Arrangements

Dec 5 (Mon): Student Presentation 1
Dec 7 (Wed): Student Presentation 2

Deadlines:

Dec 5/Dec 7: Project 2 Presentation File due at 12noon

Dec 9 (Fri): Project 2 Summary of Another Team's Work due at 11:59pm

Dec 12 (Mon): Project 2 Final Report due at 11:59pm

Topic 6: Applications

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Computational Bio-Modeling and Visualization

- Topics covered in our class
  1. Biomedical Imaging
  2. Image Processing
  3. Geometric Modeling and Visualization
  4. Mesh Generation
  5. Computational Mechanics (FEM, IGA, X-FEM, IFEM)
  6. Applications of Topics 1-5

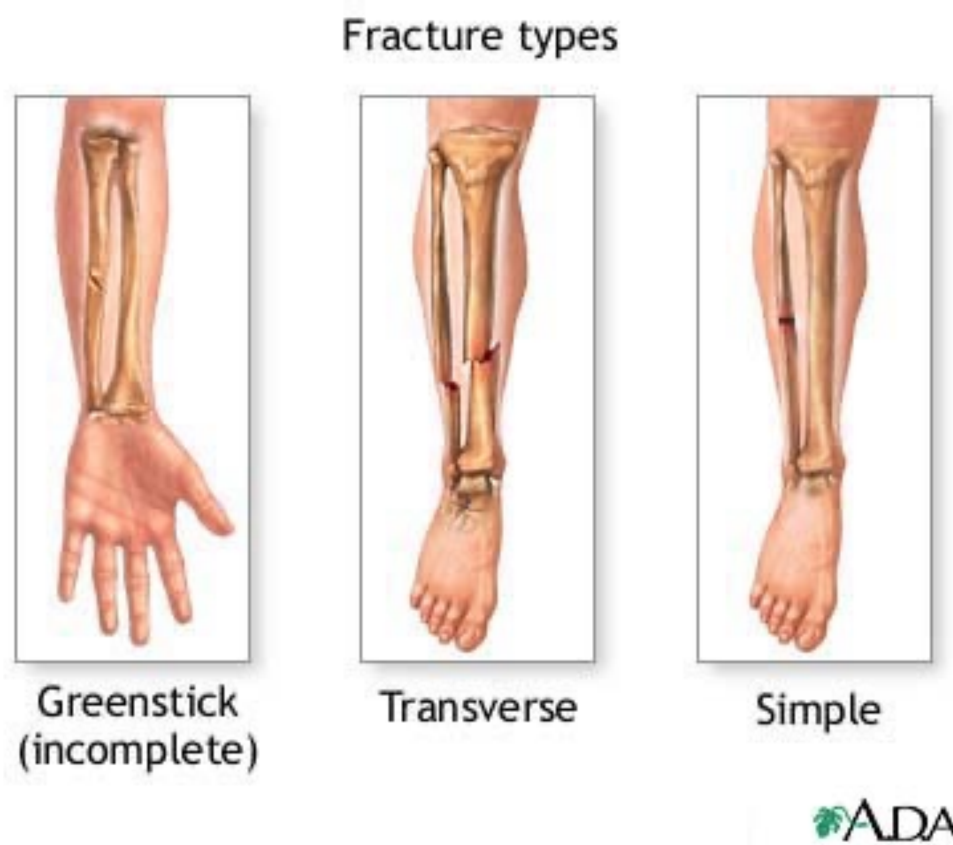
Topic 1: Biomedical Imaging

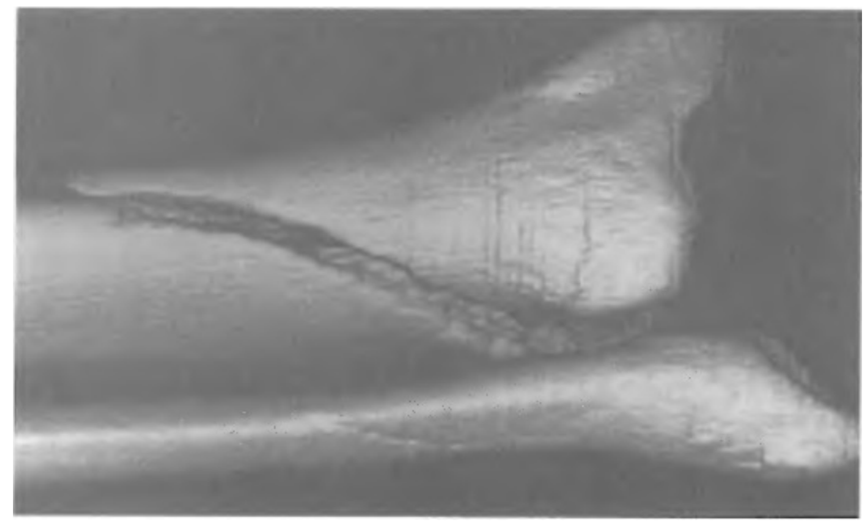
- Biomedical imaging refers to the techniques and processes used to create images of biomedical systems, including CT, MRI, Nuclear Medicine, Ultrasound, Fluoroscopy, and Cryo-EM.

