From Static to Dynamic

Visualization of Real-Time Imaging Data

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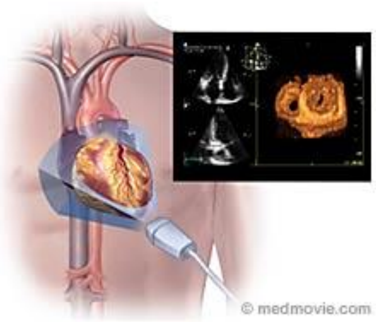
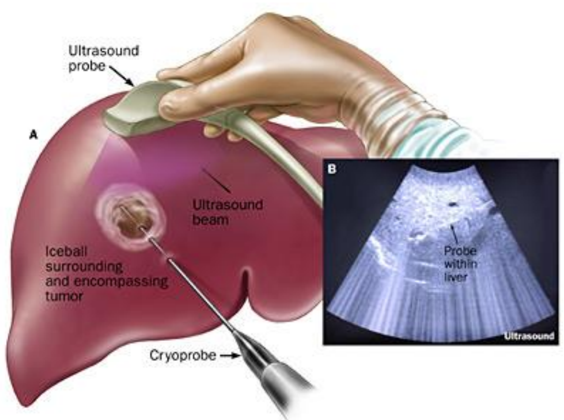
Real-Time Medical Imaging (1)

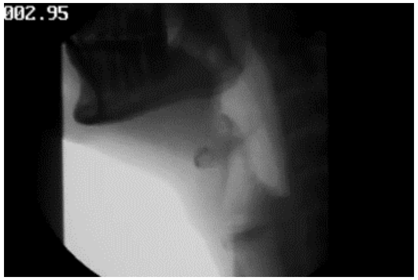
- Acquisition of live in vivo image data of the human body
  - **Imaging of dynamic processes**
    Cardiology (heart), gastroenterology (stomach & bowel), nephrology (kidney), hepatology (liver), (bladder), obstetrics (fetus)
  - **Interventional imaging**
    Surgery (e.g., tumor resections, neurosurgery, bypass surgery), biopsies





Real-Time Medical Imaging (2)

- Radiography
  - **Fluoroscopy**
    Only 2D projections, ionizing radiation
- Computed Tomography (CT)
  - **CT Fluoroscopy**
    low spatial/temporal resolution, high radiation doses
- Magnetic Resonance Imaging (MRI)
  - **FLASH (Fast Low Angle Shot) MRI**
    Only single/few slices, limited availability



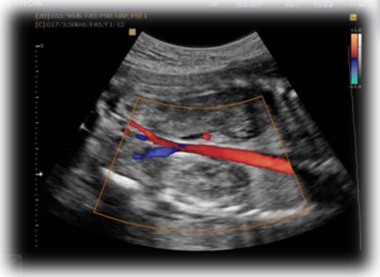
Basic Ultrasound Imaging

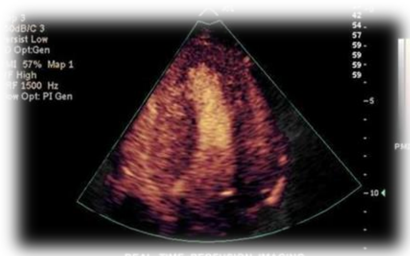
Ultrasound Characteristics

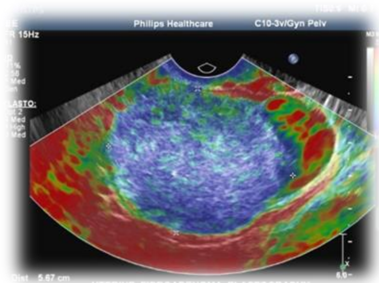
- Non-invasive
- Cheap
- High resolution
  - Spatially
  - Temporally
- Noise
  - Random
  - Speckle

Common Ultrasound Modes

- 2D Ultrasound
  - B-Mode
- 3D Ultrasound
  - Static 3D imaging
- 4D Ultrasound
  - Dynamic 3D imaging
- Doppler Ultrasound
  - Color Doppler: directional
  - Power Doppler: non-directional
- Contrast Ultrasound
  - Microbubbles-based contrast agents
- Elastography
  - Mechanical tissue properties





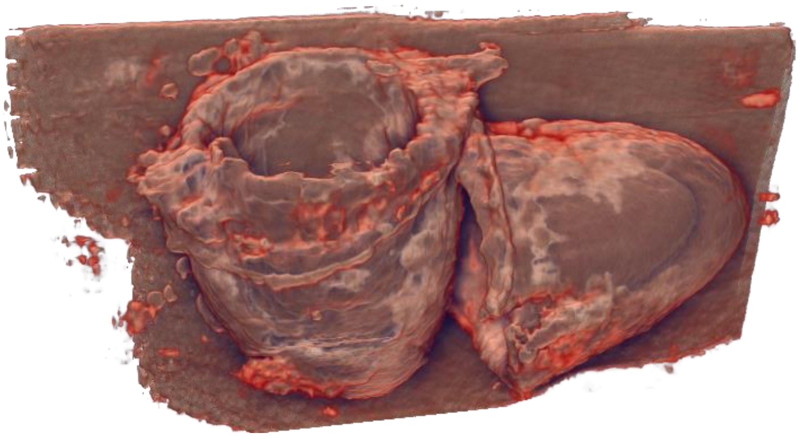


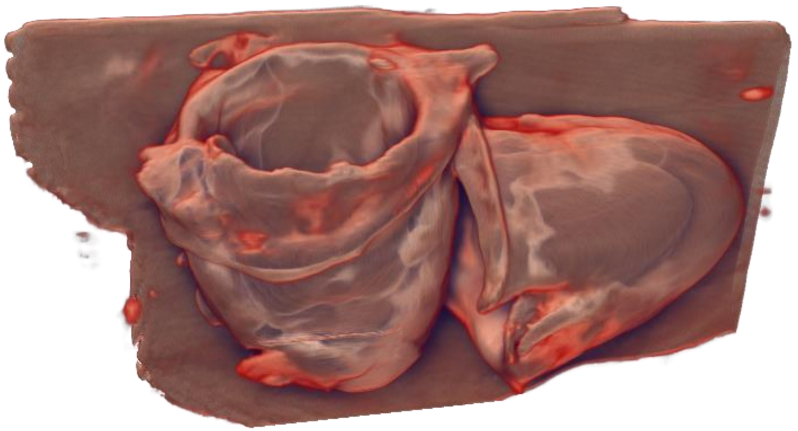
Challenges

- Real-time imaging means that no part of the visualization pipeline can be considered pre-processing
  - Limited computational budget
  - Degree of interaction limited
  - Constant changes

Outline

- Visualization of 3D/4D ultrasound data
- Recent advances in
  - Filtering
  - Classification
  - Illumination
  - Fusion and Guidance





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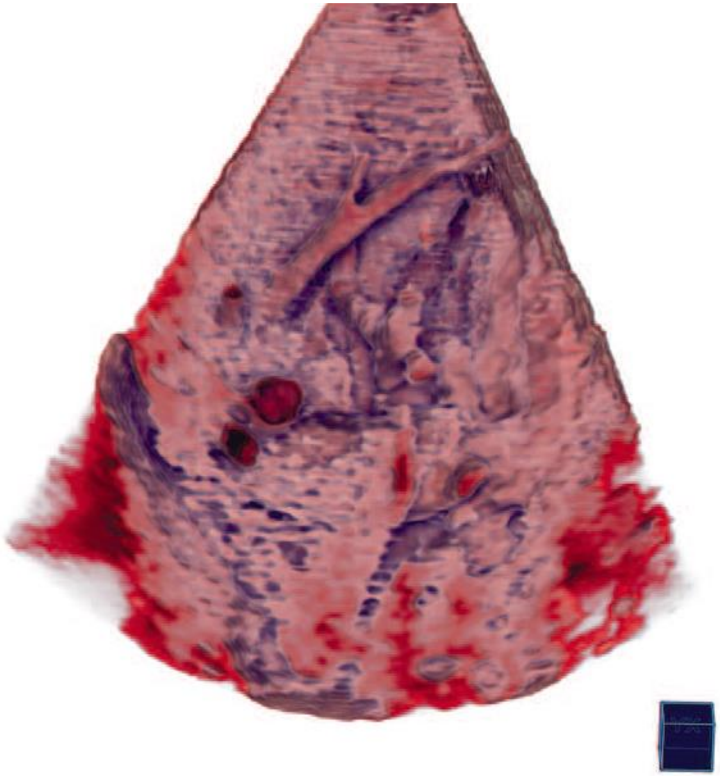
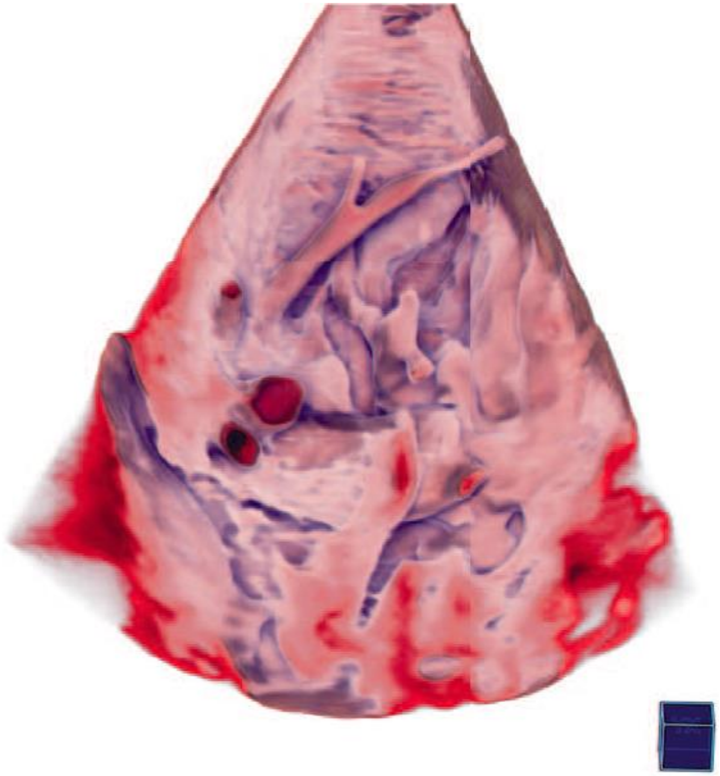
FILTERING

Filtering

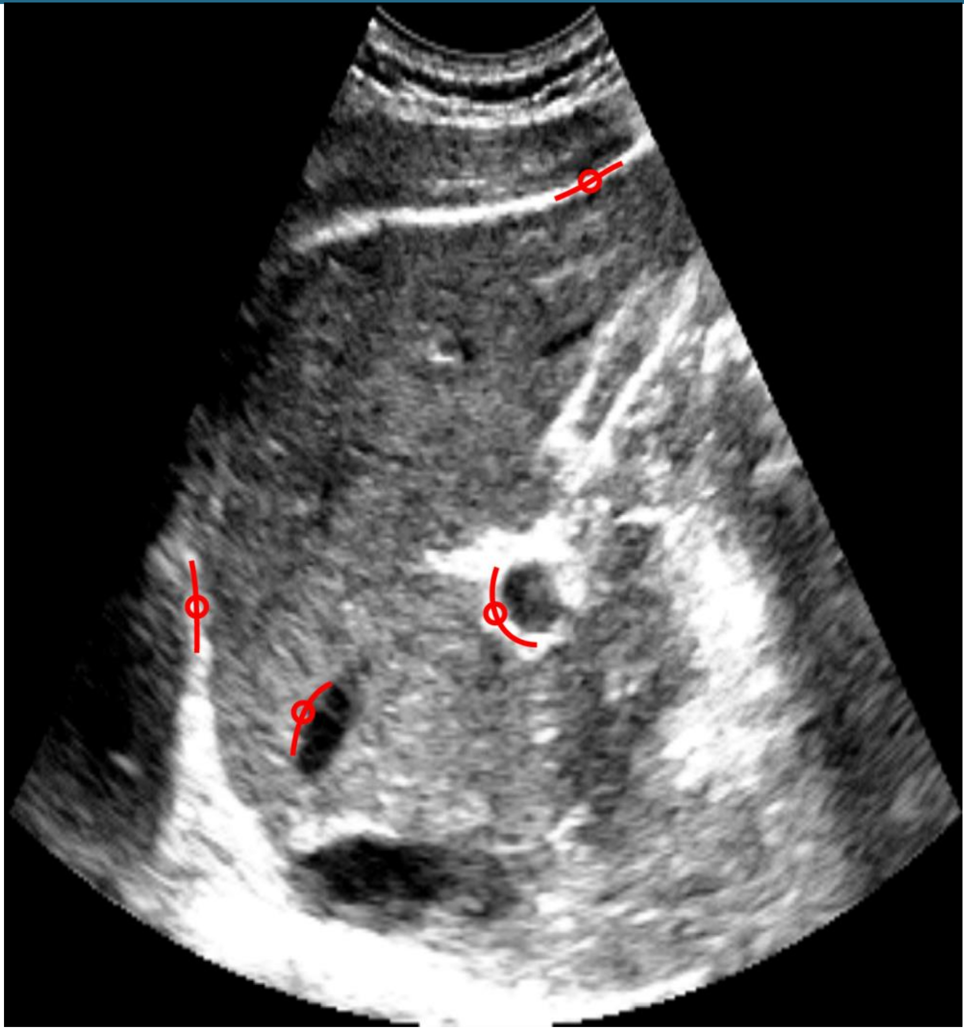
- Noisy character of ultrasound imaging makes filtering particularly important for 3D visualization





Lowest Variance Filtering

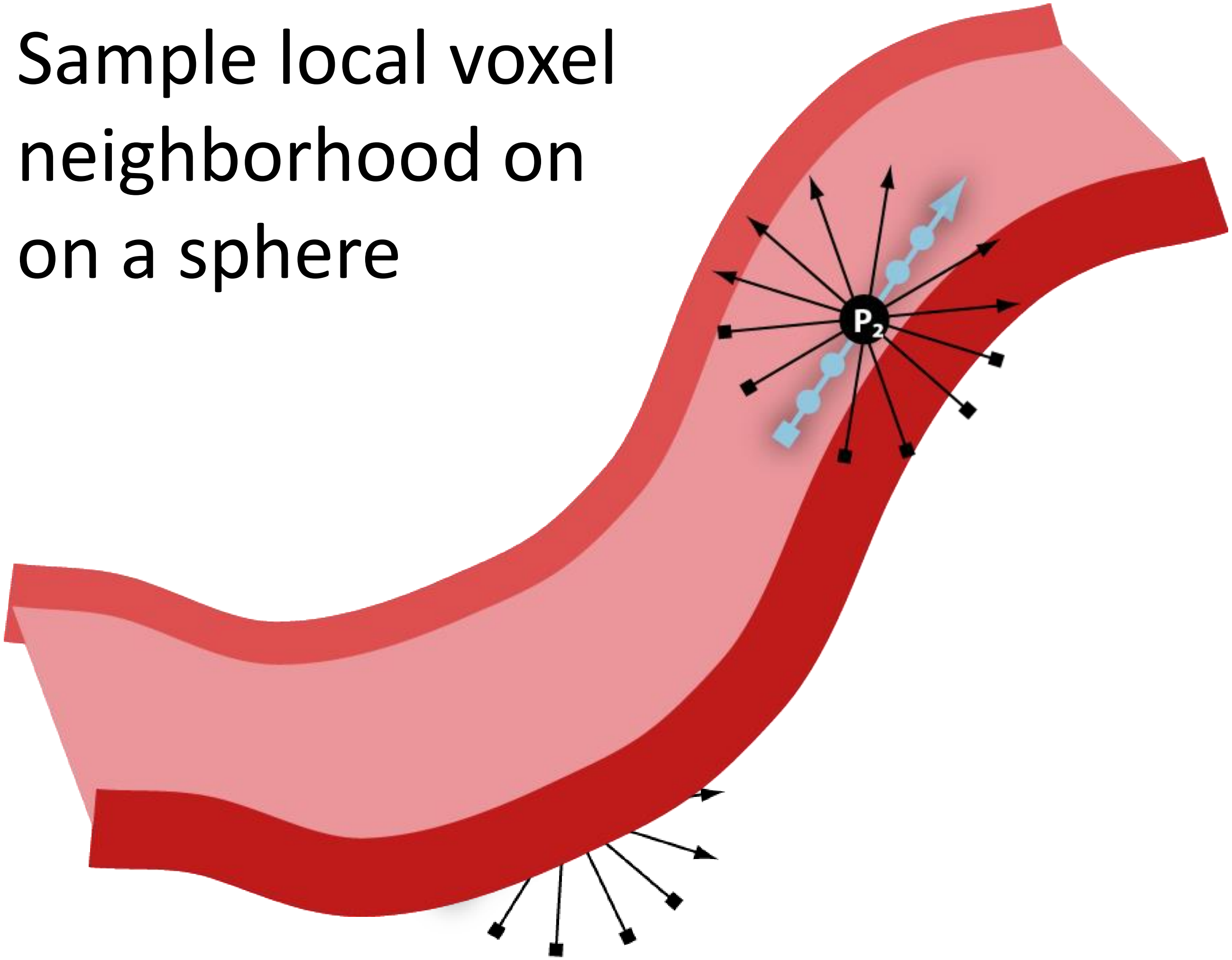
- Remove speckle and random noise
- Structure-preserving filtering
  - Determine local structure orientation
  - Filter along direction of lowest variance



Solteszova el al. 2012: Lowest-Variance Streamlines for Filtering of 3D Ultrasound

