Computer- and robot-assisted Surgery

NCT

NATIONALES CENTRUM
FÜR TUMORERKRANKUNGEN
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getragen von:
Deutsches Krebsforschungszentrum
Universitätsklinikum Carl Gustav Carus Dresden
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Helmholtz-Zentrum Dresden-Rossendorf

Visualization

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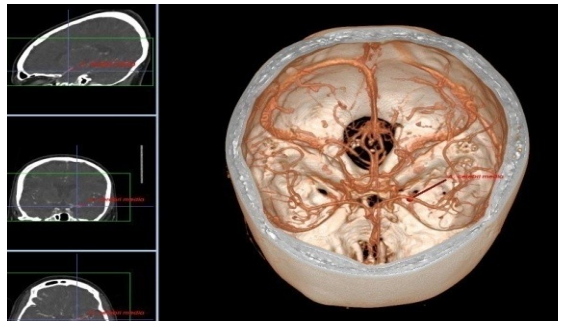
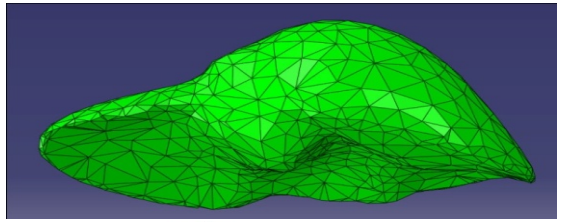
Content

- Visualization methods
  - Geometric
    - Volume models: Ray-Casting
    - Surface models: Marching Cubes, Reconstruction
- Intraoperative Visualization
  - Navigation
  - Augmented/Virtual Reality





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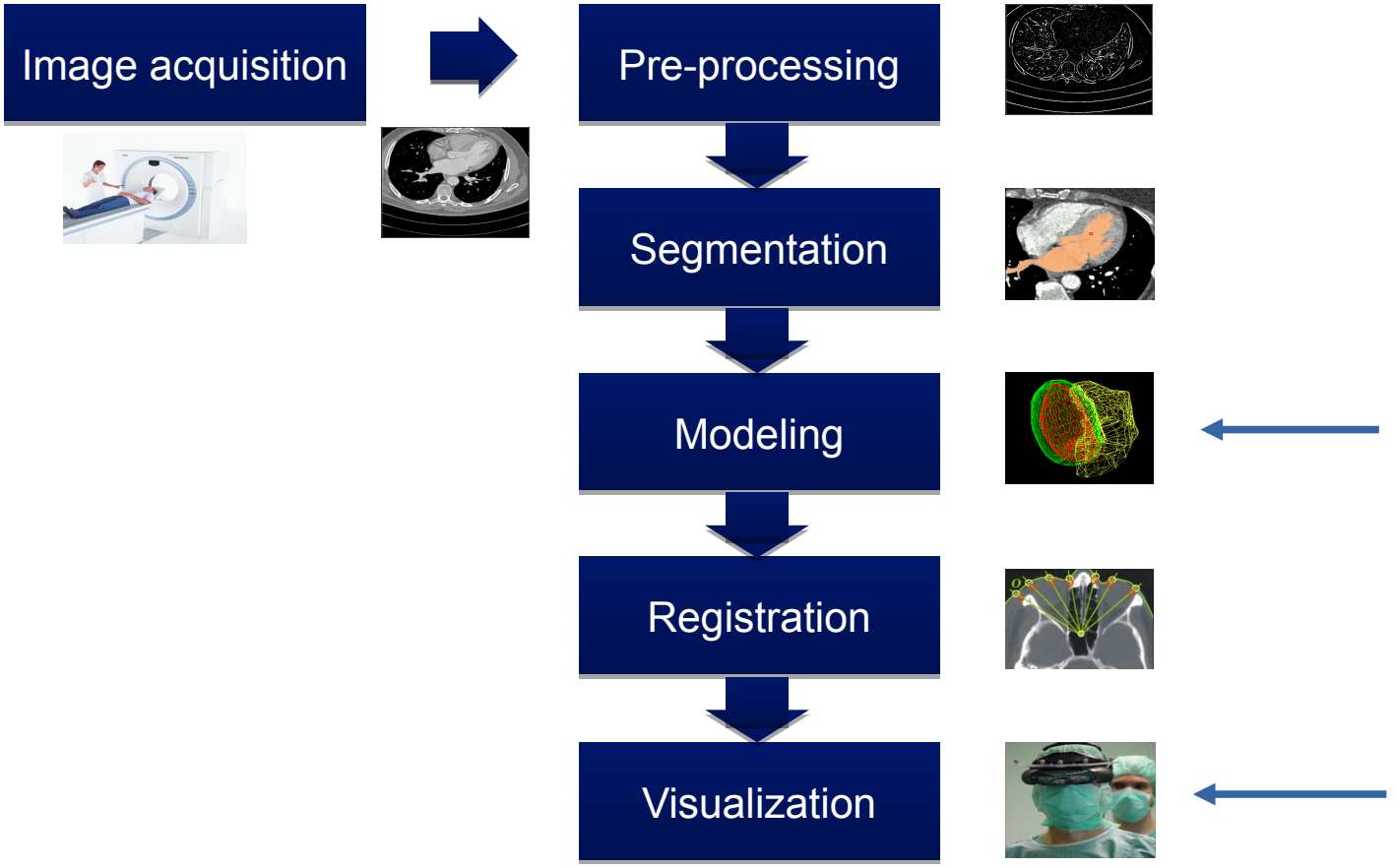
Process chain computer-assisted surgery



Introduction

Visualization in medicine:

- Integration of different data sources
- Data presentation for clinician
- Assistance for diagnosis, for planning, during surgery, for evaluation

Important questions:

- Choice of data source(s)
- Choice of visualization methods
- Choice of visualization device

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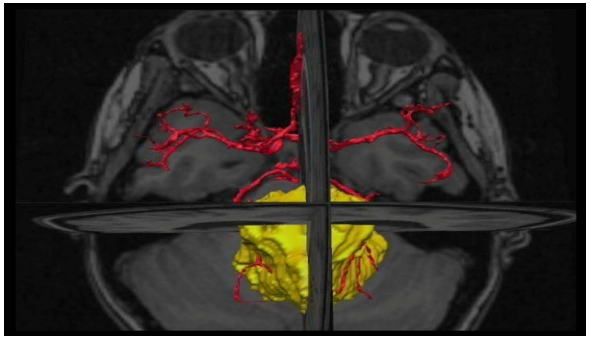
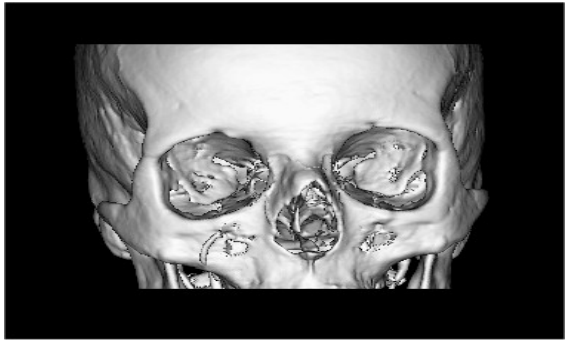
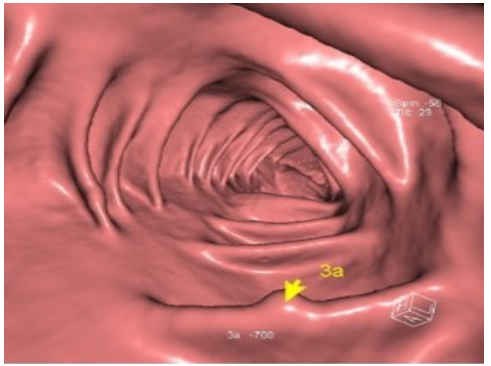
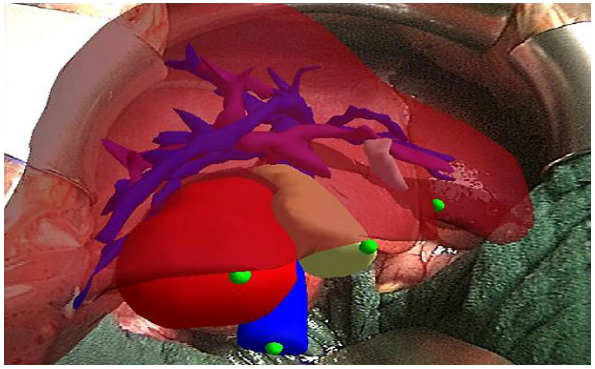
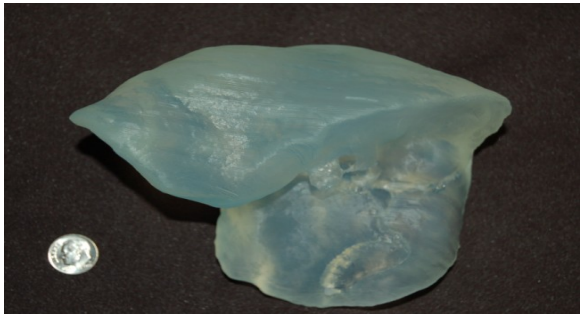
Applications

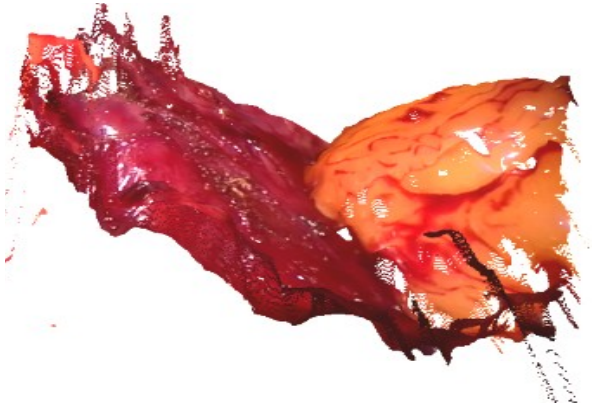












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Data Sources

- Combination of different devices
- Preoperative: X-Ray, CT, MRI, PET, SPECT,..
- Intraoperative: Ultrasound, Endoscope, intraoperative CT/MRI,..
- Knowledge base: medical Atlas, data about surgery, patient, …

PACS: **Picture Archiving and Communication System**, storage and access to images from multiple modalities

DICOM: **Digital Imaging and Communications in Medicine** standard for the communication and management of medical imaging information and related data; integration of PACSand additional systems

Goal: Hospital Digitalization

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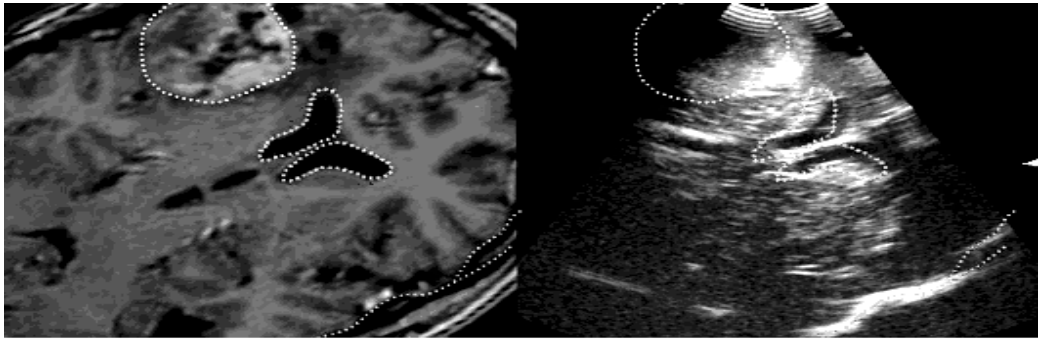
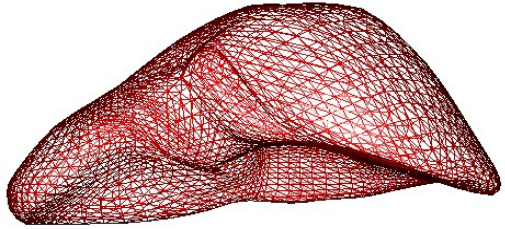
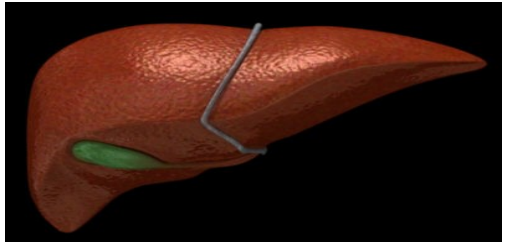
Visualization methods

Question: How should the information be presented?

- Symbols
- Contours
- Segmented 2D area
- Surface models ←
- Volume models ←
- …







- Granularity of information content is crucial for acceptance and value of the visualization

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Geometric Modeling

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Geometric Modeling

- Geometric modeling enhances the spatial understanding
- Model must be suitable for
  - Computing basis for simulation
  - Visualization model
- Models can be divided in
  - Volume models
  - Surface models

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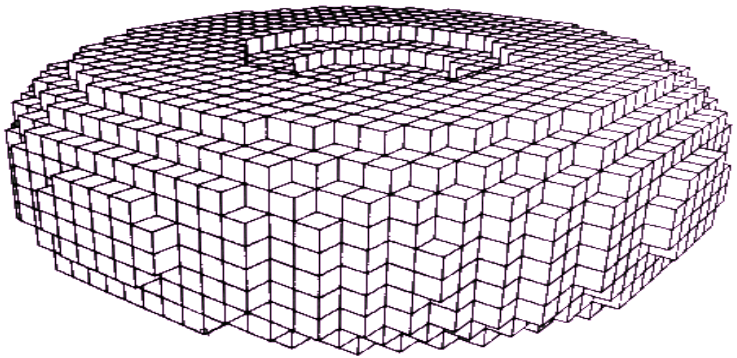
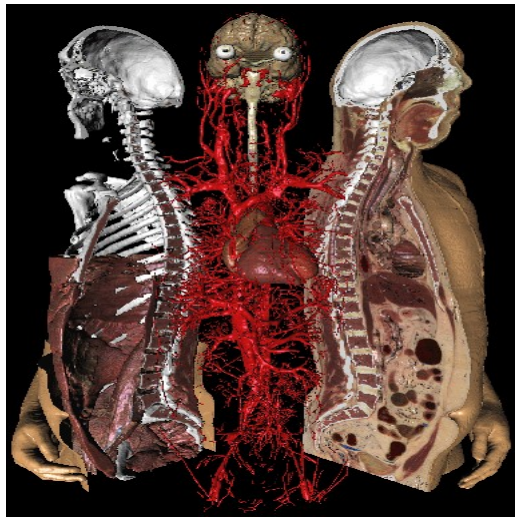
Volume models

Voxel models:

- Based on tomographic imaging data
- Geometric primitives is called „voxel“ (derived from von „pixel“), a single volume element



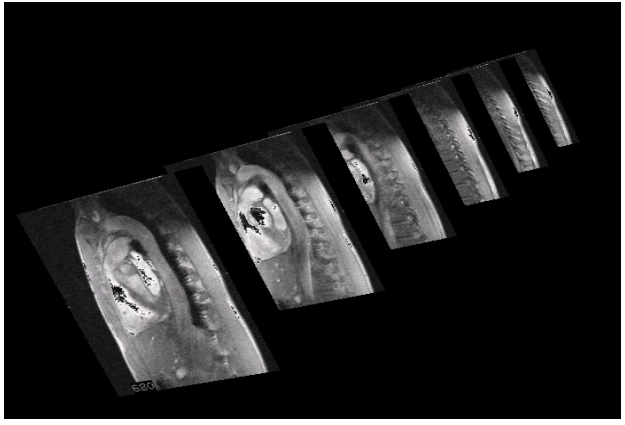


Quelle: MEET MAN, Dössel et al.