- Biomedical imaging can be used directly for clinical diagnosis.

Bone Fracture

- CT (x-rays) has been used in checking bone fracture directly.



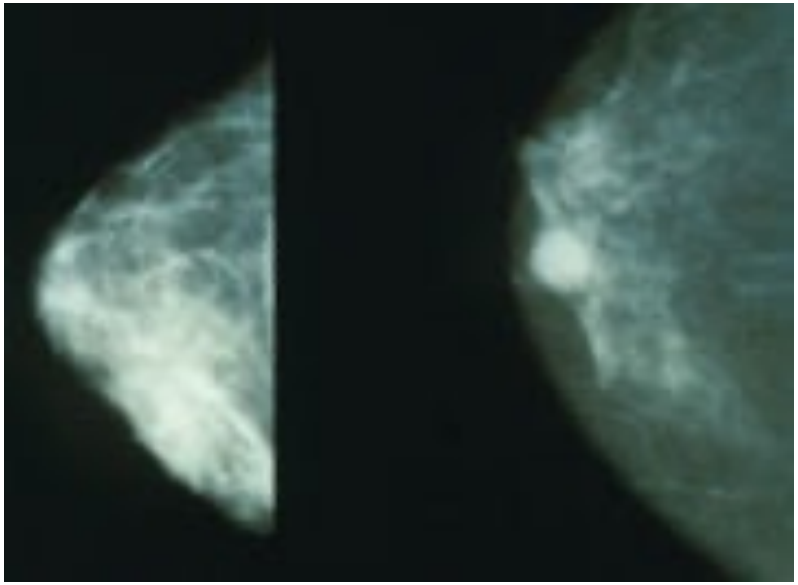


A fractured tibia bone

Breast Cancer

- Mammography is the modality of choice for screening of early breast cancer, which has been estimated to reduce breast cancer-related mortality by 20-30%.

Normal (left) versus cancerous (right) mammography image.



Fetus in a Womb

- Ultrasound studies the function of moving structures in real-time, and it is very safe to use (no ionizing radiation), cheap and quick to perform.

Ultra-Sound: A fetus in a womb

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Topic 2: Image Processing

- Image processing techniques
  - Contrast enhancement: to improve the contrast
  - Filtering: to remove noise
  - Classification: to group voxels into various categories
  - Segmentation: to find the boundary of each region
  - Registration: to match two or more images

