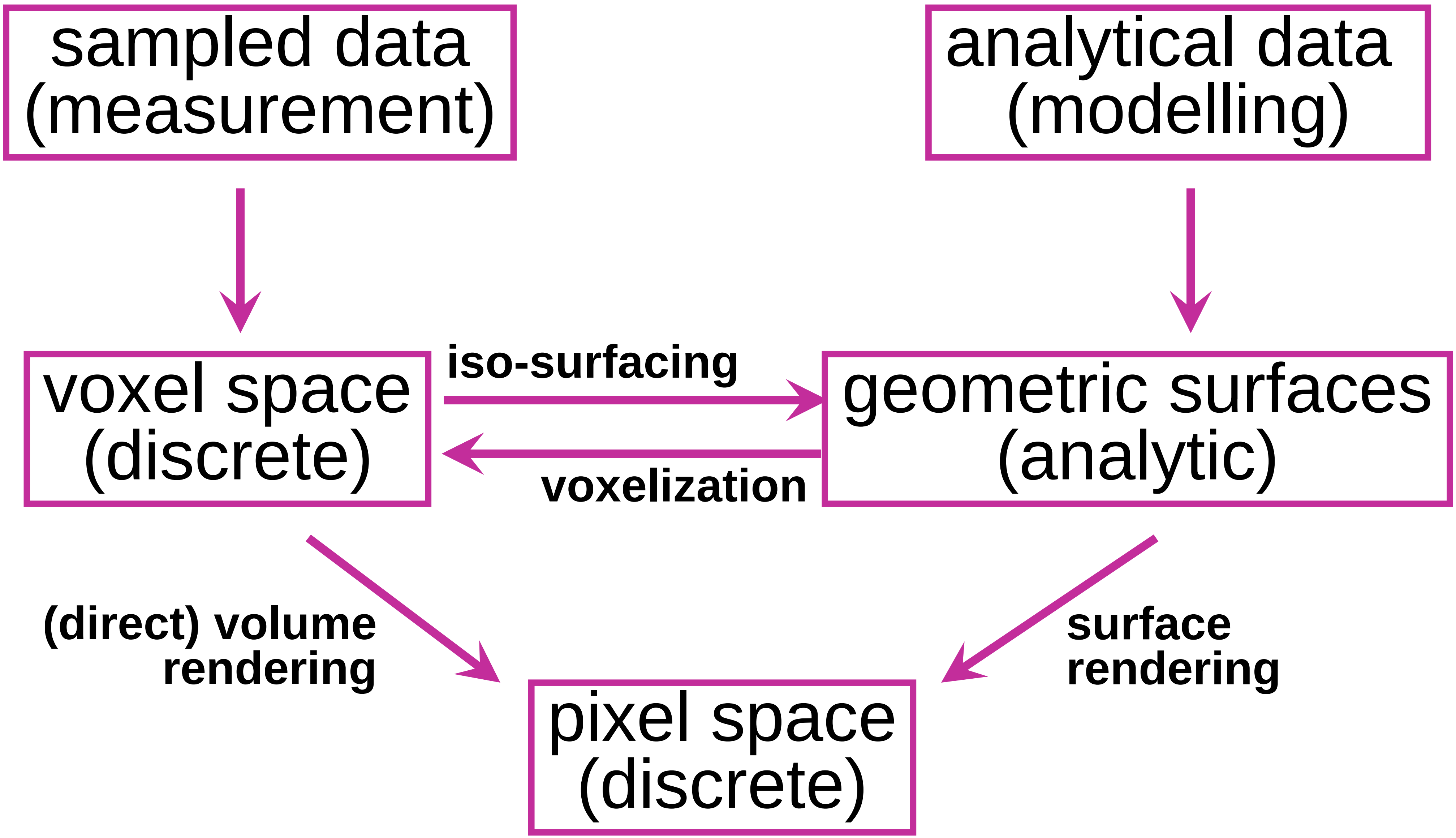
- Cartesian/regular grid
  - Most common, e.g., CT/MRI scans



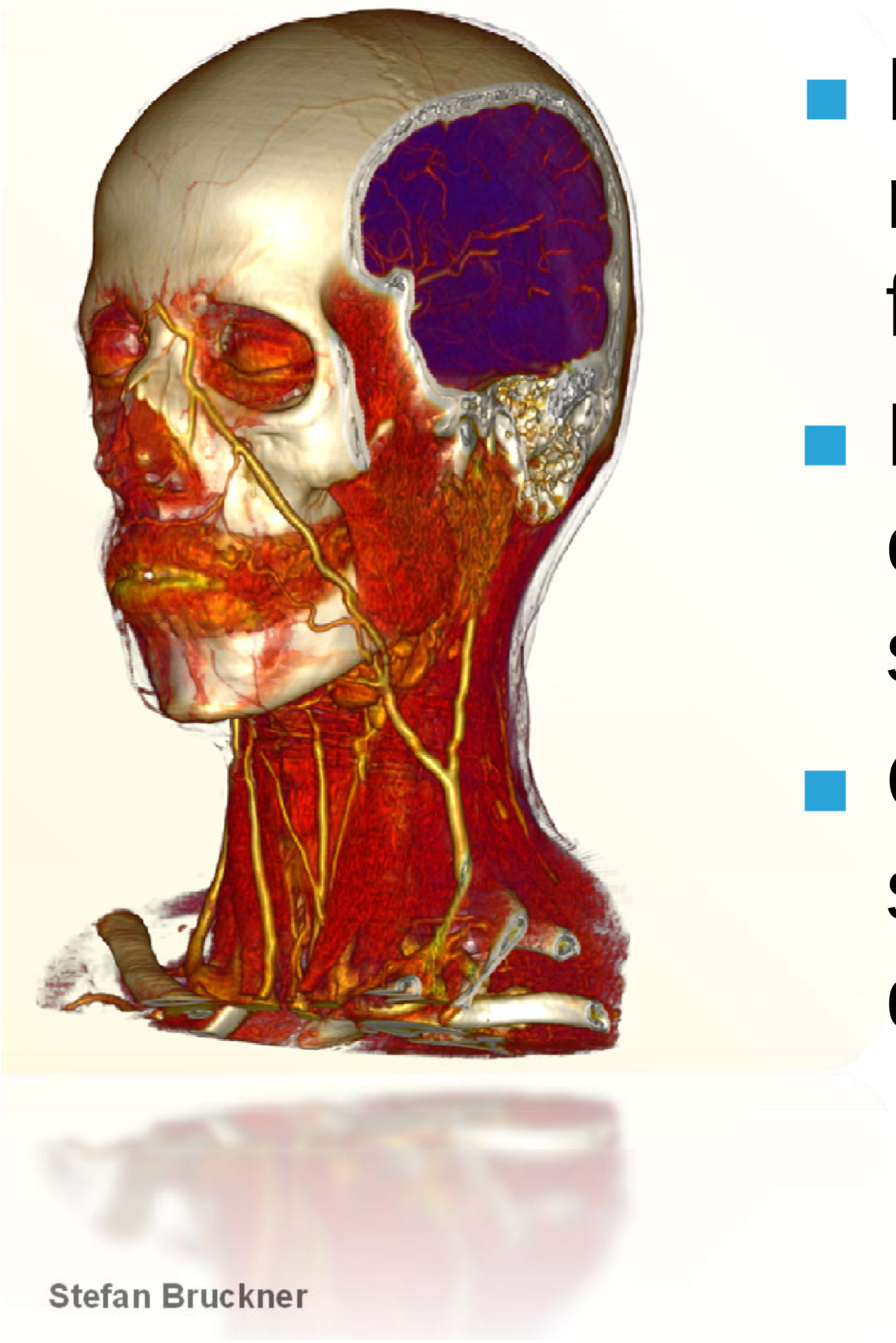
- Curvilinear/unstructured grid
  - Less frequently, e.g., simulation data



Concepts and Terms



Volume Rendering (1)



- Deals with the visual representation of 3D functions
- Frequently, but not exclusively, functions are scalar-valued
- Often aquired using sampling (e.g., medical domain)

Volume Rendering (2)

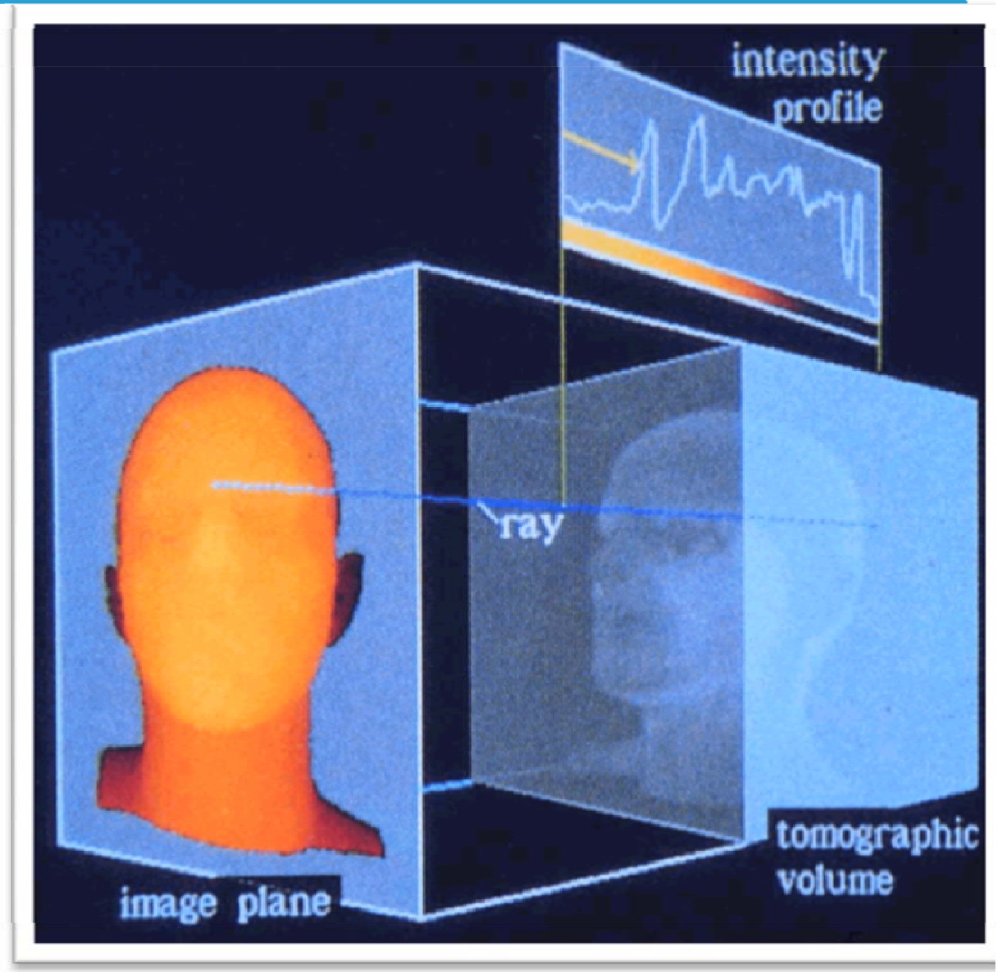
- Initially volumes were visualized using two-dimensional cuts
- Extraction of surface geometry for isosurfaces in the volume (e.g. Marching Cubes [Lorensen and Cline 1987])
- Volume rendering introduced almost simultaneously by [Levoy 1988] and [Drebin et al. 1988]

Surface vs. Volume Rendering

- Surface rendering
  - **Indirect** volume visualization
  - Intermediate representation: iso-surface
  - Pros: Less memory, fast rendering
- Volume rendering
  - **Direct** volume visualization
  - Usage of transfer functions
  - Pros: illustrate the interior, semi-transparency

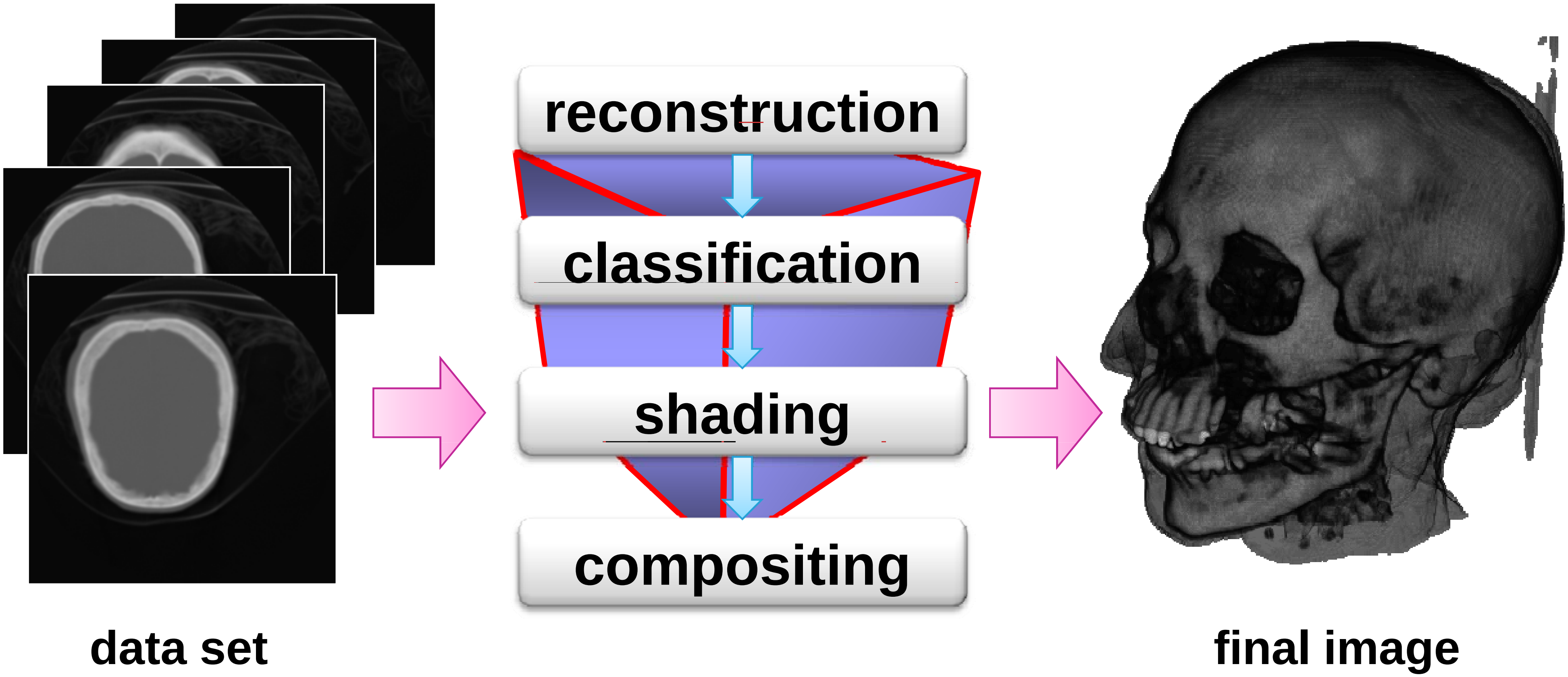
Volume Ray Casting

- Volume: 1D value defined in 3D $f(\mathbf{x}) \in R^1$, $\mathbf{x} \in R^3$
- Ray: Half-line $\mathbf{r}(t) \in R^3$, $t \in R^1 > 0$
- Intensity profile: values along a ray $f(\mathbf{r}(t)) \in R^1$, $t \in R^1 > 0$
- Image plane: starting points of rays



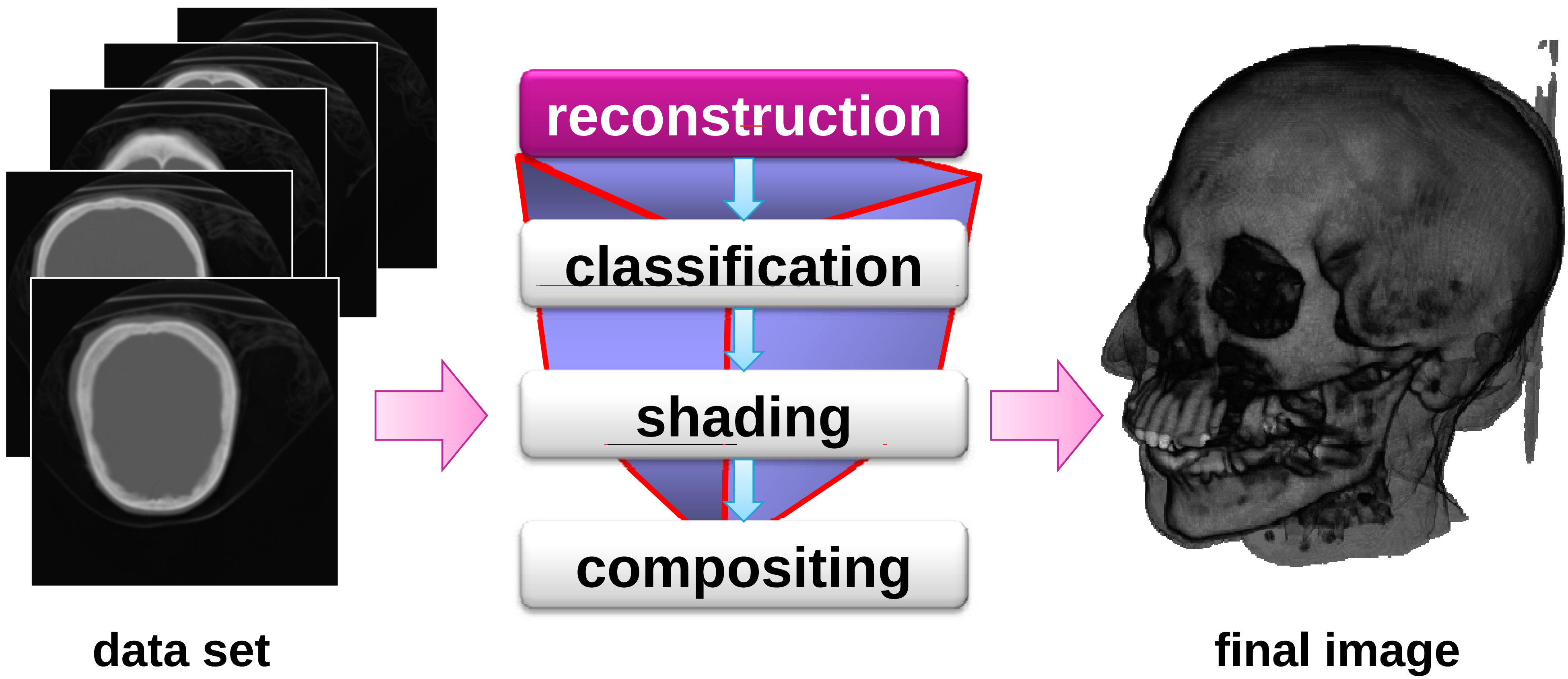
Pipeline – Overview

volume rendering pipeline



Pipeline – Reconstruction

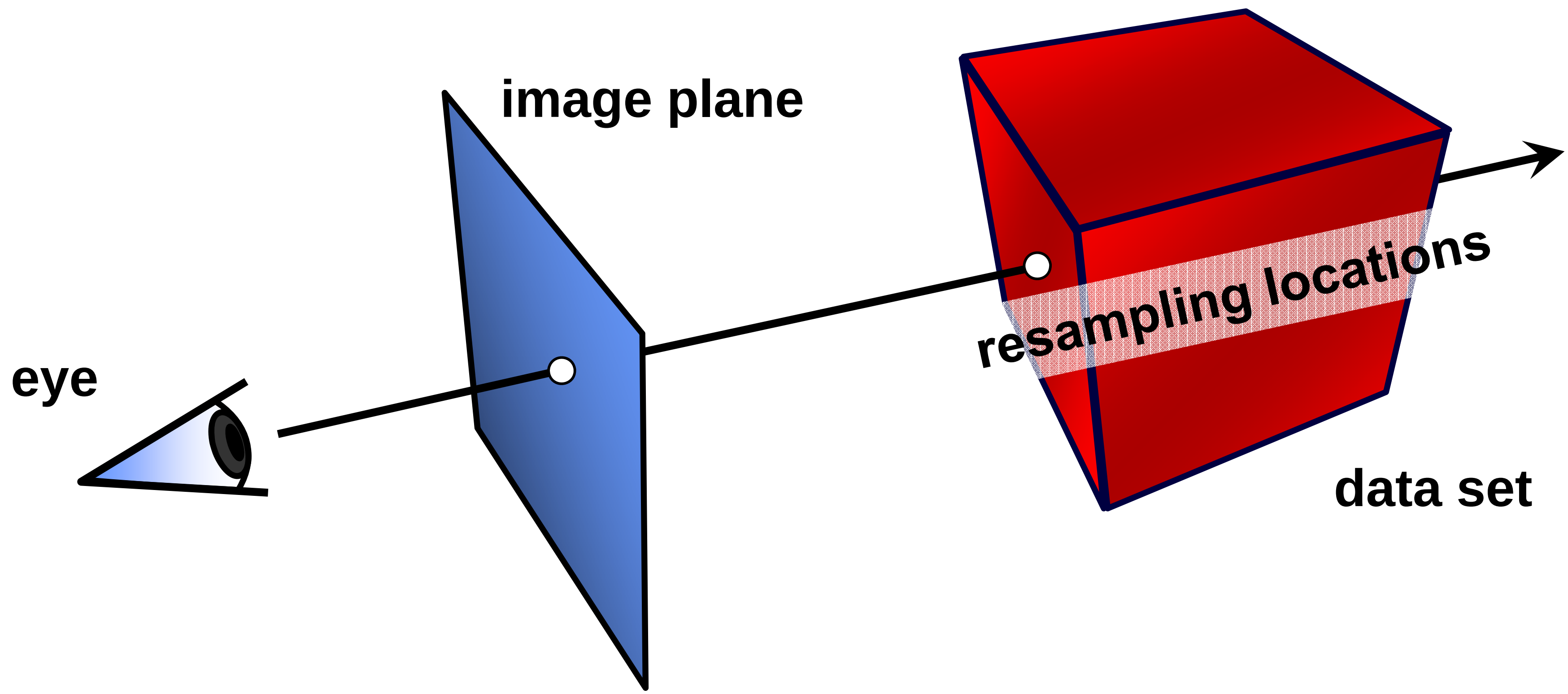
volume rendering pipeline



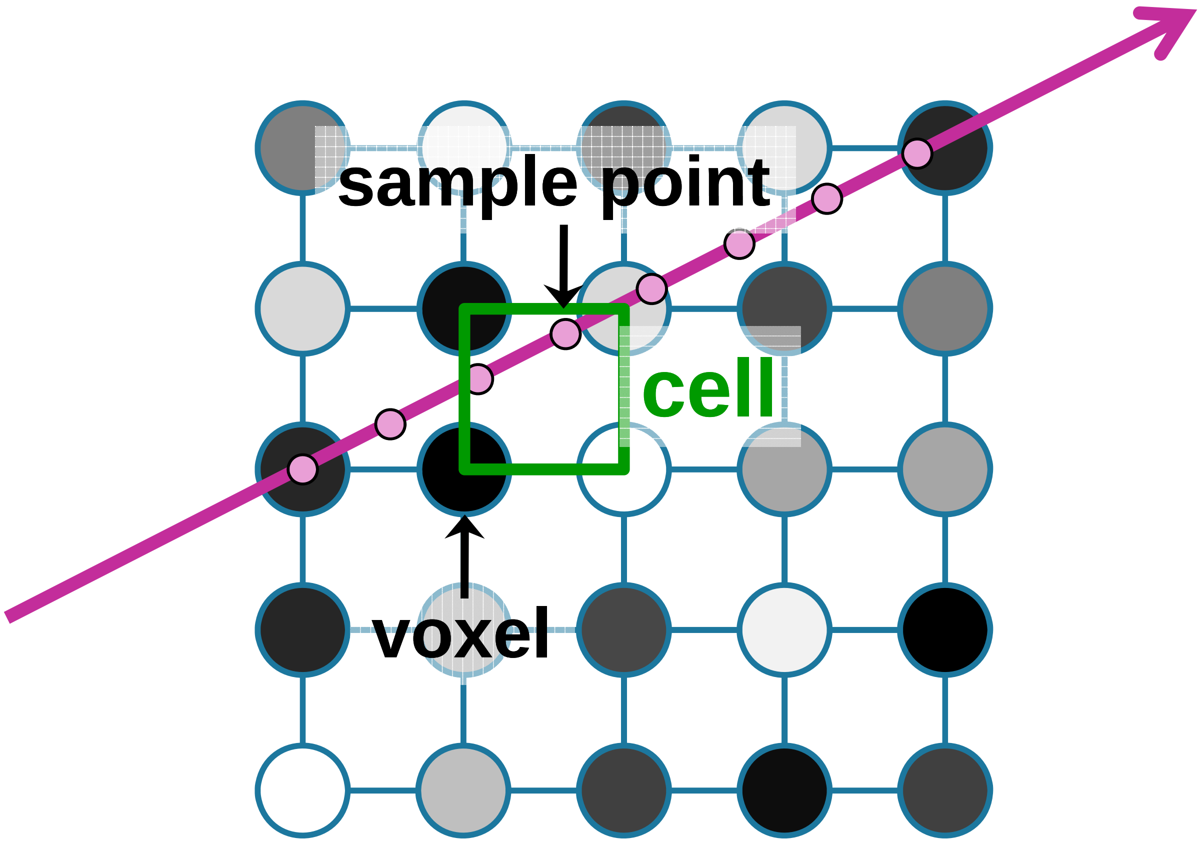
Reconstruction (1)

- Usually volume data sets are given as a grid of discrete samples
- For rendering purposes, we want to treat them as continuous three-dimensional functions
- We need to choose an appropriate reconstruction filter
- Requirements: high-quality reconstruction, but small performance overhead

Reconstruction (2)

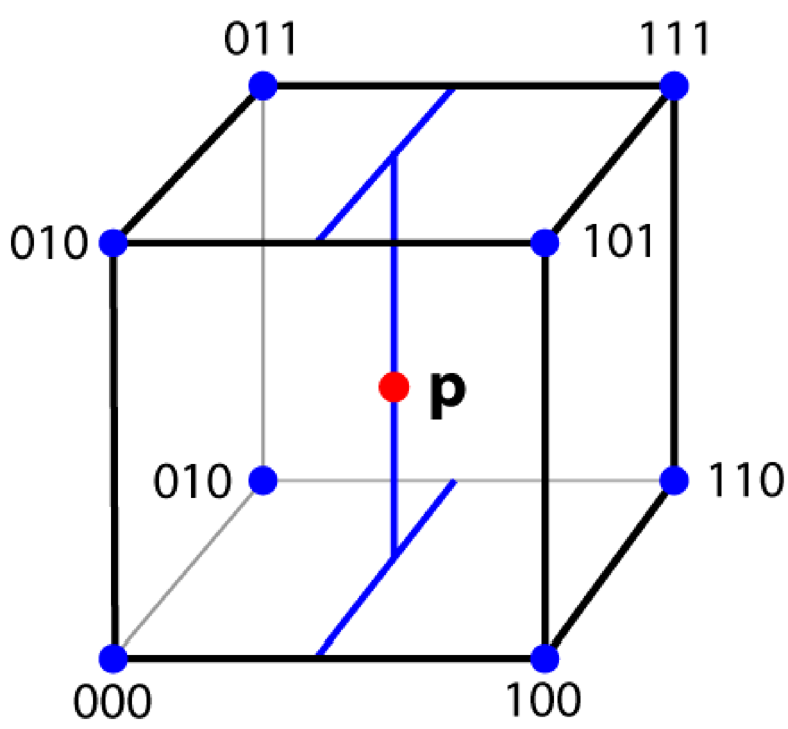


Reconstruction (3)