Image -> Model

- Image slices can be put on top of each other and form the data volume
- Typical CT-Scan has a resolution of 0,3 x 0,3 x 0,5 mm
  - Voxels are not necessarily cubes

- Due to the z-distance the image appears compressed
  - Enable scale factor in visualization
  - But attention regarding distance calculations



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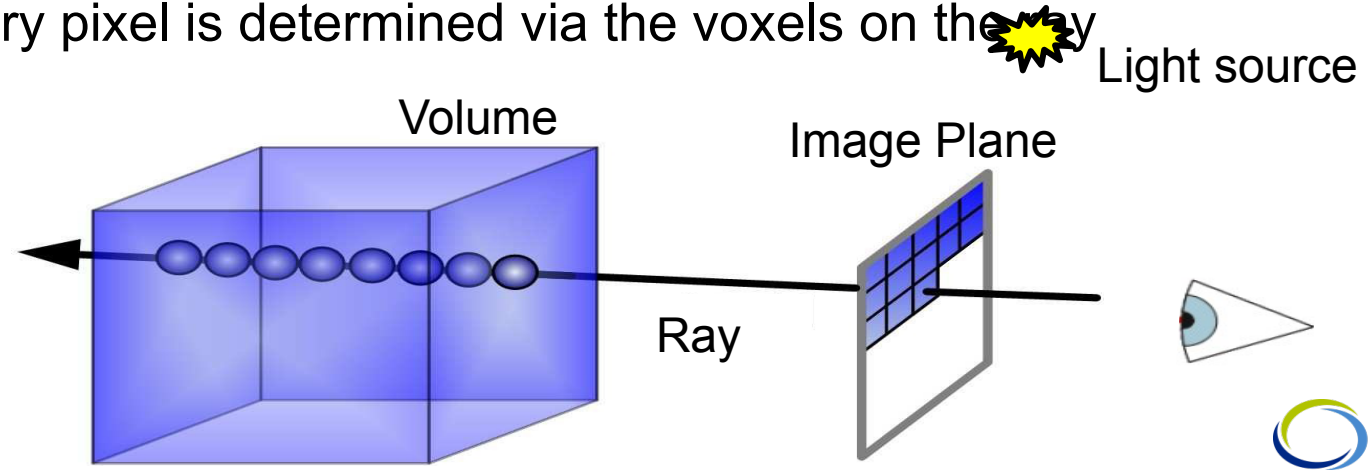
Visualization of voxel models

Raycasting:

- Every voxel has a color and transparency value
- Every voxel reflects light of a specifc color and absorbs/refracts light depending on the transparency value
- In addition: one or more light sources

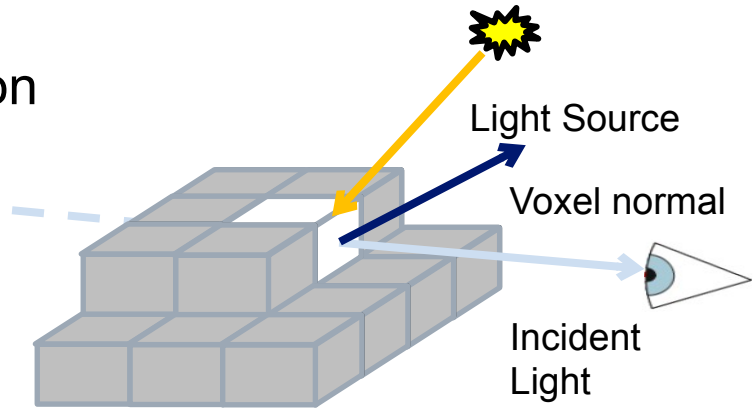
- Trace rays backwards from eye to object
- The color of every pixel is determined via the voxels on the ray



Raycasting

- Ray is emitted for every pixel in the image plane

- Calculate voxel value based on color and transparency value in defined distances on the ray
  - Calculate for every voxel normal based on the voxel gradient
  - The final color value is based on voxel color, position of the light source, voxel normal and the position of the observer
  - Transparency is based on the single absorption coefficients of the CT
  - Normally interpolation on several voxels



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Raycasting

- Compositing: Combination of single color and transparency values

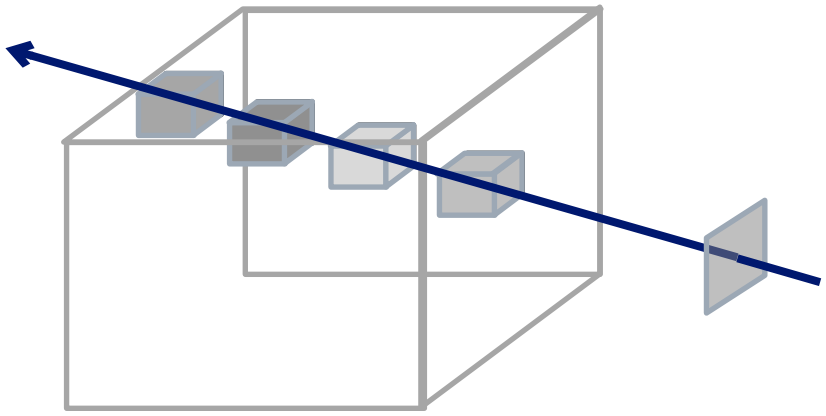
$$C_{out} = C_{in}(1 - \alpha(x_i)) + c(x_i)\alpha(x_i)$$

$$C_{Out} = emergent\ color$$

$$C_{in} = incident\ color$$

$$1 - \alpha(x_i) = Transparency\ of\ voxel\ x_i$$

$$c(x_i) = Color\ of\ voxel\ x_i$$



- Early Ray Termination:
  - Sum of transparency values
  - If sum is greater than 1, terminate calculations

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Ray Casting

Which element is not necessary for determing the color of a voxel?

- **A:** Position of the light source in relation to the voxel
- **B:** Position of the eye in relation to the voxel
- **C:** Voxel normal that describes the orientation to the light source and the eye
- **D:** Transparency value of the voxel

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Visualization of voxel models

- Provides high quality images
- Color and transparency can be chosen
- Computationally intensive
- But: rays are independent from each other
- Can be parallelized (GPU!)

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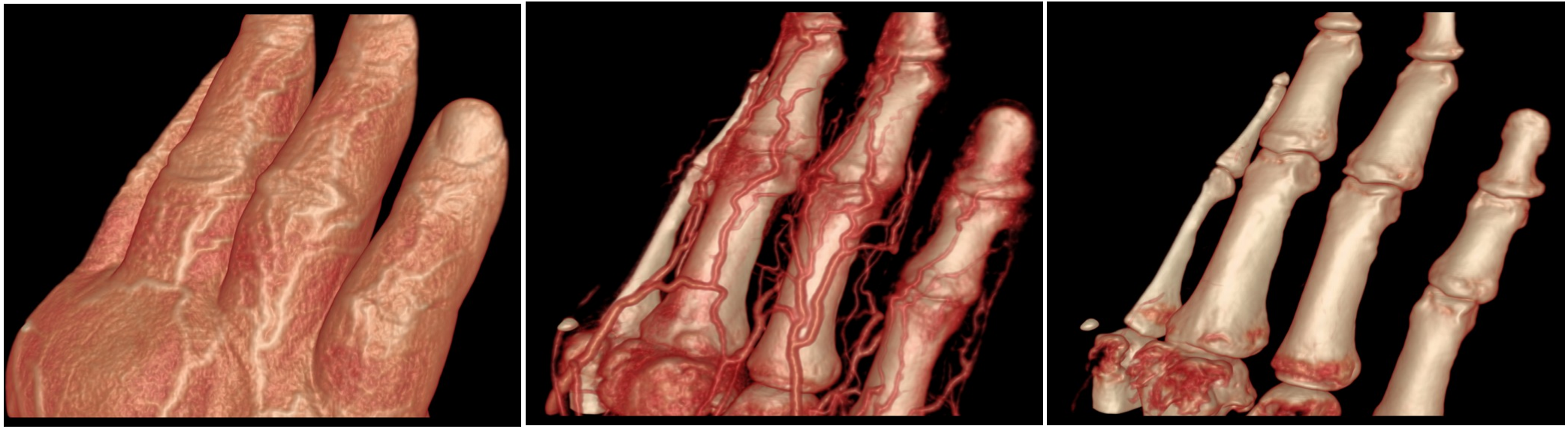
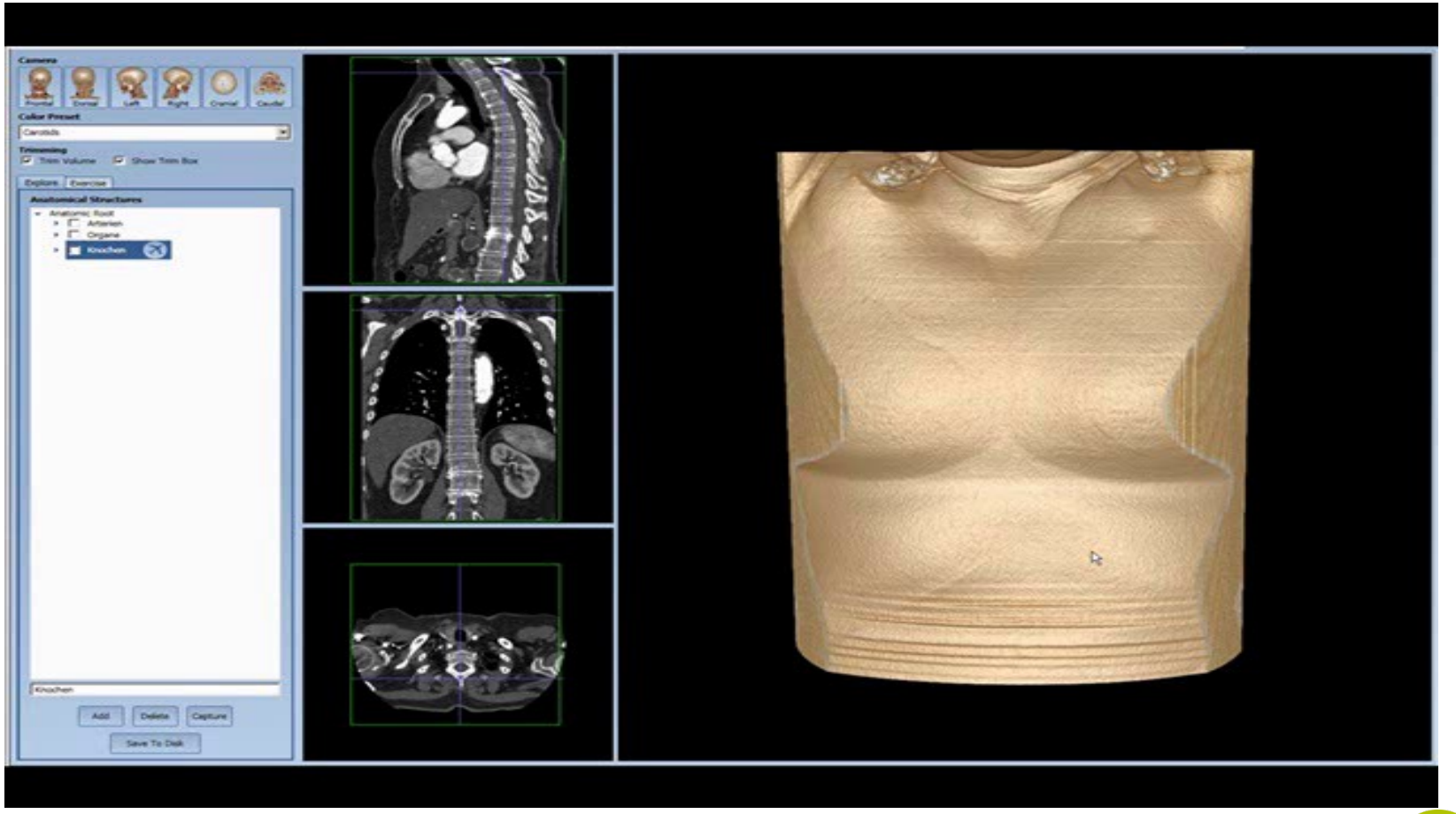
Project: Virtual Anatomy (Web based, GPU rendering)

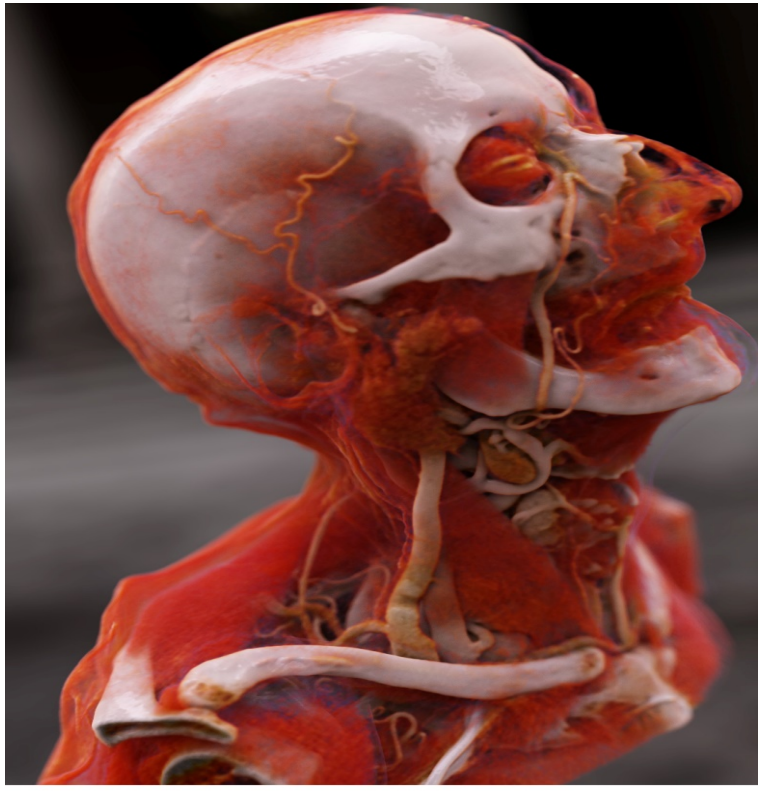
Examples for different transfer functions that define color and transparency value



