Visualization
– Volume Rendering

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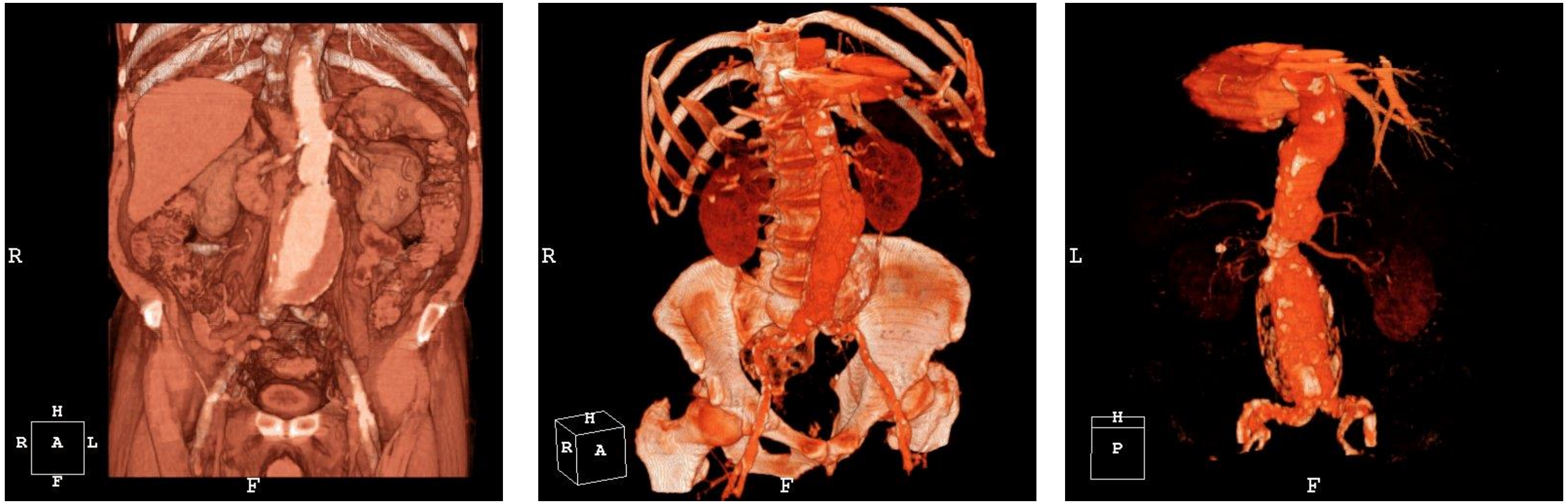
Motivation

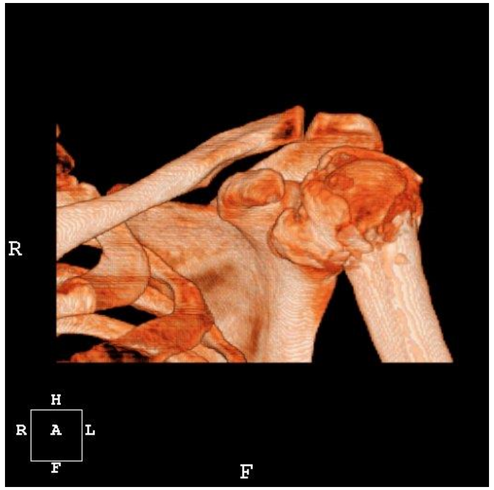
- Strongly calcified, distinctive aneurysm of the aorta



Source: www.pruemergang.de

Motivation

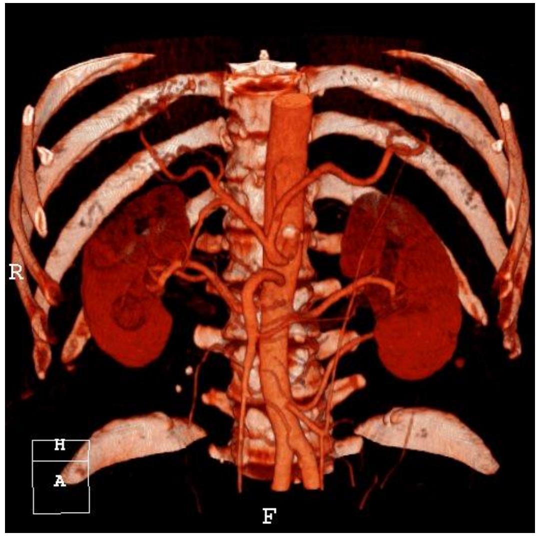
- Left and middle: Comminuted fracture of the shoulder
- Right: Detailed illustration of large vessels in the upper abdomen

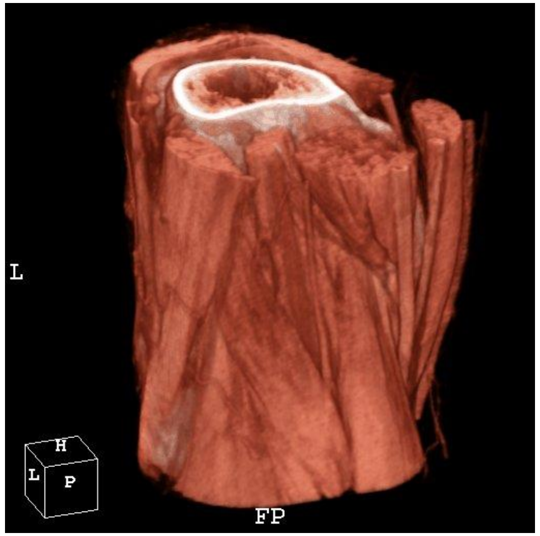


Source: www.pruemergang.de

Motivation

- Left: Two-vessel supply of the kidney
- Middle: Severe cystic kidney
- Right: Illustration of tendons and muscles in the knee region





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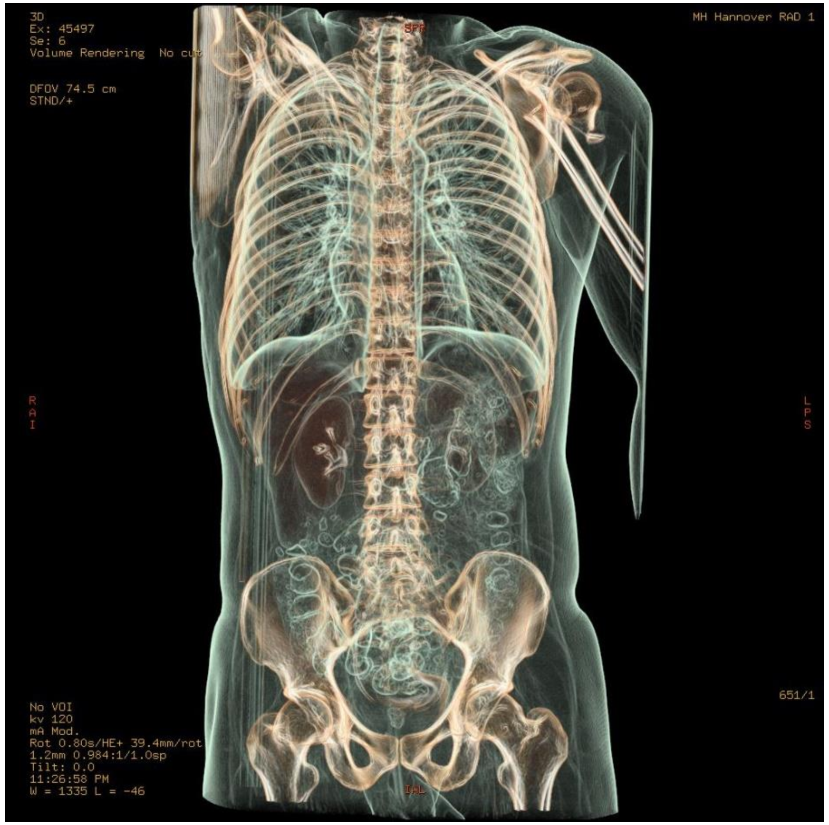
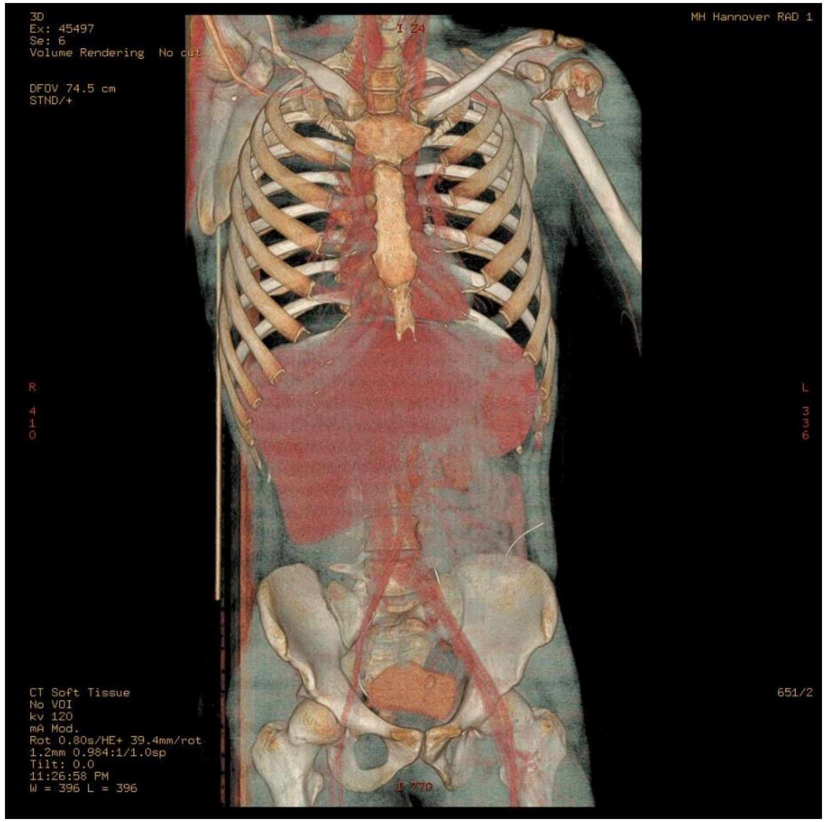
Motivation

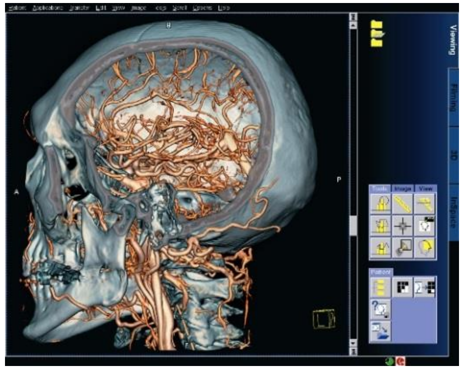




Modern volume rendering as part of clinical workstation (Courtesy of Hoen-Oh Shin, Medical School Hannover, 2013)

Introduction

- Volume visualization is of high current interest
  - High number and performance of the software tools (Voreen, 3DSlicer, ImageVis3D, integration into diverse scene graphs)
  - Integration of volume visualization procedures in clinical work stations (SIEMENS, Philips, AGFA, Vital Images...)
  - Beyond medicine: Material testing in engineering, analysis of seismic data for oil and gas industry, …



[Siemens Medical]

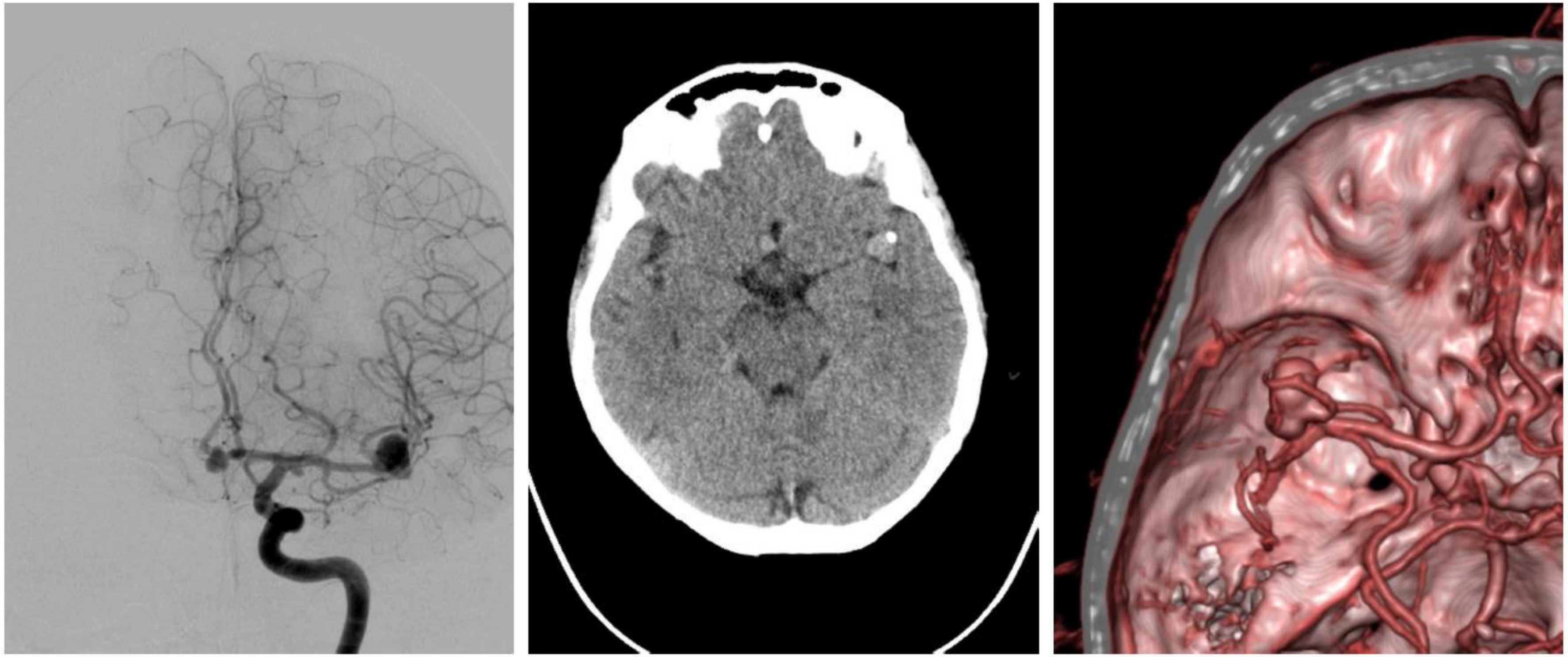
[Vital Images]

Medical Applications

- Anatomy
  - Training (e.g., Visible Human data sets)
- Radiology
  - Diagnosis of vessel diseases (stenosis, aneurysm), assessment of tumors (localization, vessel infiltration)
- Therapy planning
  - Irradiation planning (dose distribution, risk assessment)
  - Surgery planning (planning of pathways and resection areas)
  - Surgery simulation for training purposes

Medical Applications

- Surgery planning



(Image courtesy of General Hospital of Vienna)

Requirements

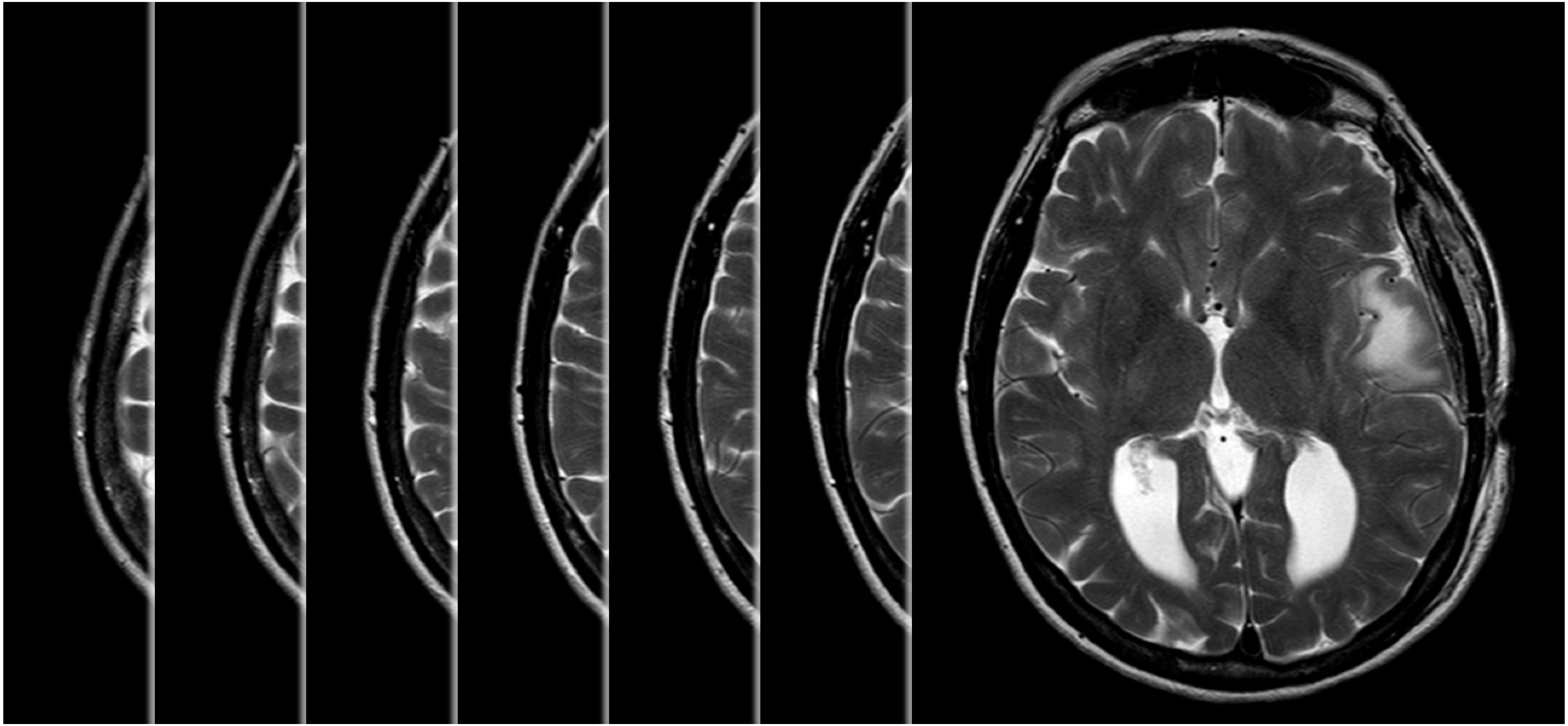
- System requirements
  - Detailed visualization of original data
    (relevance for diagnostic and therapeutic purposes)
  - Good rendering of spatial relations (visual cues, such as shadows, highlights, depth attenuation)
  - High performance
  - Integration of surface and volume data (hybrid rendering)

Process

Basic procedure:

- Loading of data,
- Direct rendering
  - » Volume sampling
    - – Different resampling filters for interpolation between the voxels
  - » Classification
    - – Definition of material composition
    - – Transfer function assigns color and opacity to volume values

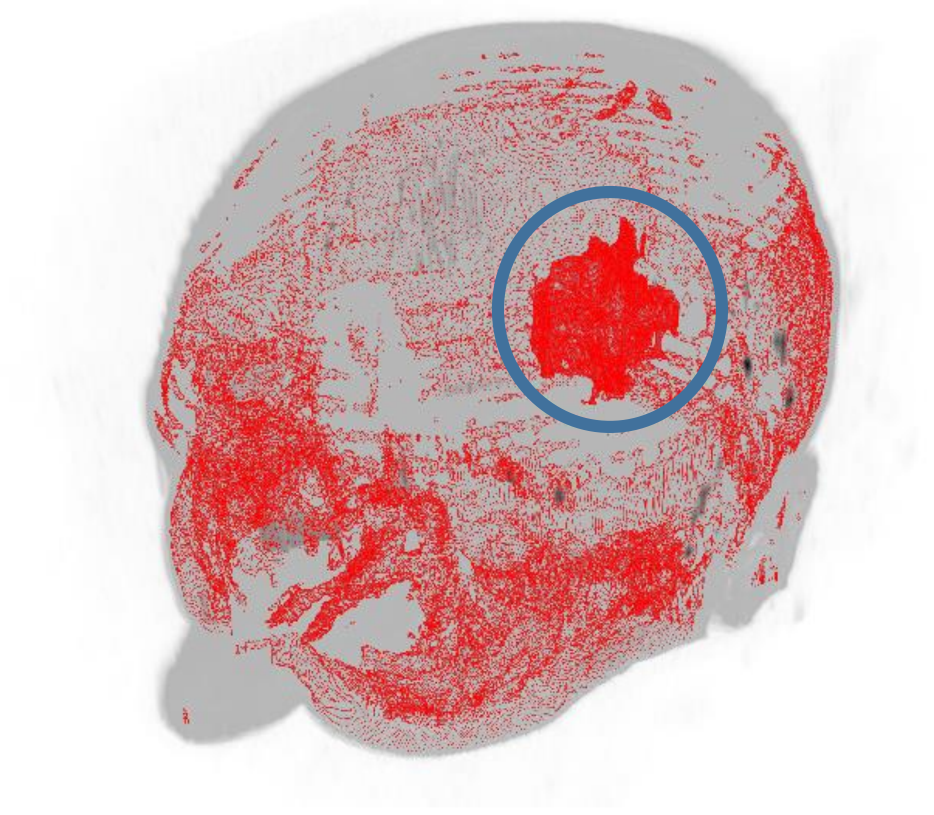
Medical Data Sets



From 2D to 3D

- Goal: Overview
- No slicing

Goal



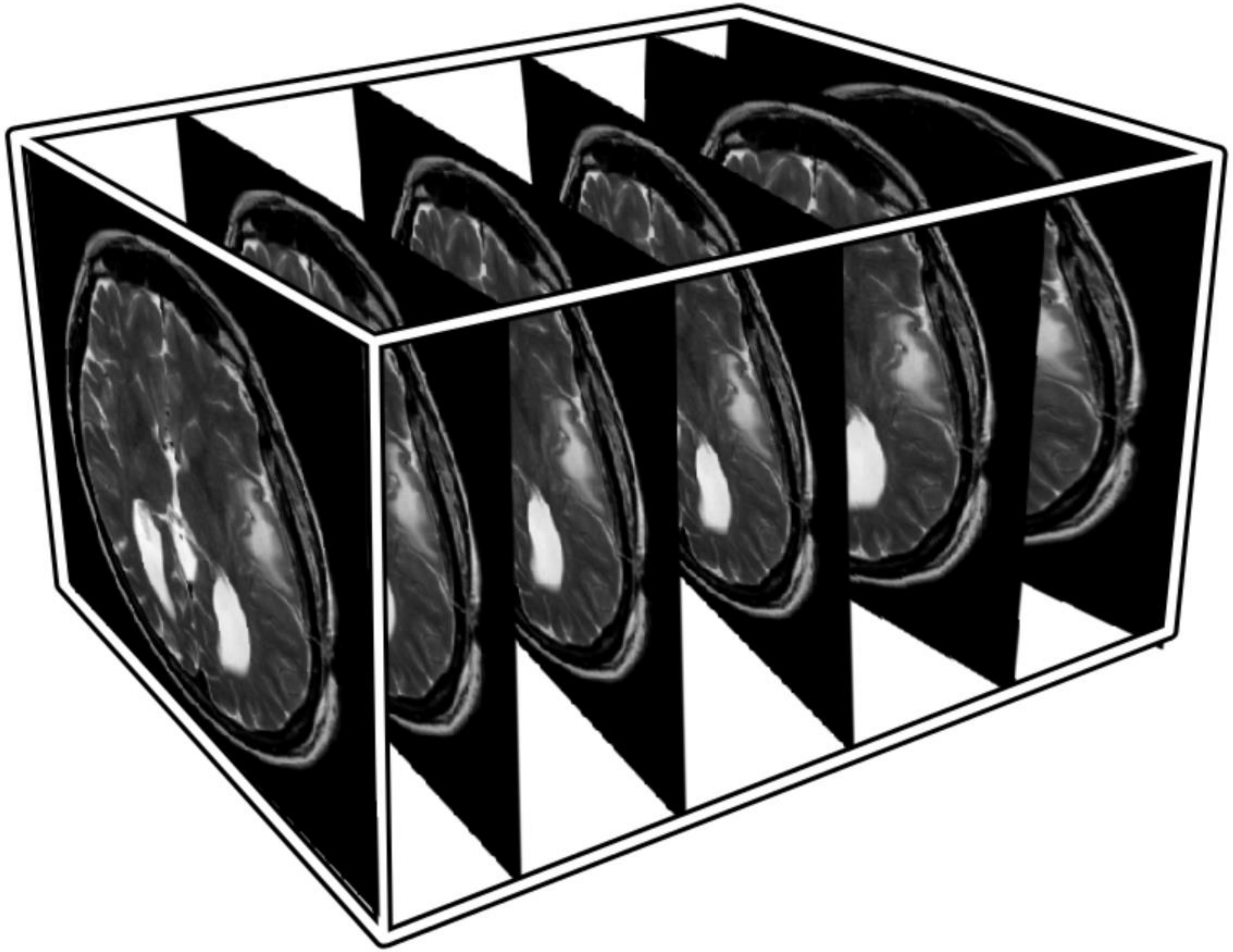
Maximum Intensity Projection

Ingredients MIP

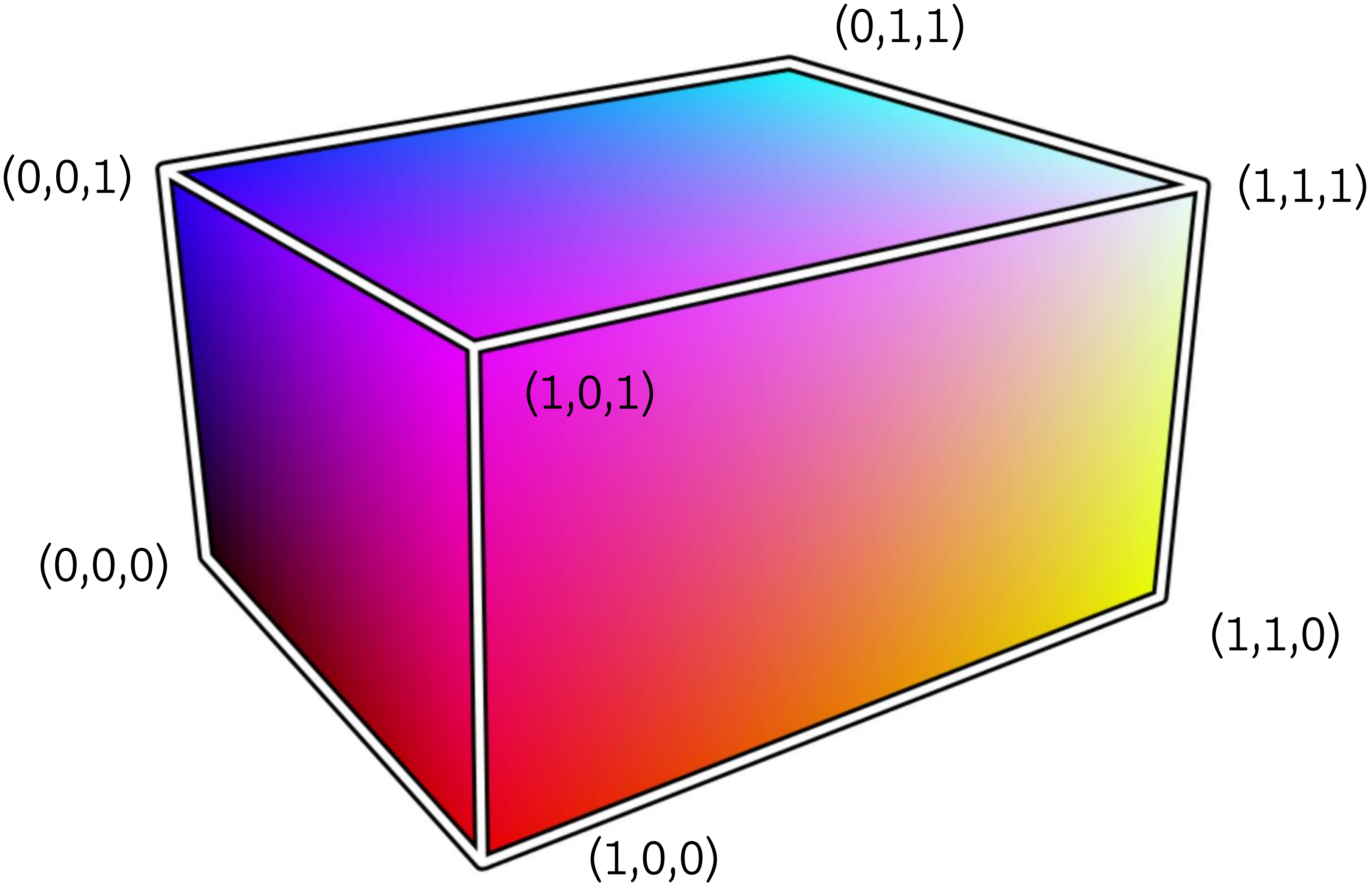
- Raytracing (Rays from the camera through the data set)
- Sampling (Rays are sampled)
- Mapping (Sampled rays are interpreted)

- Depiction of the maximum value

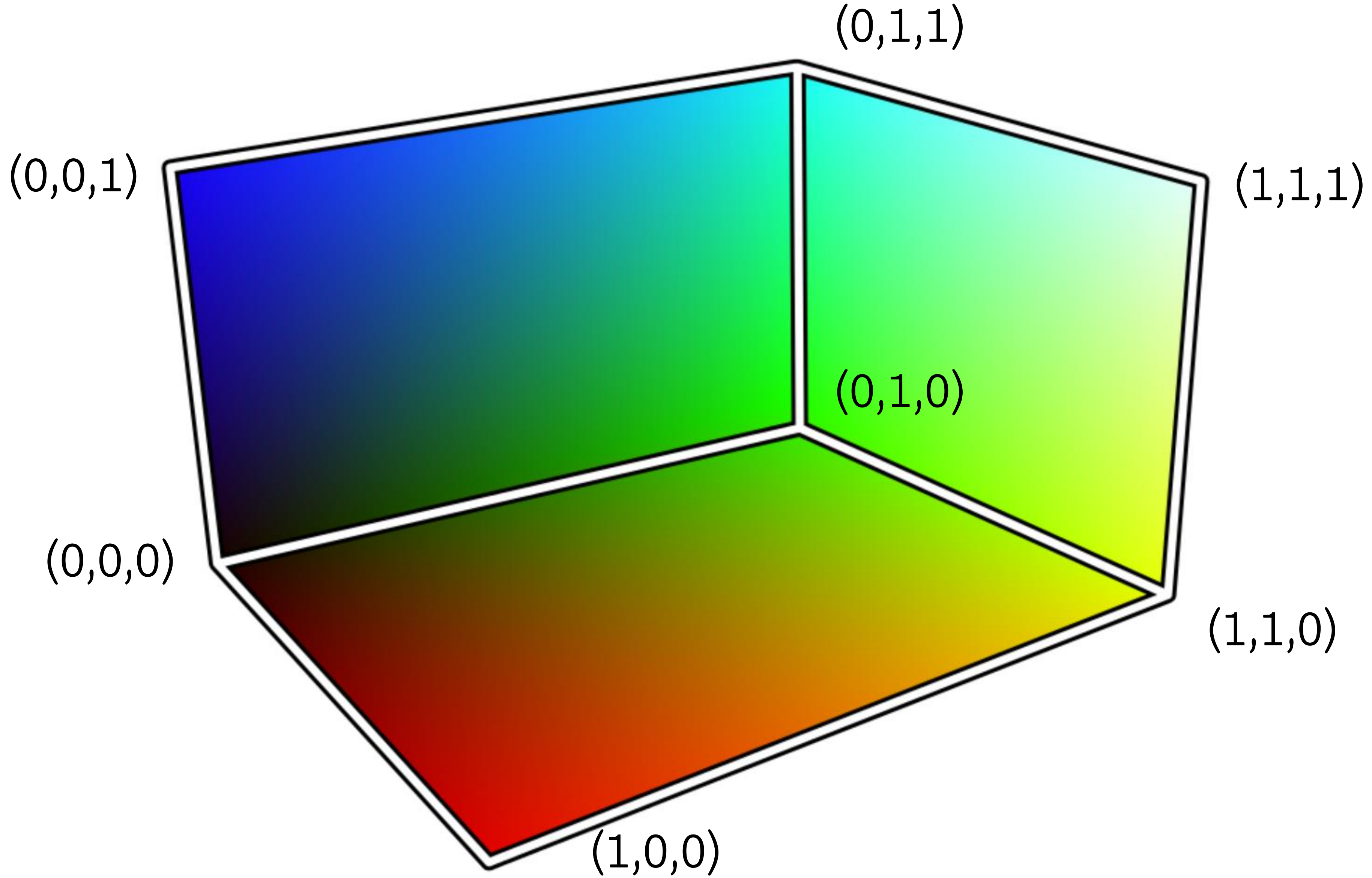
From 2D to 3D



From 2D to 3D



From 2D to 3D



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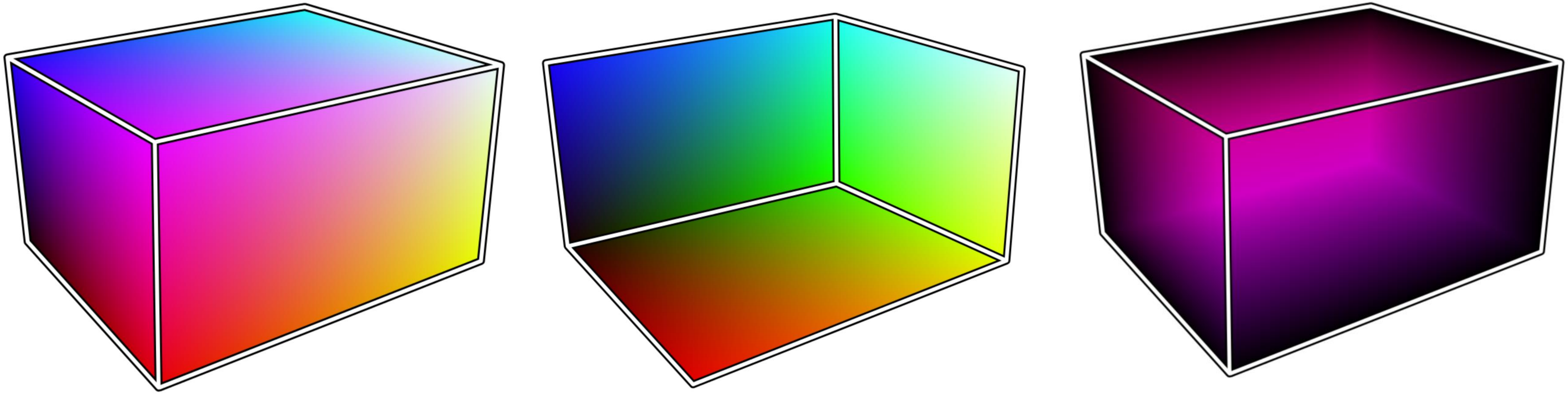
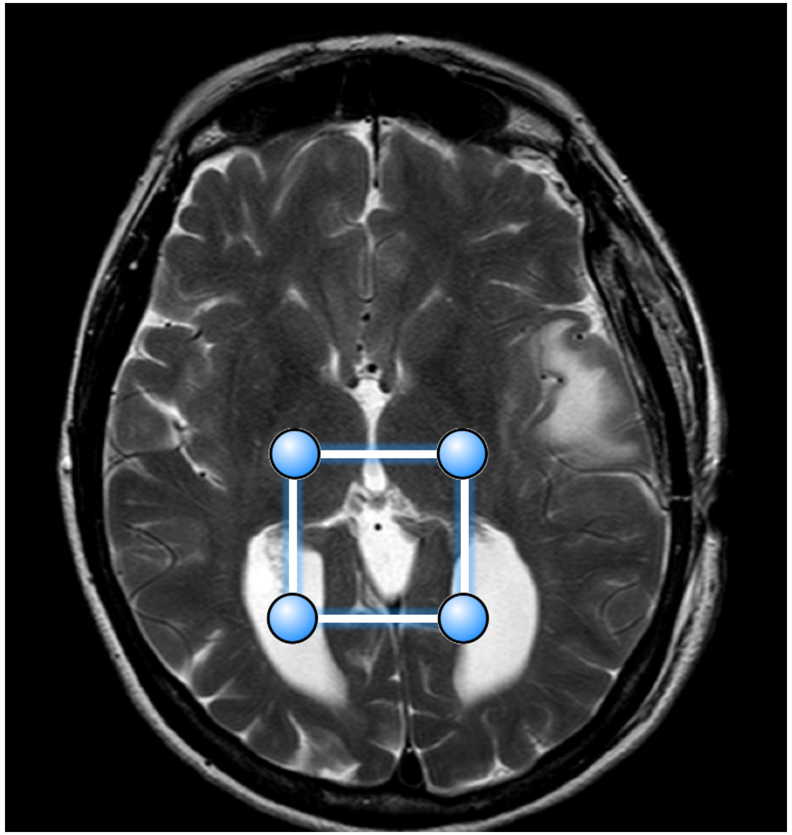
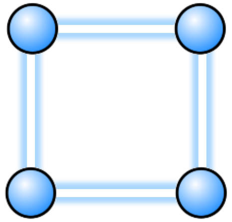