Trilinear Interpolation

- Simple extension of linear interpolation to three dimensions
- Advantage: current GPUs automatically do trilinear interpolation of 3D textures



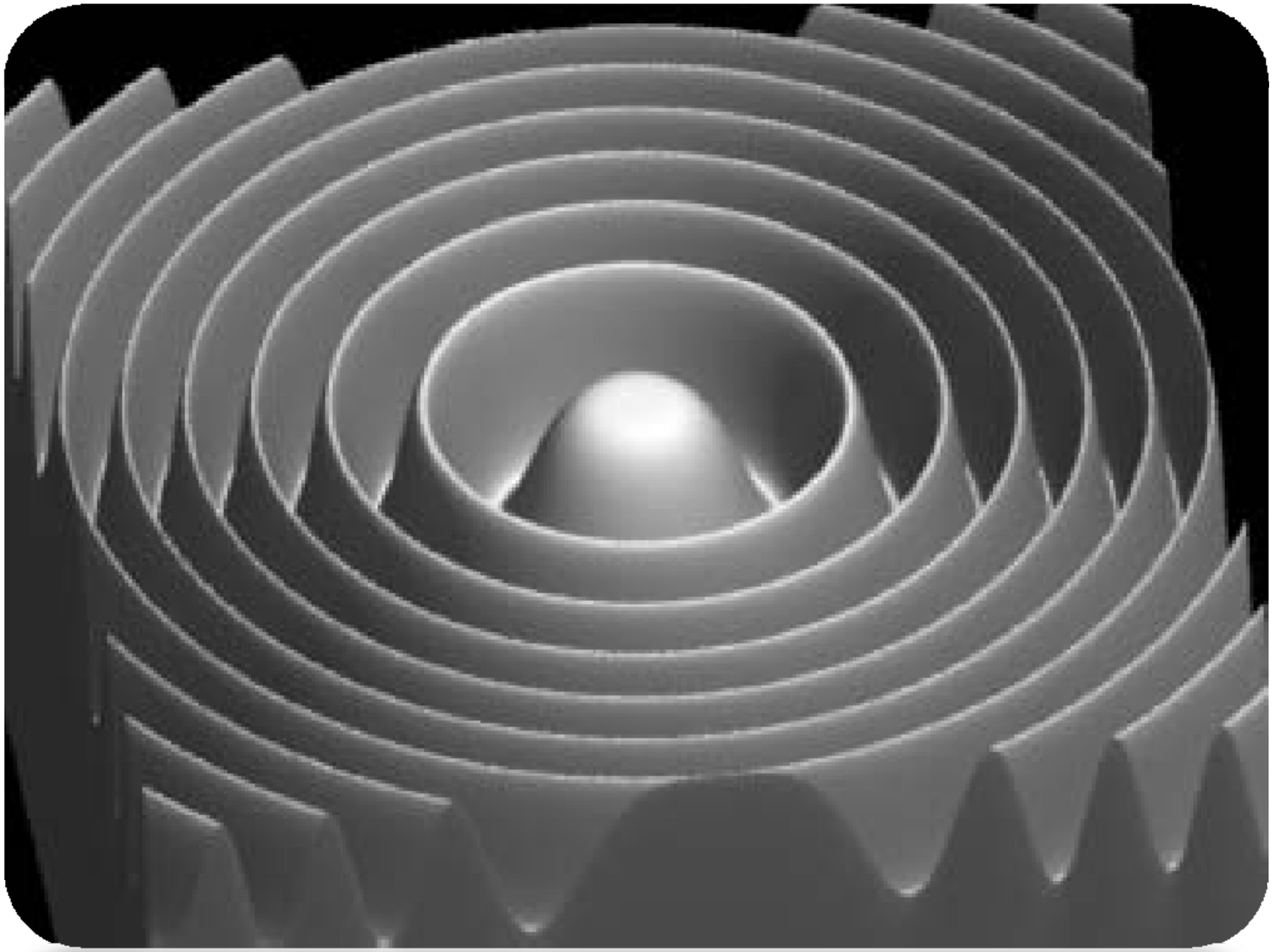
$$
\begin{aligned}
v_p = \; & v_{000}(1-x_p)(1-y_p)(1-z_p)+ \\
& v_{100}x_p(1-y_p)(1-z_p)+ \\
& v_{010}(1-x_p)y_p(1-z_p)+ \\
& v_{001}(1-x_p)(1-y_p)z_p+ \\
& v_{011}(1-x_p)y_pz_p+ \\
& v_{101}x_p(1-y_p)z_p+ \\
& v_{110}x_py_p(1-z_p)+ \\
& v_{111}x_py_pz_p
\end{aligned}
$$

Other Reconstruction Filters

- If very high quality is required, more complex reconstruction filters may be required
- Marschner-Lobb function is a common test signal to evaluate the quality of reconstruction filters [Marschner and Lobb 1994]
- The signal has a high amount of its energy near its Nyquist frequency
- Makes it a very demanding test for accurate reconstruction

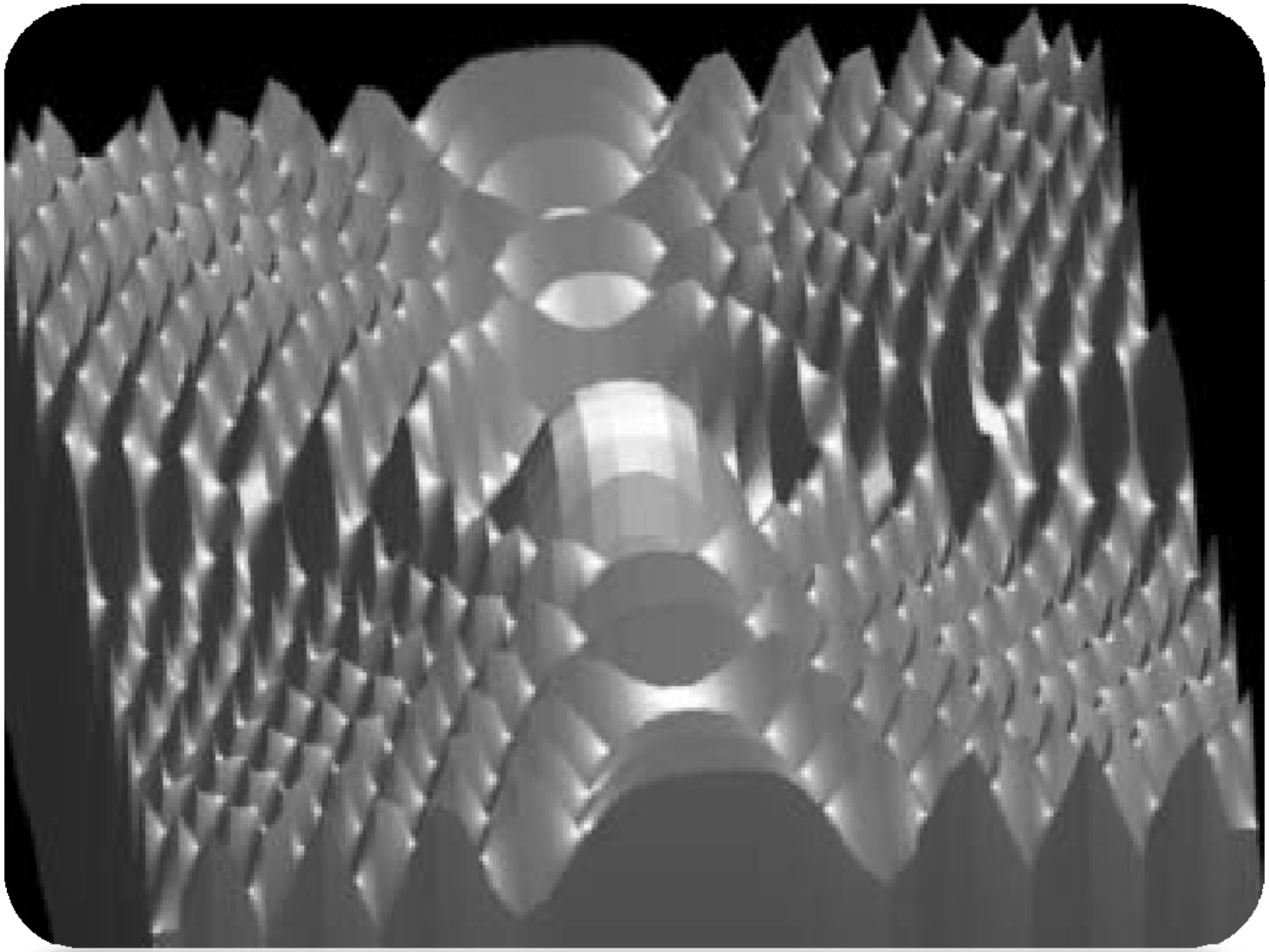
Comparison of Reconstruction Filters (1)

- Marschner-Lobb test signal (analytically evaluated)



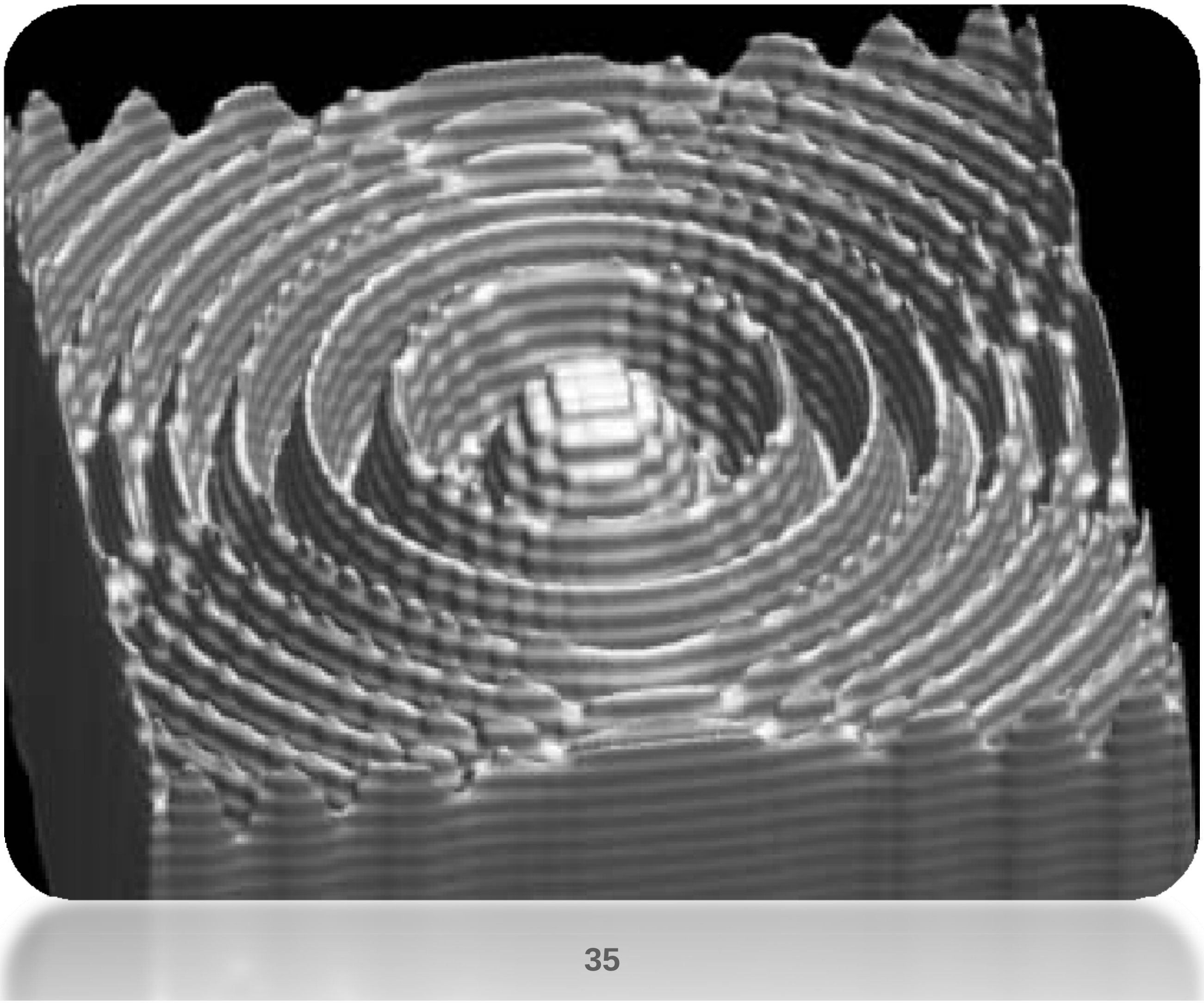
Comparison of Reconstruction Filters (2)

- **Trilinear** reconstruction of Marschner-Lobb test signal



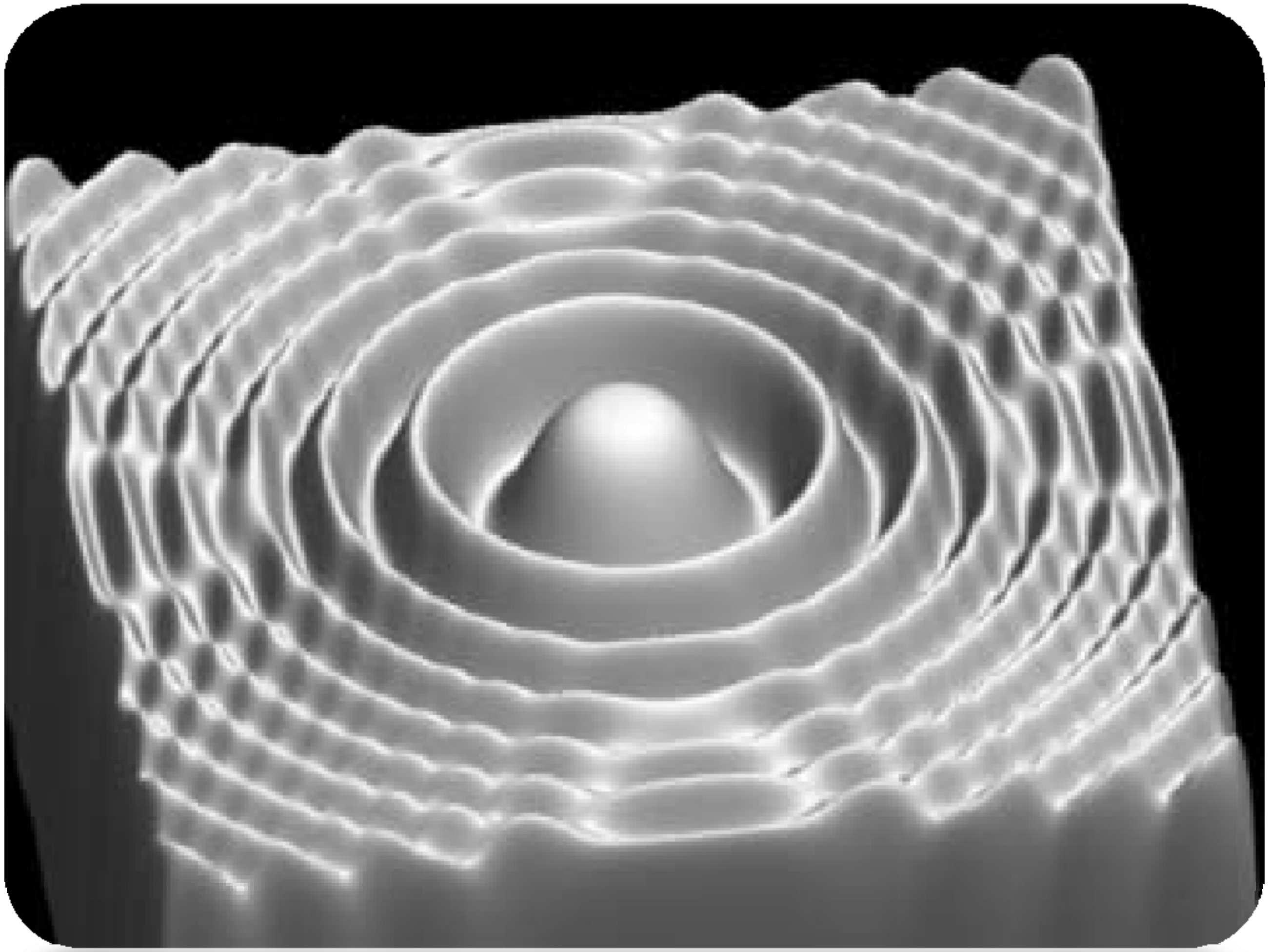
Comparison of Reconstruction Filters (3)

- **Cubic** reconstruction of Marschner-Lobb test signal



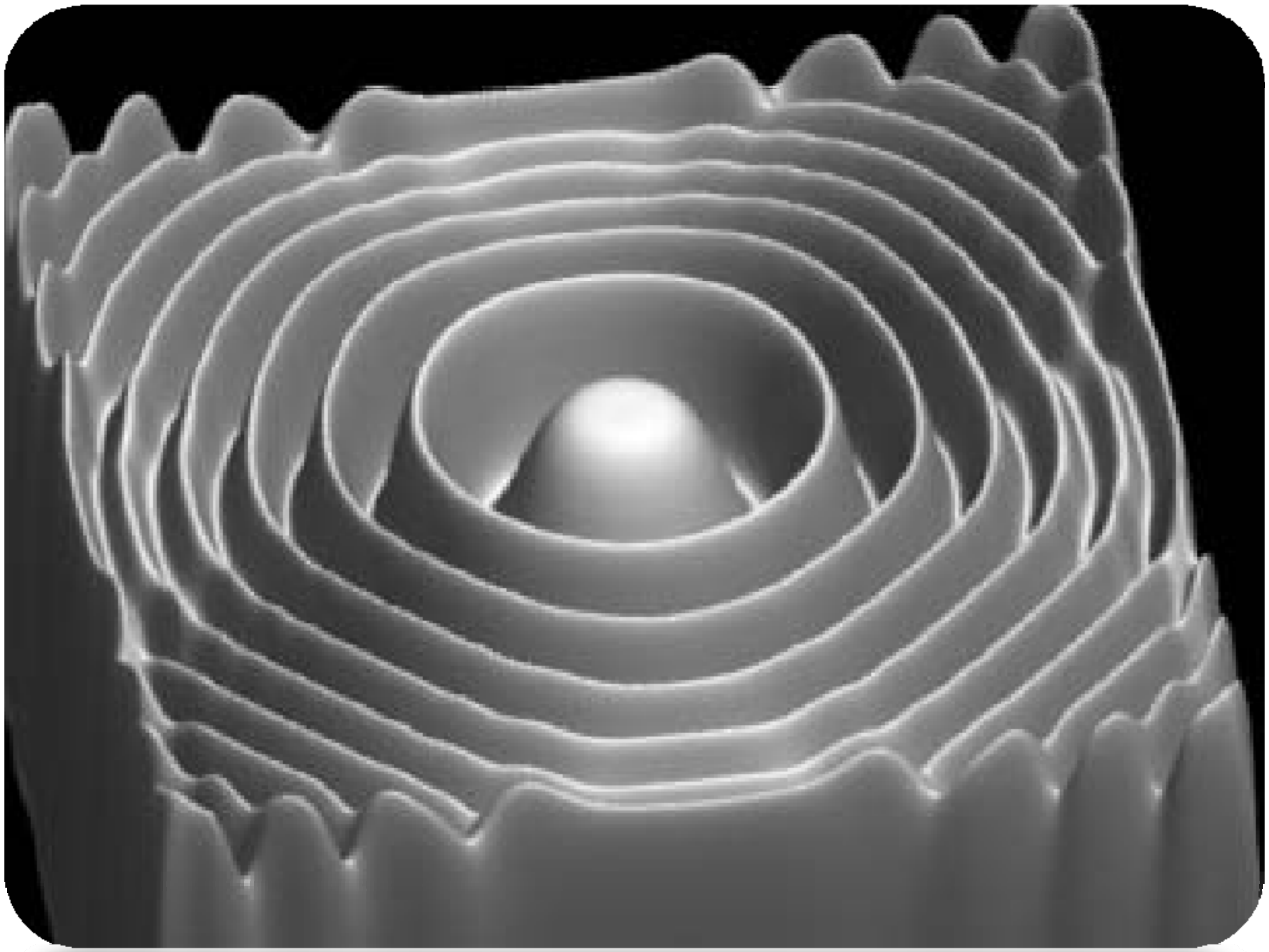
Comparison of Reconstruction Filters (4)

- **B-Spline** reconstruction of Marschner-Lobb test signal



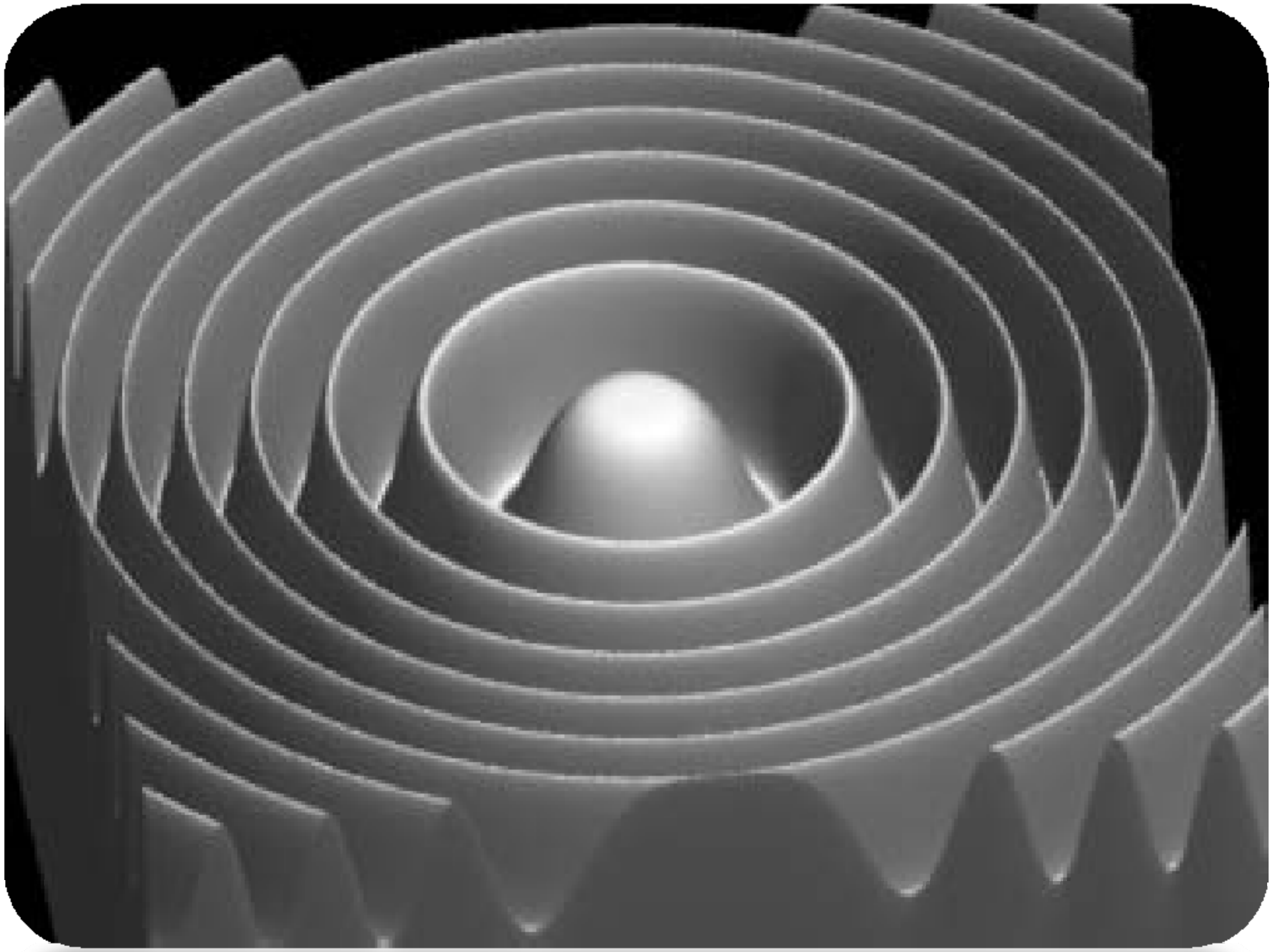
Comparison of Reconstruction Filters (5)

- **Windowed sinc** reconstruction of Marschner-Lobb test signal

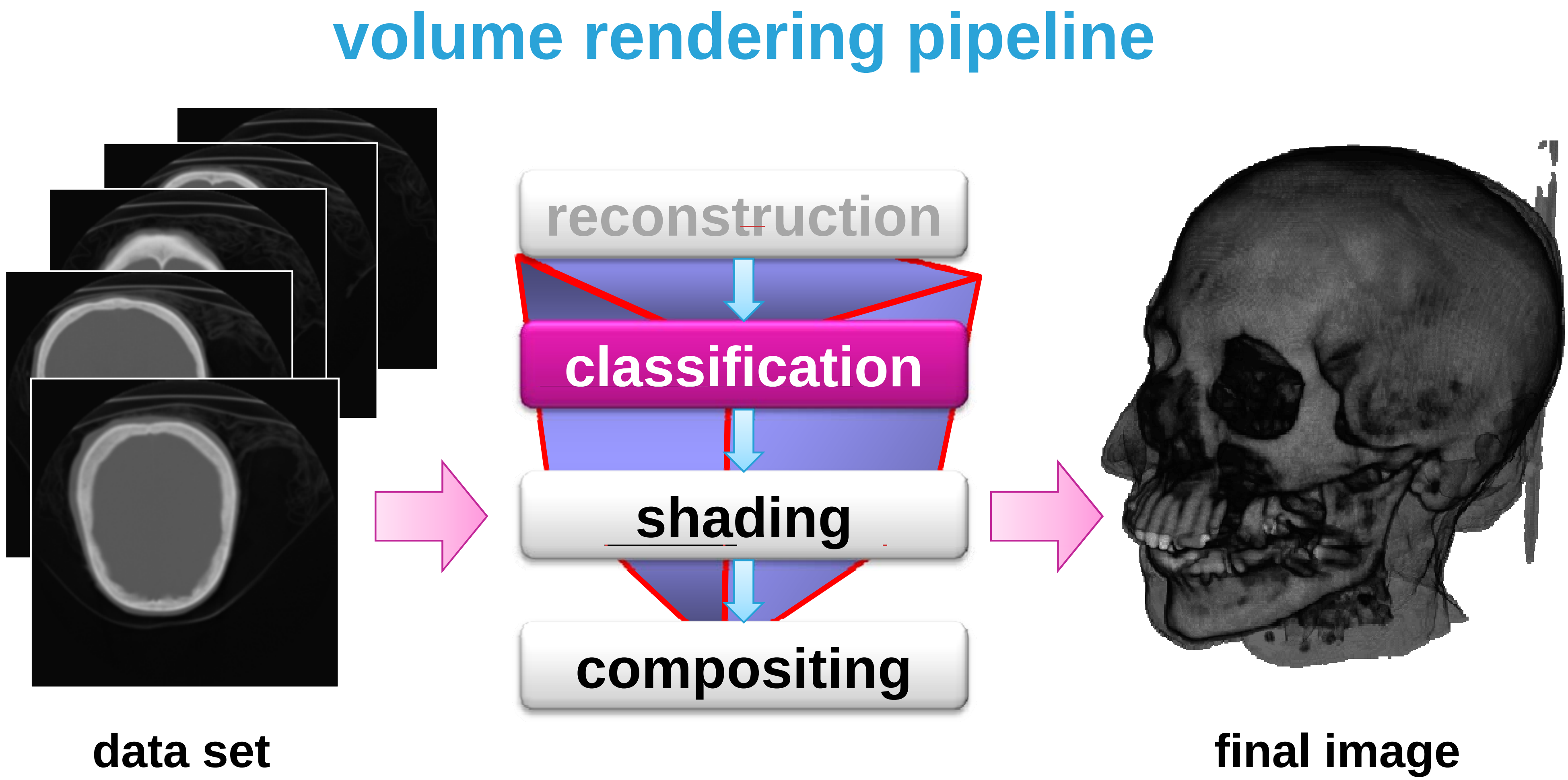


Comparison of Reconstruction Filters (6)