Virtual Anatomy



Cinematic Rendering (Siemens Healthineers)



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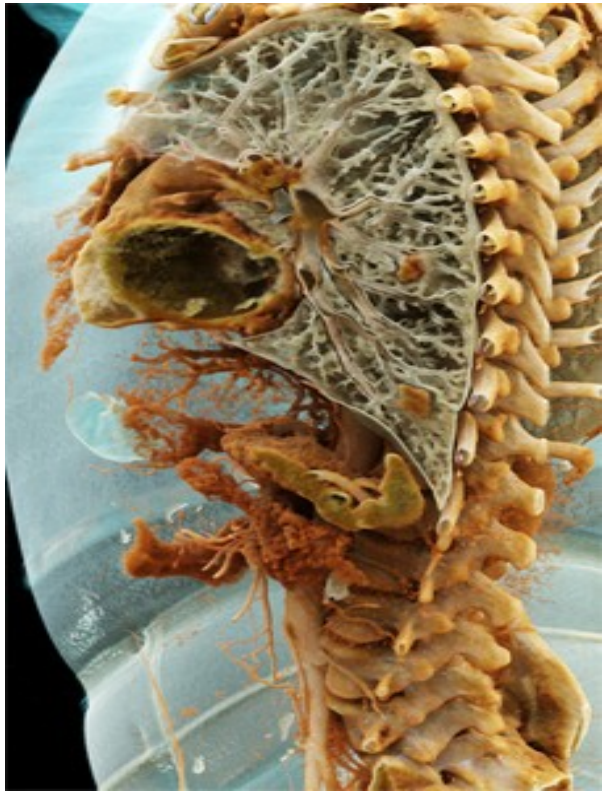

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Volume models

Voxel models

- Contain information about the volume
- Quality of visualization is high because voxel can contain additional information, resolution is high
- Every voxel can be addressed and has defined attribute

But:

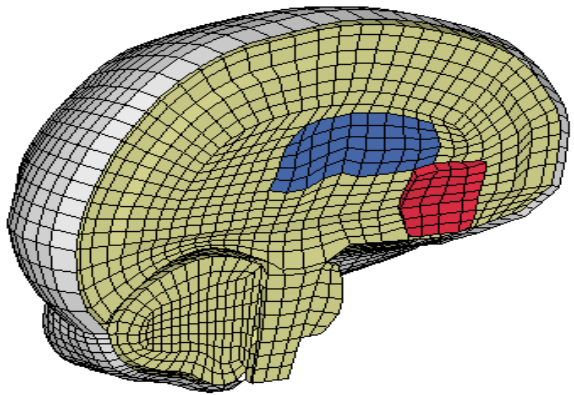
- High storage demand (512x512x1200x2= 600MB)
- Computationally intensive
- No smooth surfaces

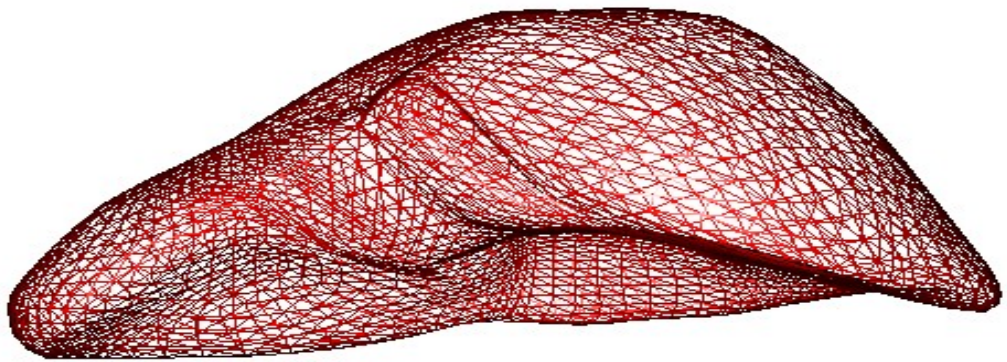
→ Polygon models

Volume models

3D Polygon models:

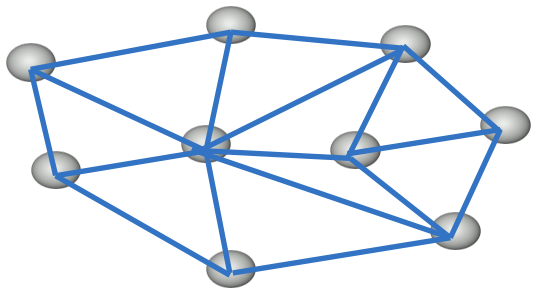
- Simplified representation of the volume with tetraeder or hexaeder mesh
- Basis for numerical simulation
- Are generated from surface models (2D polygon models)

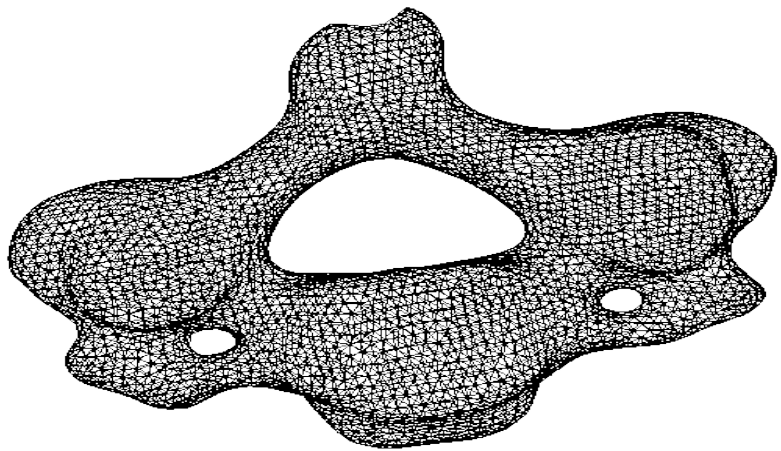




Surface models

- Objects are described with their surface
- No information about the inner structure
- Basic element is a triangle
- Other primitives are possible (square, polygon)
- Mesh consist of nodes and edges





Generation of surface meshes

Question:

- How are surface meshes calculated?

Methods:

- Based on voxels
  - Marching Cubes
- Based on point clouds
  - Delaunay Triangulation

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Marching Cubes

- Standard method for generating isosurfaces from voxels
- Paper from Lorensen und Cline 1987

Idea:

- Calculates triangle mesh for approximation of an isosurface
- Requires voxel model and isovalue (e.g. grey value of CT)
- Generates surface in an imaginary cube
- Cube is passed (march)

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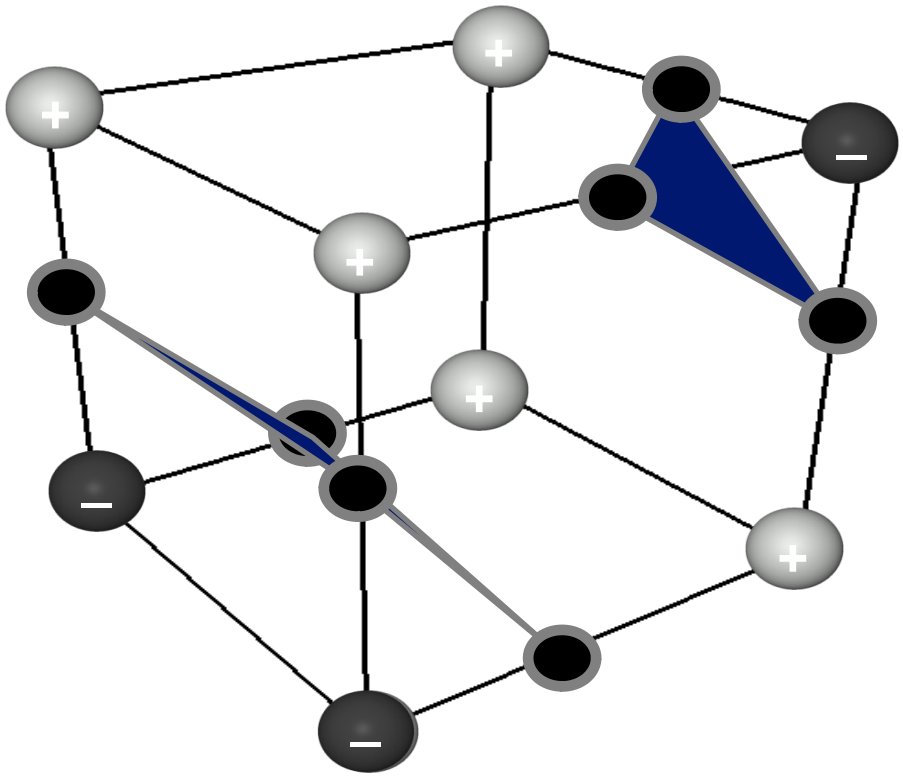
Marching Cubes

- Choose an isovalue
- Examine cells that consists of 8 data points (voxel) an form an imaginary cube
- Classify each data point with + or –, depending if the value is greater or less than the isovalue
- Calculate the intersection with the edges via interpolation
- Calculate triangulation
- Combine triangles of the current cube with neighboring cube



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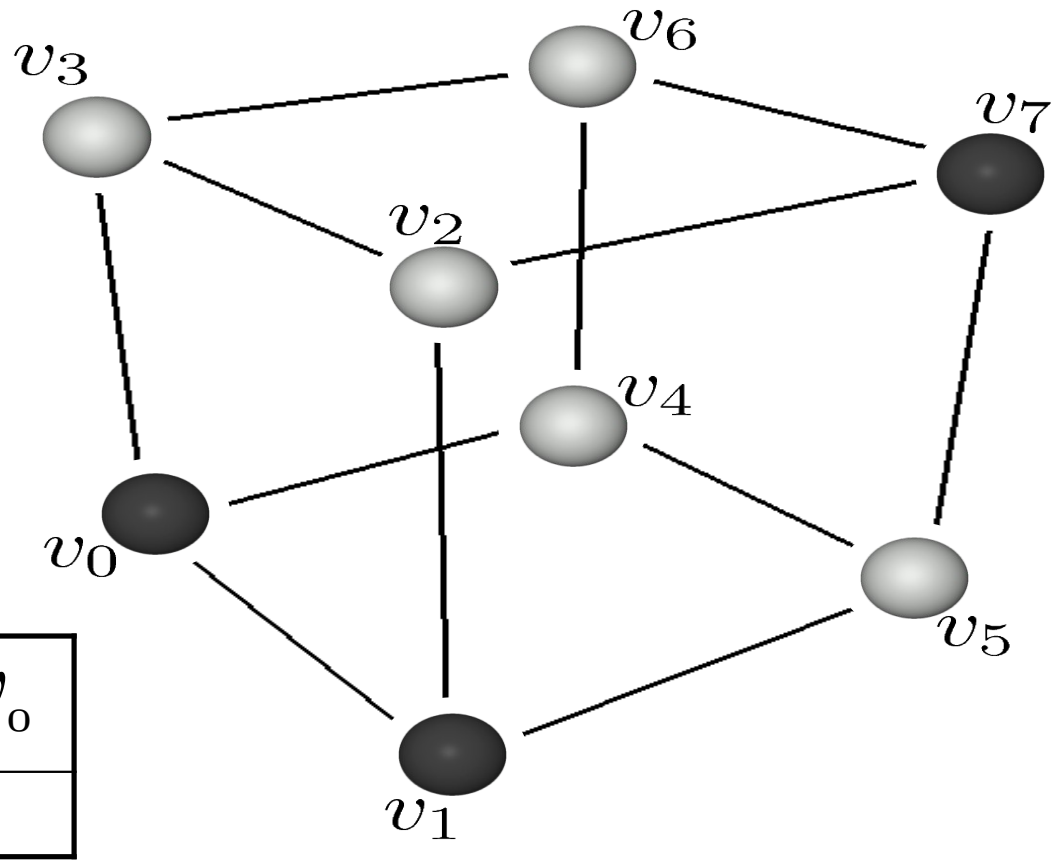
Marching Cubes

Calculation of triangulation

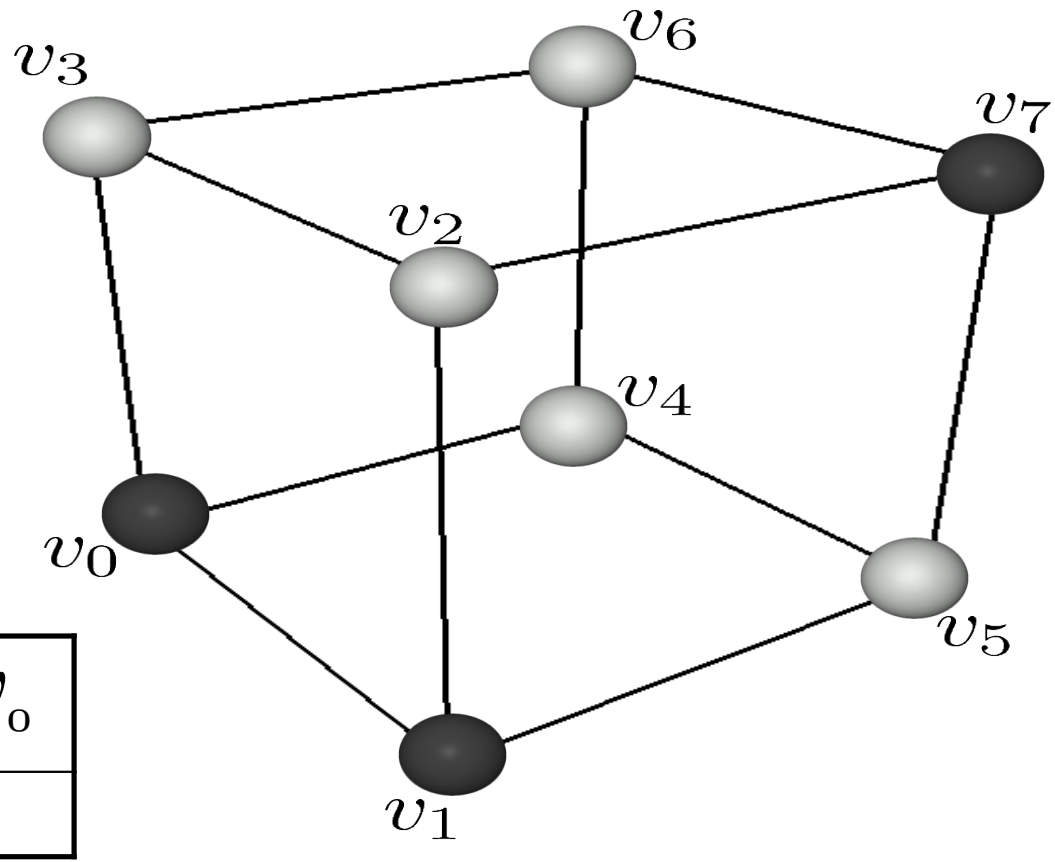


v_7	v_6	v_5	v_4	v_3	v_2	v_1	v_0
1	0	0	0	0	0	1	1

Marching Cubes

Calculation of triangulation

- Every cell configuration has a specific indes
- For every index the triangulation is stored in a look-up table