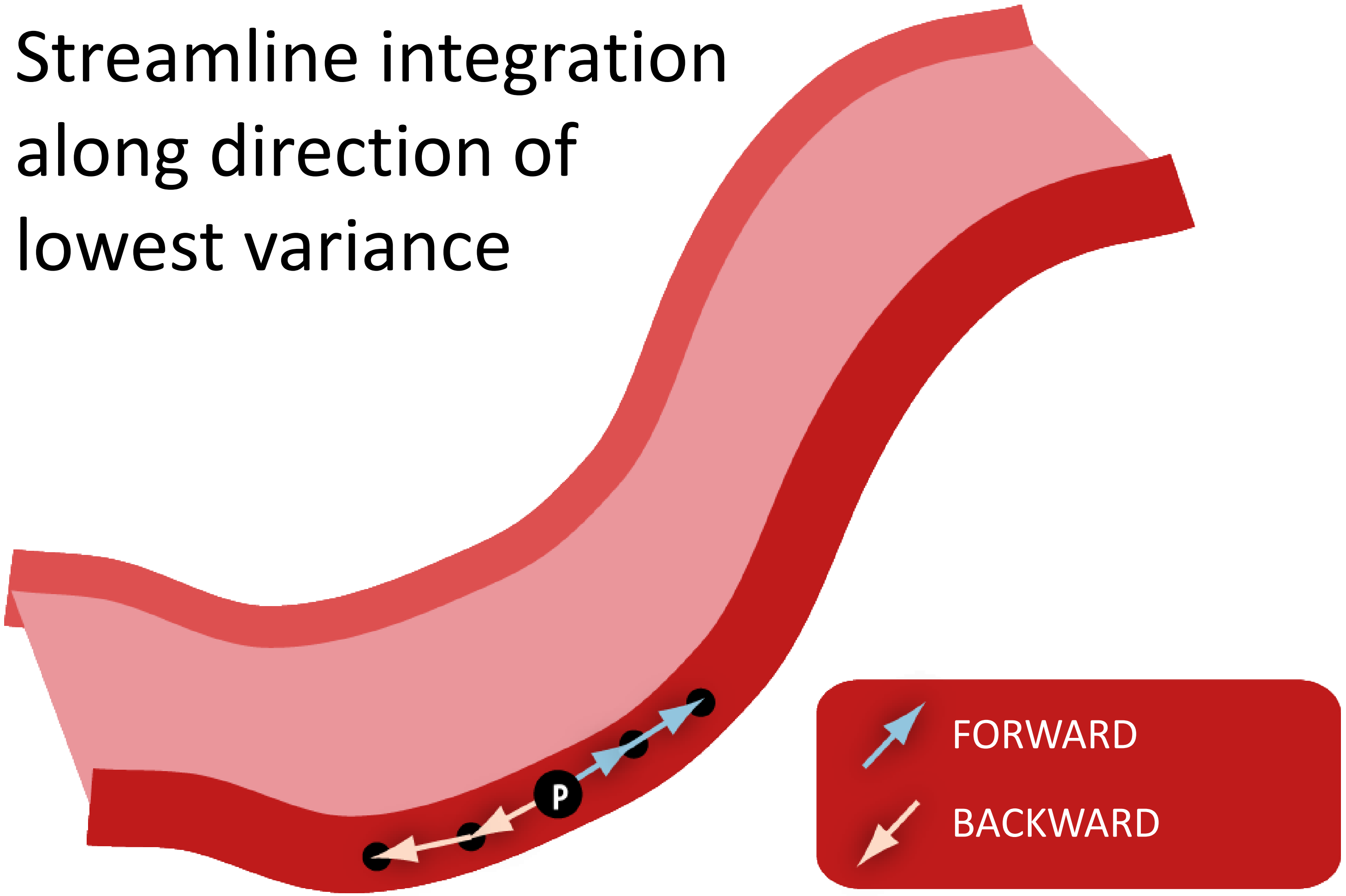
Local Structure Orientation

- Sample local voxel neighborhood on on a sphere

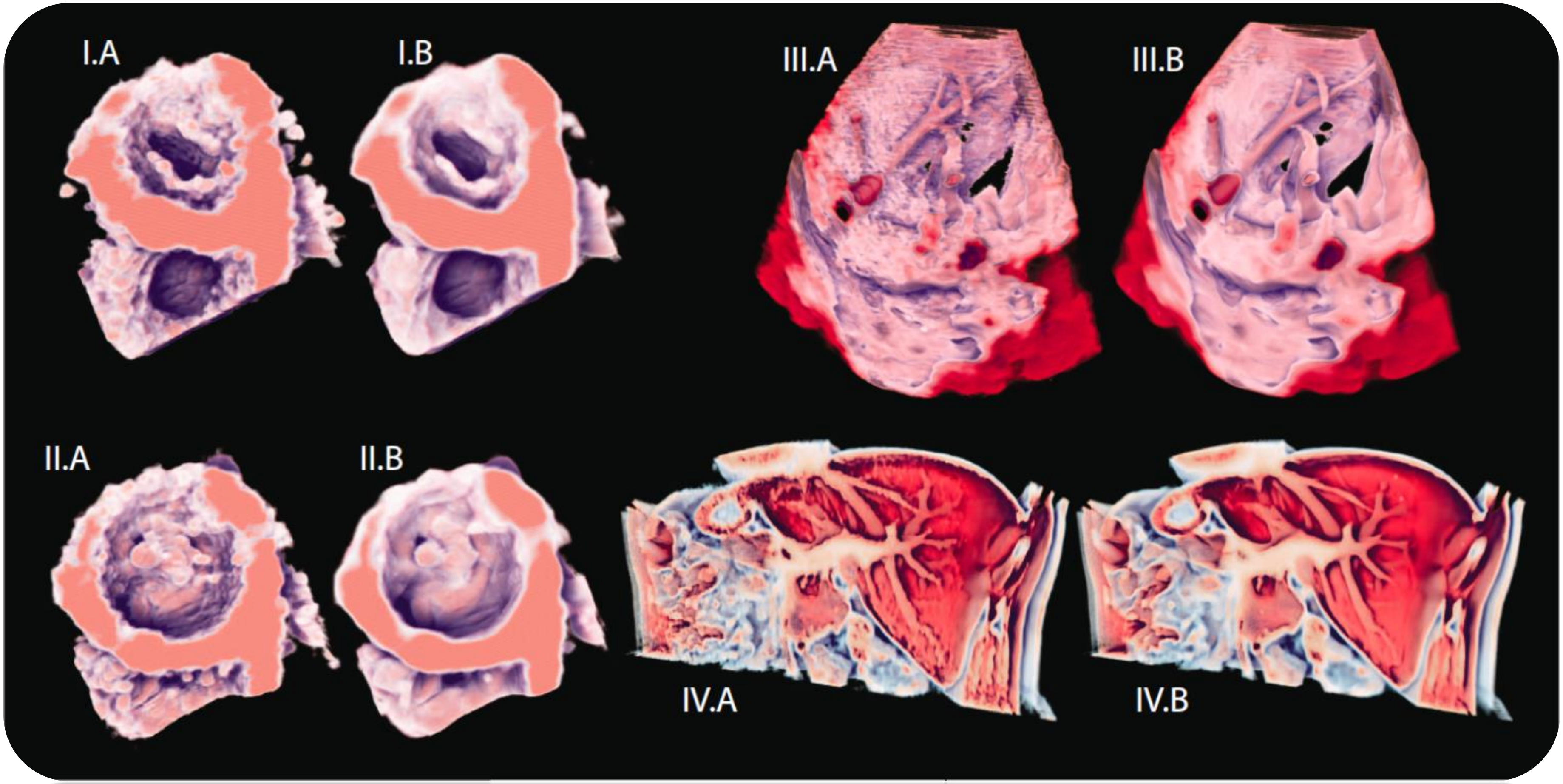


Directional Filtering

- Streamline integration along direction of lowest variance



Results



Solteszova el al. 2012: Lowest-Variance Streamlines for Filtering of 3D Ultrasound

4D Filtering (1)

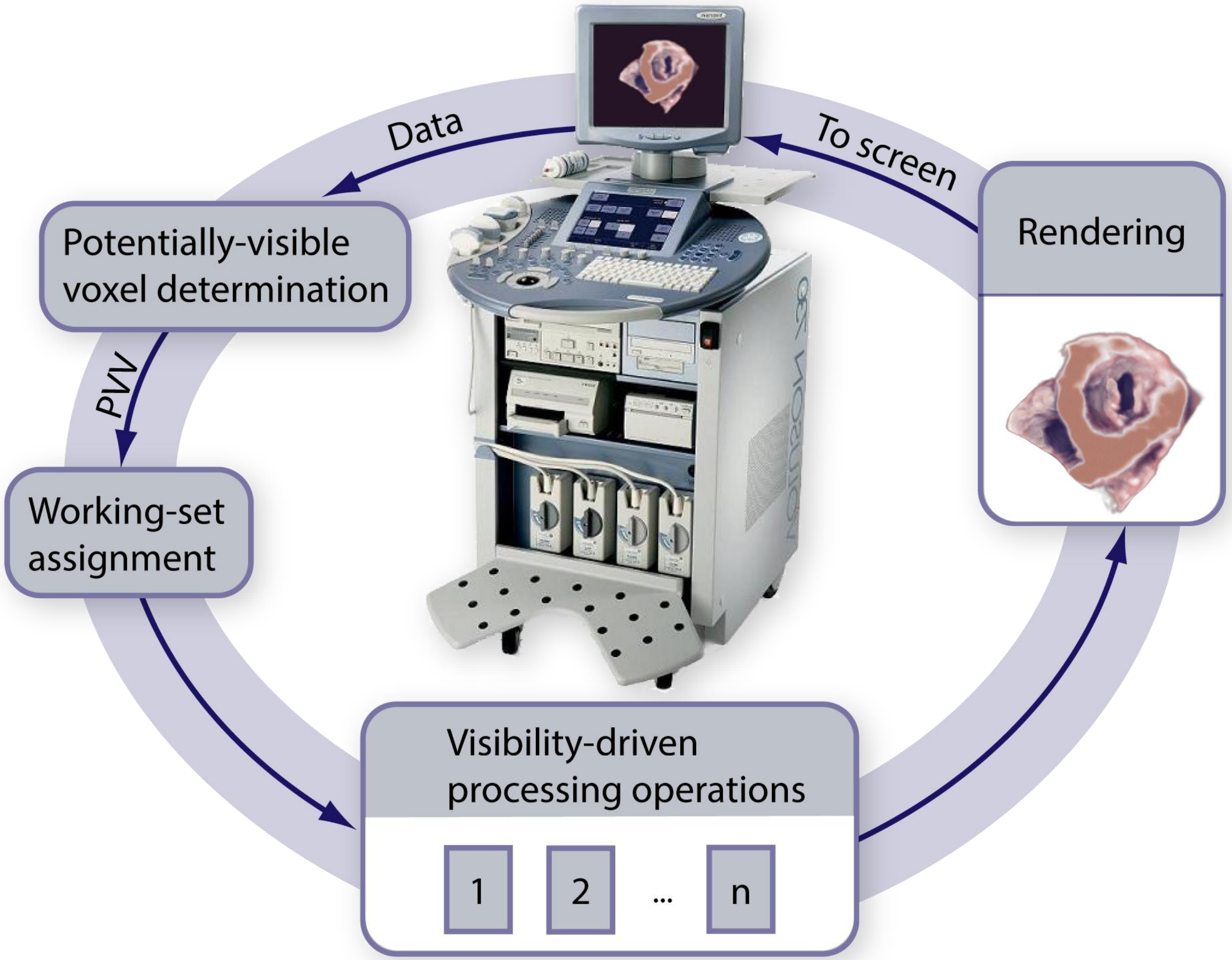
- Acceptable complexity of filtering method is limited by the target frame rate
  - **Idea:** only filter voxels that contribute to the final rendered image
  - **Problem:** filtering changes data values and hence can affect visibility globally
  - **Solution:** conservatively estimate a voxel’s visibility after filtering

4D Filtering (2)

- Only a fraction of voxels actually influence the final image due to transparency and occlusion

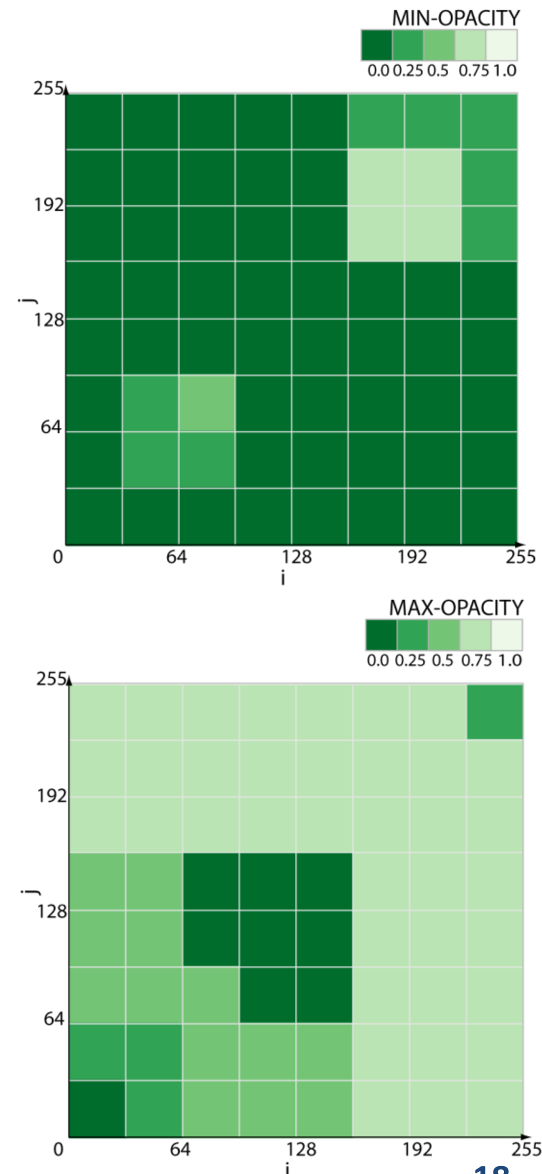
Solteszova el al. 2014: Visibility-Driven Processing of Streaming Volume Data

Visibility-Driven Filtering



Prediction of Filter Behavior

- Opacity of a filtered value of minimum and maximum of a neighborhood
- Possible for all convolution-based filters with normalized non-negative weights
- Lookup tables for conservative visibility mask calculation



Solteszova el al. 2014: Visibility-Driven Processing of Streaming Volume Data

Results (1)

unfiltered

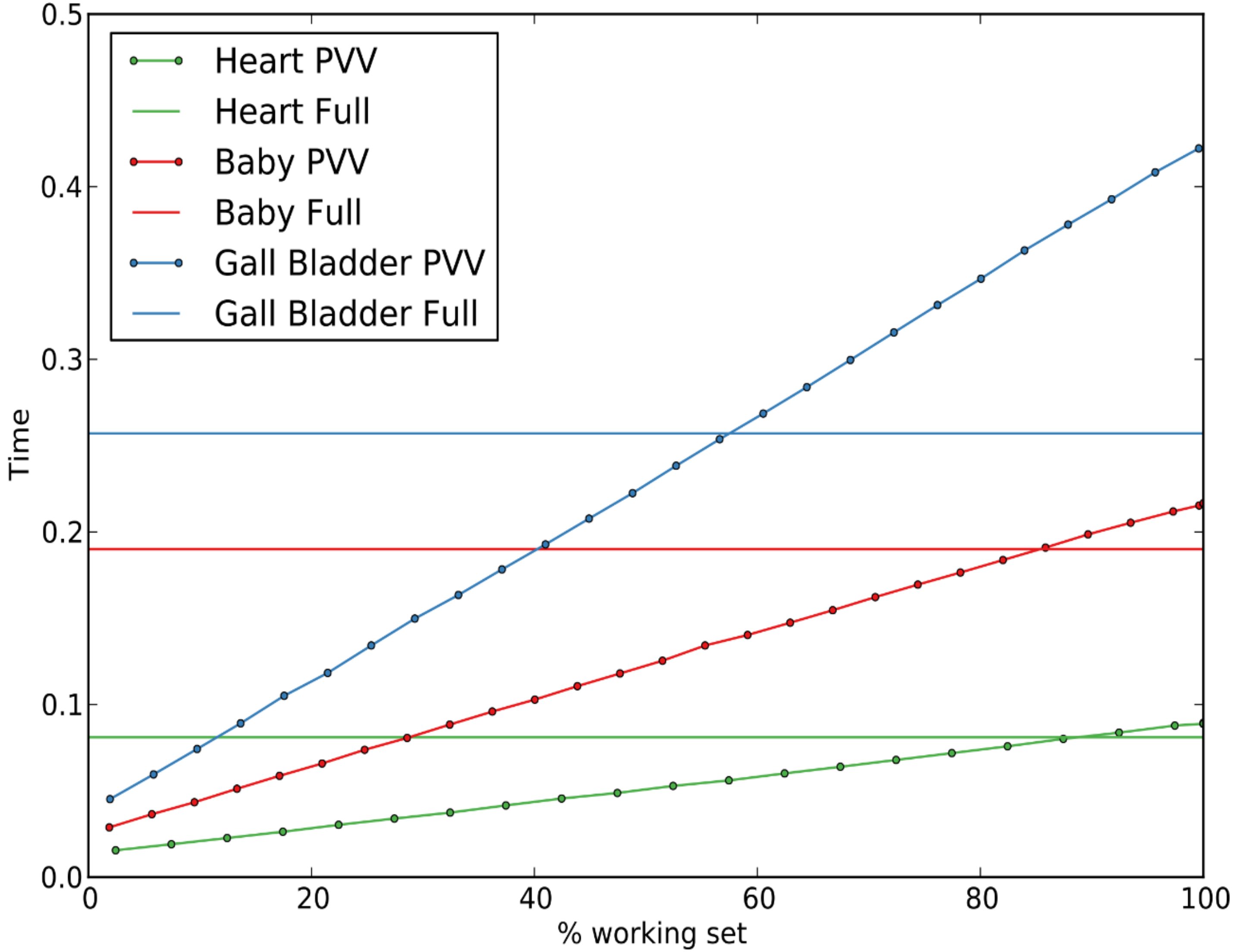
regular filtering
5 fps

=

visibility optimized
10 fps

Solteszova el al. 2014: Visibility-Driven Processing of Streaming Volume Data

Results (2)



Solteszova el al. 2014: Visibility-Driven Processing of Streaming Volume Data

From Static to Dynamic

Visualization of Real-Time Imaging Data

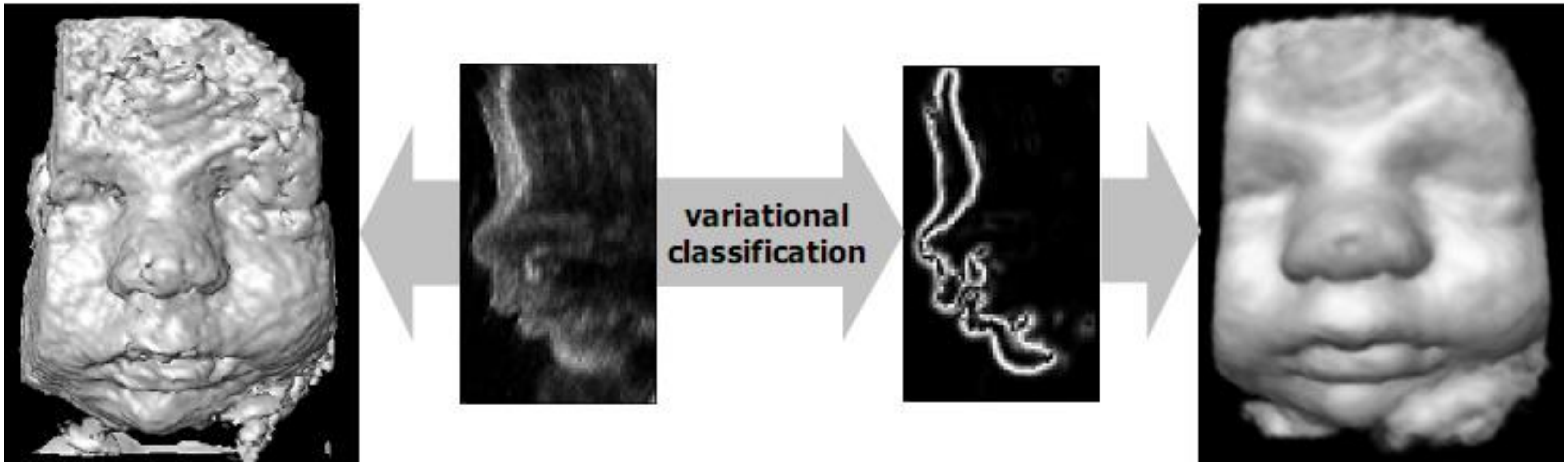
CLASSIFICATION

Classification

- Mapping of data values to optical properties (usually color and opacity)
- Several challenges
  - Low dynamic range
  - Significant amount of noise and speckle
  - Varying intensities for the same tissue
  - Fuzzy boundaries

Variational Classification

- Simultaneous denoising and opacity assignment
- Variational approach based on isovalue and gradient



Fattal and Lischinski 2001: Variational Classification for Visualization of 3D Ultrasound Data

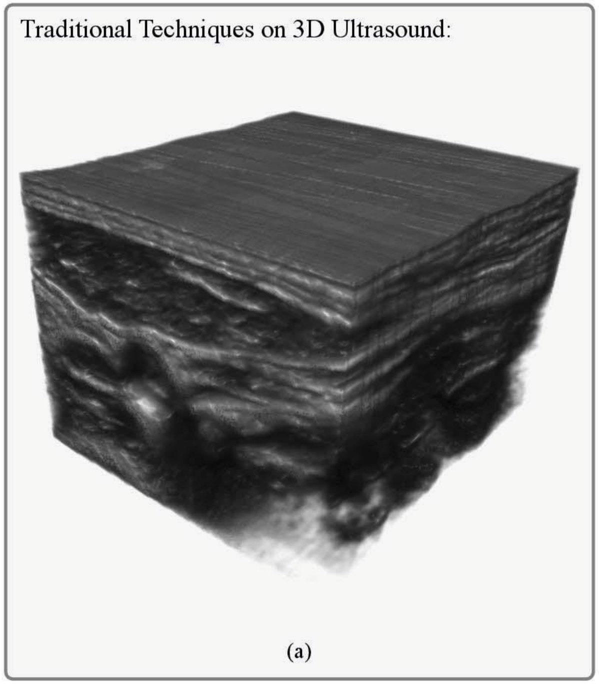
Scale Space Filtering

- Automatic adjustment of the global opacity transfer function based on scale-space filtering

Hönigmann et al. 2003: Adaptive Design of a Global Opacity Transfer Function for Direct Volume Rendering of Ultrasound Data

Predicate-based Classification

- **Problem:** classification of 3D ultrasound data for volume visualization
  - Standard 1D transfer functions don't work well for ultrasound
  - Additional attribute dimensions can help, but classification space becomes difficult to navigate
- **Approach:** define a set of point predicates which can be combined via logical operations



(a)