Voxel & Cell

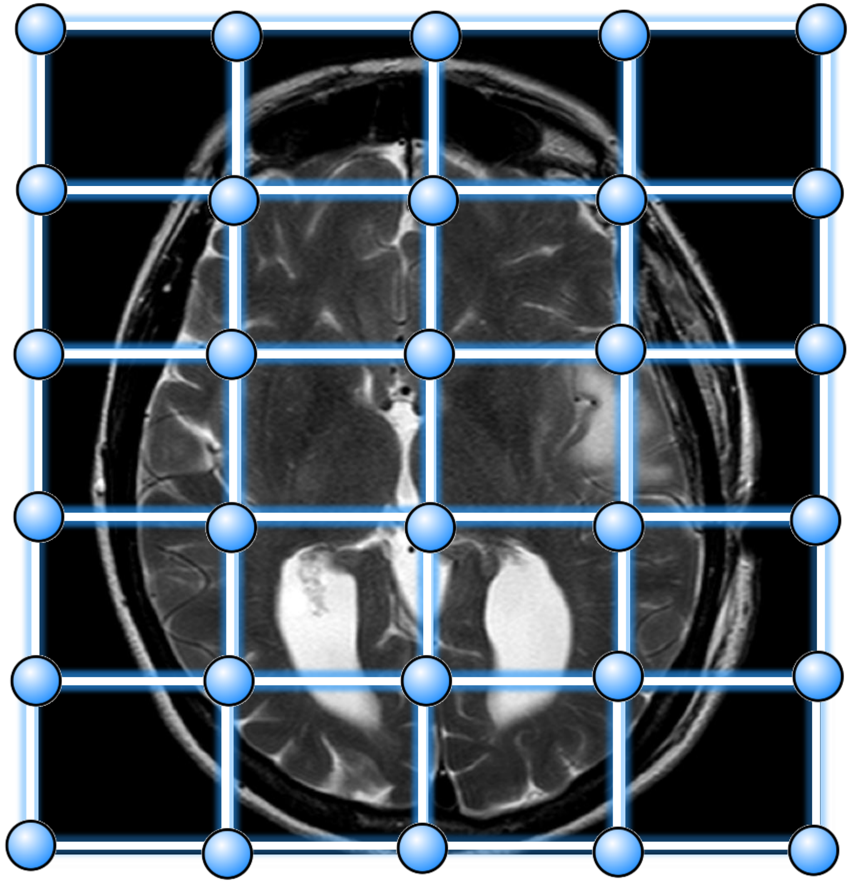


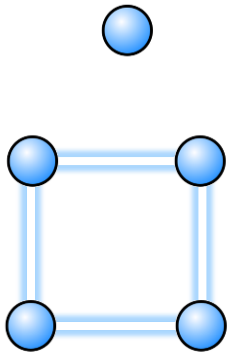
Voxel – Gray value



Cell – Enclosed by voxel

Voxel & Cell





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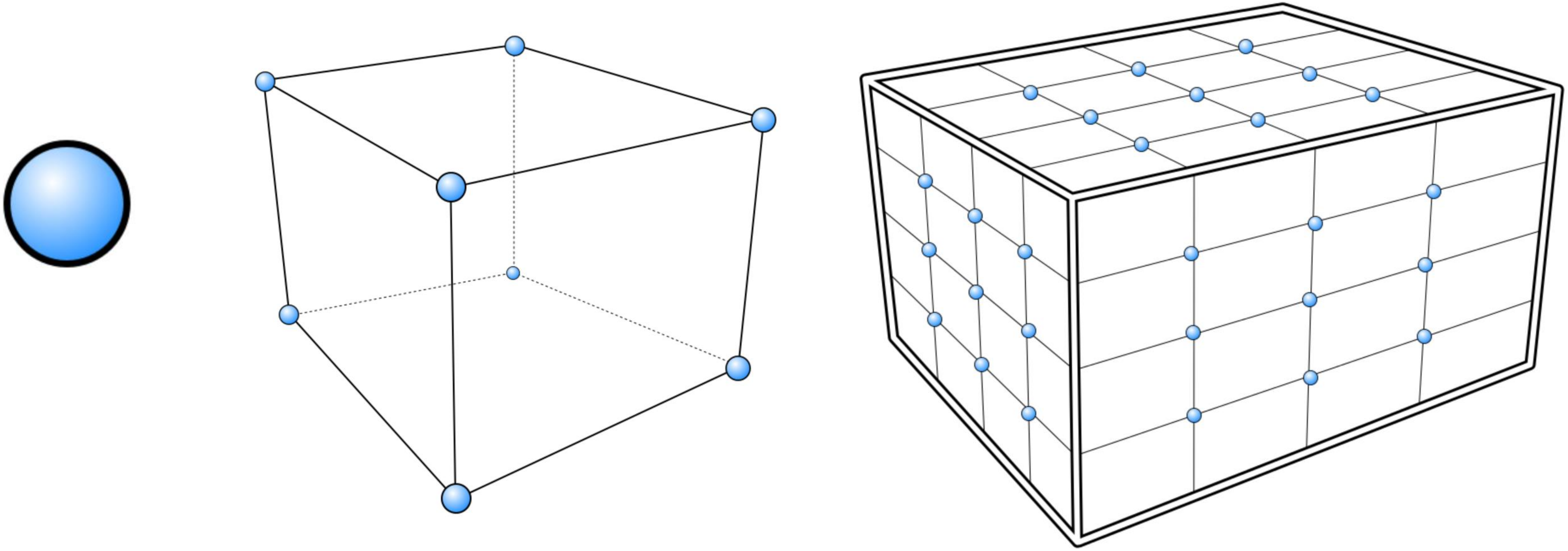
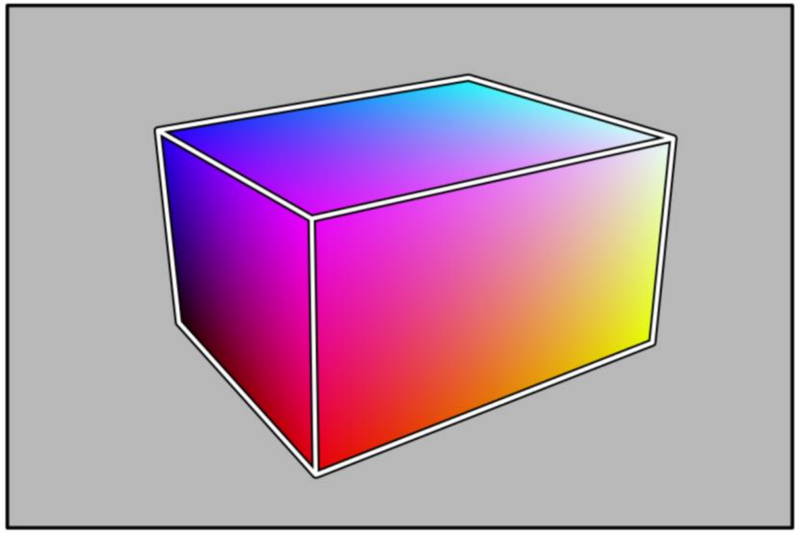
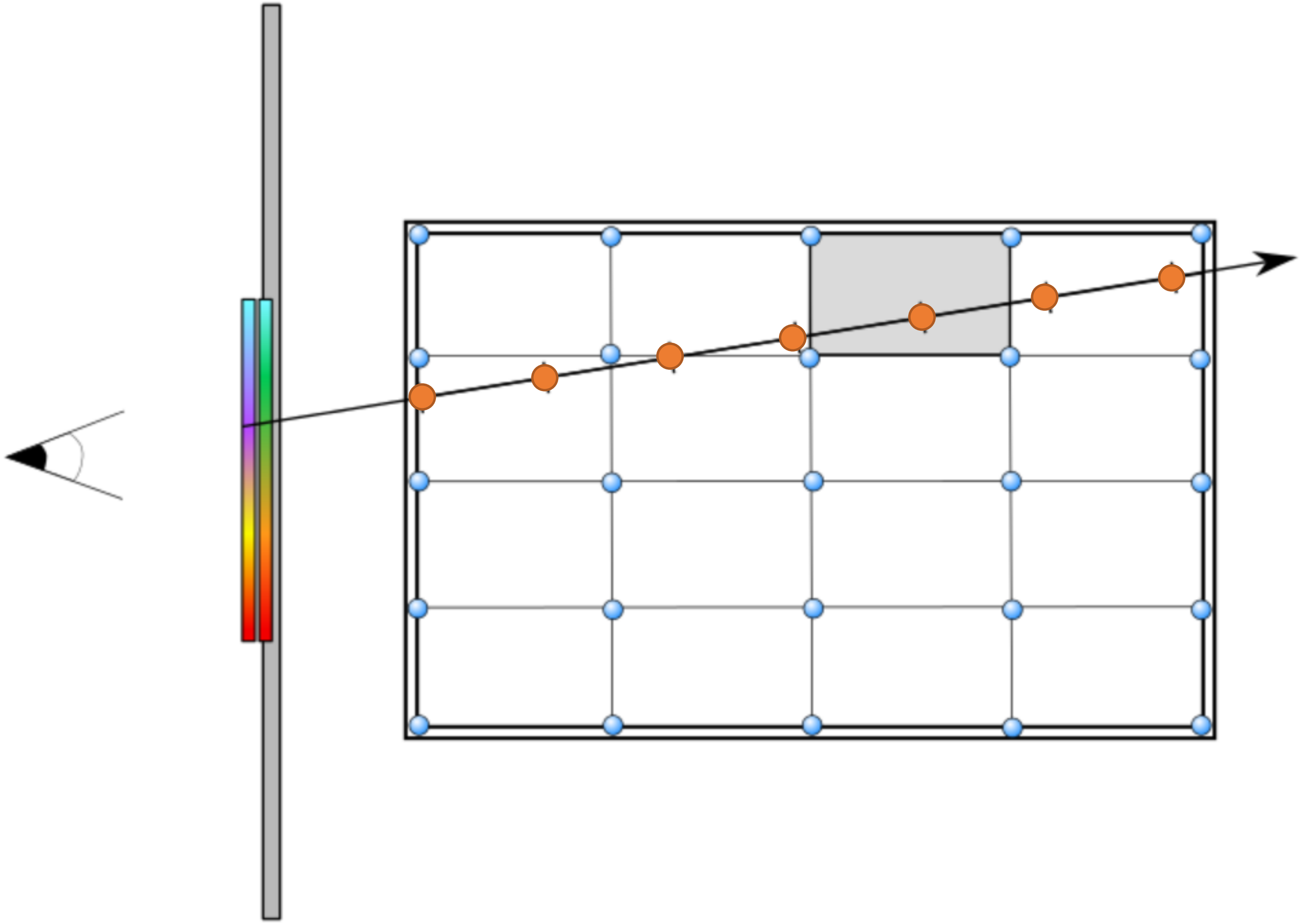
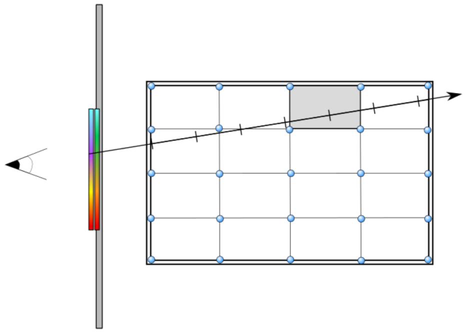


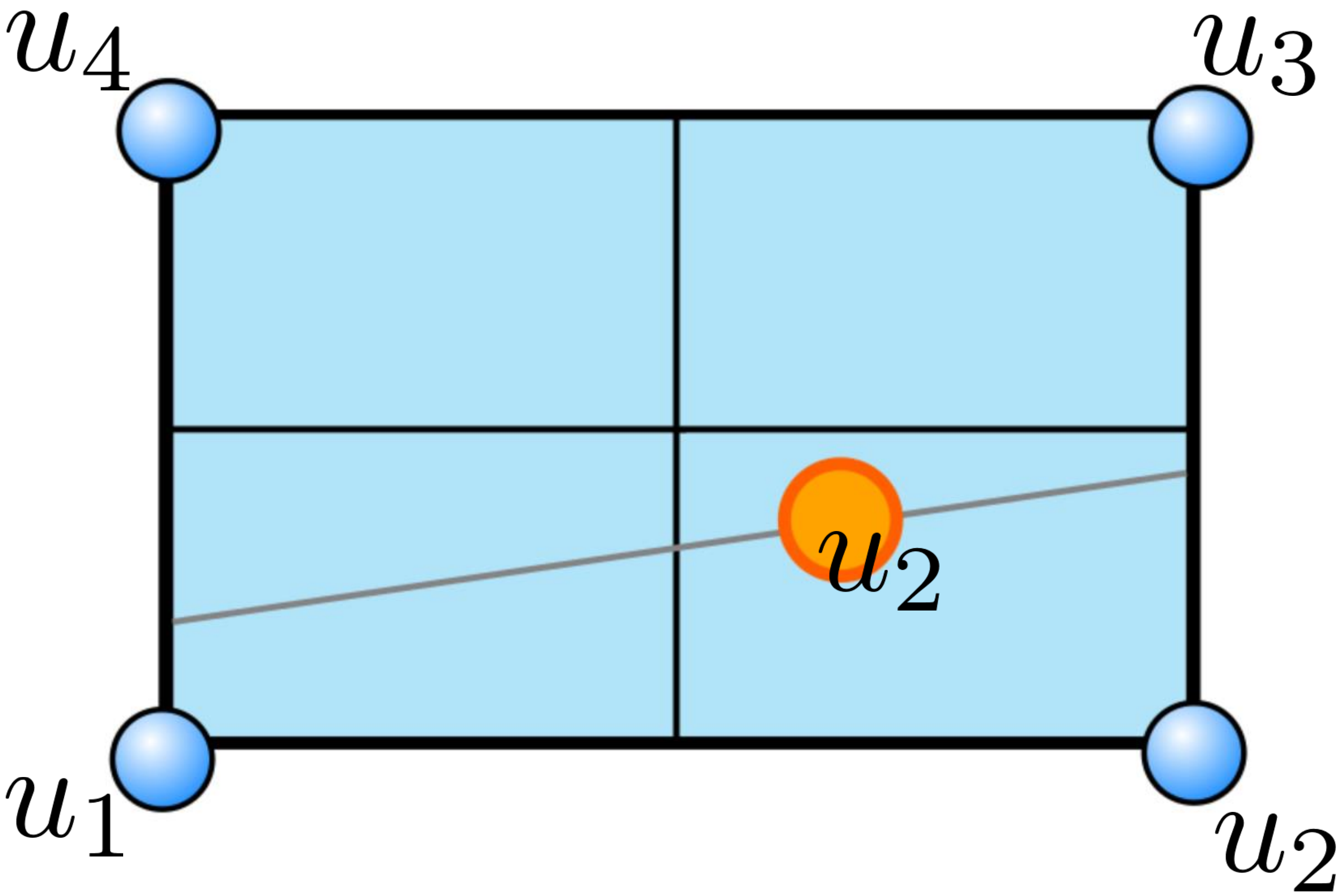
Raytracing
Sampling



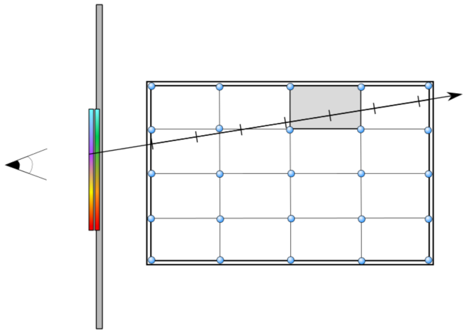


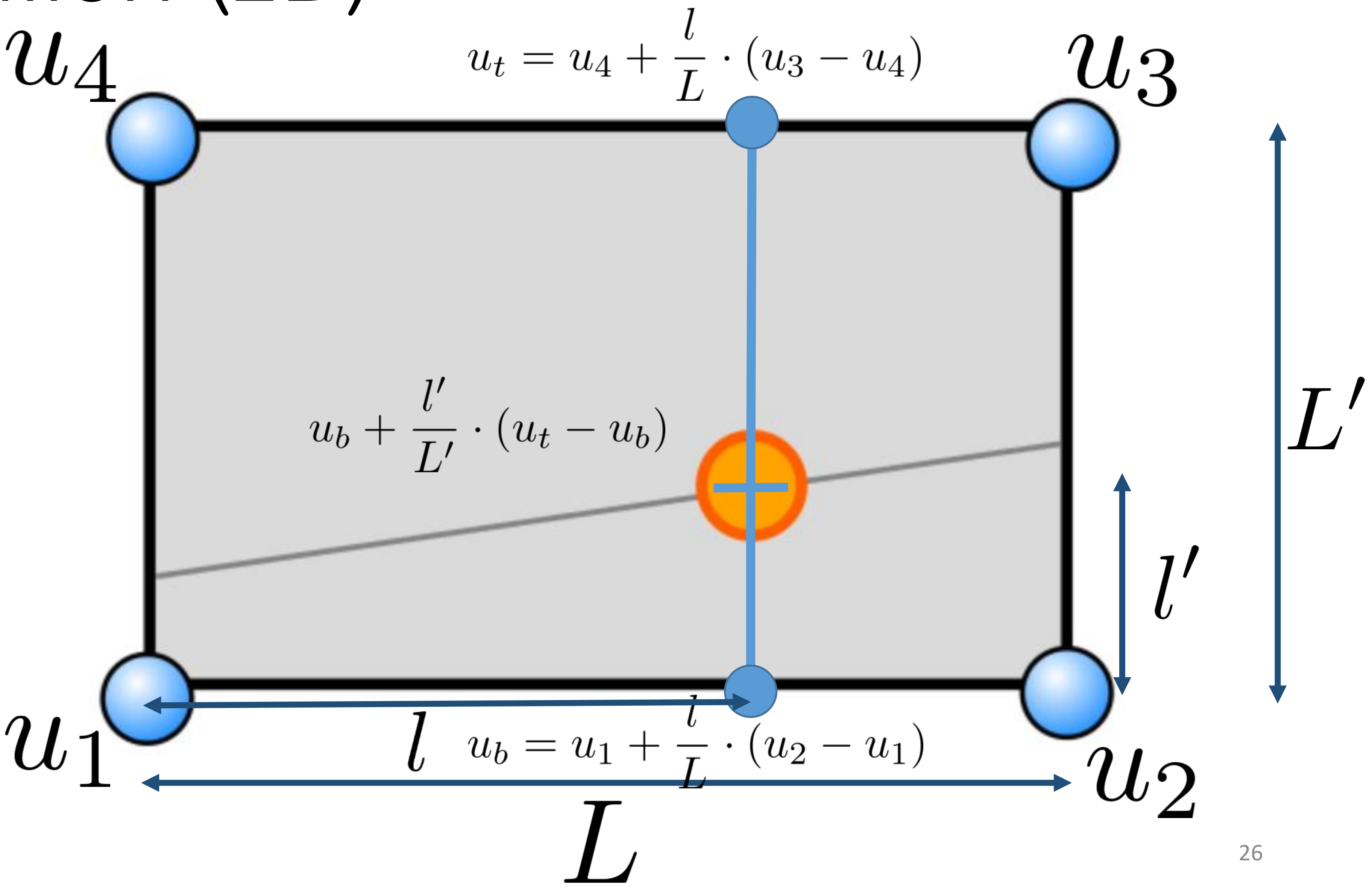
Nearest Neighbor (2D)



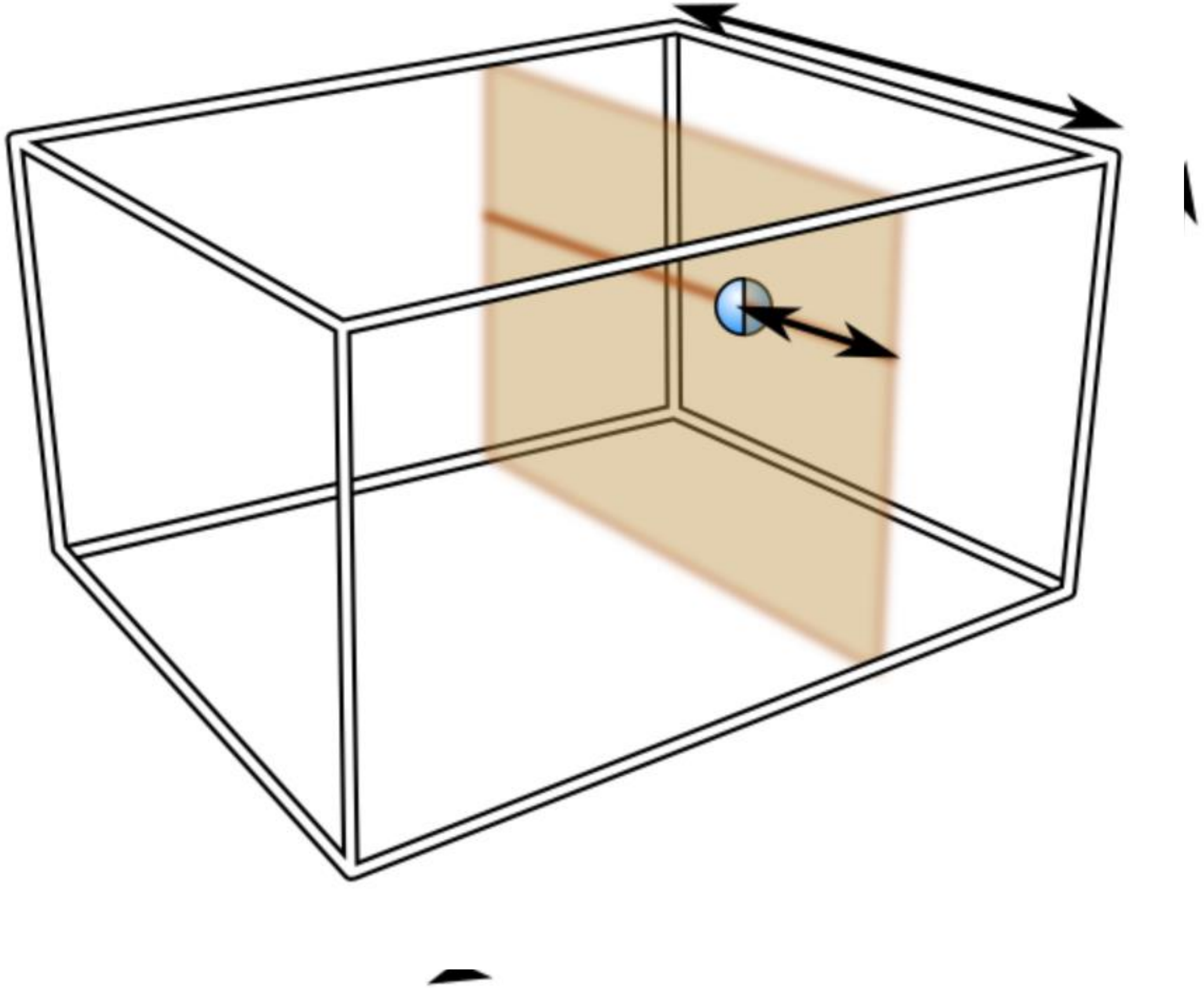


Interpolation (2D)

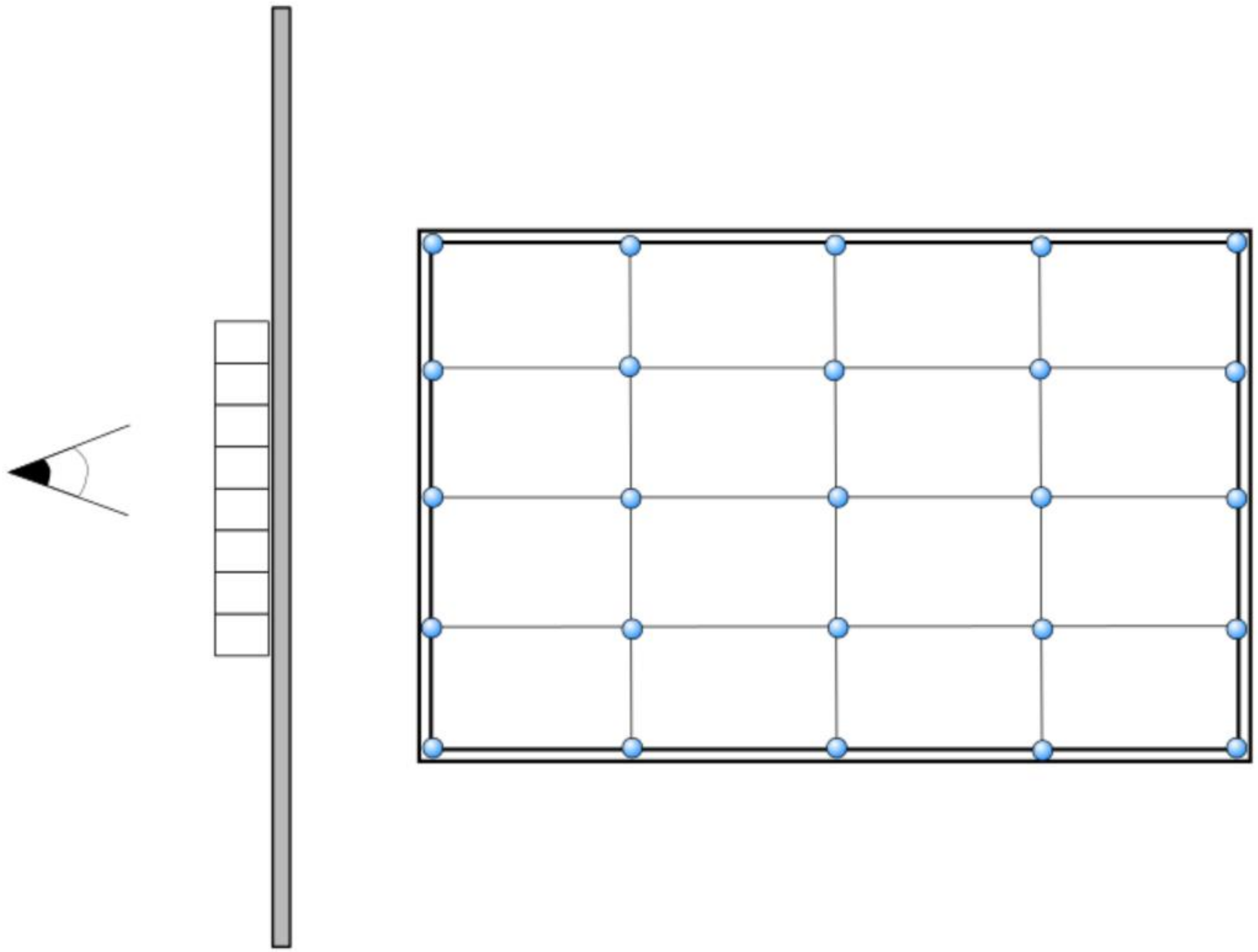




Interpolation (3D)



MIP (nearest neighbor)



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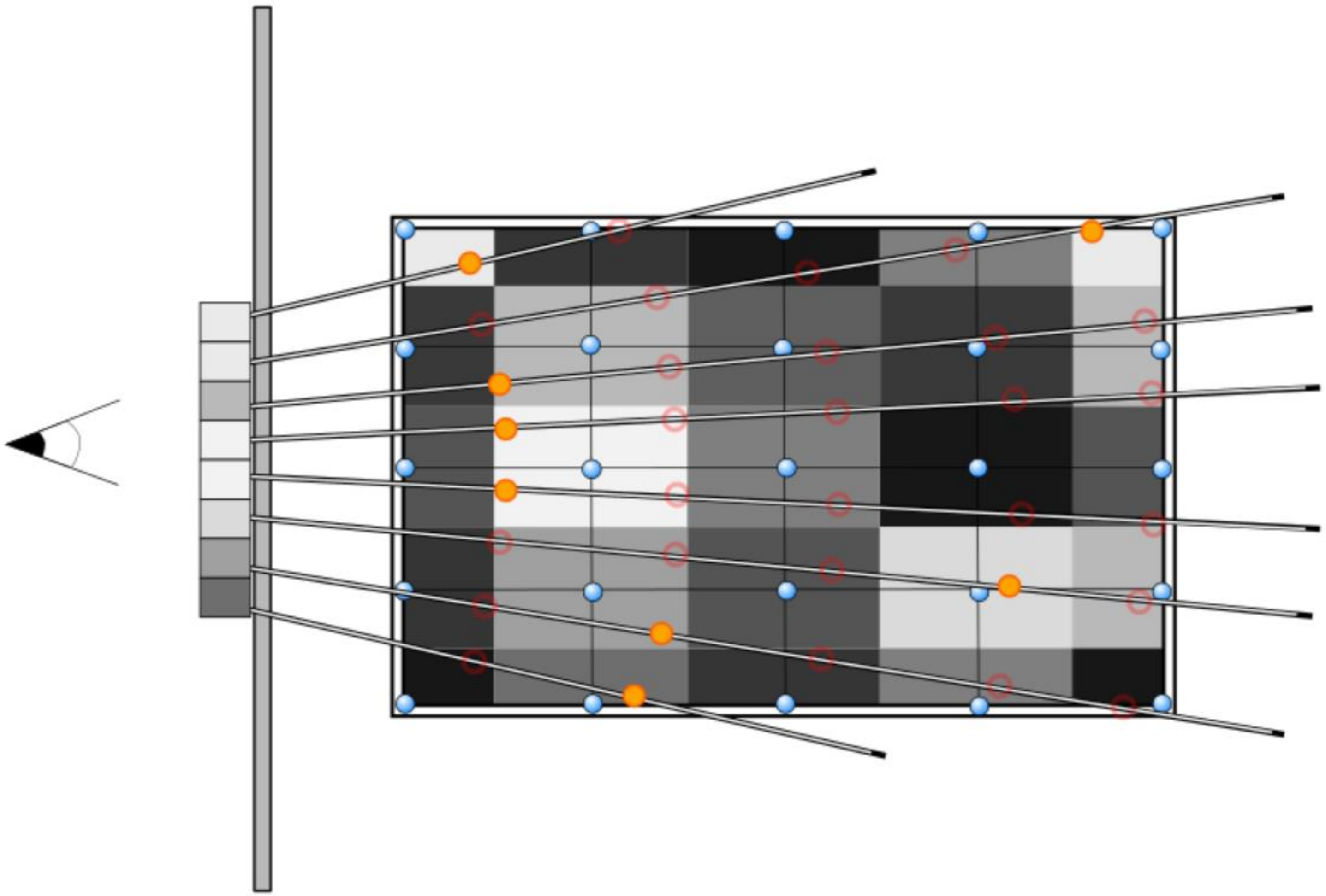
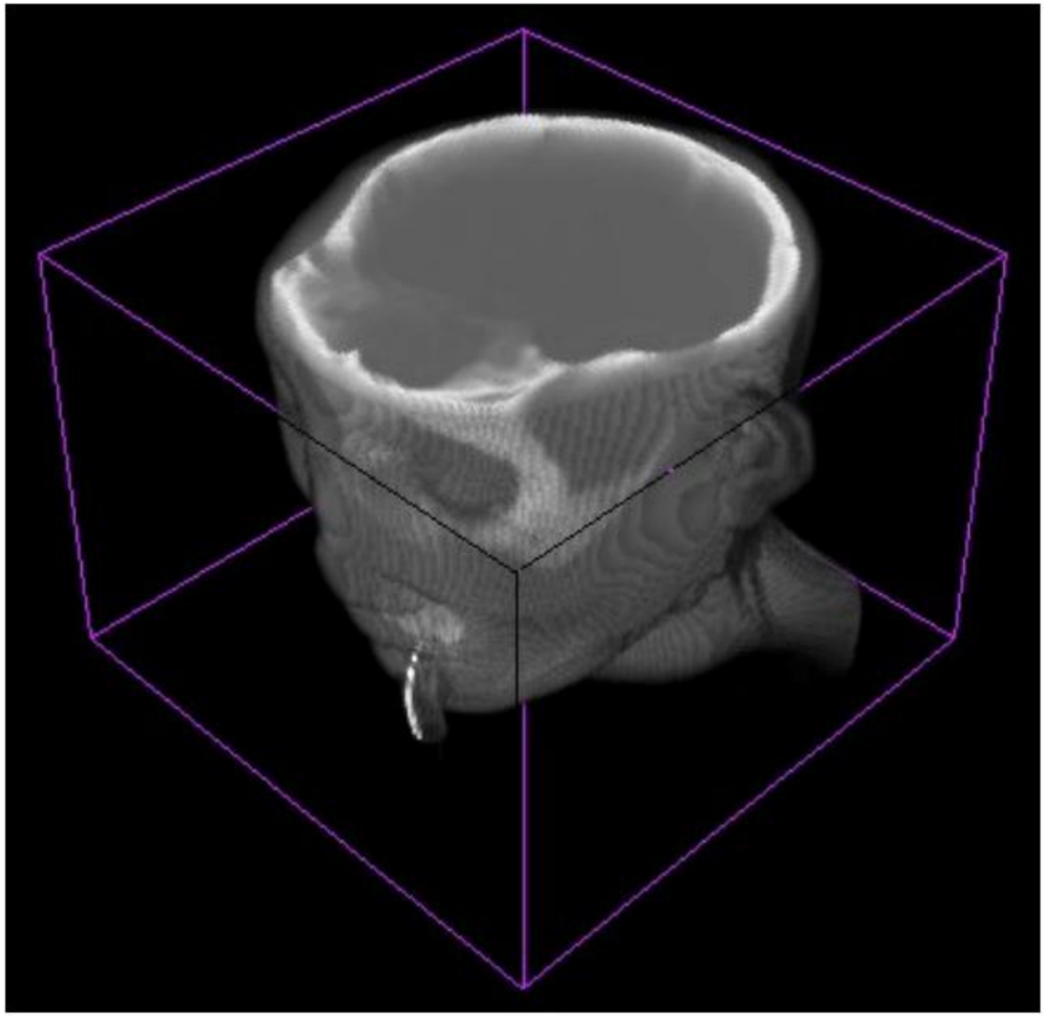
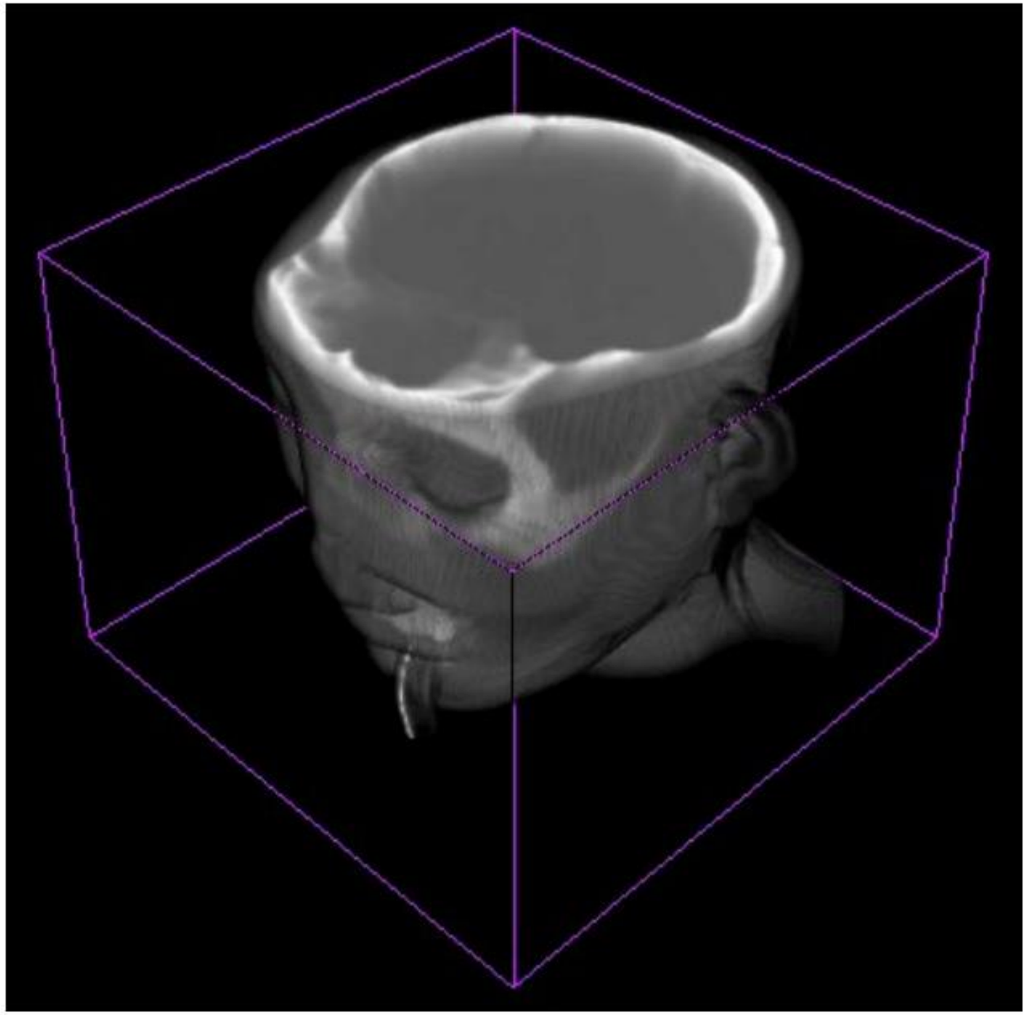


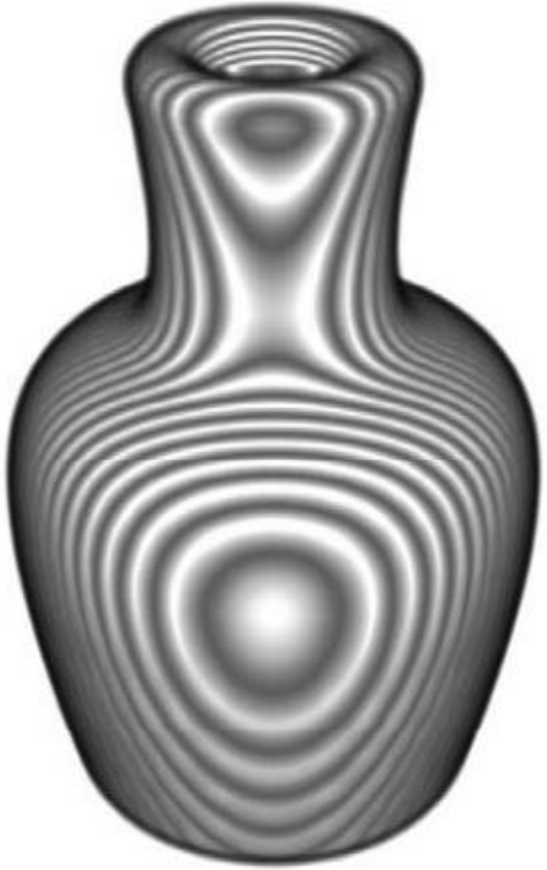
Nearest Neighbor vs. Interpolation



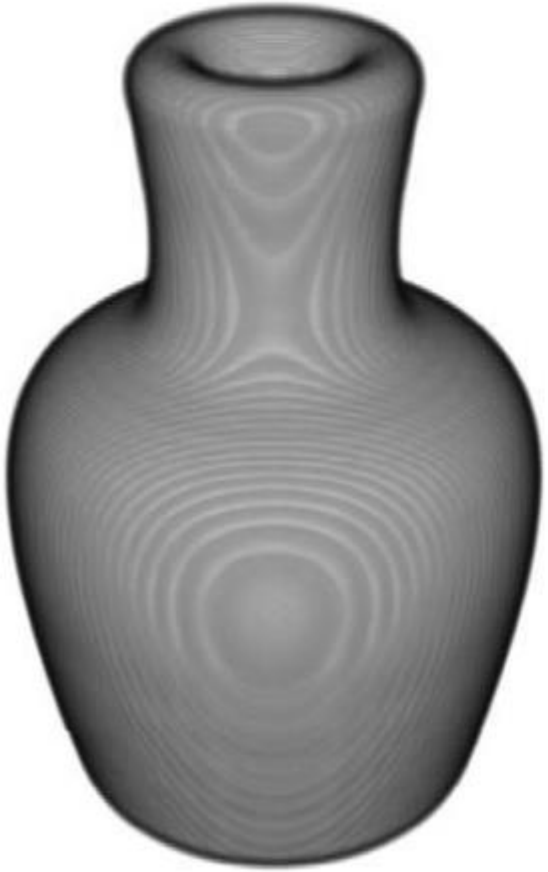


Bilder von Taku Komura

Sampling Rate



2 Voxel

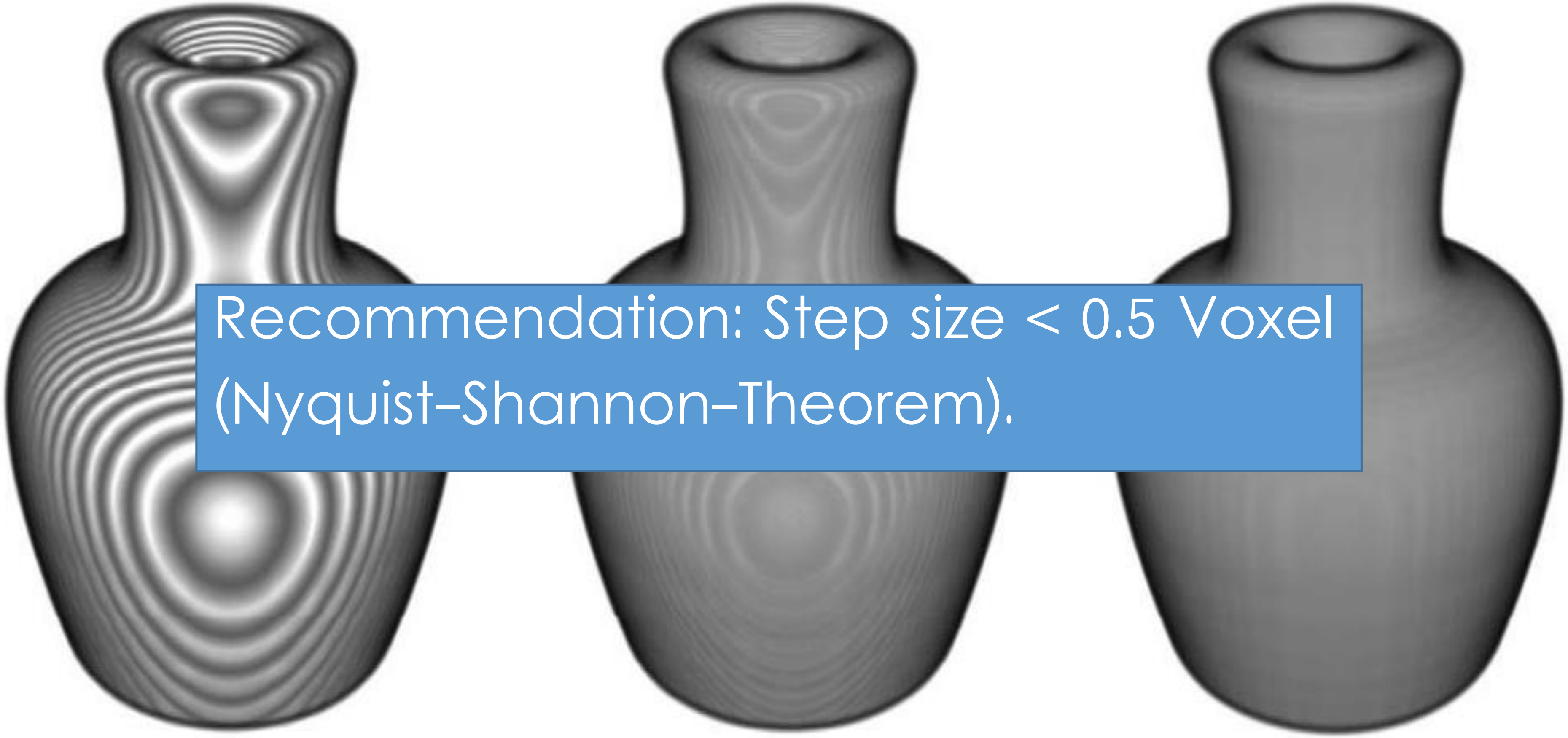


1 Voxel

0.1 Voxel

(From: Schröder et al. [1998])

Sampling Rate



Recommendation: Step size < 0.5 Voxel (Nyquist–Shannon–Theorem).