- Marschner-Lobb test signal (analytically evaluated)



Pipeline – Classification

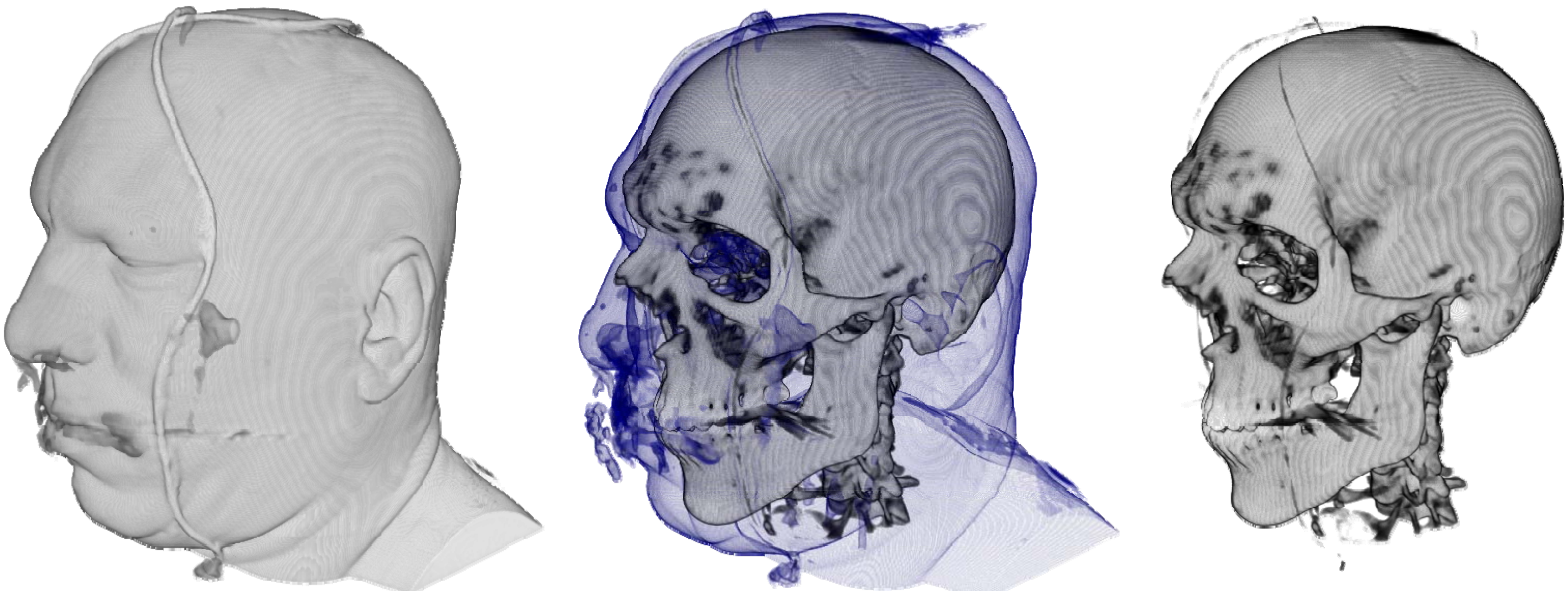


Classification (1)

- Projecting a 3D data set onto a 2D image is problematic
- Not all information contained in the volume is relevant to the user
- Classification allows the user to extract the important parts of the data

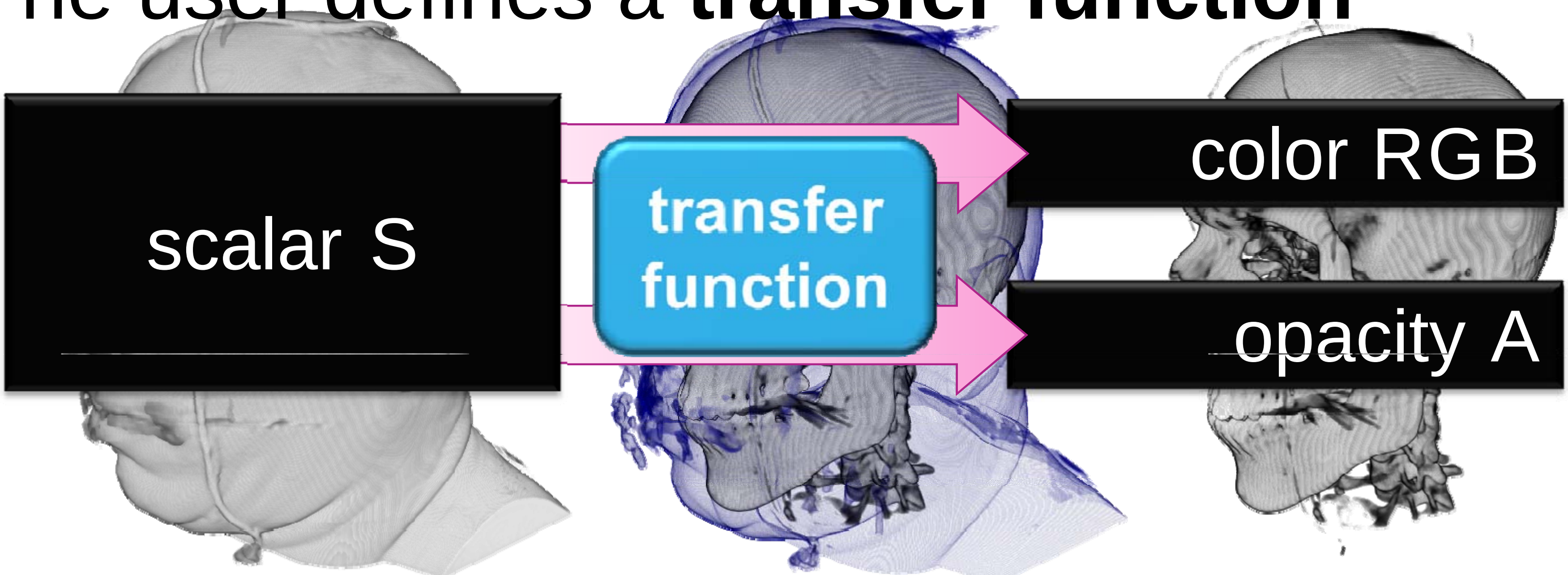
Classification (2)

- During Classification the user defines the appearence of the data
  - Which parts are transparent?
  - Which parts have which color?

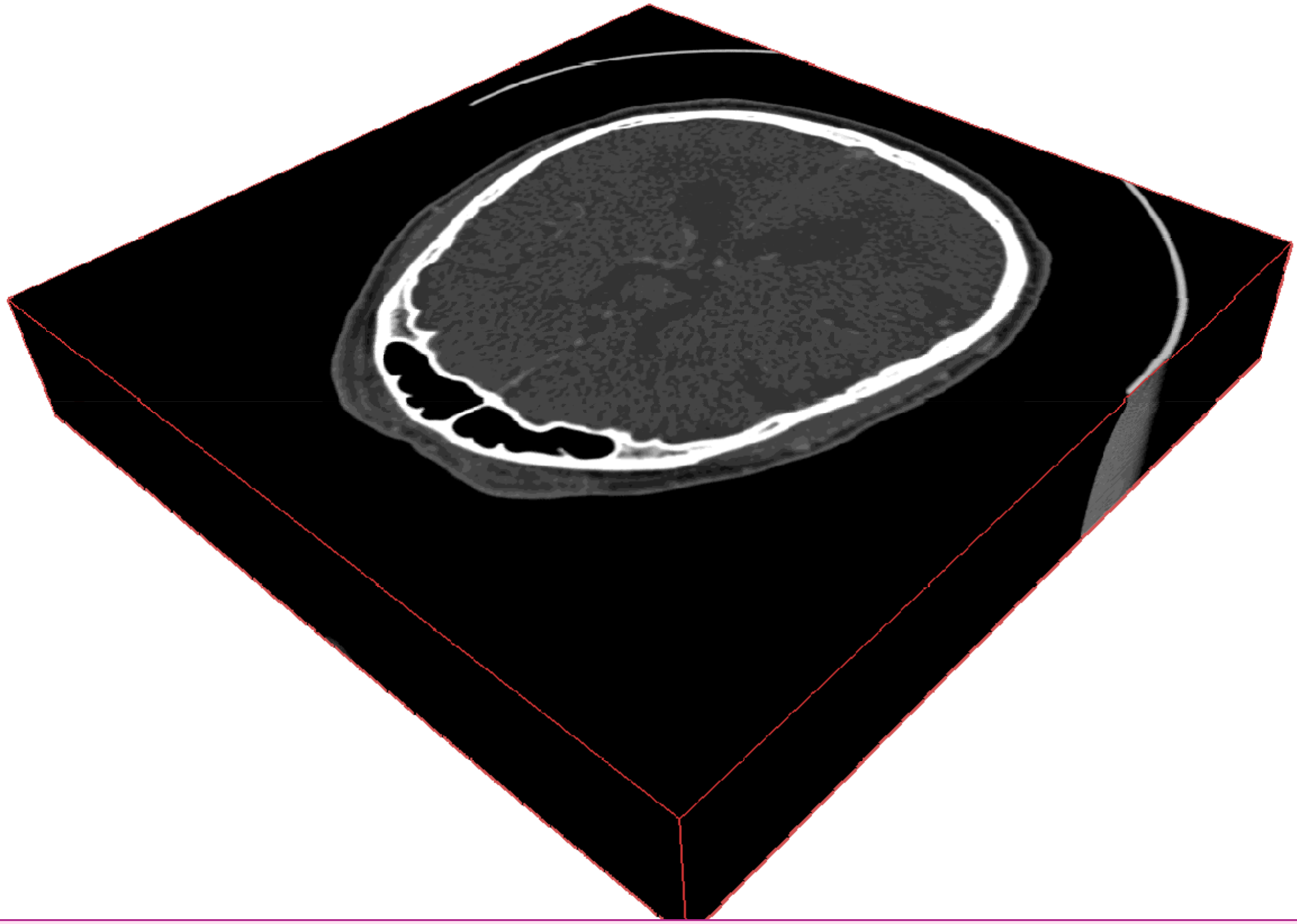


Classification (3)

- During Classification the user defines the appearence of the data
  - Which parts are transparent?
  - Which parts have which color?
- The user defines a **transfer function**

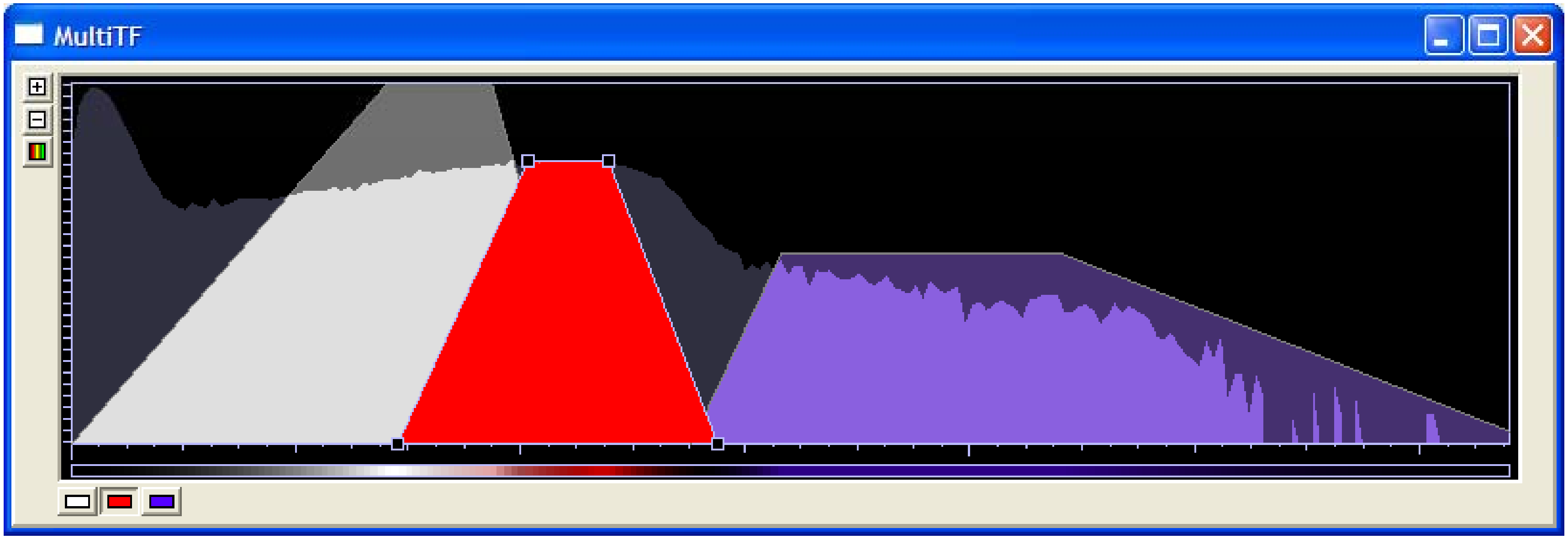


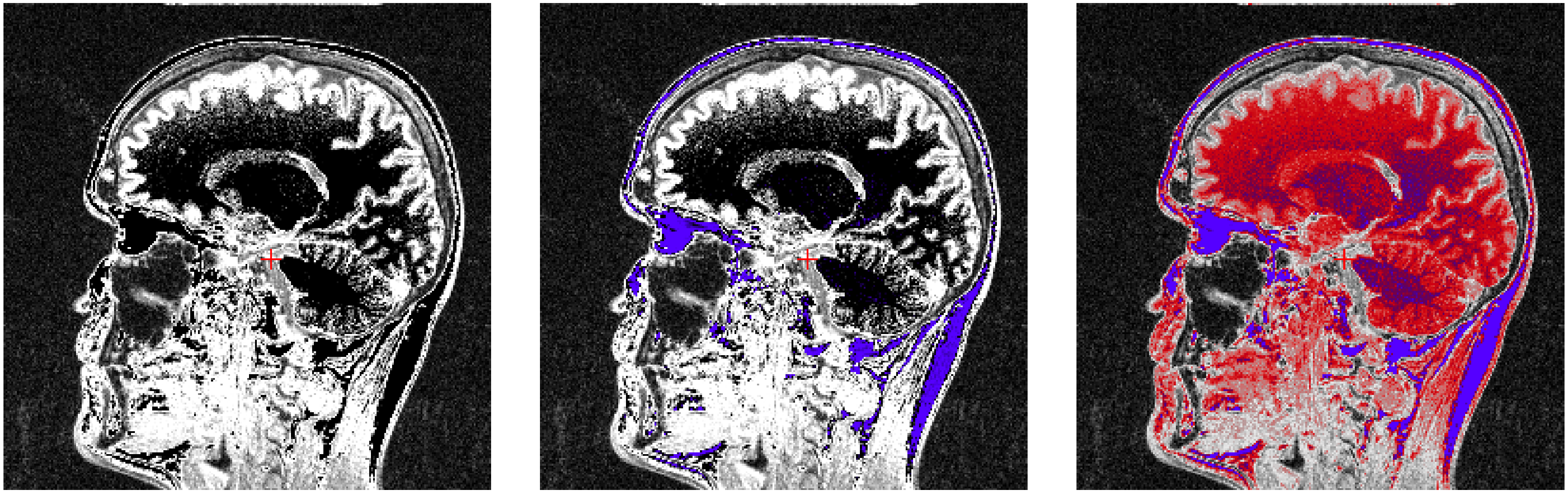
Transfer Functions (1)



real-time update of the transfer function important

Transfer Functions (2)

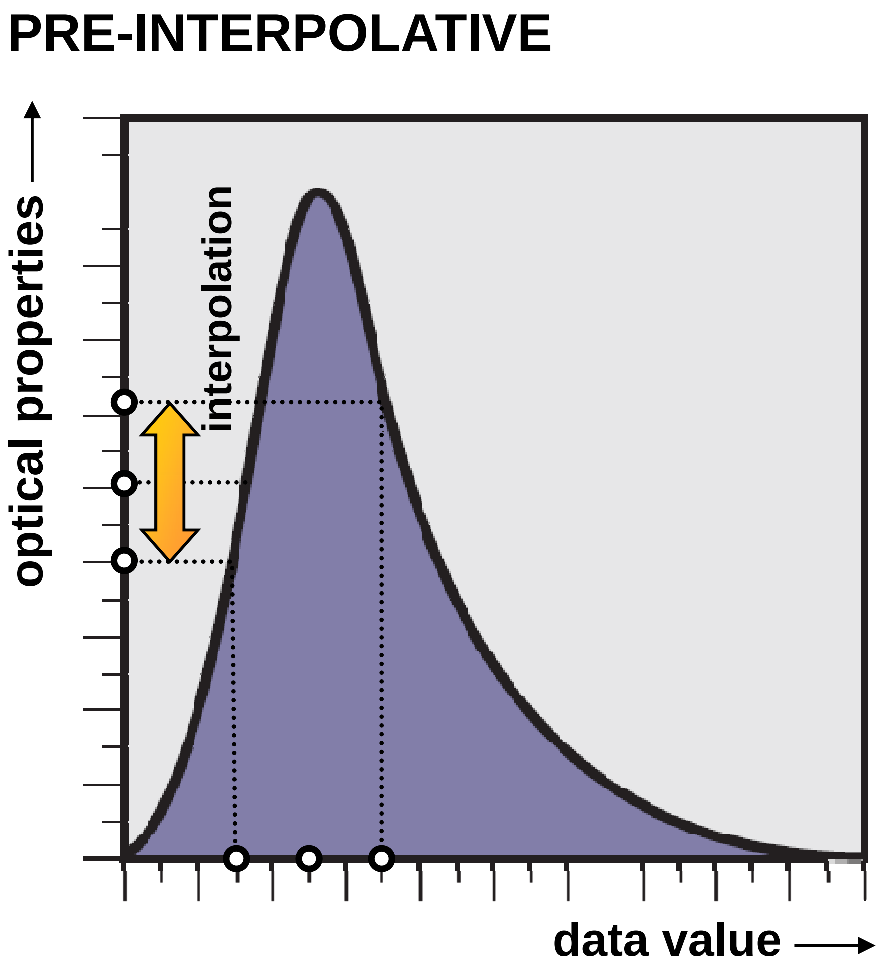


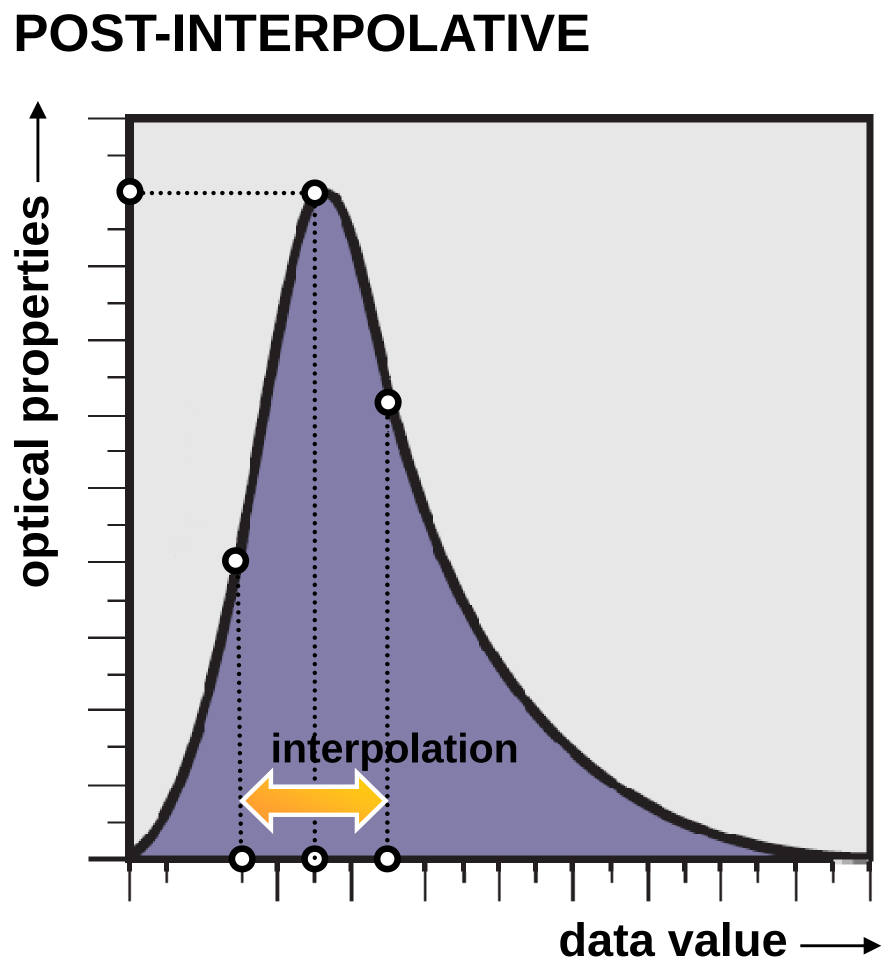


Classification Order (1)

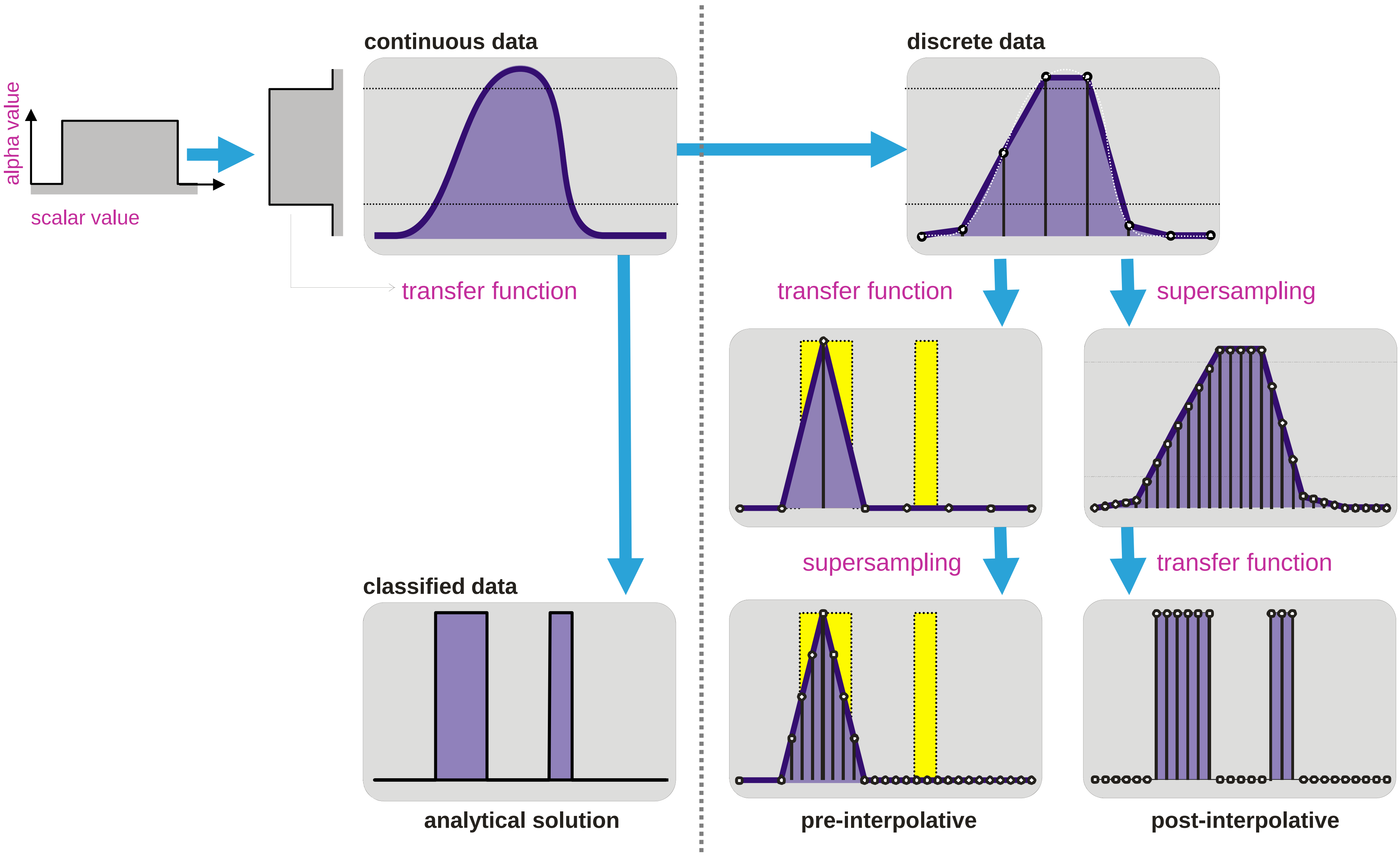
- Classification can occur before or after reconstruction
- **Pre-interpolative:** classify all data values and then interpolate between RGBA-tuples
- **Post-interpolative:** interpolate between scalar data values and then classify the result

Classification Order (2)