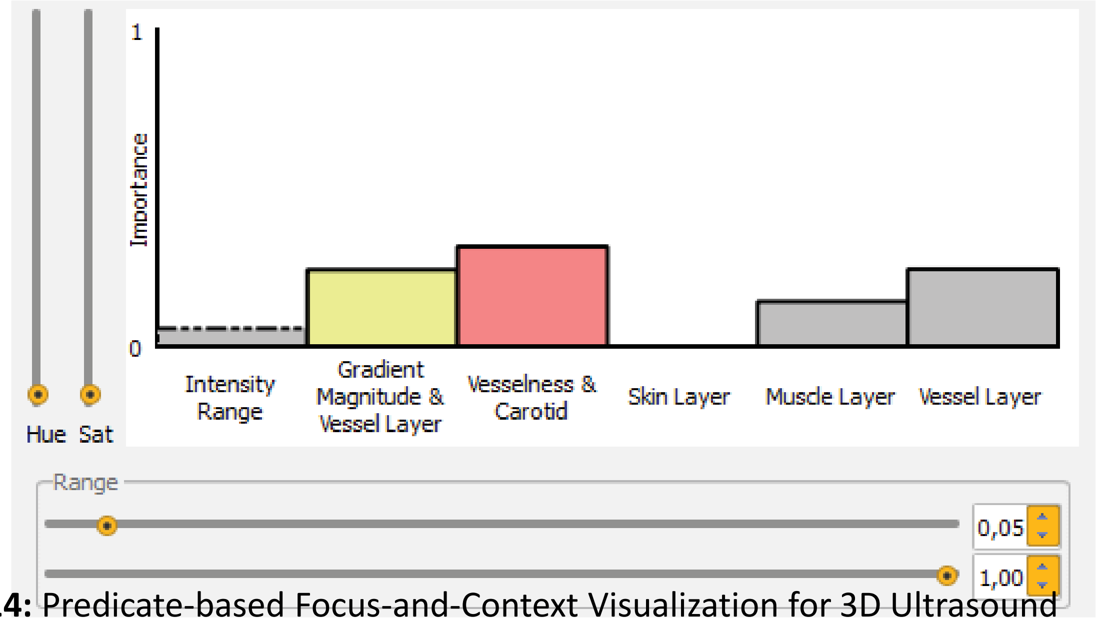
Predicate Library

- Set of different local and non-local predicates $P = (f_P\colon X \rightarrow \{true, false\}, \kappa_P, \delta_P)$
  - κ_P is an importance factor
  - δ_P is the color modulation
- Examples of possible predicates
  - Range-based predicates
  - Direction-based predicates
  - Signal-to-Noise ratio predicate
  - Vesselness predicate
  - Confidence predicate
  - Label predicate

Schulte zu Berge et al. 2014: Predicate-based Focus-and-Context Visualization for 3D Ultrasound

Predicate Setup

- Simple widget to assign importances and colors
- Combination of predicates with Boolean operations (and, or, not)



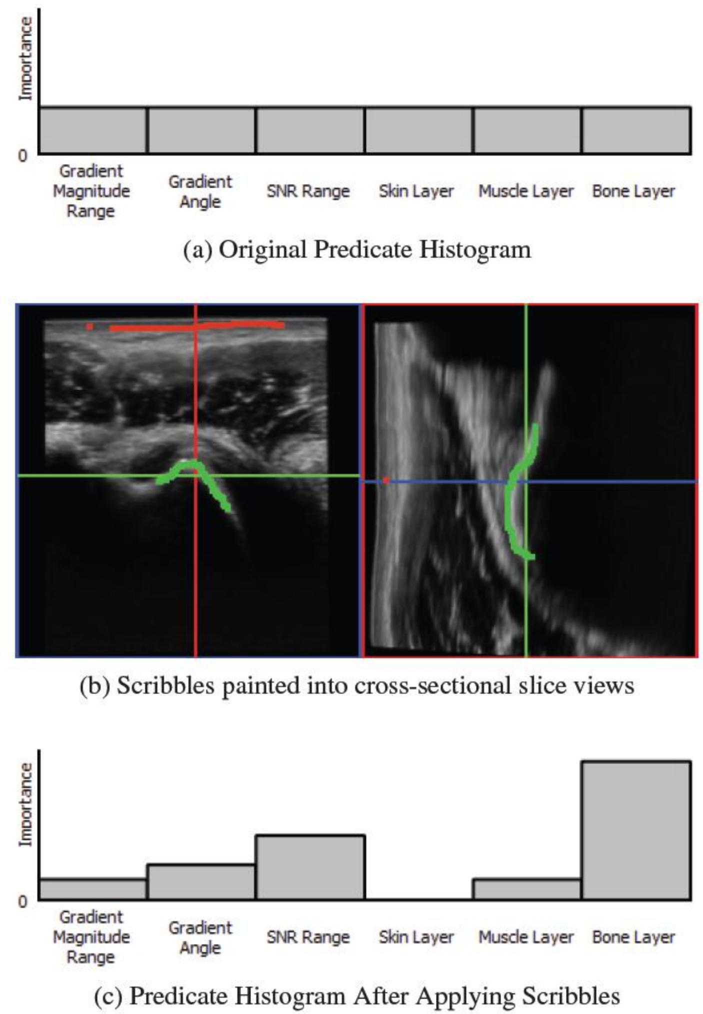
Schulte zu Berge et al. 2014: Predicate-based Focus-and-Context Visualization for 3D Ultrasound

Visual Mapping

- Importance-driven layered compositing, cf.
  [Viola et al. 2004, Rautek et al. 2007]
- High-importance layers receive higher visibility (depth relationships can be overridden)
- Predicates only affect hue and opacity, luminance comes from data values

Predicate Histogram

- Sketch-based interface for predicate setup
- User draws *positive* and *negative* sketch
- Importance of each predicate is modulated accordingly



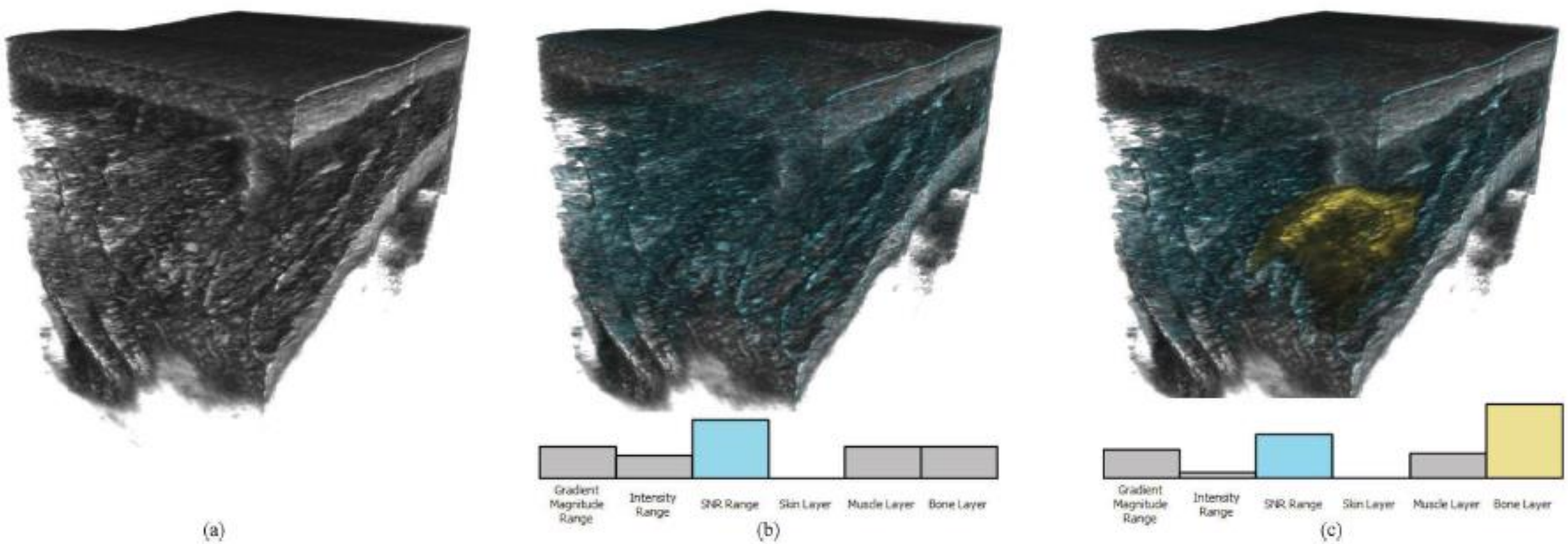
(a) Original Predicate Histogram

(b) Scribbles painted into cross-sectional slice views

(c) Predicate Histogram After Applying Scribbles

Results (1)

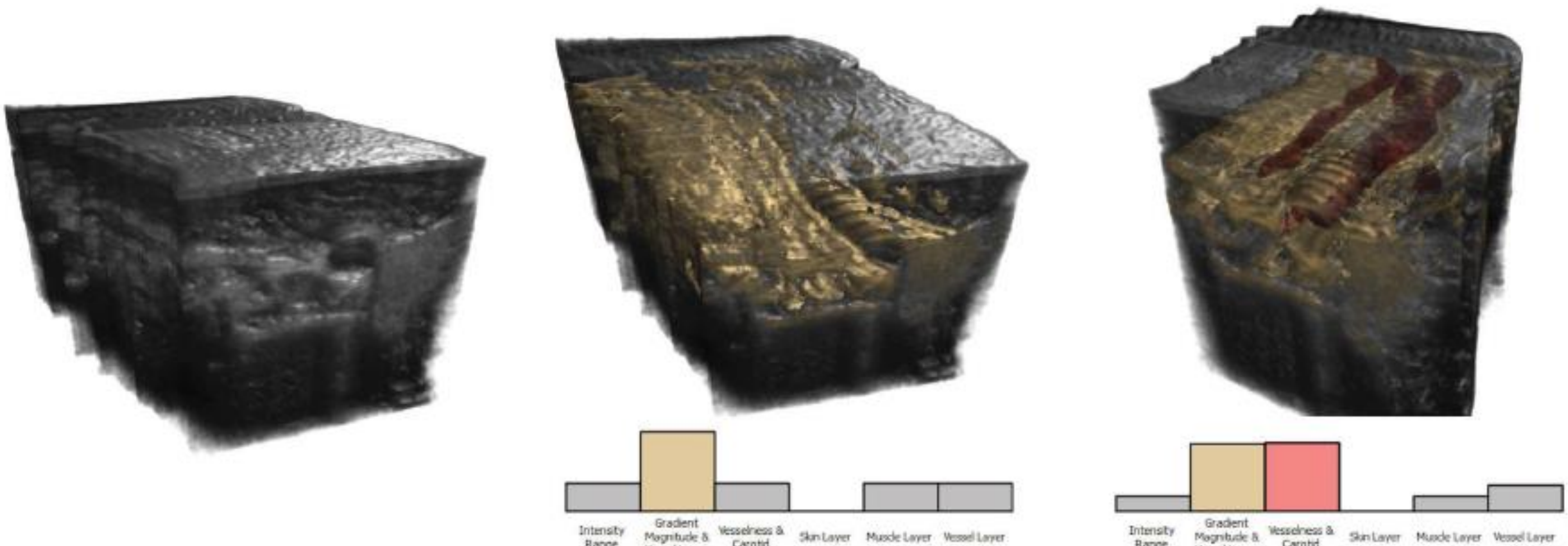
- Shoulder dataset: combines visualization of **bone** and **muscle** tissue



Schulte zu Berge et al. 2014: Predicate-based Focus-and-Context Visualization for 3D Ultrasound

Results (2)

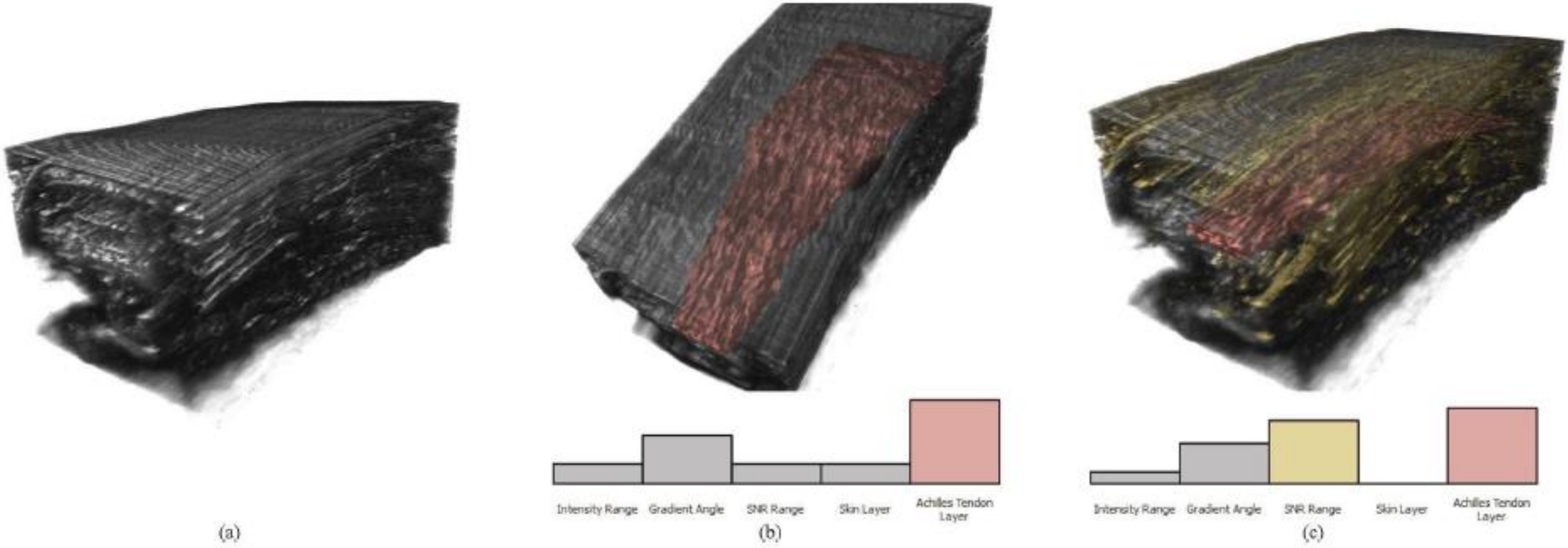
- Path of the **carotid artery** is shown in red



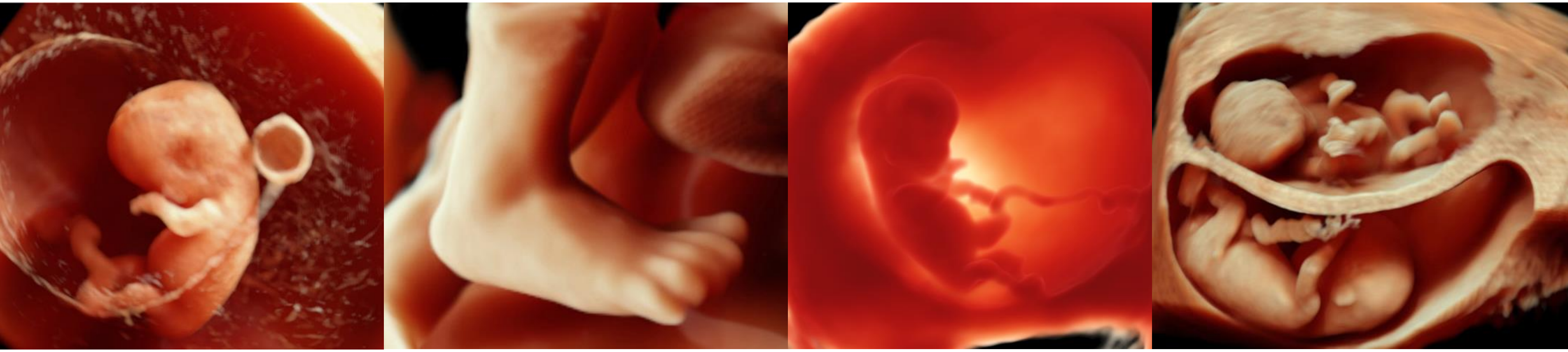
(a) (b) (c)

Results (3)

- **Achilles tendon** is shown in red



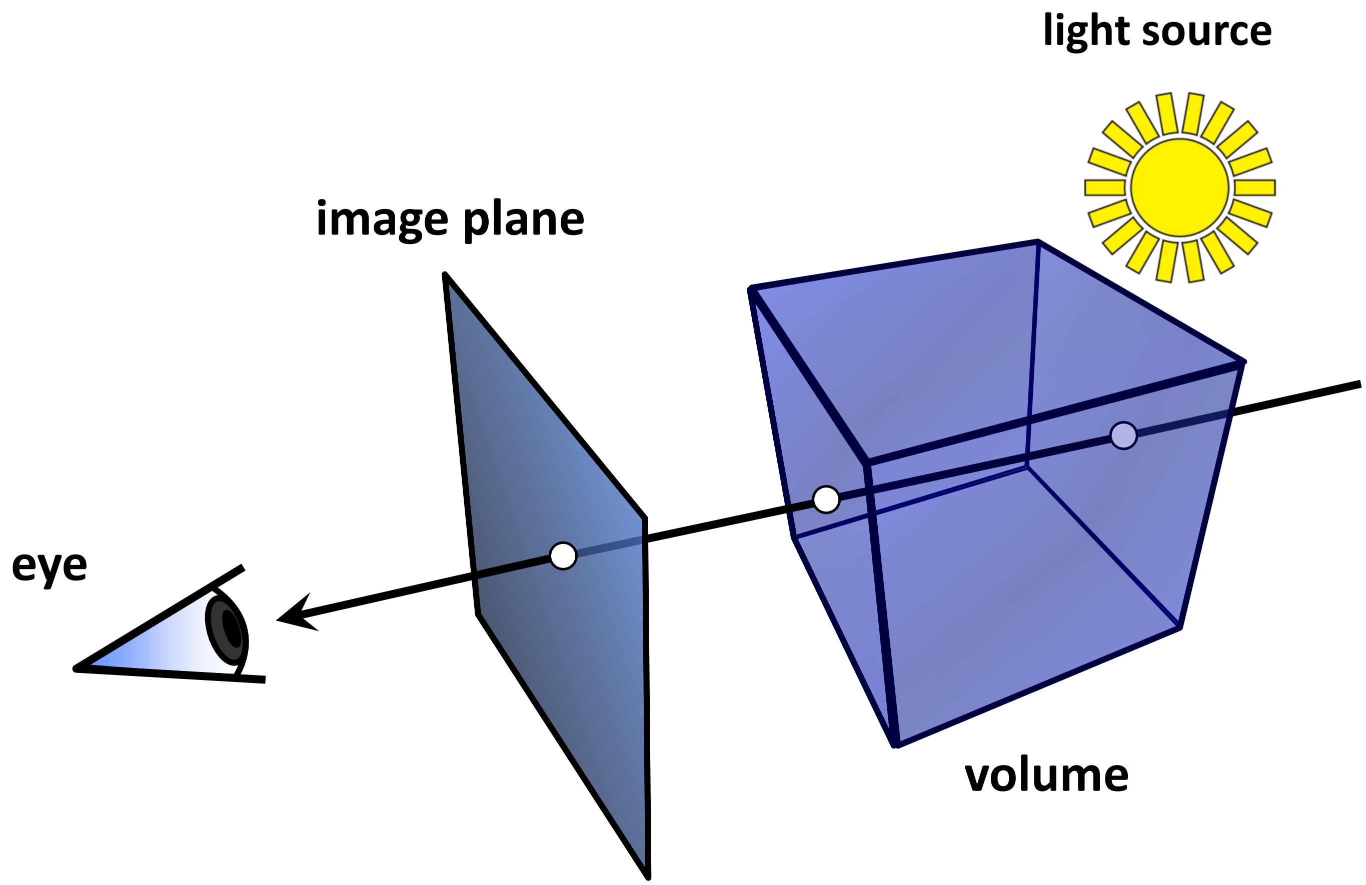
Schulte zu Berge et al. 2014: Predicate-based Focus-and-Context Visualization for 3D Ultrasound