2 Voxel 1 Voxel 0.1 Voxel

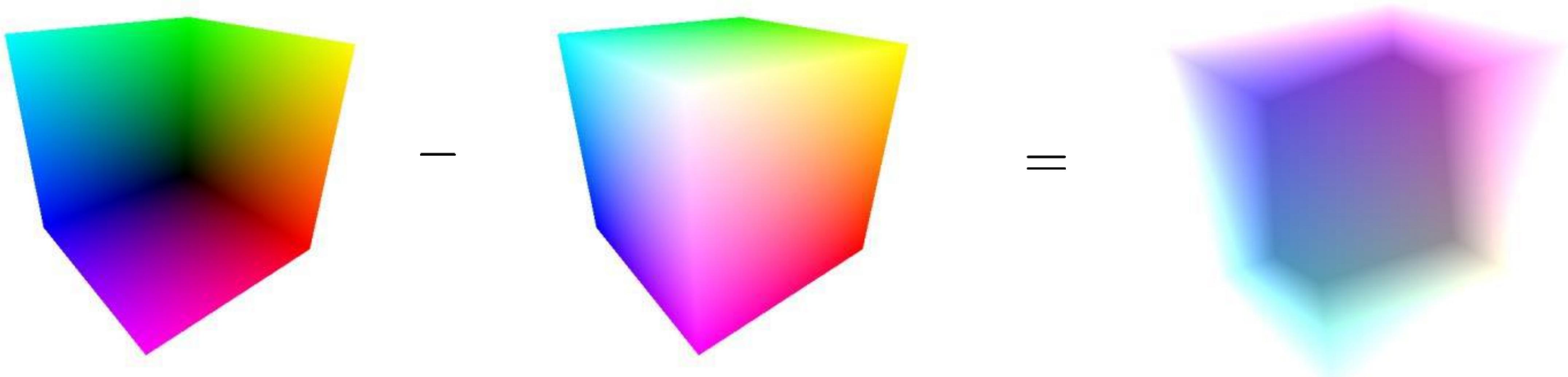
(From: Schröder et al. [1998])

Maximum Intensity Projection

- Advantages:
  - Fast overview
  - Easy to implement
  - High performance
- Disadvantages:
  - No depth cues
  - Loss of structures (if high intensity objects overlap lower intensity objetcs)

Raycast – Remark

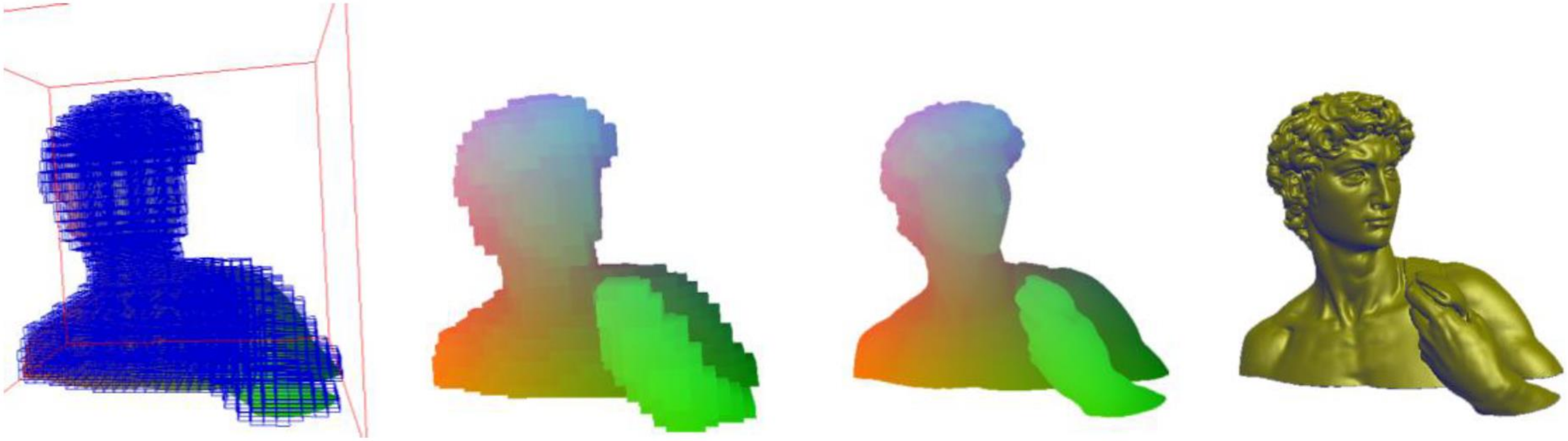
- Texture gives the start point and the direction vector
- Rasterize bounding box



- Same procedure for orthogonal and perspective projection

Raycast – Remark

- Modify rasterization



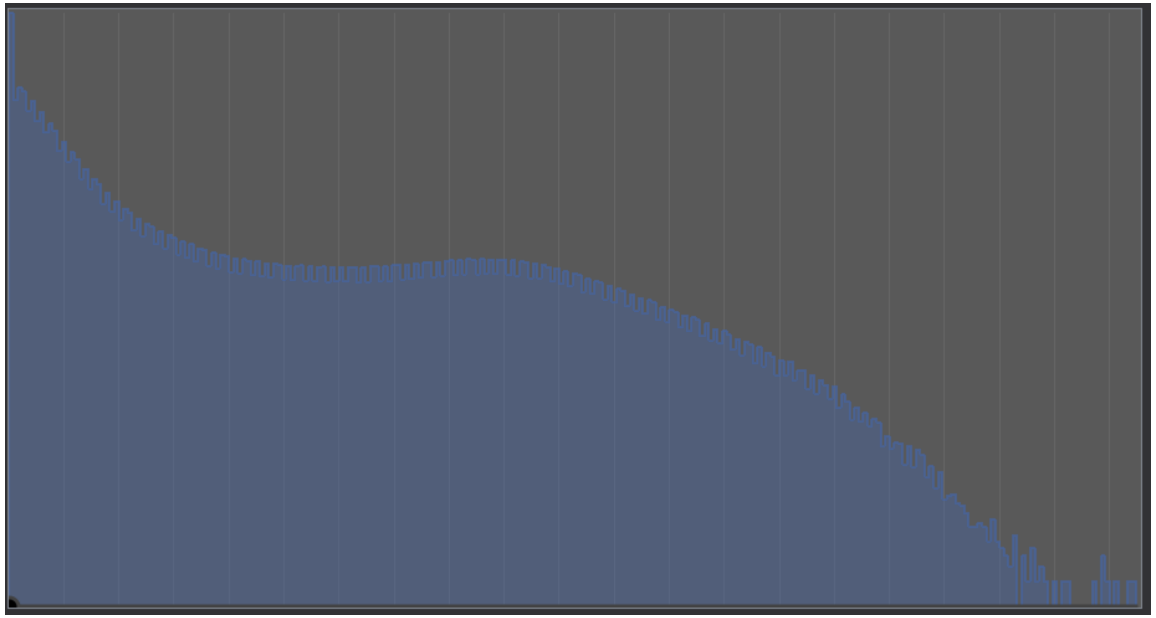
Analyze the Data

- How can we explore the data set?

Transfer Functions

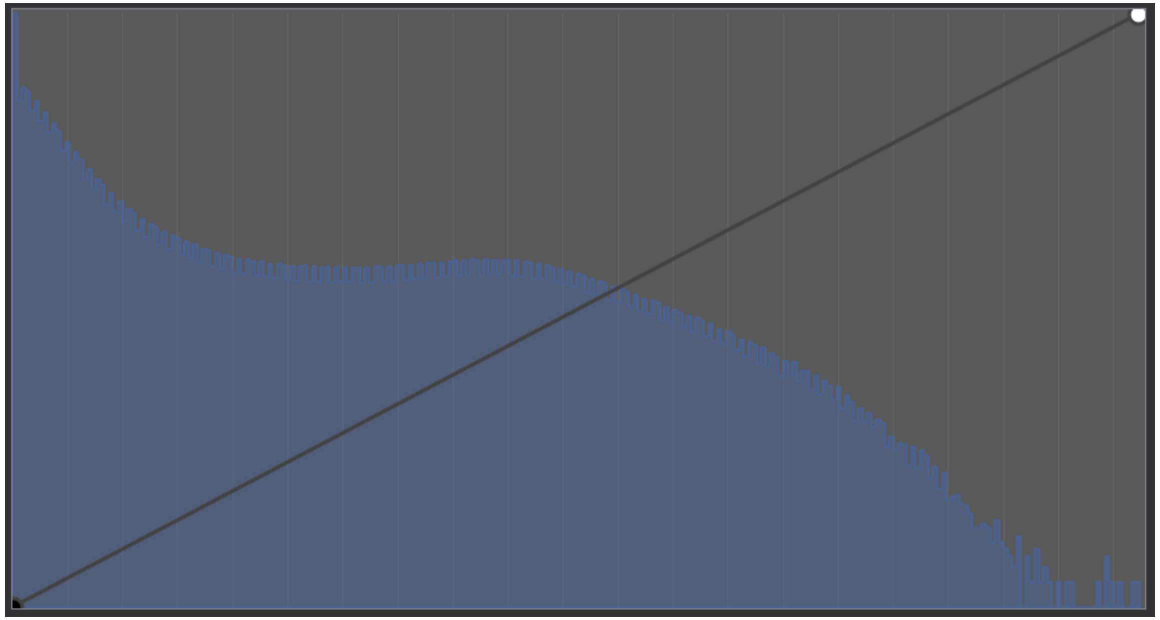
Transfer Functions

- Histogram of the gray values is depicted

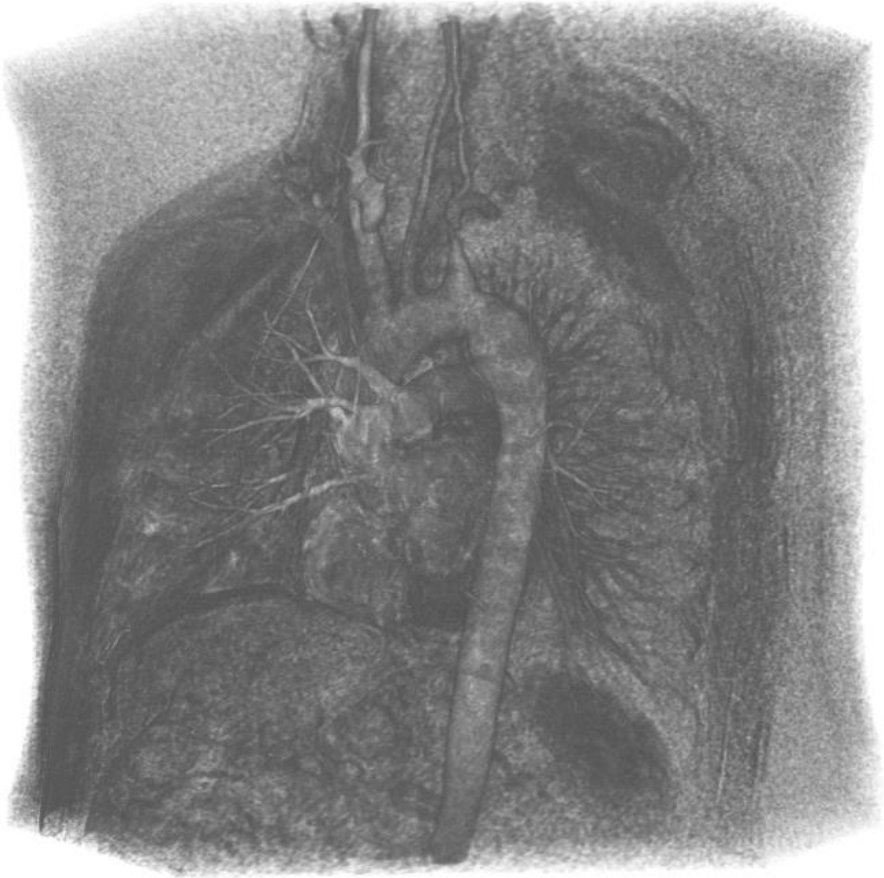


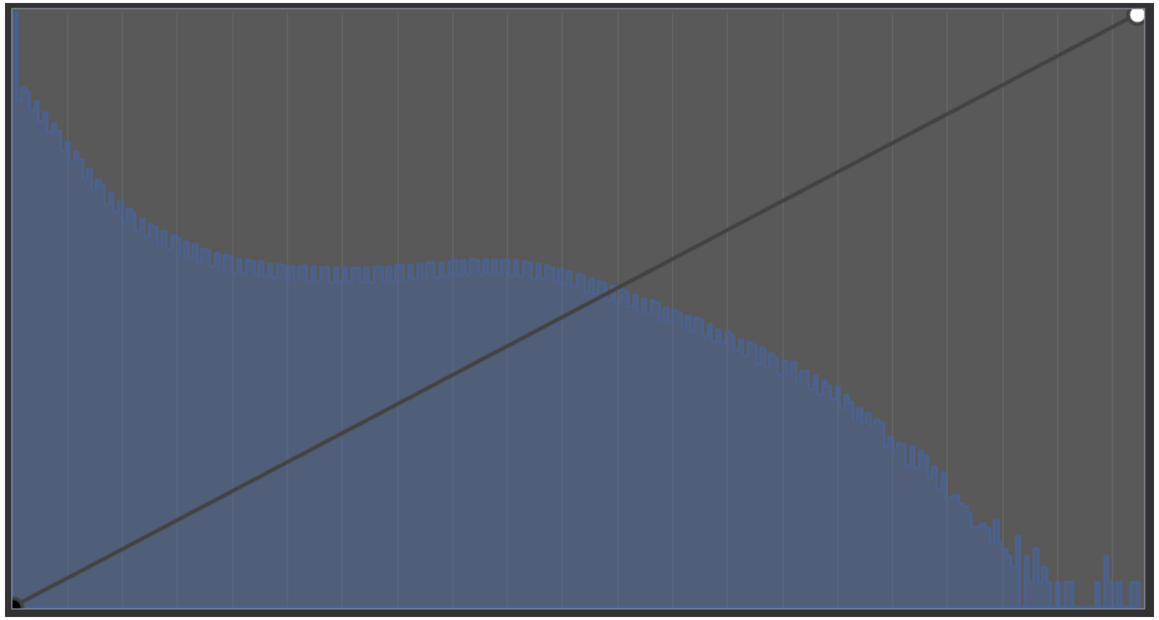
Transfer Functions

- Histogram of the gray values is depicted
- Can be used to visualize regions
- Set new intensities for gray values
- Histogram depicted as context in a graphical editor

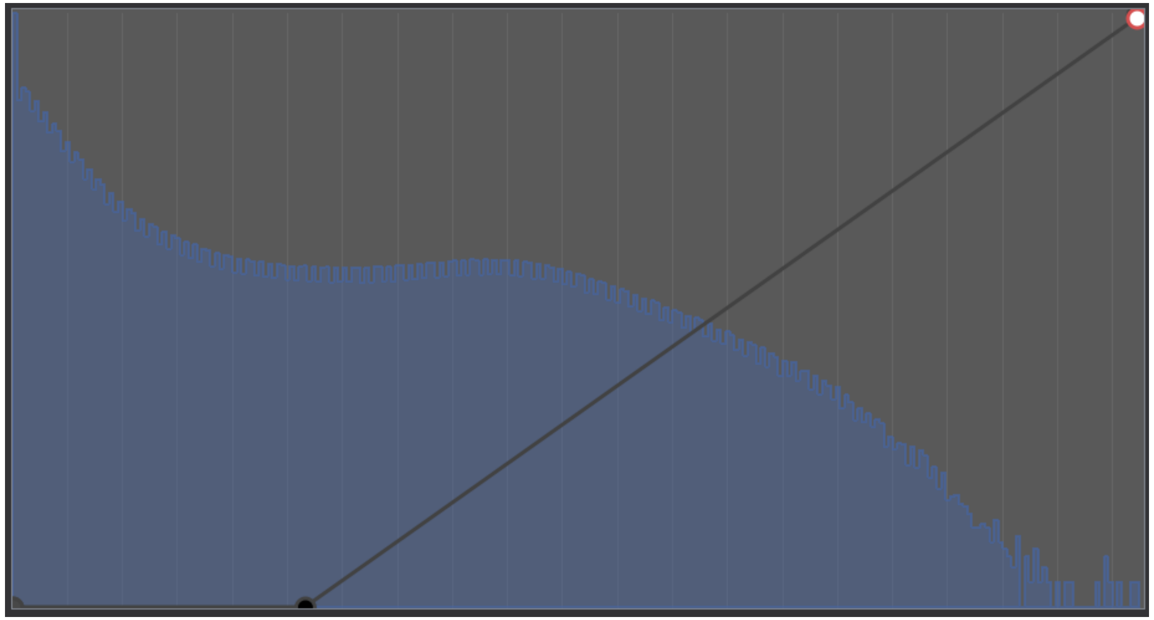


Transfer Functions

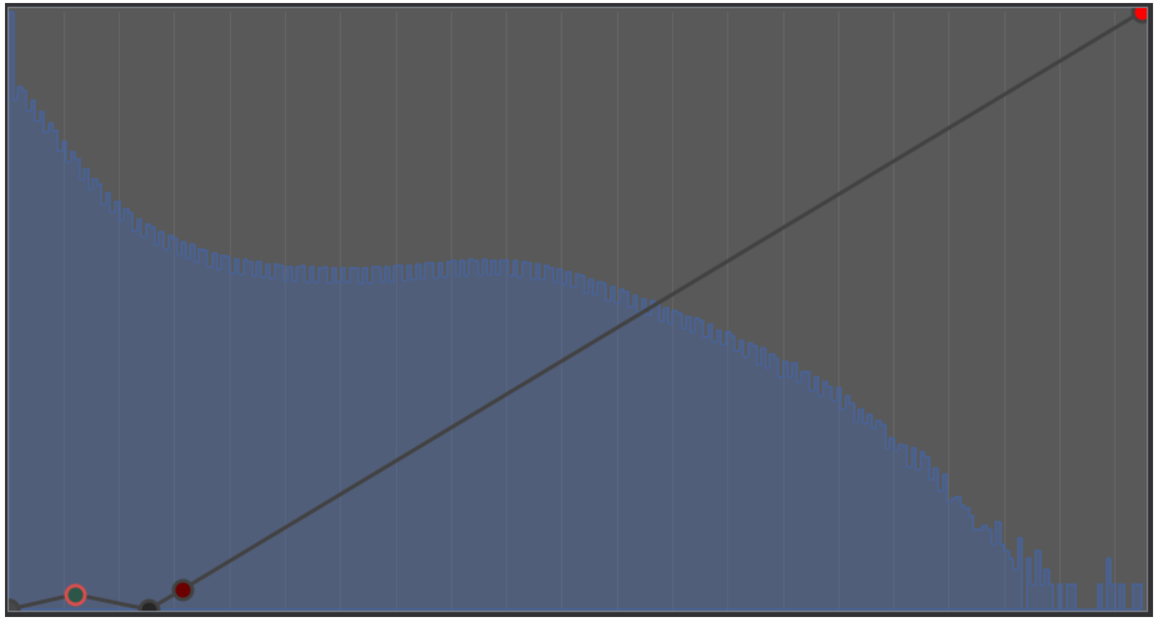




Transfer Functions

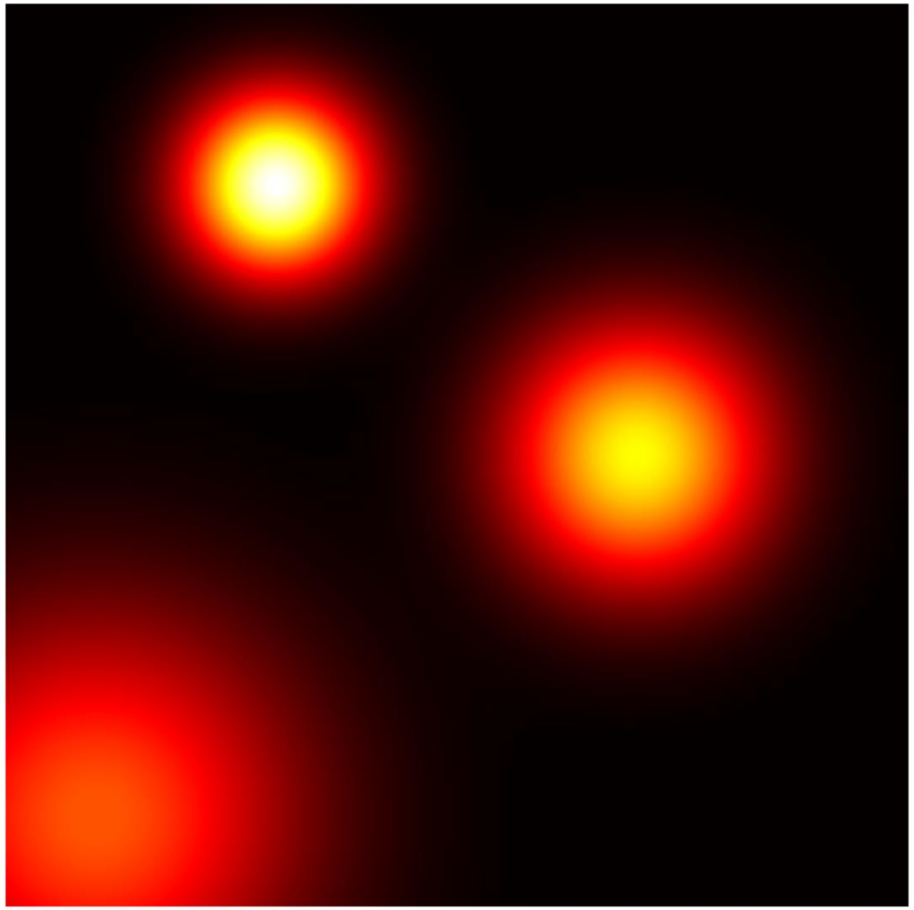


Transfer Functions



2D Transfer Functions – Motivation

- How to visualize these objects separately? (without segmentation)



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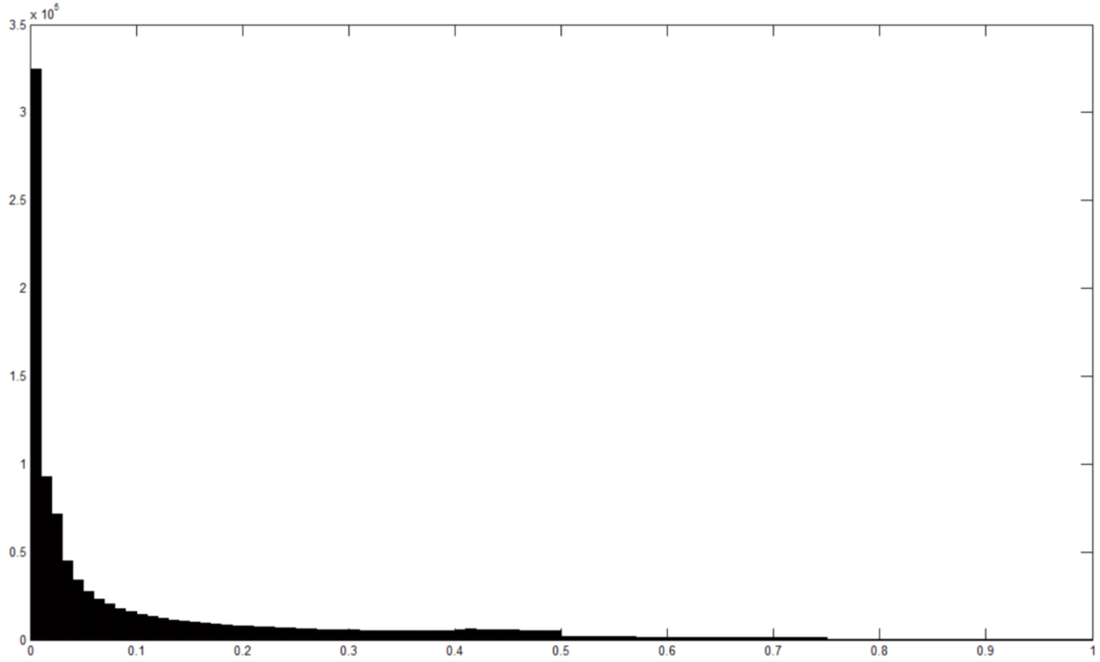
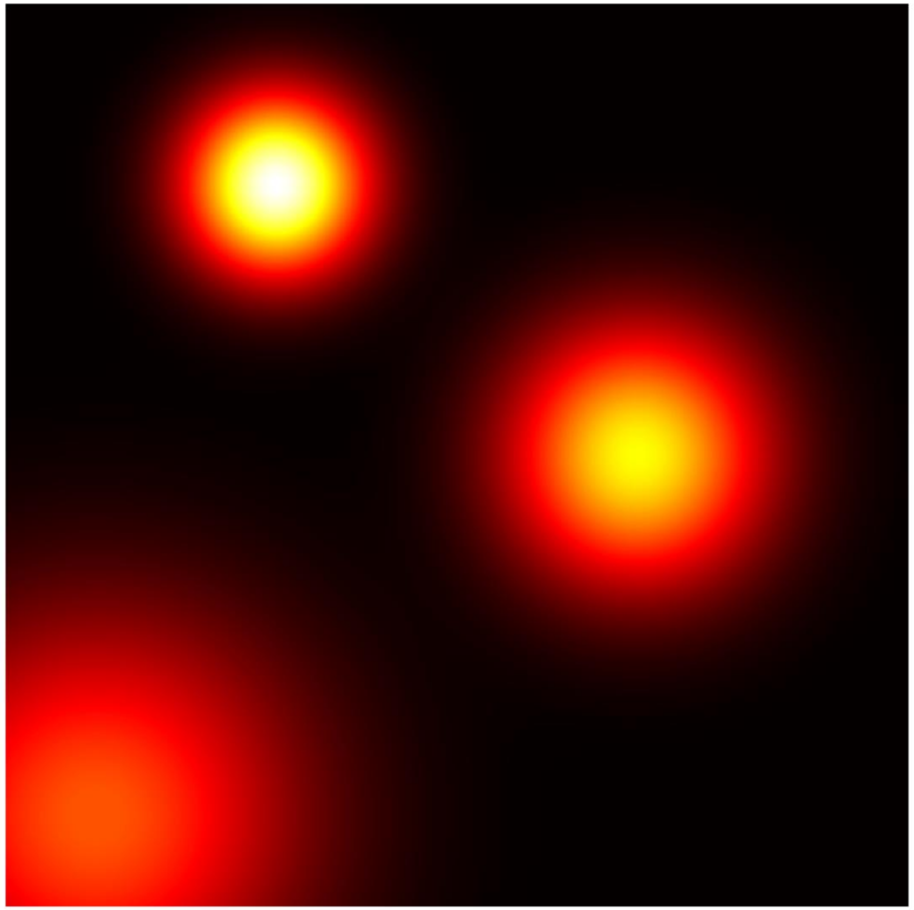
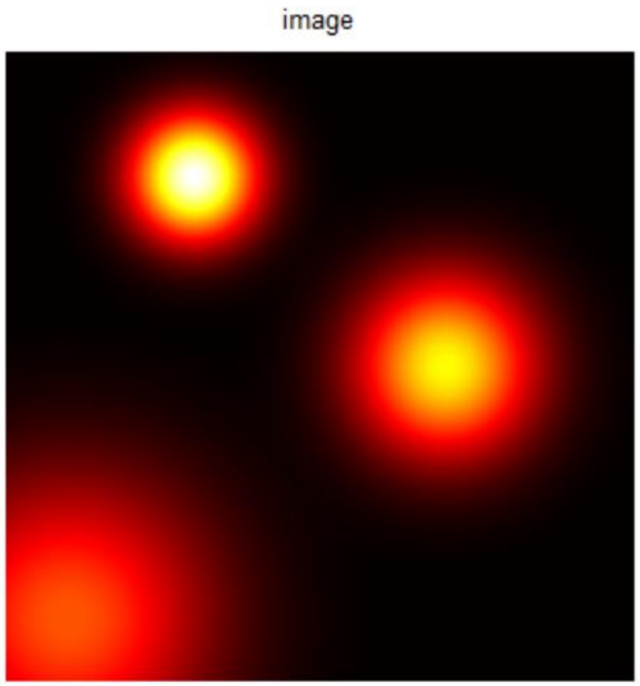
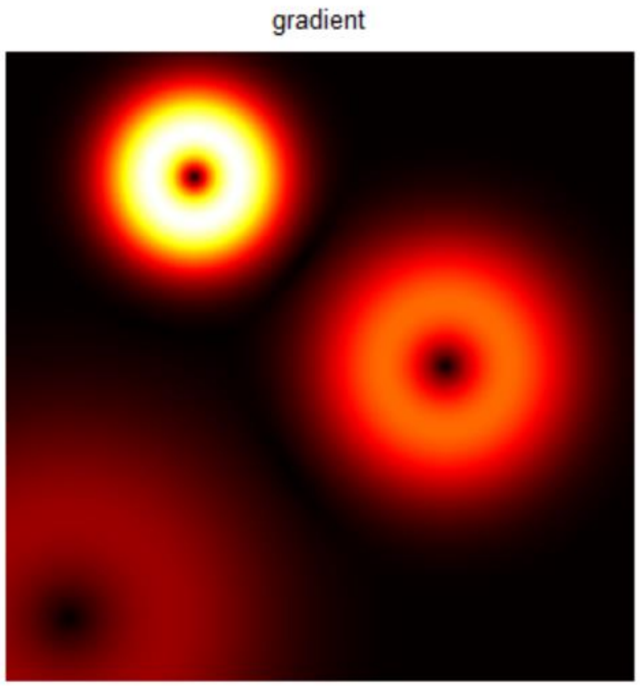


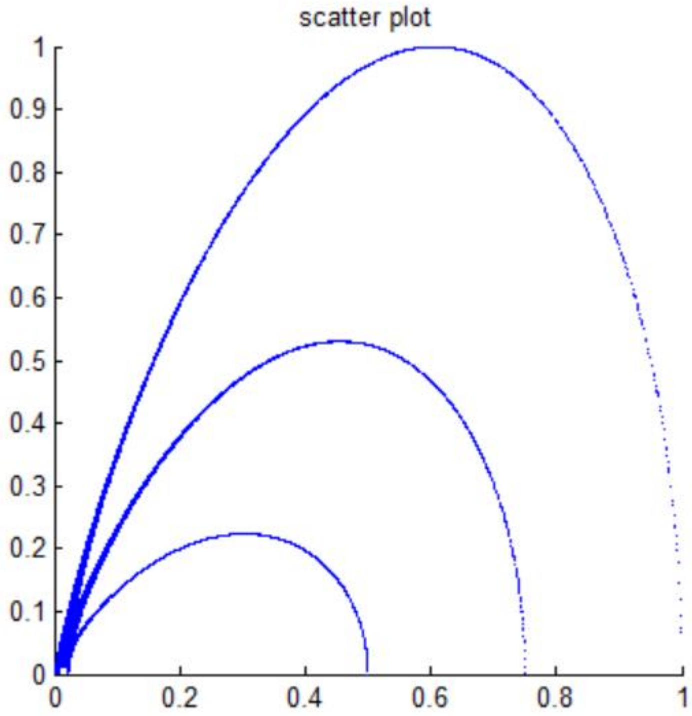


2D Transfer Functions – Motivation

- Visualize the intensities and the gradient in a scatter plot

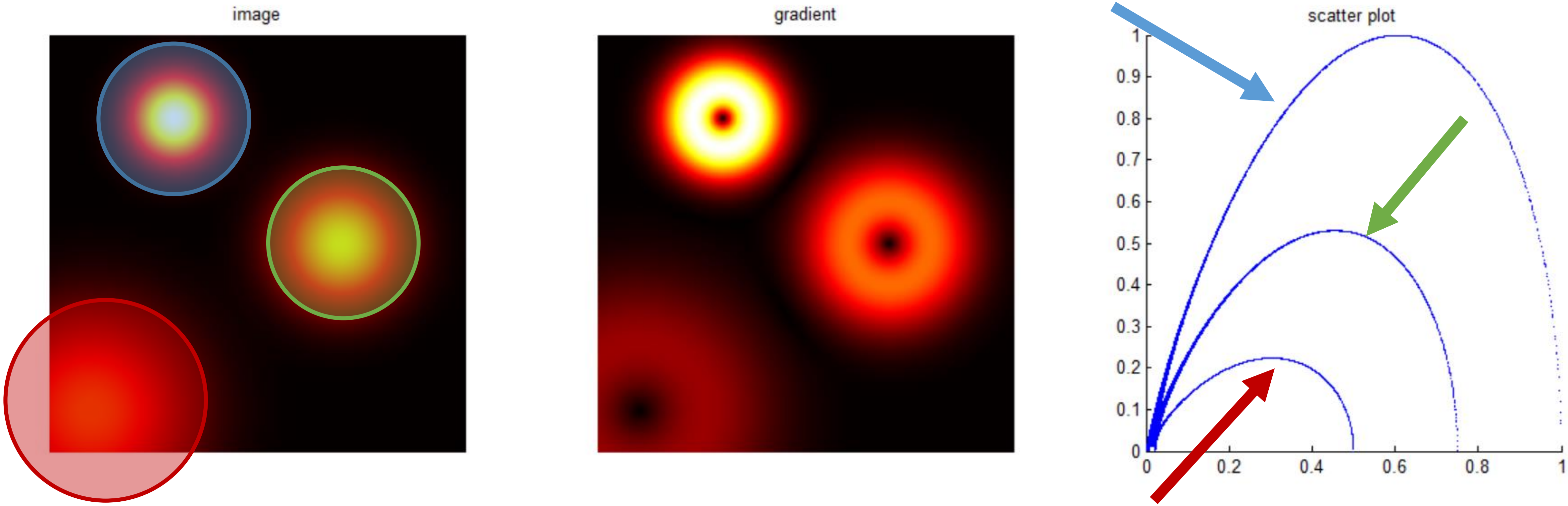






2D Transfer Functions – Motivation

- 2D transfer functions are based on intensities and gradient values



2D Transfer Functions

- 2D transfer functions are based on intensities and gradient values

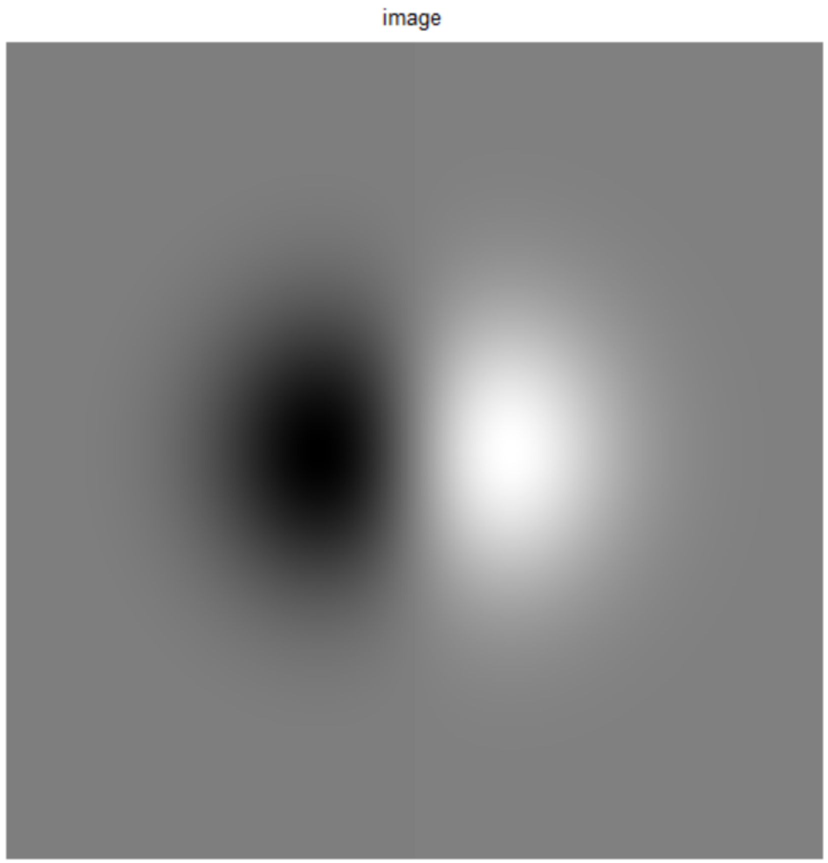
Gradient

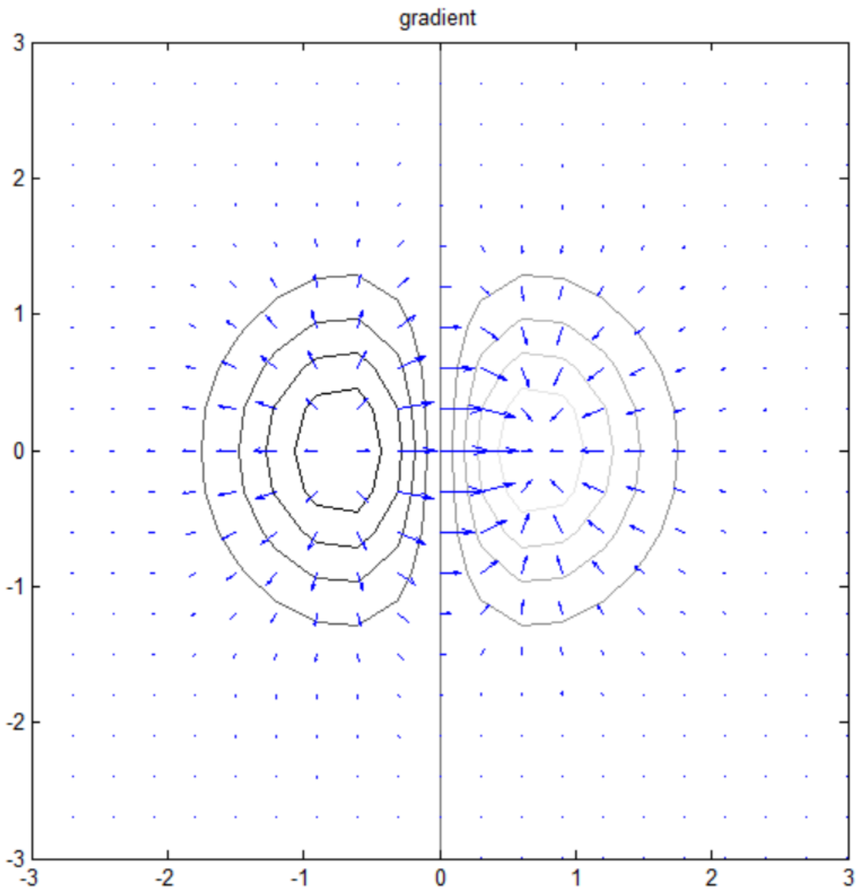
- The gradient points in the direction of the greatest rate of increase

$$f : \mathbb{R}^n \to \mathbb{R}$$

$$\nabla f = \left(\frac{\partial f}{\partial x_1}, \frac{\partial f}{\partial x_2}, \frac{\partial f}{\partial x_3}, \ldots, \frac{\partial f}{\partial x_n} \right)^T$$

Gradient





Gradient

- Example

$$f(x, y) = 5 - x^2 - y^2$$

Gradient

- Example

$$f(x, y) = 5 - x^2 - y^2$$

$$\frac{\partial f(x, y)}{\partial x} = -2x$$

$$\frac{\partial f(x, y)}{\partial y} = -2y$$

Gradient

- Example

$$f(x,y) = 5 - x^2 - y^2$$

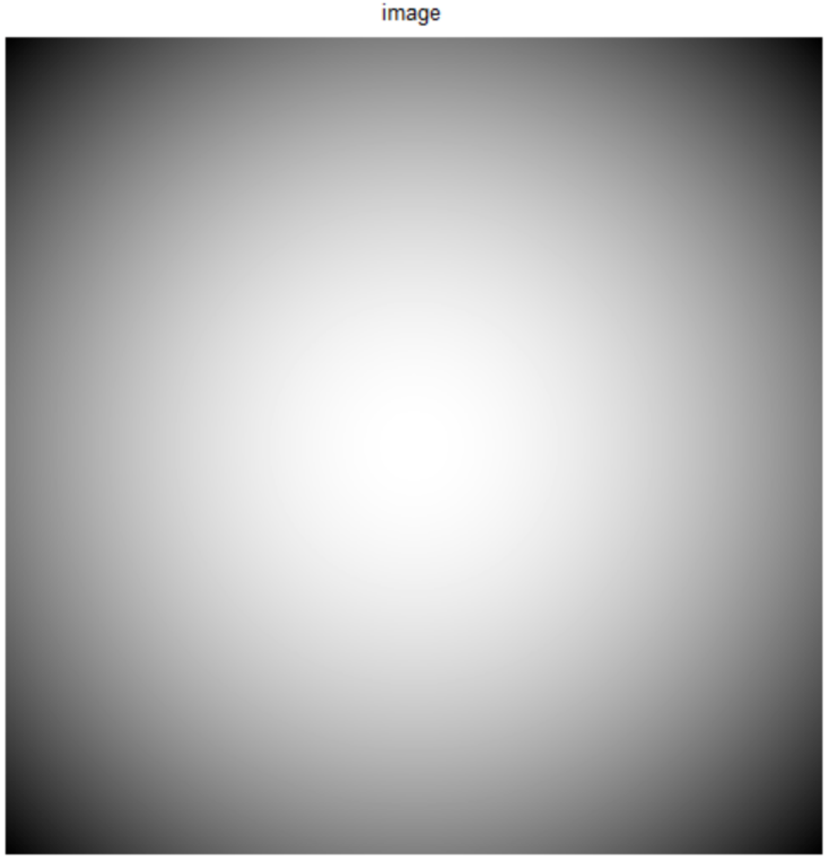
$$\frac{\partial f(x,y)}{\partial x} = -2x$$

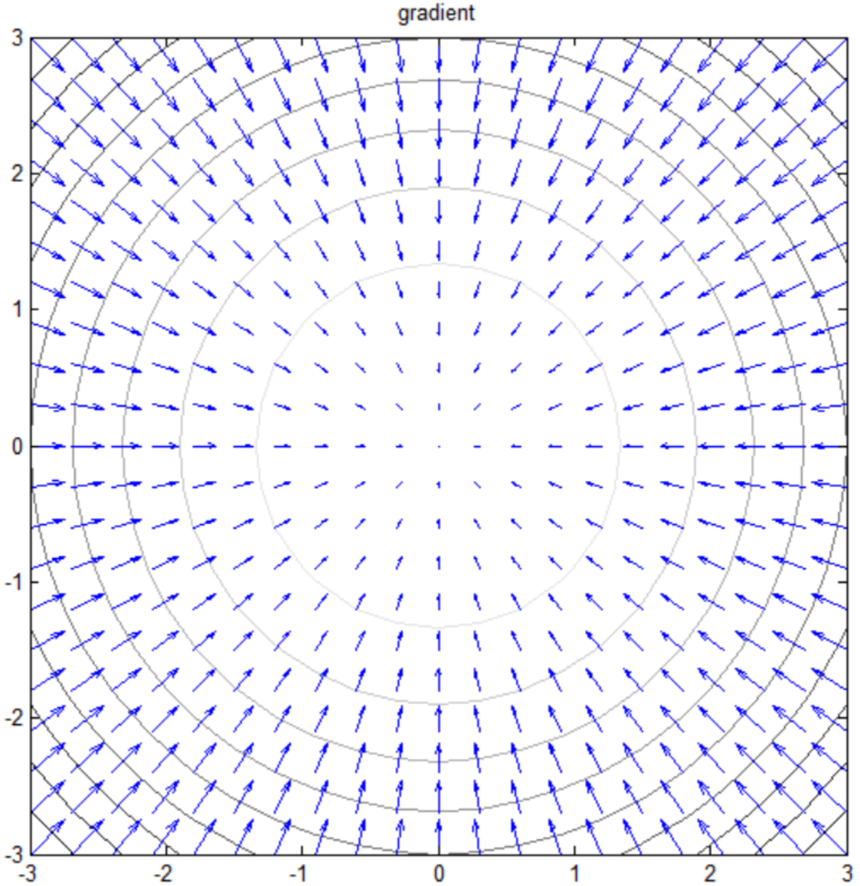
$$\frac{\partial f(x,y)}{\partial y} = -2y$$

$$\nabla f(x,y) = \begin{pmatrix} -2x \\ -2y \end{pmatrix}$$

Gradient

$$f(x, y) = 5 - x^2 - y^2$$





Gradient – Approximation

- Forward difference

$$\nabla f(x,y,z) = \begin{pmatrix} f(x+1) - f(x) \\ f(y+1) - f(y) \\ f(z+1) - f(z) \end{pmatrix}$$

Gradient – Approximation

- Backward difference

$$\nabla f(x,y,z) = \begin{pmatrix} f(x) - f(x-1) \\ f(y) - f(y-1) \\ f(z) - f(z-1) \end{pmatrix}$$