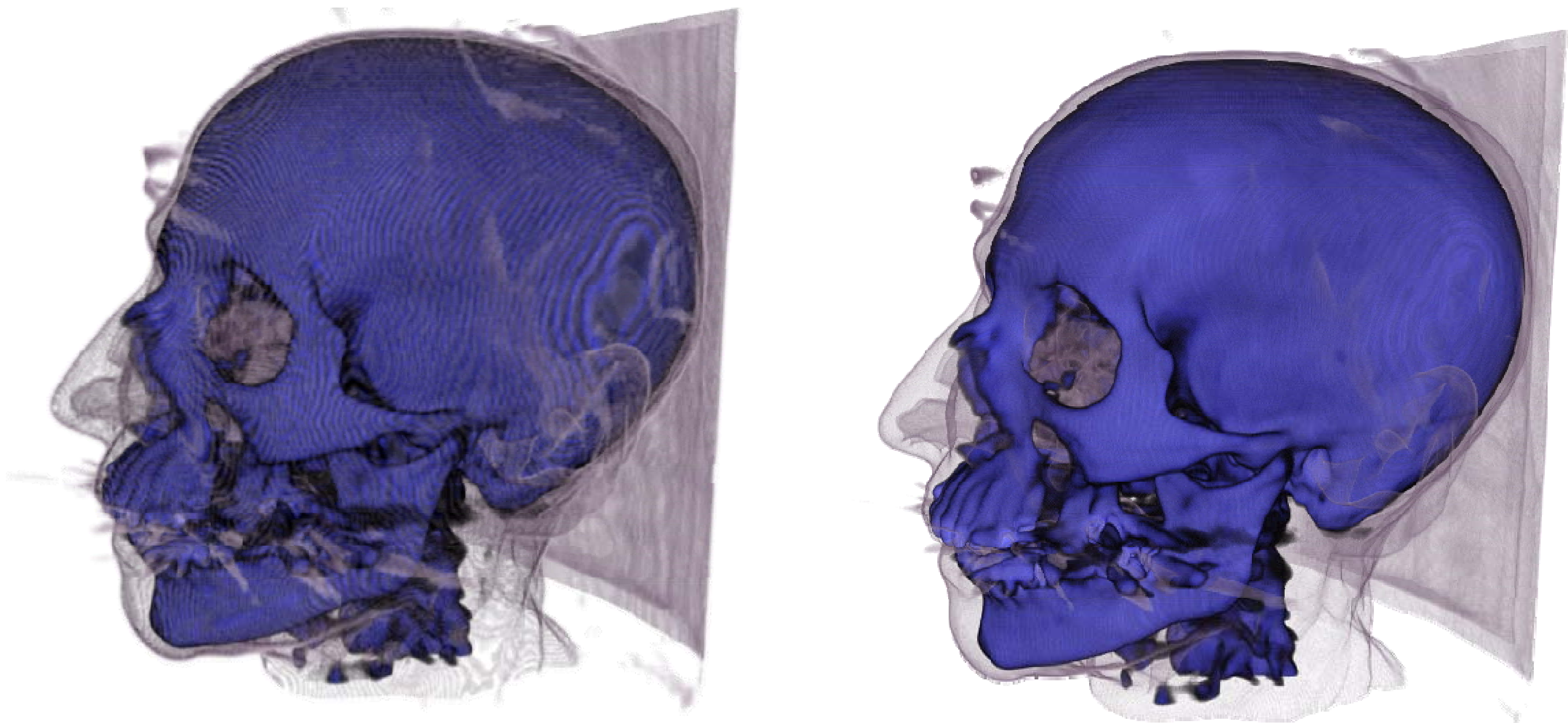




Classification Order (3)



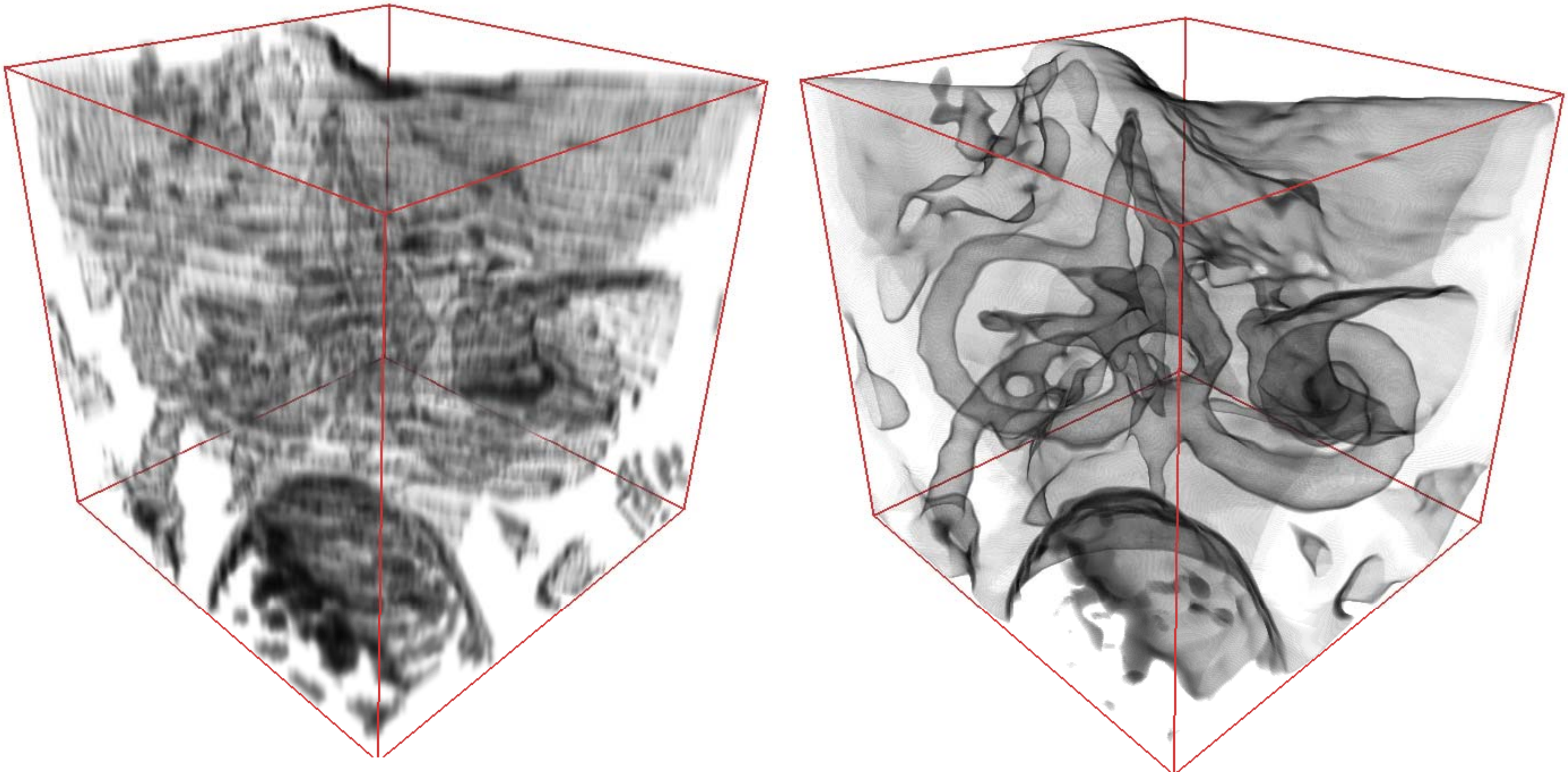
Classification Order (4)



pre-interpolative **post-interpolative**

same transfer function, resolution, and sampling rate

Classification Order (5)

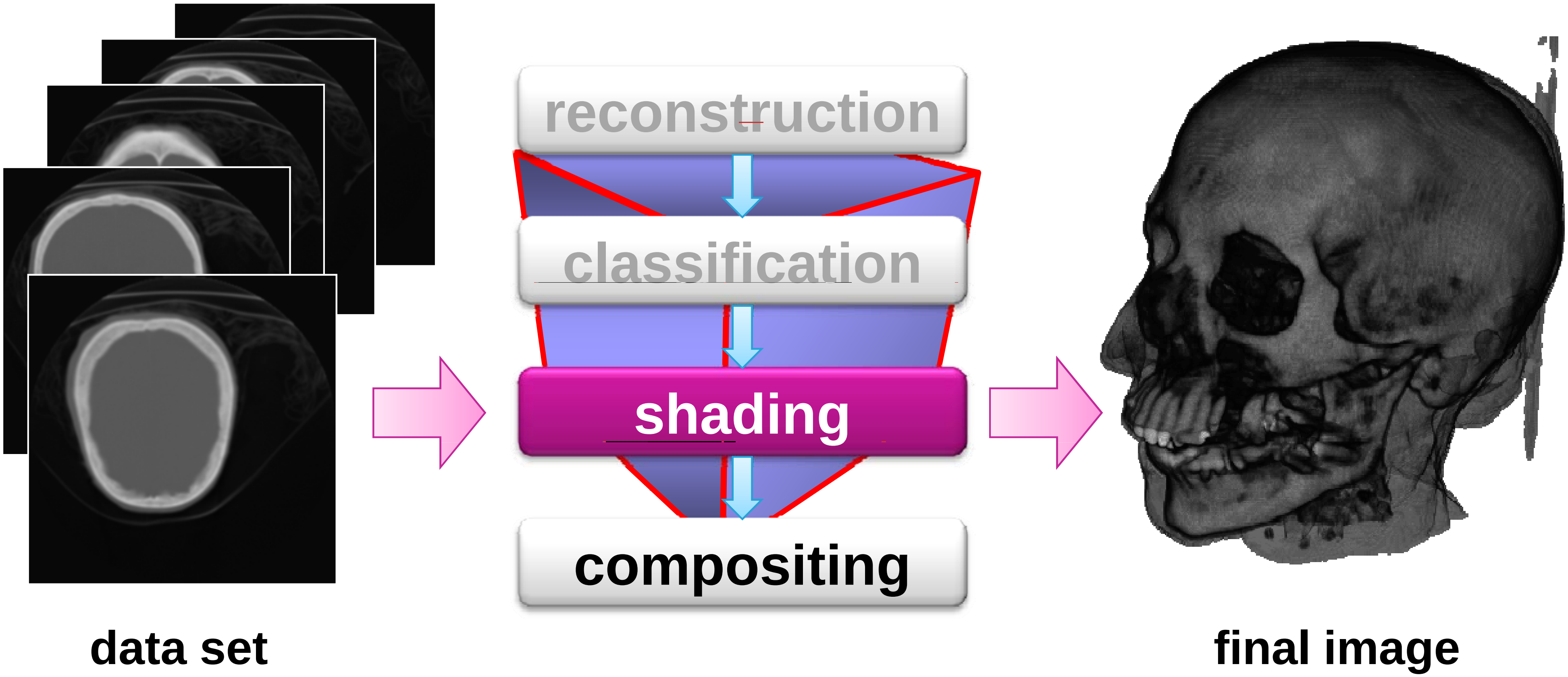


pre-interpolative **post-interpolative**

same transfer function, resolution, and sampling rate

Pipeline – Shading

volume rendering pipeline

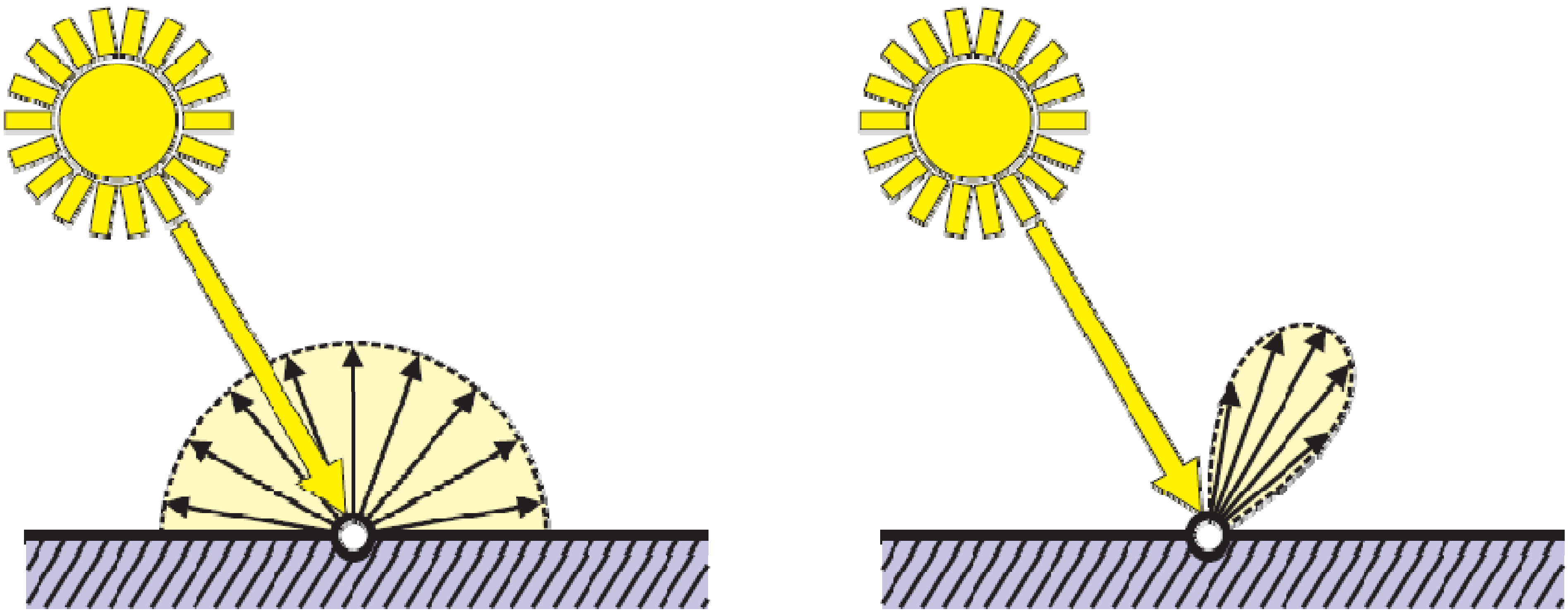


Shading (1)

- Make structures in volume data sets more realistic by applying an illumination model
- Shade each sample in the volume like a surface
- Any model used in real-time surface graphics suitable
- Common choice: Blinn-Phong illumination model

Shading (2)

- Local illumination, similar to surface lighting
  - **Lambertian reflection**
    light is reflected equally in all directions
  - **Specular reflection**
    light is reflected scattered around the direction of perfect reflection



Shading (3)

shaded volume rendering

unhaded volume rendering

Gradient Estimation (1)

- Normalized gradient vector of the scalar field is used to substitute for the surface normal
- The gradient vector is the first-order derivative of the scalar field

$$\nabla f(\mathbf{x}) = \begin{pmatrix} \frac{\partial f(\mathbf{x})}{\partial x} \\ \frac{\partial f(\mathbf{x})}{\partial y} \\ \frac{\partial f(\mathbf{x})}{\partial z} \end{pmatrix}$$

partial derivative **in x-direction**

partial derivative **in y-direction**

partial derivative **in z-direction**

Gradient Estimation (2)

- We can estimate the gradient vector using finite differencing schemes, e.g. central differences:

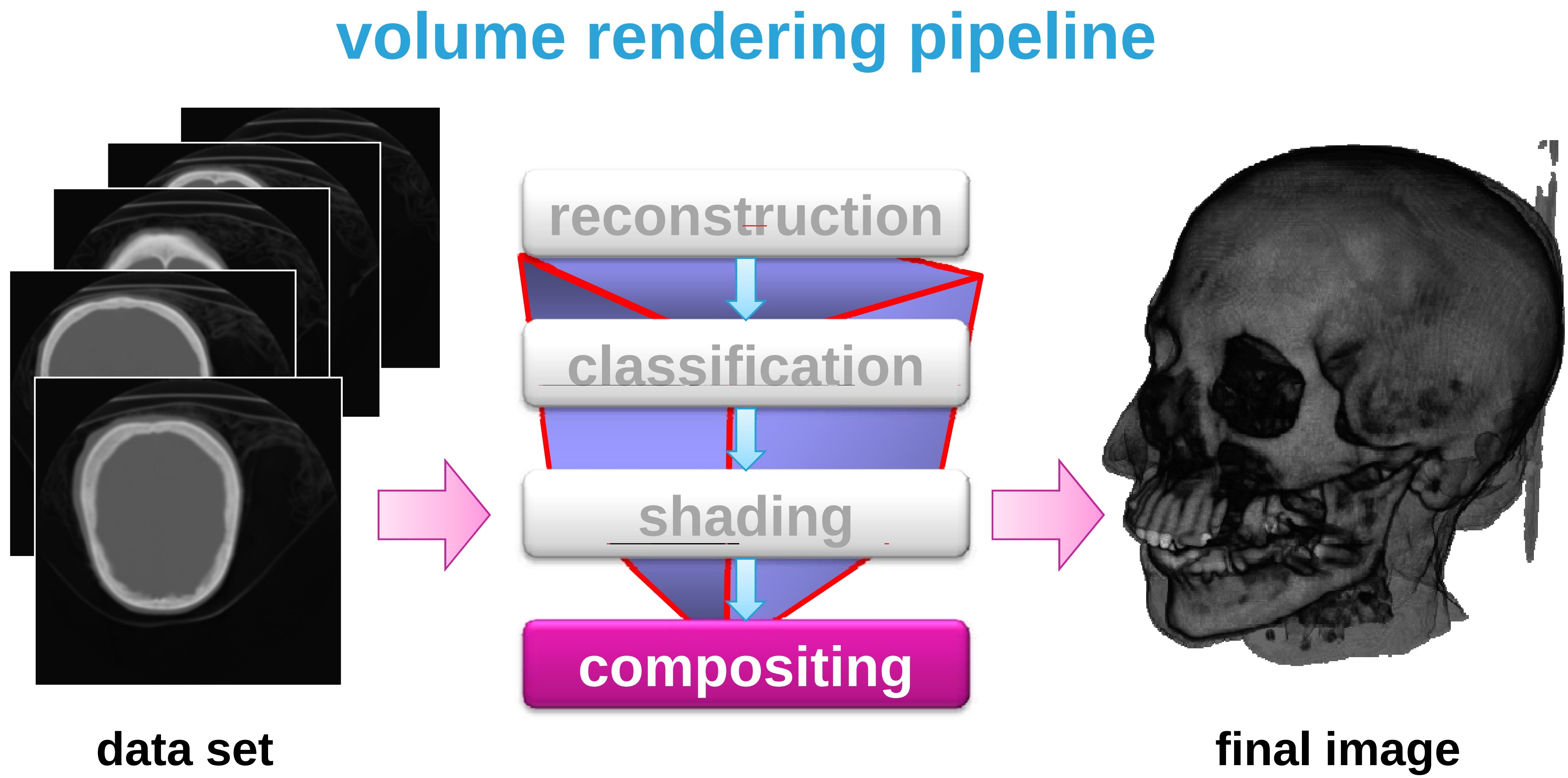
$$\nabla f(x,y,z) \approx \frac{1}{2h} \begin{pmatrix} f(x+h,y,z) - f(x-h,y,z) \\ f(x,y+h,z) - f(x,y-h,z) \\ f(x,y,z+h) - f(x,y,z-h) \end{pmatrix}$$

- Noisy data may require more complex estimation schemes

Gradient Magnitude

- Magnitude of gradient vector can be used to measure the “surfaceness” of a point
  - Strong changes → high gradient magnitude
  - Homogenity → low gradient magnitude
- Applications
  - Use gradient magnitude to modulate opacity of sample
  - Interpolate between unshaded and shaded sample color using gradient magnitude as weight

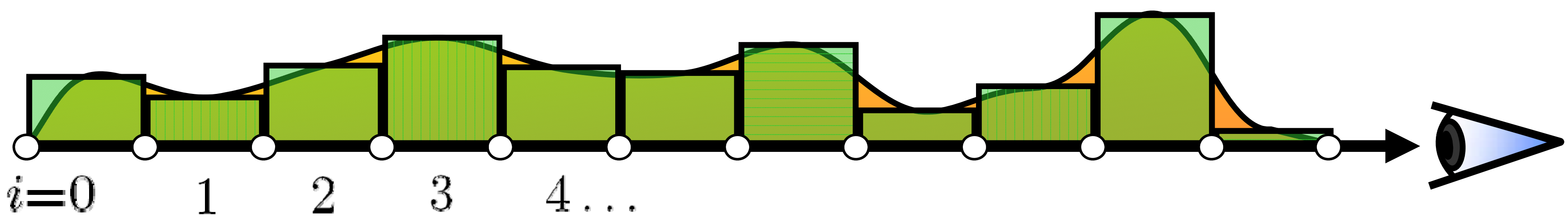
Pipeline – Compositing



Compositing (1)

- So far, everything discussed applies to single sample points along a viewing ray
- How to subsequent sample when traversing the ray?
- Common models
  - Maximum Intensity Projection
  - Emission-Absorption Model

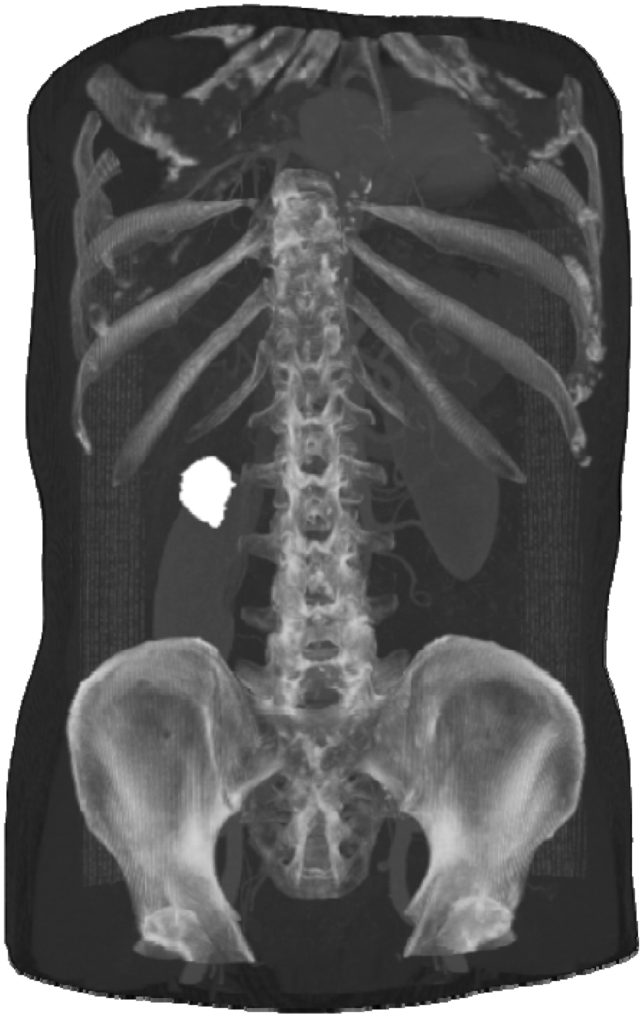
Maximum Intensity Projection (1)



- Always display the maximum value along a viewing ray
- Motivation: visualization of contrast-enhanced tomographic scans
- Parameterless rendering, very common in medical domain

Maximum Intensity Projection (2)

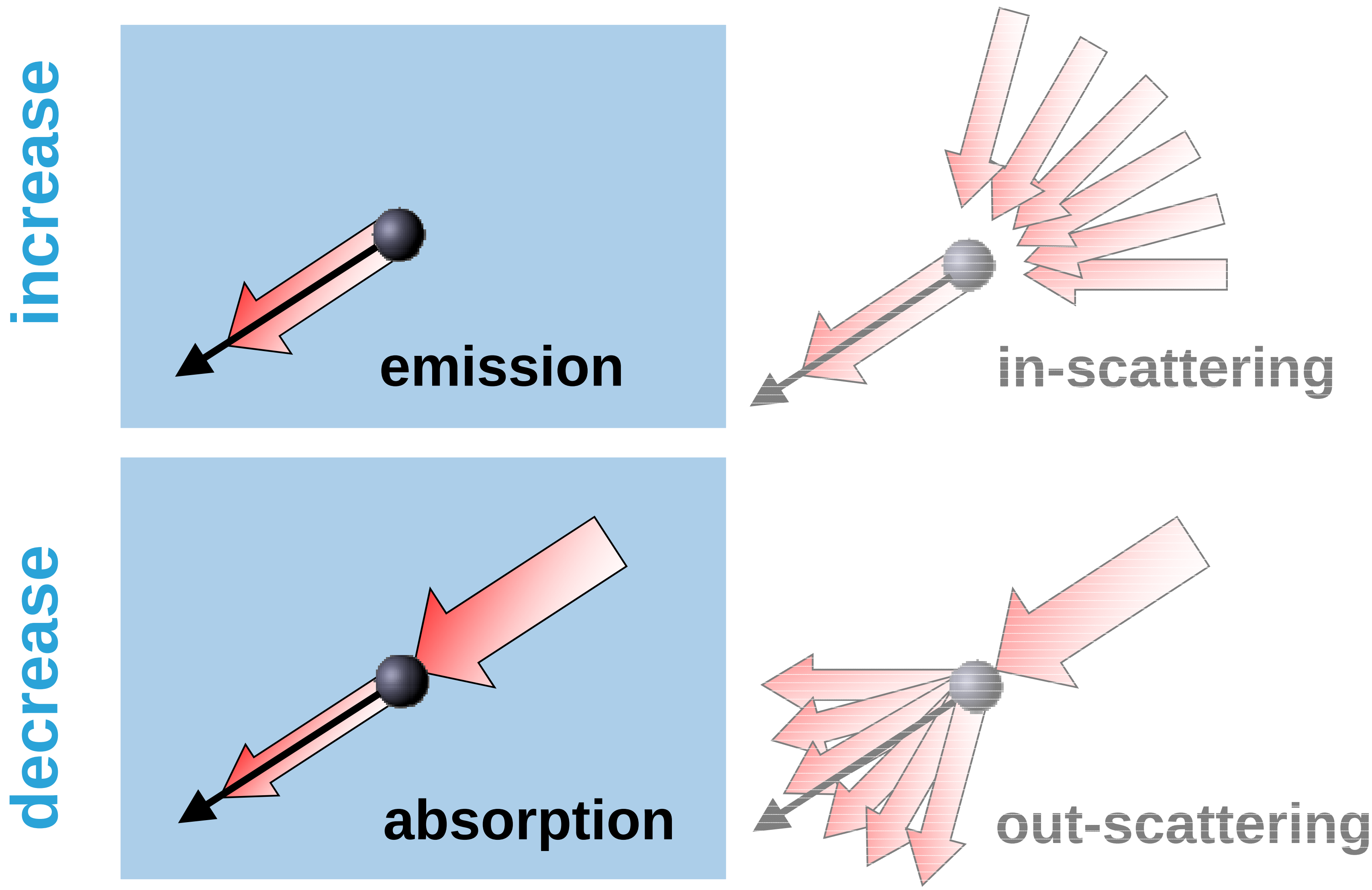
- Probem: loss of spatial relationships between different structures