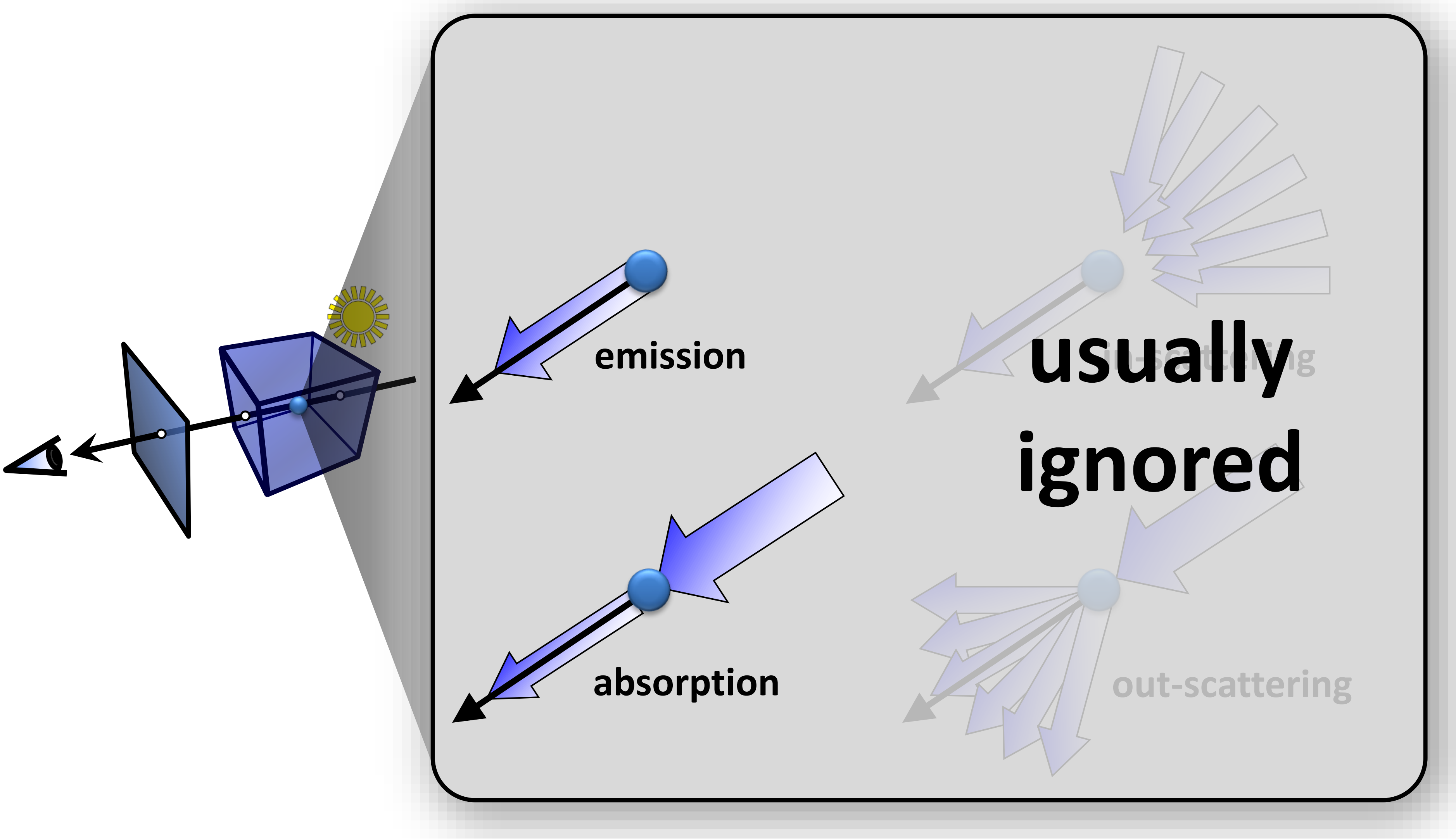
Recent Developments in Ultrasound Visualization

RENDERING

Volume Rendering (1)



Volume Rendering (2)



Local Volume Illumination

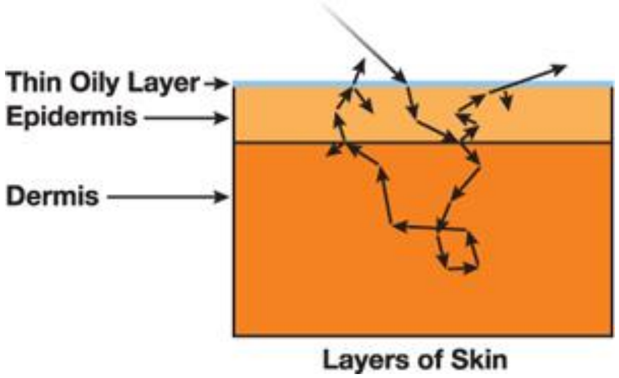
- Only a function of gradient direction and light source parameters
  - Volumetric absorption between light source and sample point is ignored → no shadows
  - Multiple scattering is ignored → no color bleeding effects

conventional rendering

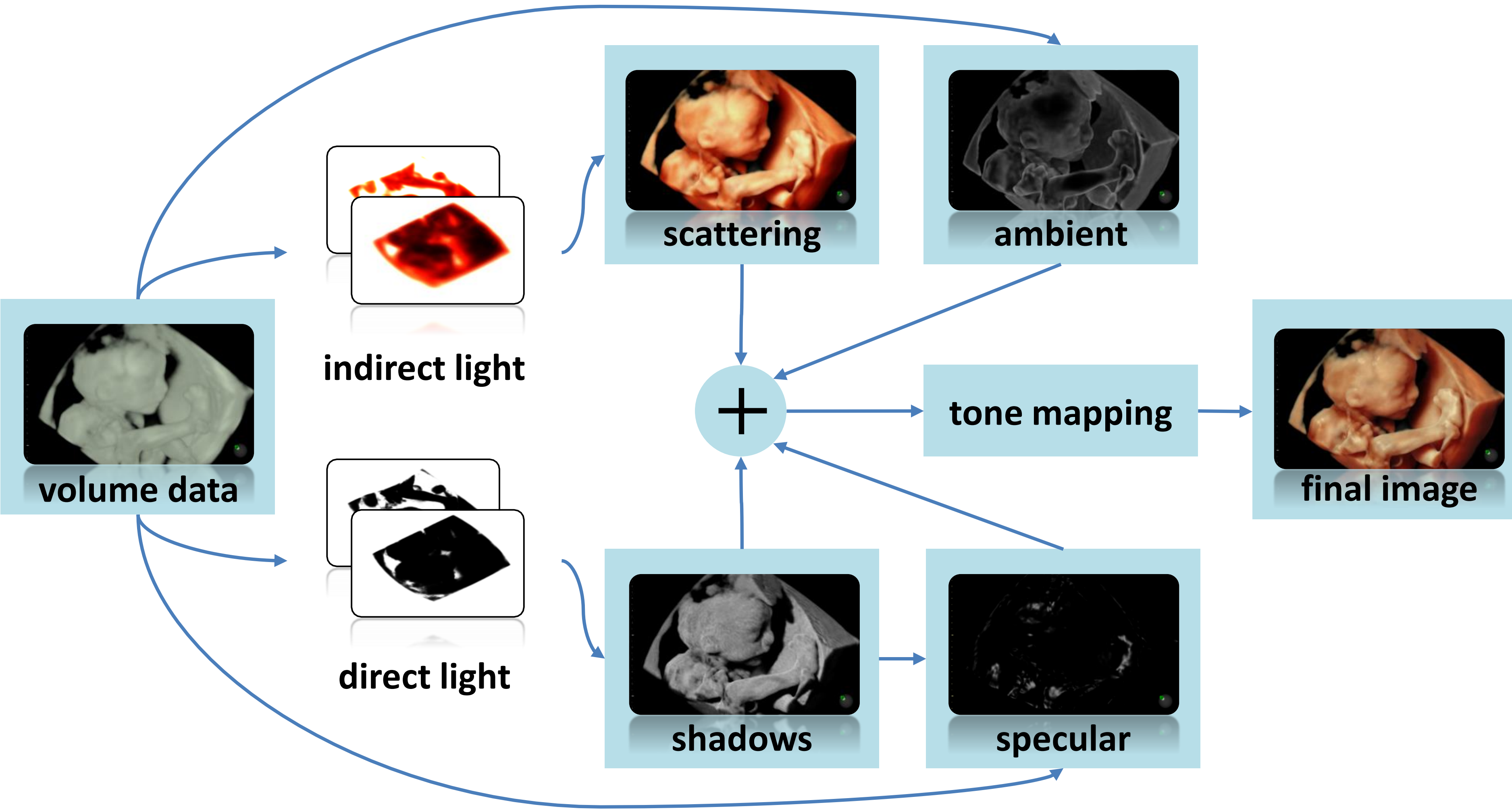
fetoscopic image

Light Propagation in Tissue

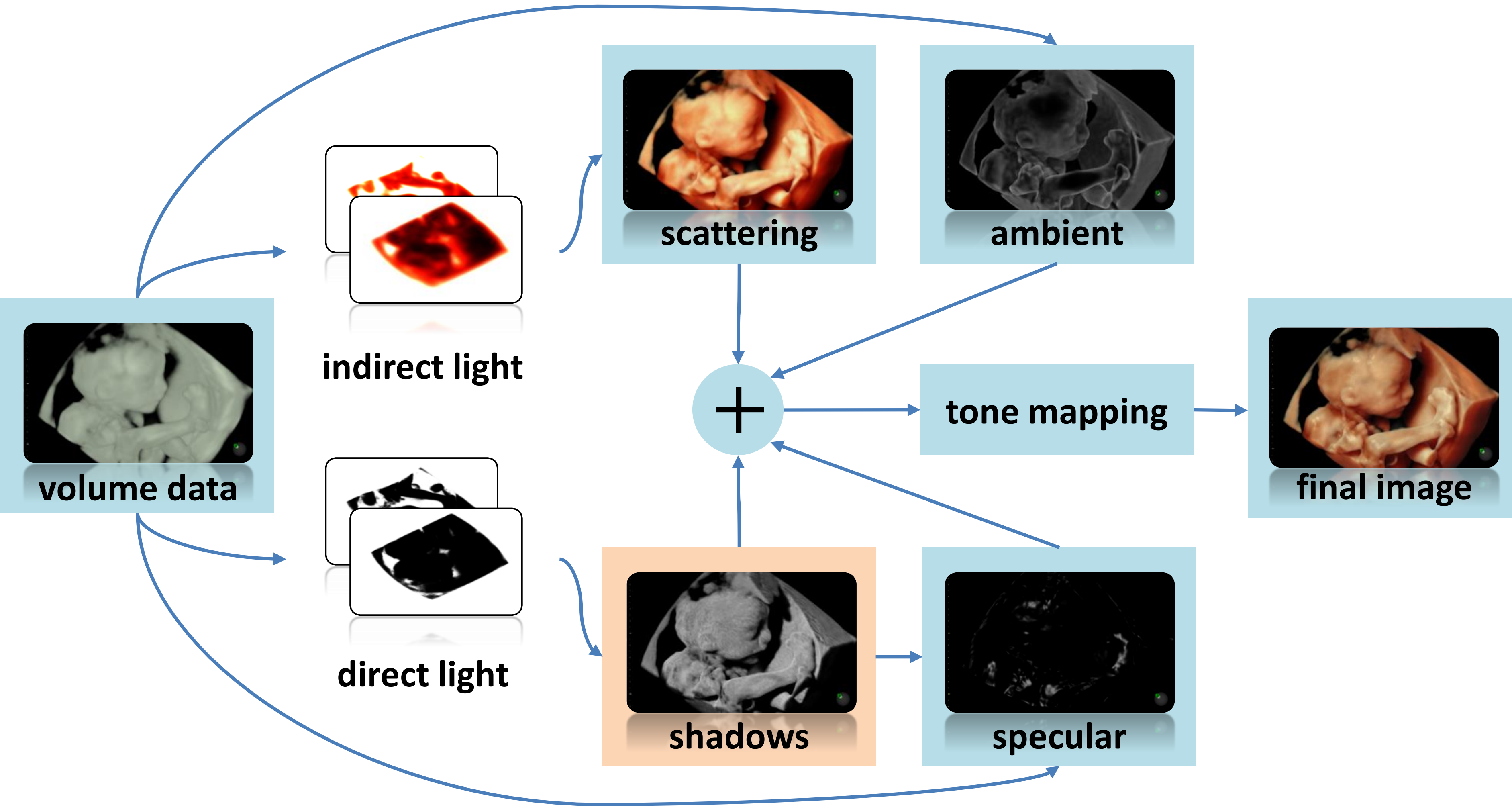
- Human skin (and tissue in general) is translucent
  - Red penetrates deeper than blue and green light
  - Light scatters predominantly in forward direction
  - Light propagation tends to become isotropic after multiple scattering events



Fetoscopic Illumination Model

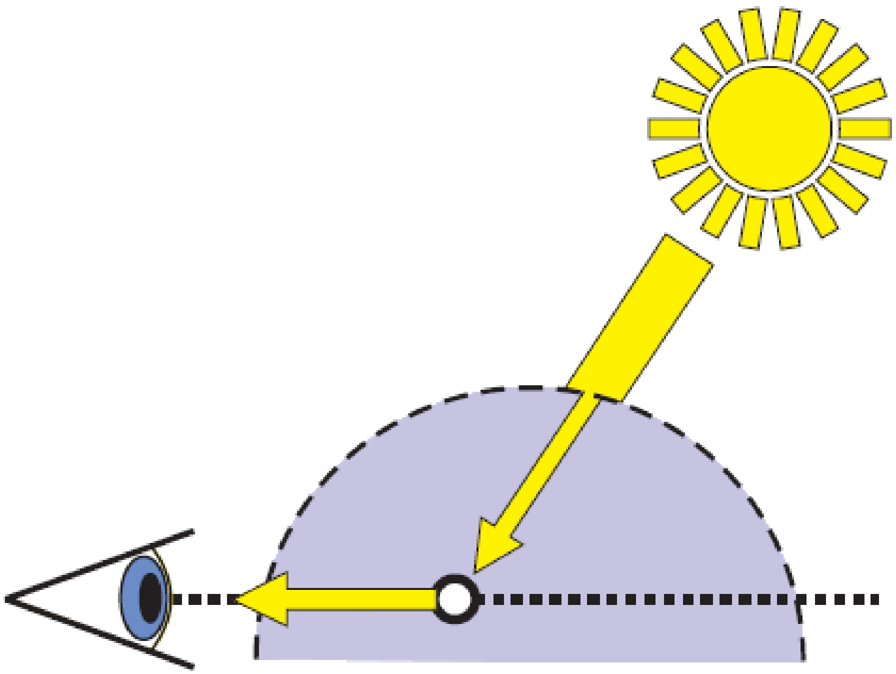


Fetoscopic Illumination Model

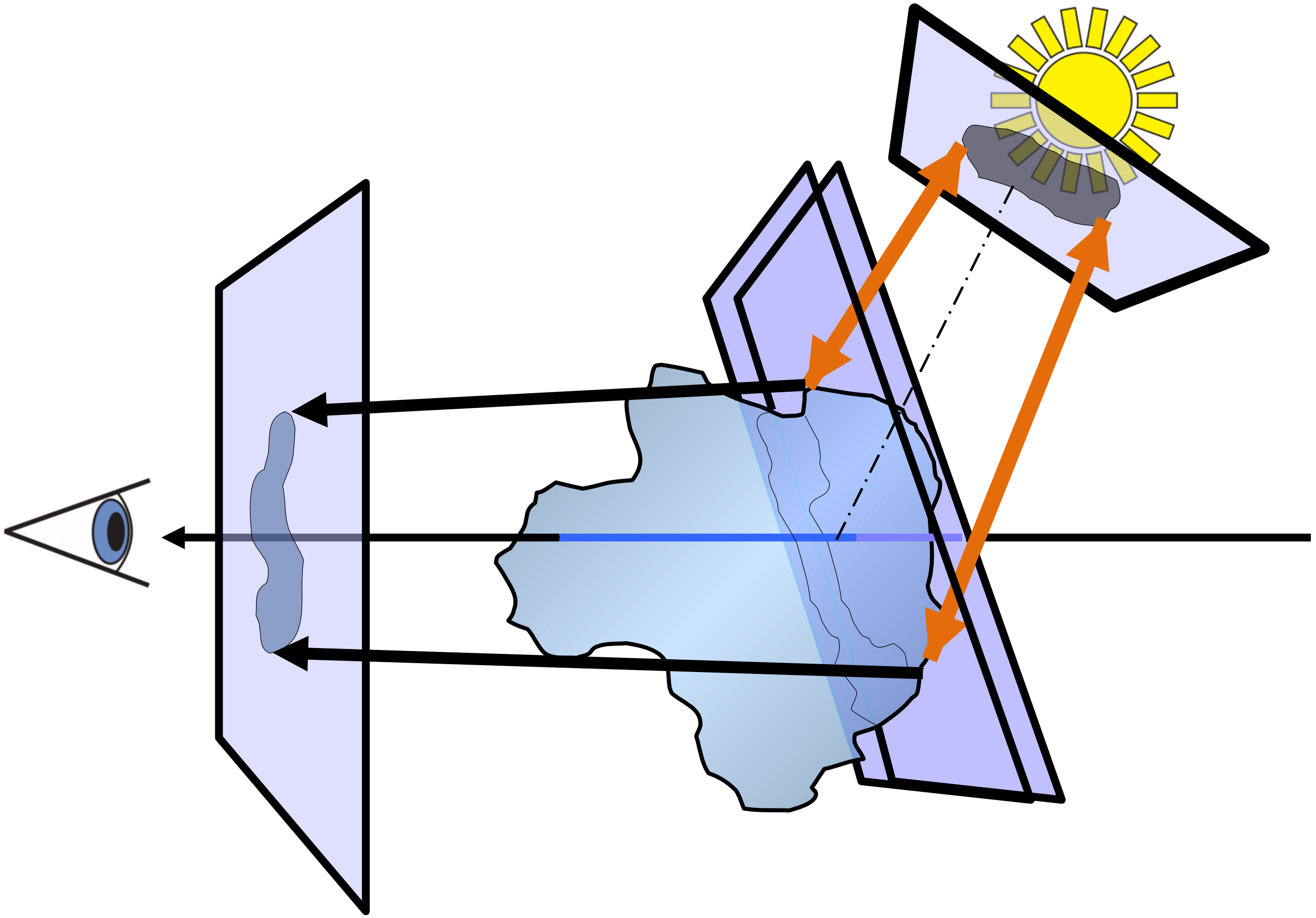


Direct Lighting (1)

Light is attenuated along its way through the volume

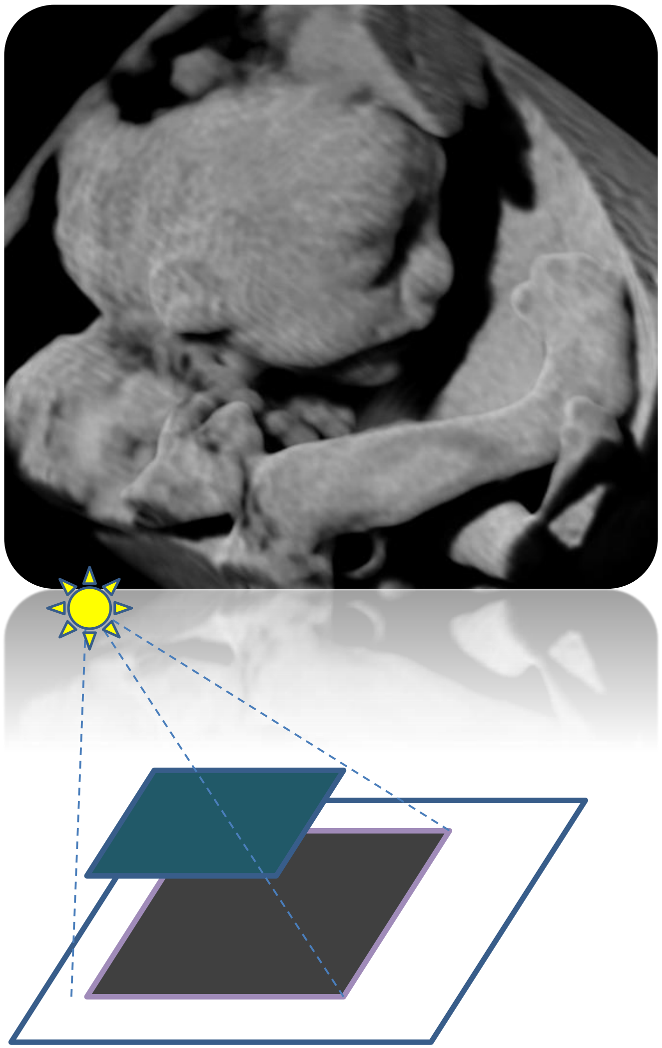


Direct Lighting (2)