Dynamic Lung Modeling Tumor Tracking using Deformable Image Registration

➔Decrease treatment margin

➔Minimize normal tissue exposure

ITV

Internal Target Volume (ITV) = Motion Envelop

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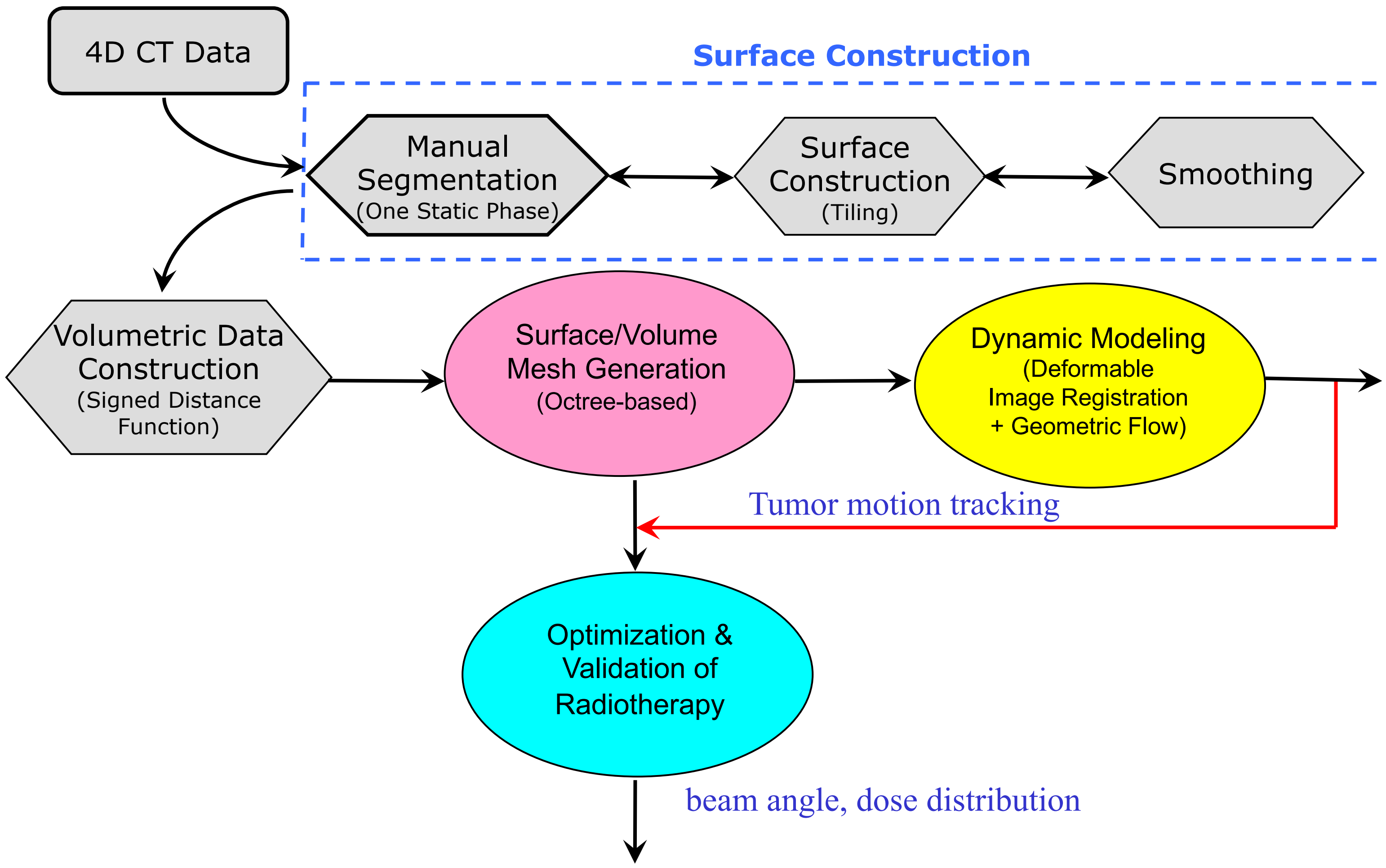
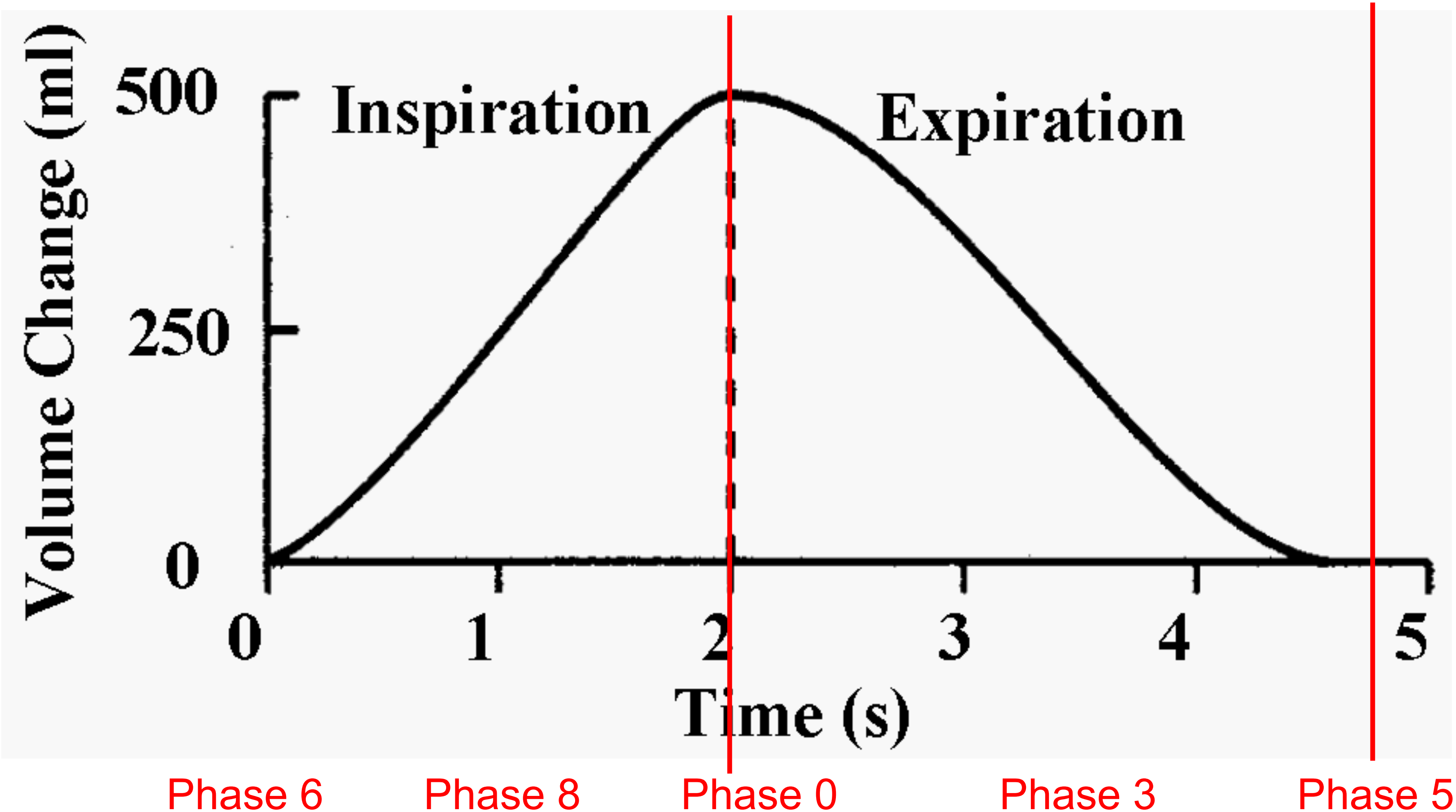
Motivation