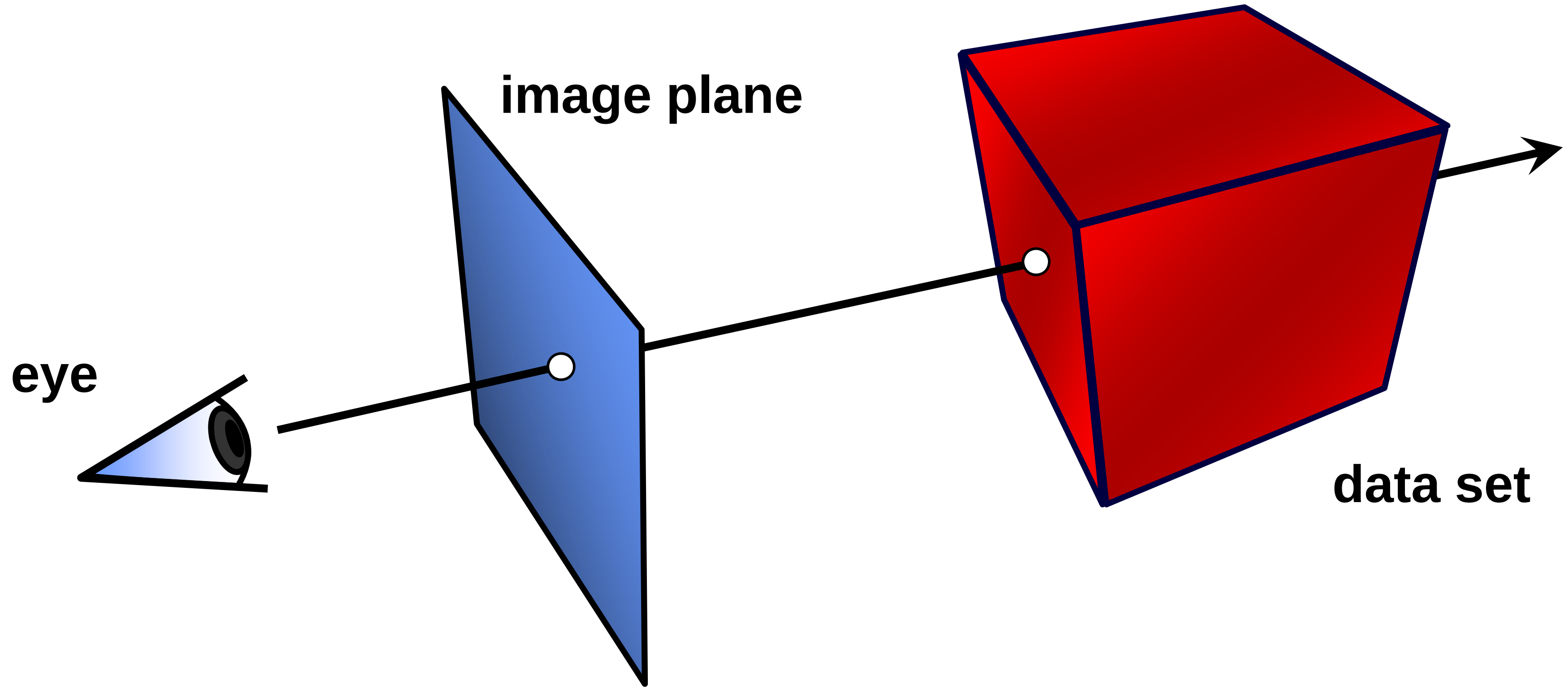
Emission-Absorption Model (1)

- Conventional volume rendering uses an emission-absorption model
- Scattering effects are usually ignored due to high computational complexity
- For each pixel on the image plane, a the ray integral has to be solved
- For each step along he viewing ray, perform accumulate RGBA from transfer function

Emission-Absorption Model (2)



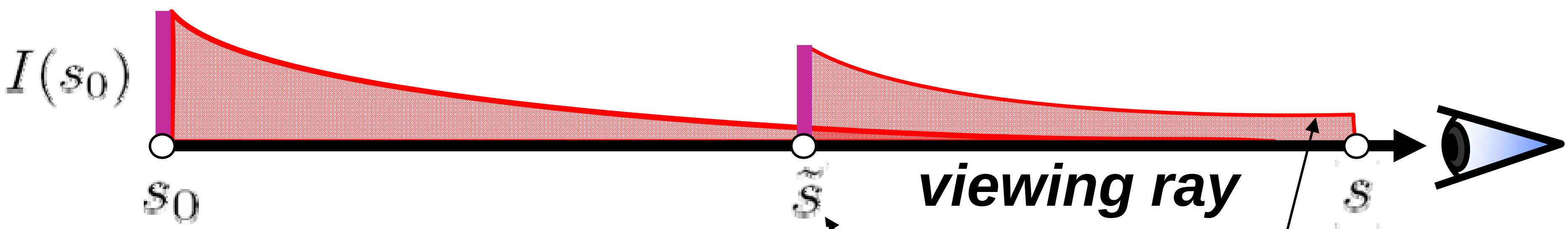
Ray Integration (1)



Ray Integration (2)

How do we determine the radiant energy along the ray?

Physical model: emission and absorption, no scattering



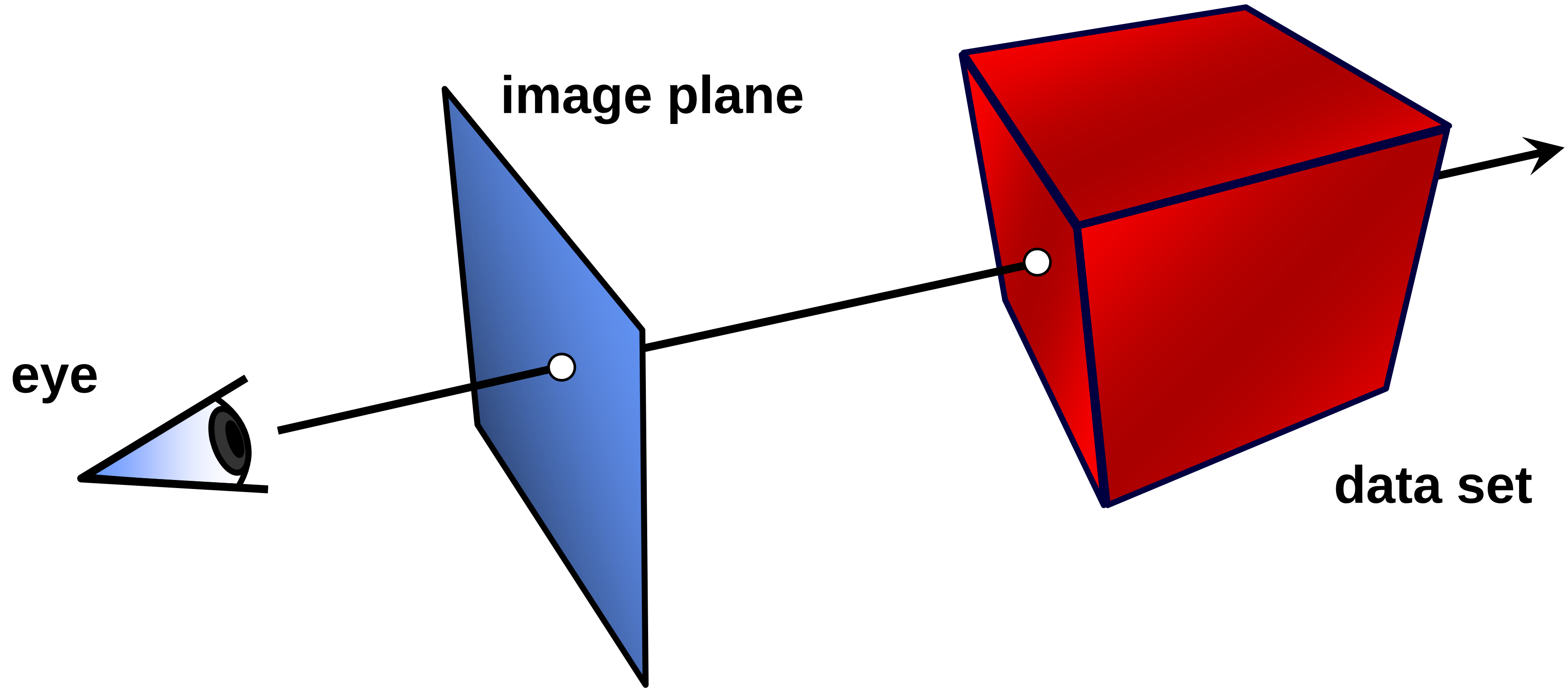
Every point $\tilde{s}$ along the viewing ray emits additional radiant energy

active emission at point $\tilde{s}$

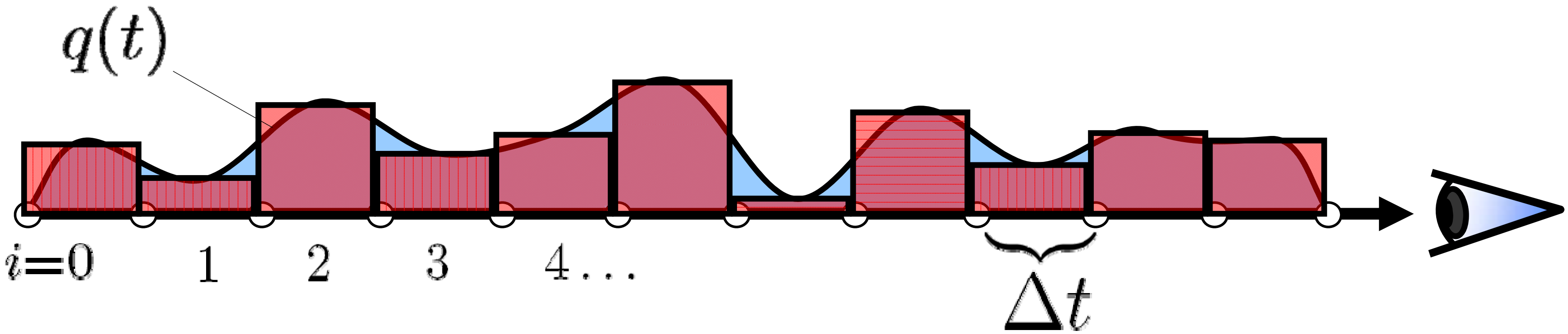
absorption along the distance $s - \tilde{s}$

$$I(s) = I(s_0)\, e^{-\tau(s_0, s)} + \int_{s_0}^{s} q(\tilde{s})\, e^{-\tau(\tilde{s}, s)}\, d\tilde{s}$$

Numerical Solution (1)



Numerical Solution (2)



$$\tilde{C} = \sum_{i=0}^{\lfloor T/\Delta t \rfloor} C_i \prod_{j=0}^{i-1} (1 - A_j)$$

can be computed recursively

$$C'_i = C_i + (1 - A_i) C'_{i-1}$$

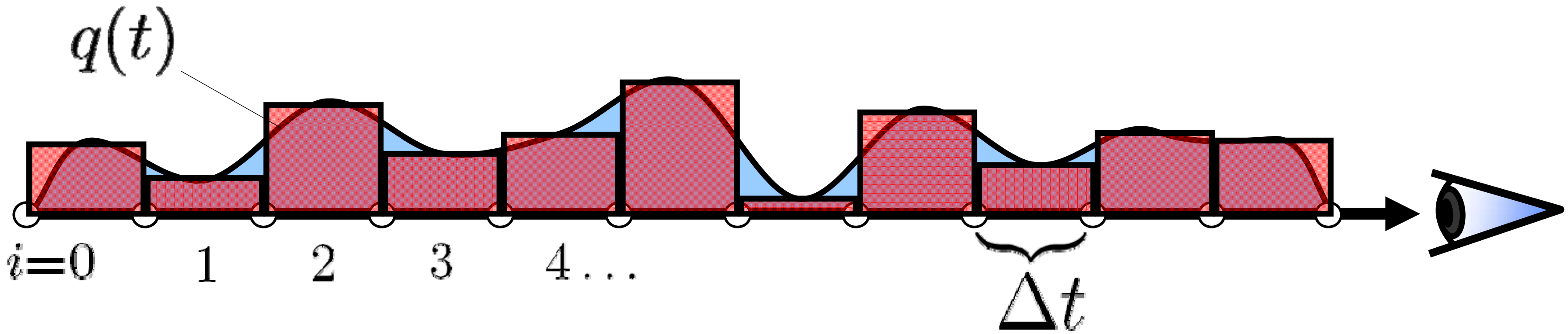
radiant energy observed at position ***i***

radiant energy emitted at position ***i***

absorption at position ***i***

radiant energy observed at position ***i–1***

Numerical Solution (2)



back-to-front compositing

$$C'_i = C_i + (1 - A_i)C'_{i-1}$$

front-to-back compositing

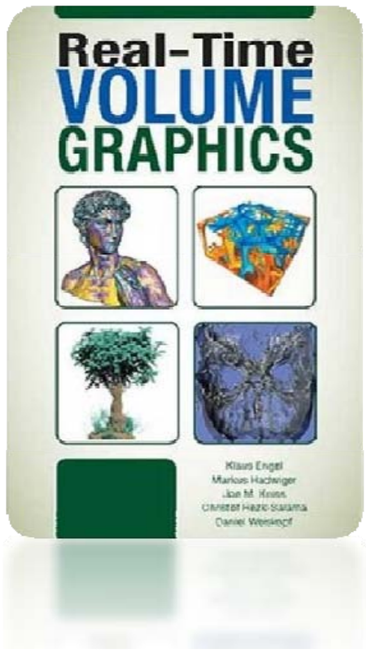
$$C'_i = C'_{i+1} + (1 - A'_{i+1})C_i$$
$$A'_i = A'_{i+1} + (1 - A'_{i+1})A_i$$

early ray termination: stop the calculation when

$$A'_i \approx 1$$

Further Reading

- M. Levoy. Display of Surfaces from Volume Data. *IEEE Computer Graphics and Applications*, 8(3):29-37, 1988.
- R. Drebin, L. Carpenter, P. Hanrahan. Volume Rendering. *ACM SIGGRAPH Computer Graphics*, 22(4):65-74, 1988.
- W. Lorensen, H. Cline. Marching cubes: A high resolution 3D surface construction algorithm. *ACM SIGGRAPH Computer Graphics*, 21(4):163-169, 1987.
- C. Rezk-Salama, K. Engel, M. Hadwiger, J. Kniss, D. Weiskopf. Real-Time Volume Graphics, AK Peters, 1-56881-266-3, 2006.



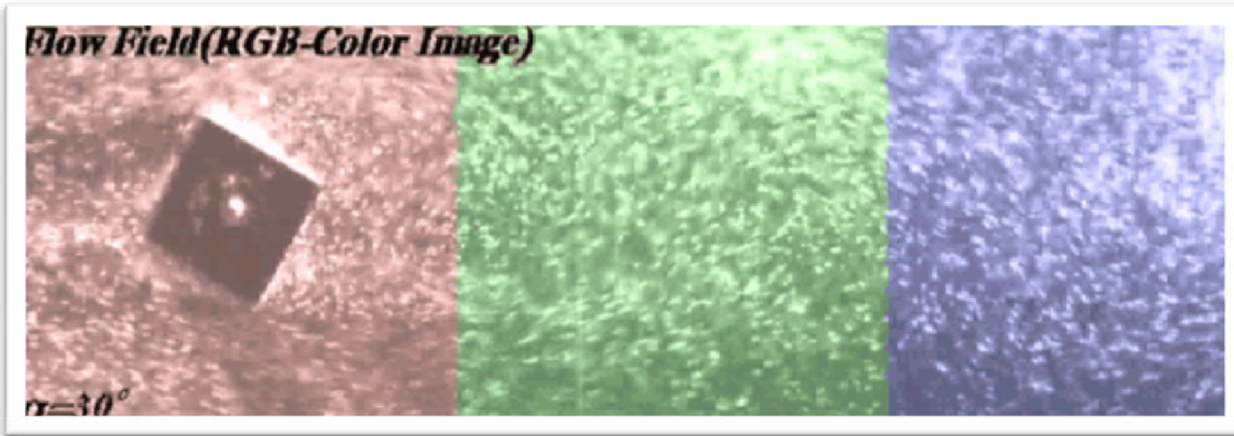
Flow Visualization

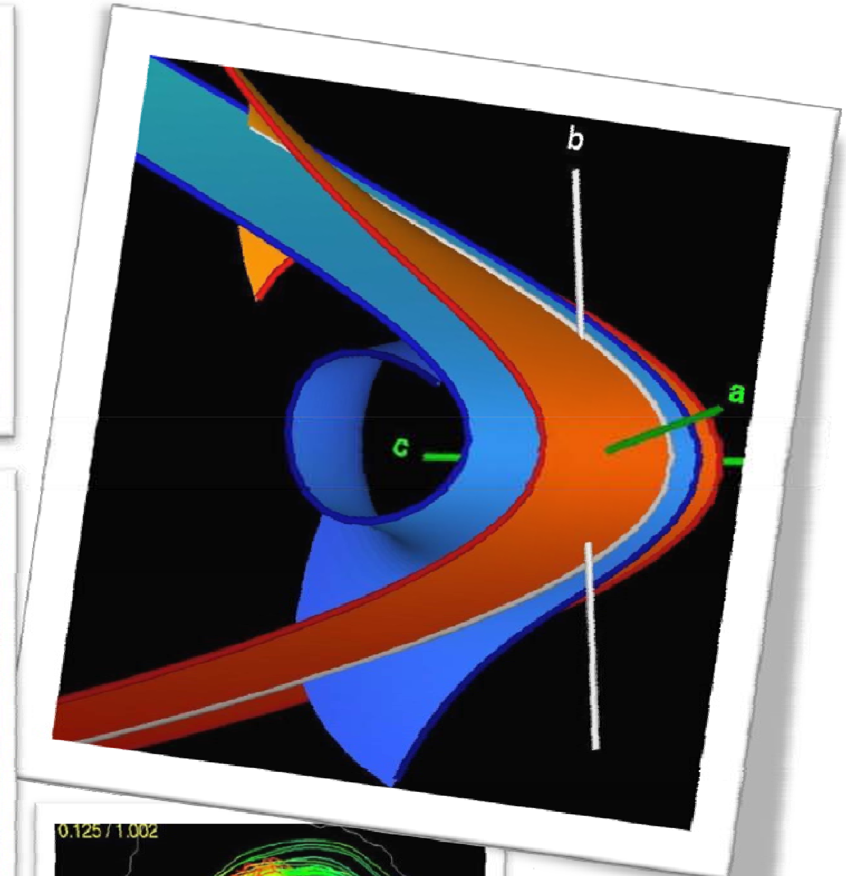
- FlowVis = visualization of flows
  - Visualization of change information
- Flow data
  - nD×nD data, $1D^2$ / $2D^2$ / nD^2 (models), $2D^2$ / $3D^2$
  - Vector data (nD) in nD data space
  - Steady vs. time-dependent flow
- User goals
  - Overview vs. details (with context)

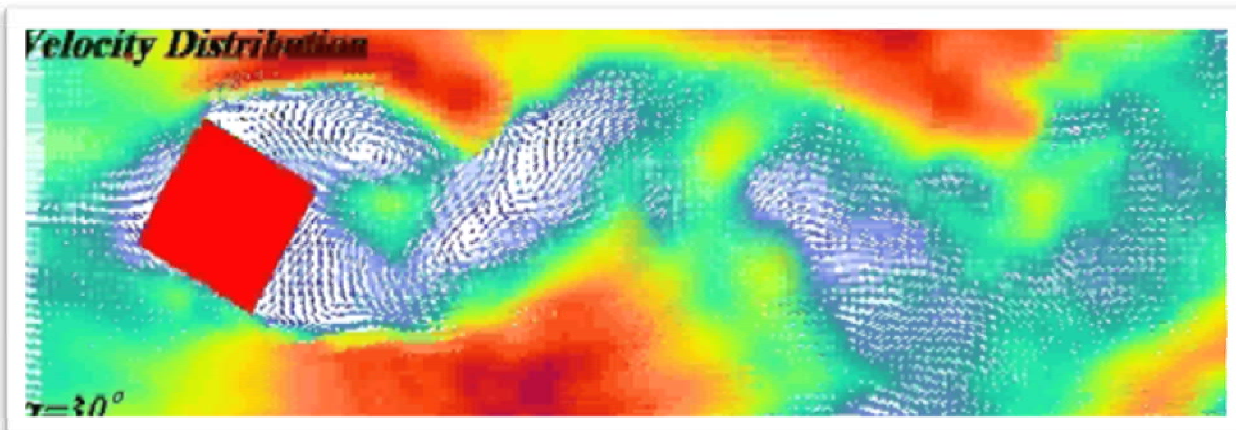
Flow Data (1)

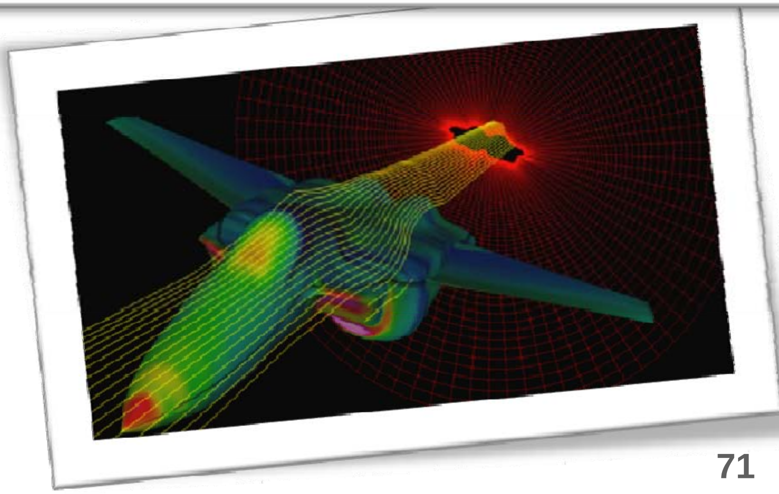
- Simulation
  - Flow space modelled with grid
  - FEM (finite elements method), CfD (computational fluid dynamics)
- Measurements
  - Optical methods + pattern recognition, e.g.: PIV (particle image velocimetry)
- Models
  - Differential equation systems d**x**/dt

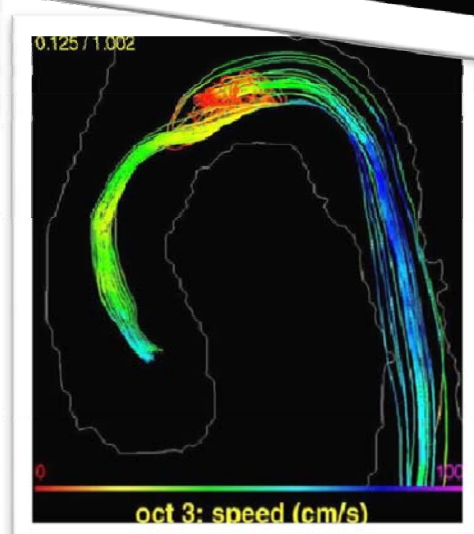
Flow Data (2)


Flow Field(RGB-Color Image)

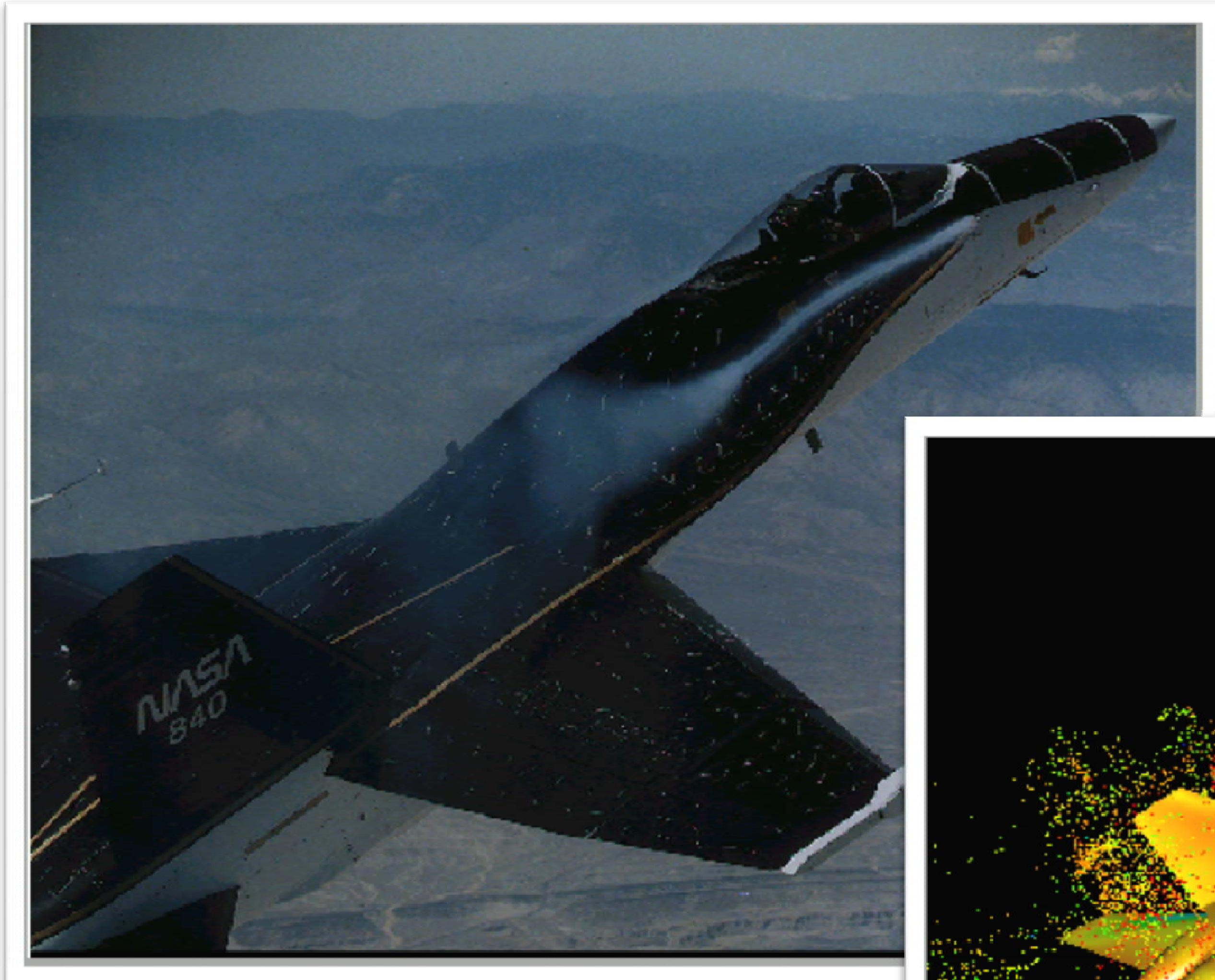

b
a
c


Velocity Distribution

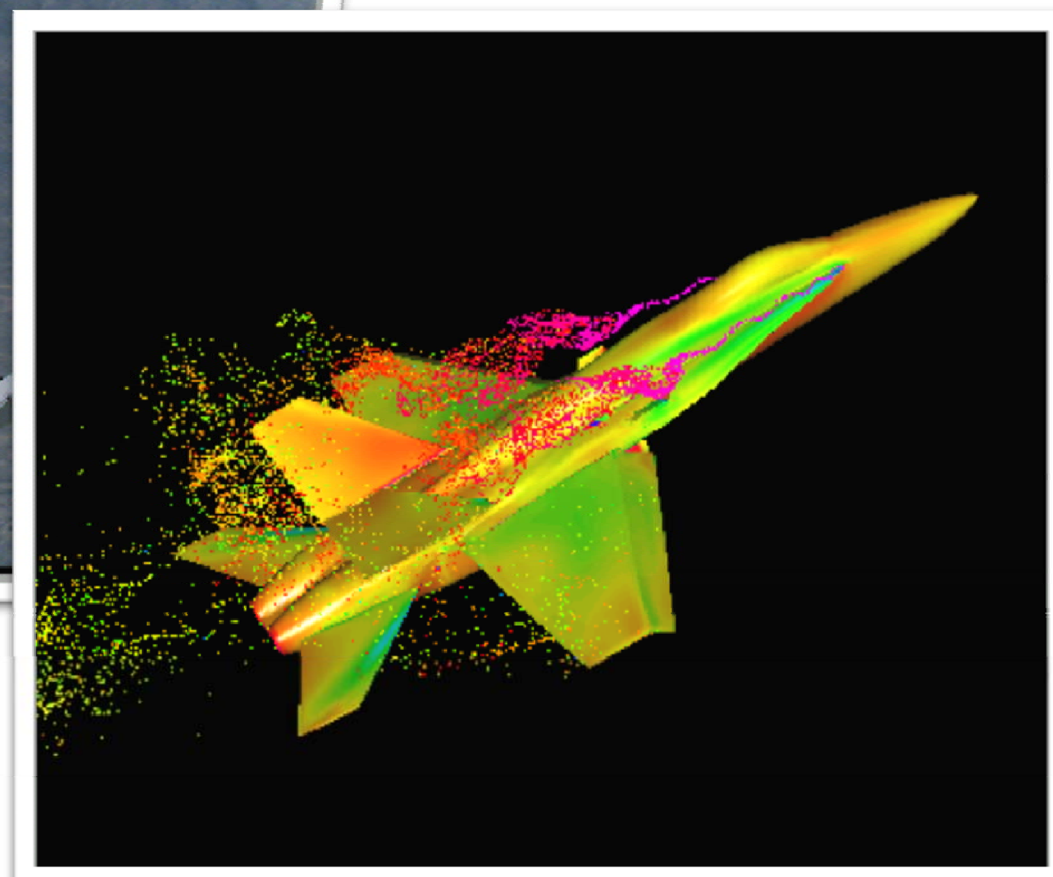



0.125 / 1.002
0
oct 3: speed (cm/s)