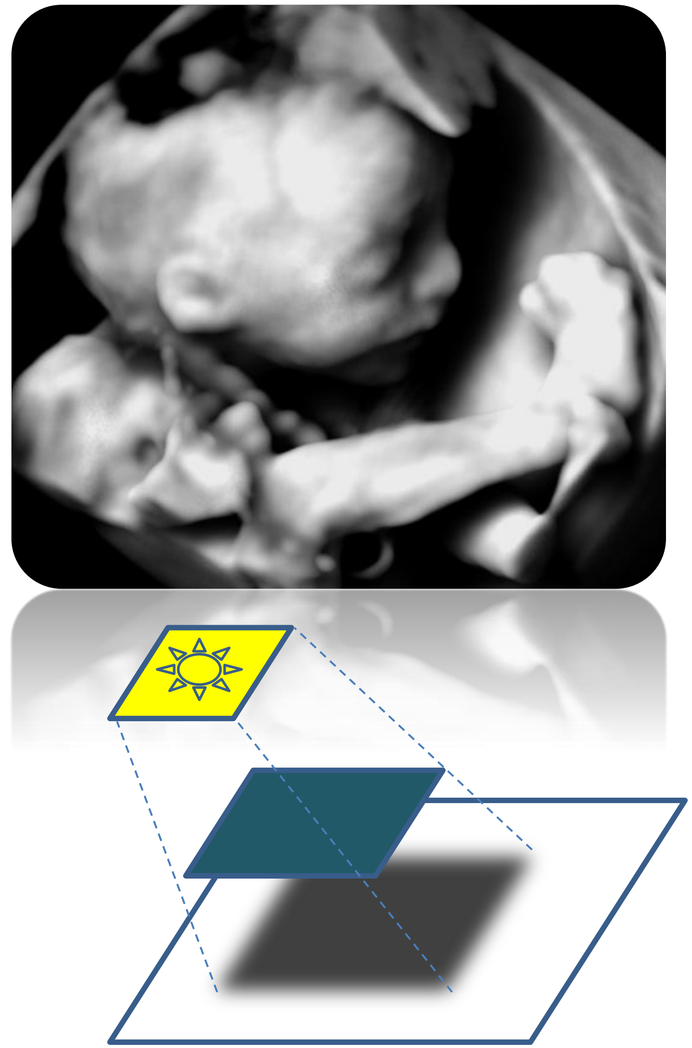


Kniss et al. 2003: A Model for Volume Lighting and Modeling

Light Source Extent (1)

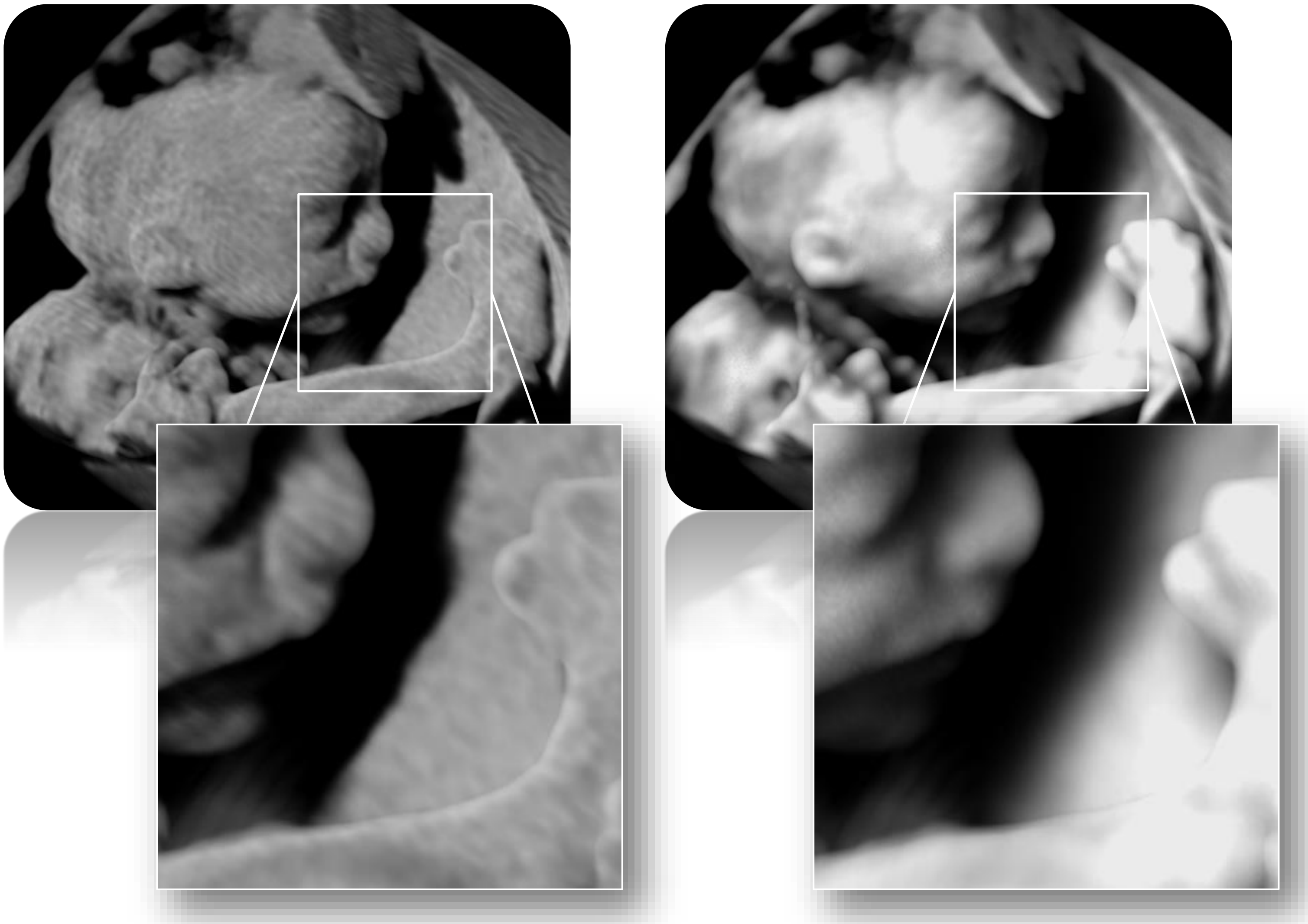


hard shadows

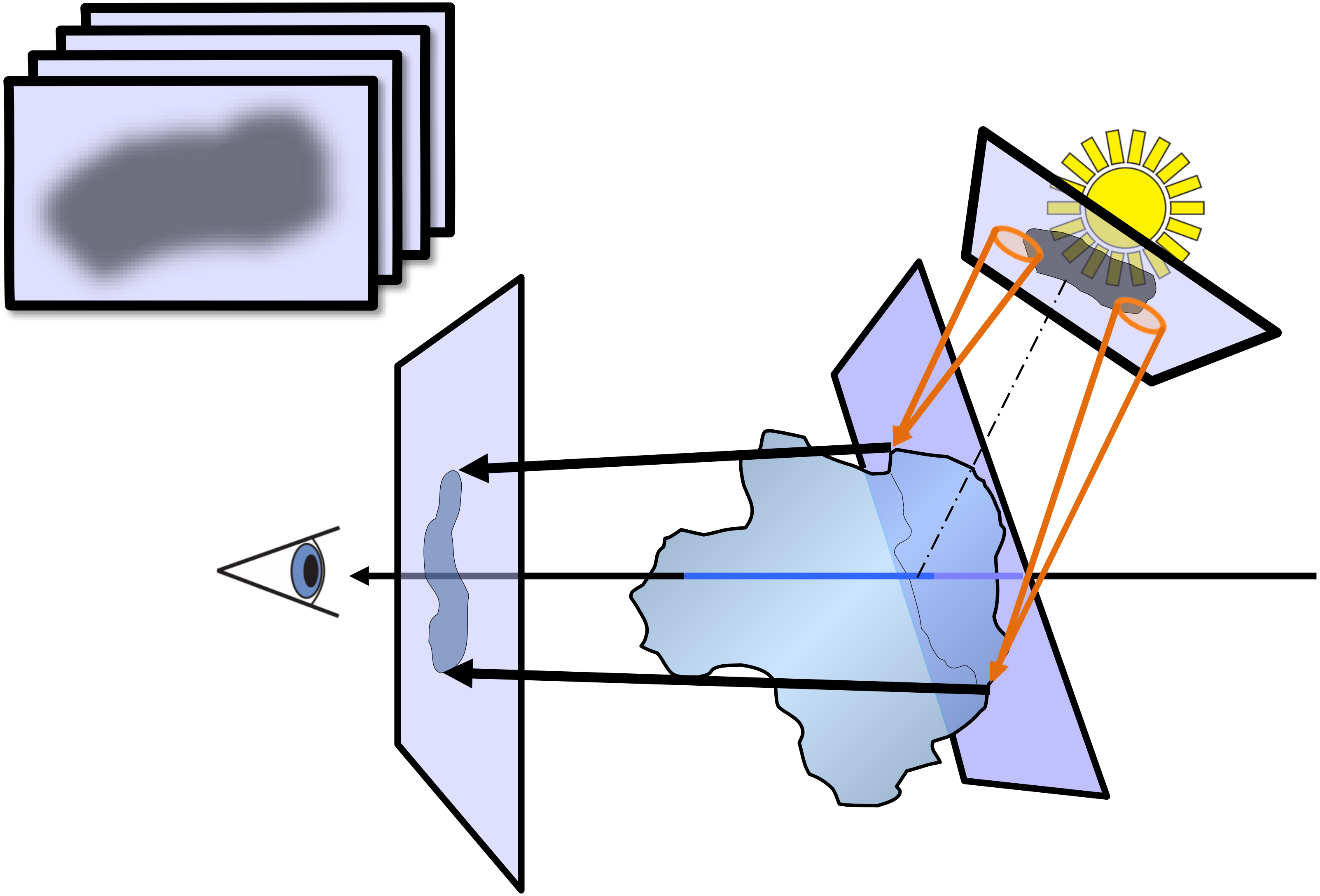


soft shadows

Light Source Extent (2)

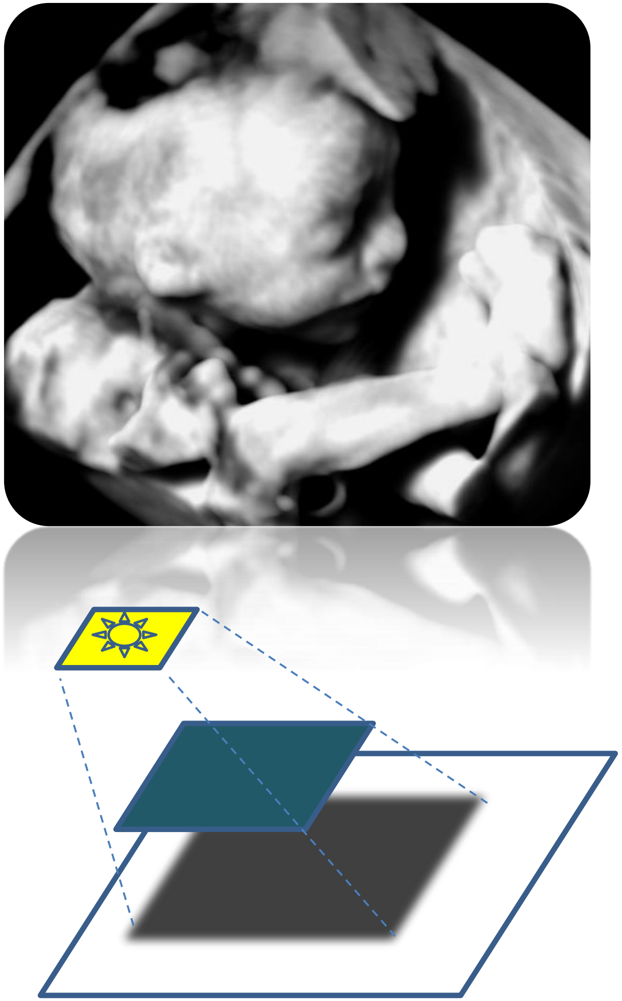


Soft Shadows



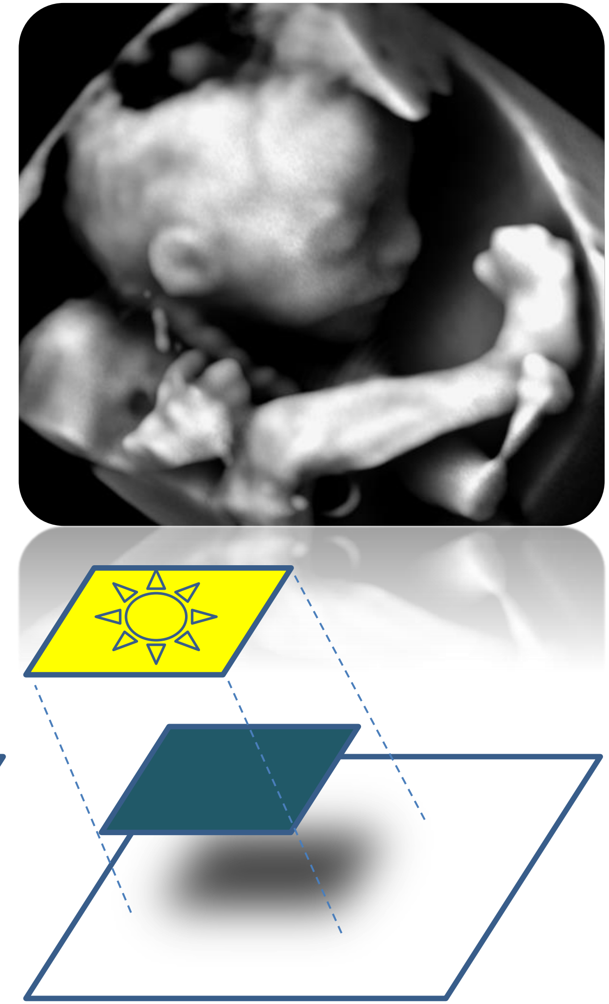
Patel et al. 2013: Instant Convolution Shadows for Volumetric Detail Mapping

Kernel Size (1)



shadow softness - low

shadow softness - medium



shadow softness - high

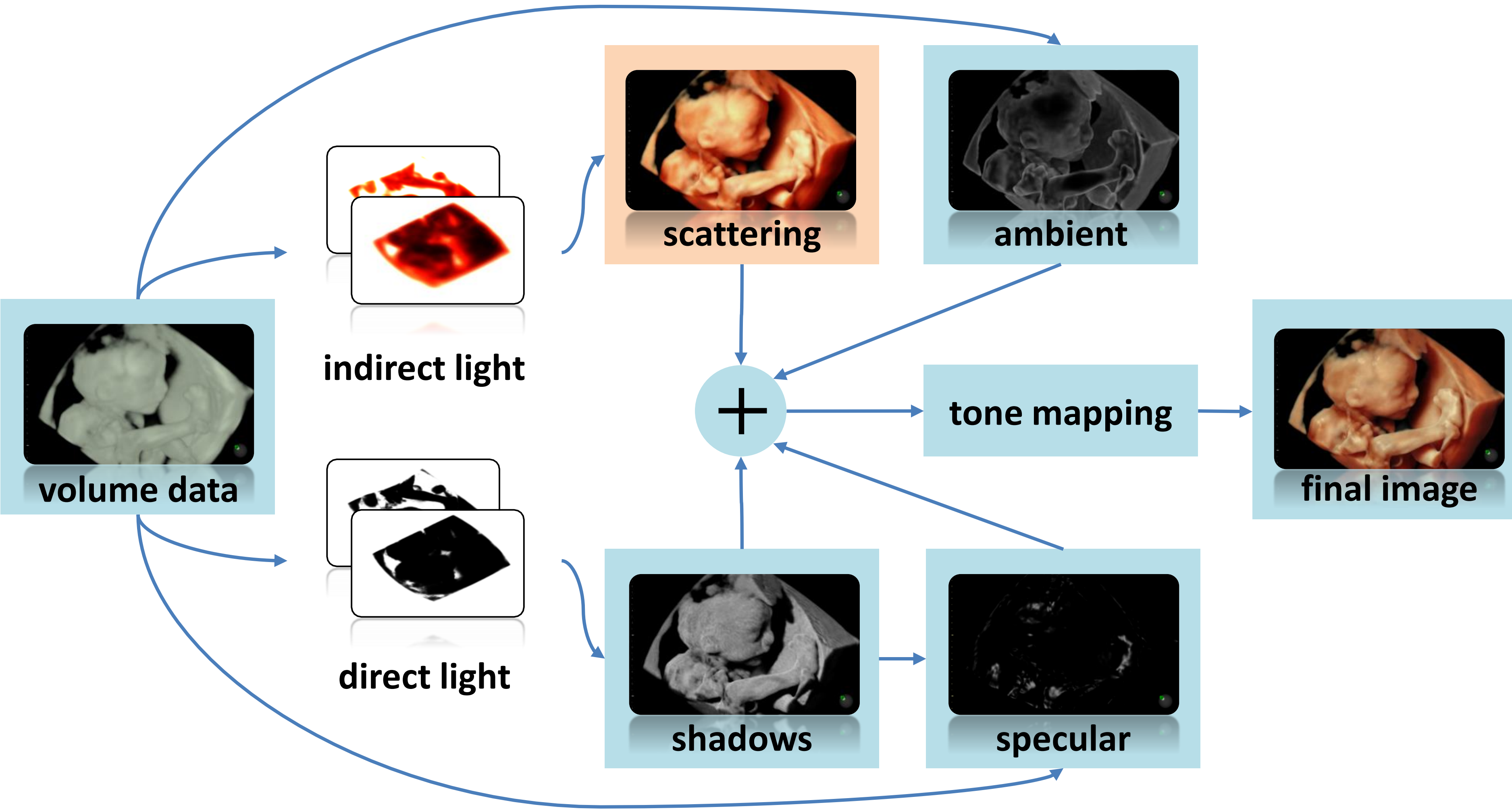
Kernel Size (2)

shadow softness - low

shadow softness - medium

shadow softness - high

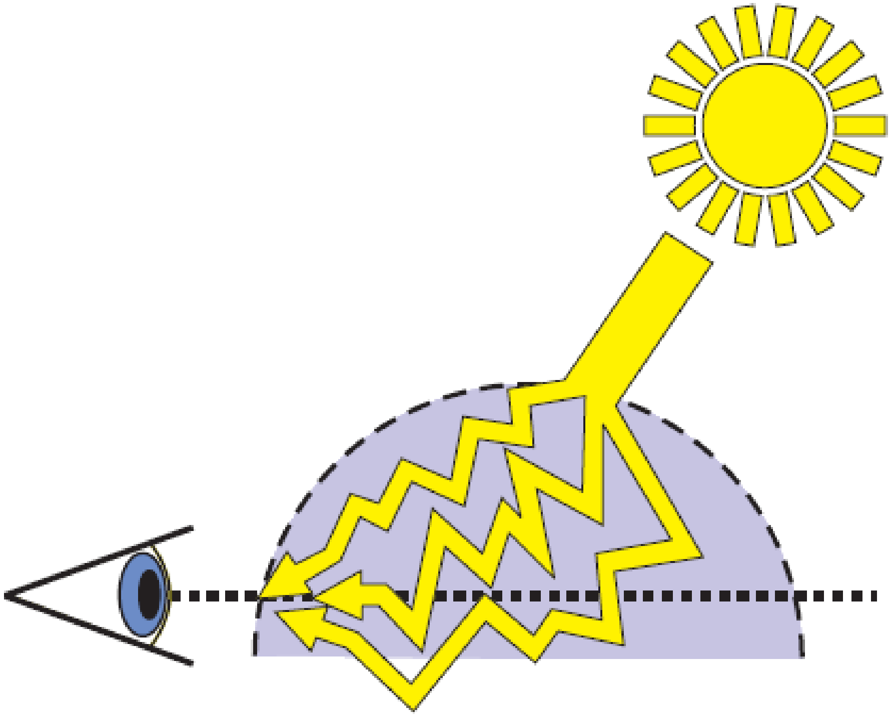
Fetoscopic Illumination Model



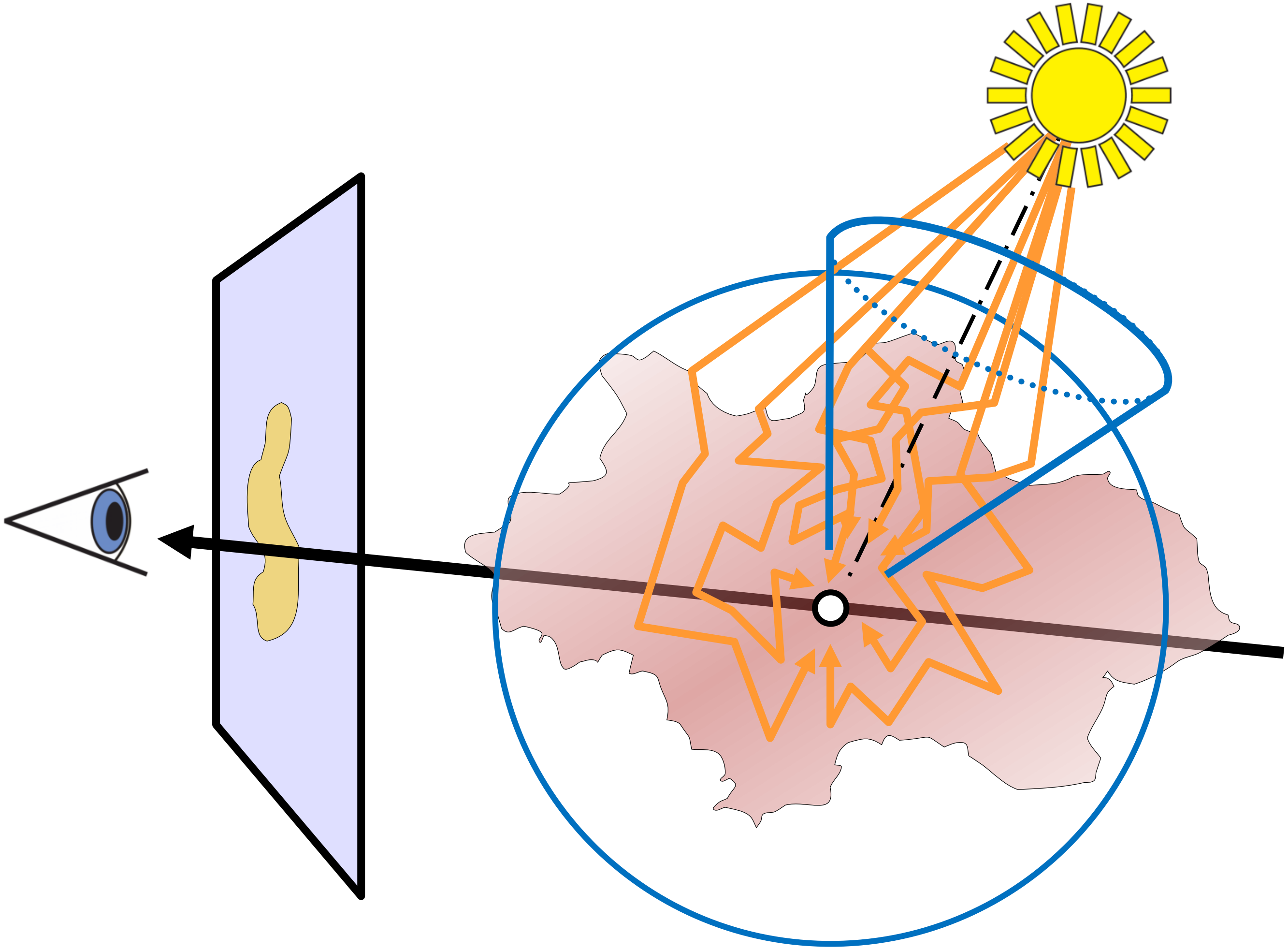
Varchola 2012: Live Fetoscopic Visualization of 4D Ultrasound Data