- Lung cancer is the leading cause of cancer death in the US among every ethnic group… 1 in every 3 cancer deaths.
- The physical basis for radiation therapy is to expose cells to high-energy x-rays to damage their DNA structures and genetic functions, making it impossible for these cells to continue to grow or divide.
- Laser therapy uses high-intensity light to increase the local temperature to kill cancer cells.
- Cryosurgery (cryotherapy) is the application of extreme cold to destroy abnormal or diseased tissue.
- The main goal of this research project is to perform pre-clinical modeling and tumor tracking analysis of radiation/laser/cryo- therapy for lung cancer treatment planning, considering the lung/tumor motion during respiration.

A Comprehensive Computational Pipeline for Radiation Therapy



Lung Volume Change and 10 Phases



WP Segars, BMW Tsui, EC Frey, GA Johnson, SS Berr - **Molecular Imaging** and Biology, 2004.

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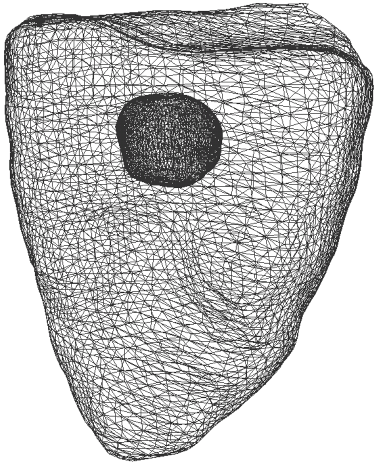
Surface Reconstruction and Smoothing

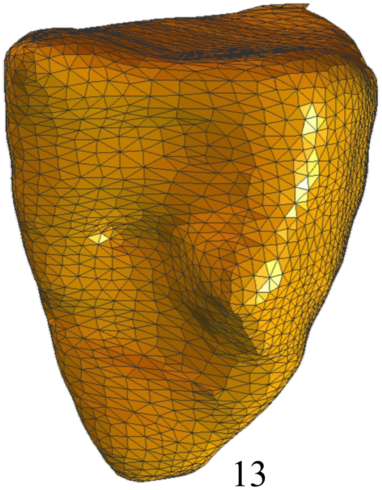
- During the respiration, the exhale phases (e.g. Phases 4 to 6) are relatively stable, and physicians have manually segmented the Phase 5 data for each 2D slice.
- We construct a surface model of the lung as well as the tumor from the segmented data at Phase 5 using the tiling technique, and define it as the reference.
- Noise may exist in the constructed 3D surface models, therefore geometric partial differential equations are adopted to smooth the surface and improve the aspect ratio of the surface mesh, while preserving surface features.

$$\frac{\partial x}{\partial t} = V_n(k_1, k_2, x)\vec{n}(x) + v(x)\vec{T}(x)$$

- Mean Curvature Flow: $Vn = -H = -(k_1 + k_2)/2$
- Average Mean Curvature Flow: $Vn = h(t) - H(t)$

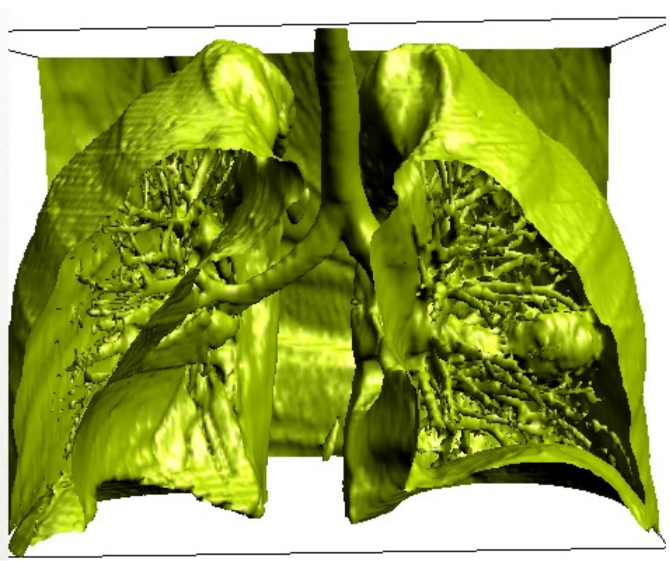
  where $h(t) = \int_{M(t)} H d\sigma / \int_{M(t)} d\sigma$
- Surface Diffusion Flow: $V_n = \Delta H$
- High Order Flow: $\frac{\partial x}{\partial t} = (-1)^{k+1}\Delta^k HN(x)$