Flow Data (3)



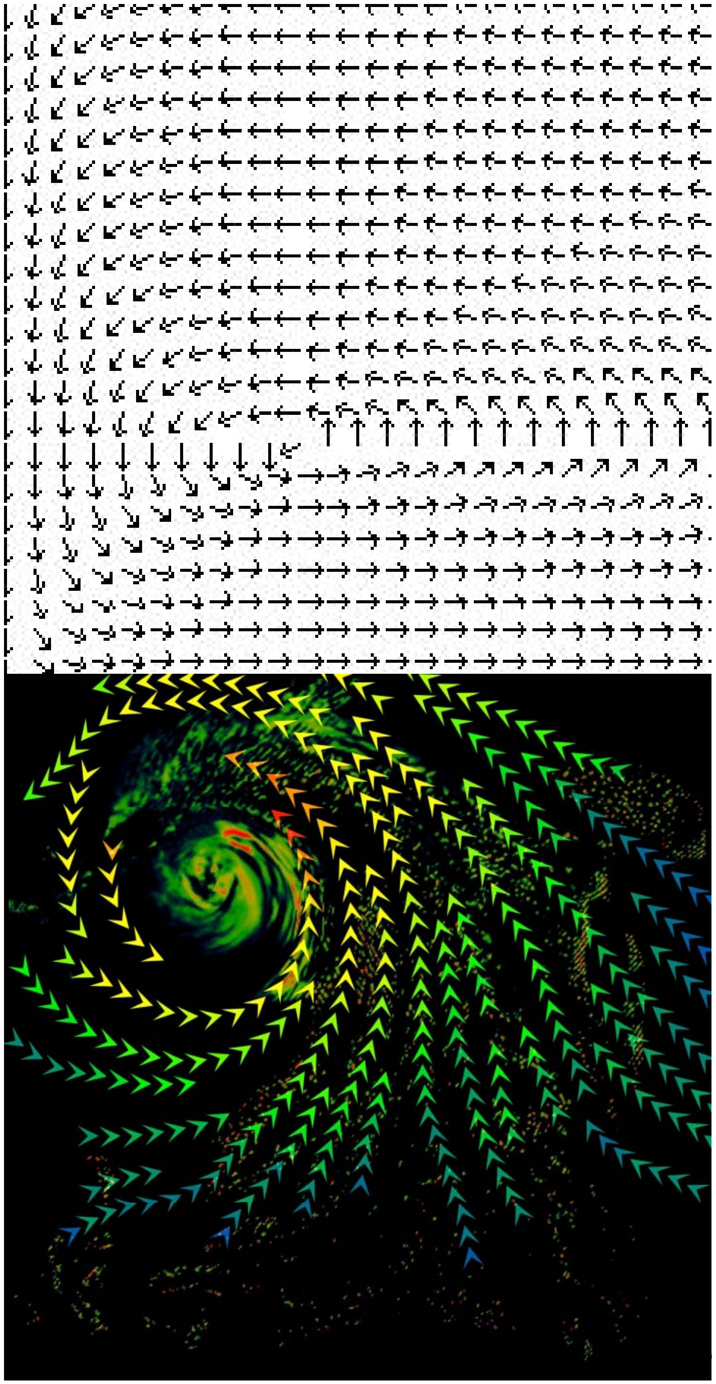
experiment



simulation

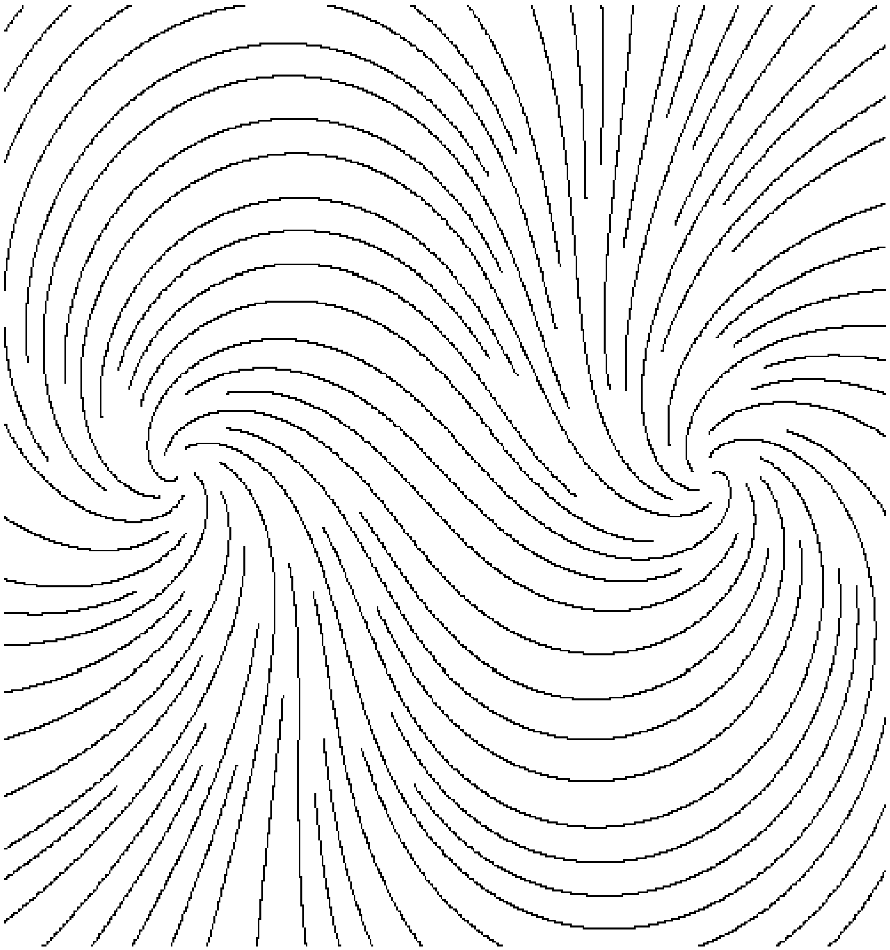
Direct Flow Visualization

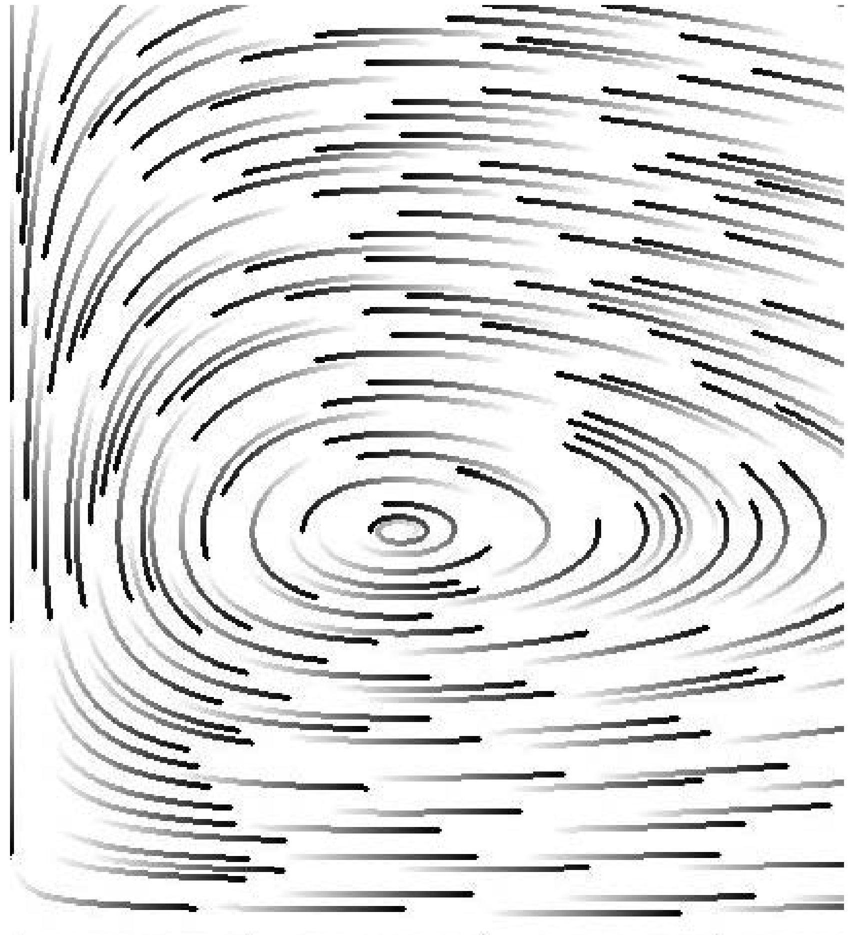
- Grid of arrows to visualize flow directions
- Normalized arrows vs. scaling with velocity
- Quite effective in 2D, problematic in 3D
- Sometimes limited expressivity (temporal component missing)



Geometric Flow Visualization

- Idea: follow the flow in time (integration) to extract the path of a particle





Streamlines – Theory

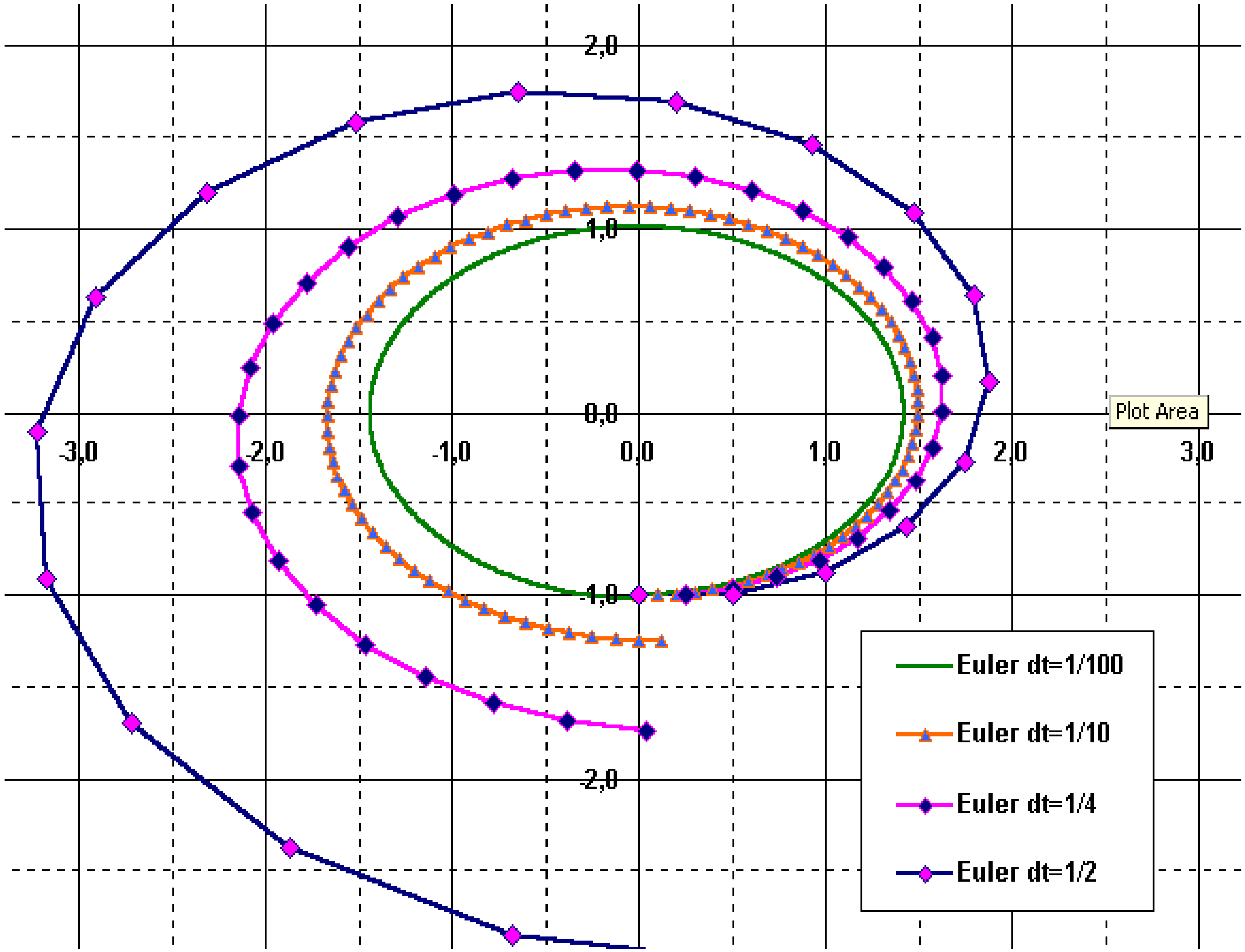
- Flow data **v**: derivative information
  - d**x**/dt = **v**(**x**)
    spatial points $\mathbf{x} \in R^n$, flow vectors $\mathbf{v} \in R^n$, time $t \in R$
- Streamline **s**: integration over time, also called trajectory, solution, curve
  - $\mathbf{s}(t) = \mathbf{s}_0 + \int_{0 \leq u \leq t} \mathbf{v}(\mathbf{s}(u))\, du$
    seed point $\mathbf{s}_0$, integration variable u
- Difficulty: result **s** also in the integral, analytical solution usually impossible

Streamlines – Practice (1)

- Solve using numerical integration techniques
- Assume that locally the solution is approximately linear
- Euler integration
  - $\mathbf{s}_{i+1} = \mathbf{s}_i + \mathrm{d}t \cdot \mathbf{v}(\mathbf{s}_i)$
    Follow the current flow vector $\mathbf{v}(\mathbf{s}_i)$ from the current streamline point $\mathbf{s}_i$ for a short time ($\mathrm{d}t$)

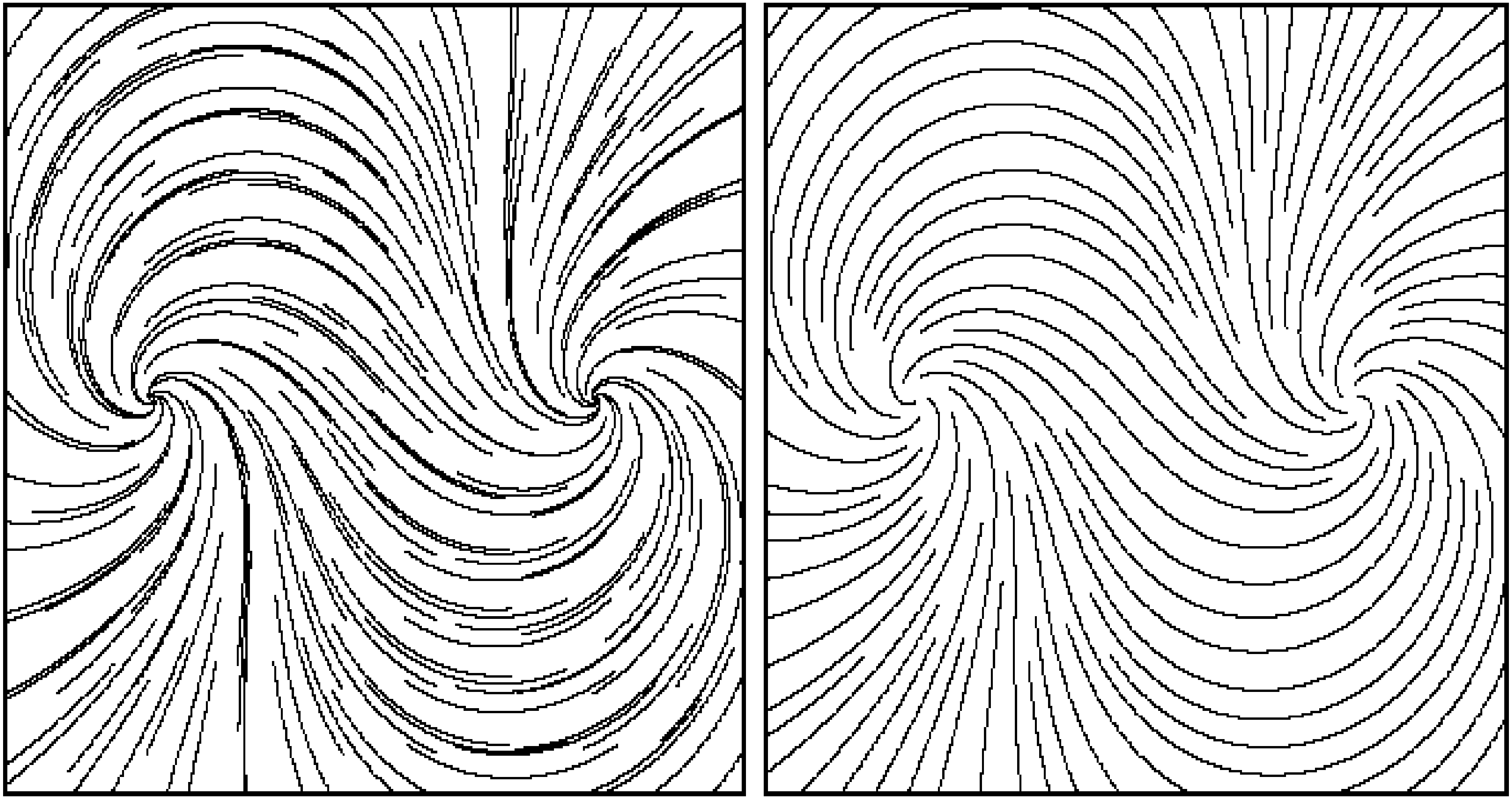
Streamlines – Practice (2)

- Accuracy of results is strongly dependent on step size d*t*



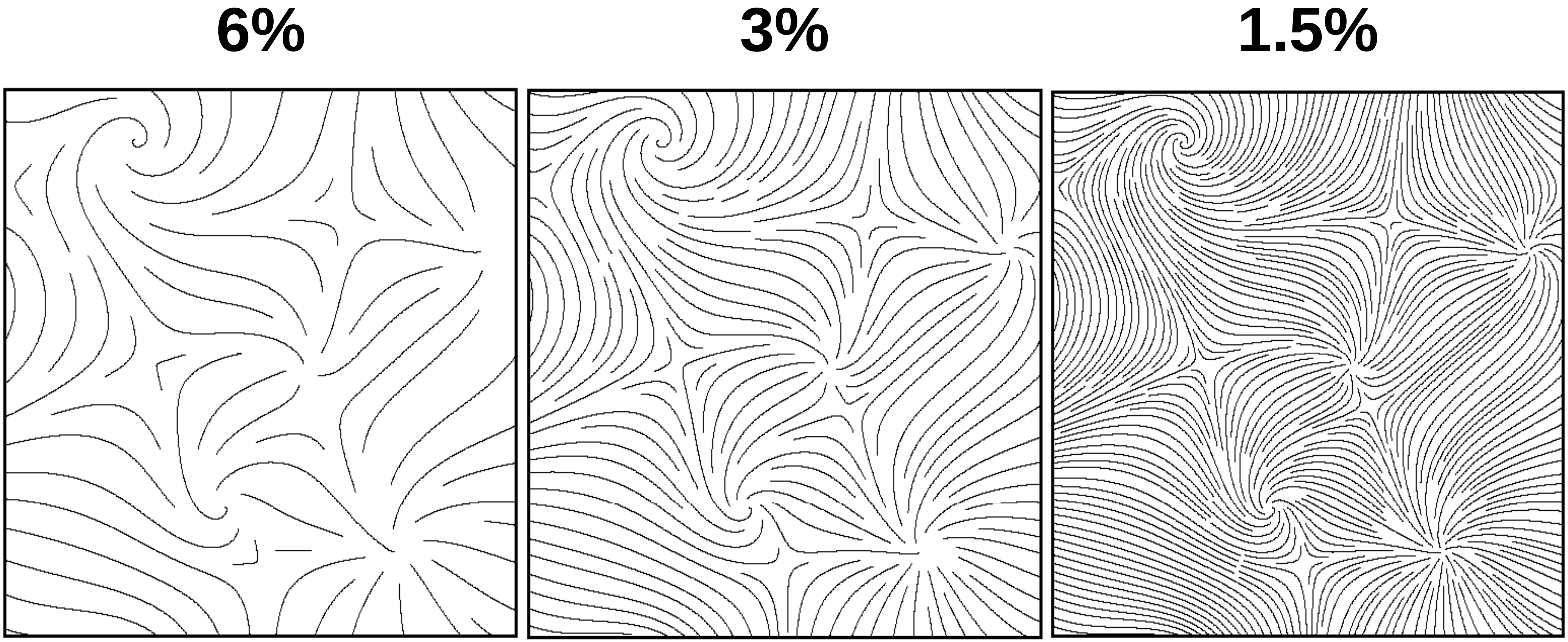
Streamlines – Placement (1)

- Seed fill with streamlines to achieve equal density



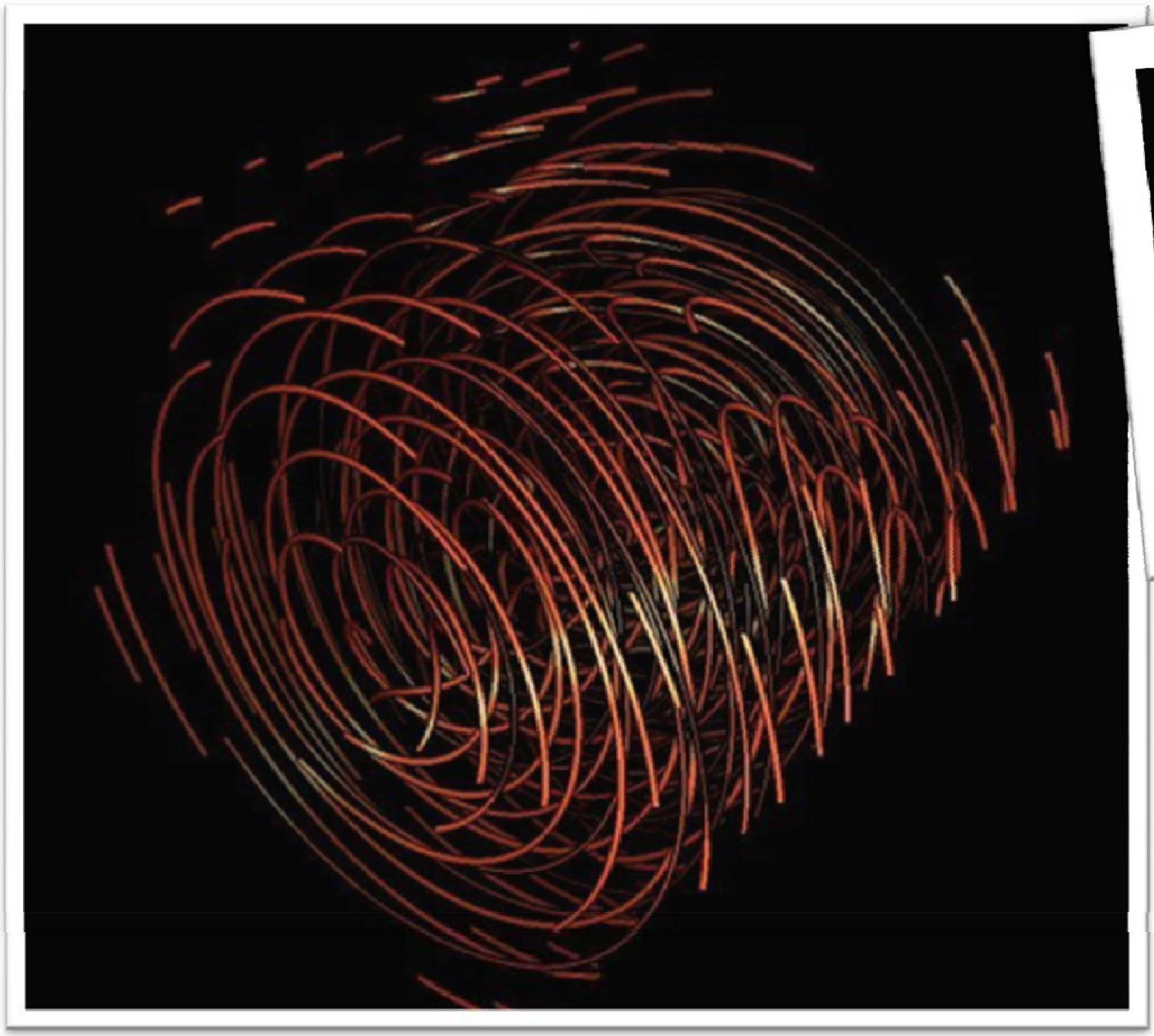
Streamlines – Placement (2)