Gradient – Approximation

- Central difference

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

Gradient – Approximation

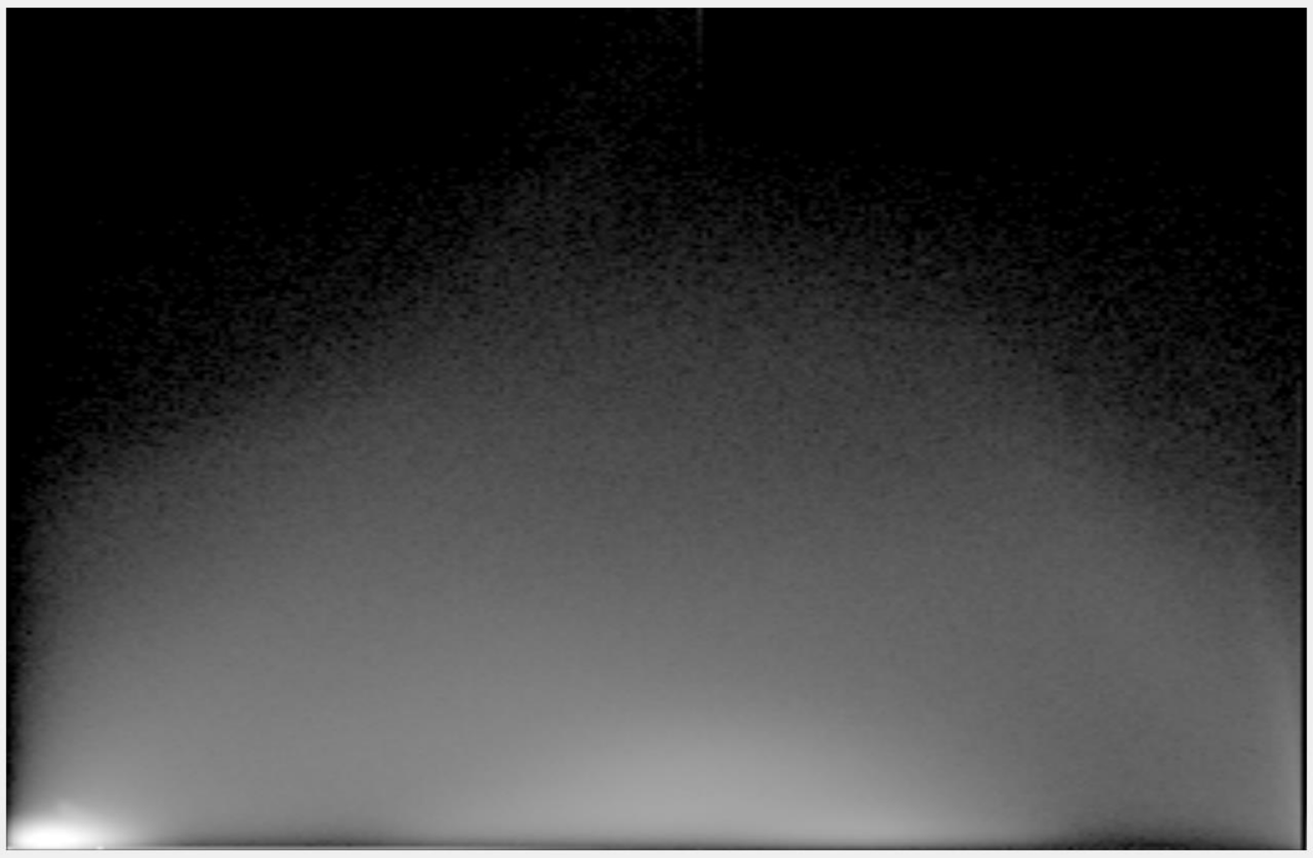
- Forward difference: $$\nabla f(x,y,z) = \begin{pmatrix} f(x+1) - f(x) \\ f(y+1) - f(y) \\ f(z+1) - f(z) \end{pmatrix}$$

- Backward difference: $$\nabla f(x,y,z) = \begin{pmatrix} f(x) - f(x-1) \\ f(y) - f(y-1) \\ f(z) - f(z-1) \end{pmatrix}$$

- Central difference: $$\nabla f(x,y,z) = \frac{1}{2} \begin{pmatrix} f(x+1) - f(x-1) \\ f(y+1) - f(y-1) \\ f(z+1) - f(z-1) \end{pmatrix}$$

2D Transfer Functions

- Scatterplot:
  - X-axis: Intensities
  - Y-axis: Gradient magnitude



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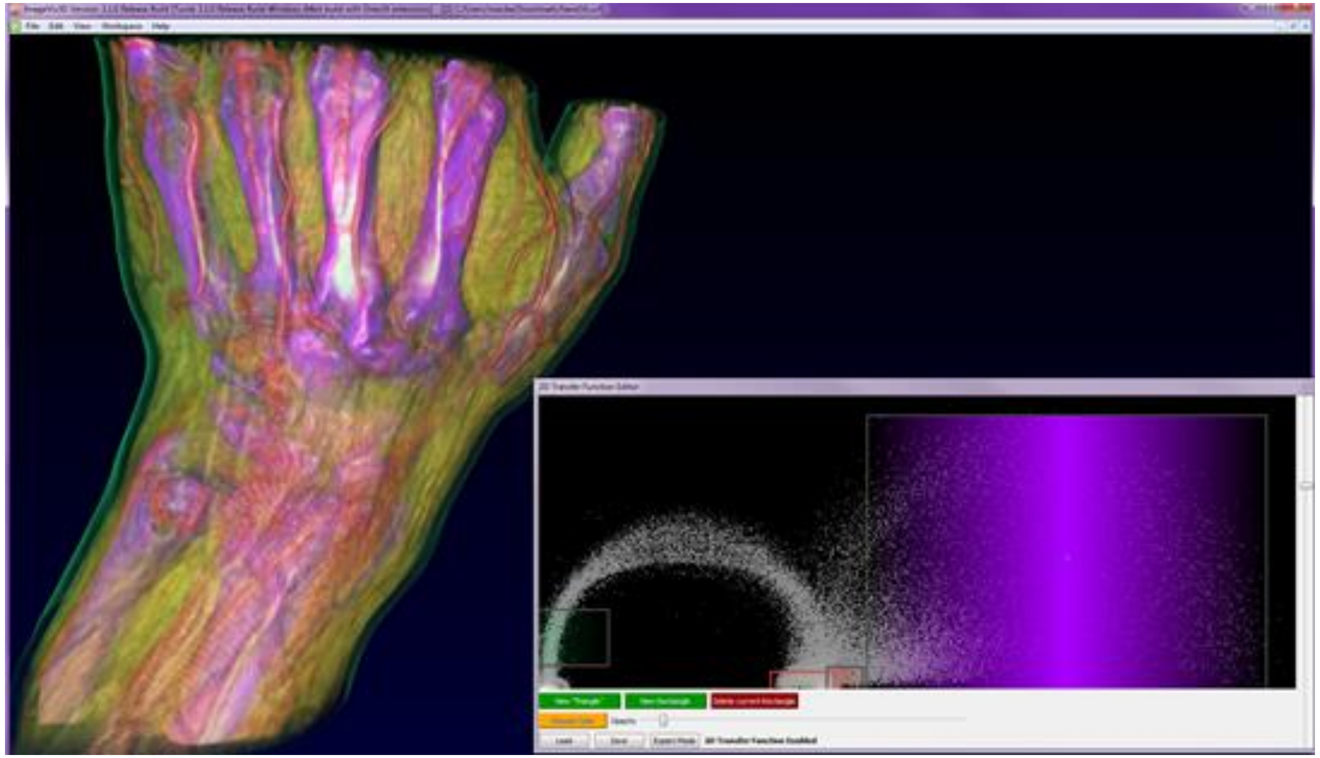
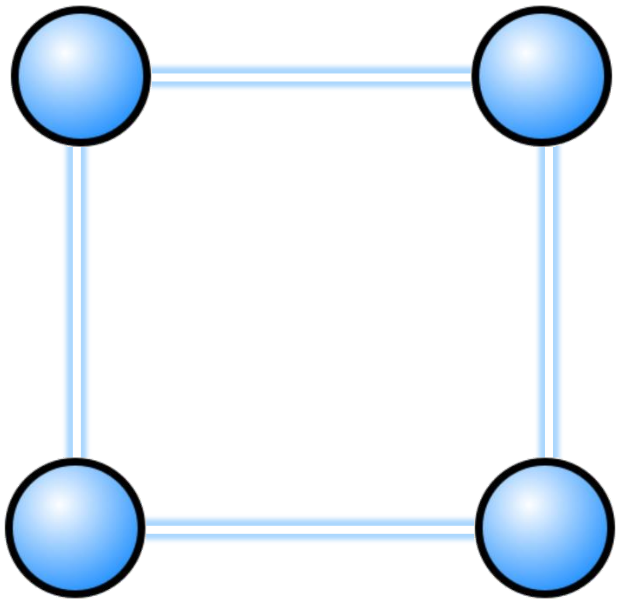
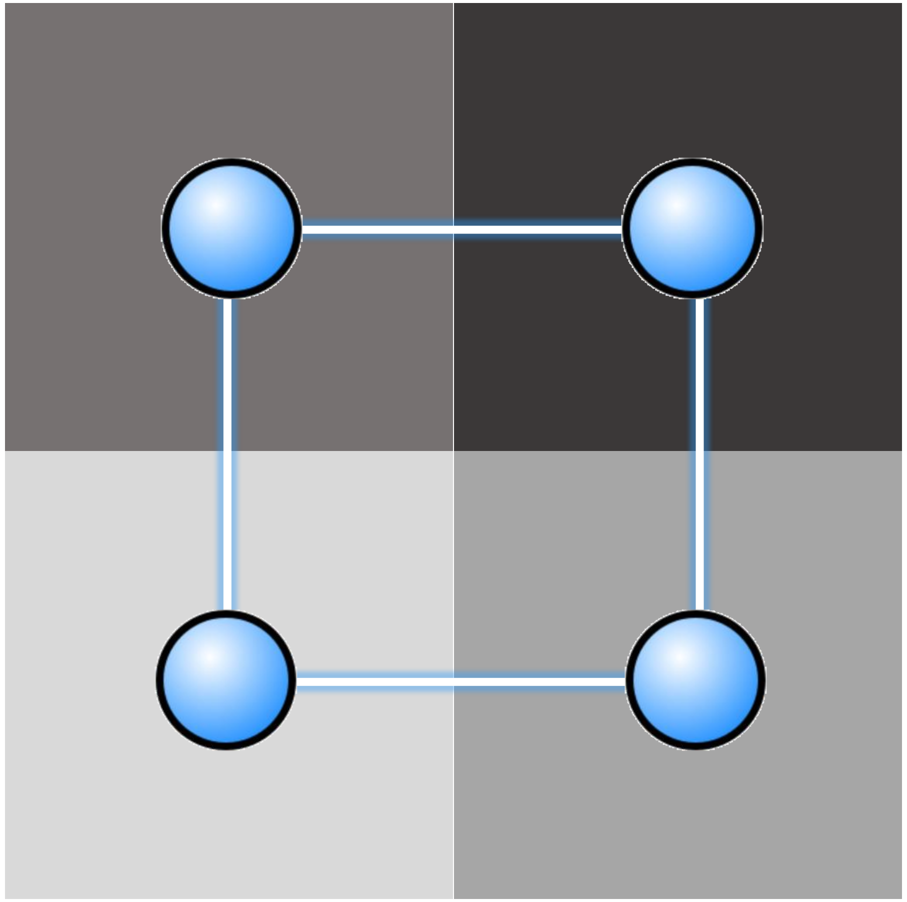


Classification

Classification

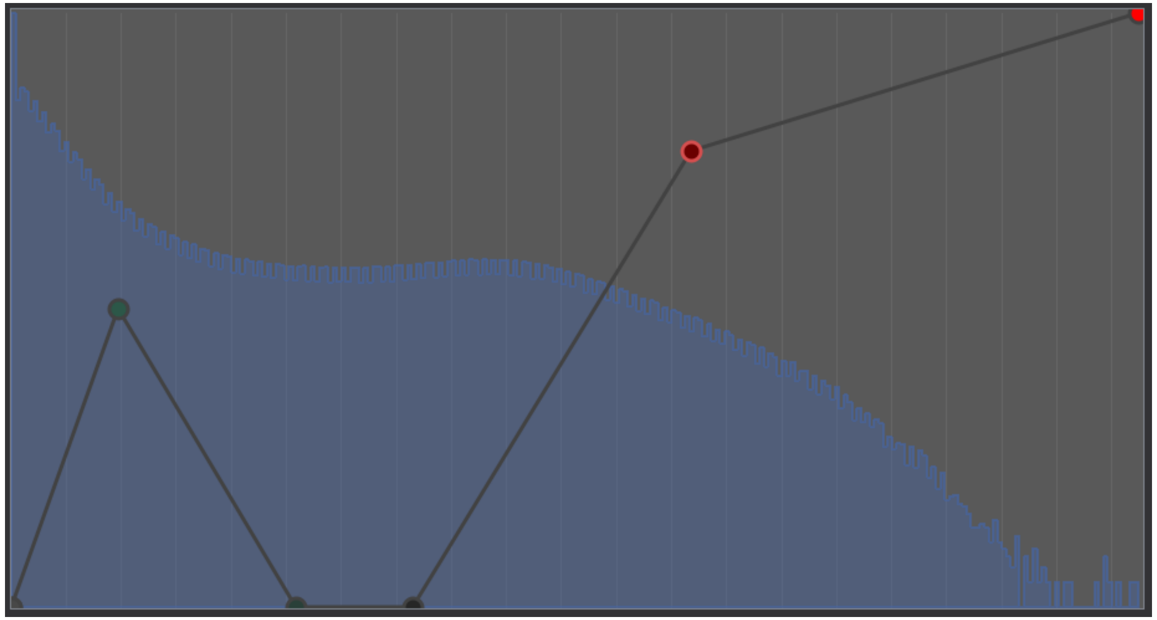


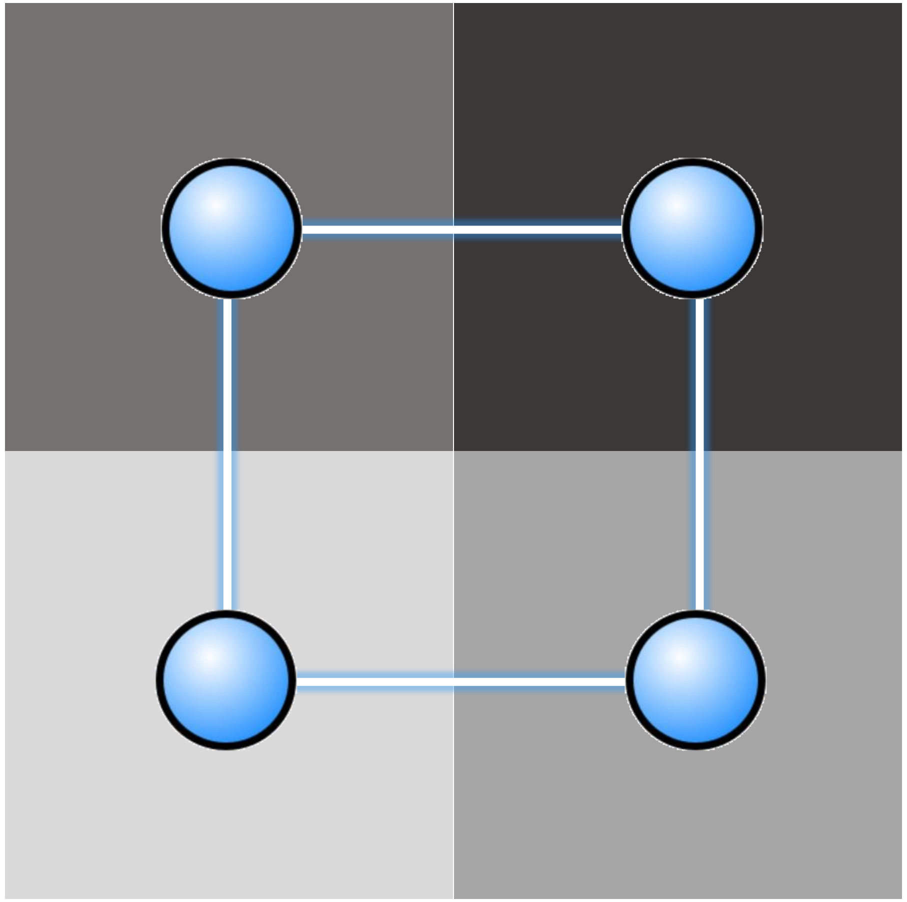
Classification



Classification

Pre-Classification:





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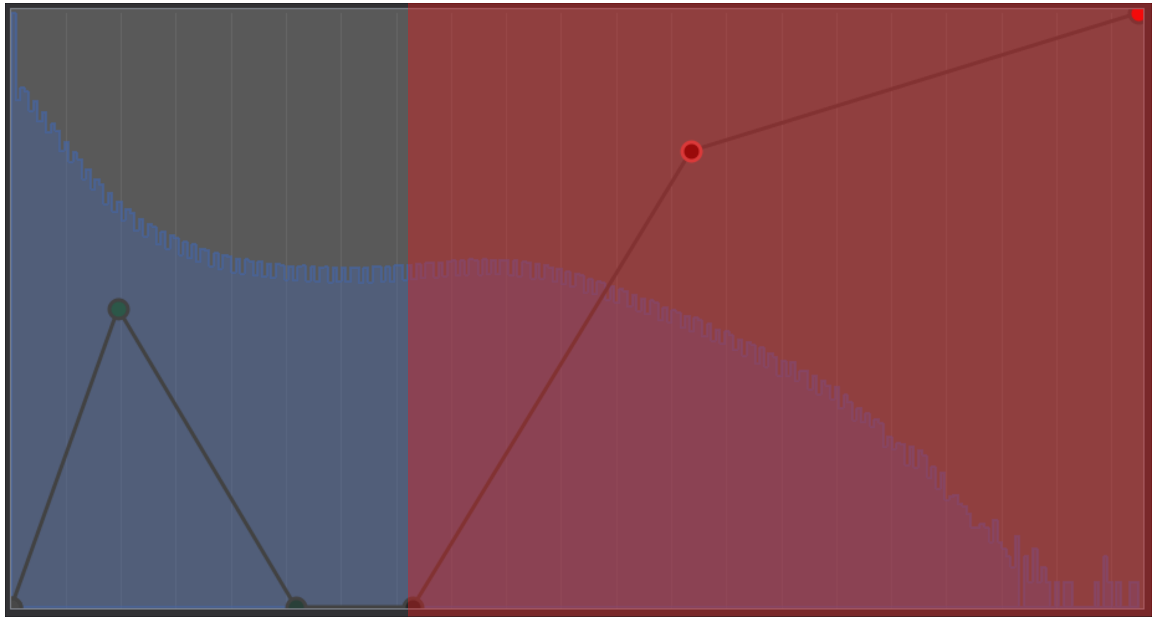
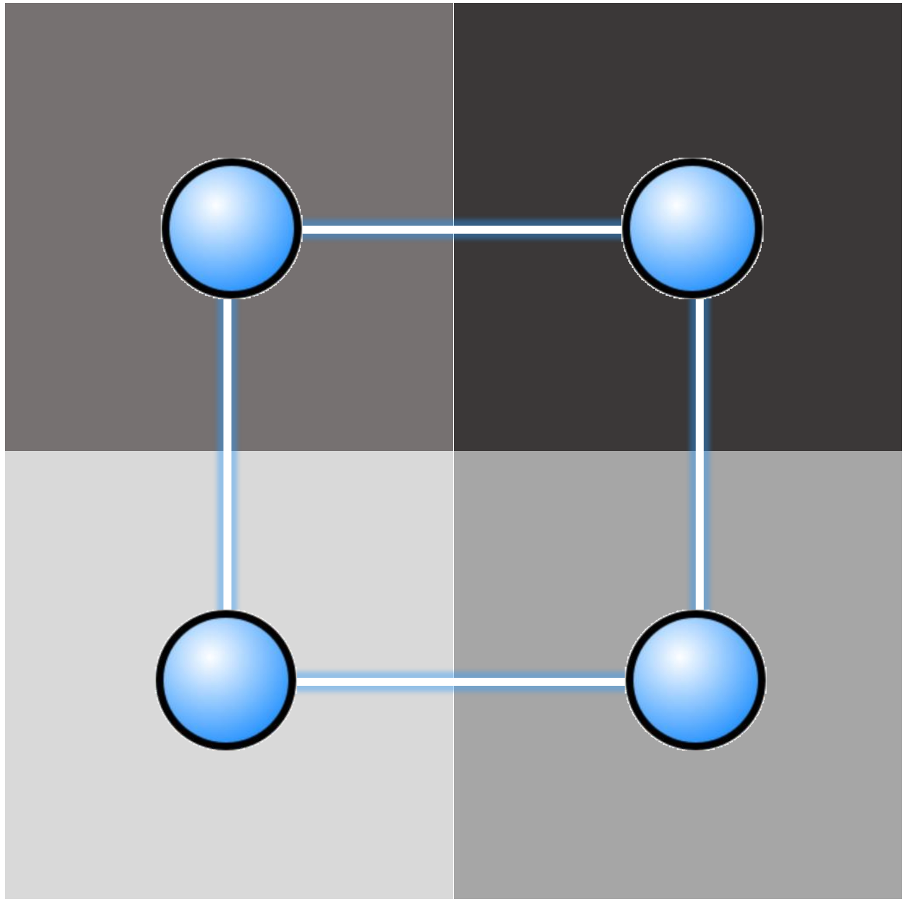
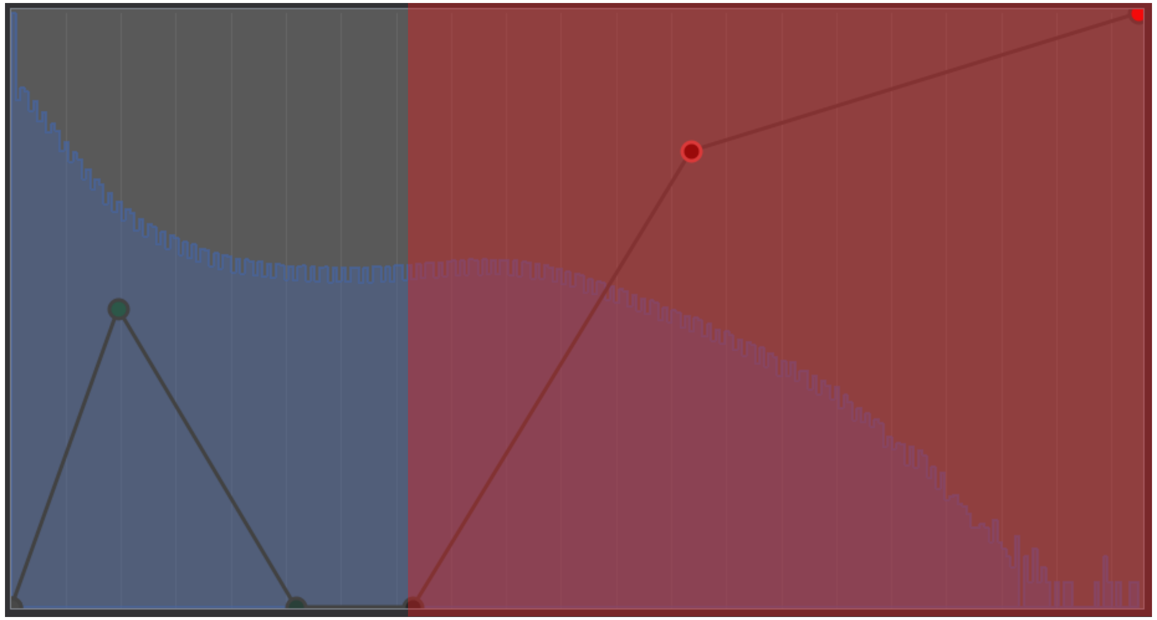
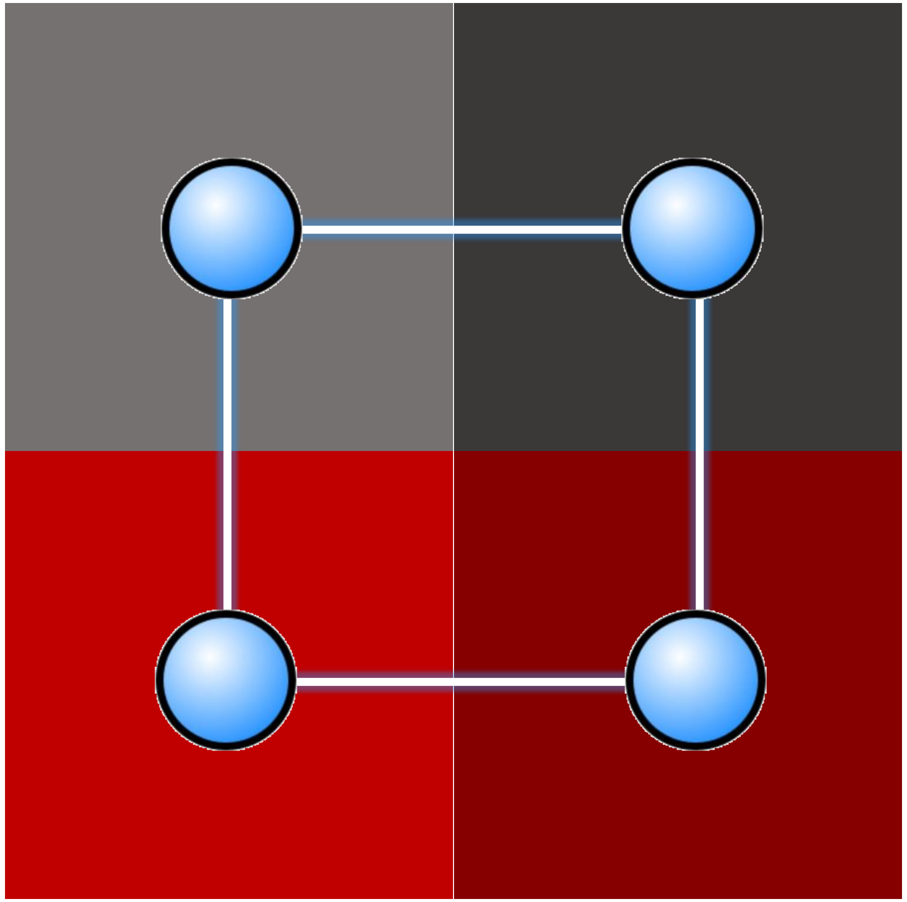




Classification

Pre-Classification:





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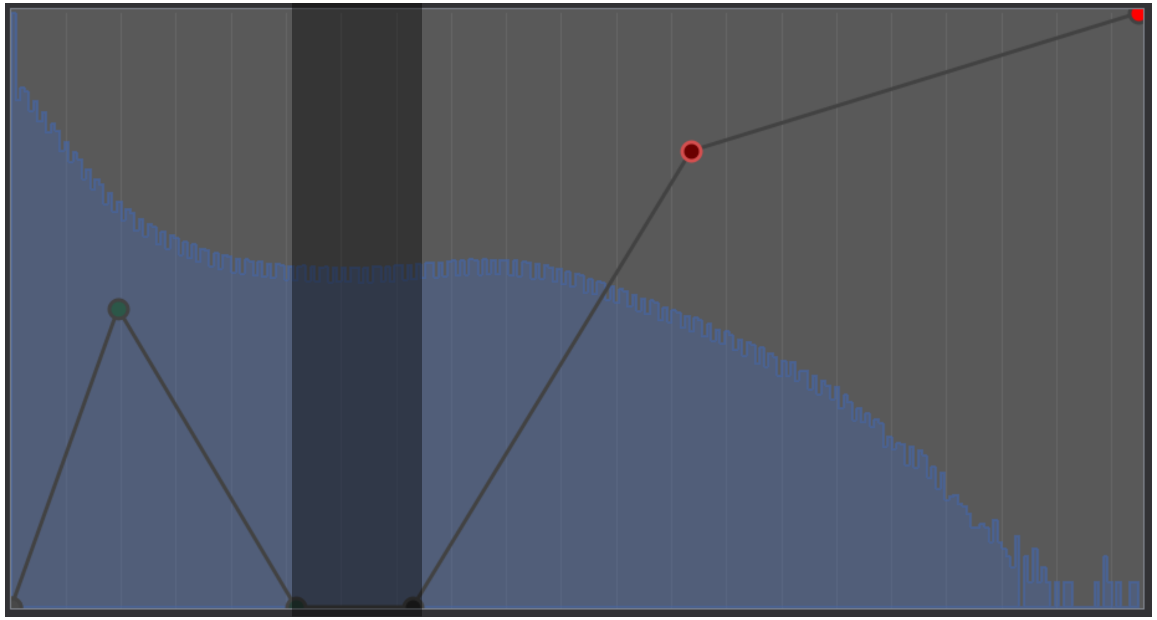

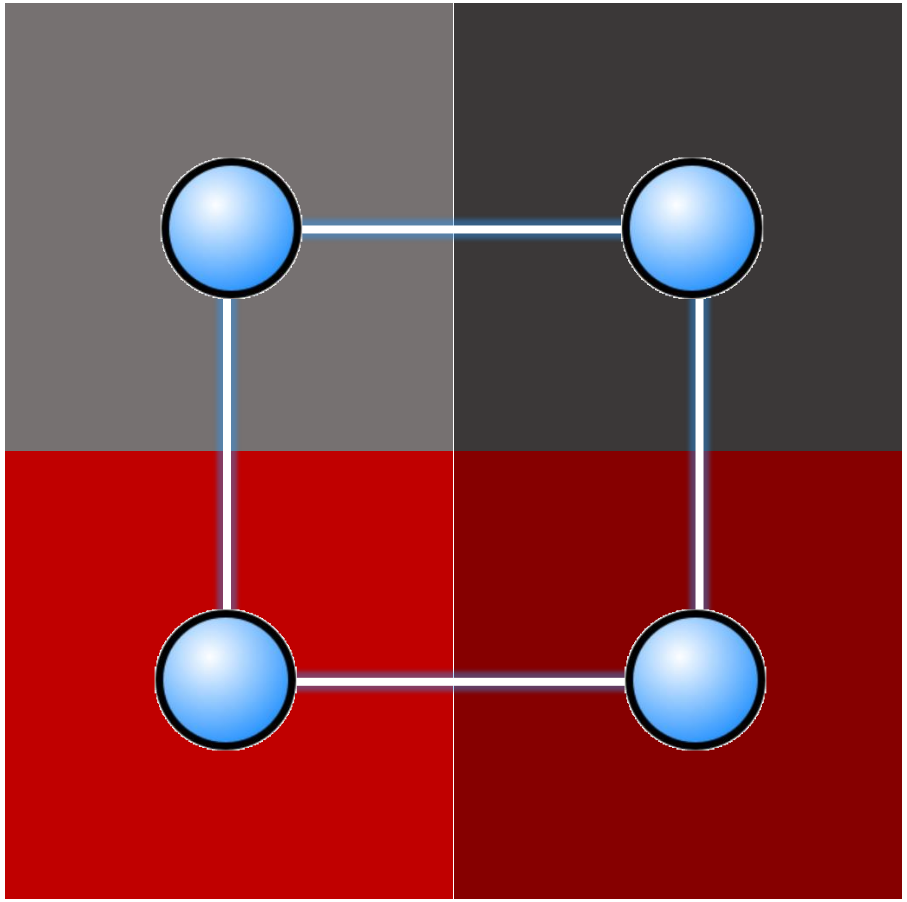

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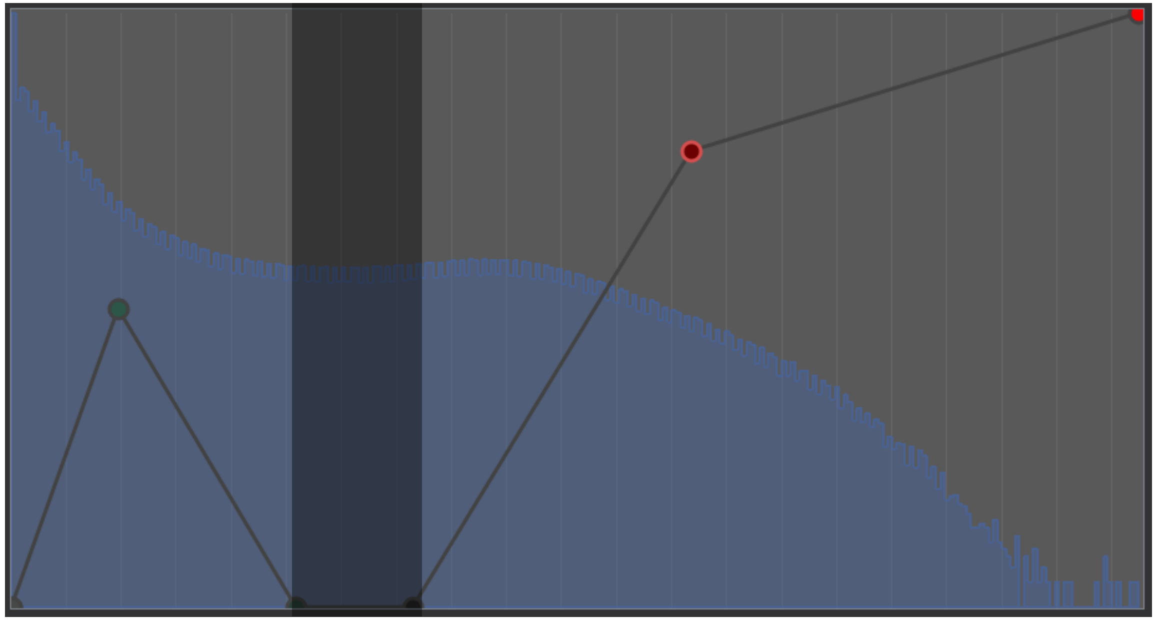

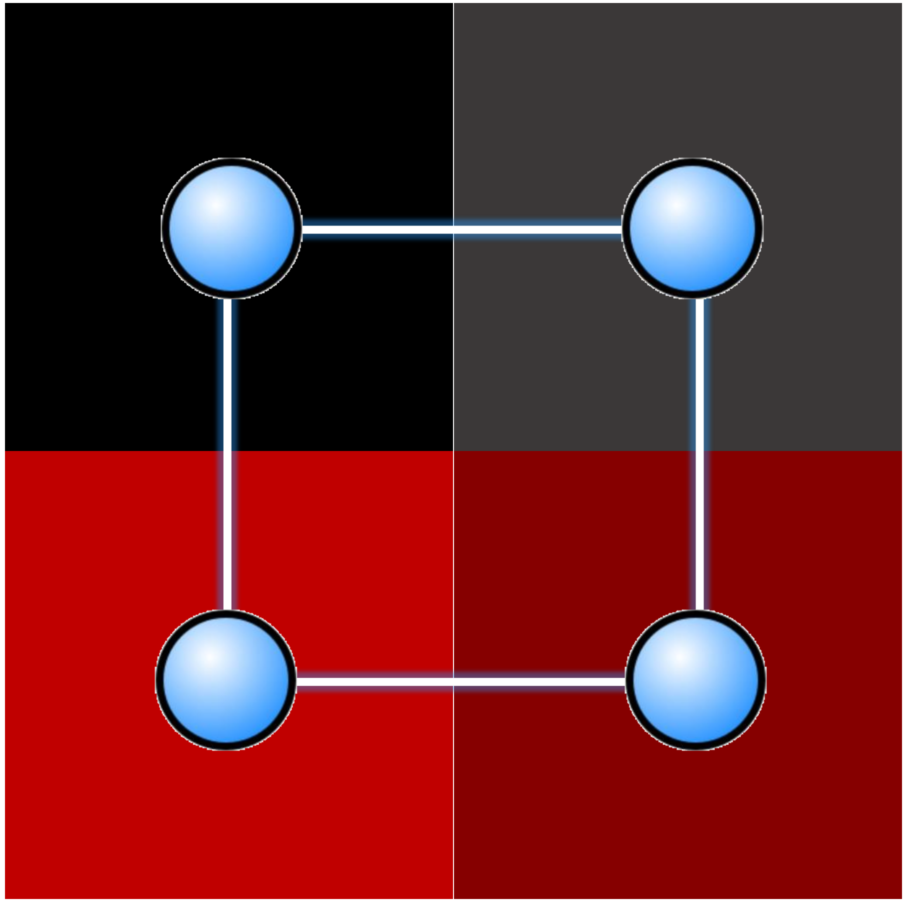

Classification

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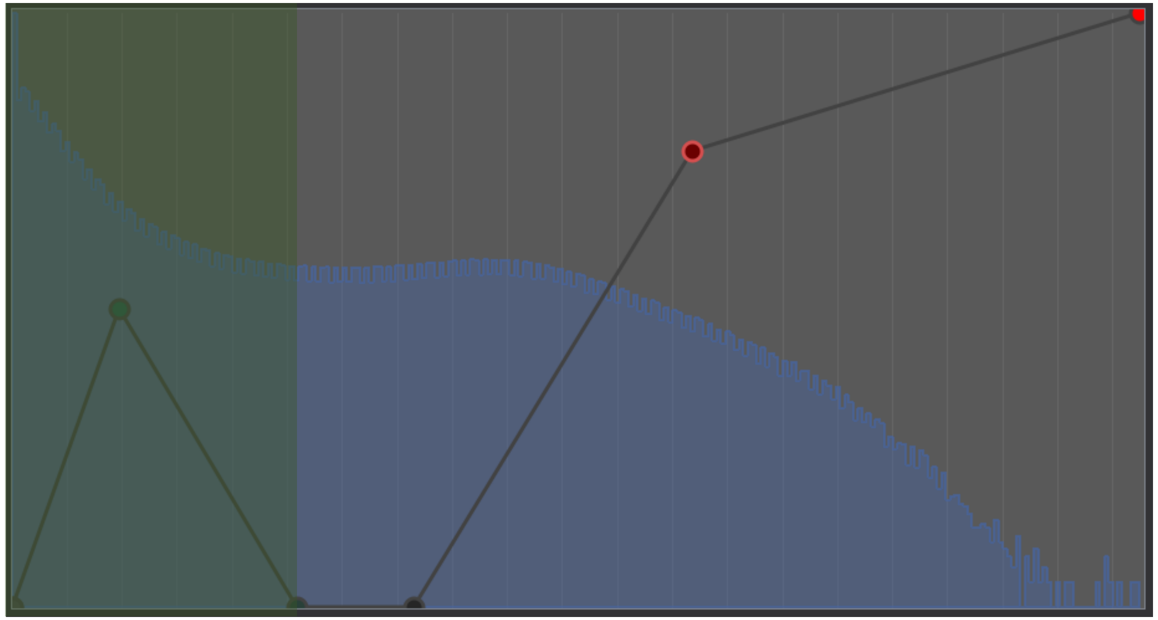

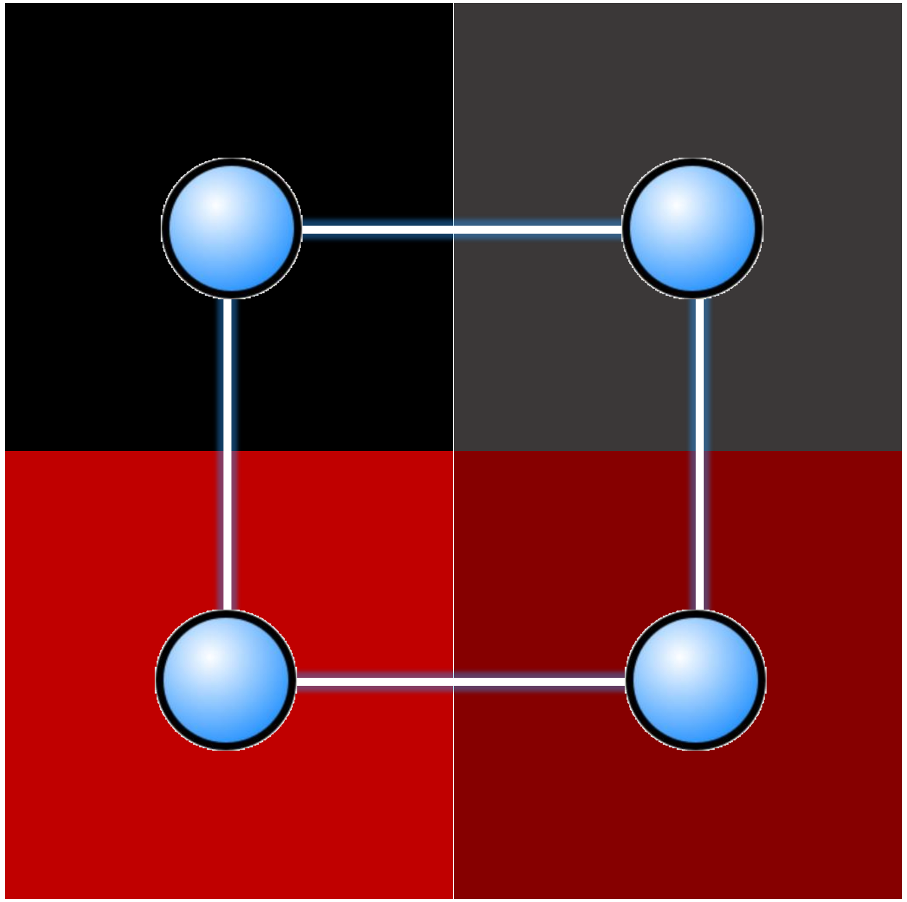

Classification

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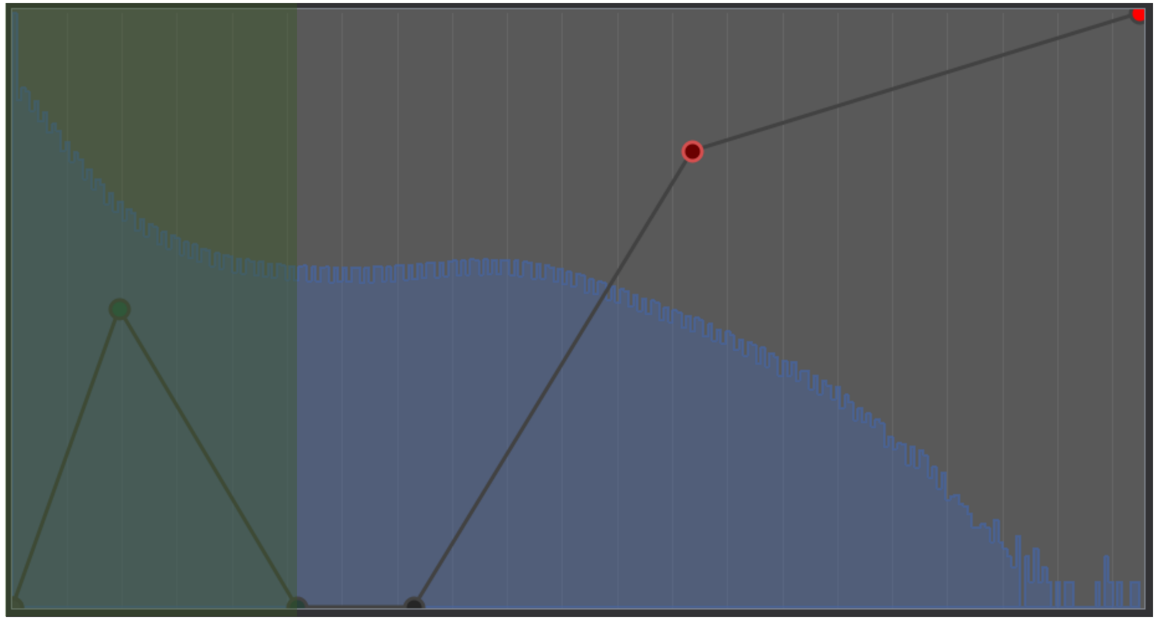