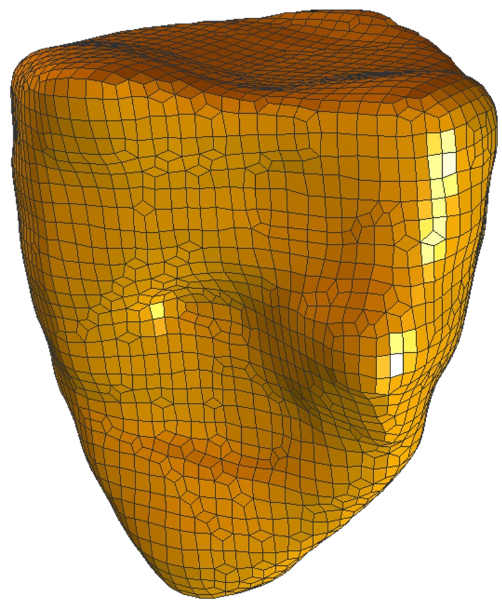


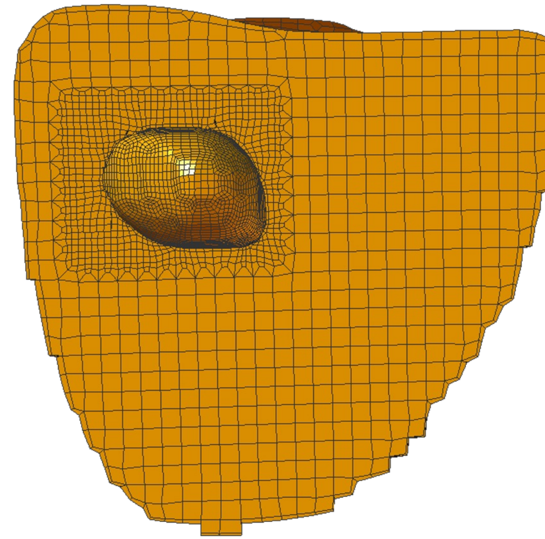


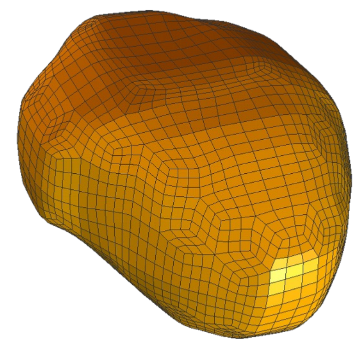
Octree-based Meshing

- A top-down octree-based isocontouring method
- Mesh adaptation:
  - Feature sensitive error function
  - Various areas users are interested in
  - Finite element solutions
  - User defined









Deformable Image Registration

- Phase 5 is chosen as the reference data, and deformable image registration is used to match the reference data to the target data.

- Here we couple a deformable image registration algorithm with a geometry smoothing technique. The optical flow equation is used here.

Deformable Image Registration

- For a given point P, let s be the intensity in static image S and m the intensity of the moving image M. The estimated displacement required for point to match the corresponding point is given by

$$\vec{u} = (m-s) \times \left(\frac{\vec{\nabla} s}{\left|\vec{\nabla} s\right|^2 + (m-s)^2} + \frac{\vec{\nabla} m}{\left|\vec{\nabla} m\right|^2 + (s-m)^2} \right),$$

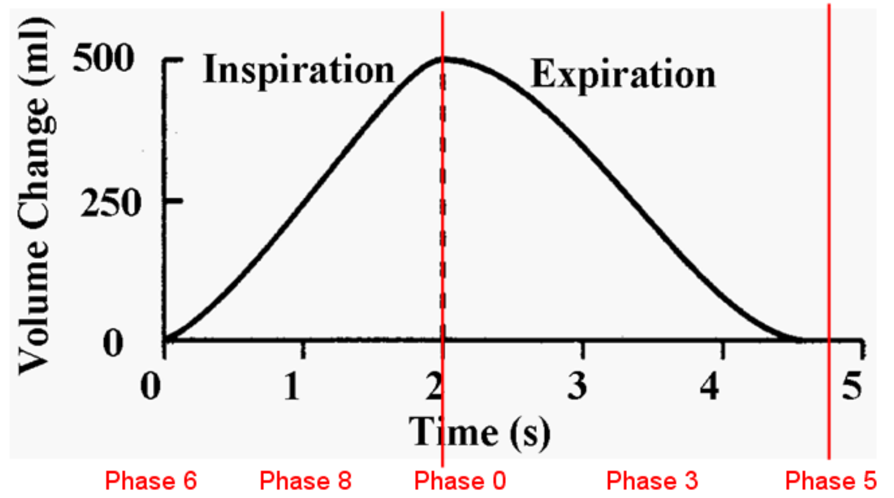
where $\vec{u} = (u_x, u_y, u_z)$, $\vec{\nabla} s$ is the gradient of the static (reference) image S, and $\vec{\nabla} m$ is the gradient of the moving image M. $\vec{\nabla} s$ and $\vec{\nabla} m$ represent the relationship between the neighboring points in the static and moving images, respectively.