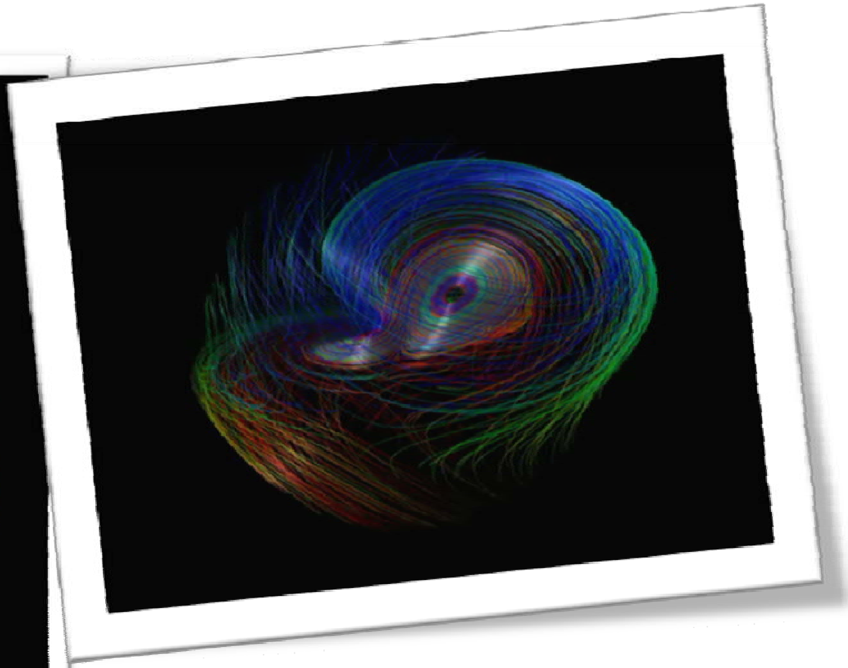
- Variations of distance in relation to image width



Illuminated Streamlines

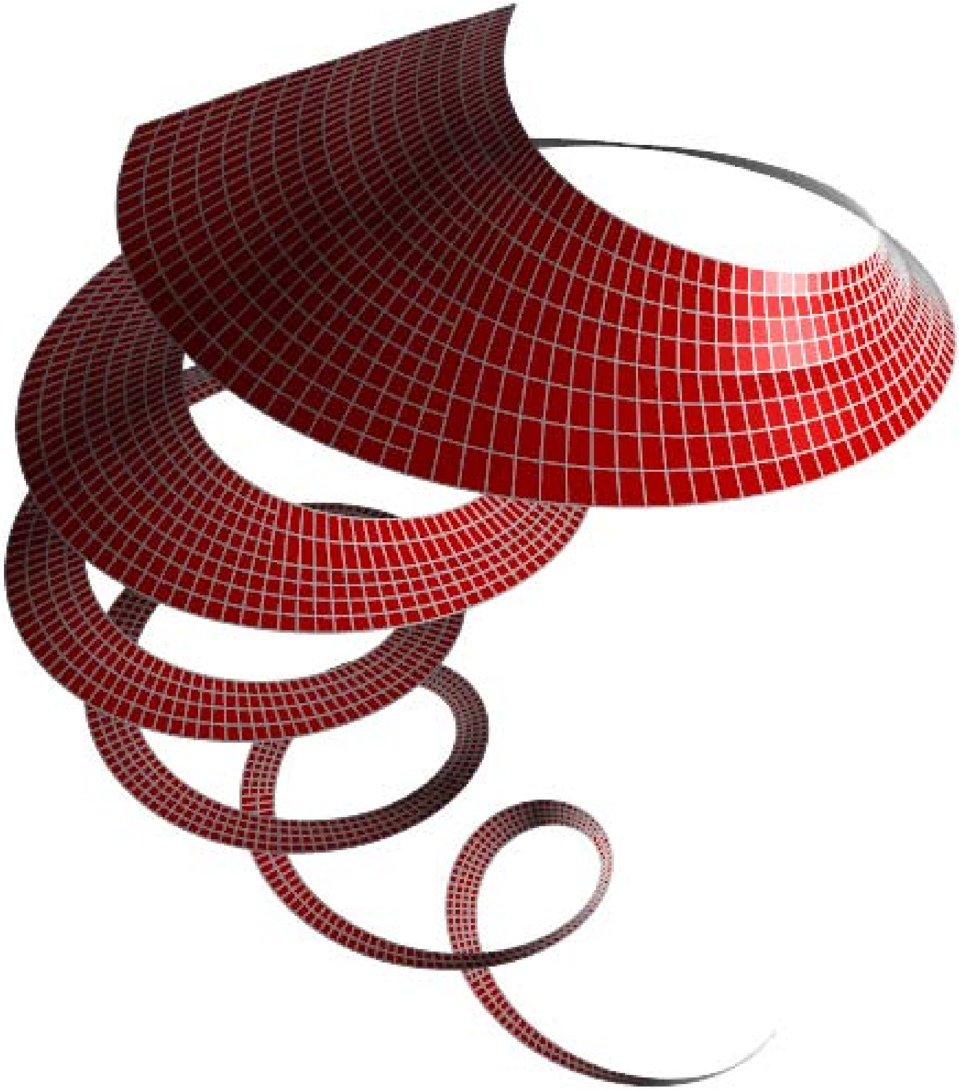
- Illuminated 3D curves improve perception





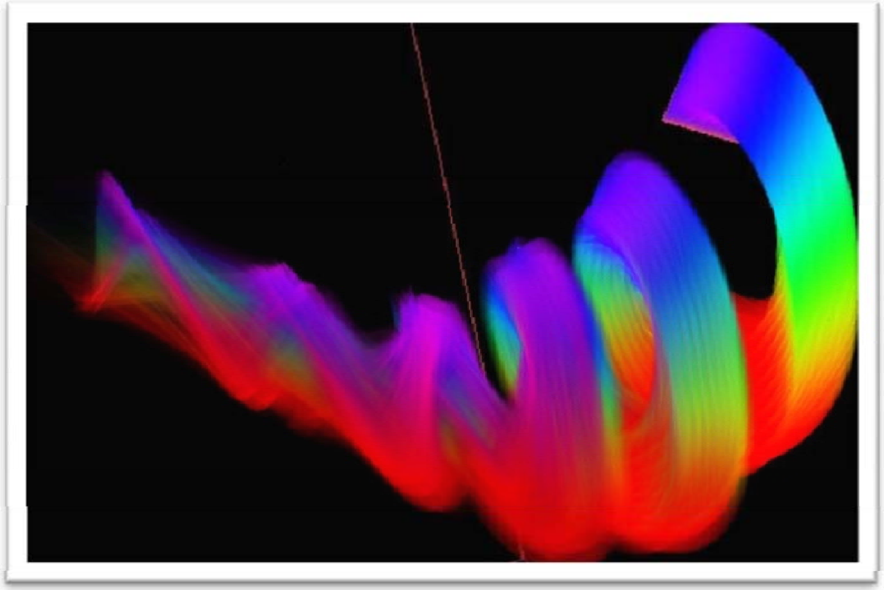
Stream Surfaces

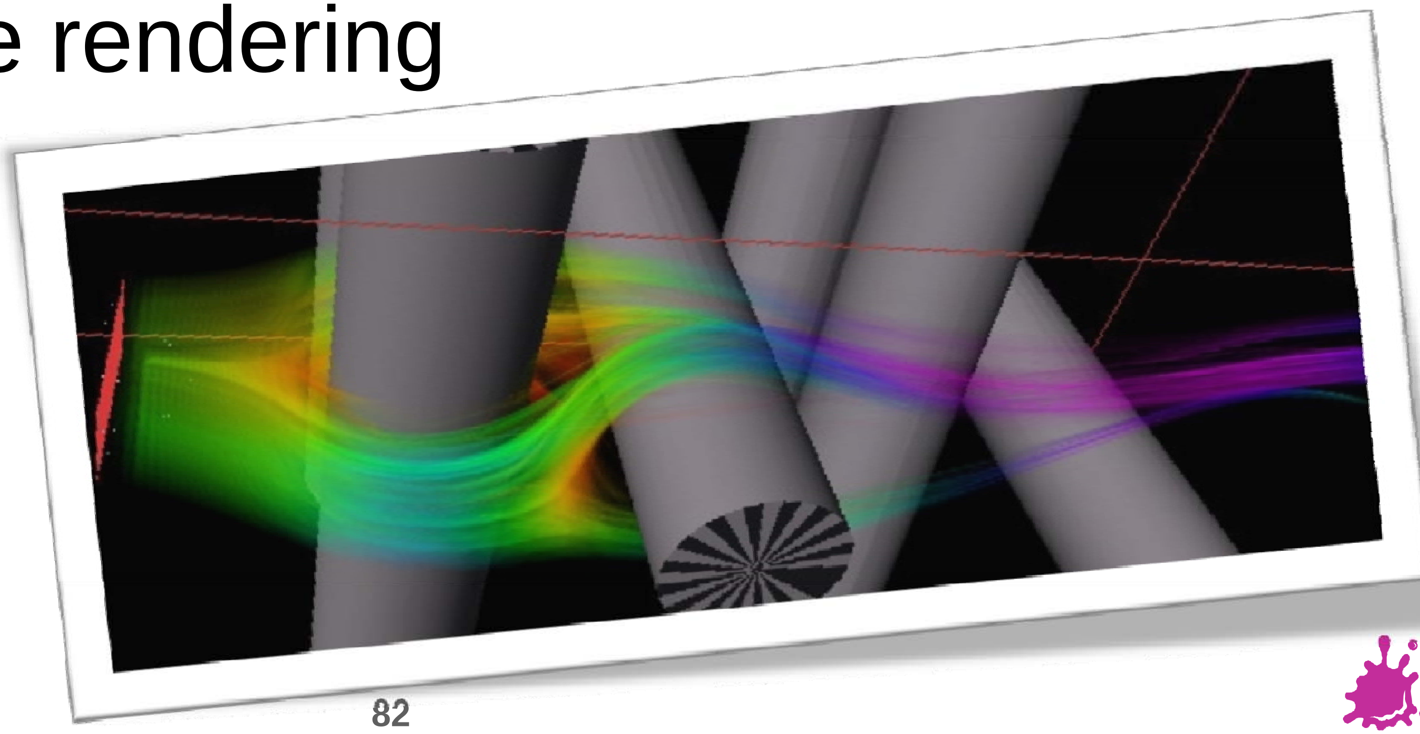
- Natural extension of streamlines to 3D
- Surfaces which are tangential to the vector field everywhere
- Challenges related to occlusion and visual complexity



Flow Volumes

- Volumetric equivalents of streamlines, subset of a 3D flow domain is traced in time
- Can be visualized with direct volume rendering methods



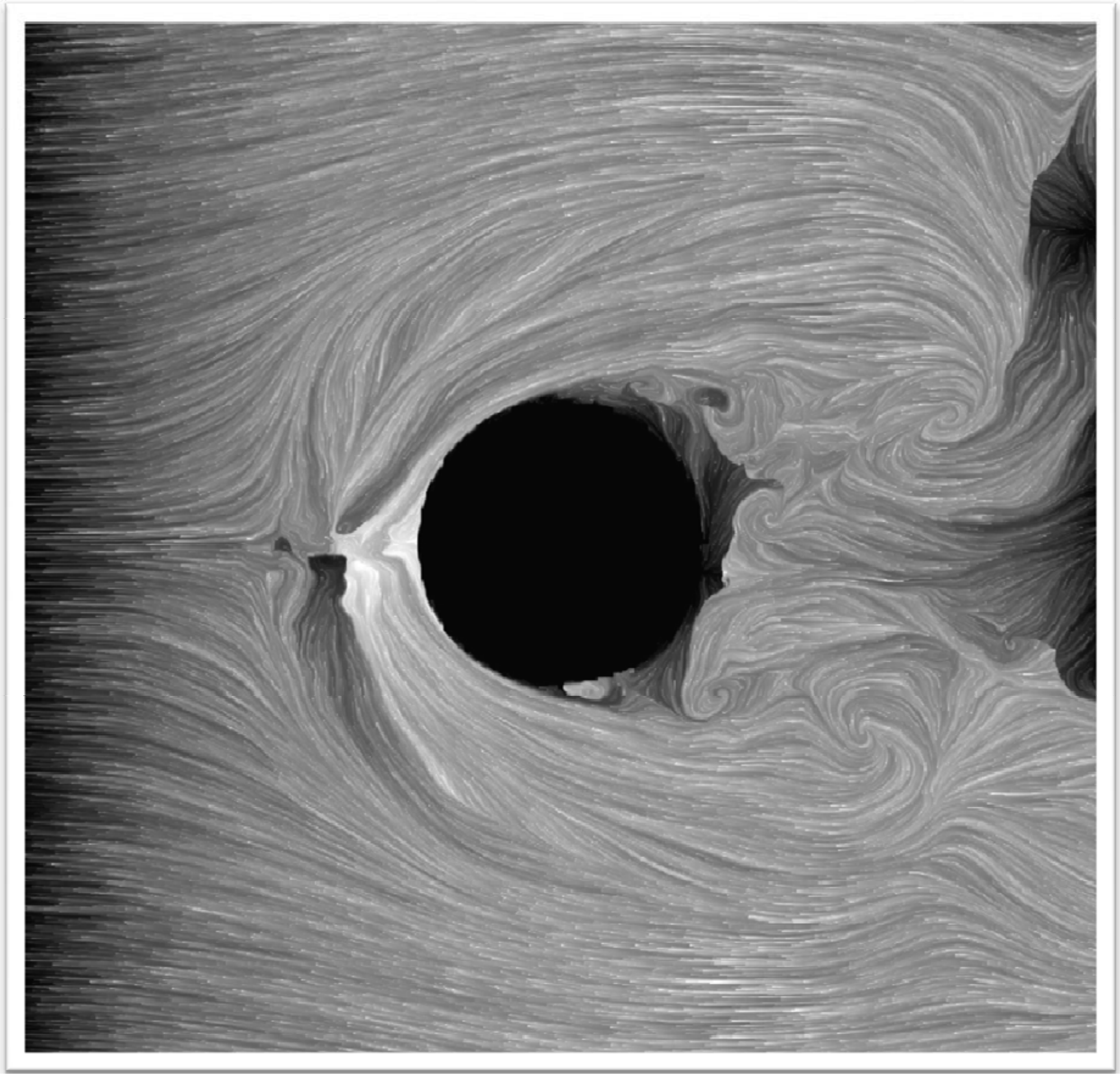


Unsteady Flow

- Path line
  - Trajectory of an individual particle in the fluid flow
- Timeline
  - Joins the positions of particles released at the same instant in time
- Streak line
  - Connects particles that have passed through a certain point in space

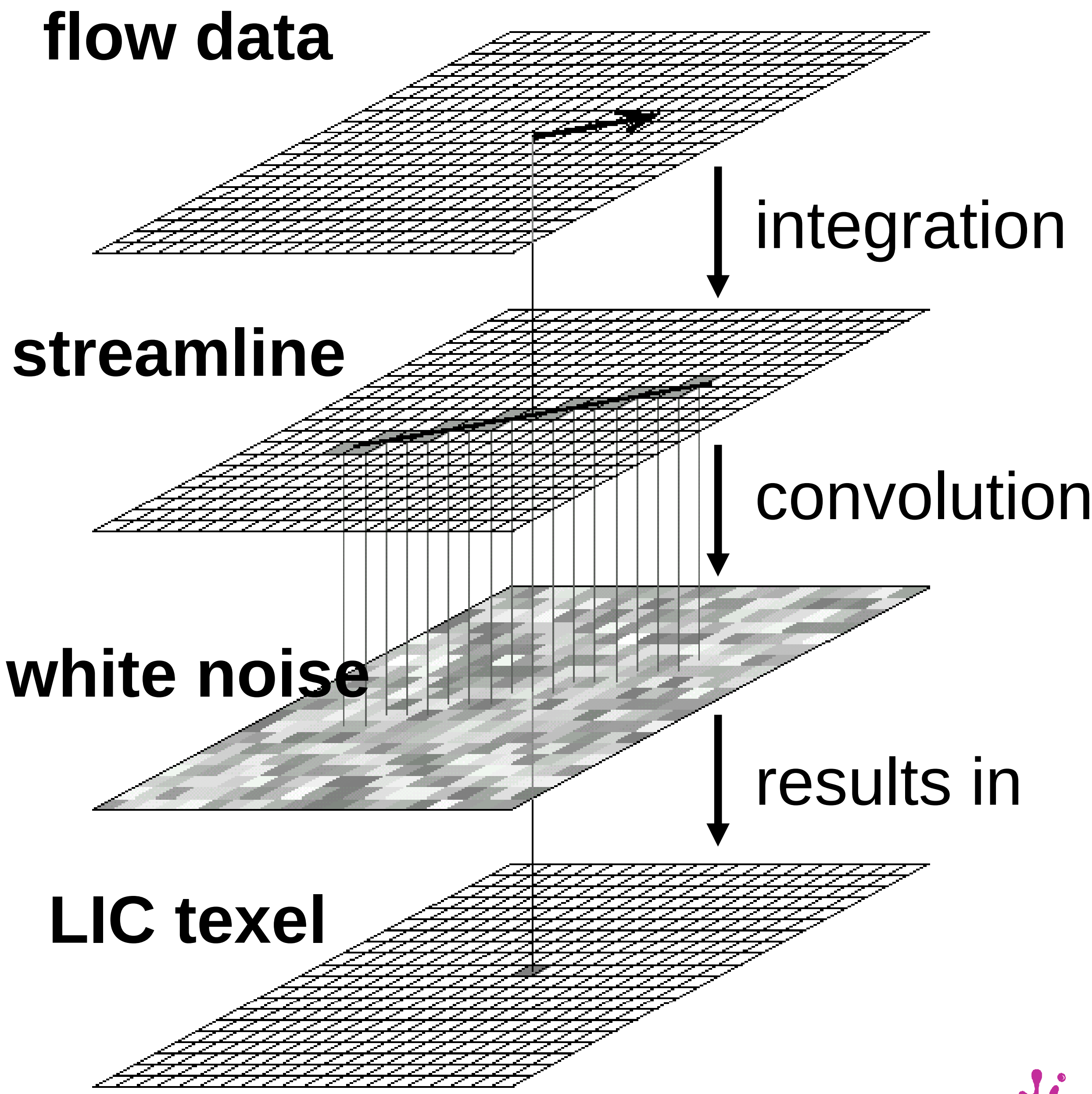
Texture-based Flow Visualization

- Idea: exploit visual correlations to provide a dense visualization of the flow

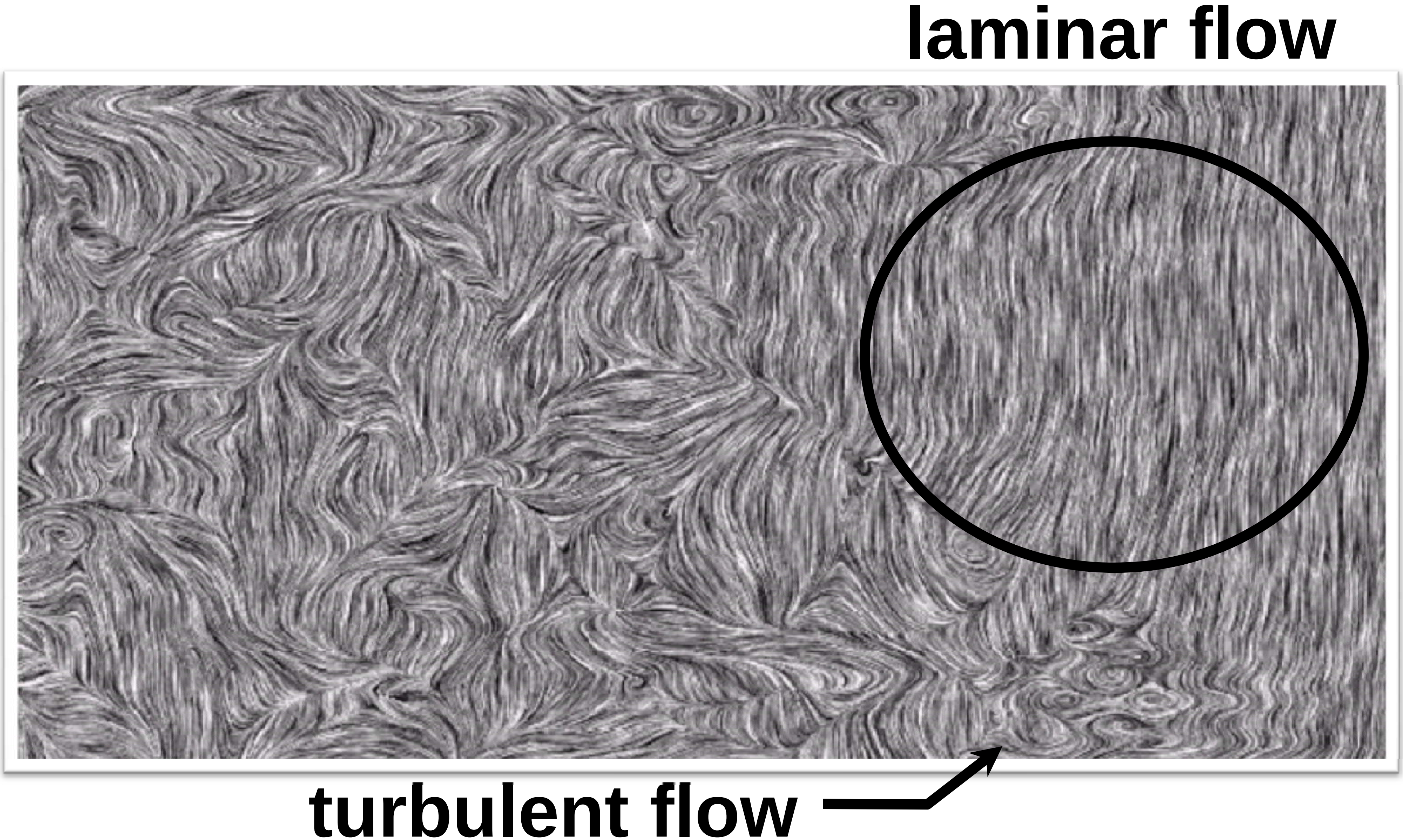


Line Integral Convolution

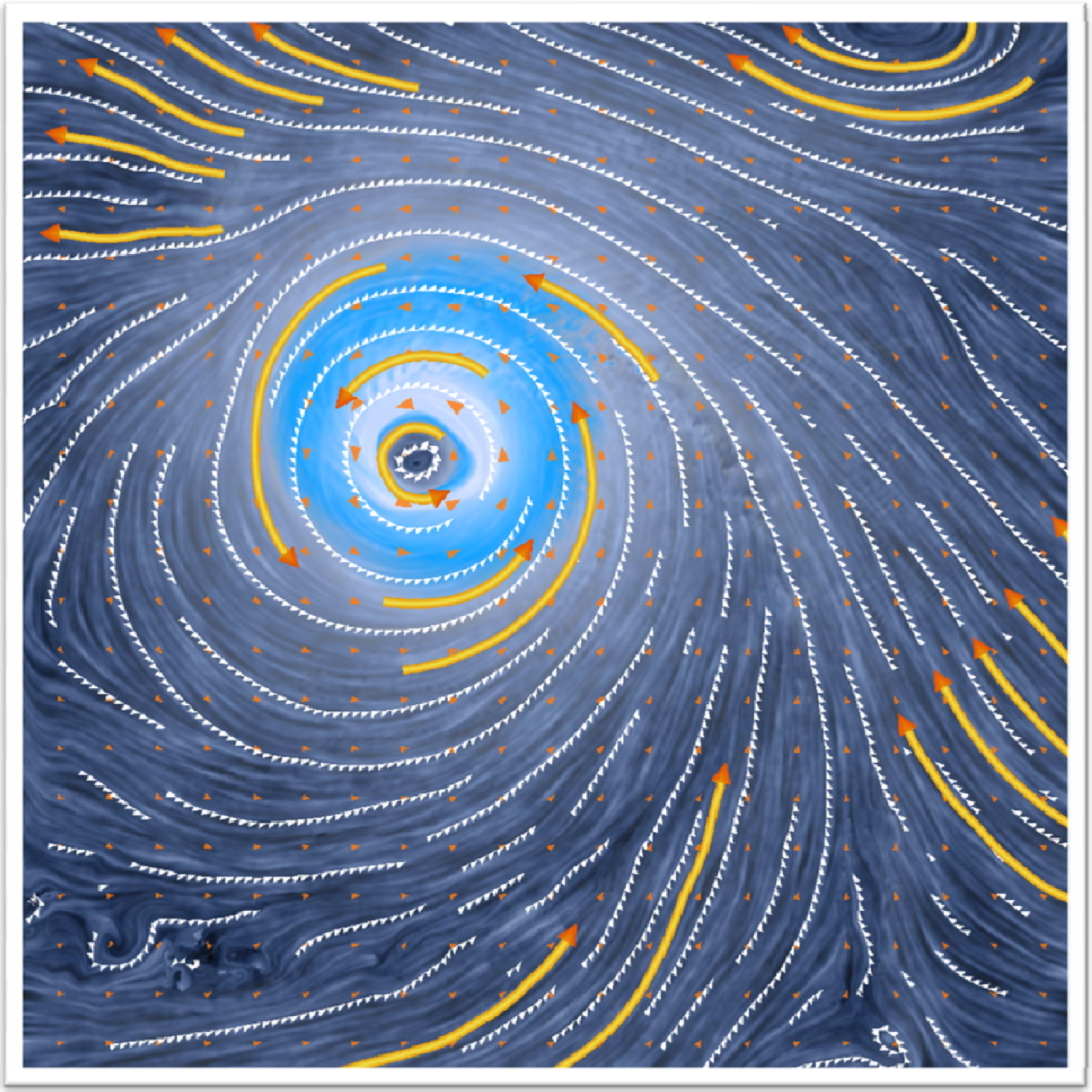
- Calculation of a texture value
  - look at streamline through point
  - filter white noise along streamline

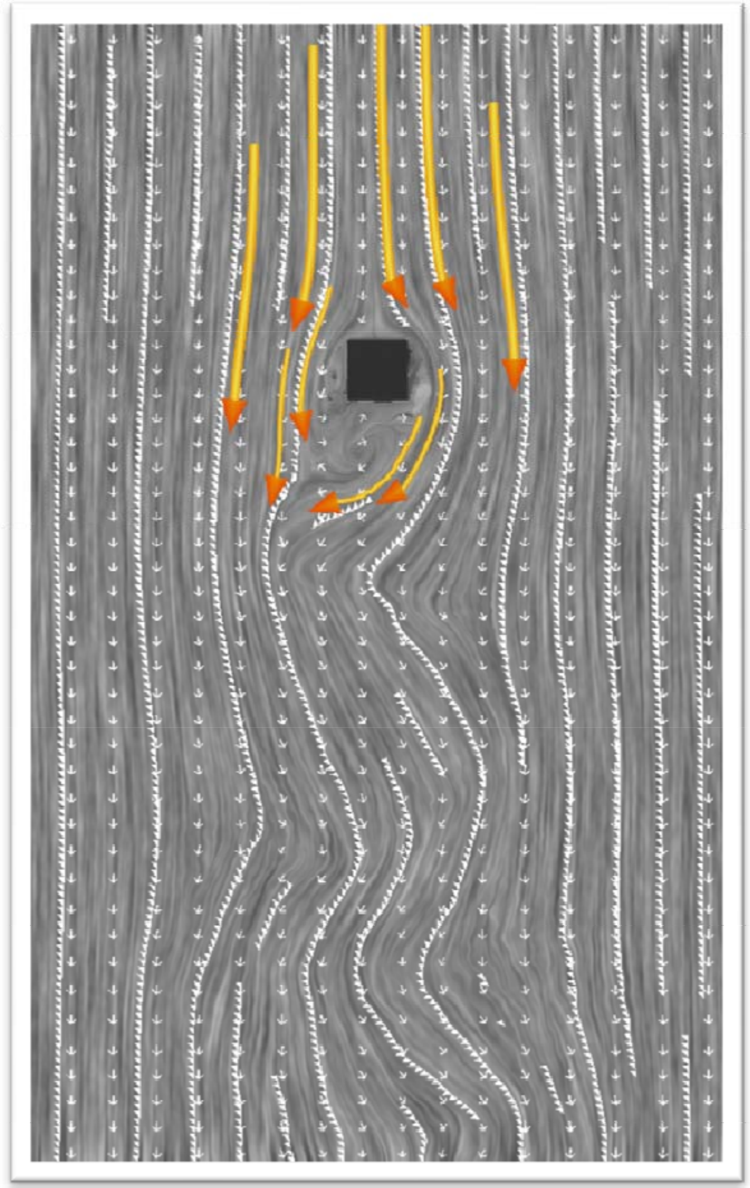


Line Integral Convolution – Examples (1)