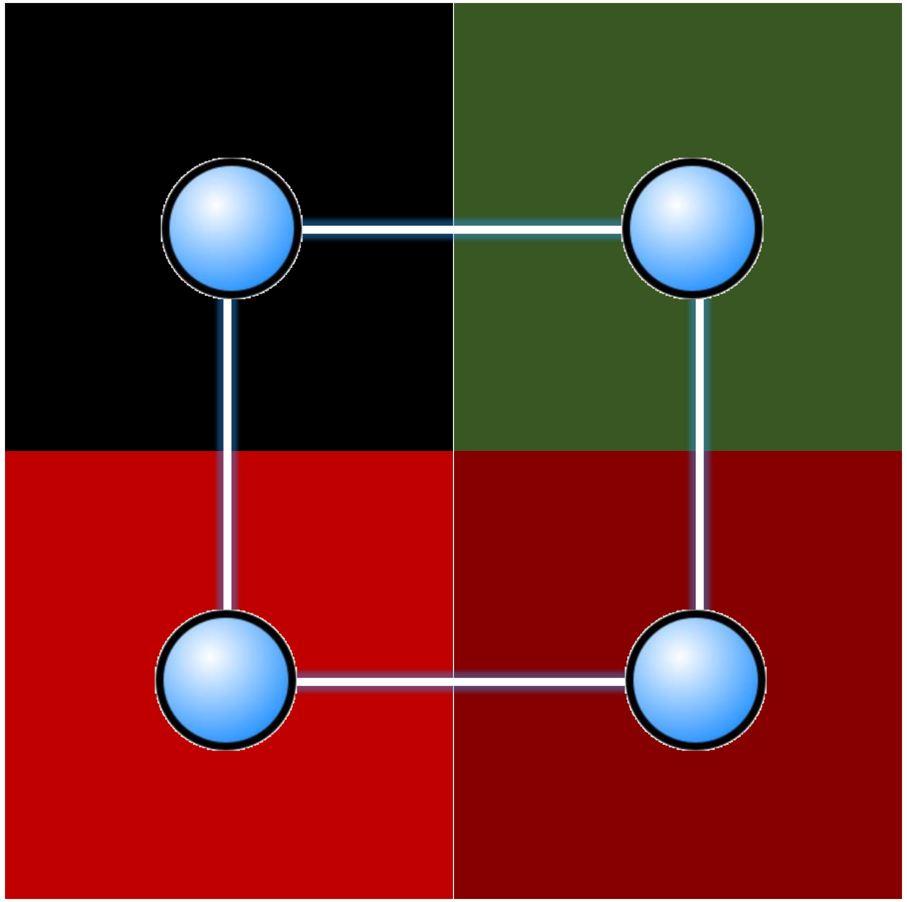

Classification

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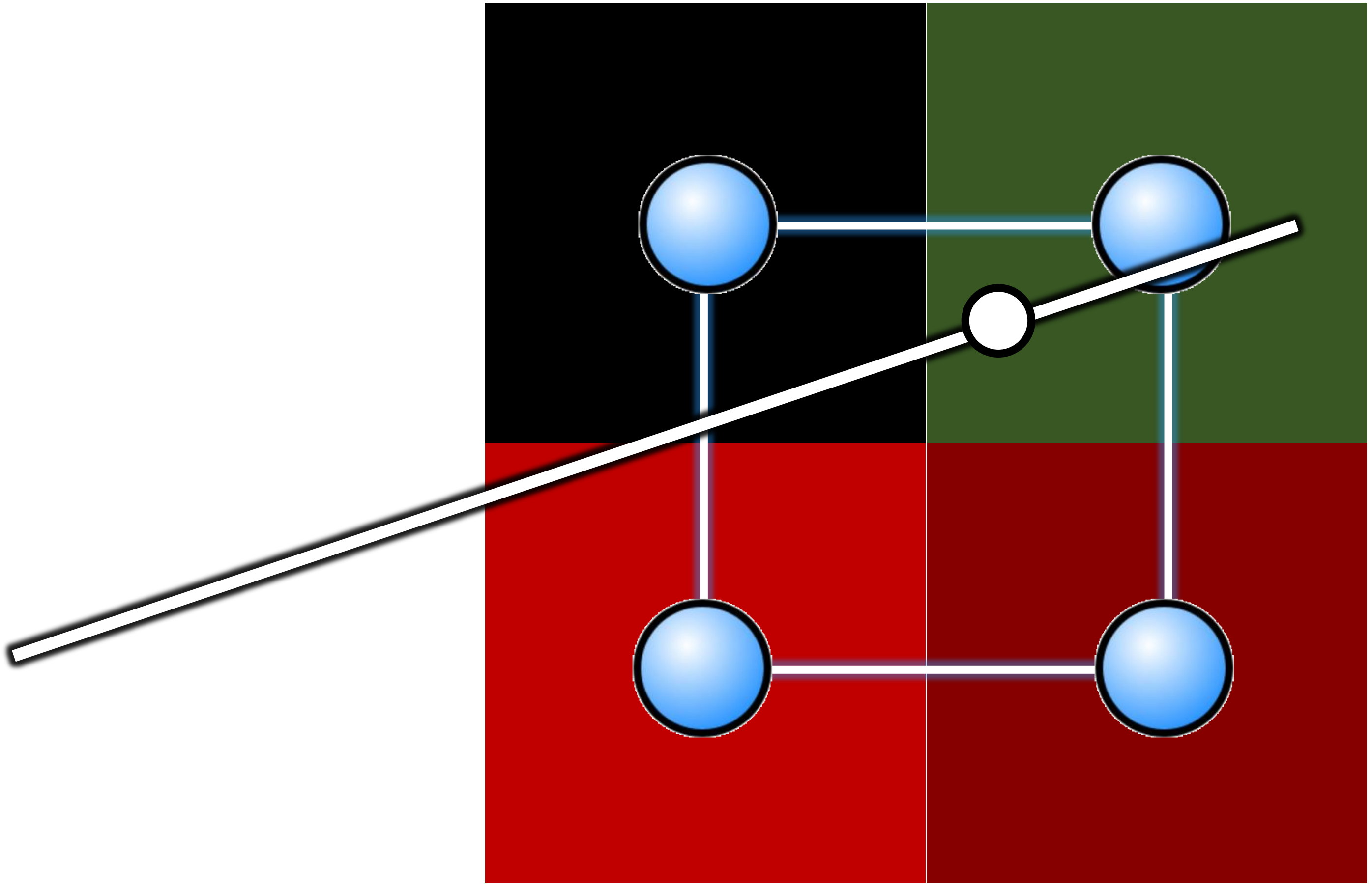
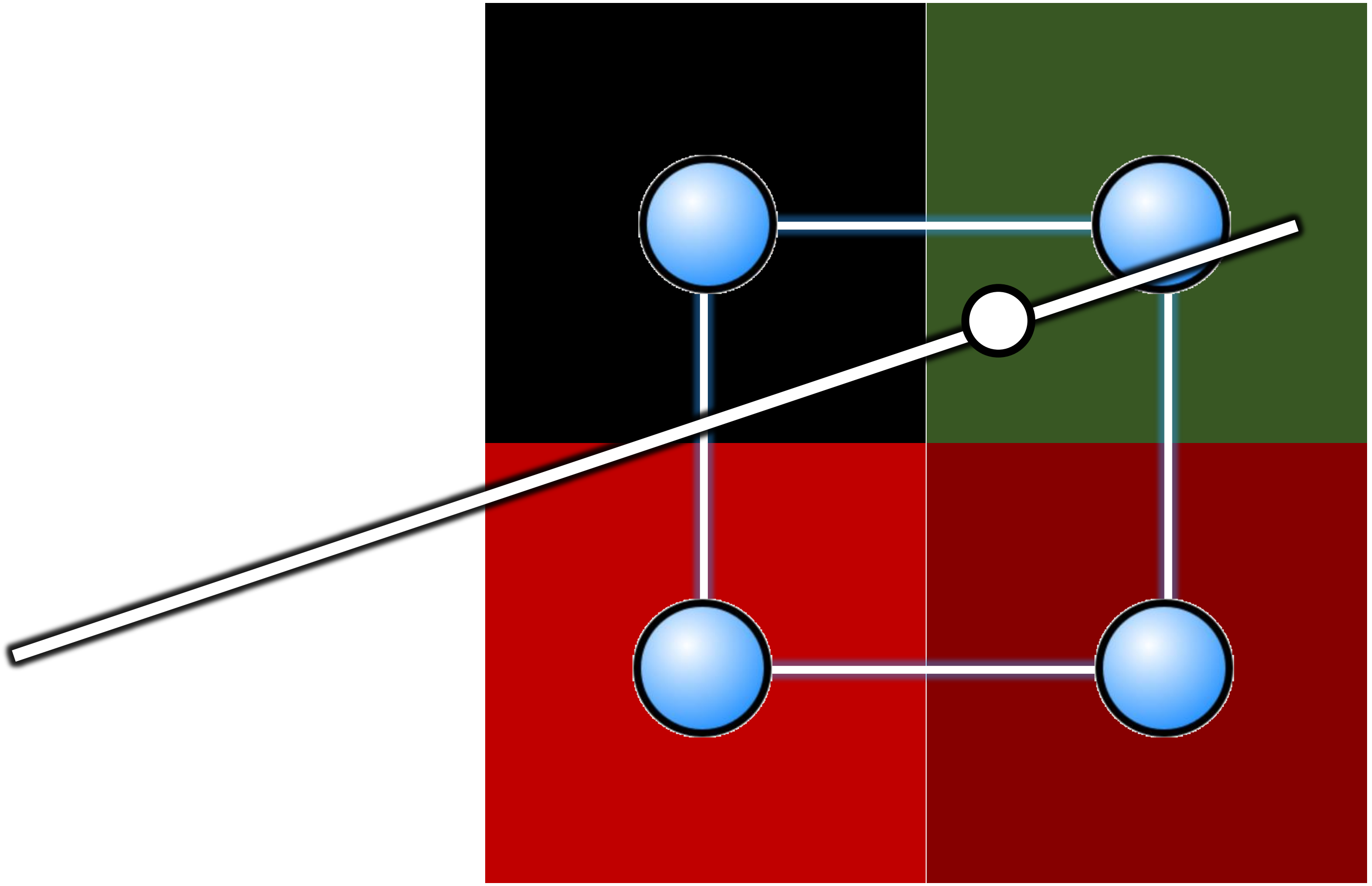


Classification

Pre-Classification:

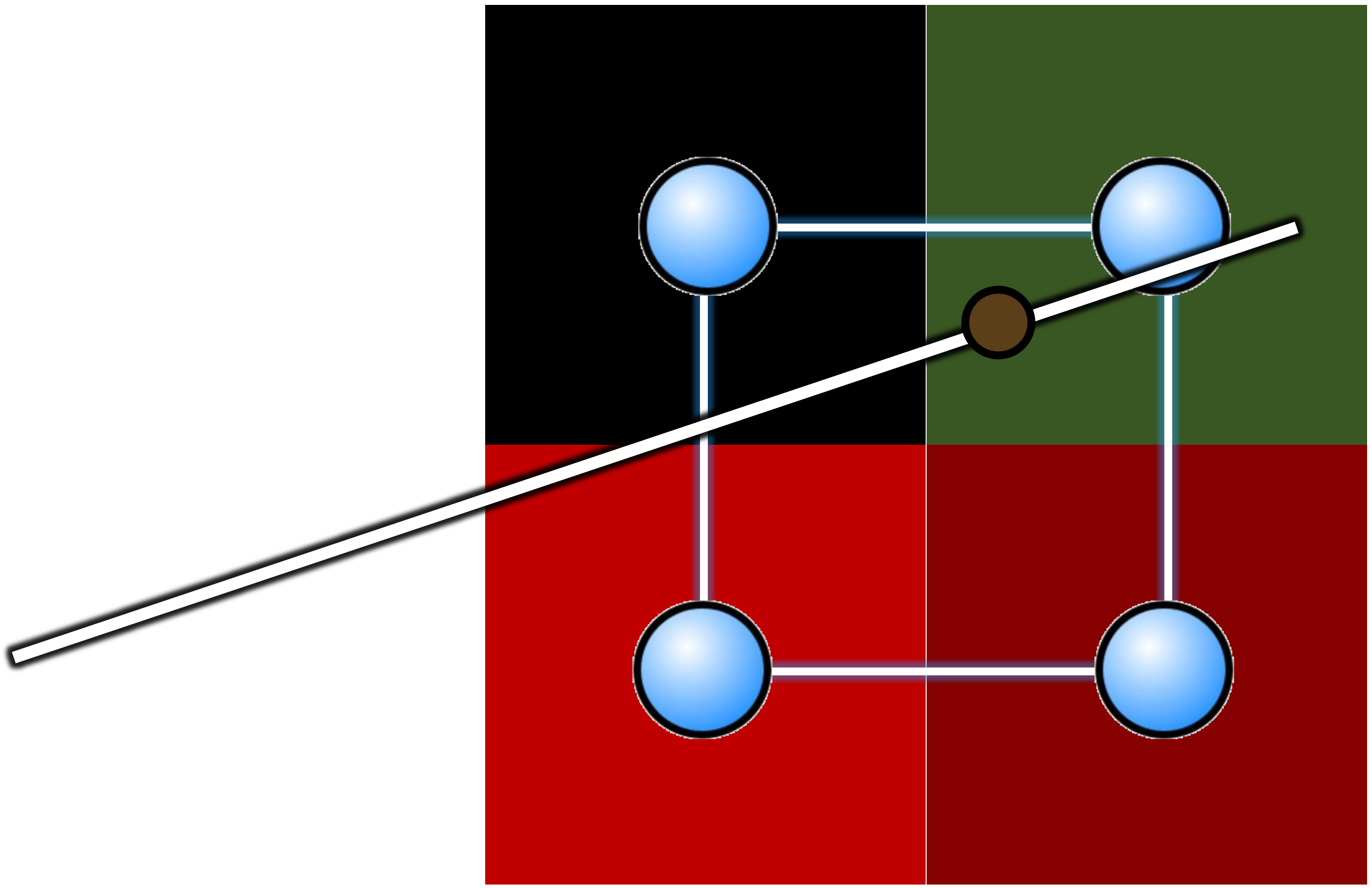
Interpolation



Classification

Pre-Classification:

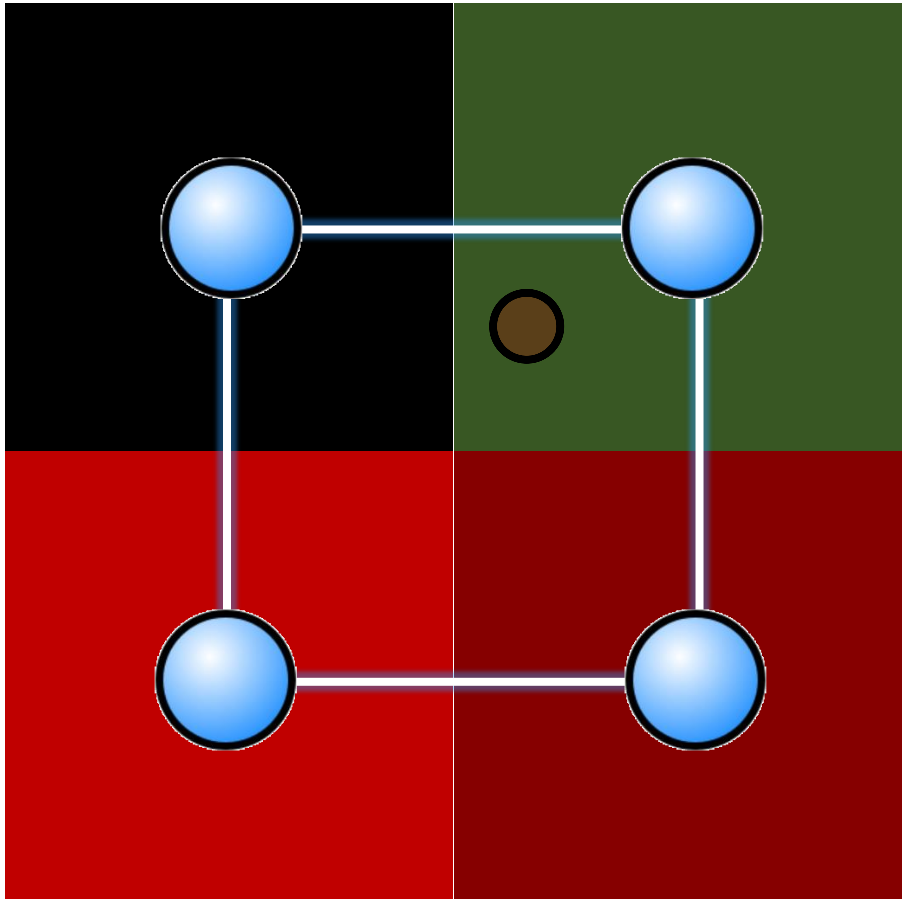
Interpolation



Classification

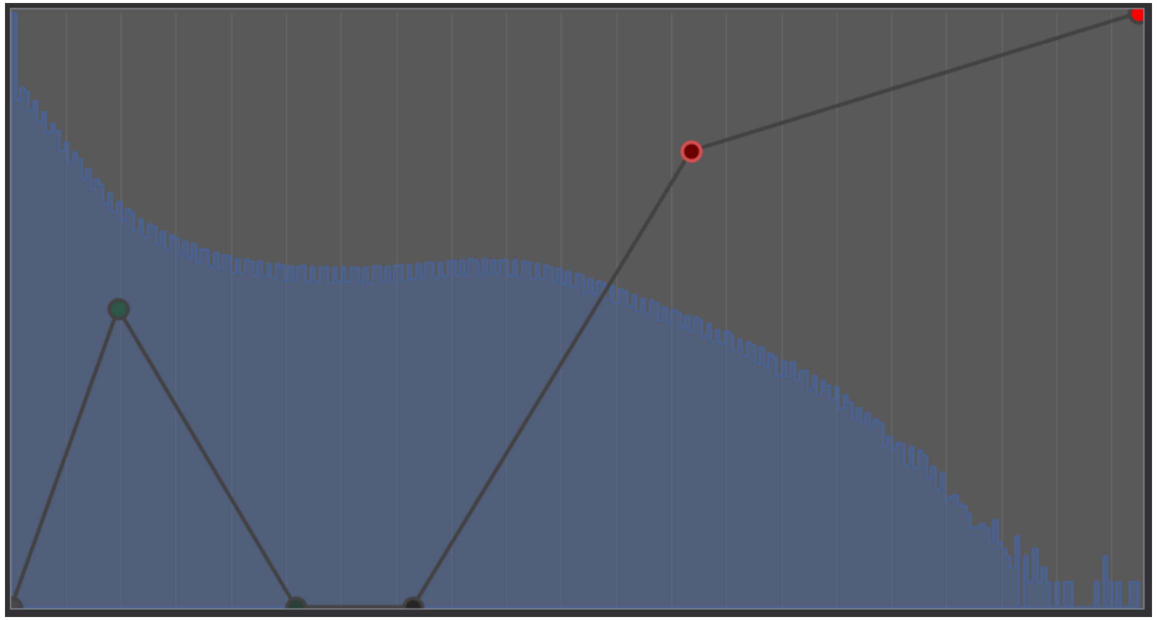
Pre-Classification:

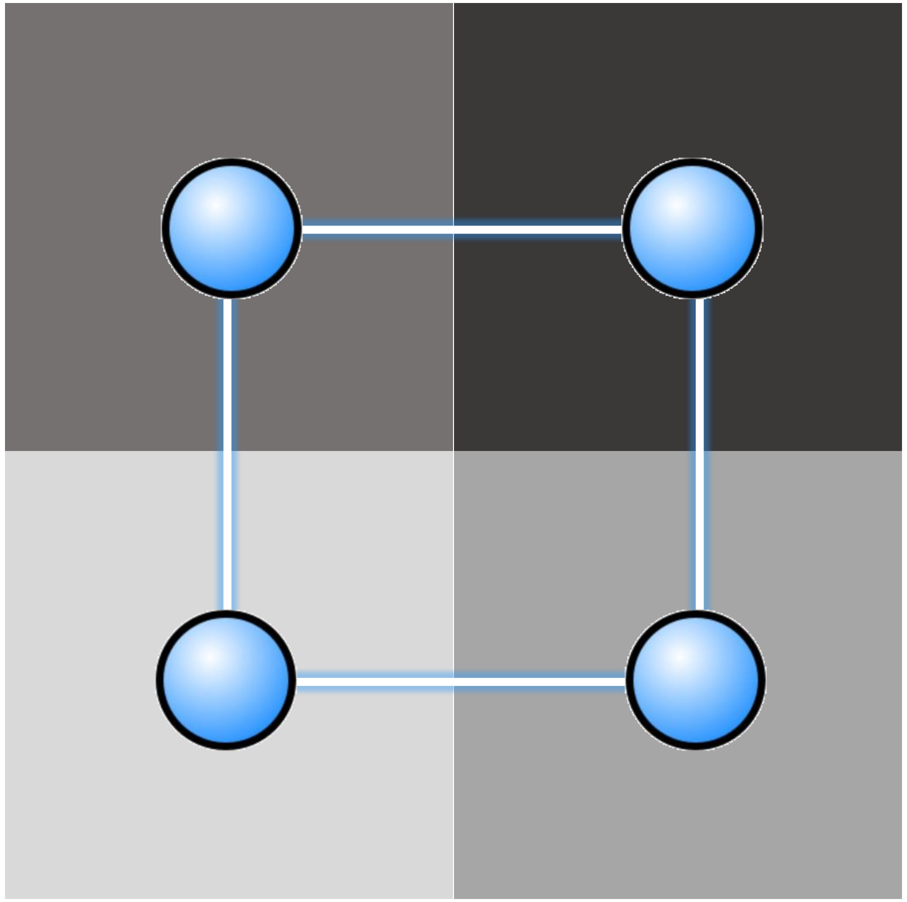
- Application of TF to all edge points in the filter range (result: RGBA quadruple); afterwards: (tri)linear interpolation of this quadruple



Classification

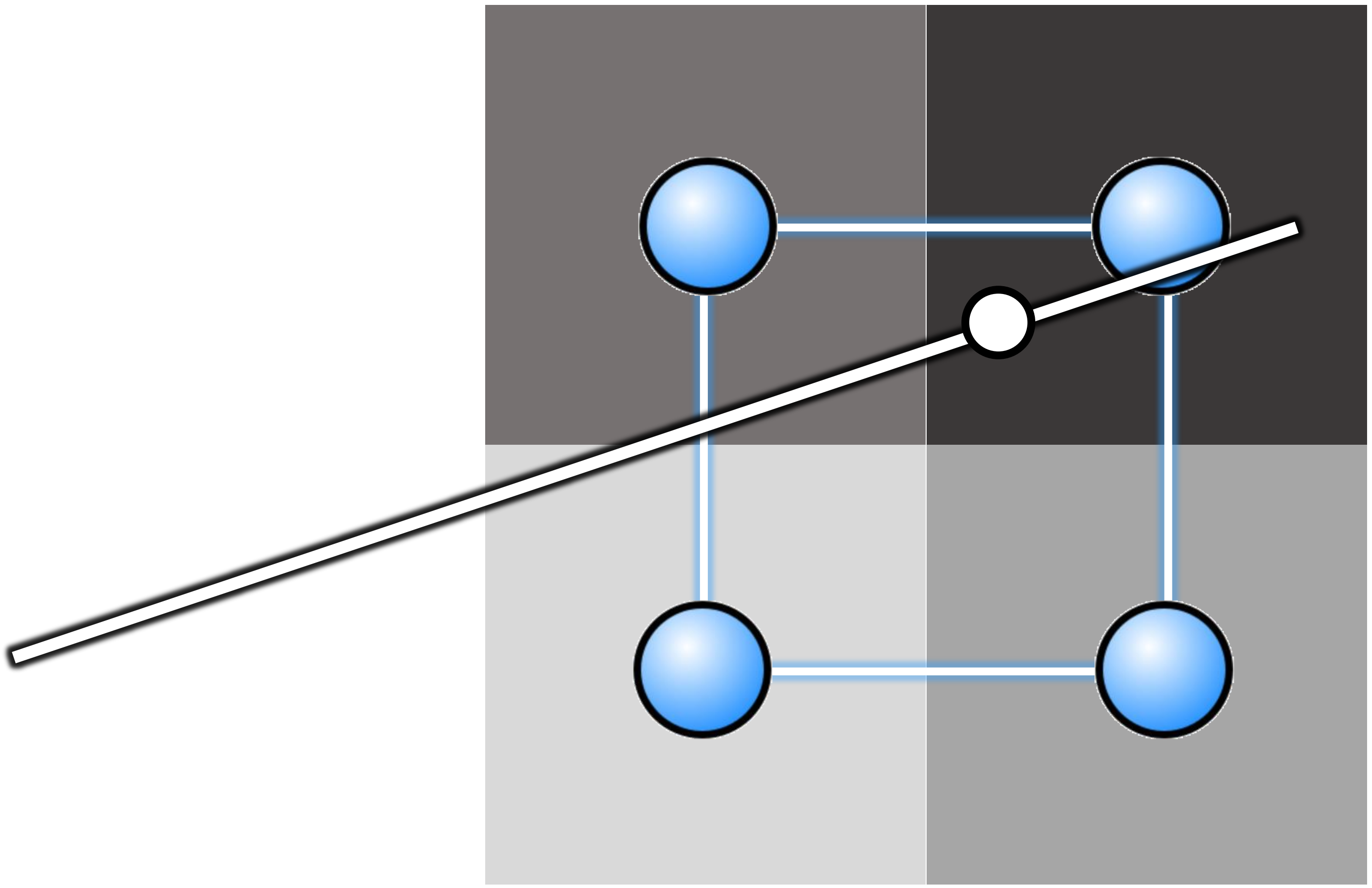
Post-Classification:





Classification

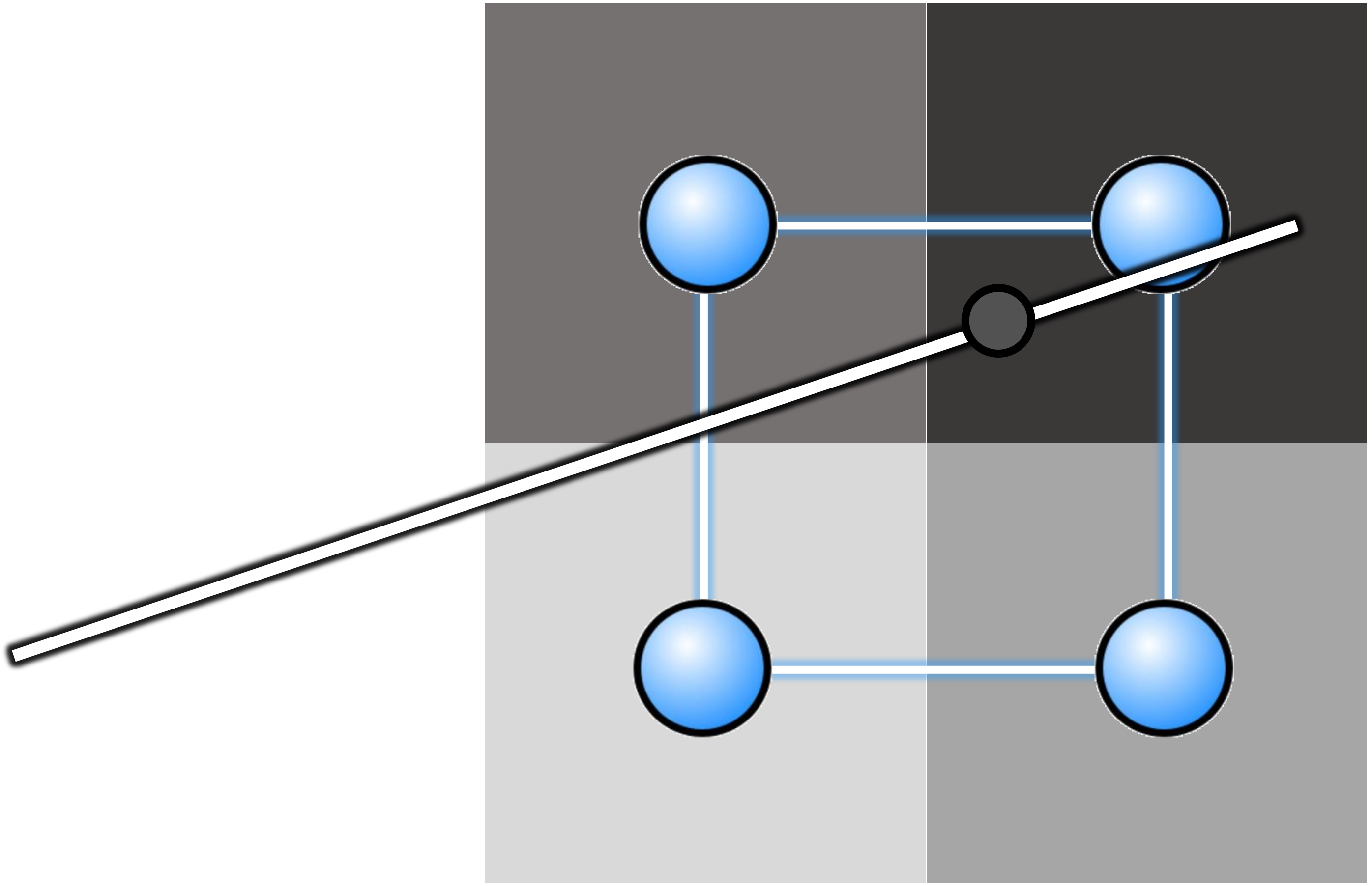
Post-Classification:



Classification

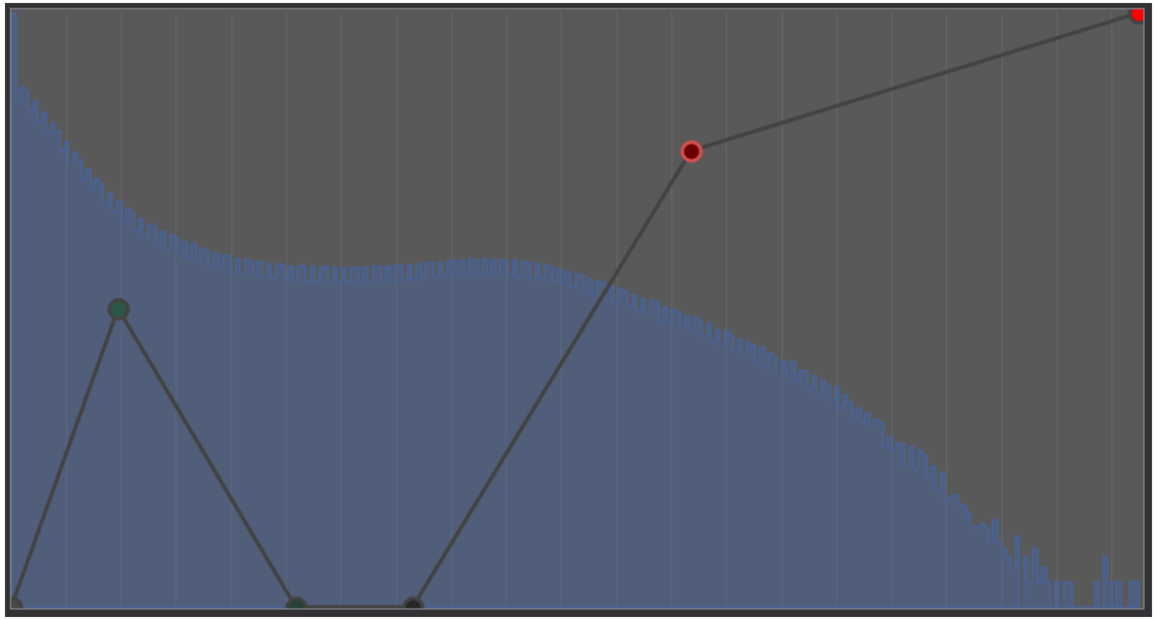
Post-Classification:

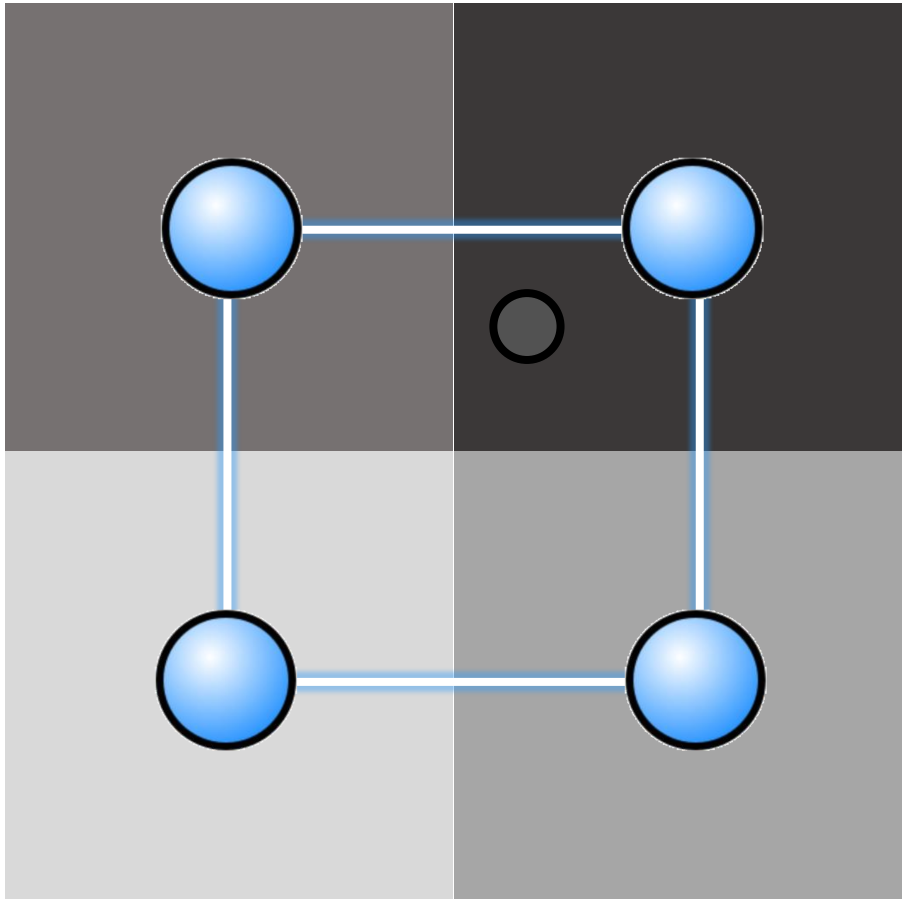
Interpolation



Classification

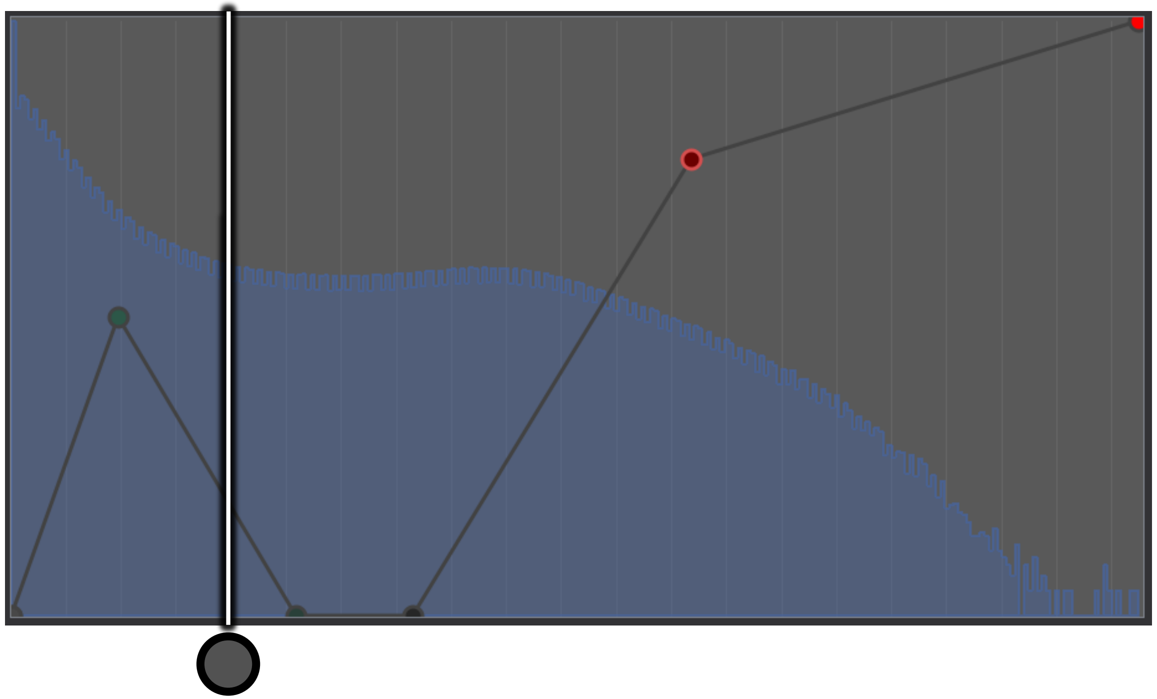
Post-Classification:

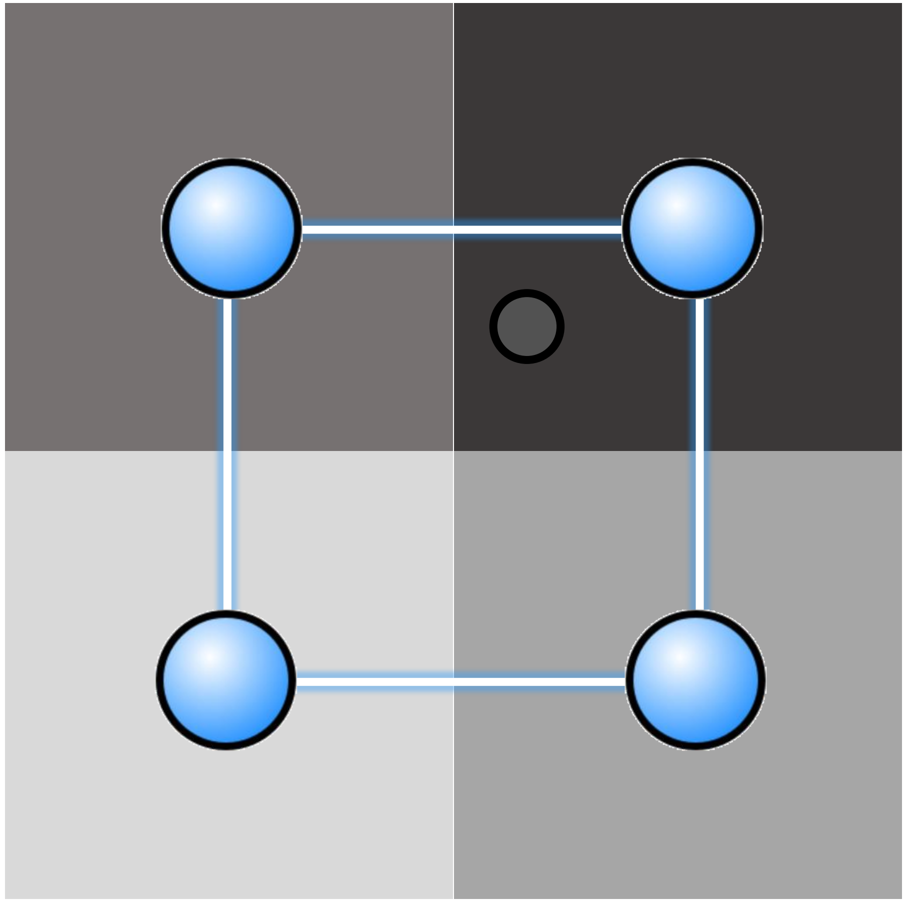




Classification

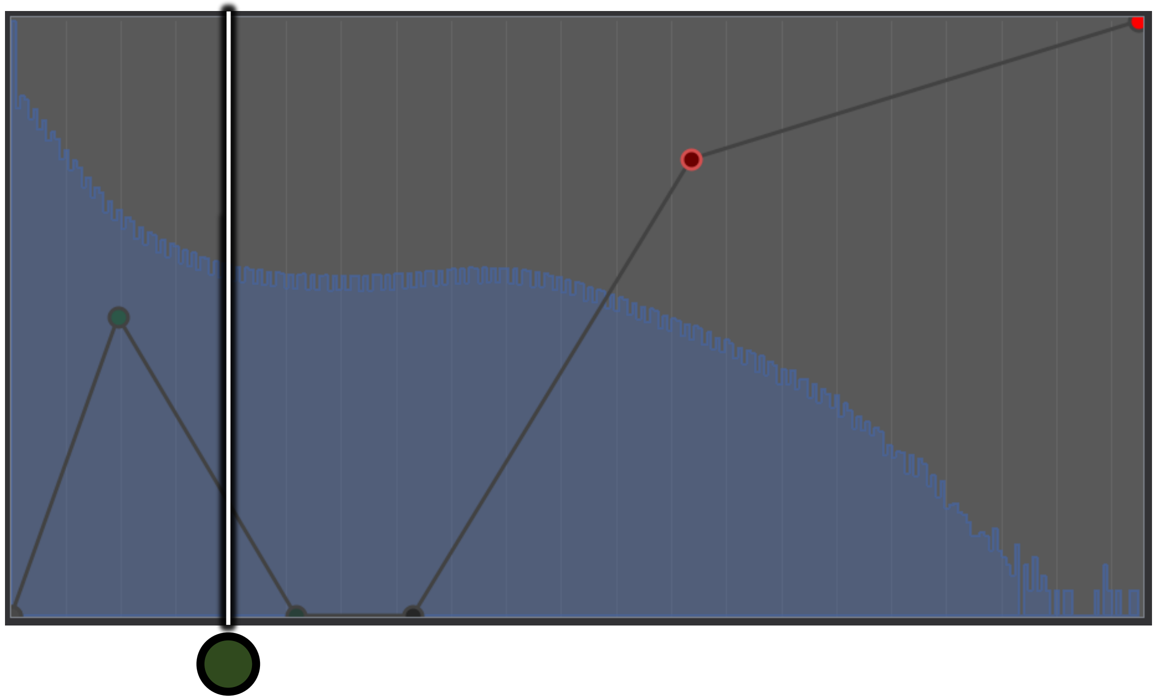
Post-Classification:

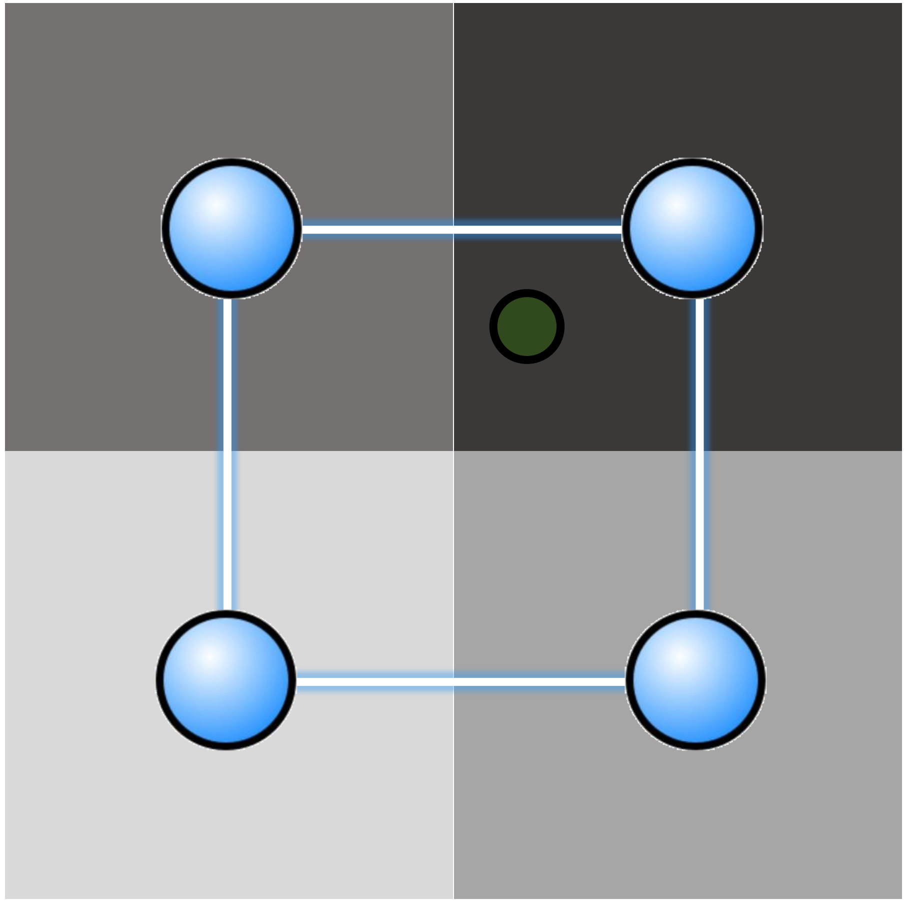




Classification

Post-Classification:

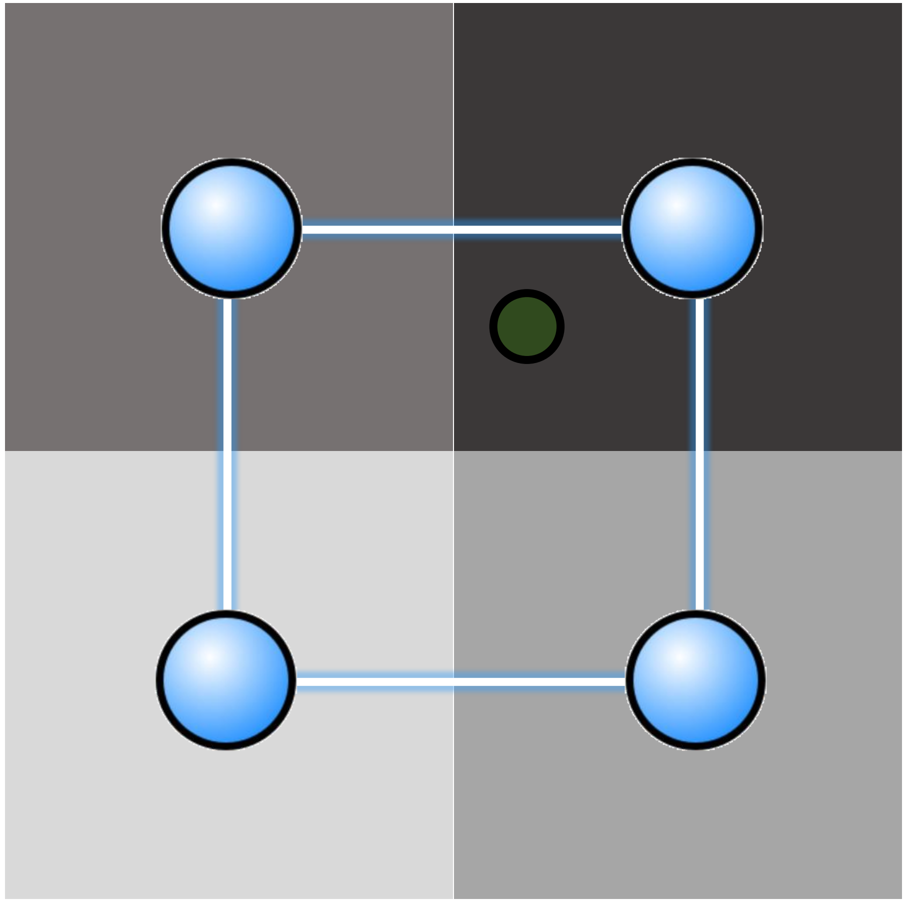




Classification

Post-Classification:

- Interpolation of the intensity values from the data (e.g., Hounsfield Units); afterwards: application of transfer function to the interpolated result (pre-integrated for quality enhancement)

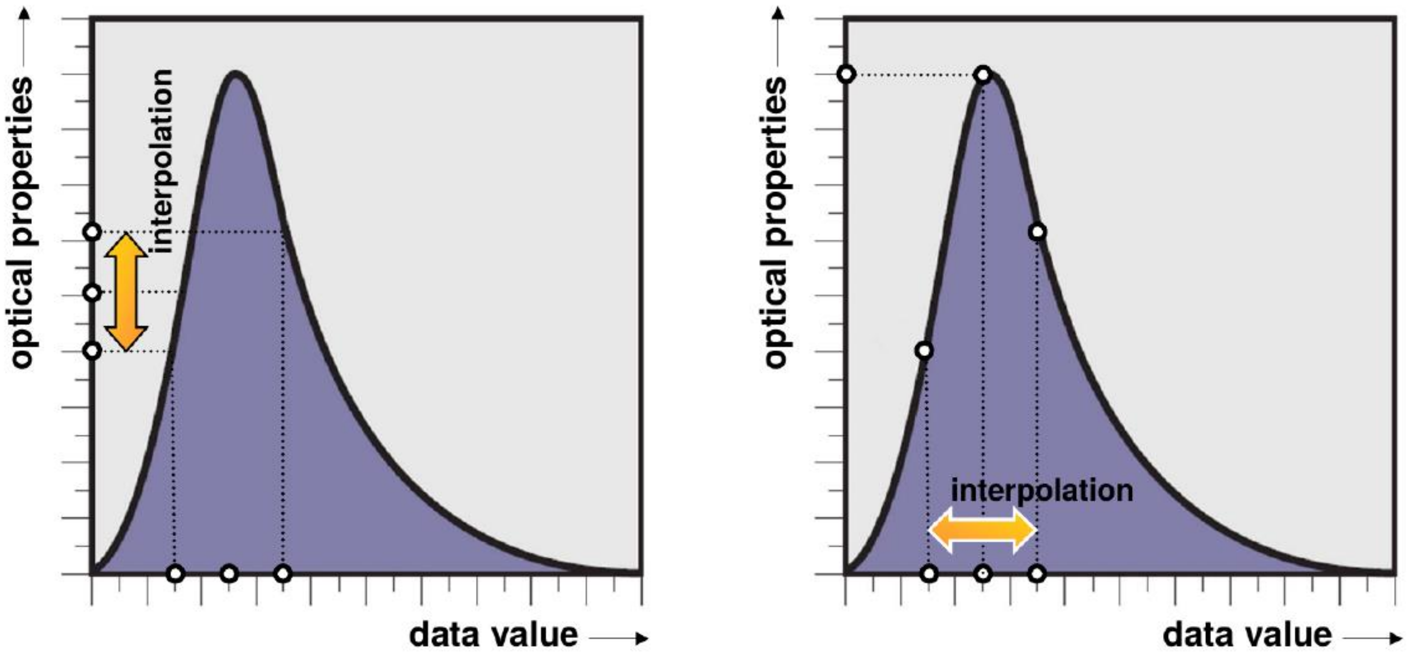


Classification

- Interpolation and application of TF (classification)
  - **Pre-Classification:** Application of TF to all edge points in the filter range (result: RGBA quadruple); afterwards: (tri)linear interpolation of this quadruple
  - **Post-Classification**: Interpolation of the intensity values from the data (e.g., Hounsfield Units); afterwards: application of transfer function to the interpolated result (pre-integrated for quality enhancement)
- Pre-classification problems:
  - Perception of the interpolated colors is non-linear
  - Imprecise classification

Classification

- Interpolation and application of the transfer function



Late application of TF is more precise!

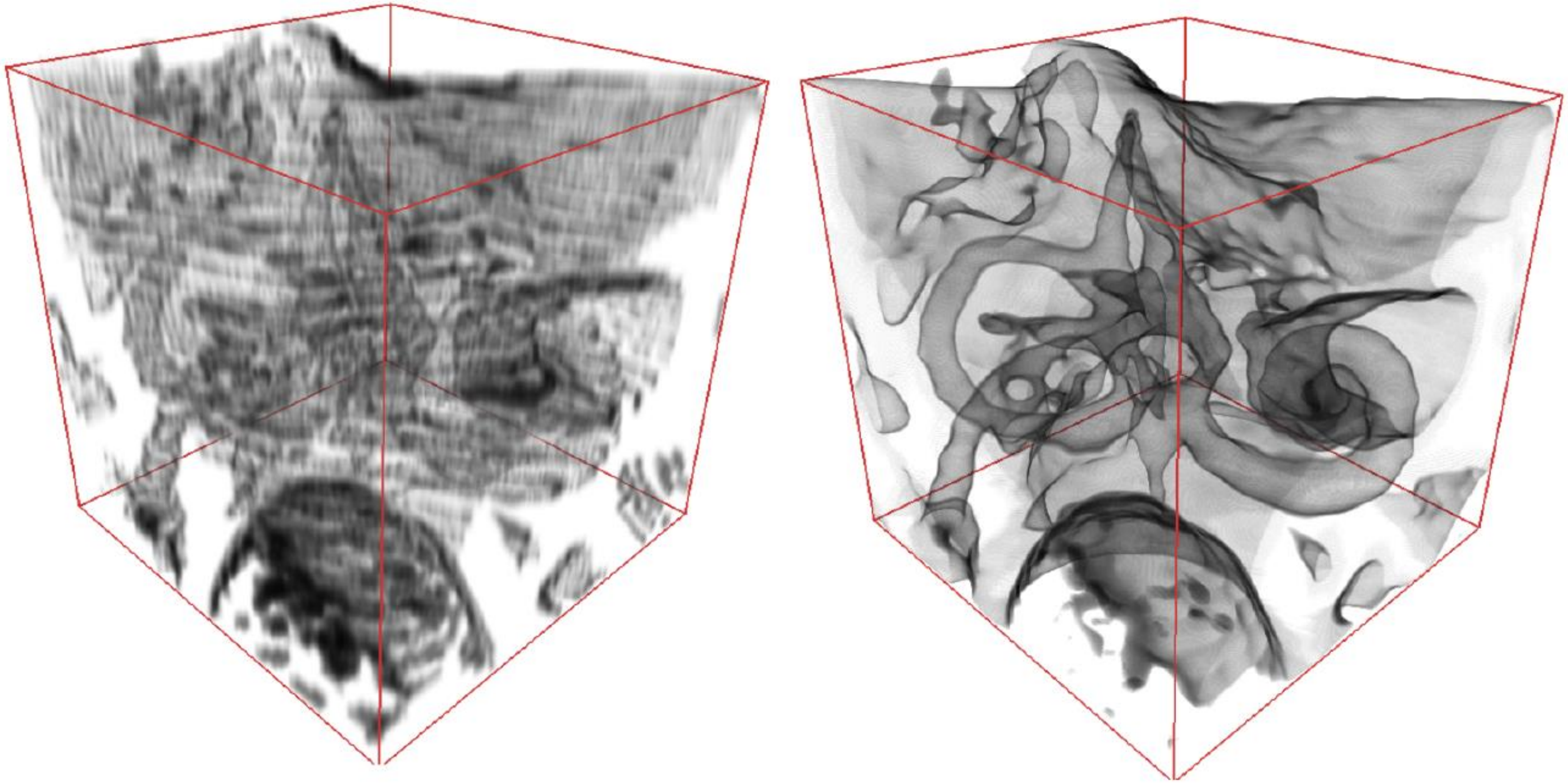
Left: Pre-Classification

Right: Post-Classification

Source: Eduard Gröller

Classification

- Left: Pre-Cl.
- Right: Post-Cl.

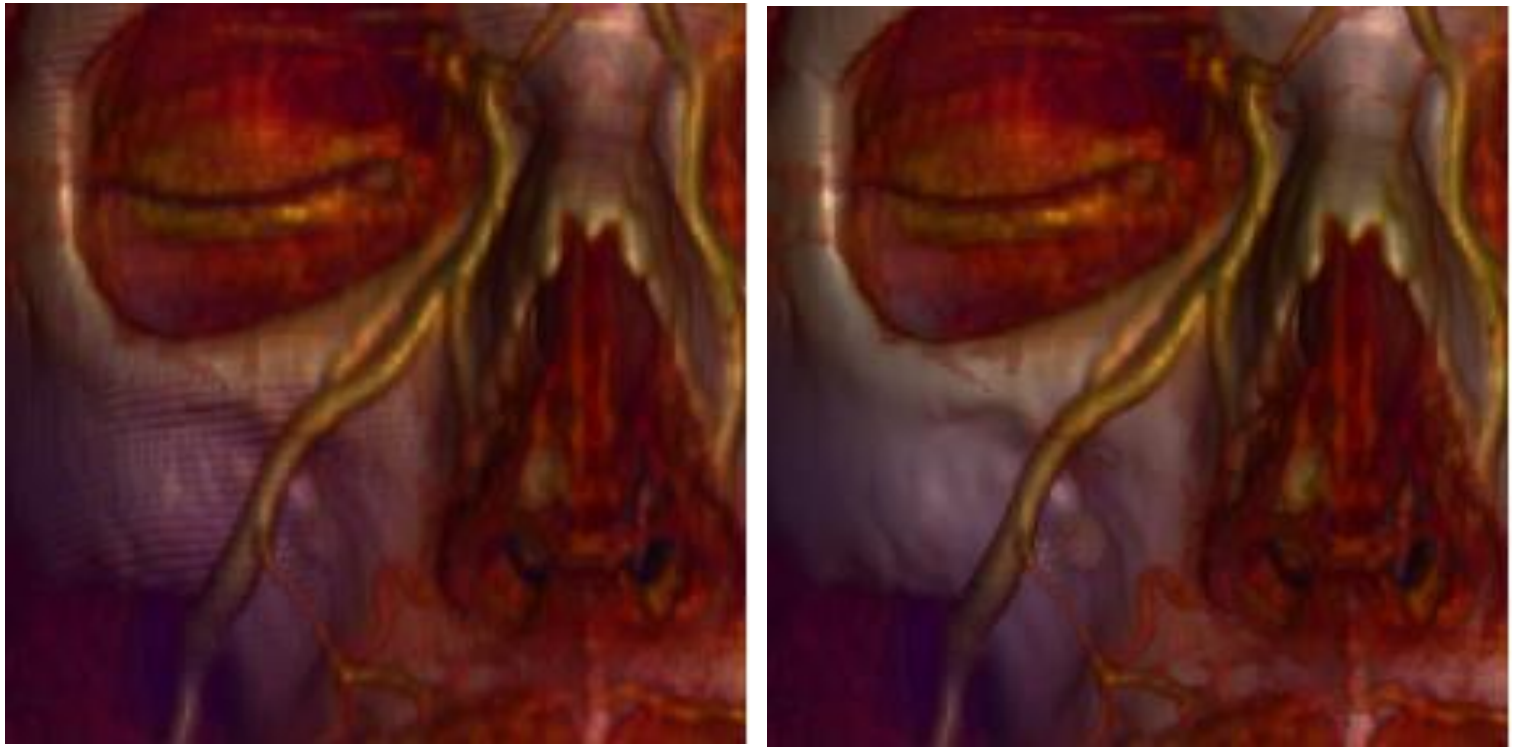


Late application of TF is more precise!

Source: Rezk-Salama, 2002

Classification

- Interpolation and application of the transfer function (pre- and post classification)



Source: Bruckner, 2004 (Master thesis)

Volume Rendering Equation

Volume Rendering Equation

- Volume rendering equation (without shadows and diffusion):

$$I(s) = I(s_0)$$

I	Amount of light
s	Current point on the light ray

Volume Rendering Equation

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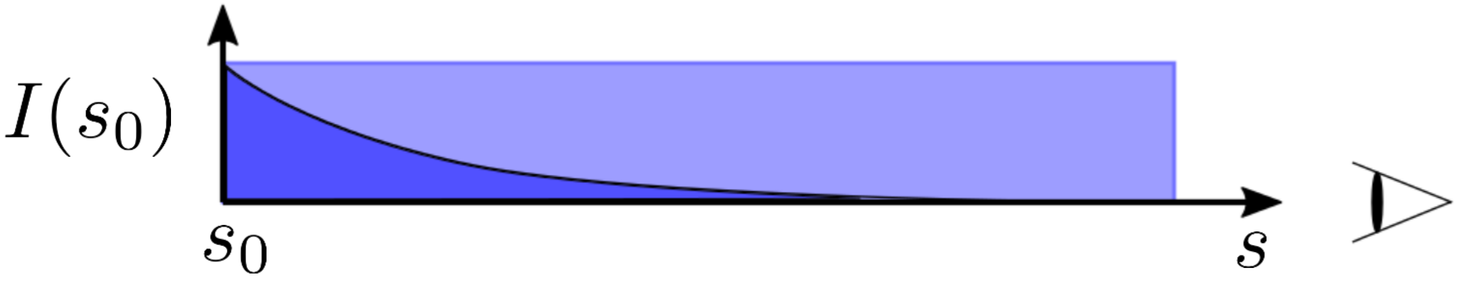
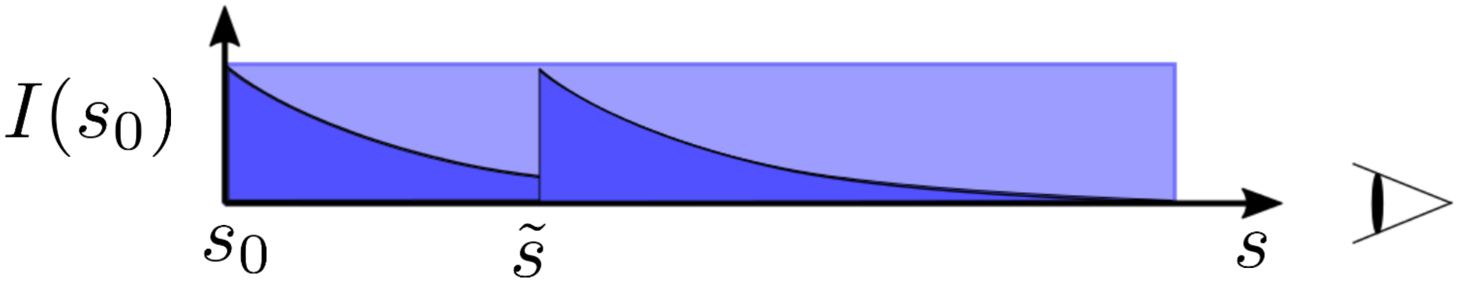


$$I(s) = I(s_0)\boxed{e^{-\tau(s_0,s)}} \qquad \tau(s_1, s_2) = \int_{s_1}^{s_2} \kappa(s)\,\mathrm{d}s$$

I	Amount of light
s	Current point on the light ray
τ	Optical depth
κ	Absorption

Volume Rendering Equation

- Volume rendering equation (without shadows and diffusion):

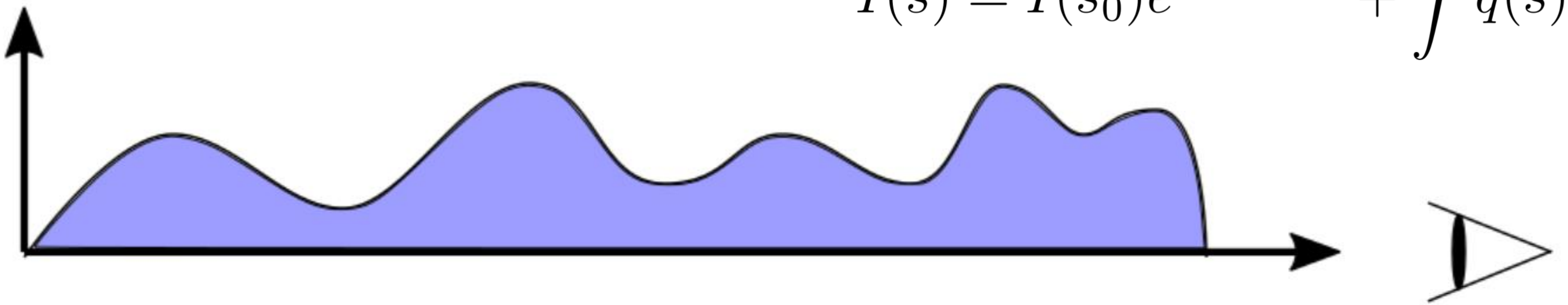


$$I(s) = I(s_0)e^{-\tau(s_0,s)} + \int q(\tilde{s})e^{-\tau(\tilde{s},s)}\,\mathrm{d}\tilde{s}$$

I	Amount of light
s	Current point on the light ray
τ	Optical depth
κ	Absorption
q	Emission

Numerical Approximation

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



Numerical Approximation

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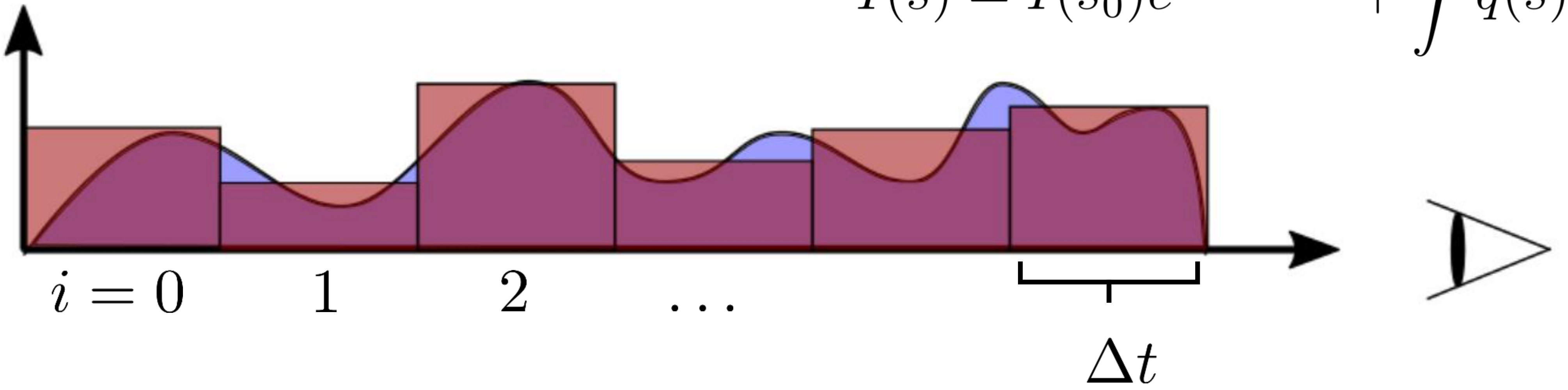
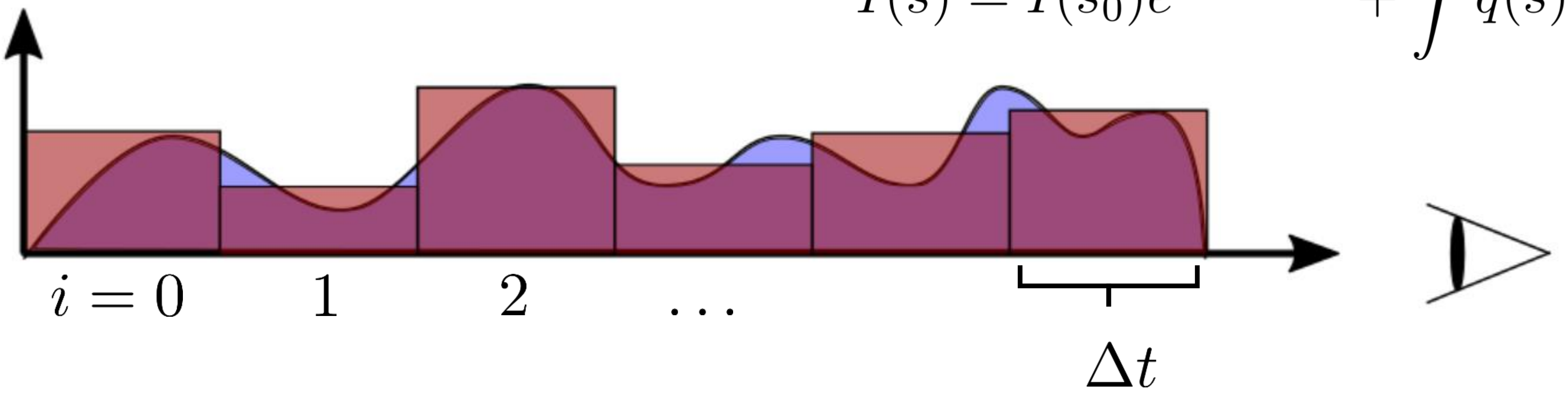


Numerical Approximation

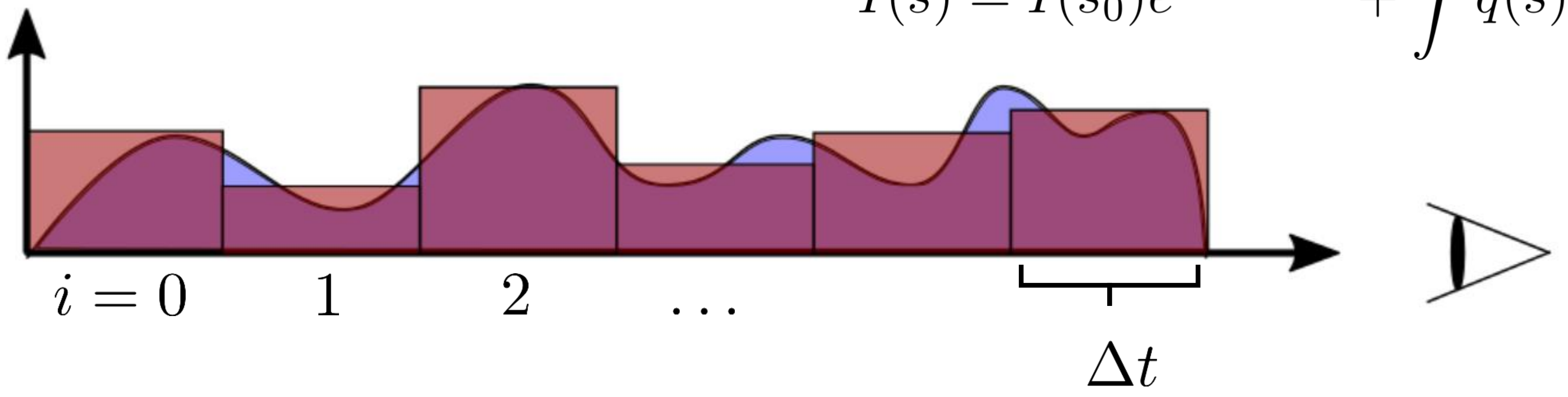
$$I(s) = I(s_0)e^{-\tau(s_0,s)} + \int q(\tilde{s})e^{-\tau(\tilde{s},s)}\,\mathrm{d}\tilde{s}$$



$$\tau(0,t) = \int_0^t \kappa(s)\,\mathrm{d}s \longrightarrow \tau(0,t) \approx \sum_{i=0}^{\lfloor t/\Delta t \rfloor} \kappa(i \cdot \Delta t)\Delta t$$

Numerical Approximation

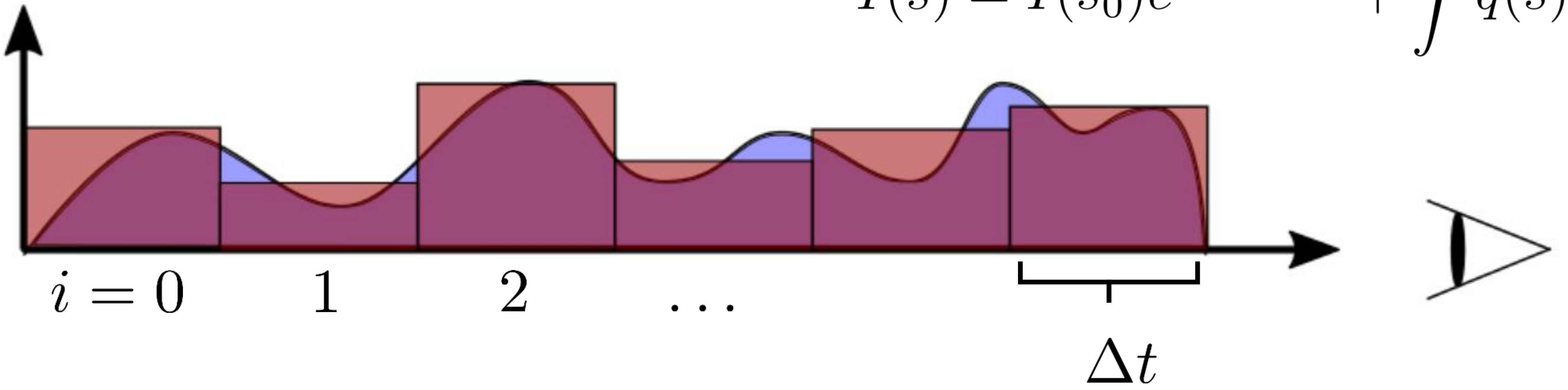
$$I(s) = I(s_0)e^{-\tau(s_0,s)} + \int q(\tilde{s})e^{-\tau(\tilde{s},s)}\,\mathrm{d}\tilde{s}$$



$$e^{-\tau(0,t)} = e^{-\int_0^t \kappa(s)\,\mathrm{d}s} \longrightarrow e^{-\tau(0,t)} \approx e^{-\sum_{i=0}^{\lfloor t/\Delta t \rfloor} \kappa(i\cdot\Delta t)\Delta t}$$

Numerical Approximation

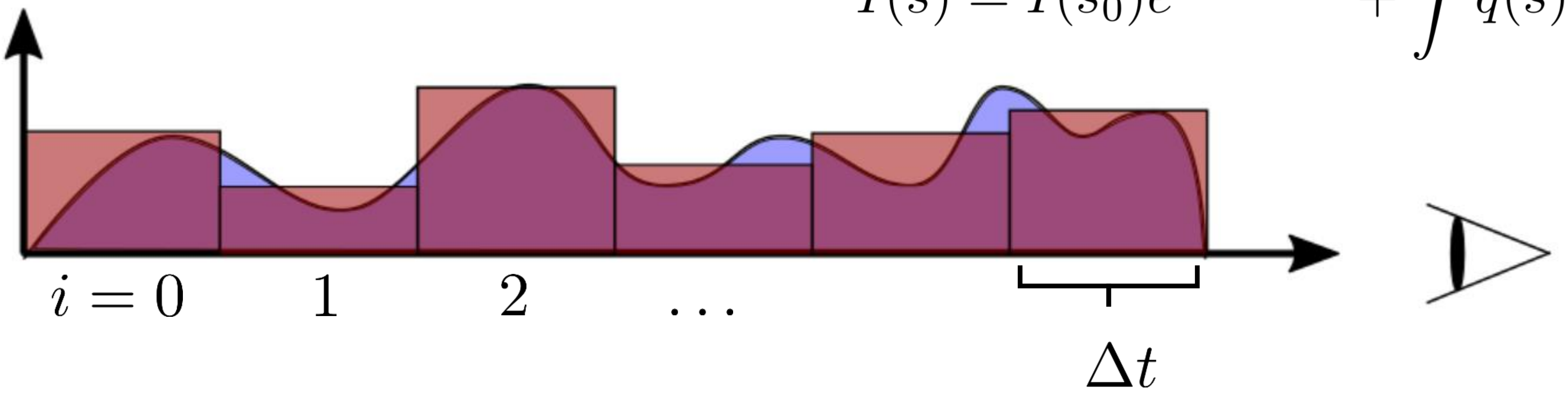
$$I(s) = I(s_0)e^{-\tau(s_0,s)} + \int q(\tilde{s})e^{-\tau(\tilde{s},s)}\,\mathrm{d}\tilde{s}$$



$$e^{-\tau(0,t)} \approx e^{-\sum_{i=0}^{\lfloor t/\Delta t \rfloor} \kappa(i\cdot\Delta t)\Delta t}$$

Numerical Approximation

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

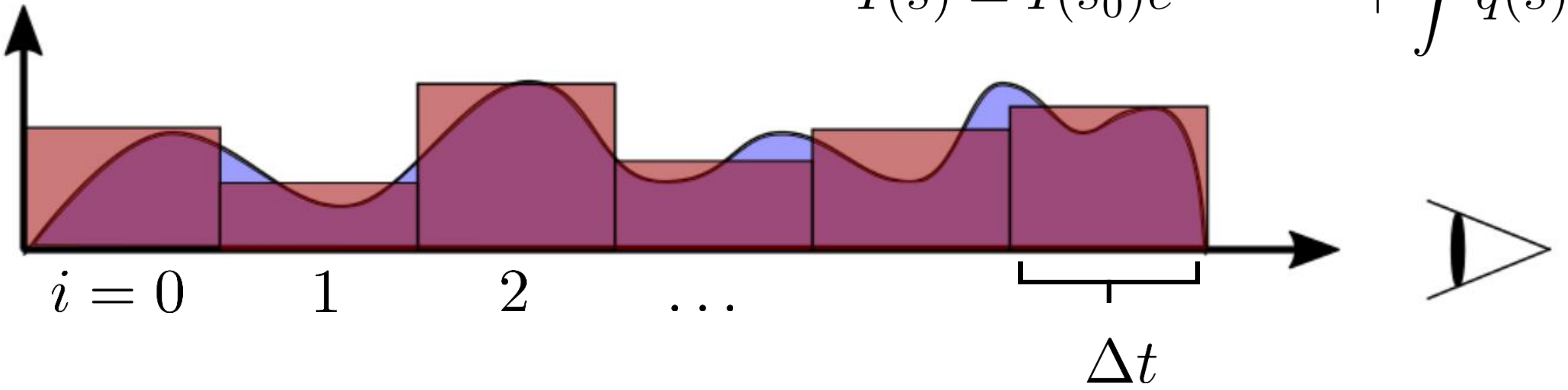


$$e^{-\tau(0,t)} \approx e^{-\sum_{i=0}^{\lfloor t/\Delta t \rfloor} \kappa(i\cdot\Delta t)\Delta t}$$

$$= \prod_{i=0}^{\lfloor t/\Delta t \rfloor} e^{-\kappa(i\cdot\Delta t)\Delta t}$$

Numerical Approximation

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

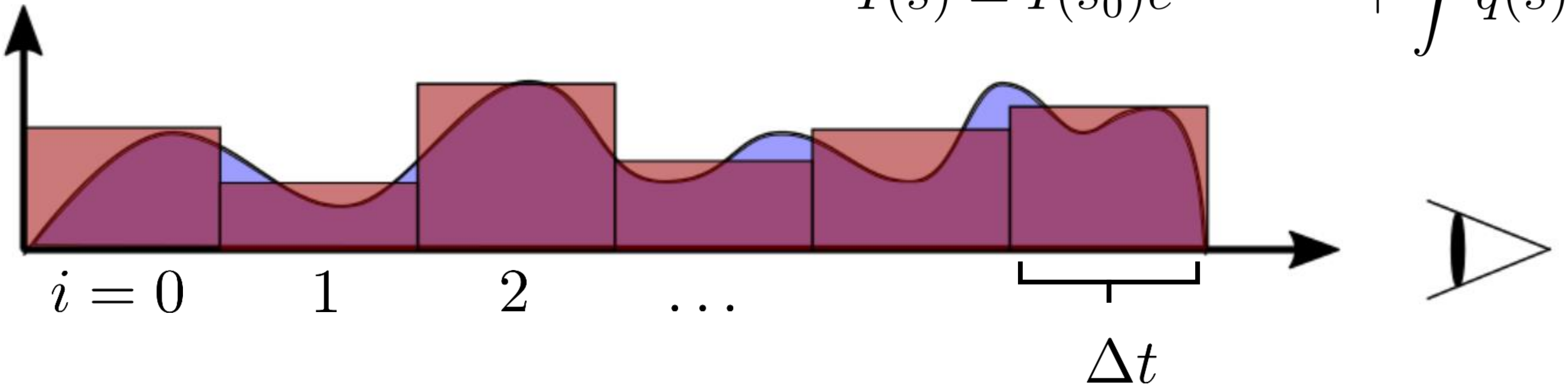


$$e^{-\tau(0,t)} \approx e^{-\sum_{i=0}^{\lfloor t/\Delta t \rfloor} \kappa(i\cdot\Delta t)\Delta t}$$

$$= \prod_{i=0}^{\lfloor t/\Delta t \rfloor} \underbrace{e^{-\kappa(i\cdot\Delta t)\Delta t}}_{1-A_i}$$

Numerical Approximation

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

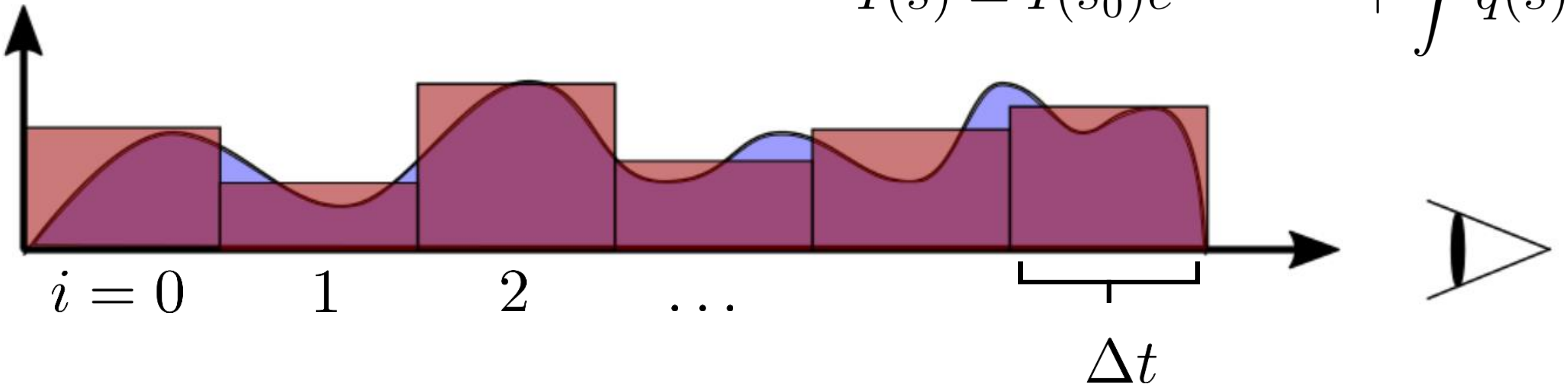


$$q(s) \approx C_i = c(i \cdot \Delta t)\Delta t$$

$$C = \sum_{i=0}^{\lfloor t/\Delta t \rfloor} C_i e^{-\tau(0,t)}$$

Numerical Approximation

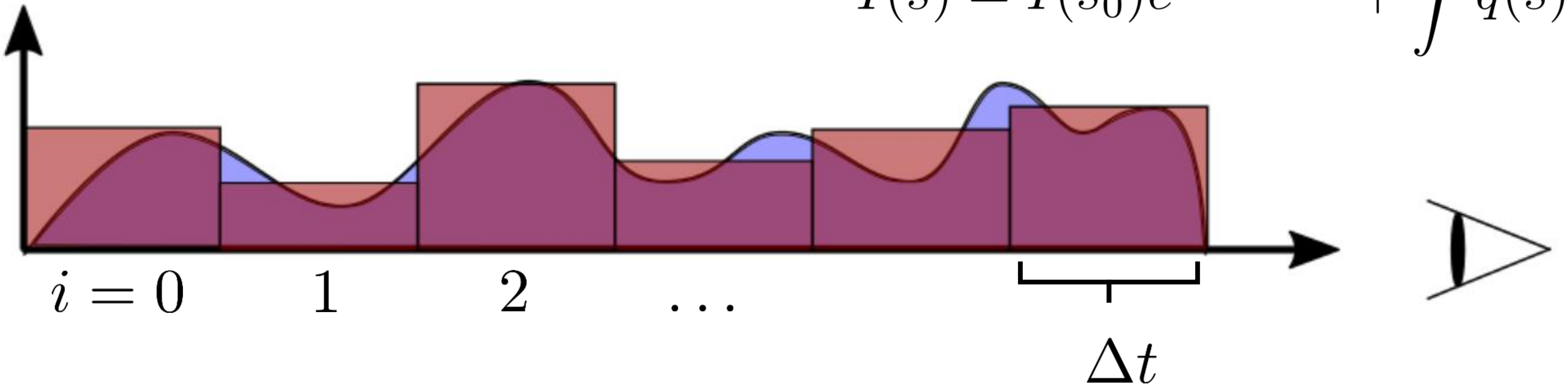
$$I(s) = I(s_0)e^{-\tau(s_0,s)} + \int q(\tilde{s})e^{-\tau(\tilde{s},s)}\,\mathrm{d}\tilde{s}$$