v_7	v_6	v_5	v_4	v_3	v_2	v_1	v_0
1	0	0	0	0	0	1	1

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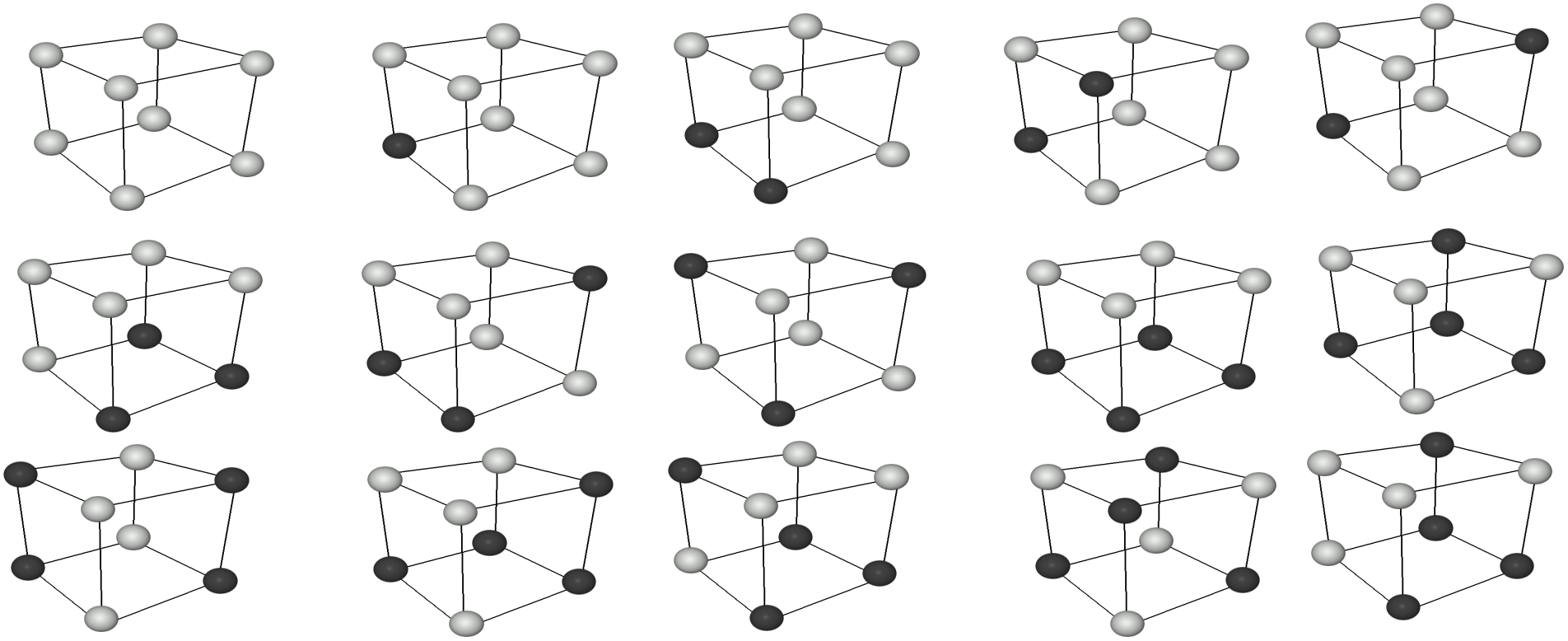
Marching Cubes

Reduction to 15 possible configurations (complementary, rotation symmetry):



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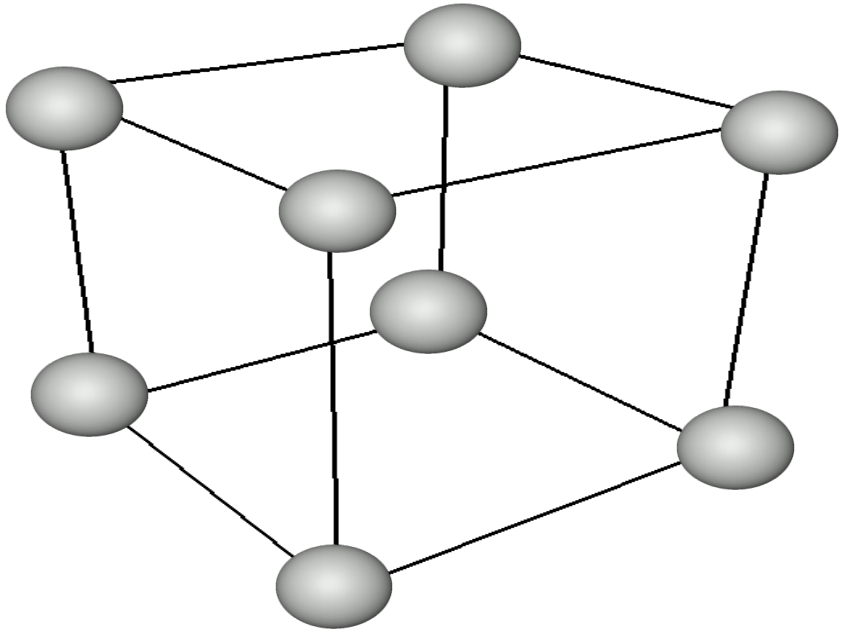
Marching Cubes

Configuration 0:

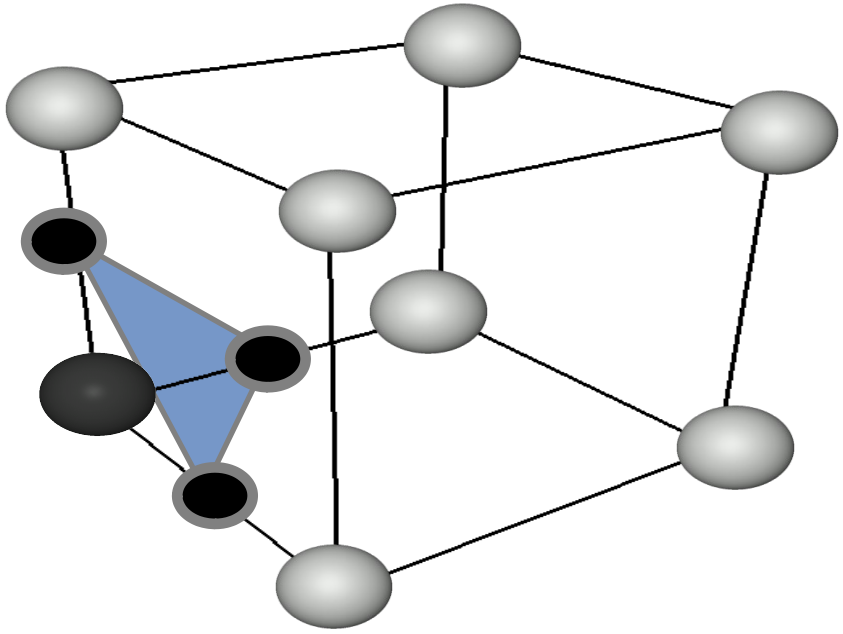
- Iso-surface is not intersecting



Marching Cubes

Configuration 1:

- Isosurface intersects 3 edges
- Integrate triangle



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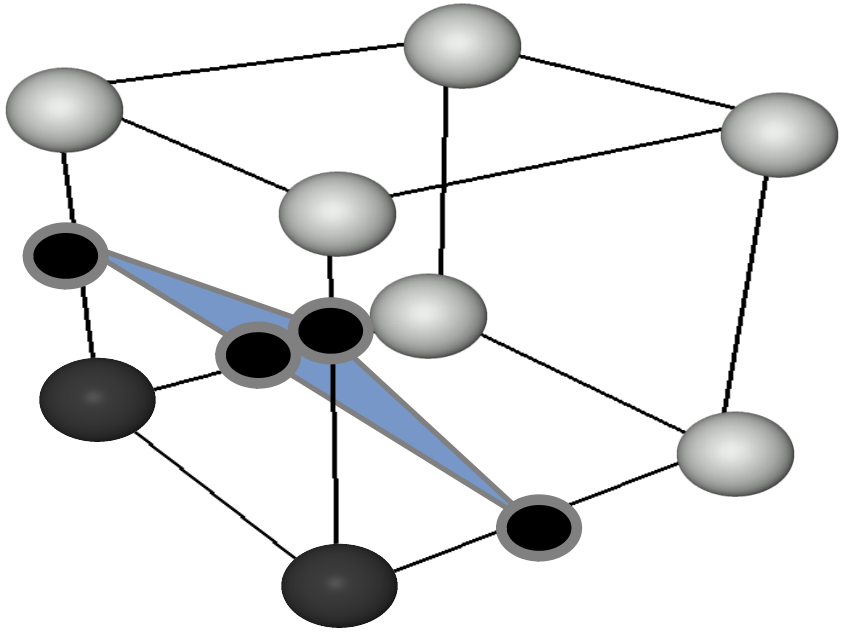
Marching Cubes

Configuration 2:

- Isosurface intersect 4 edges.
- Integrate 2 triangles



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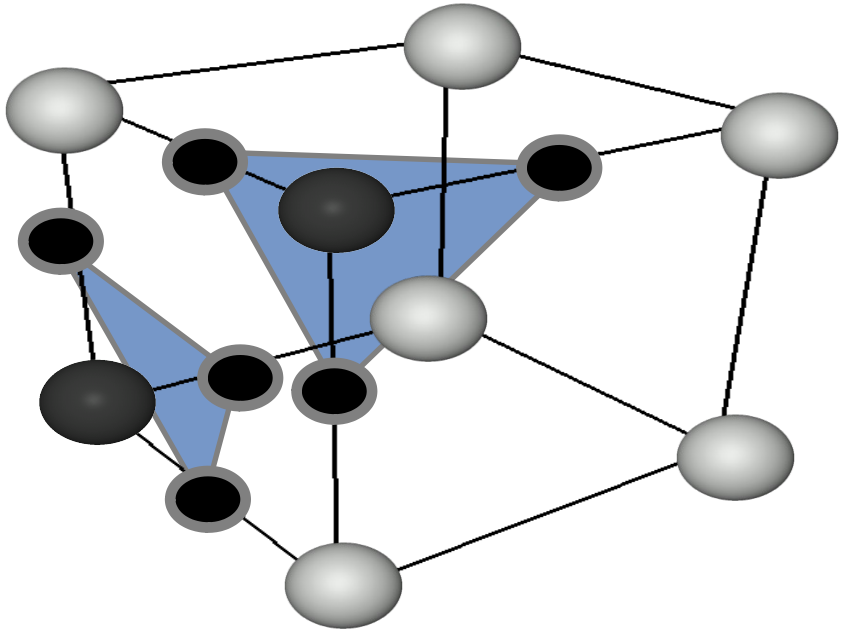
Ambiguity

Configuration 3:

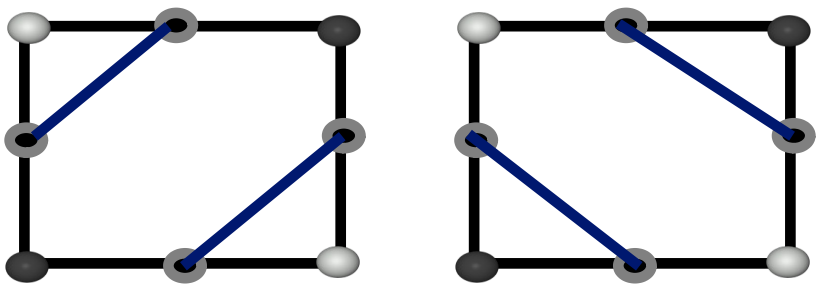
- Isosurface intersects 6 edges

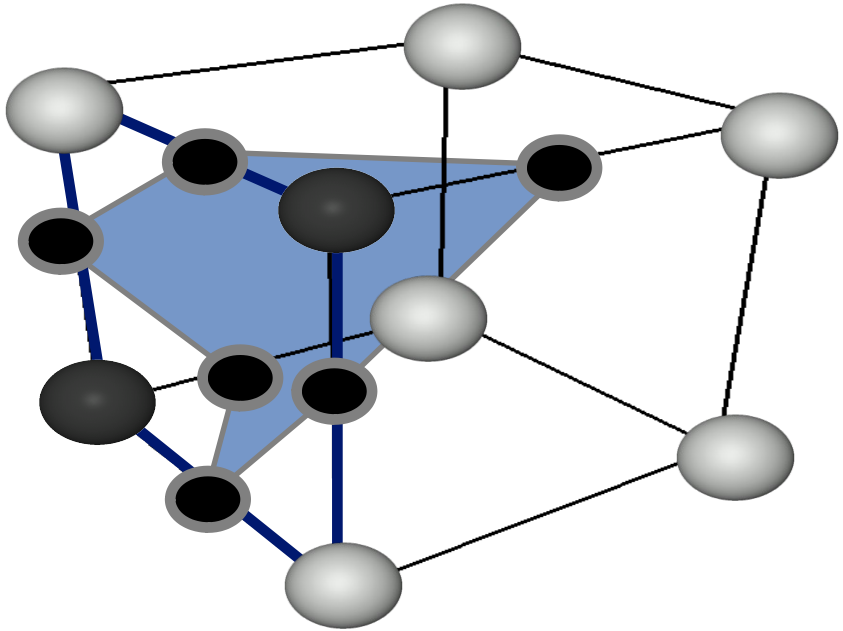


Ambiguity

Config 3:

- Isosurface intersects 6 edges
- Several triangulations possible

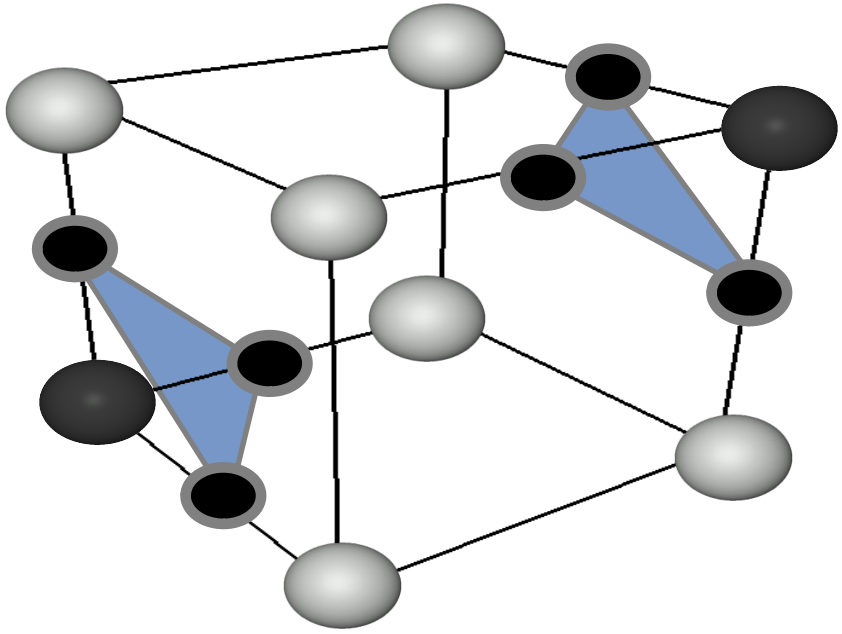




Ambiguity

Config 4:

- Isosurface intersects 6 edges
- Integrate two triangles



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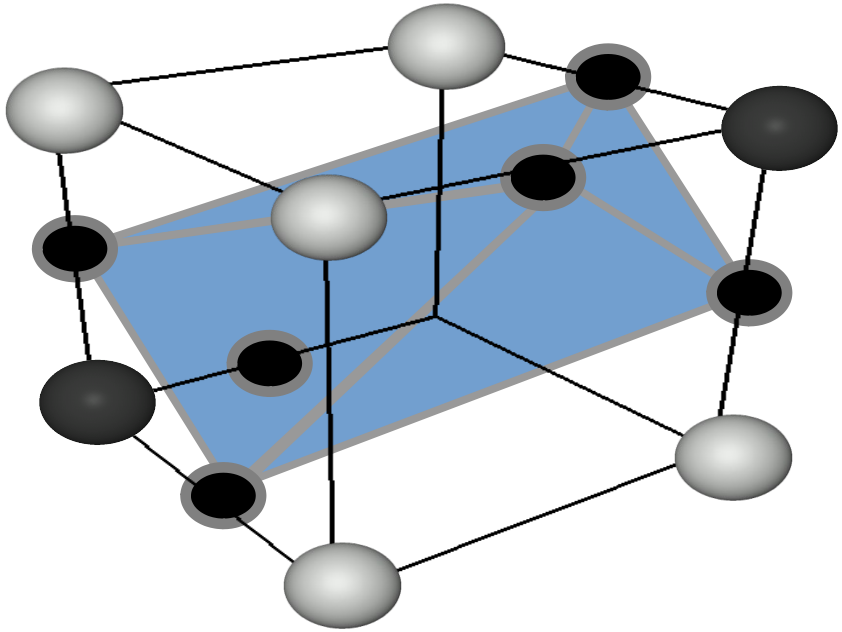
Ambiguity

Configuration 4:

- Iso-surface intersects 6 edges
- Ambiguities in the cube

- With ambiguities 33 configurations



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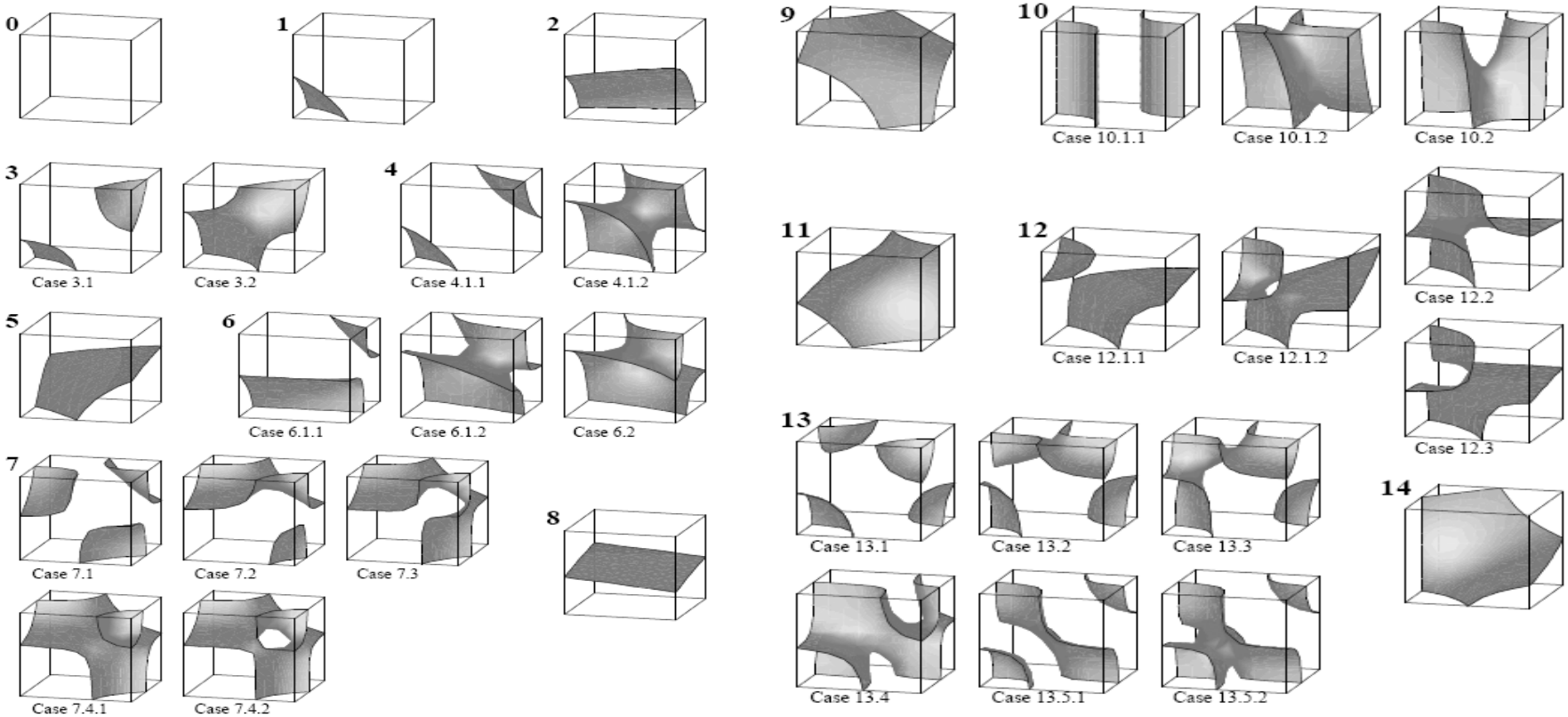
Ambiguity

With ambiguities 33 configurations

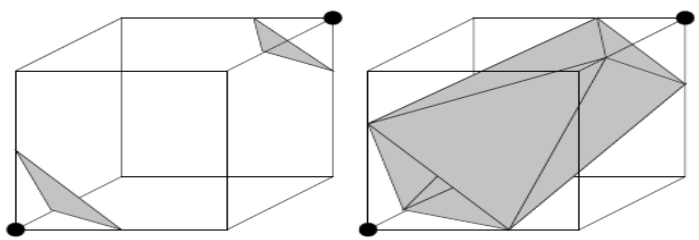


Marching Cubes

Drawbacks:

- A lot of very small triangles are generated
- Computationally intensive
- 30 – 70% of the computing time is done on empty cells
- Limitation: regular grids
- Ambiguities are possible

→ Choice of suitable configuration



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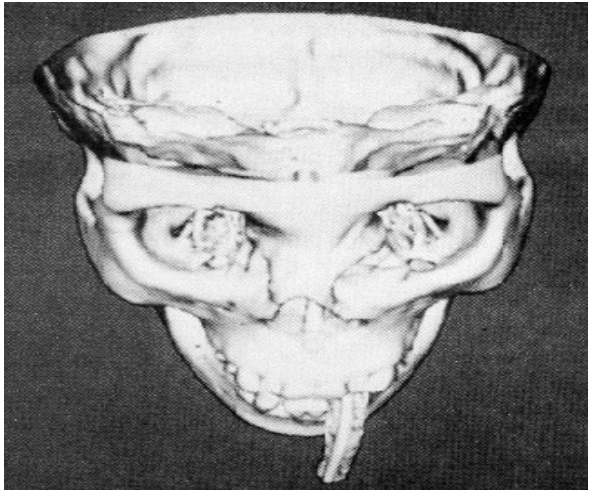
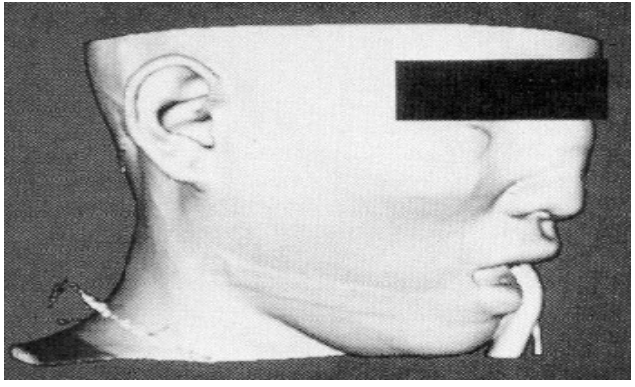
Marching Cubes Results





- Results from original paper (1987!)

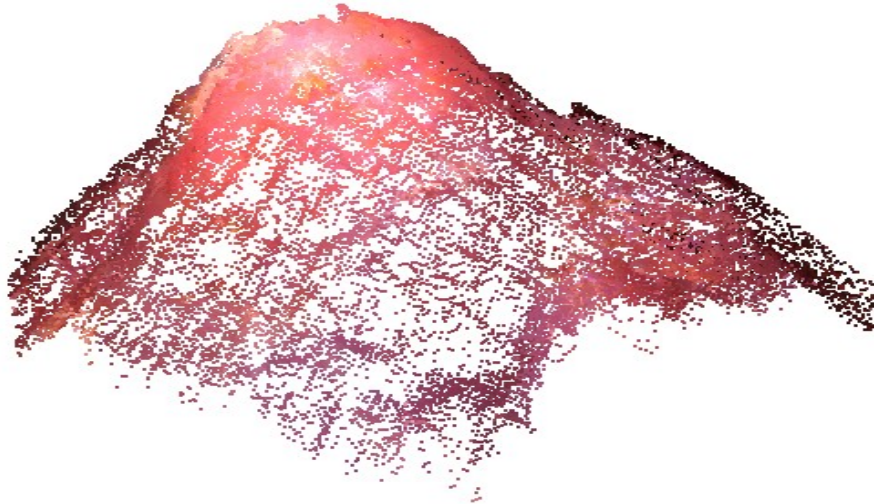
Surface models from point clouds

- Given: set of sample points of an unknown surface S

- Wanted: Surface S‘ which approsimates S

Variances in the input:

- Only 3D coordinates
- Additional attributes
  - Normals
  - Color values



Surface models from point clouds

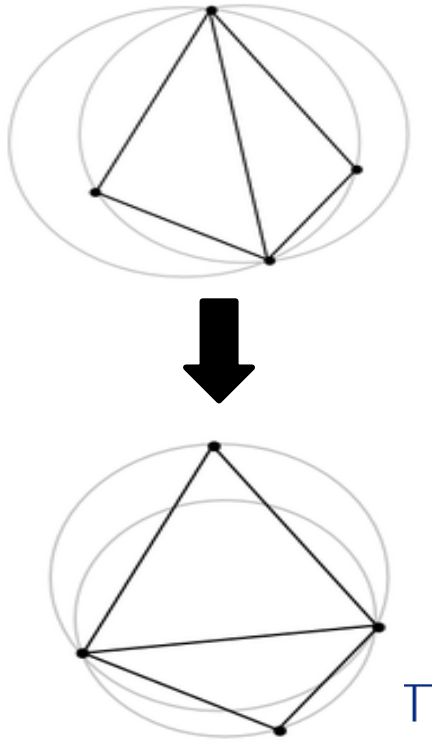
Important criteria

- Dense or sparse point cloud
- Point cloud structured or not structured
- Point cloud noise
- Representation of surface:
  - Parametric: Bezier curves, B-Splines
  - Implicit as function: Radial Basis-Functions, Moving Least Squares
  - As points, edges, triangles: triangulation
- Interpolation or Approximation of the surface

Generation of a triangle mesh

Delaunay-Triangulation of the point cloud

- Delaunay condition (2D): Choose triangles such that the circumcircle of the triangle does not contain additional points of the cloud
  - ~ minimum angles are maximised



Application:

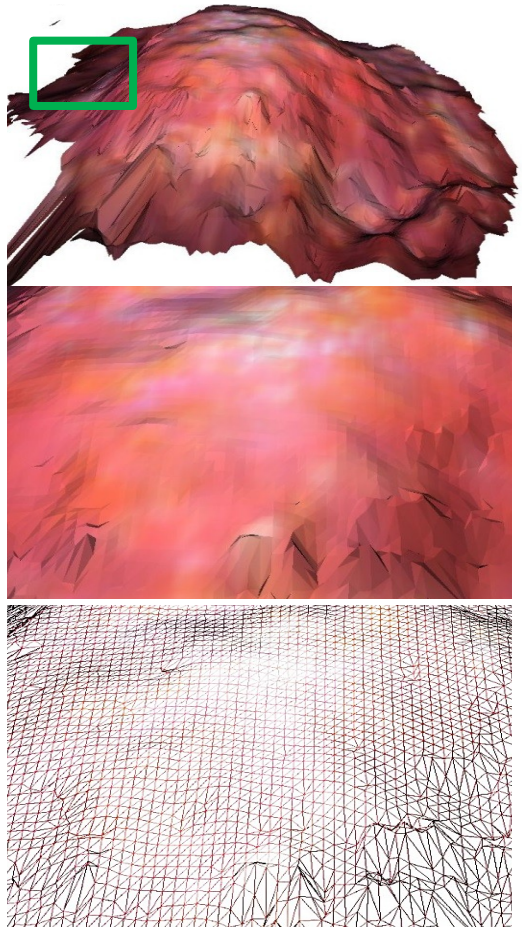
- Generate arbitrary triangle mesh
- Test if delaunay condition is met for neighboring triangles
- If not: flip common edge