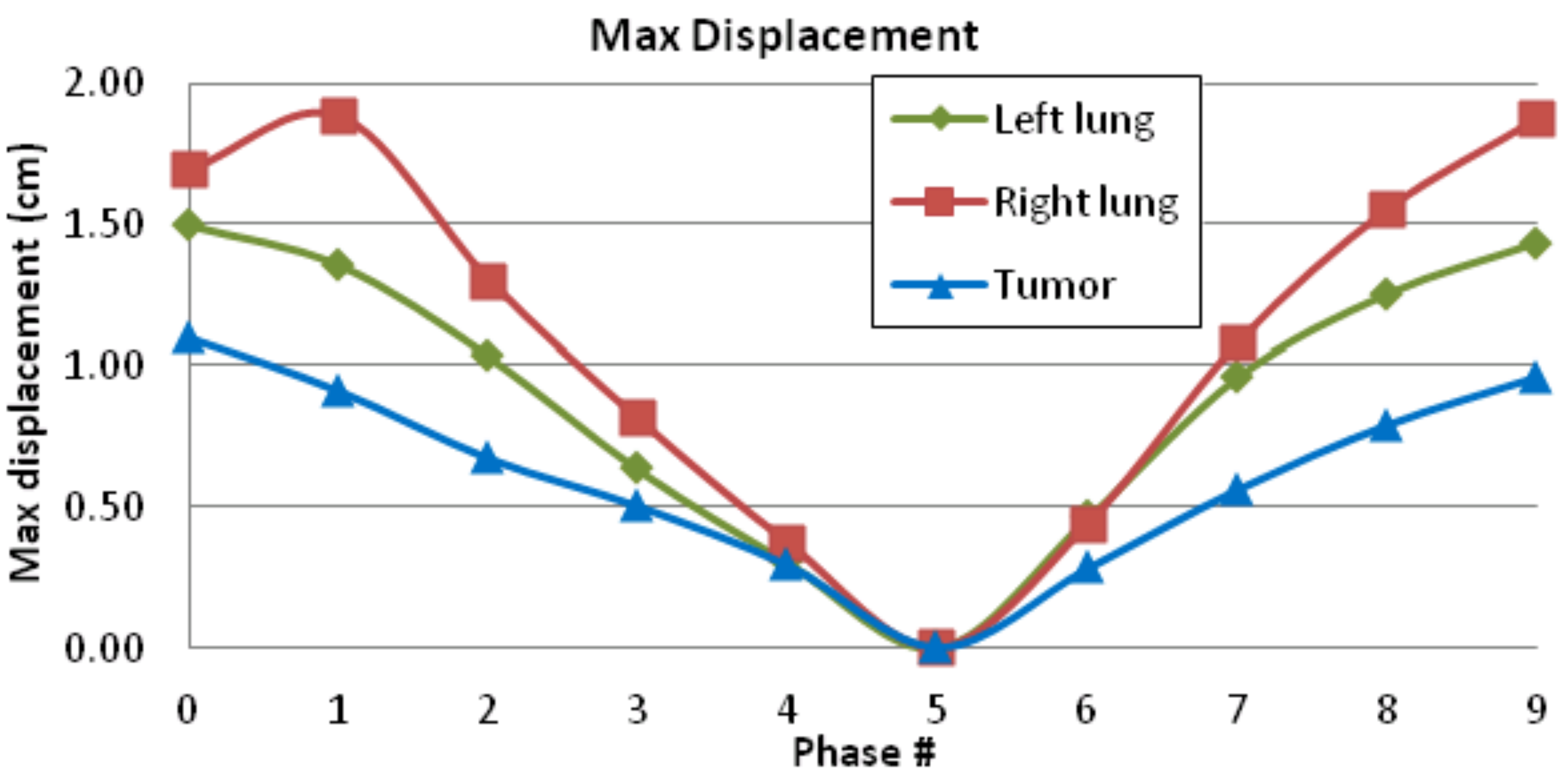
- The optical flow computation is followed by a regularization of the deformation parametric space using geometric flows, or geometric partial differential equations (GPDEs)