Indirect Lighting (1)

Light is scattered multiple times before it reaches the eye

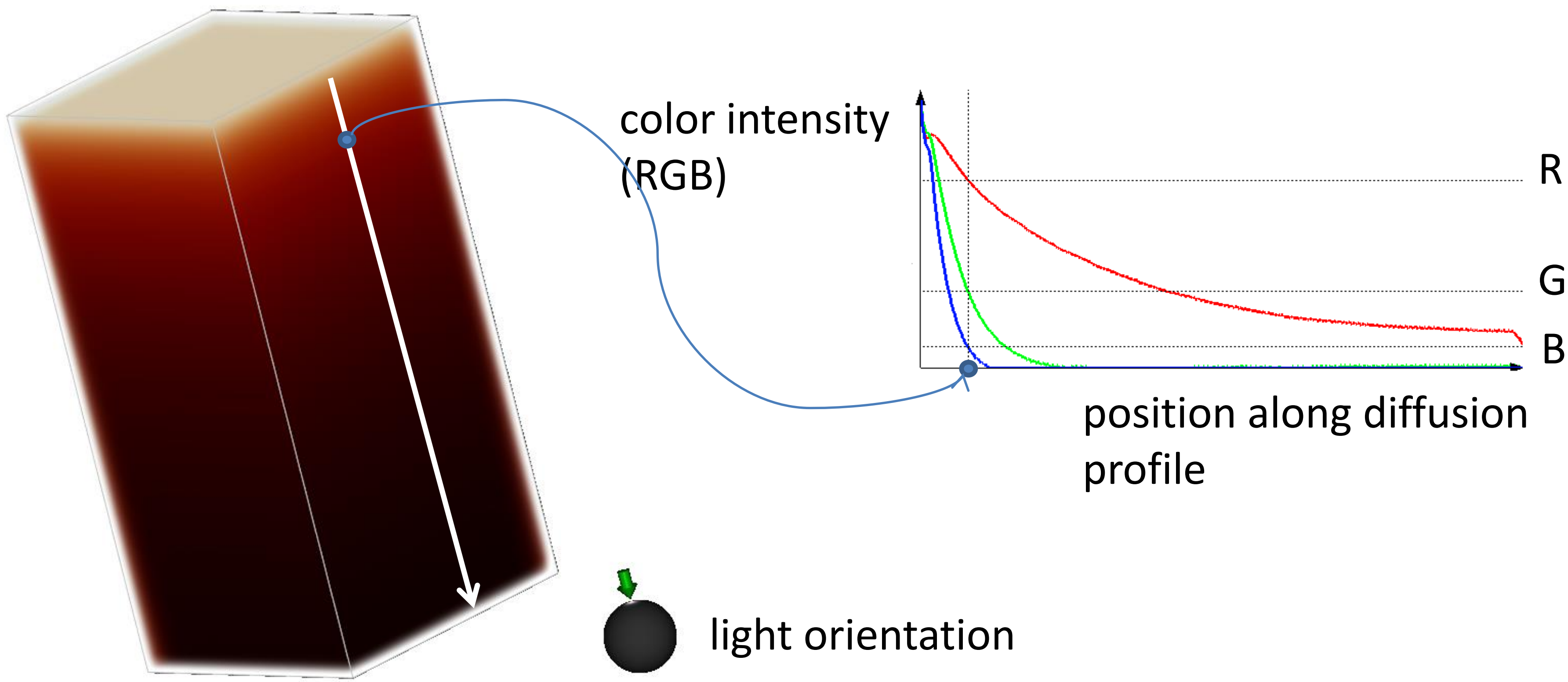


Indirect Lighting (2)

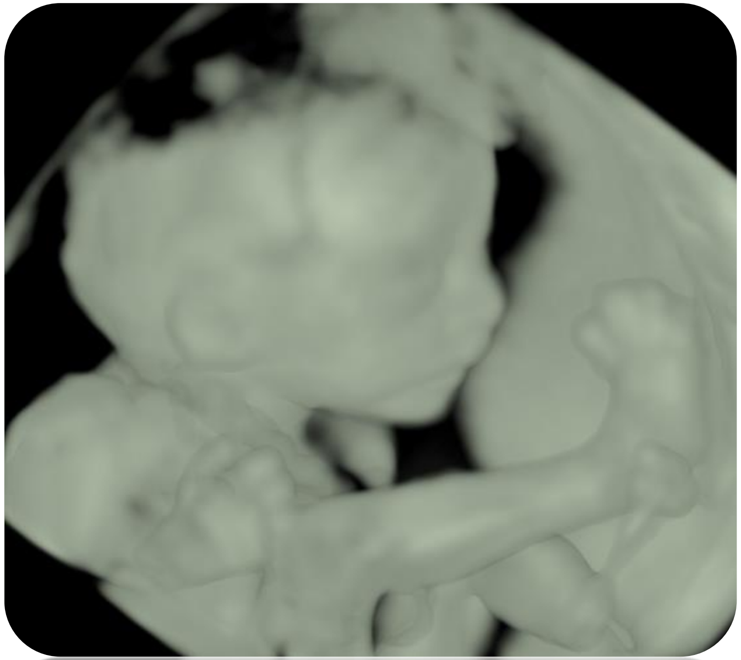


Kniss et al. 2003: A Model for Volume Lighting and Modeling

Chromatic Light Attenuation



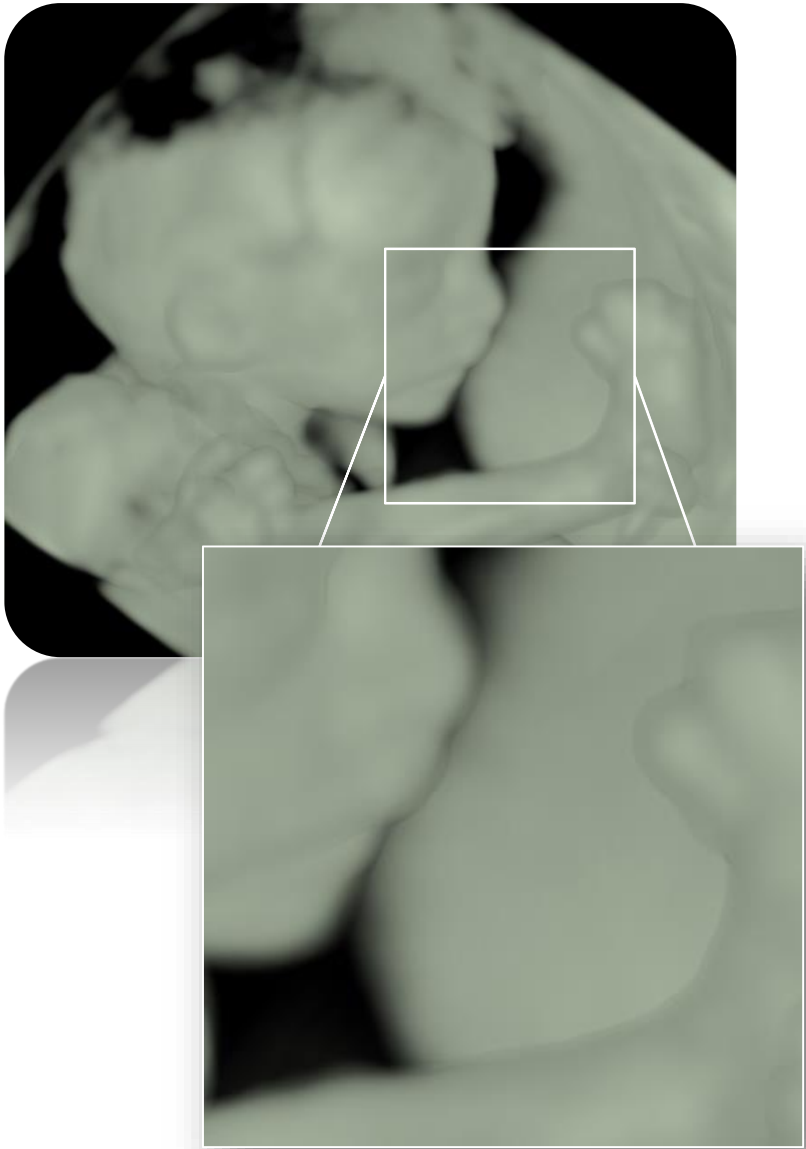
Forward Scattering (1)

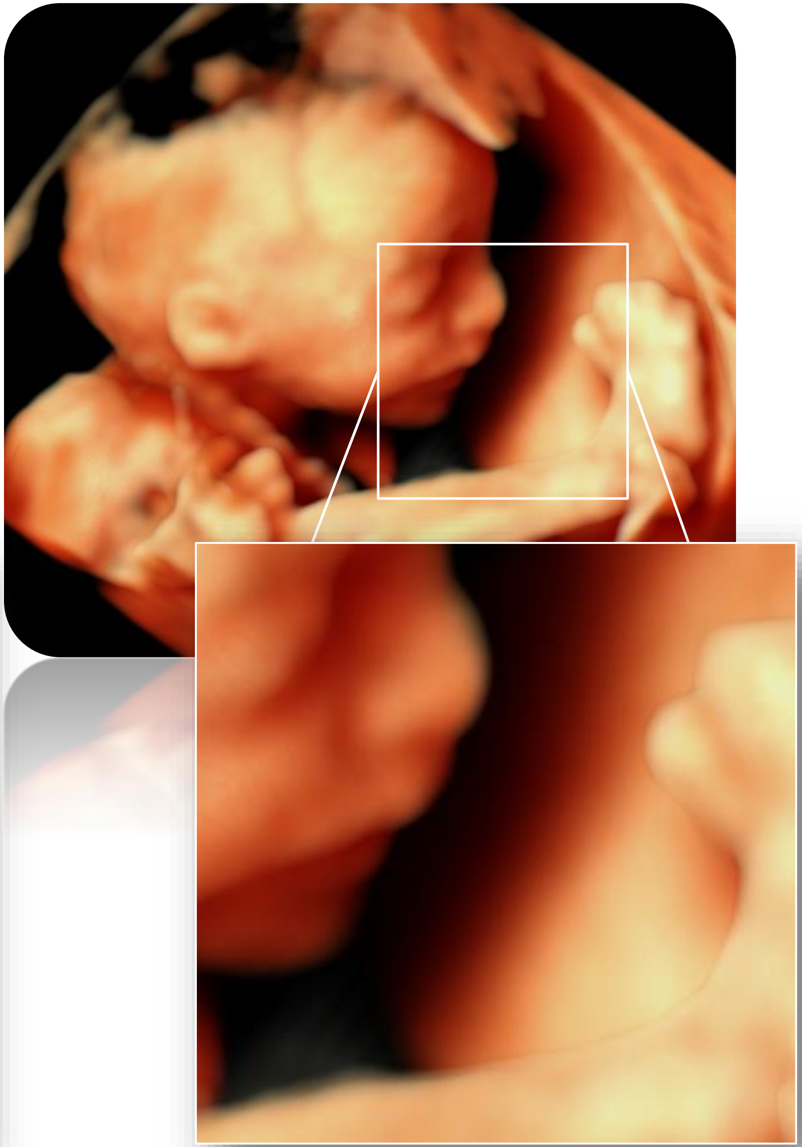


rendering without scattering

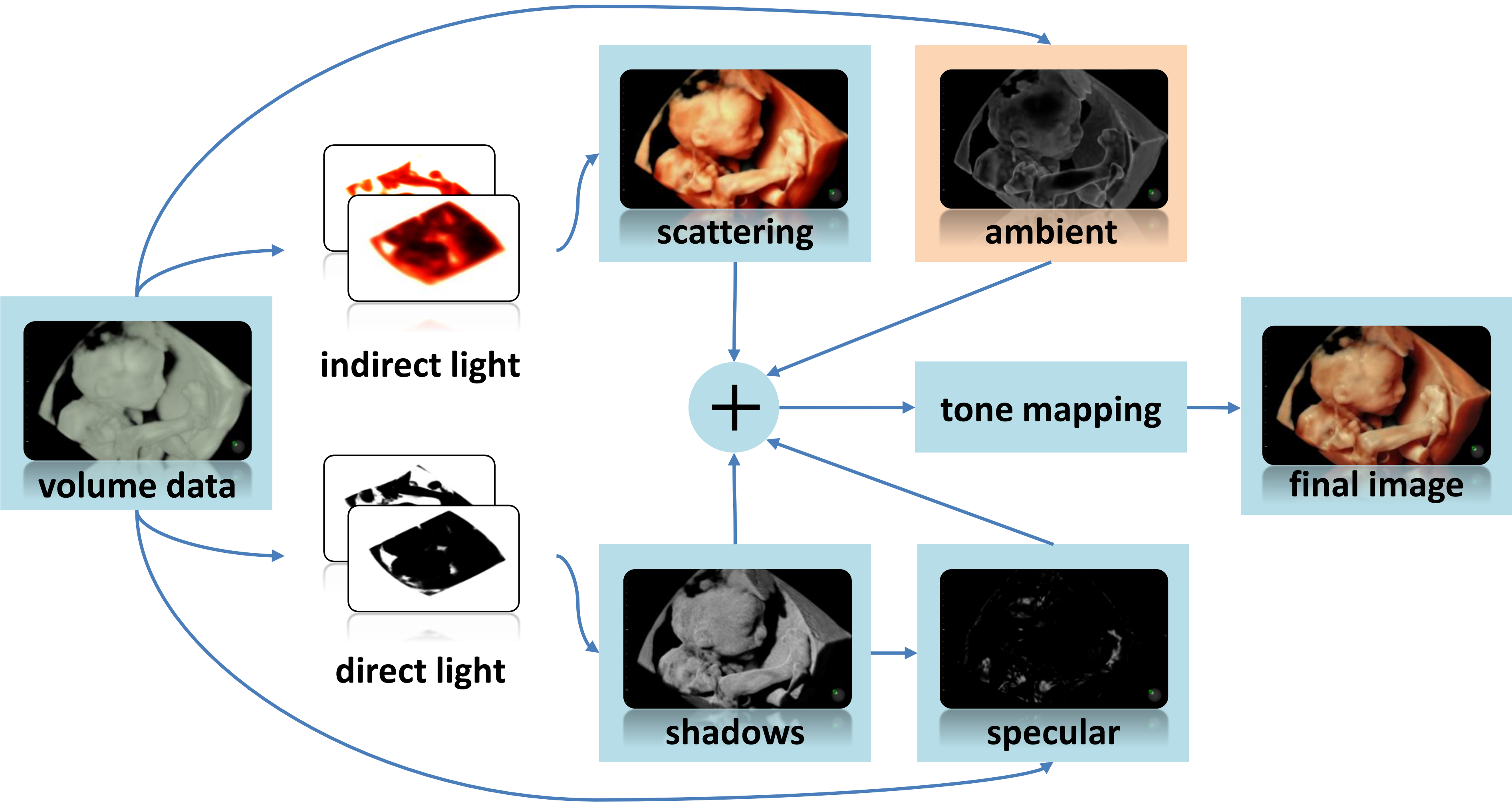
rendering with scattering

Forward Scattering (2)