Generation of a triangle mesh

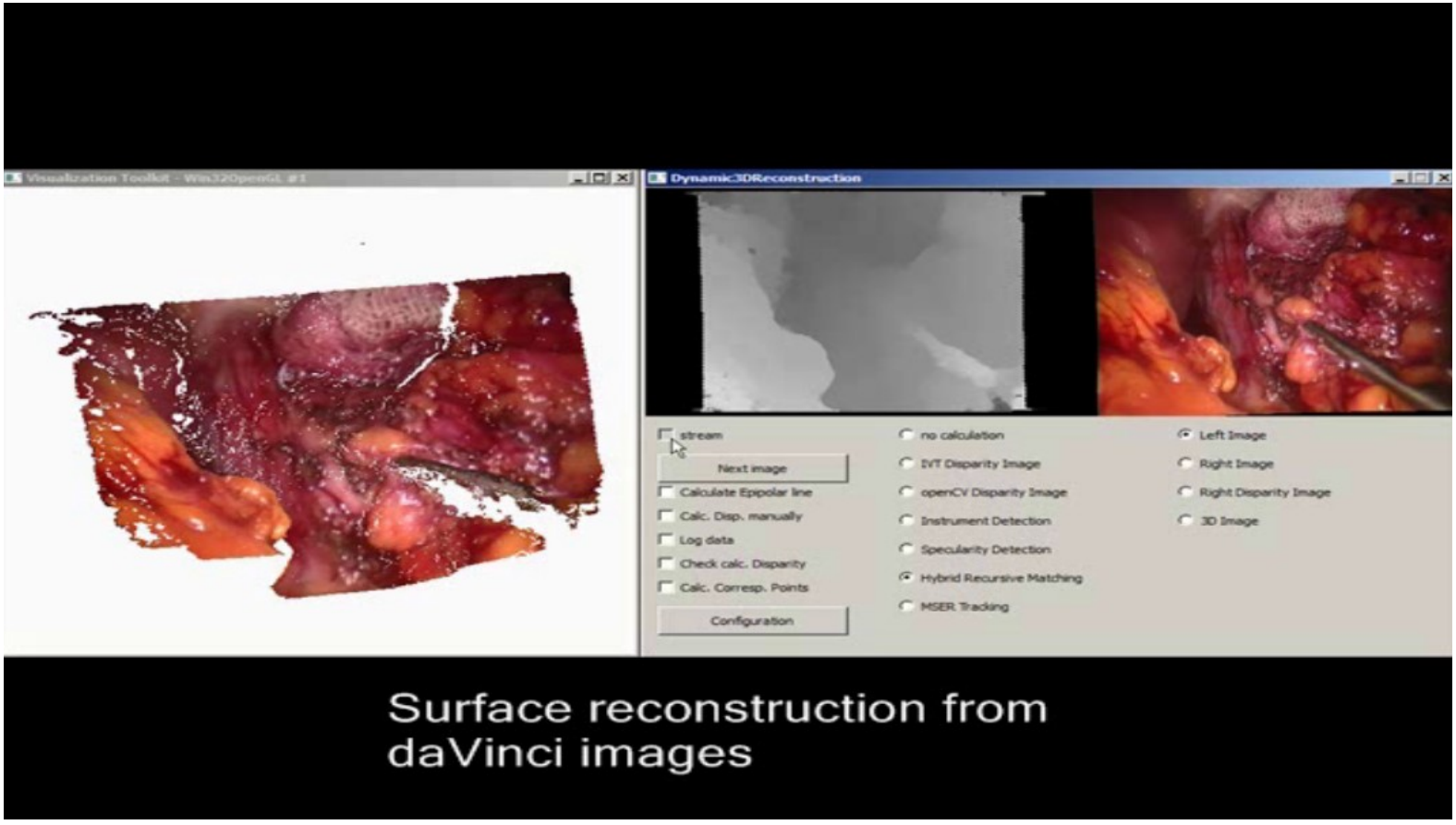
- Problem: expensive calculation of the triangle points in 3D

- Simplifiation for structured point clouds:
  - Use implicit ordering of the points
  - Connect neighbors
  - Reduction from 3D to 2D
  - Computation time reduced

- Application: Surface from endoscopic images



Surface model



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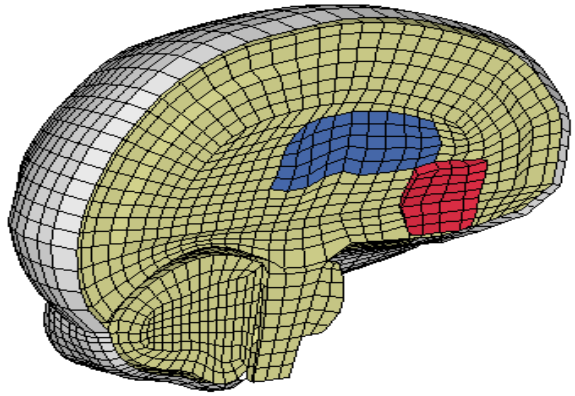
Volume model

3D Polygon model:

- Extraction from surface models
- Segmentation of the surface necessary
- Uniform division of the volume necessary

  ➔ Information loss
- Representation of curved/smooth surfaces possible
- Resolution of the model easily adaptable
- Easy and fast to implement

  ➔ Basis for numerical simulation



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3D Polygon model

Which sentence is wrong?

- **A:** Curved surfaces can be represented
- **B:** Can be generated from voxel models
- **C:** Contain information about the inner structure
- **D:** Can be deformed via numerical simulation

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Visualization devices/Navigation

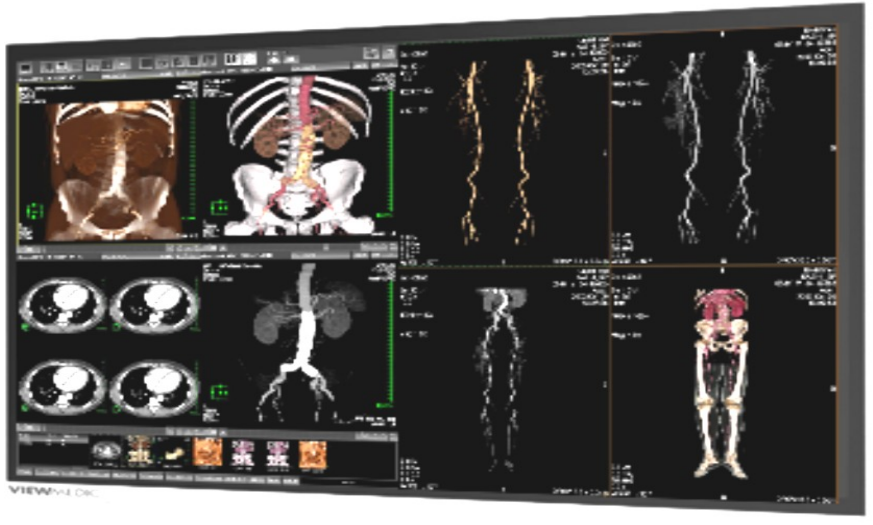
Visualization devices

What is necessary?

- Preoperative Imaging: direct visualization of the slices
- Diagnosis: Assistance for detection of pathologies
- Operation planning: Interactive visualization possible
- Intraoperative Assistance:
  Real-time visualization in the OR
- Validation:
  Before/After Comparison
- Patient Consent:

Simple visualization of complex tasks

→ Different visualization devices necessary



Virtual Reality Technology

VIVE

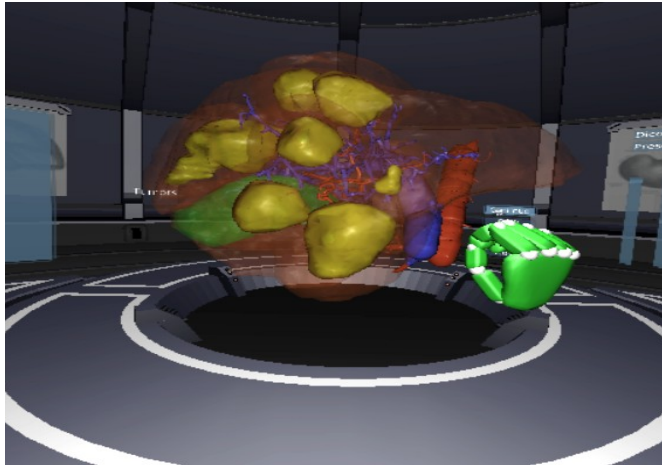
oculus

PlayStation VR

NCT

Potential for Surgery

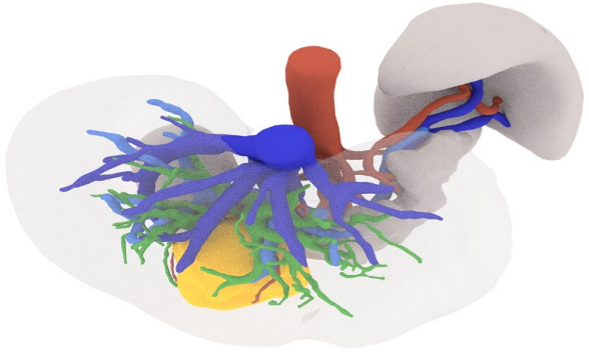
Planning



Training

Axonom Inc.

Patient Consent



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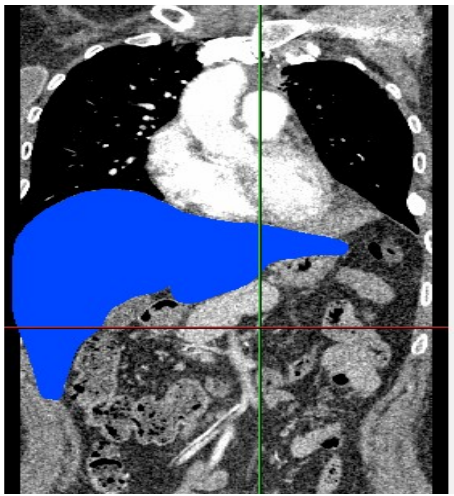
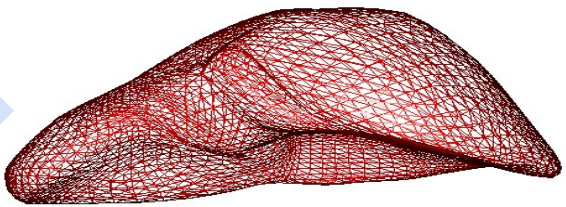
Virtual 3D Model

CT Images



Segmentation



3D Model

Preoperative VR-Assistance

OR Visualization

Visualization of

- Target structures
- Risk structures
- Preoperative/intraoperative simulation results
- Preoperative Planning
- Deviation of OR-Plan …

Preferred: Visualization directly in the surgeon‘s view

Advantage: Surgeons does not have to chance view between patient and monitor

➔ Augmented Reality

Augmented Reality

Definition [Azuma et al.]:

- Overlay of virtual objects in real environment
- Interaction and Realtime Performance
- Registration of virtual and real objects

R. Azuma

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Augmented Reality - Examples

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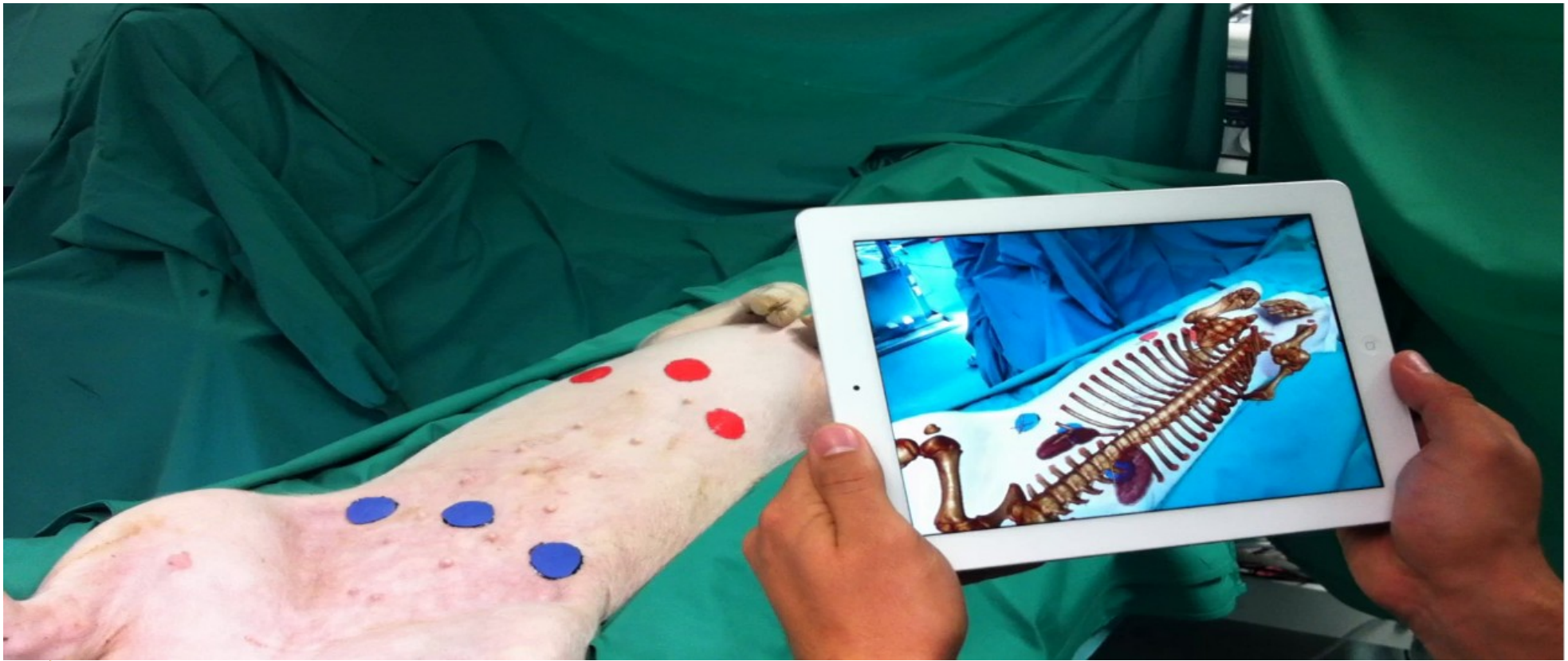
Augmented Reality - Examples

Augmented Reality - Examples



Augmented Reality - Examples

Augmented Reality - Examples

Quelle: Hager et al., Johns Hopkins

Augmented Reality - Examples

AR: History

- 1965: First see-through device
  [Sutherland 65]
- 1990: Research focus
  (UNC, UWash, Rockwell, TU Wien)
- 1997: First review
  [Azuma 97]
- 1998: Dedicated conferences
  (IWAR, ISMR, ISAR, ISMAR, MMVR)
- 2000: AR Toolkits
  (ARToolKit, Studierstube)