$$\frac{\partial P}{\partial t} = V_n(k_1, k_2, P) n(P) + v(P) T(P).$$

Thirion, Medical Image Analysis, 2(3):243-260, 1998

Max Displacement from Image Registration





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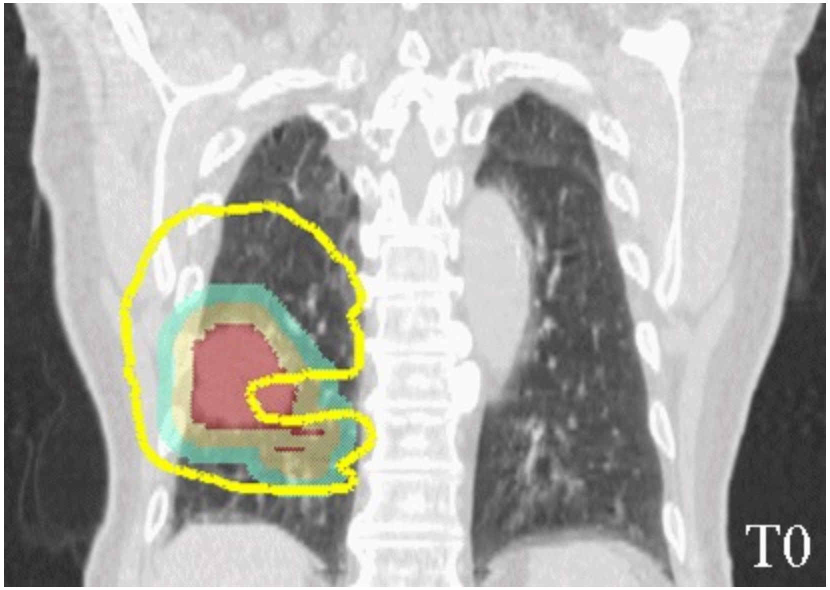
Impact of Organ Motion on Dose Distributions



Treatment planned based on single free-breathing (FB) CT image (conventional approach)

Final composite dose distribution after deformable image registration

Kang et al. IJROBP, Vol 67, No.3, Page 906, 2007

Topic 3: Geometric Modeling and Visualization

- In Topic 3, we talked about
  - Fundamentals of geometric modeling and computer graphics
  - Objects and transformations
  - Curve and surface representations
  - Scientific visualization

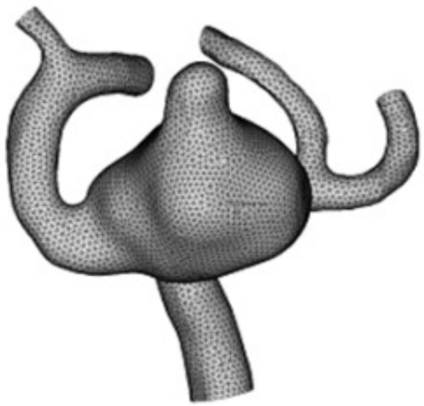
- Applications
  - Computer-aided design
  - Geometric modeling from medical imaging data
  - Computer animation for movie and game industry

    ACM SIGGRAPH conference

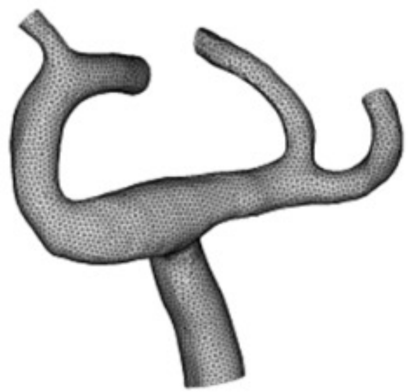
    http://www.siggraph.org/

Estimating Material Property of Cerebral Aneurysm Vessel Wall Through Mesh Deformation

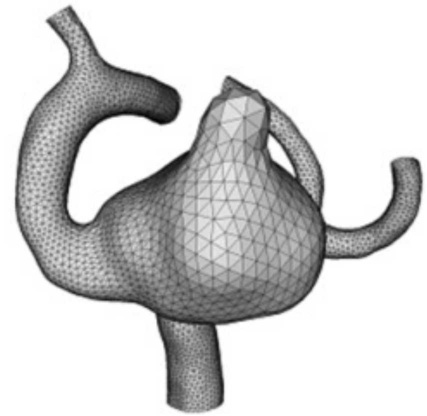
- Deform the mesh from a "healthy" vessel into one with an aneurysm through mesh deformation and a spring model.
- By comparing the original and deformed mesh, the material strength and anisotropy can be estimated (wall thickness, Young's modulus).