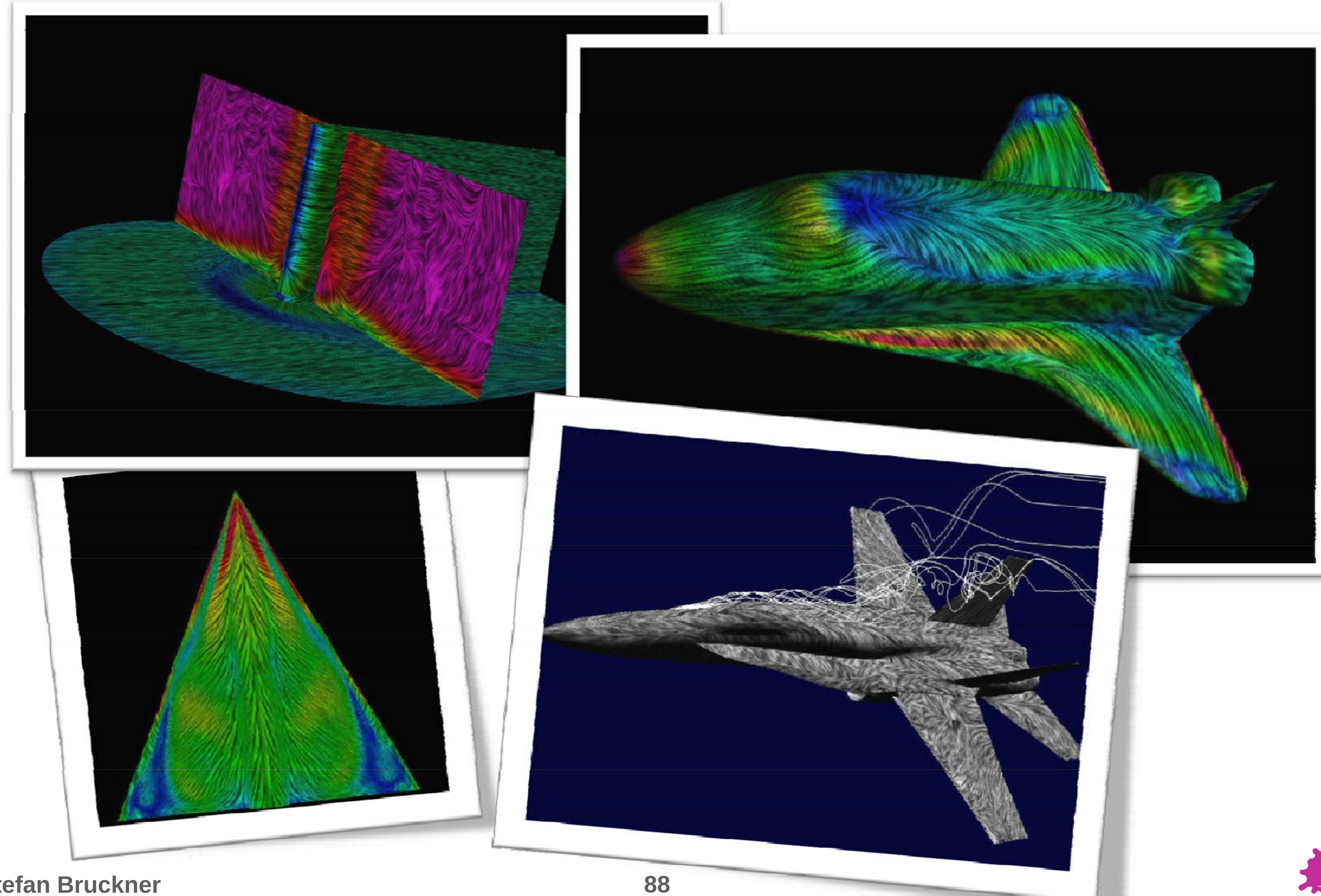


Line Integral Convolution – Examples (2)

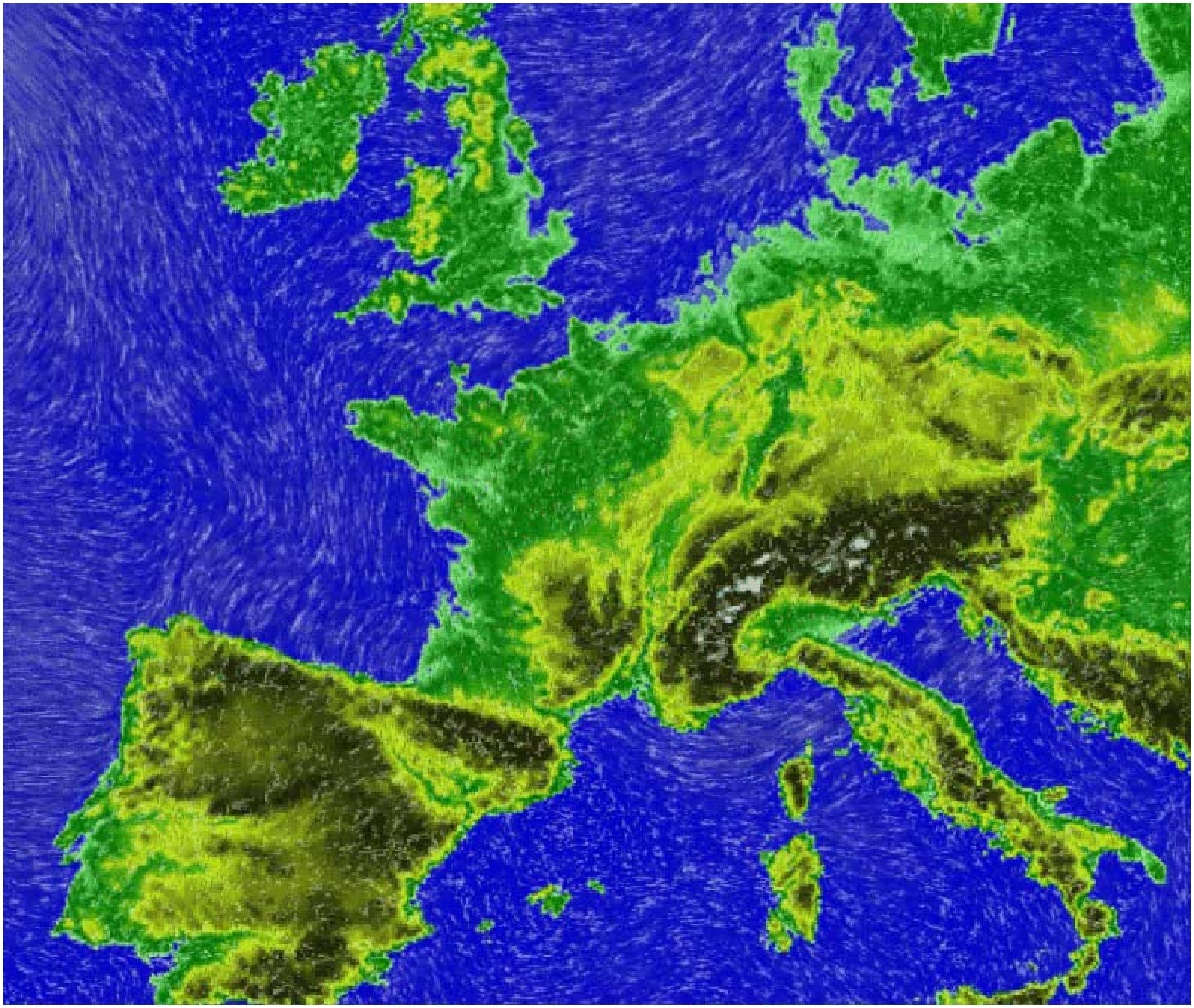




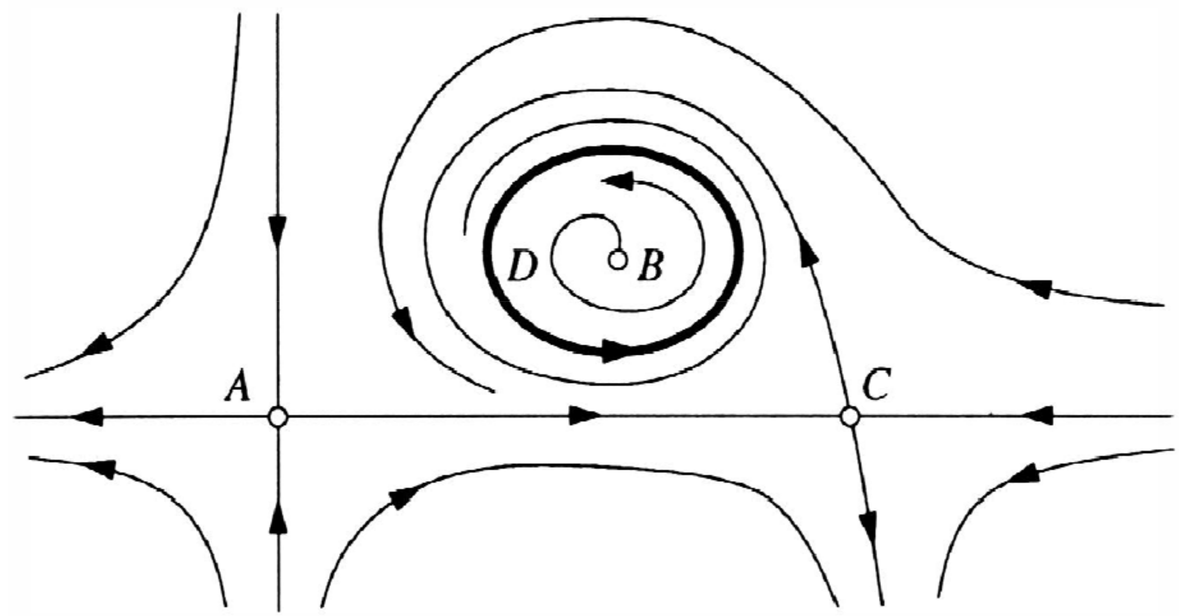
Line Integral Convolution on Surfaces



Texture Advection – Unsteady Flows

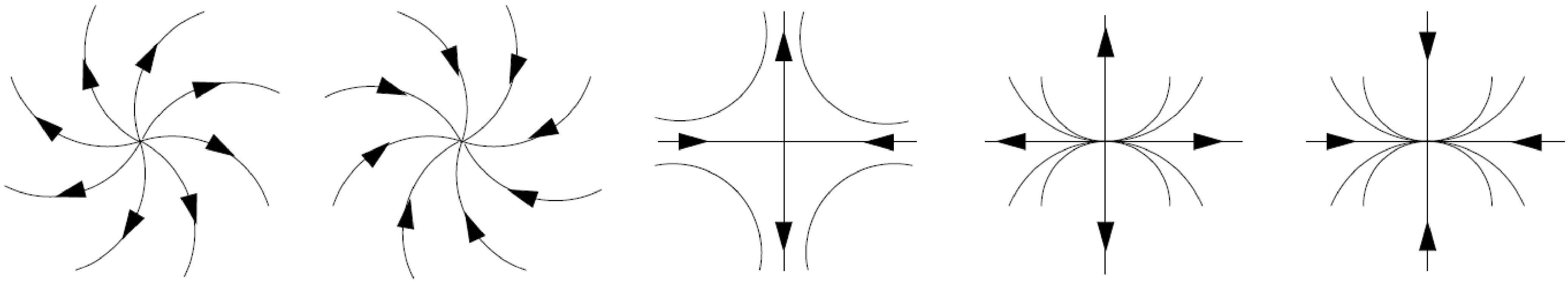


- Extract and visualize the abstract structure of a flow



- Different elements
  - Checkpoints, defined through v(x)=0
  - Cycles, defined through sx(t+T)=sx(t)
  - Connecting structures (separatrices, etc.)

Vector Field Topology

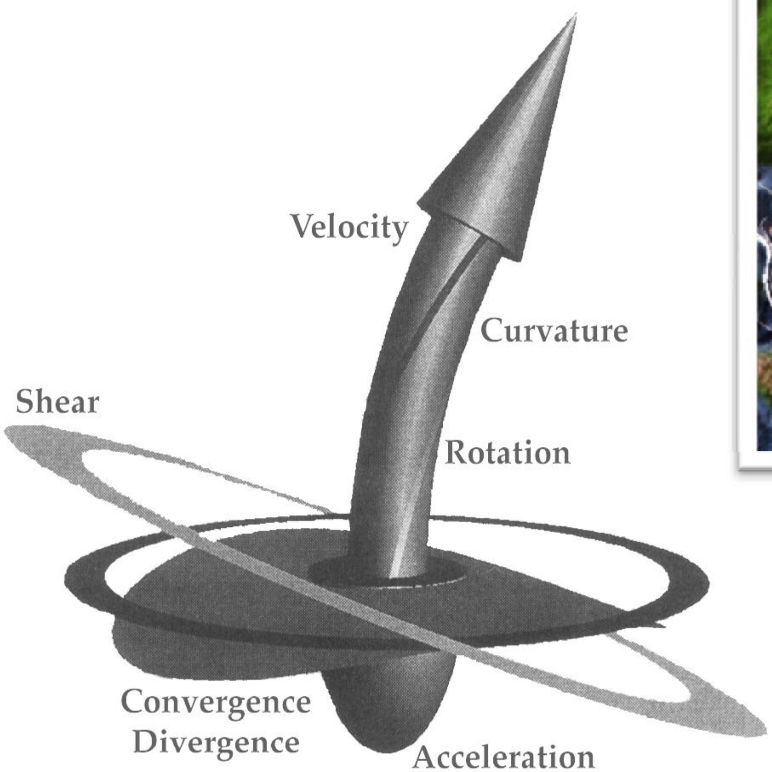


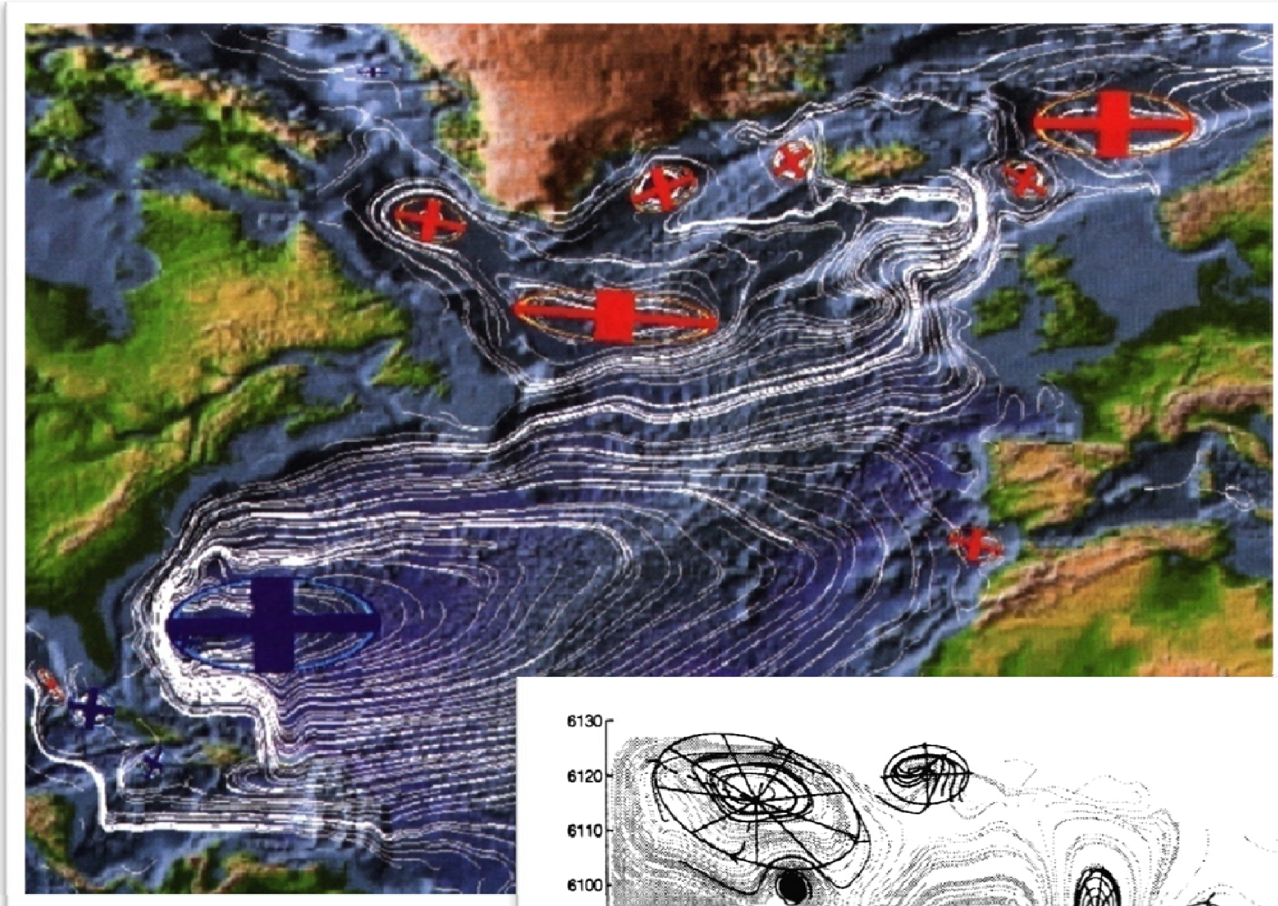
Repelling Focus	Attracting Focus	Saddle Point	Replling Node	Attracting Node
R1, R2 > 0	R1, R2 < 0	R1 * R2 < 0	R1, R2 > 0	R1, R2 < 0
I1, I2 <> 0	I1, I2 <> 0	I1, I2 = 0	I1, I2 = 0	I1, I2 = 0

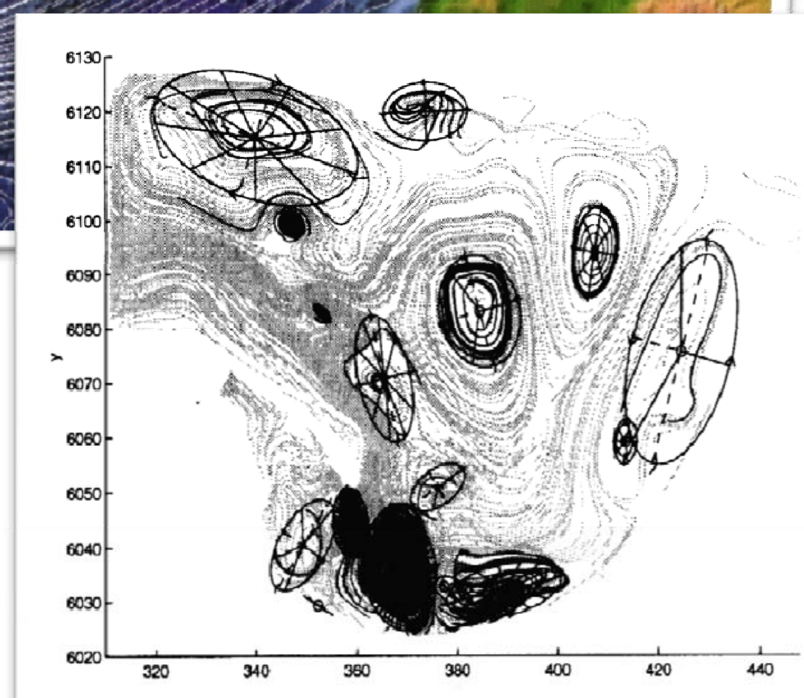
- Critical points can be classified by the Eigenvalues of the Jacobian
  R = real components, I = imaginary components

Glyphs/Icons

- Local/ topological properties





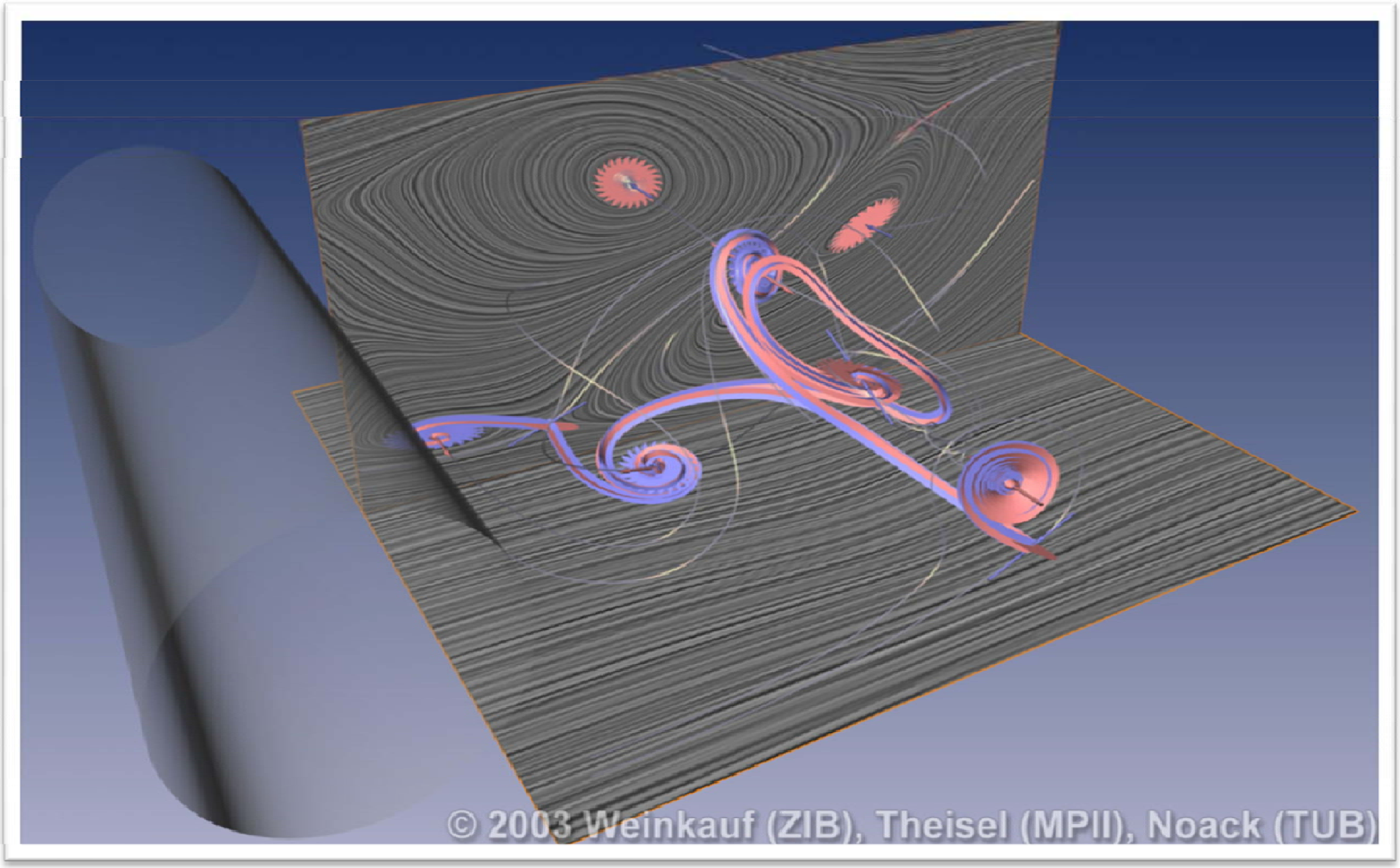


Examples (1)

- Topology of a hurricane simulation

Examples (2)

- Visualization of flow past a circular cylinder using critical points and saddle connectors



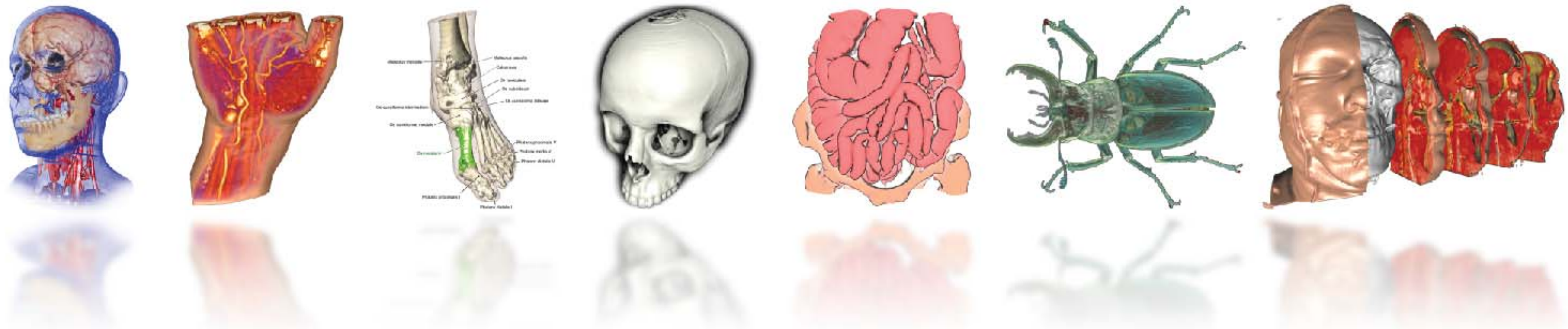
Further Reading

- R. Laramee, H. Hauser, H. Doleisch, B. Vrolijk, F. Post, D. Weiskopf. The State of the Art in Flow Visualization: Dense and Texture-Based Techniques. *Computer Graphics Forum*, 23(2):203-221, 2004.
- F. Post, B. Vrolijk, H. Hauser, R. Laramee, H. Doleisch. The State of the Art in Flow Visualization: Feature Extraction and Tracking. *Computer Graphics Forum*, 22(4):775-792, 2003.

Summary

- Scientific visualization is data-driven, but it is crucial to keep the goal of the user in mind
- **Volume visualization**
  3D scalar data
  - Important to provide detailed view of structures of interest
- **Flow visualization**
  2D/3D vector data
  - Provide overview and characterize flow behavior

Thank you for your attention!



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