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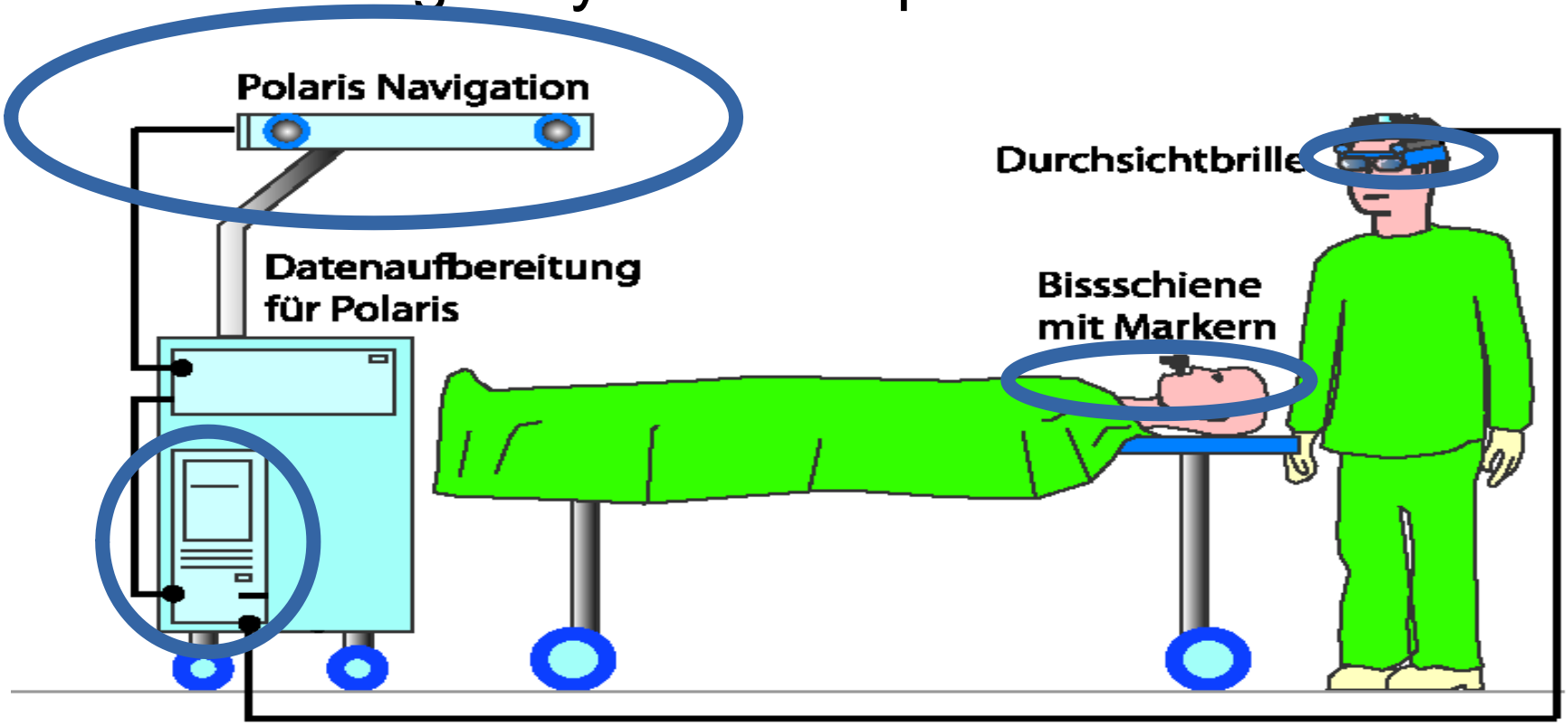
AR See-Through: System components



Methods (Software)

Visualization Navigation

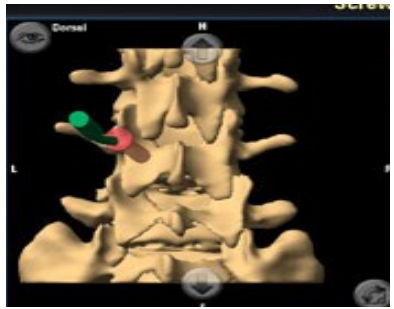
NCT

Navigation

- Sensor-based tracking of the object necessary to get the pose (position+orientation)

Quelle: Brainlab.

- Dedicated systems for medicine
- Application (Medicine):
  - Detection of pathologies
  - Image-guided surgery
  - Supervision of robotic devices



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Navigation: Requirements in medicine

- High Accuracy
- Real-time (low latency)
- Scalability (number of objects, spatial)
- Robustness
- Reliability
- Error Tolerance
- Resilience
- Intuitive Interaction
- Sterilizable

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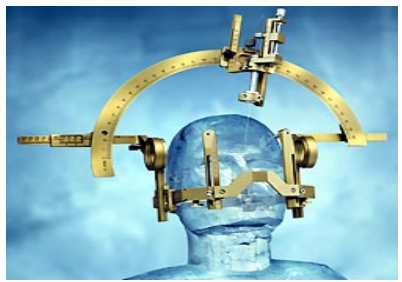
Navigation: Possible Sensors

- Optical
  - with/without markers
  - Light/Infrared light
- (Electro-) magnetic
- Mechanical
- Via ultrasound
- Mixed
  (Multi-Sensor-Fusion)

Quelle: NDI



Quelle: Elekta

Optical Tracking

Markerbased Tracking

- Calculation of the marker position in relation to the camera system via triangulation
- Calculation of position and orientation of the instrument with at least 3 markers

Quelle: NDI

Optical Tracking

Markerbased Tracking

- Passive Markers:
  - (Infrared-) light source of an active camera is emitting light
  - Surface is highly reflective
  - Reflective light is captured by cameras, markers appear as bright spots
  - Alternative: geometrical pattern with high contrast
- Active Marker:
  - Marker consists of an infrared LED
  - Navigation system switches single markers in sequential order

Quelle: NDI

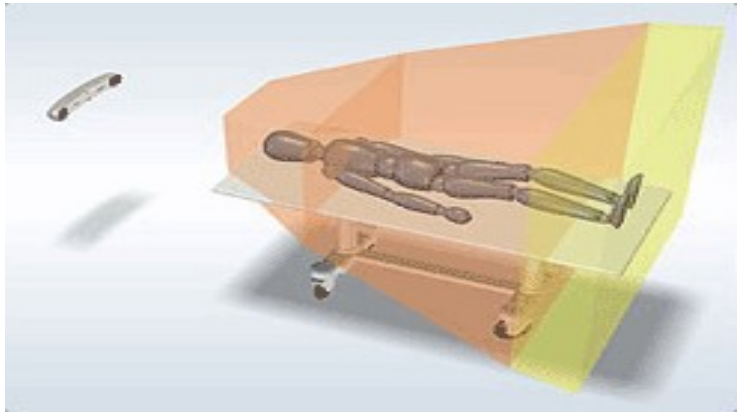
Optical Tracking - Example

Stereo camera system

NDI Polaris

- Certified for clinical use (clinical standard)
- Markerbased system
- Optics: Infrared light
- Active / passive Tracker
- Working space: 0,9 / 2,5 m³
- Accuracy: ~ 0,25 mm

Quelle: NDI

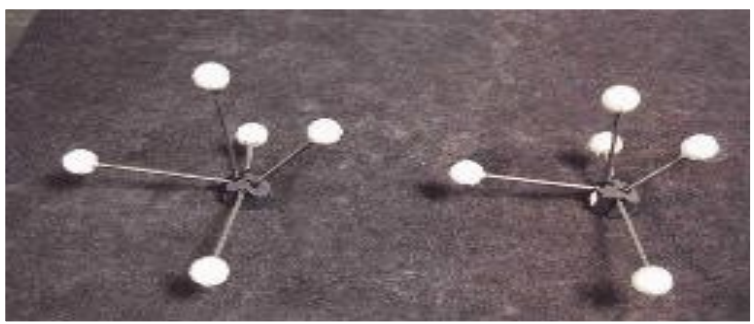


Optical Tracking - Example

Modular Multi-Camera system A.R.T. ARTtrack3

Differences to Polaris:

- Not for medical use
- Scales considering cameras
- Only passive Trackers
- Working space up to 10 x 10 x 3 m³



Quelle: ART

Optical Tracking

Markerless Tracking

- Idea: Moving (central) camera, localization via feature detection in image sequence
- Feature:
  - Natural Landmarks: Face (eyes, nose, …)
  - Corners / Edges
  - Textures

- Problem: Feature detection and tracking in real-time

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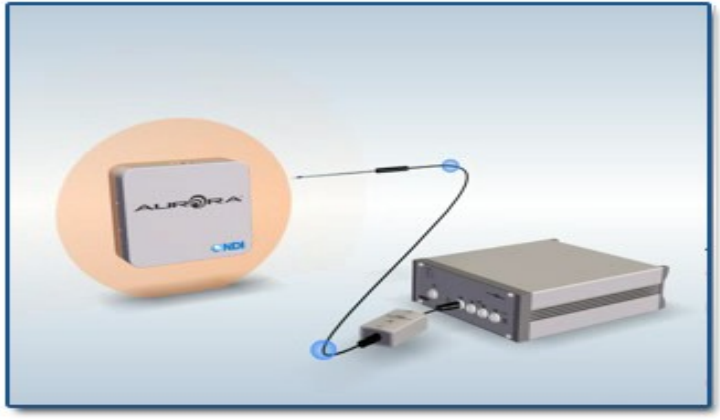
Elektromagnetic Tracking

Concept:

- Consists of fixed transmitter and receiver that is attached on the tracked object
- Transmitter creates three orthogonal magnetic fields
- Receiver consists of three orthogonal antennas
- Magentic field is inducing power dependent of position and orientation of the receiver

Two approaches:

- Alternating current: electromagnetic alternating field
- Direct current: static magnetic field



Quelle: NDI

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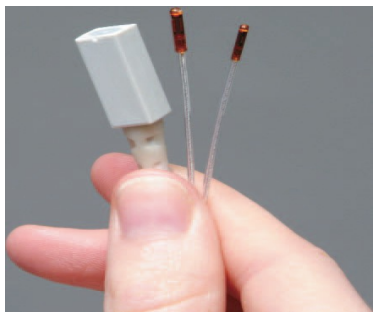
Elektromagnetic Tracking - Examples

Ascension trakSTAR:

- Up to 4 Objects
- Accuracy: ~ 1,4 mm, 0,5 at
- 78 cm distance
- Sensor size up to 1,5 mm
- Direct current



Quelle: Ascension

NDI Aurora

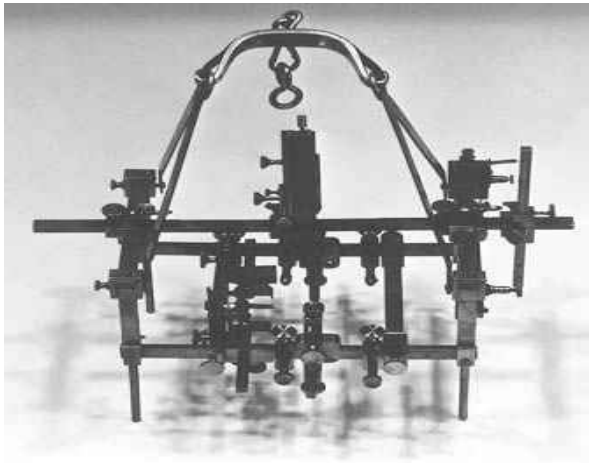
- 5 DOF or 6 DOF
- Up to 8 Objects
- Accuracy (6 DOF): up to 1,1 mm
- Alternating current

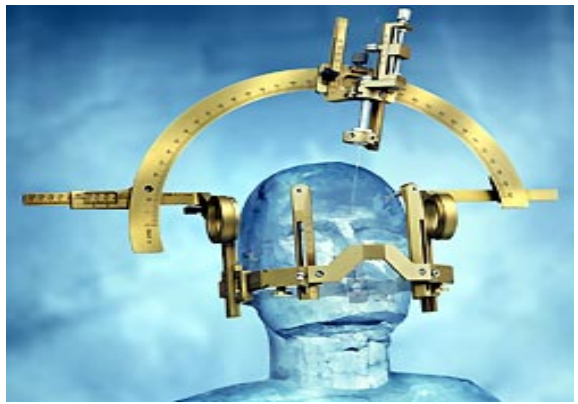
Quelle: NDI

Mechanical Navigation

Stereotaxie:

- Mechanical frame for patient fixation
- 1908: First device
- Today CT- or MRI- recordings with integrated frame
  - simple registration and planning
- Application: Neurosurgery, e.g. biopsies, „Deep Brain Stimulation“





Quelle: Elekta

Navigation: Features

- Optical Navigation:
  - + Very accurate, low latency, high data rates, robust, reliable, sterilizable
  - - Occlusion, Noise (e.g. OR) no flexible instruments, big markers
- Elektro-Magnetic Navigation:
  - + Low latency, high data rates, no line of sight necessary, no optical disturbances, very small receiver, can be used inside the body (e.g. catheter)
  - - Not so accurate, interference because of metallic devices, high costs

- Mechanical Navigation: very accurate, very fast, simple registration, but small working space, not flexible, bulky, no soft tissue navigation

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Navigation: Conclusion

1. Optical Navigation:
   - Commercial stereo camera system for medicine available:
     Clinical approved, often used
   - Commercial Multi-camera systems:
     Experimental use in clinical settings, flexible
   - Non-commercial systems: prototypes, research applications
2. Elektromagnetic Navigation: Occasionally in clinical use, e.g. Biopsies (sensor in needle, combination with ultrasound). New generation no longer so susceptible to interference from metallic objects in the OR.

3. Mechanical Navigation: Clinical use in neurosurgery

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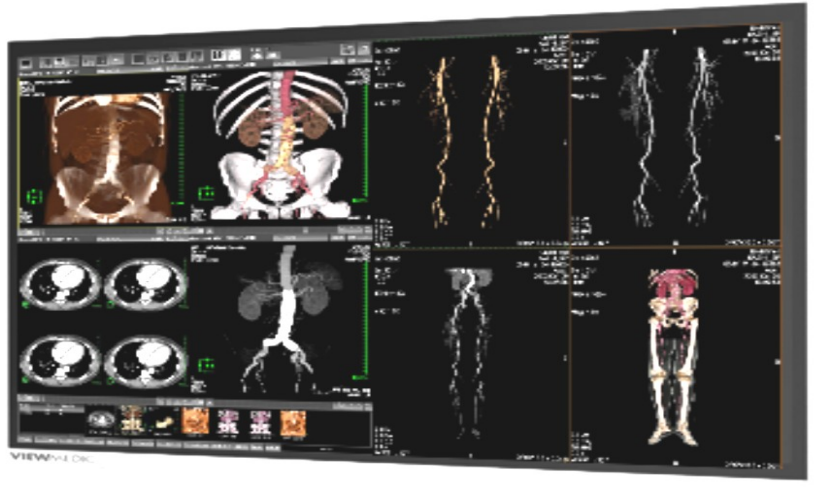
Visualization in the OR

Presentation of results on a monitor close to the patient

- High image quality, diverse information can be presented

Quelle: Brainlab.