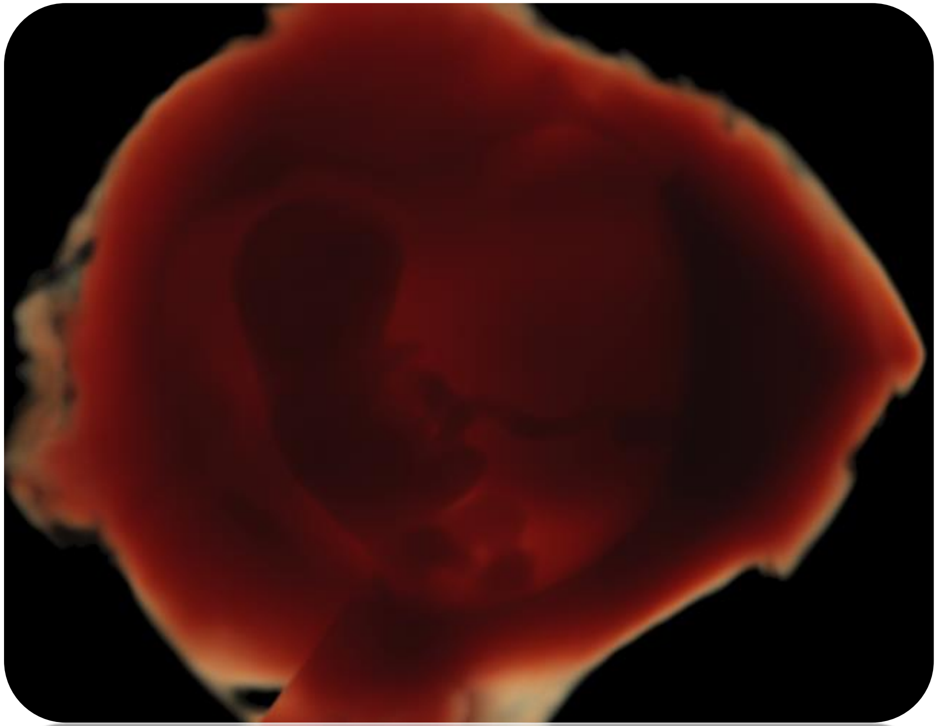


Fetoscopic Illumination Model

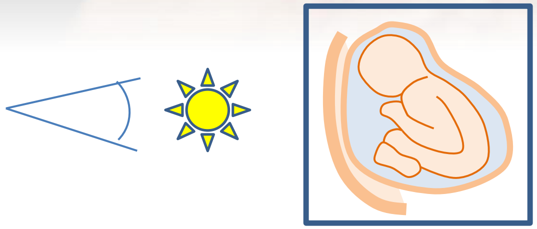


Varchola 2012: Live Fetoscopic Visualization of 4D Ultrasound Data

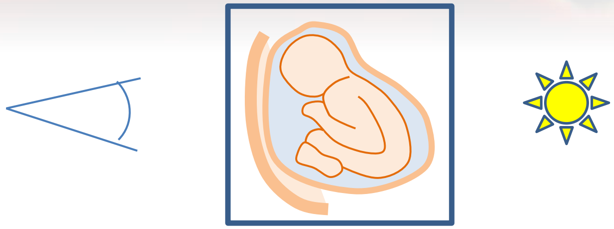
Front and Back Lighting



Light positioned in front

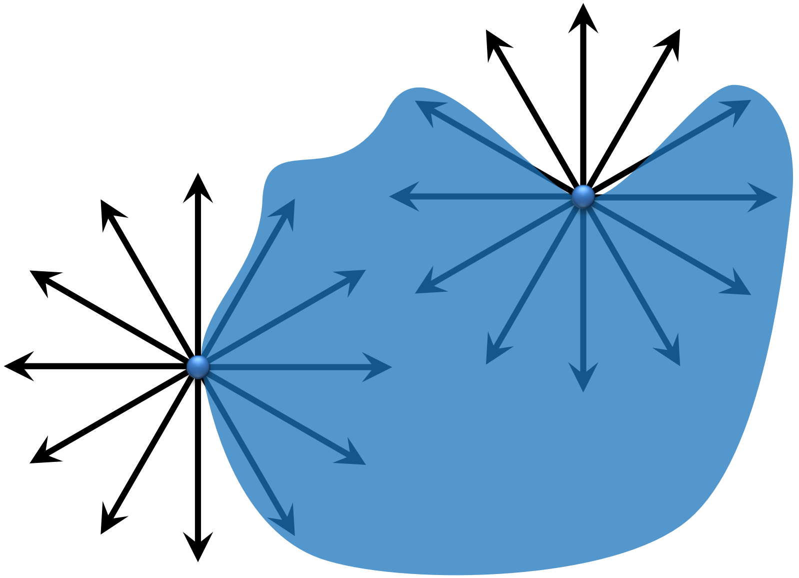


Light positioned behind the scene

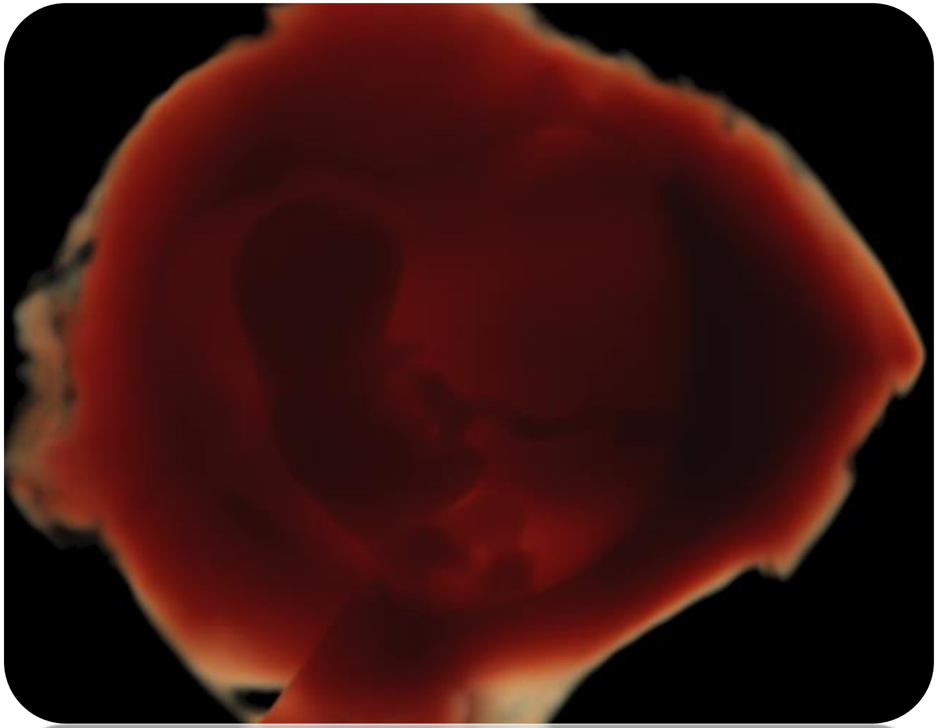


Local Ambient Occlusion (1)

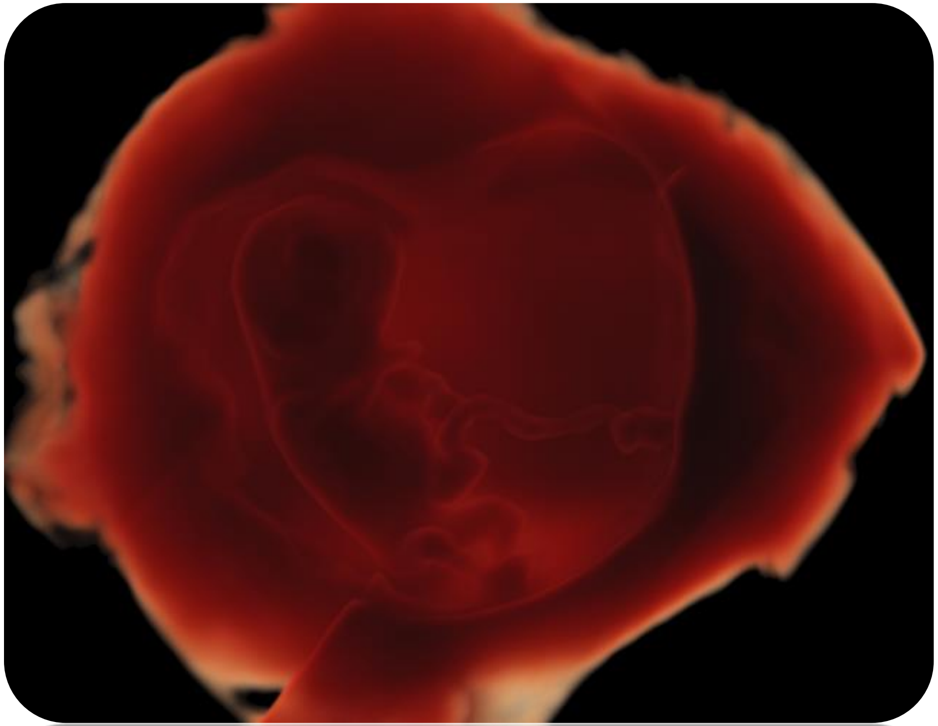
- Evaluate the average visibility of each point
  - Perform sampling in a small spherical neighborhood
  - Modulate ambient illumination intensity by the result



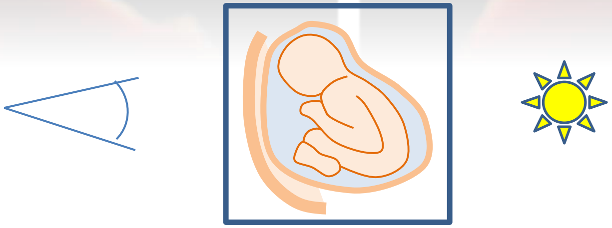
Local Ambient Occlusion (2)



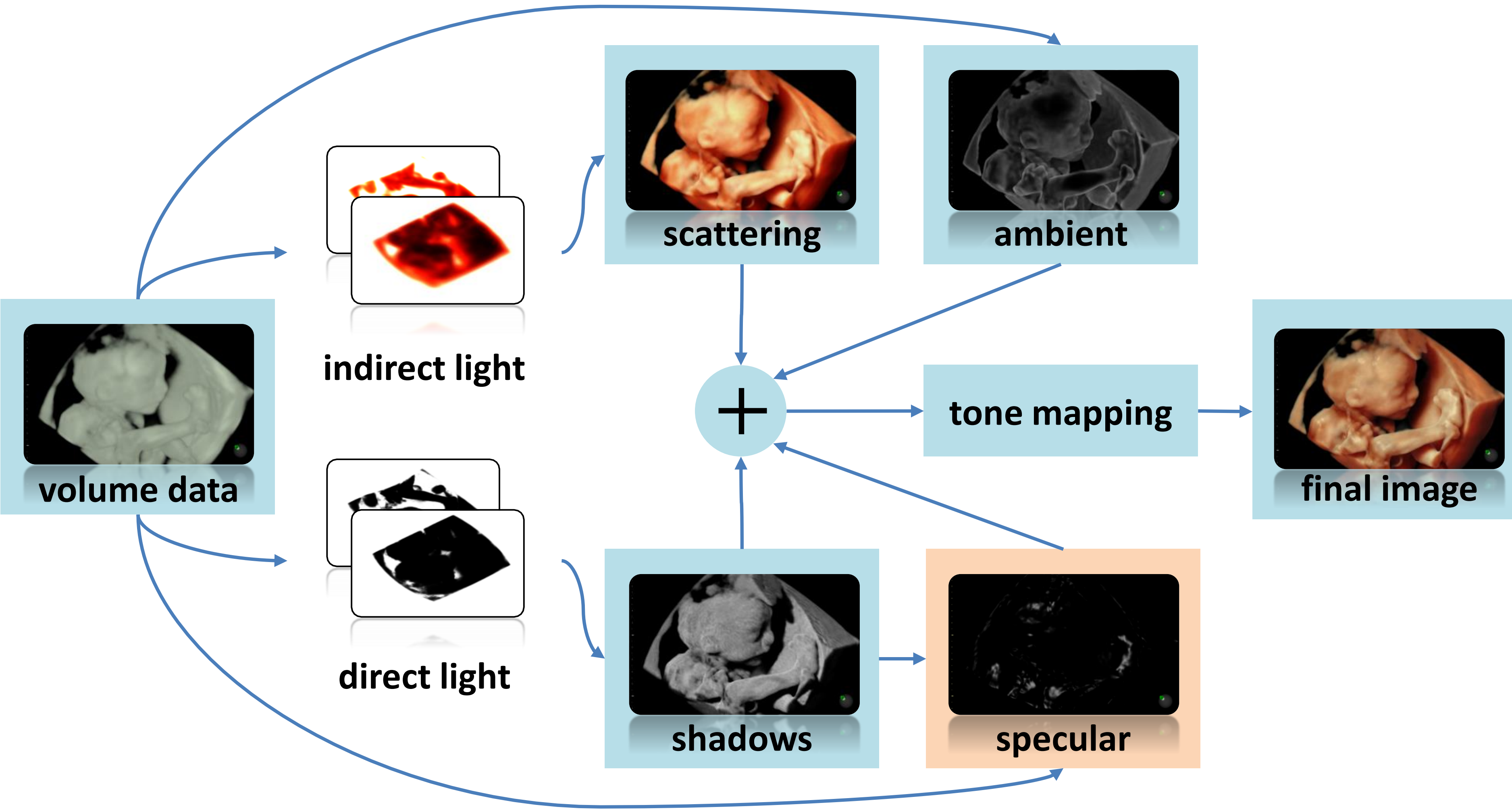
without ambient term



with ambient term

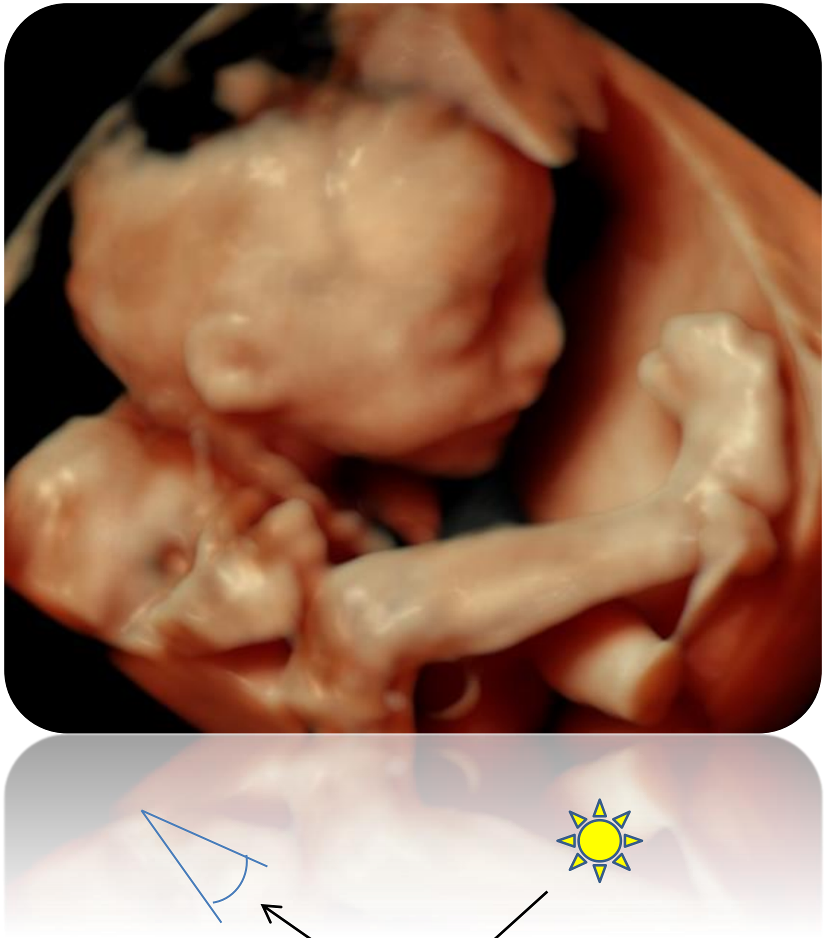


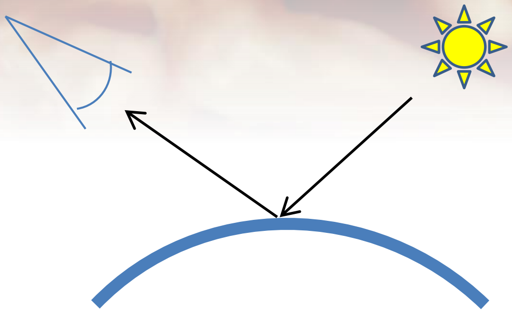
Fetoscopic Illumination Model



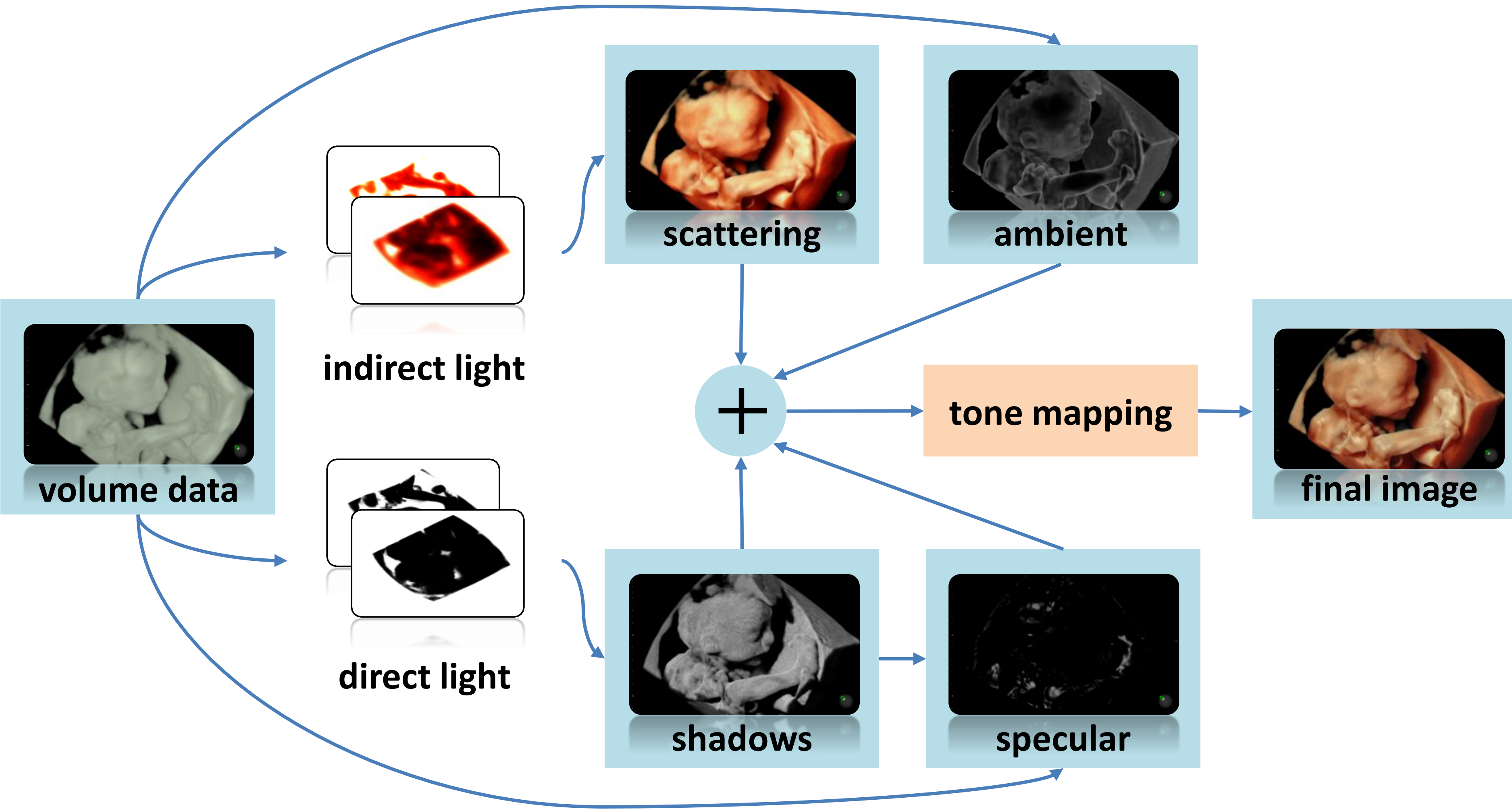
Varchola 2012: Live Fetoscopic Visualization of 4D Ultrasound Data

Specular Highlights





Fetoscopic Illumination Model



Implementation

- GPU-based implementation using DirectX
  - Available as *HDlive* in GE's latest generation of ultrasound machines (Voluson E8 / Expert)
  - Interactive performance of 15-20 fps limited by data acquisition

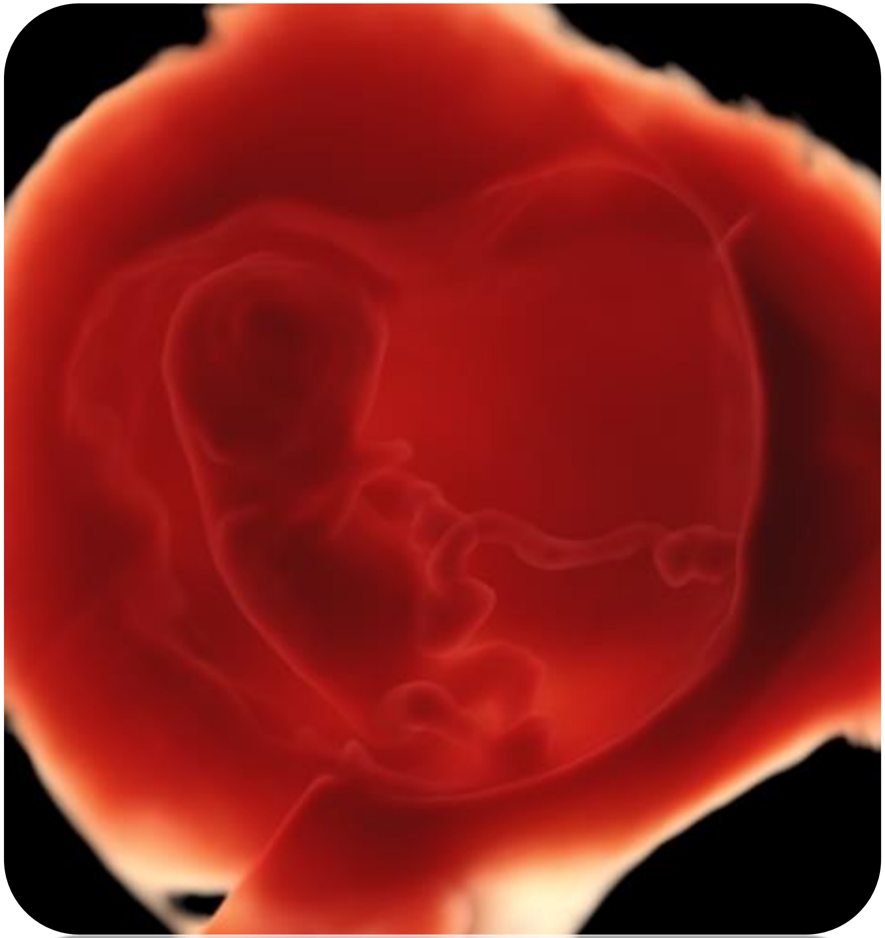
Results (1)

conventional rendering

fetoscopic rendering

Results (2)

conventional rendering



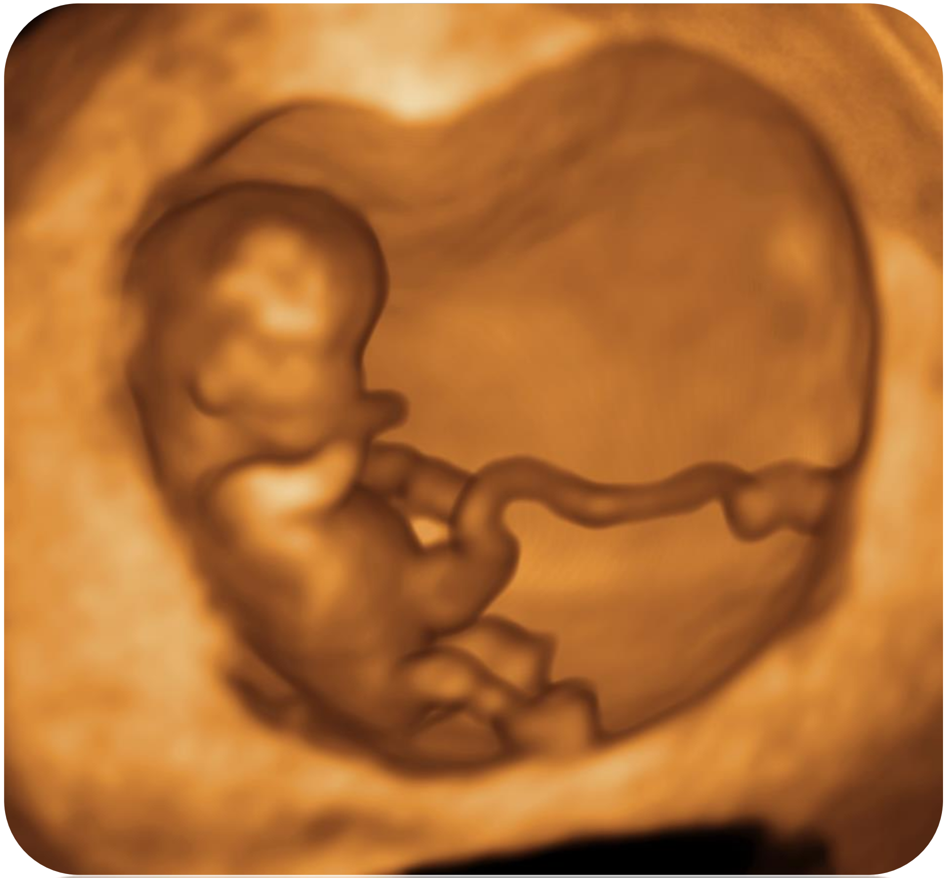
fetoscopic rendering

Results (3)

conventional rendering

fetoscopic rendering

Results (4)



conventional rendering

fetoscopic rendering

Results (5)

photograph acquired with fetoscope
[A Child is Born, Nilson and Hamberger]

fetoscopic rendering
[Picture of the Month, Ultrasound in Obstetrics & Gynecology 38(5)]