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

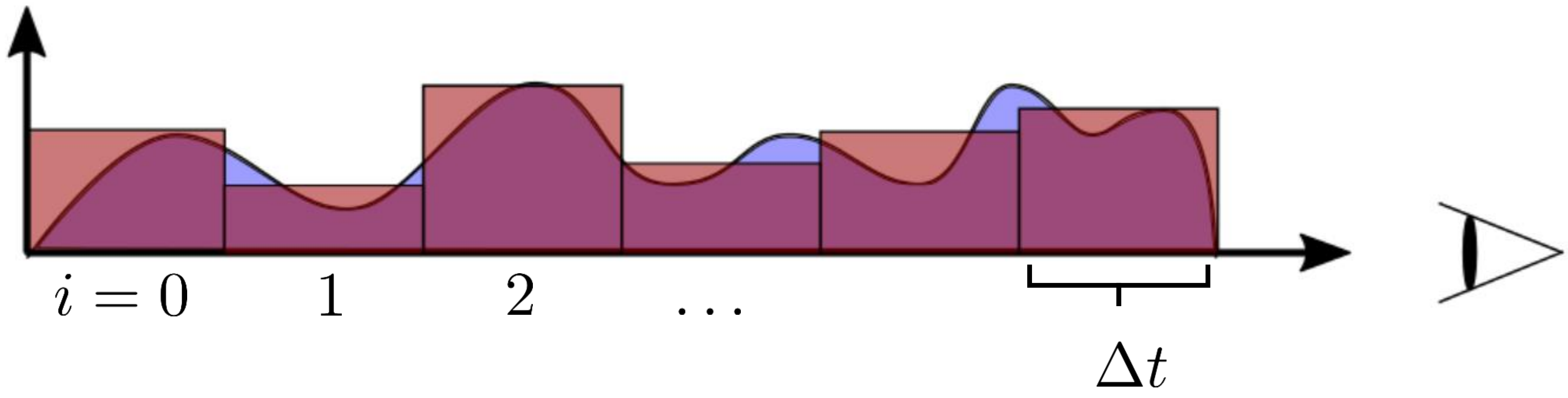
Numerical Approximation

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



$$\tilde{C} = \sum_{i=0}^{\lfloor t/\Delta t \rfloor} C_i \prod_{j=0}^{i} (1 - A_j) \;\rightarrow\; C_i' = C_i + (1 - A_i)C_{i-1}'$$

Numerical Approximation



$$C_i' = C_i + (1 - A_i)C_{i-1}'$$

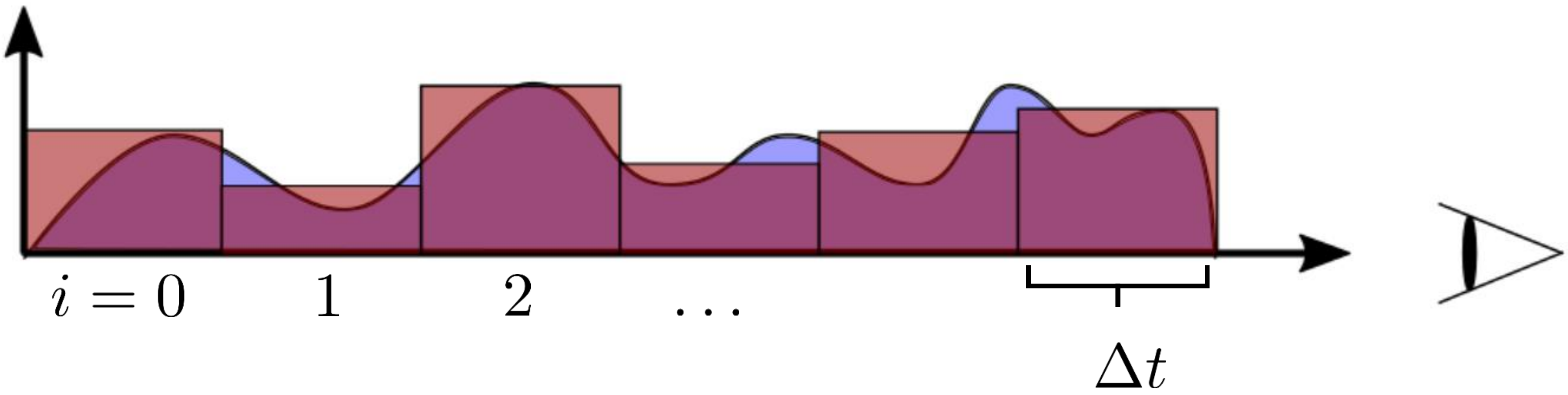
C_i' Radiant energy observed at position i

C_i Radiant energy emitted at position i

$(1 - A_i)$ Absorption at position i

C_{i-1}' Radiant energy emitted at position i-1

Numerical Approximation

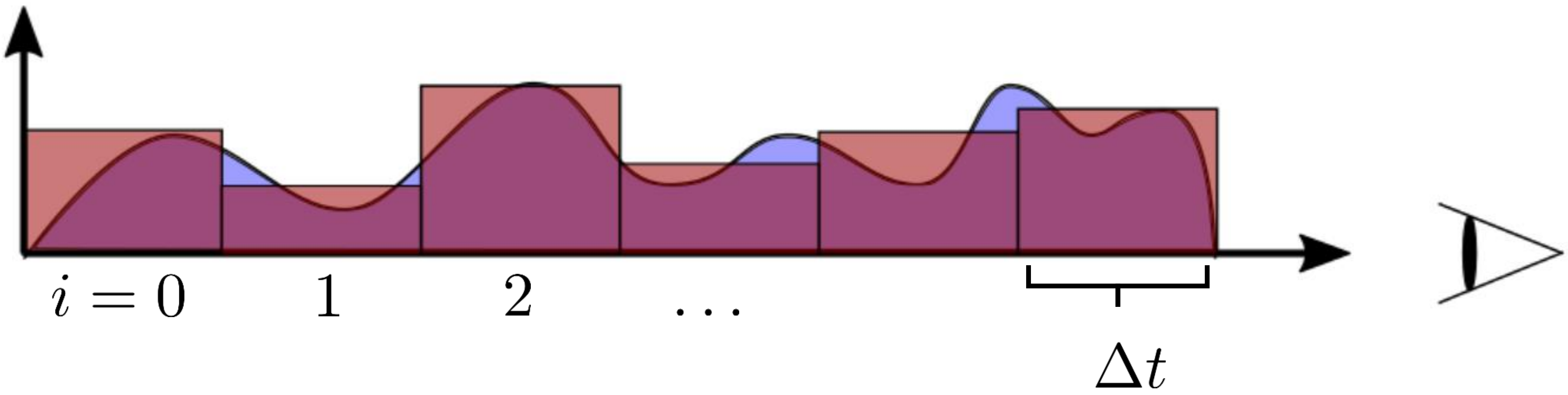


$$C_{out} = C + (1 - \alpha)C_{in}$$

C Color assigned with TF

α Opacity assigned with TF

Numerical Approximation



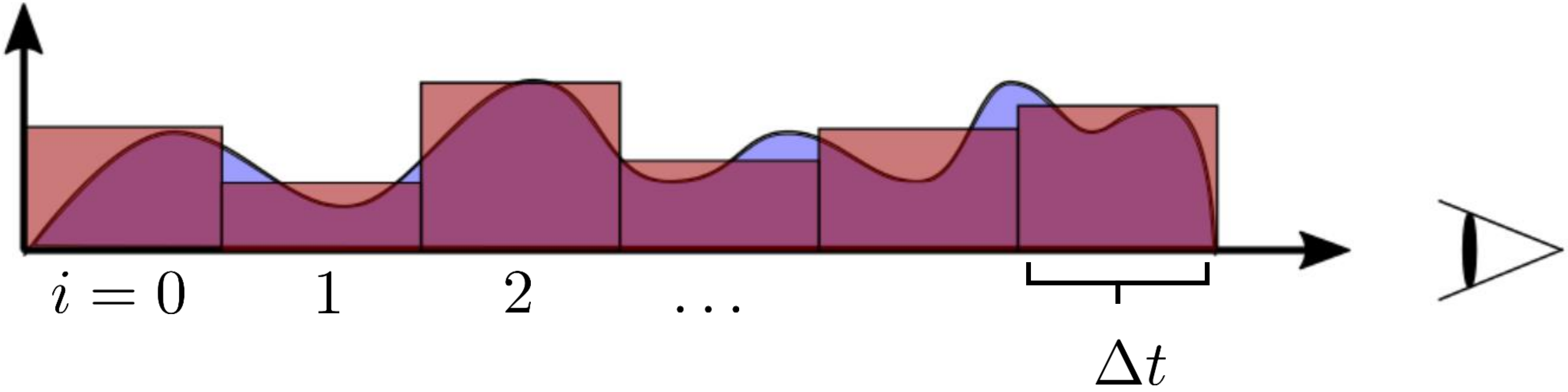
Back-to-front compositing

$$C_{out} = C + (1 - \alpha)C_{in}$$

C Color assigned with TF

α Opacity assigned with TF

Numerical Approximation



$$C_{out} = C_{in} + (1 - \alpha_{in})C$$
$$\alpha_{out} = \alpha_{in} + (1 - \alpha_{in})\alpha$$

Front-to-back compositing
(most often used in ray casting)

Numerical Approximation

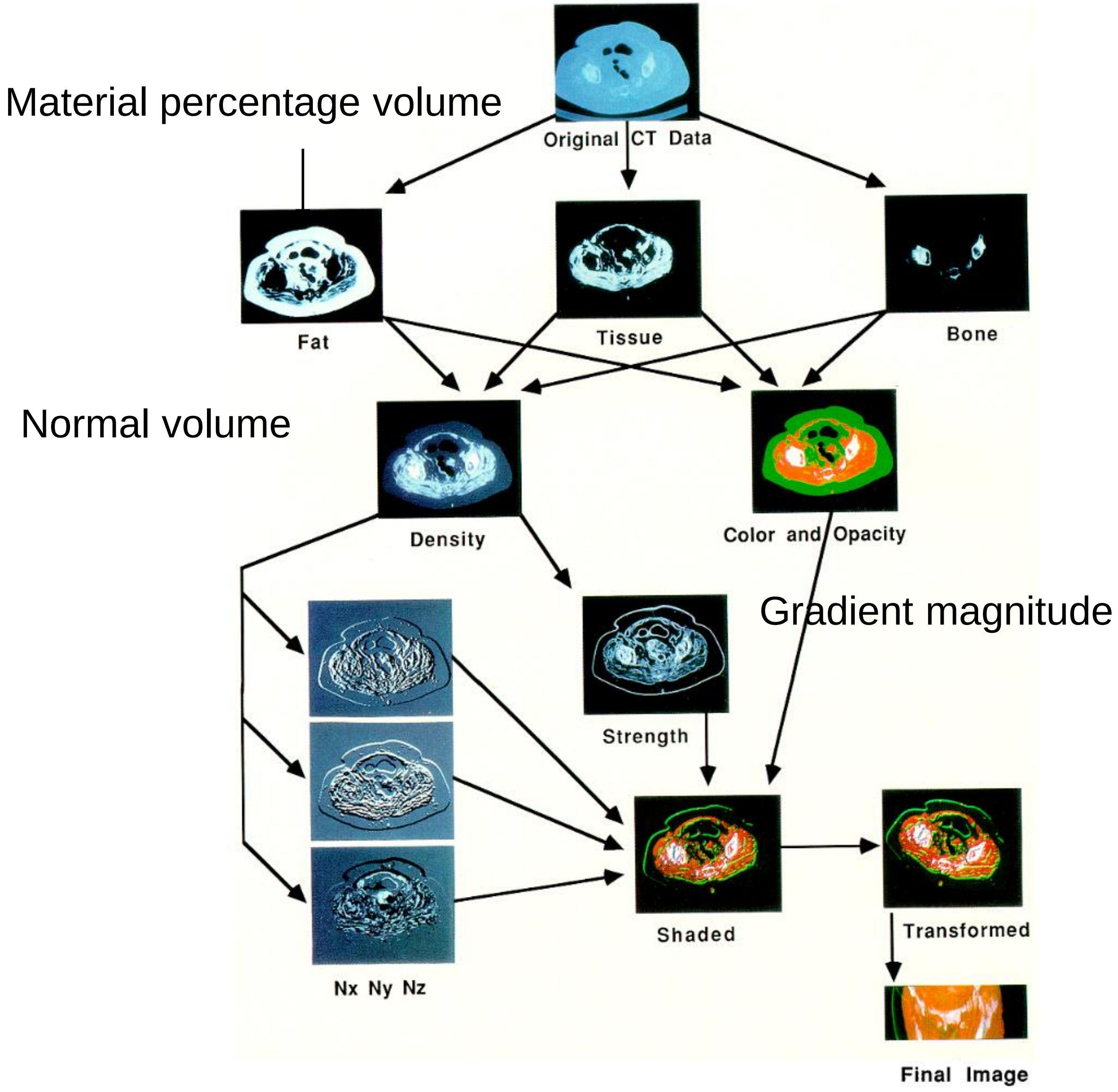
- Note that every color is multiplied by its corresponding opacity:

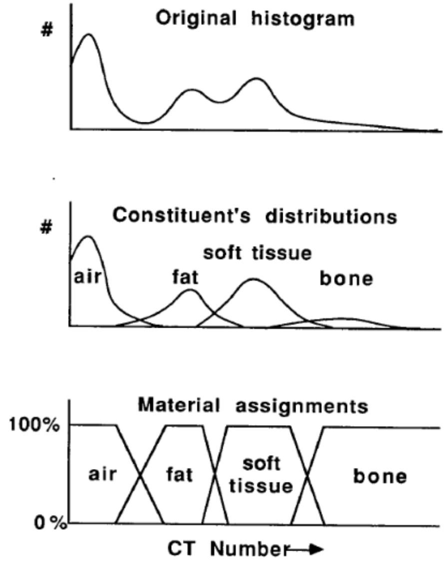
$$(r, g, b, \alpha) \rightarrow (\alpha r, \alpha g, \alpha b, \alpha)$$

Classification and Transfer Functions

- **Ambiguity** of volume data: A certain intensity value in CT or MRI data may represent one tissue type or a mixture of tissue types in the boundary region (partial volume effect).
- The correct visualization requires to resolve this ambiguity (Drebin, 1988).
- Ideally, volume data is transformed in a *material percentage volume* representing for each voxel to which materials it belongs (with a certain percentage).
- **Prerequisite**:
  - A priori knowledge of material types and their intensity range

Classification and Transfer Functions

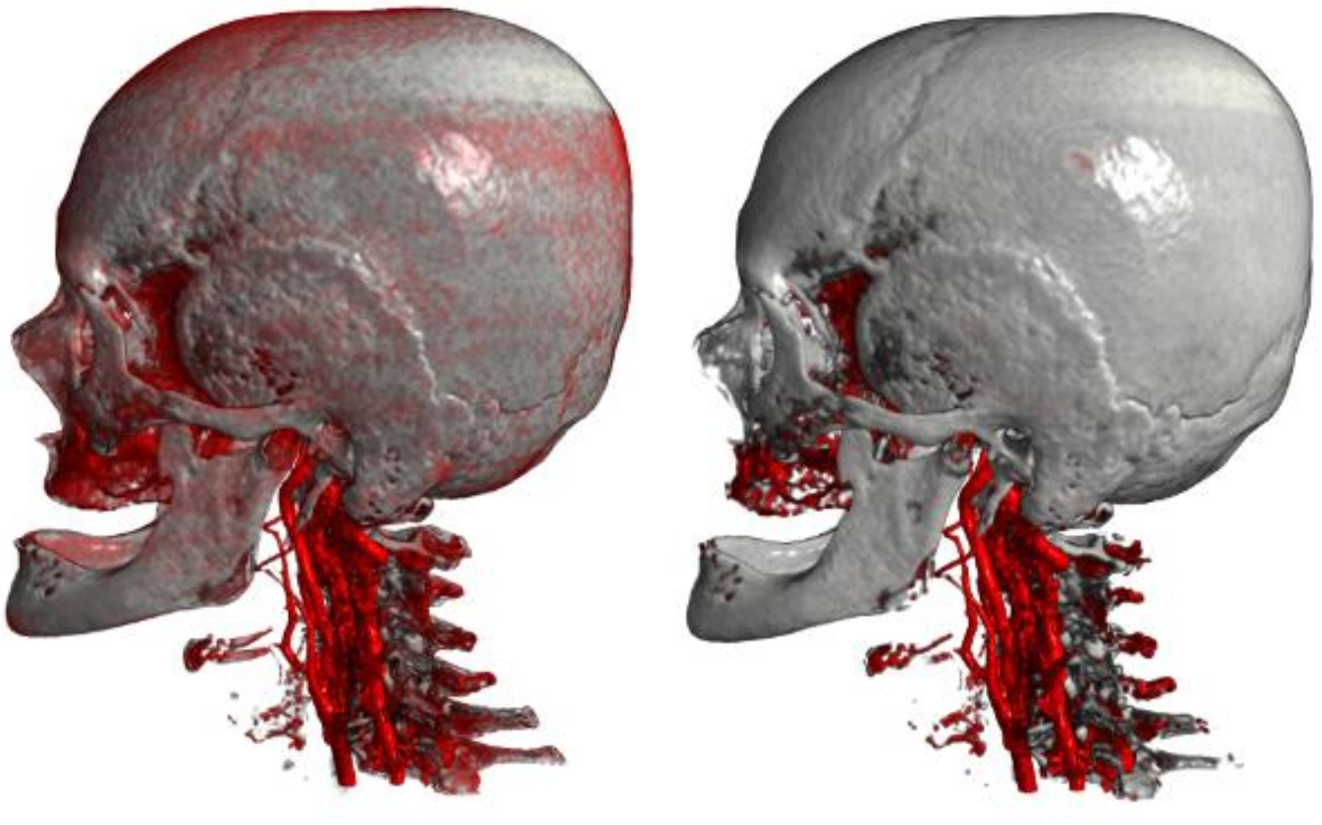




- Volume data modelled as a mixture model of four components.
- Percentages are determined linearly between two tissue types.
- The TF considers intensity values and material percentage data (Drebin, 1988).

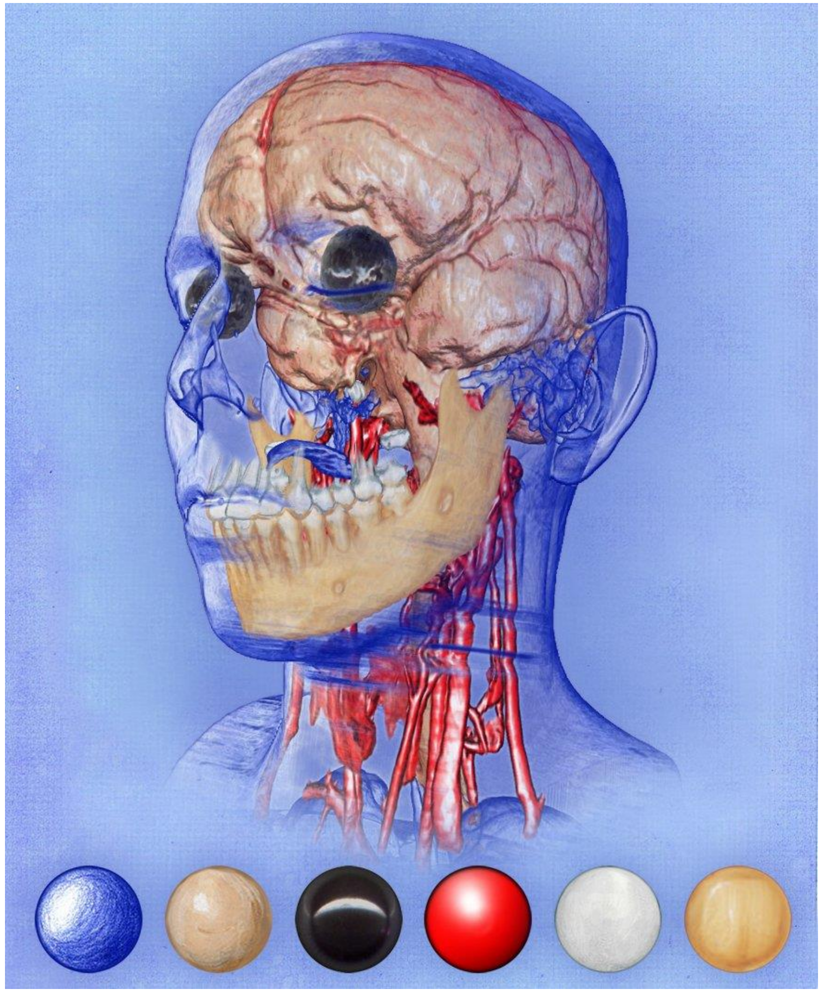
Classification and Transfer Functions

- **Boundary-aware volume reconstruction**. Without knowledge of materials and boundaries, the data is treated as continuous and reconstructed erroneously (left). Interpolation needs to be restricted to voxels within one tissue type and prevented between them (right) (Lindholm, 2014)



Materials

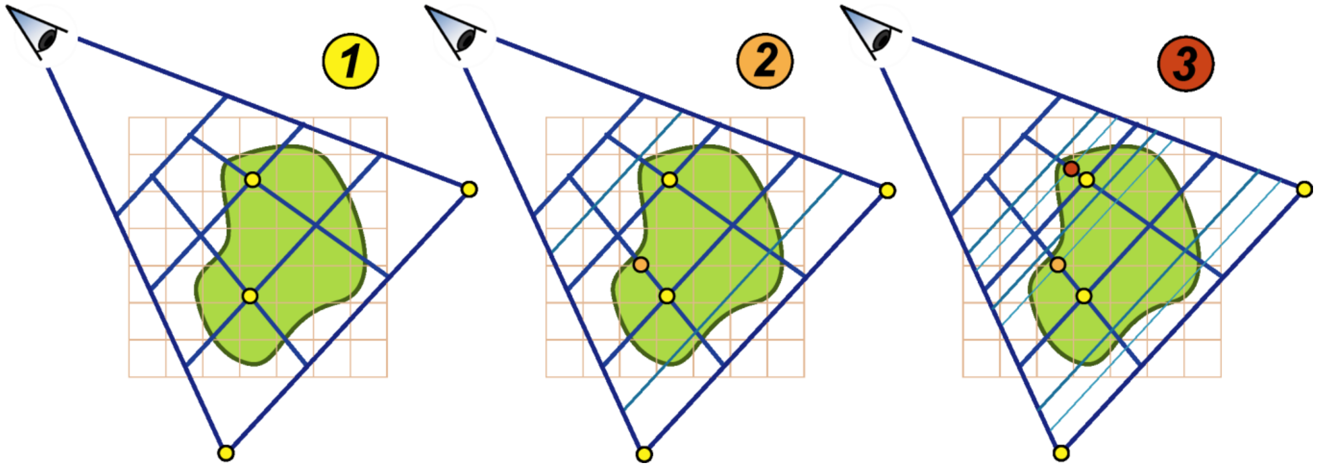
- Additional per-object shading variation is possible
  - Here, materials are encoded per "lit-spheres“
  - (Illumination is discussed in the next lecture)



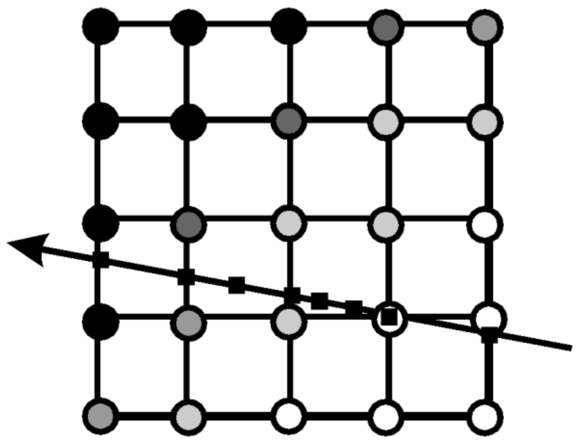
[Bruckner2007]

Acceleration Methods

- Early ray termination (e.g., in case of 95% opacity) (Levoy [1990])
- Adaptive ray sampling (sampling rate in strongly transparent areas, or increase in case of higher distance) (Danskin, Hanrahan [1992])
- Hitpoint refinement (binary search of intersection point for iso-surfaces) (Hadwiger, 2005)



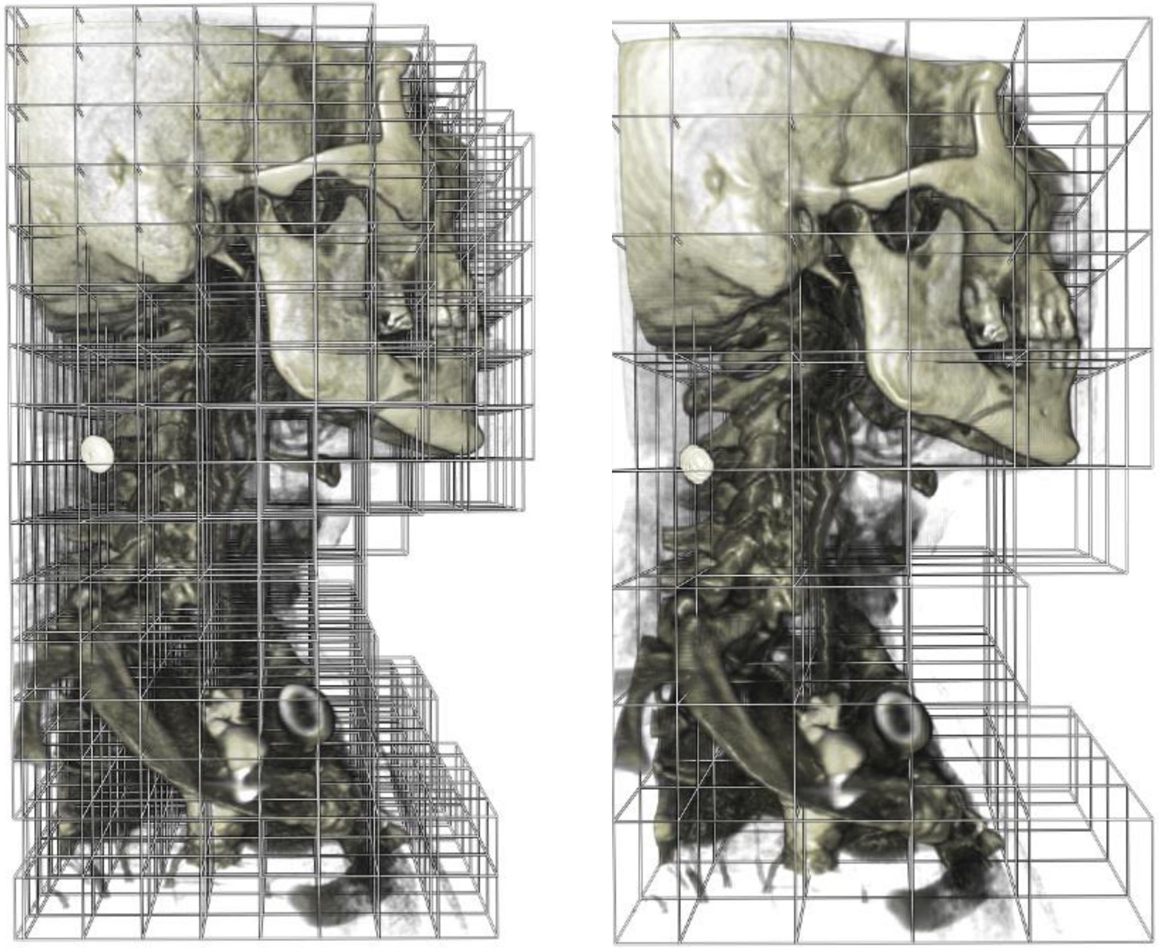
Binary search by dividing the step sizes [Hadwiger, 2005]



Adaptive ray sampling

Octree

- Two different octree-levels (64x64x64 and 32x32x32



(Source: Florian Link, Fraunhofer MEVIS)

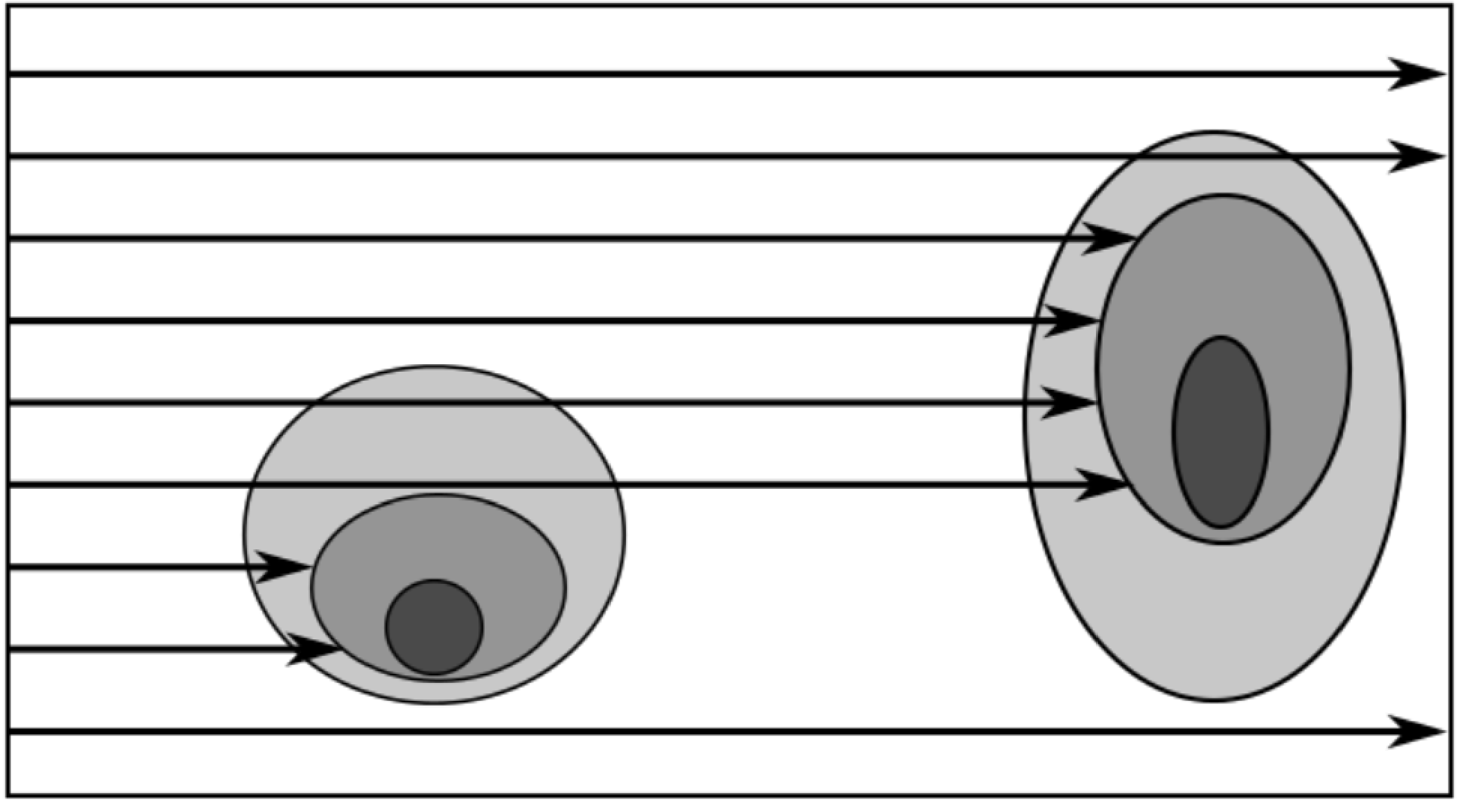
Projection Methods

Projection Methods

First Hit	First voxel	Illustration of surface
Closest Vessel Projection (CVP)	Per ray: first local maximum above a threshold value	Illustration of Vessels
Maximum (minimum) Intensity Projection (M(m)IP)	Per ray: brightest (darkest) hit voxel	Illustration of vessels, noisy data
Average Projection	Per ray: average of all hit voxels	Simulation of X-ray projections

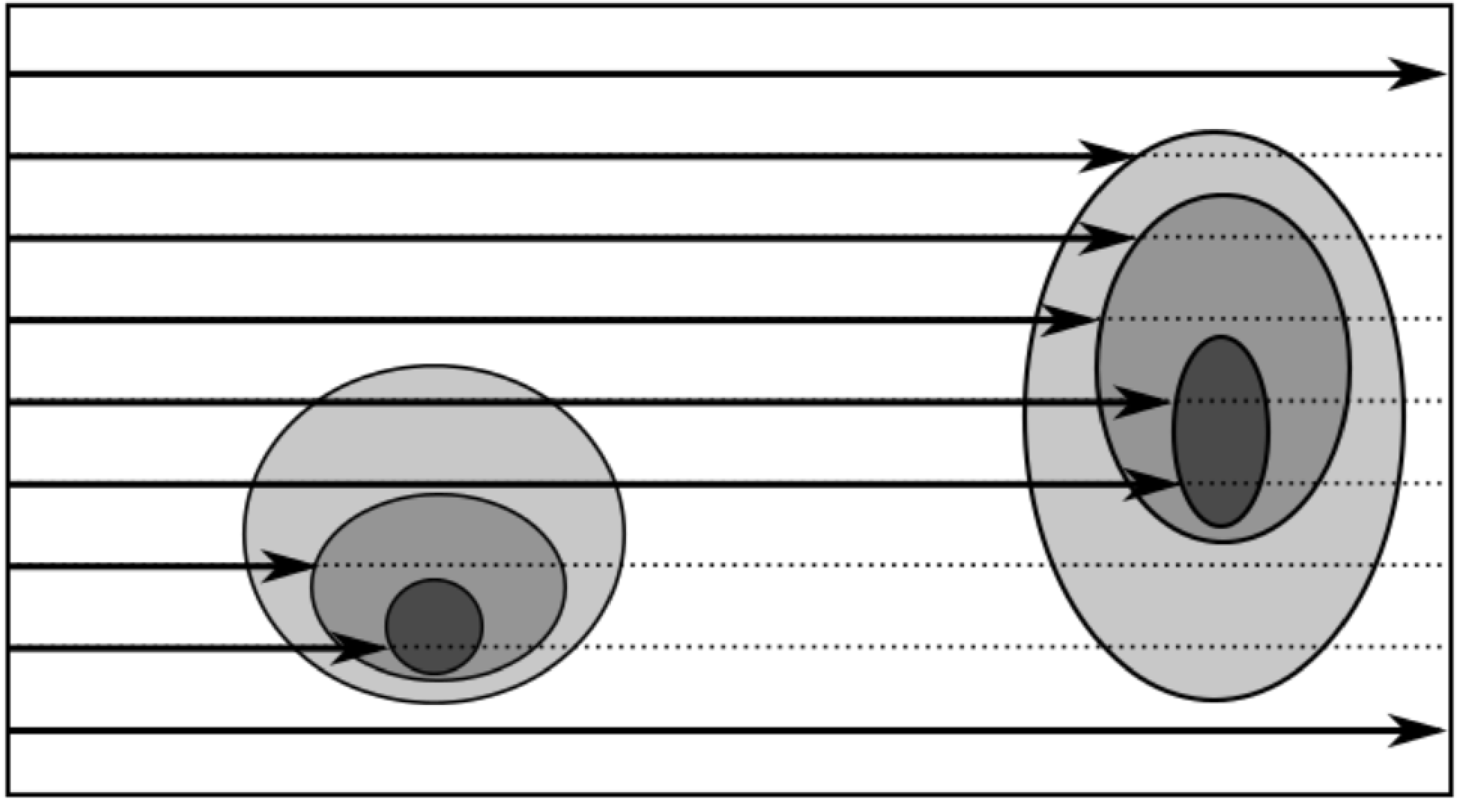
First Hit/Closest Vessel Projection

- CVP: first local maximum above a threshold value (terminate after)
- First Hit: threshold = 0



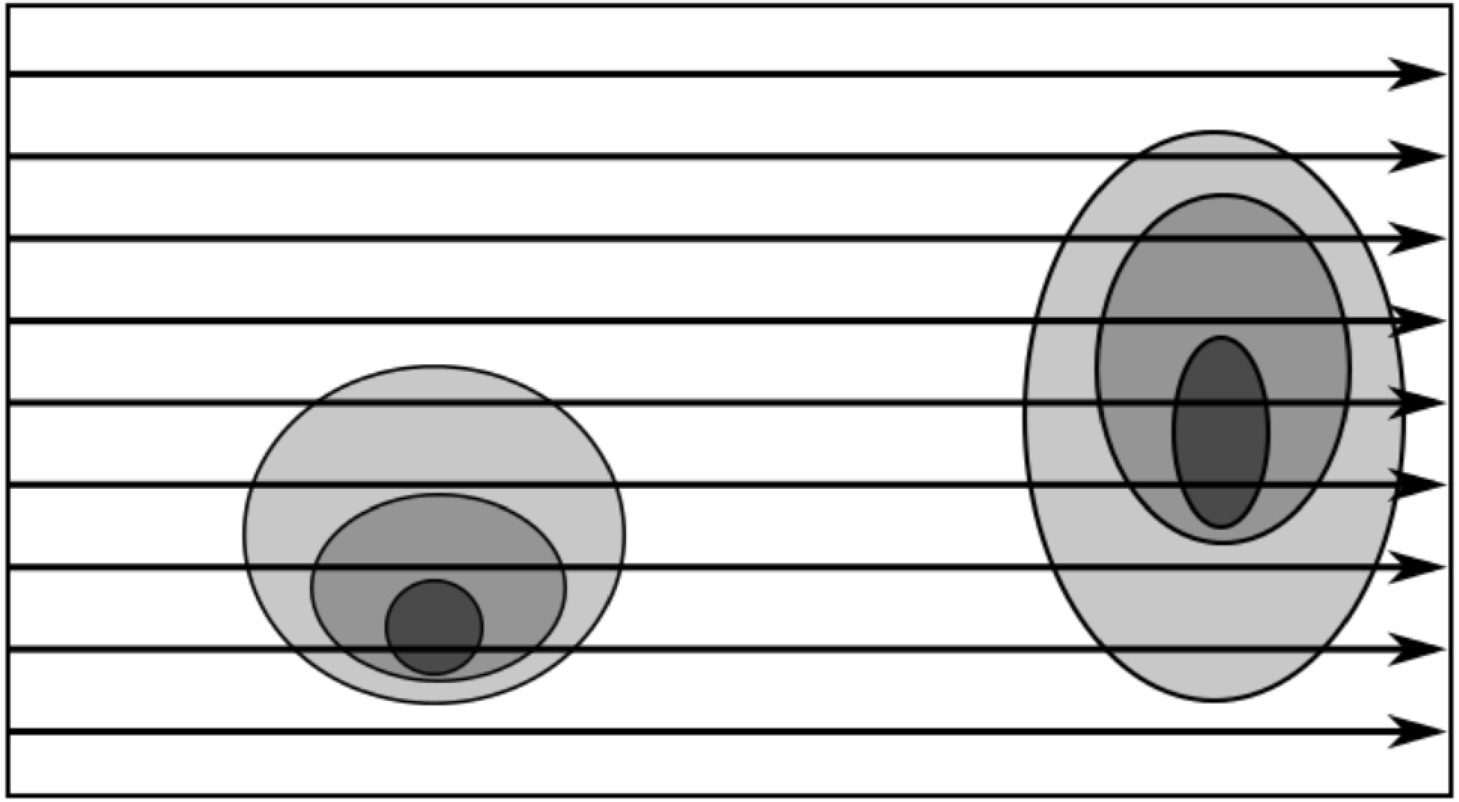
Maximum (minimum) Intensity Projection

- Per ray: brightest (darkest) hit voxel

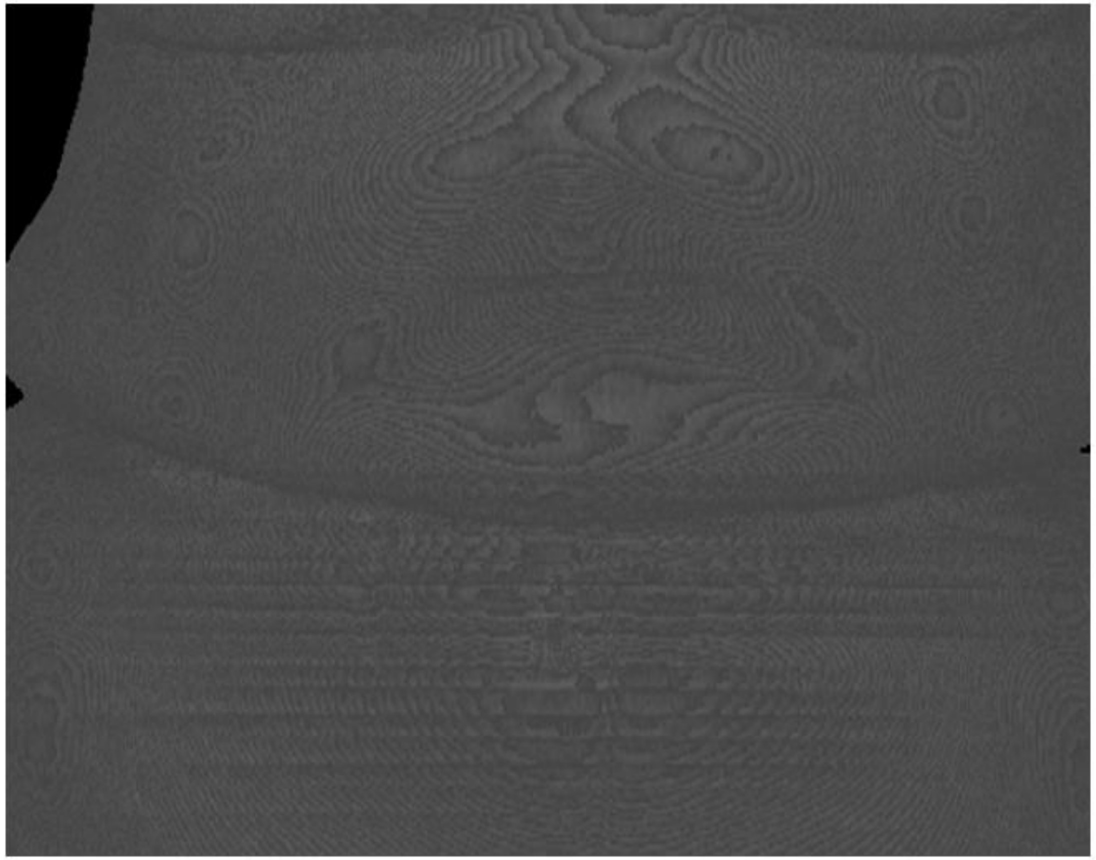


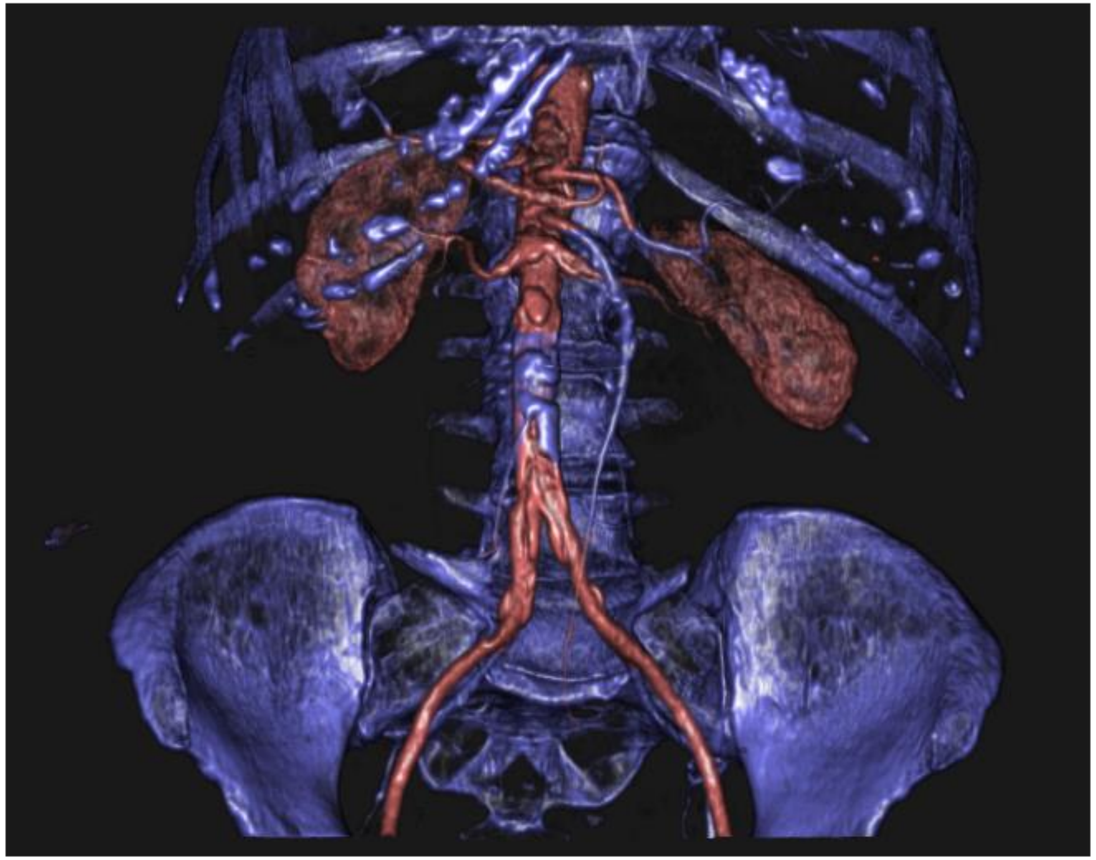
Average Projection

- Per ray: average of all hit voxels



First Hit/Closest Vessel Projection





(From: Gabriel Mistelbauer, Slides)