Disadvantage:

- Change of view (Patient/Monitor)
- Accuracy loss

Visualization in the surgeons view

- Head-up Display
  - Optical see-through
  - Video
  - Laser on retina
- Projection system
- Others
  - Semipermeable mirror
  - …

HoloLens

Magic Leap

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Projections

- Two possible appraoches for intraoperative projections:
  - Laser
    - High Sharpness
  - Projector system (LCD, Glass fiber,….)
    - High Flexibility
    - Depth of focus low

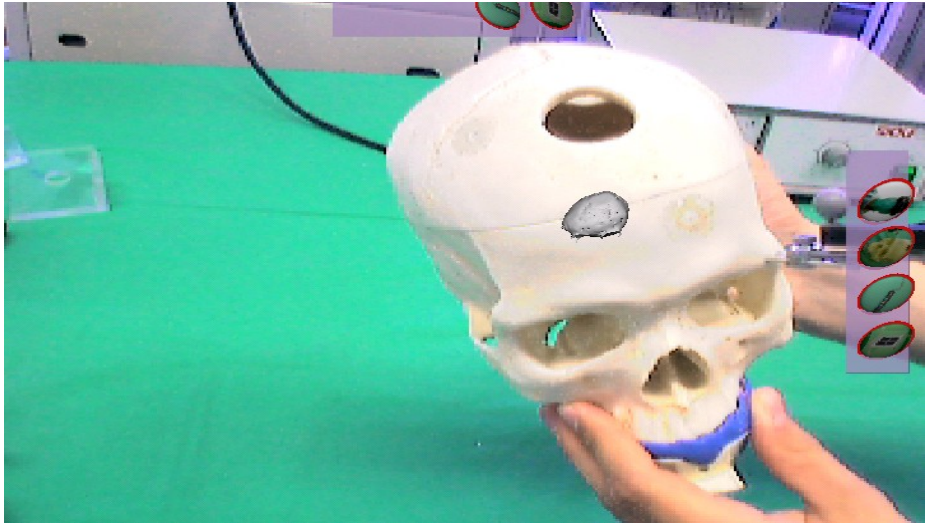
- OR team might occlude the projection
- Hardware effort high
- Several persons can see the projection

Projections

- Projections are very accurate if only cut lines are projected onto surfaces
- In this case independent of the point of view
- If deeper structures are projected, there is a dependence on the viewer's perspective.
  - Tracking the head is necessary
  - The surface that is being projected must be known

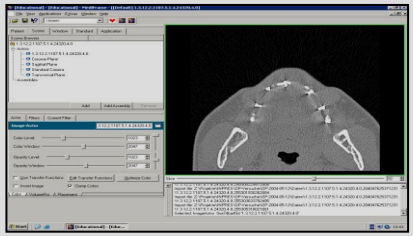
Example - INPRES

- See-through Sony Glasstron with 800 x 600 Pixels, 28° FOV
- Navigation with NDI Polaris
- Visualization of 3D Structures

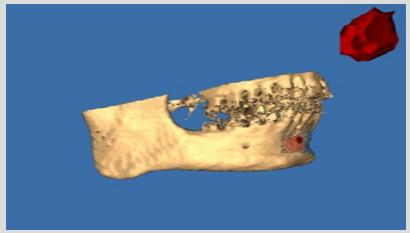


INPRES-Concept

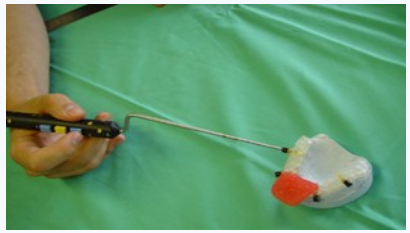
Datenerfassung



Segmentierung & Modellerstellung

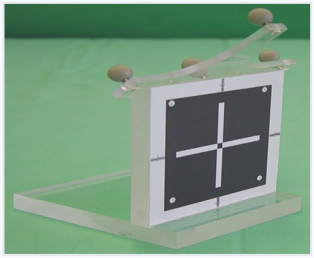


Registrierung



preoperative

intraoperative

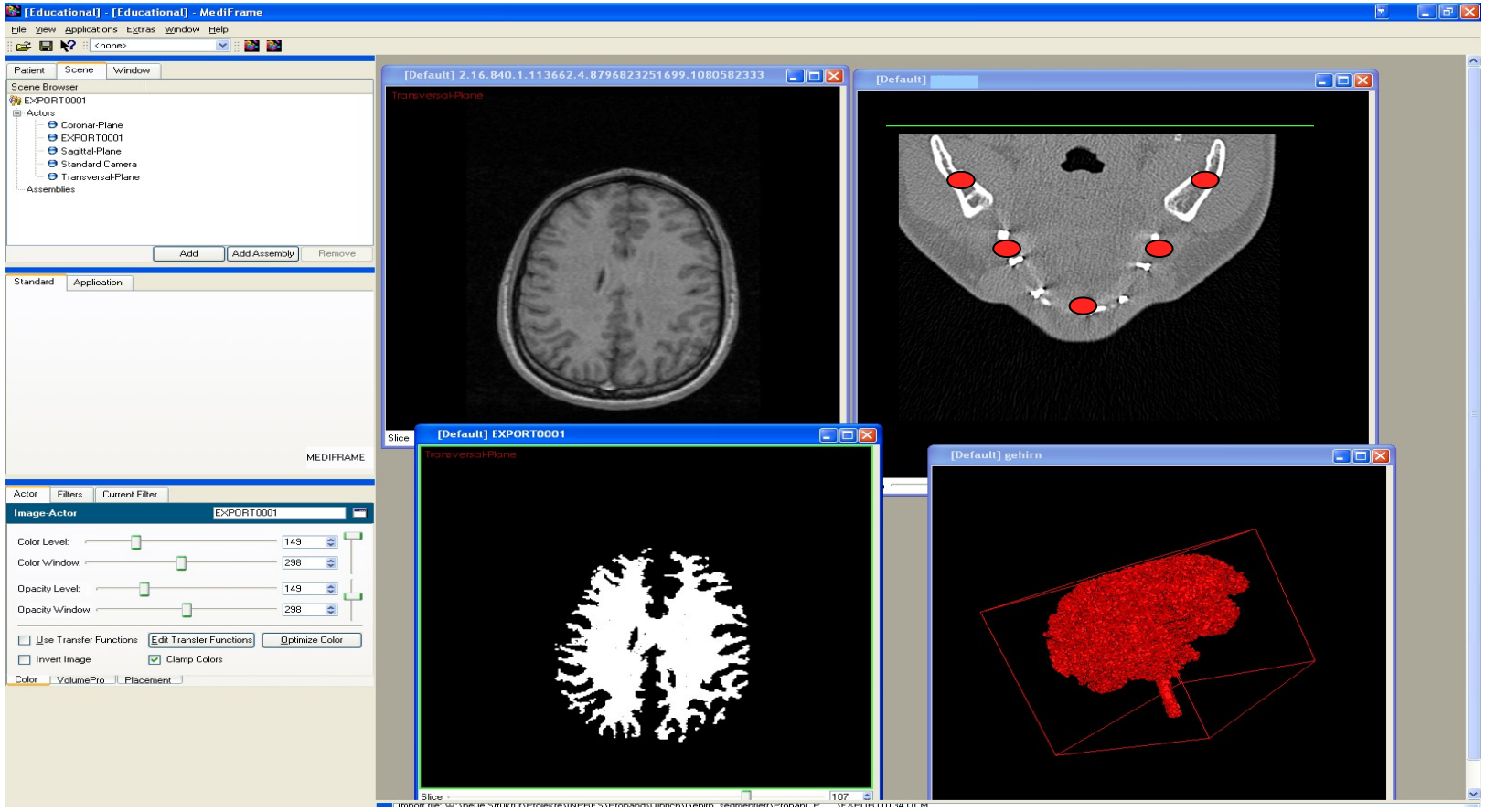


Kalibrierung

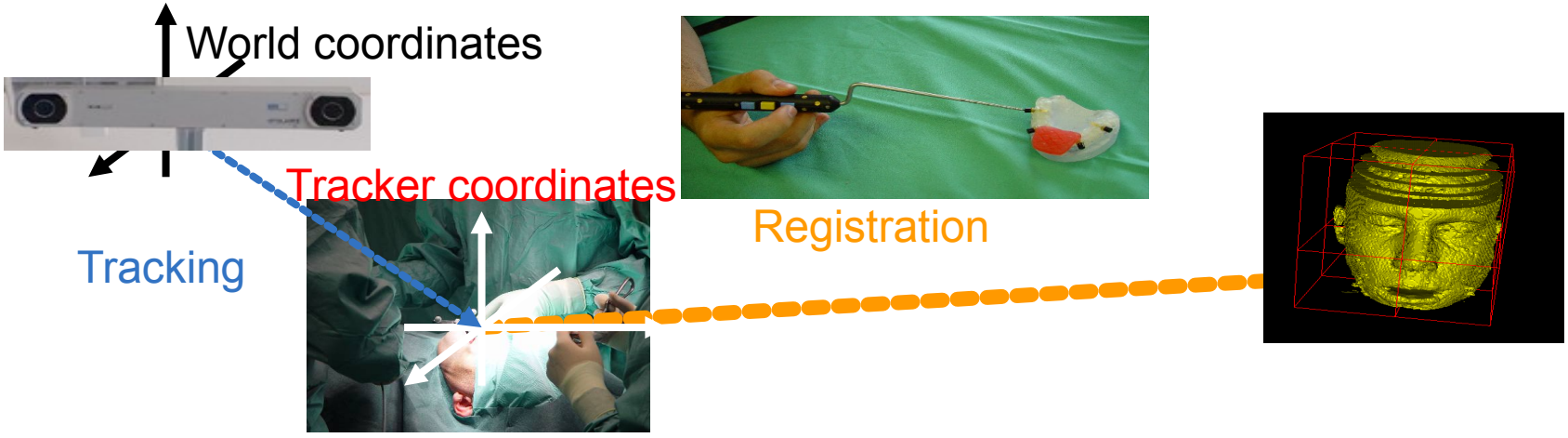
Tracking

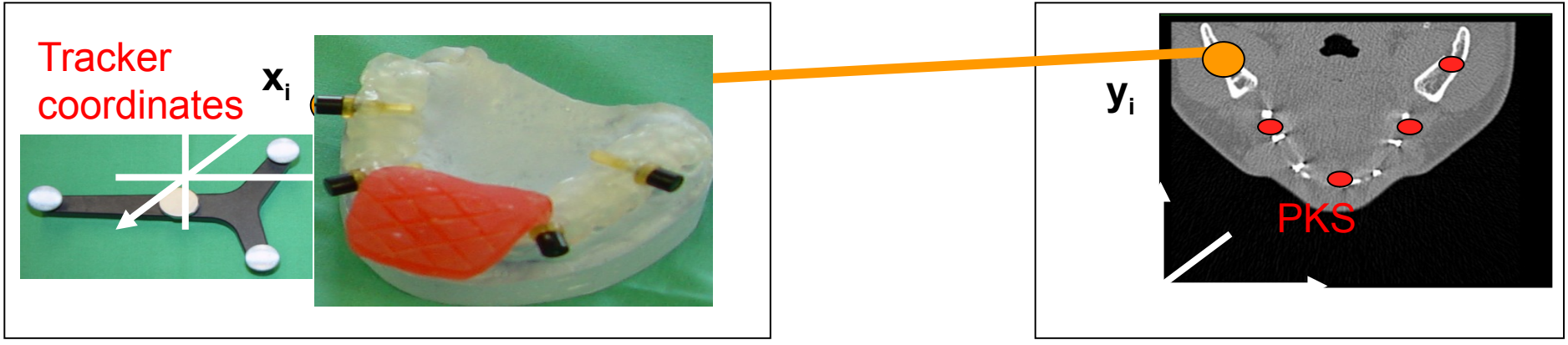
Visualisierung

INPRES: Segmentation & Modeling



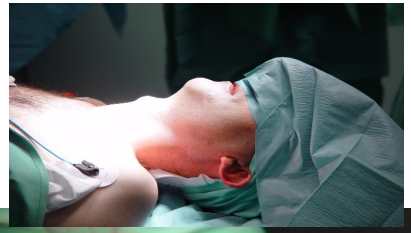
INPRES: Registration

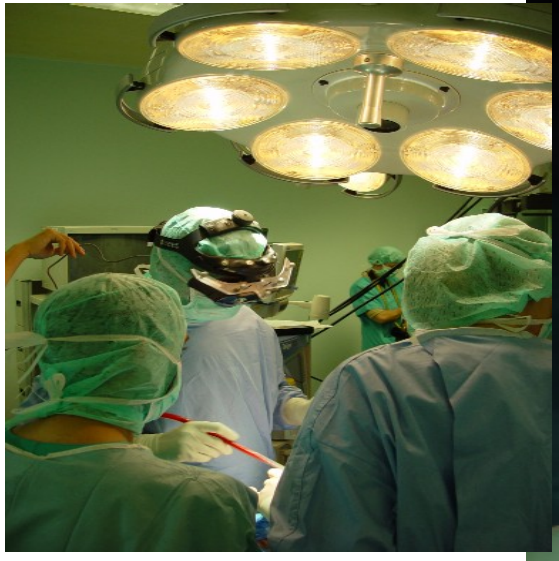


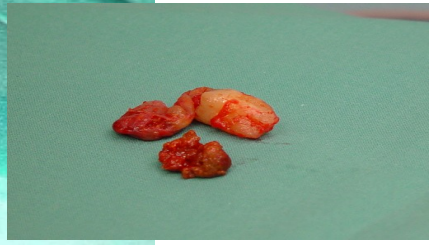


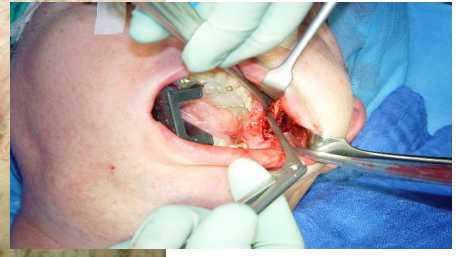
INPRES: clinical Evaluation

- 3 Patients









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- UNC: http://www.cs.unc.edu/~us/web/headmounts.htm
- Harvard: http://spl.bwh.harvard.edu:8000/pages/papers/ shin/book_chap/manus.html

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