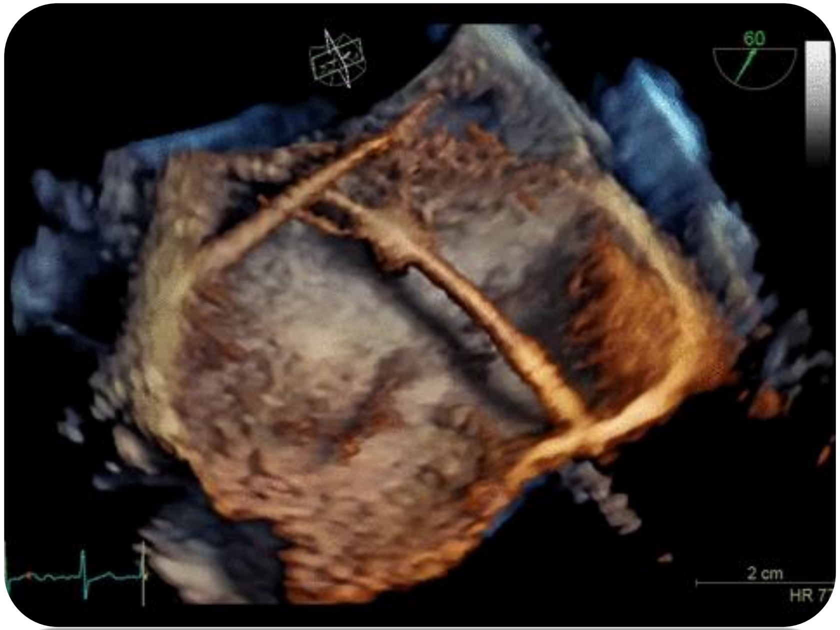
Benefits

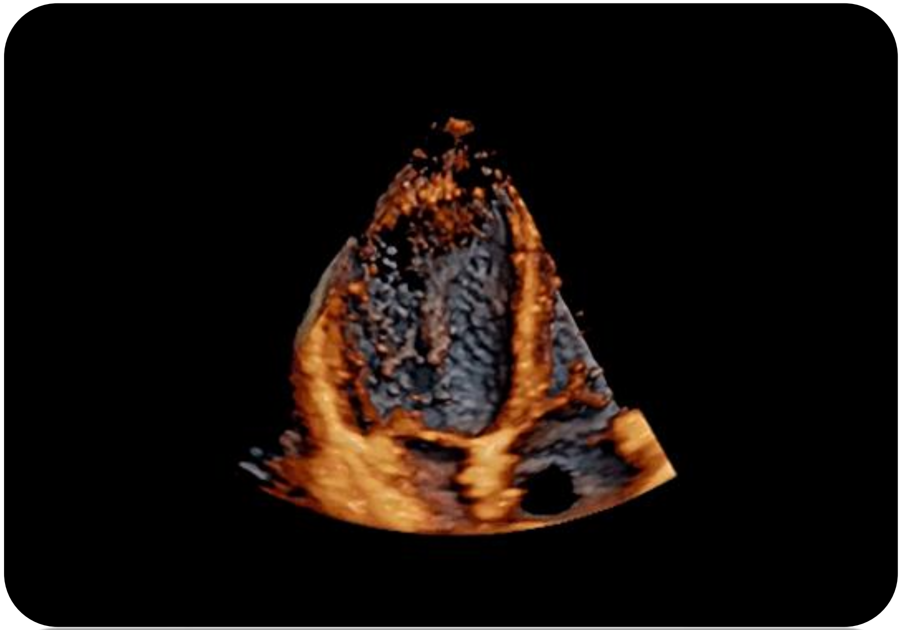
- Approximates realistic illumination in real-time
- Robust against noise and artifacts
- Better 3D perception may have diagnostic benefits
- Currently investigating other application scenarios (e.g., cardiac)

cleft lip: better visibility of border and separation

down syndrome: inclanation of palpepral fissures

Cardiac Ultrasound





FUSION AND GUIDANCE

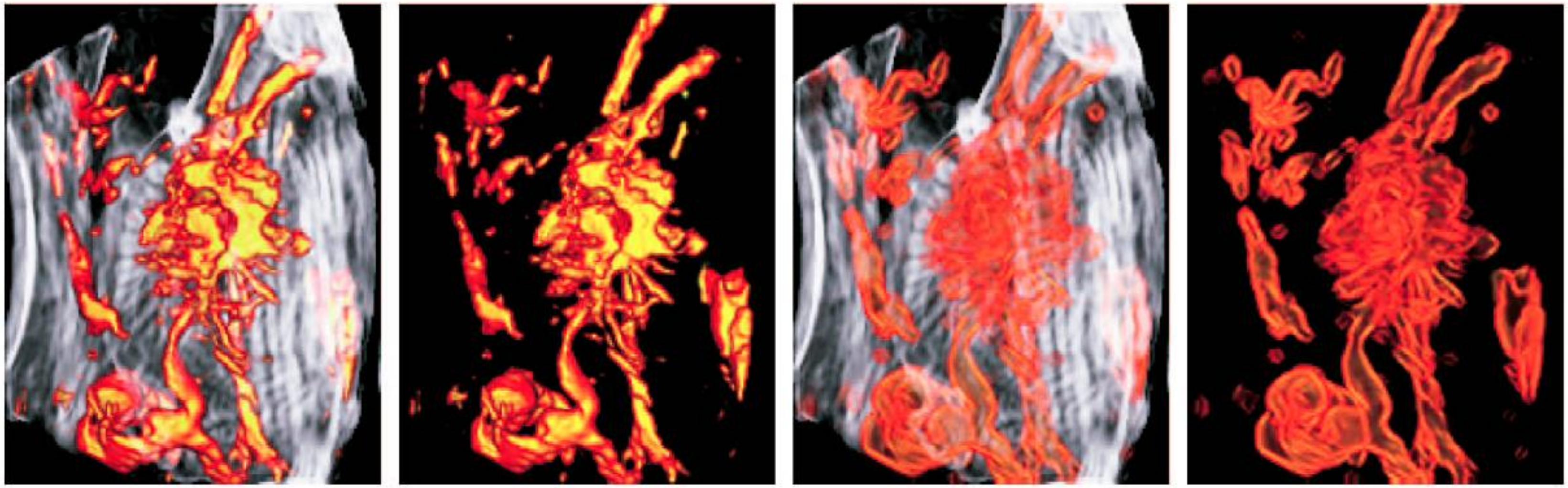
Fusion and Guidance

- **Fusion:** combine multiple modalities to improve diagnostic value
  - Registered CT/MRI scans, blood flow, etc.

- **Guidance:** augment images with additional information
  - Orientation and navigation aids, etc.

B-Mode/Doppler Fusion

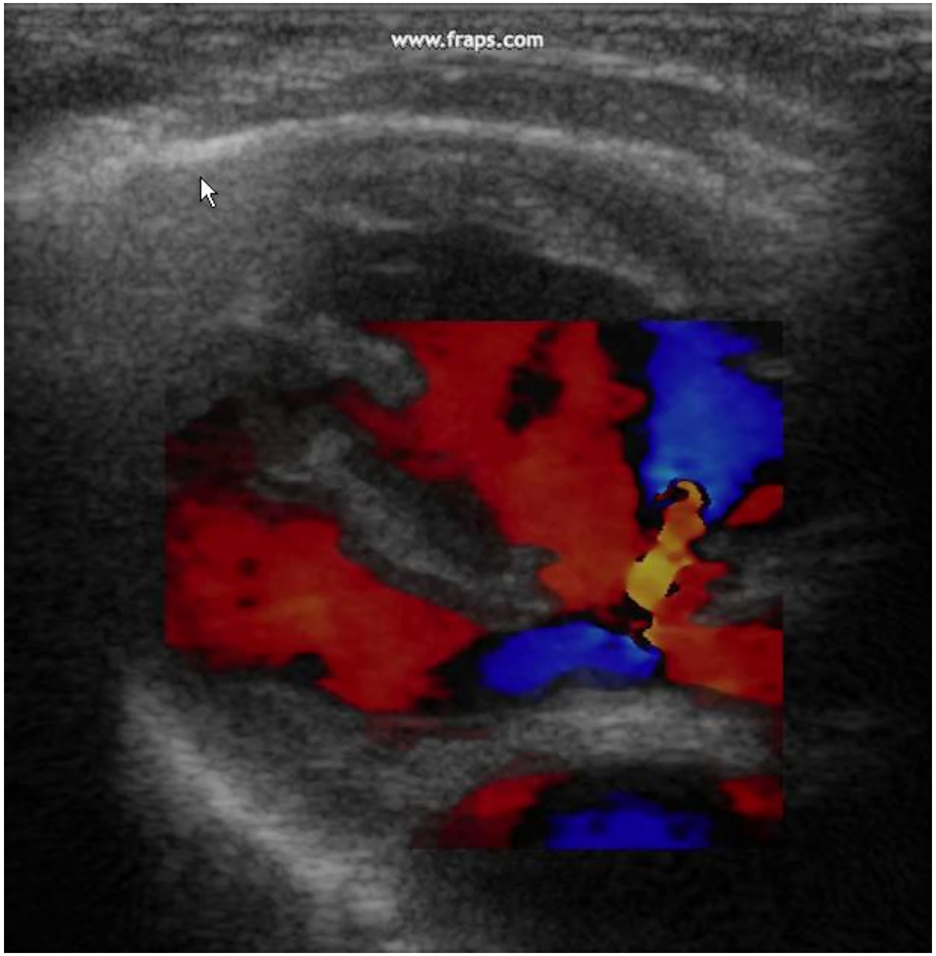
- Integrated visualization of B-Mode and Doppler data
- Non-photorealistic silhouette rendering for reduced visual clutter



Petersch et al. 2007: Blood Flow in Its Context: Combining 3D B-Mode and Color Doppler Ultrasonic Data

Vector Flow Imaging Visualization

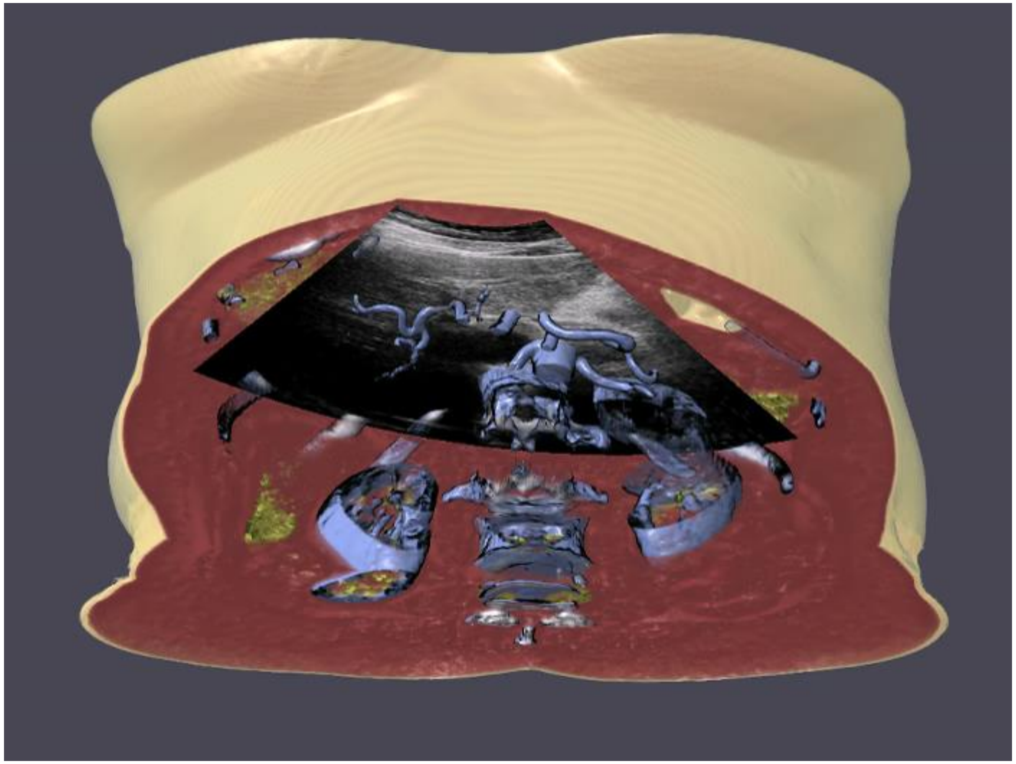
- Vector Flow Imaging provides 3D velocity information
  - Pathlets-based visualization
  - Pathline integration on the GPU



Angelelli et al. 2014: **Live ultrasound-based particle visualization of blood flow in the heart**

Anatomical Context

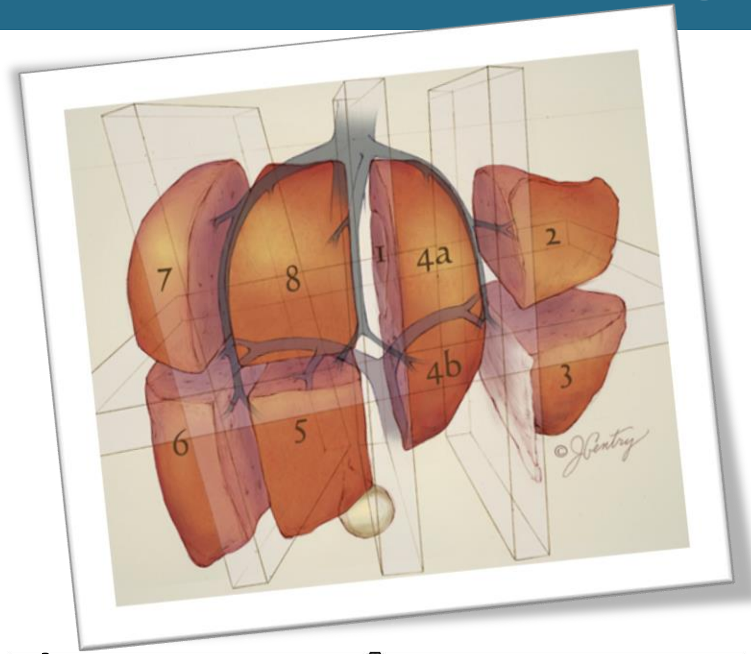
- Tracked 2D probe registered with pre-interventional CT scan
- Cutways for unoccluded depiction of the ultrasound slice

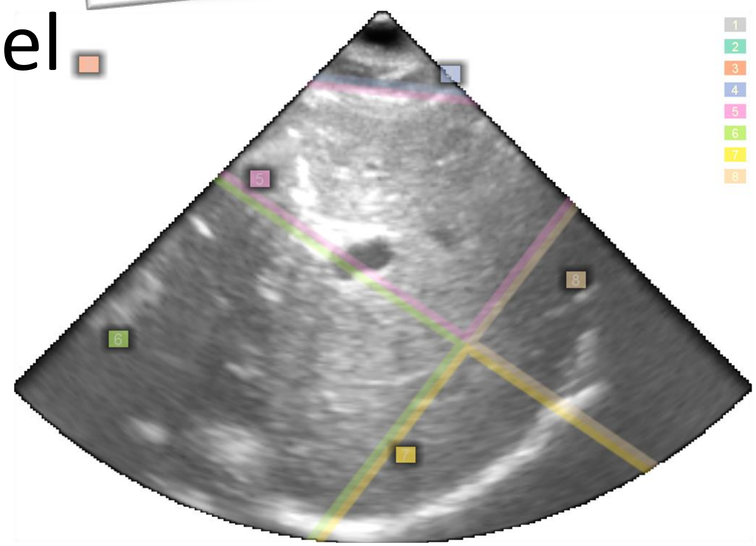


Burns et al. 2007: Feature Emphasis and Contextual Cutaways for Multimodal Medical Visualization

Guidance in Liver Examinations

- Couinaud segmentation: divides the liver into different sections dependent on the blood vessels
- Registration to a liver model for real-time Couinaud overlays during the scan





Cardiac Ultrasound Guidance

- Real-time augmentation of the ultrasound slice using an animated heart model

Ford et al. 2012: HeartPad: Real-Time Visual Guidance for Cardiac Ultrasound

From Static to Dynamic

Visualization of Real-Time Imaging Data

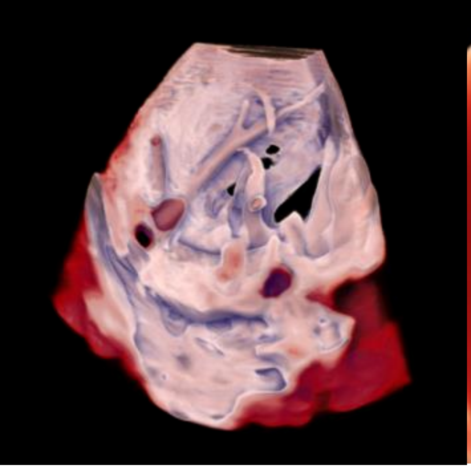
CONCLUSIONS

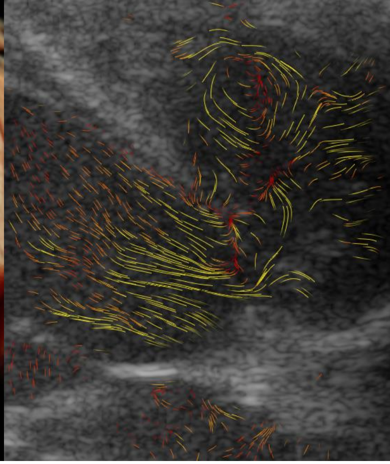
Conclusions (1)

- Selection of recent approaches for improved visualization of ultrasound data
- Importance of 4D ultrasound as a cheap and effective imaging modality is ever-increasing
- Technological advances (e.g. beamforming) offer continuous improvements in frame rate and image resolution
- Live 4D data is still very challenging and many problems remain unsolved

Conclusions (2)

- Technical challenges
  - Real-time filtering, segmentation, registration, rendering, …
- Visualization challenges
  - Integration of anatomy and physiology (more after the break)
  - Visualization of high-speed processes
  - Interaction with real-time visualizations
  - Quantitative visualization
  - Collaborative visualization



Thank you for your attention!

Acknowledgements

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