Maximum Intensity Projection

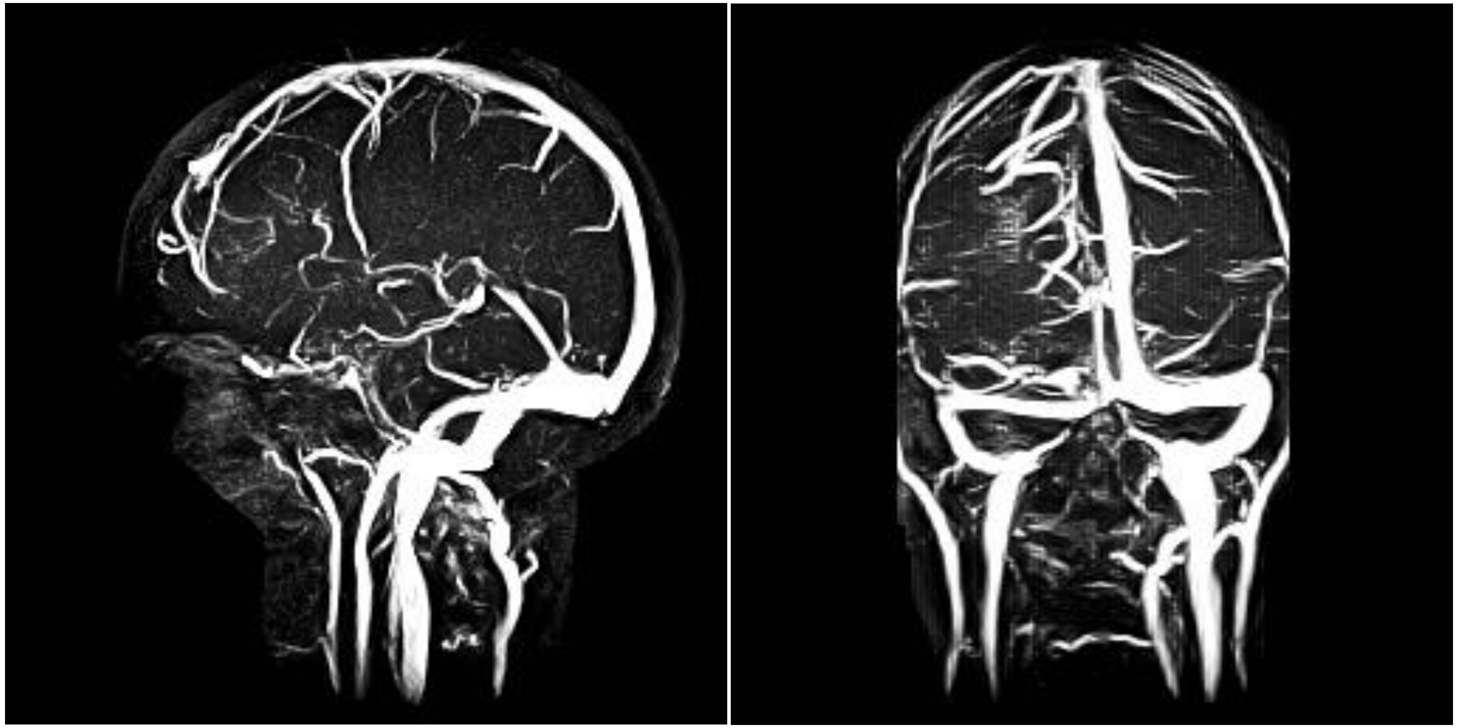
- MIP Applications
- Original application: Nuclear medicine (highest activity is most interesting) (Wallis, 1989)
- Current applications:
  - Search for lung nodules in CT data
  - Vessel visualization

Maximum Intensity Projection

(From: Gabriel Mistelbauer, Slides)

Maximum Intensity Projection

- MIP (data: MR angiography).
- The low spatial perception is in practice improved by interaction (rotation) and/or the use of animated movements.



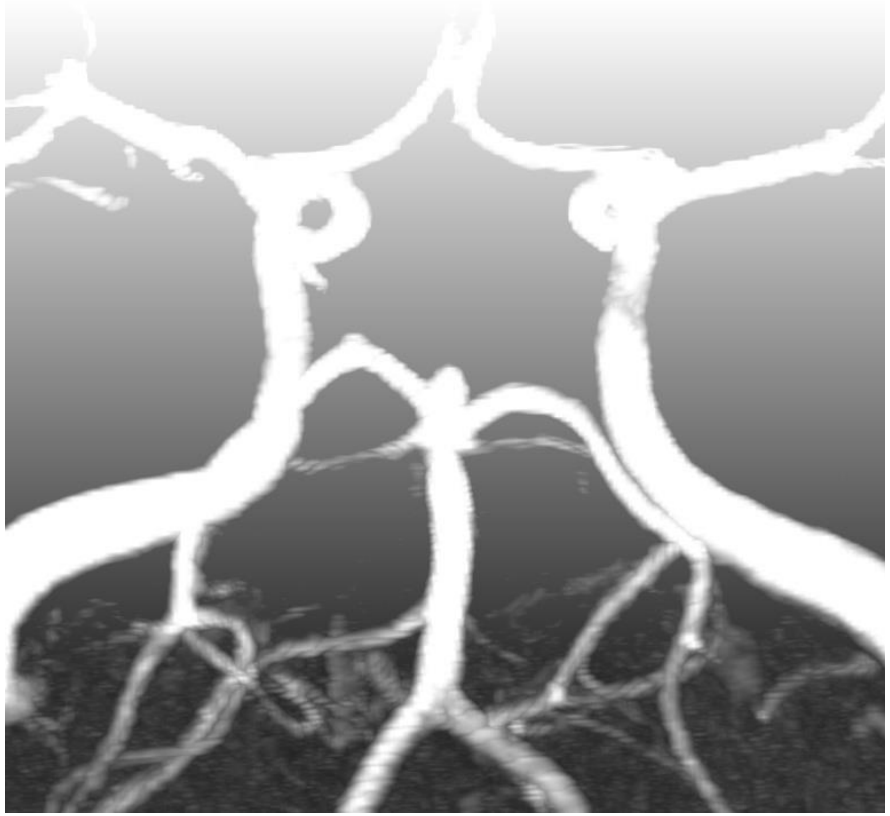
Projection Methods

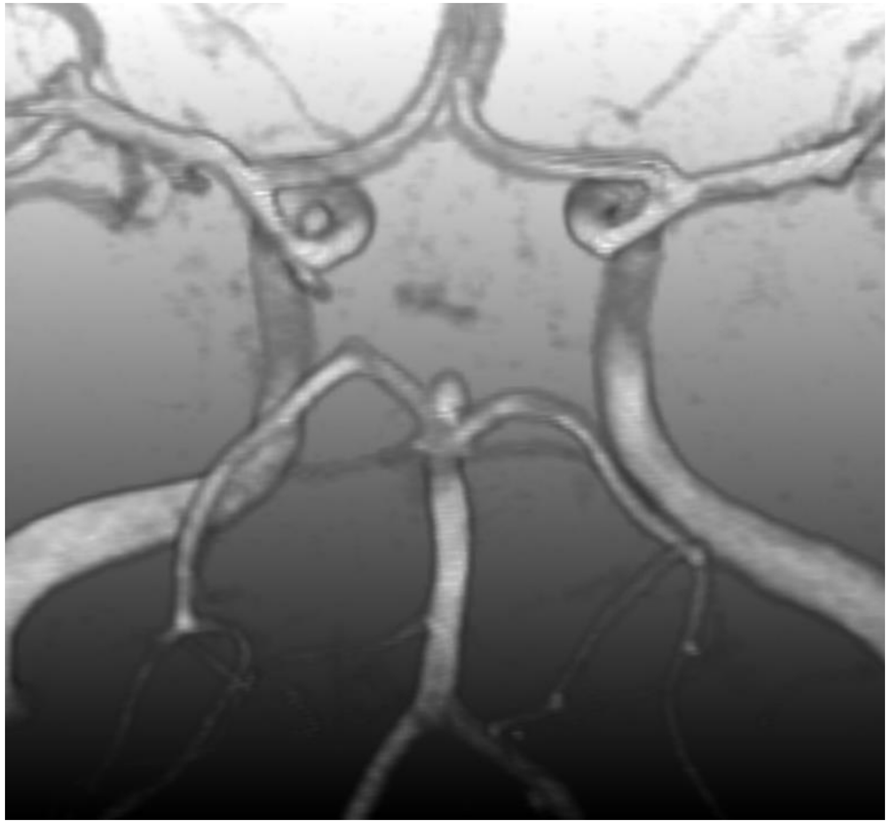
- Projection methods require *no* opacity transfer function.
- Transfer functions *can* be used with projection methods (e.g., adjustment of a transfer function that depicts bones fully transparent, and consideration of transparency during application of MIP).
- **Combination of MIP and DVR**: Weighted overlapping of the voxels resulting from MIP and DVR (continuum between MIP and DVR).

Projection Methods

- Comparison of MIP and DVR of cerebral vessels

(Data: MR Angiography, Prof. Terwey, Bremen)



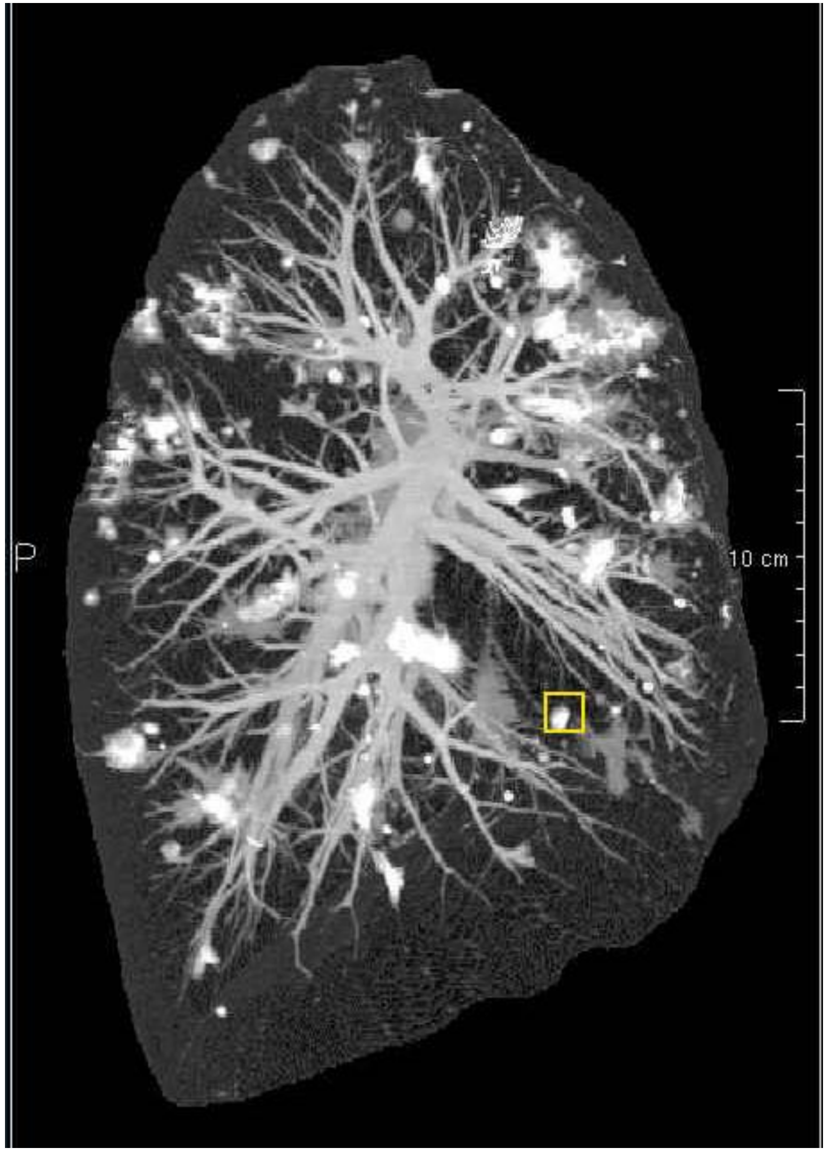


Projection Methods

- Advanced MIP concepts:
  - (1) Remove structures that disturb the MIP interpretation.
    - » Example: Removal of bones (interactively through region growing and placing a seed point)
  - (2) Apply the MIP to a certain partial volume.
    - » Example: MIP visualization in a segmented organ for targeted assessment of this organ

Projection Methods

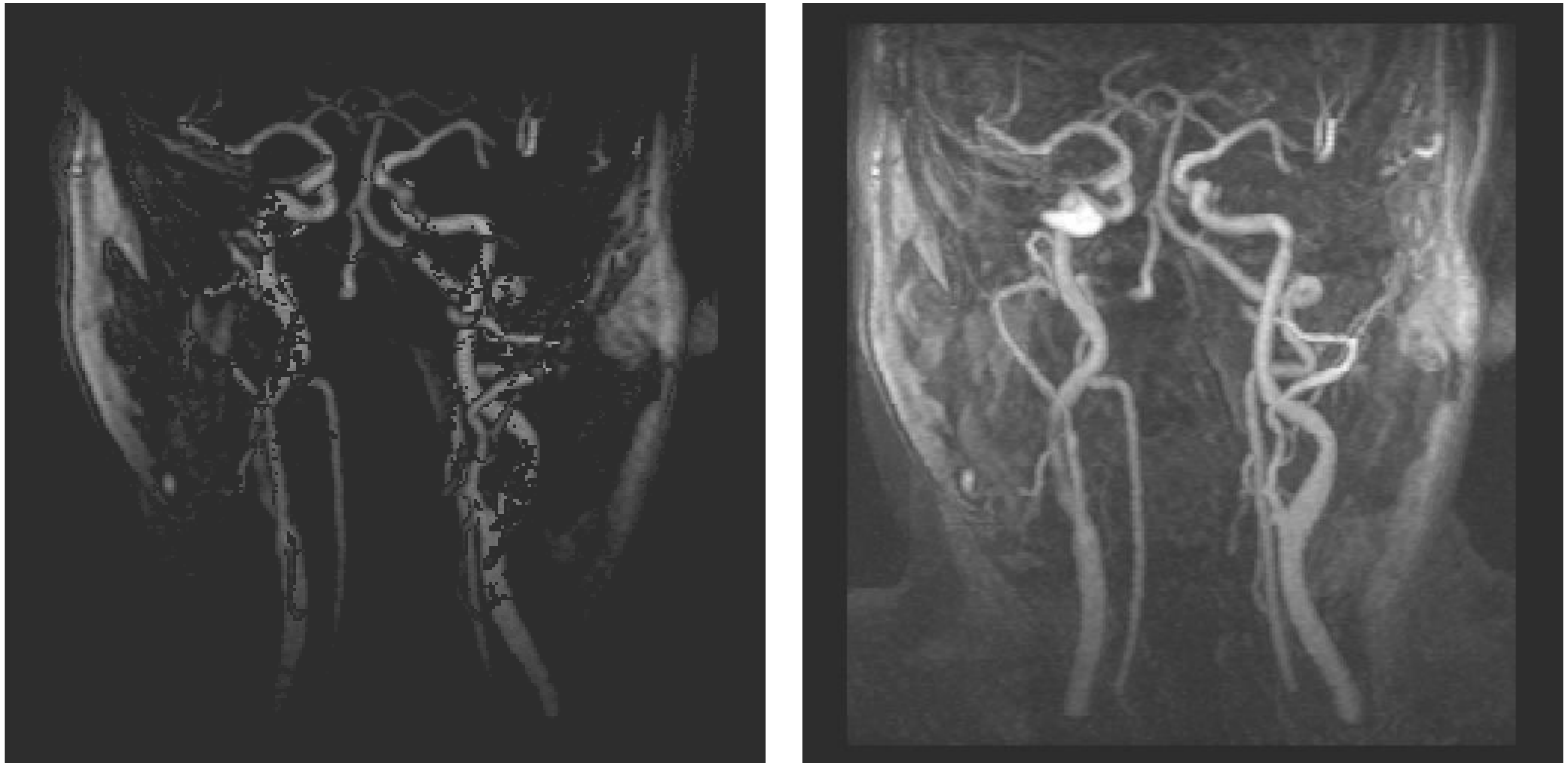
- MIP visualization of a segmented lung
- Tumors at the lung boundary become visible



(Source: Dicken et al., BVM 2003, Data: Prof. Günther)

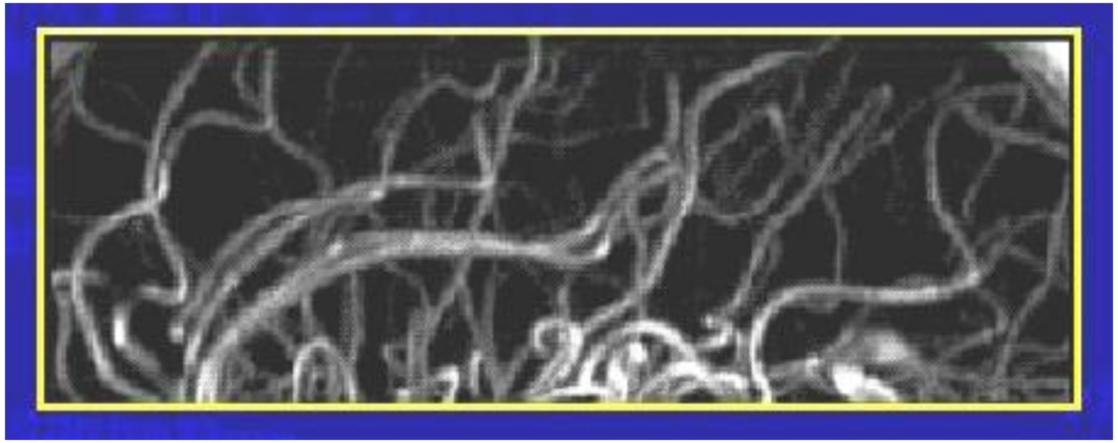
Projection Methods

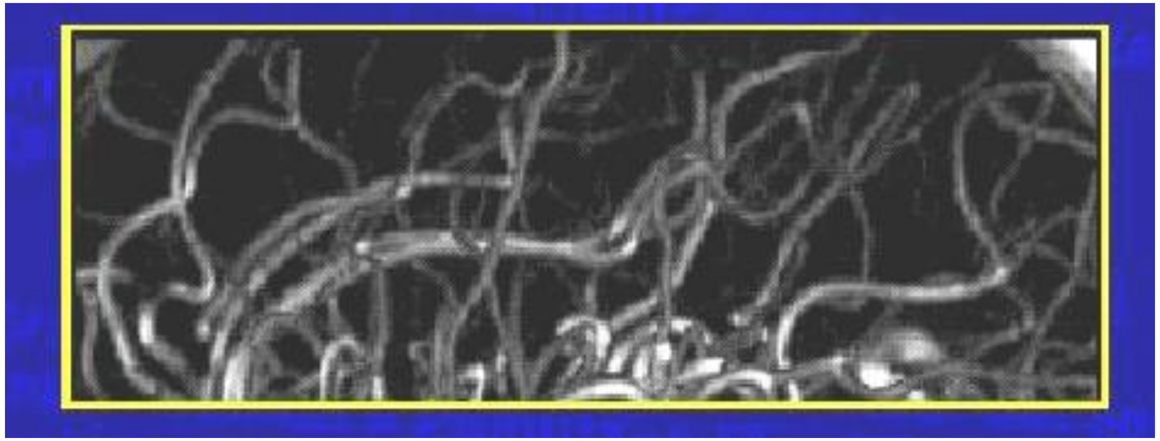
- Comparison of MIP and CVP (data: MR angiography)
- Difficulty when applying CVP: selection of a suitable threshold value



Projection Methods

- MIP and CVP of brain vessels (© Karel Zuiderveld)
- Often, movies with MIP and CVP rotations in a central perspective are used for assessment of spatial relations.



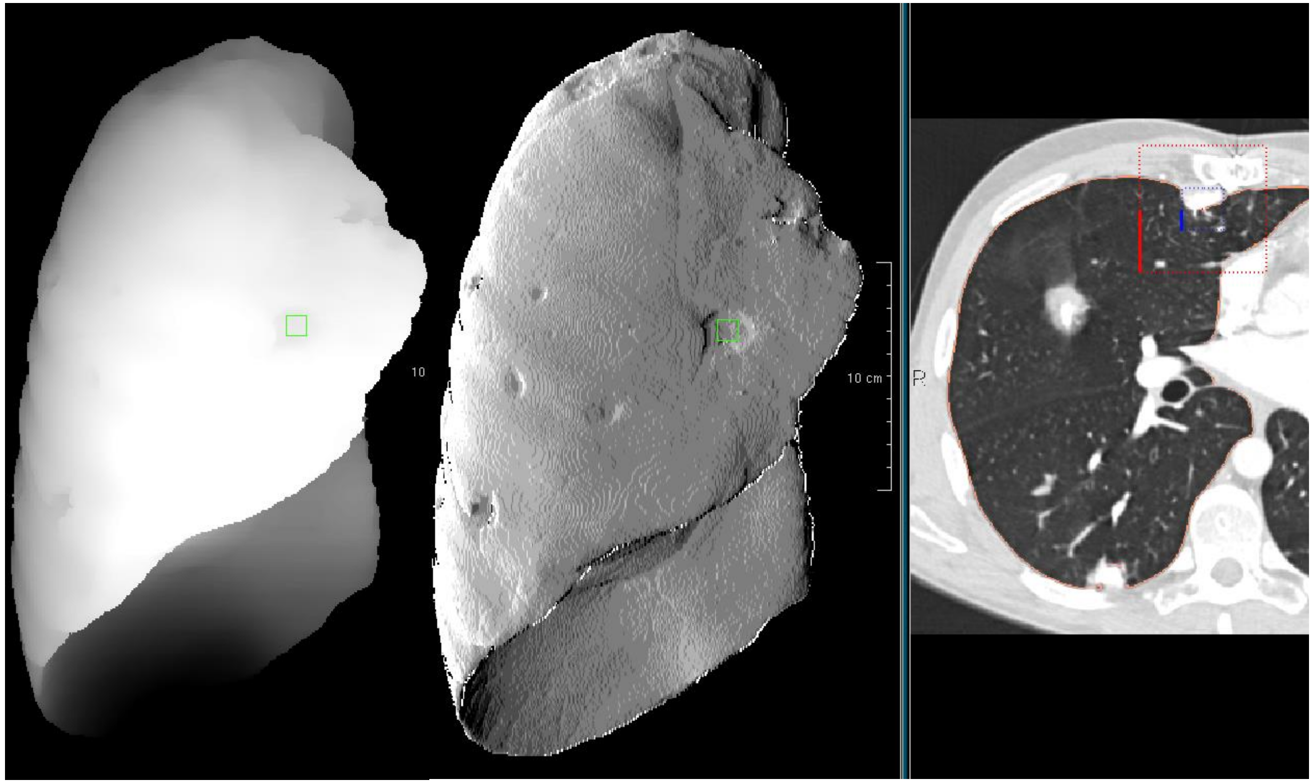


Projection Methods

- Distance maps: Illustration of the projection of a segmented surface. The brightness encodes the distance to the viewer.
- Option: Gradient filtering for accentuation of surface-near bumps.
- Combined views: For diagnosis, a synchronization with the view of (familiar) tomographic images is essential.

Projection Methods

- Distance map of a segmented lung. Right: Gradient-filtered
- Distance image (Roberts-Cross Operator) and tomographic image display



(Source: Dicken et al., BVM 2003, Data: Prof. Günther (RWTH Aachen))

Maximum Intensity Difference Accumulation (MIDA)

- Classify local maximum change of intensity

$$\delta_i = \begin{cases} I(i) - I_{max}(i) & \text{if } I(i) > I_{max}(i) \\ 0 & \text{otherwise} \end{cases}$$

$$\beta_i = \begin{cases} 1 - \delta_i \cdot (1+\gamma) & \text{if } \gamma \leq 0 \\ 1 - \delta_i & \text{otherwise} \end{cases}$$

$$C_{out} = \beta_i C_{in} + (1 - \beta_i \alpha_{in}) C$$

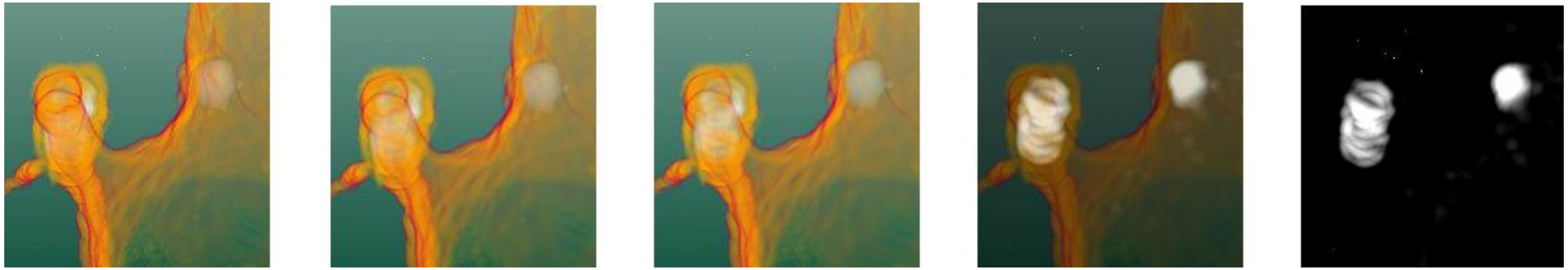
$$\alpha_{out} = \beta_i \alpha_{in} + (1 - \beta_i \alpha_{in}) \alpha$$

$$\gamma \begin{cases} \text{DVR} & \text{-> -1} \\ \text{MIDA} & \text{-> 0} \\ \text{MIP} & \text{-> 1} \end{cases}$$

If $\gamma > 0$ interpolation between MIDA and MIP

Projection Methods

- Maximum Intensity Difference Accumulation (MIDA)
  - Hybrid approach between MIP and standard alpha compositing
  - Alpha value is changed, such that large opacity jumps are additionally highlighted (although they would otherwise be occluded)
  - Control value enables smooth transition from classical DVR compositing to MIDA to MIP

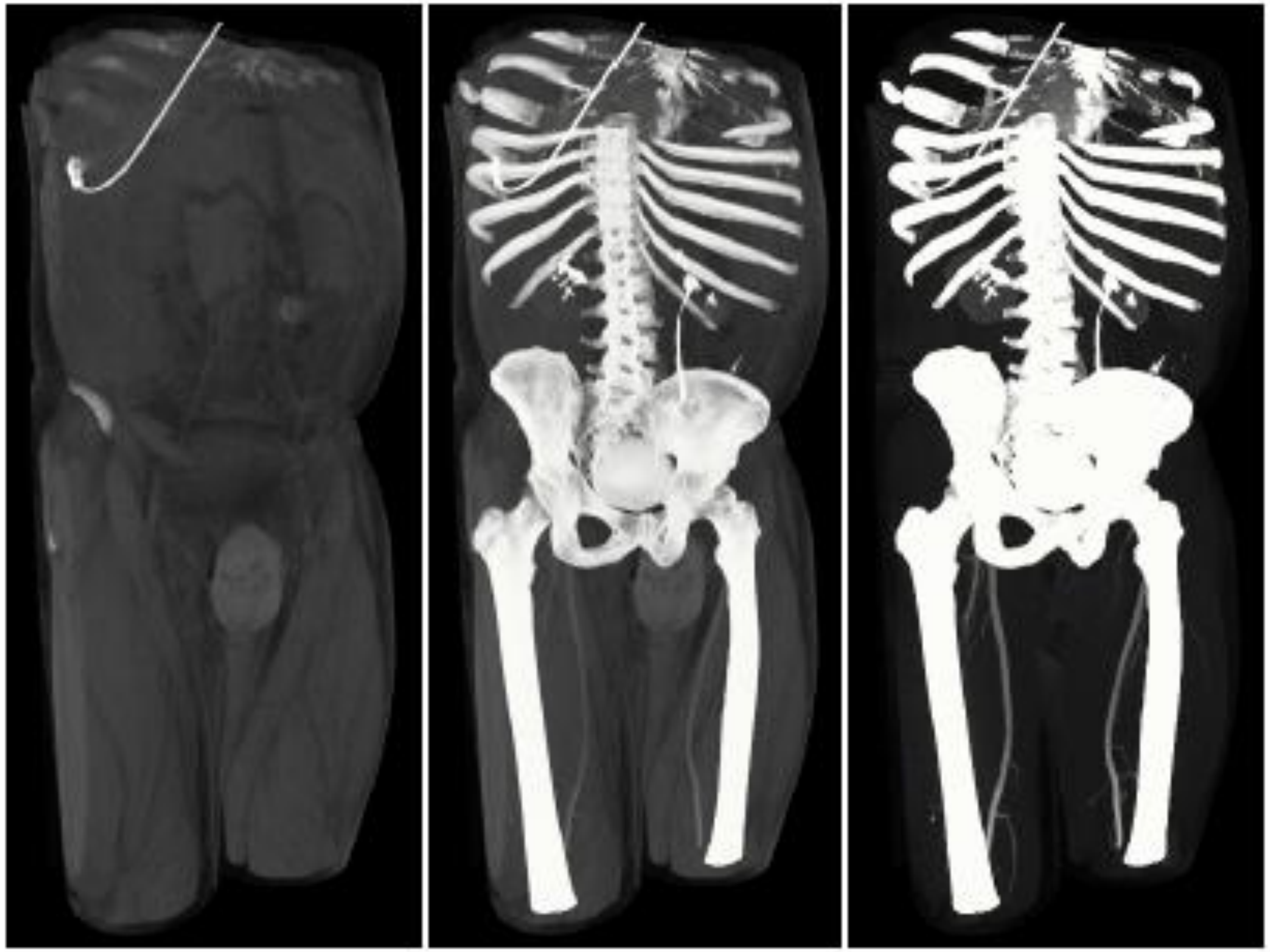


[From: Kubisch, 2012]

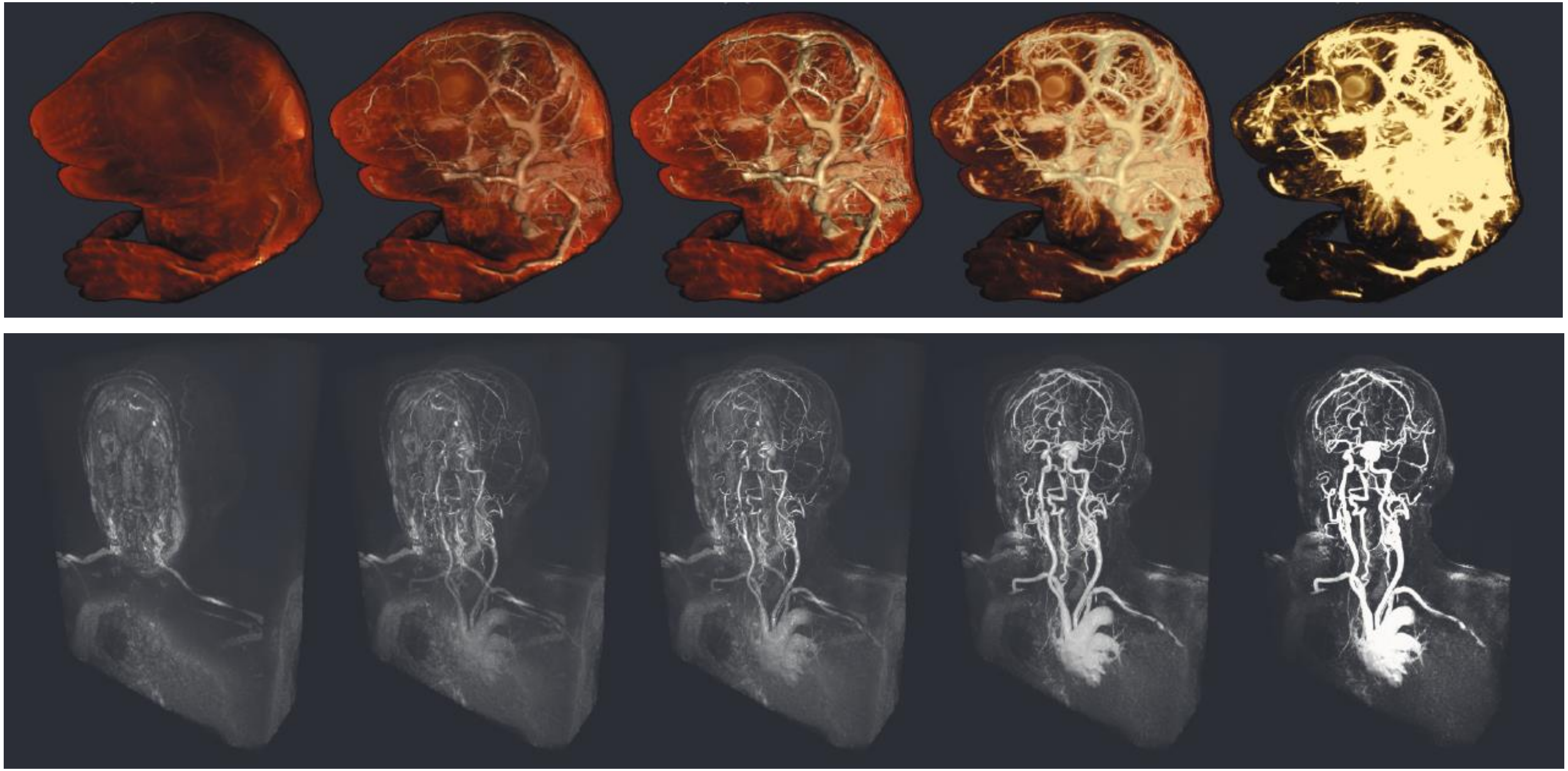
Projection Methods

Comparison of DVR, MIDA, MIP (from left to right)

Courtesy of Stefan Bruckner (University of Bergen)



Projection Methods

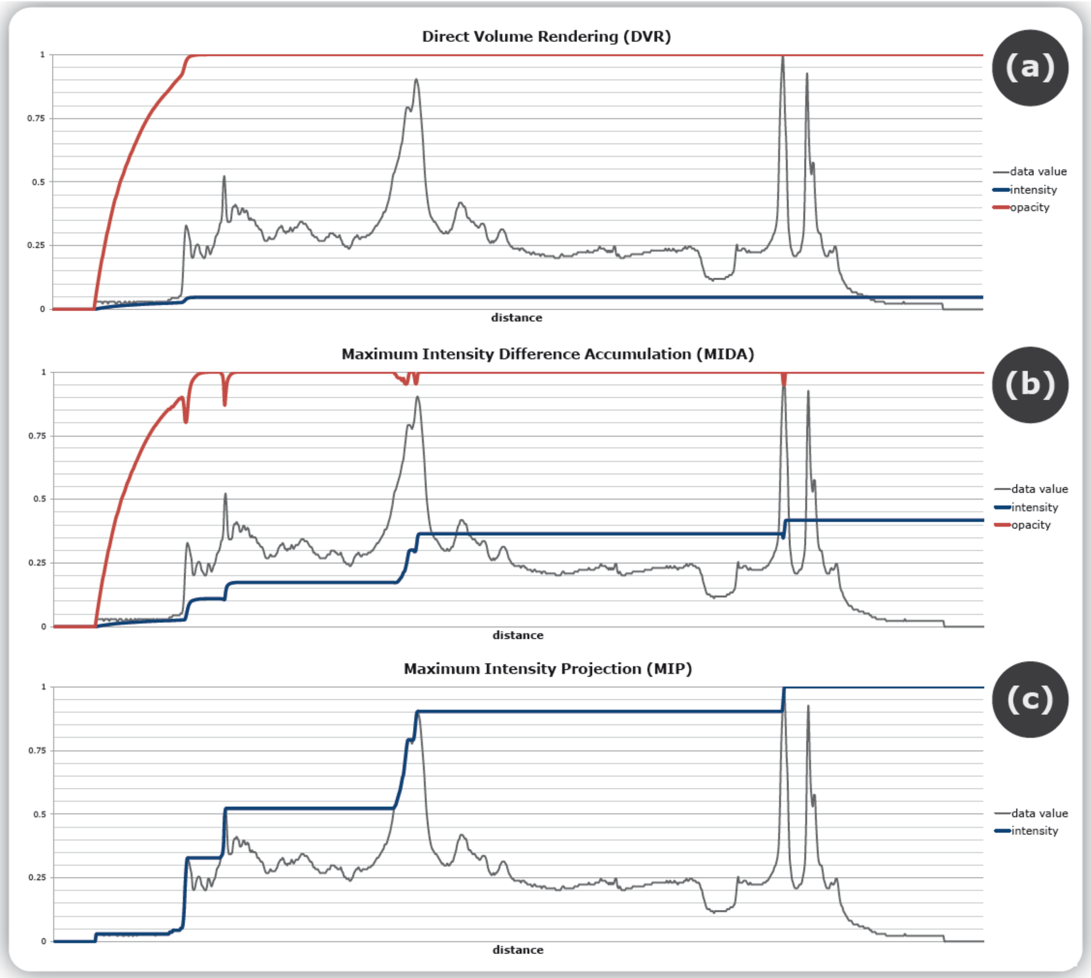


Comparison of DVR, MIDA, MIP (from left to right)

Courtesy of Stefan Bruckner (University of Bergen)

Projection Methods

- A ray profile is evaluated according to DVR (a), MIDA (b) and MIP (c). Note, how the opacity (red) reaches high values in DVR early (making boundaries behind the first slices invisible. In (b) opacity is not monotone and by decreasing it boundaries further behind are visible (steps in intensity (grey value)



(From: Bruckner, 2009)

Summary

- Important parameters in terms of quality and calculation effort:
  - Sampling rate in z-direction (i.e., ray step size)
  - Interpolation (nearest neighbor, (tri)linear, (tri)cubic interpolation)
  - Termination of ray tracing in case of a certain cumulative intensity
  - Compromise:
    - » For interactions: reduced resolution (interactive resolution)
    - » For display (printout): high resolution (static resolution)

Summary

- Direct volume visualization of regular data sets
- Projection methods (MIP, CVP, average projection, MIDA)
- Criteria: Efficiency and quality of the image generation

Questions???