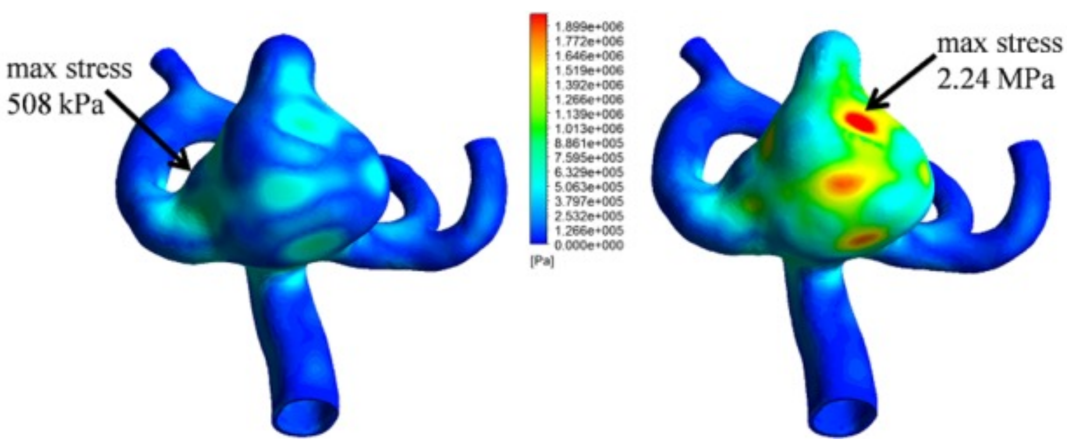
Target mesh



Healthy model



Deformed healthy model



Max wall stress with uniform material property

Max wall stress with improved material property

E. Johnson, **Y. Zhang**, K. Shimada. Using Conformal Mapping and Springs to Determine Aneurysm Wall Thickness. *IJNMBE*, 2010.

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Topic 4: Mesh Generation

- Mesh Generation:
  - Unstructured tri/tet mesh generation: octree-based, Delaunay, advancing front method
  - Unstructured quad/hex mesh generation: grid-based, medial axis/surface, plastering, whisker weaving
  - Quality improvement: cleanup, smoothing
  - High-order element construction

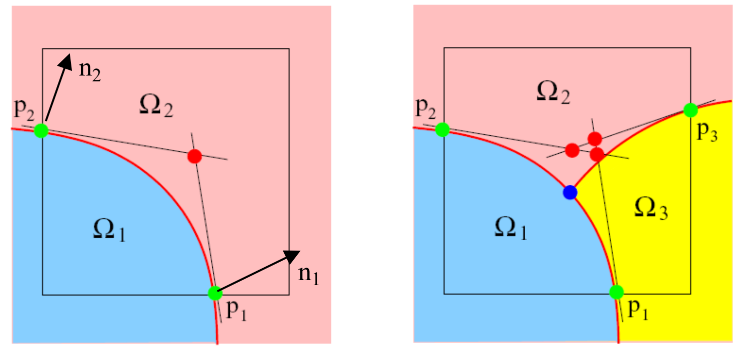
- Applications:
  - Visualization and animation, generally only surface models are required.

  - Engineering computations
    - Finite difference method
    - Finite volume method
    - Finite element method

Automatic Mesh Generation for Heterogeneous Domains

* Minimizer Point Calculation:

$$QEF[x] = \sum_i (n_i \cdot (x - p_i))^2$$

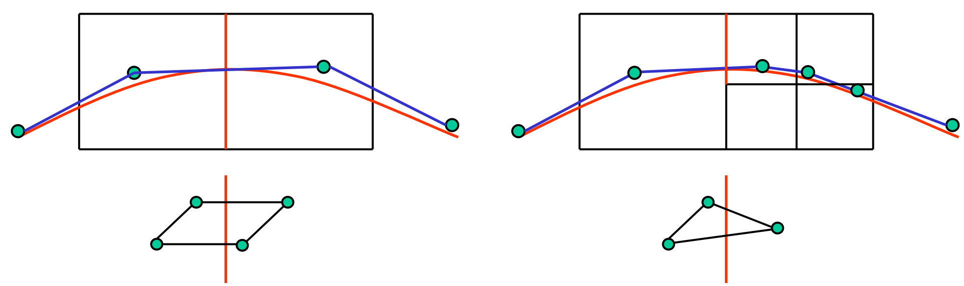


Sign Change Edge - A sign change edge is an edge whose one vertex lies inside the isocontour (we call it the interior vertex), while the other vertex lies outside.

Material Change Edge - A material change edge is an edge whose two end points lie in two different material regions. A material change edge must be an edge in a boundary cell.

* Tri/Tet meshing:
- Material change edge
- Interior edge

* Quad/Hex meshing:
- Interior grid point
- Refinement templates



uniform adaptive

• **Y. Zhang**, T. J.R. Hughes, C. L. Bajaj. An Automatic 3D Mesh Generation Method for Domains with Multiple Materials. CMAME, 2010.

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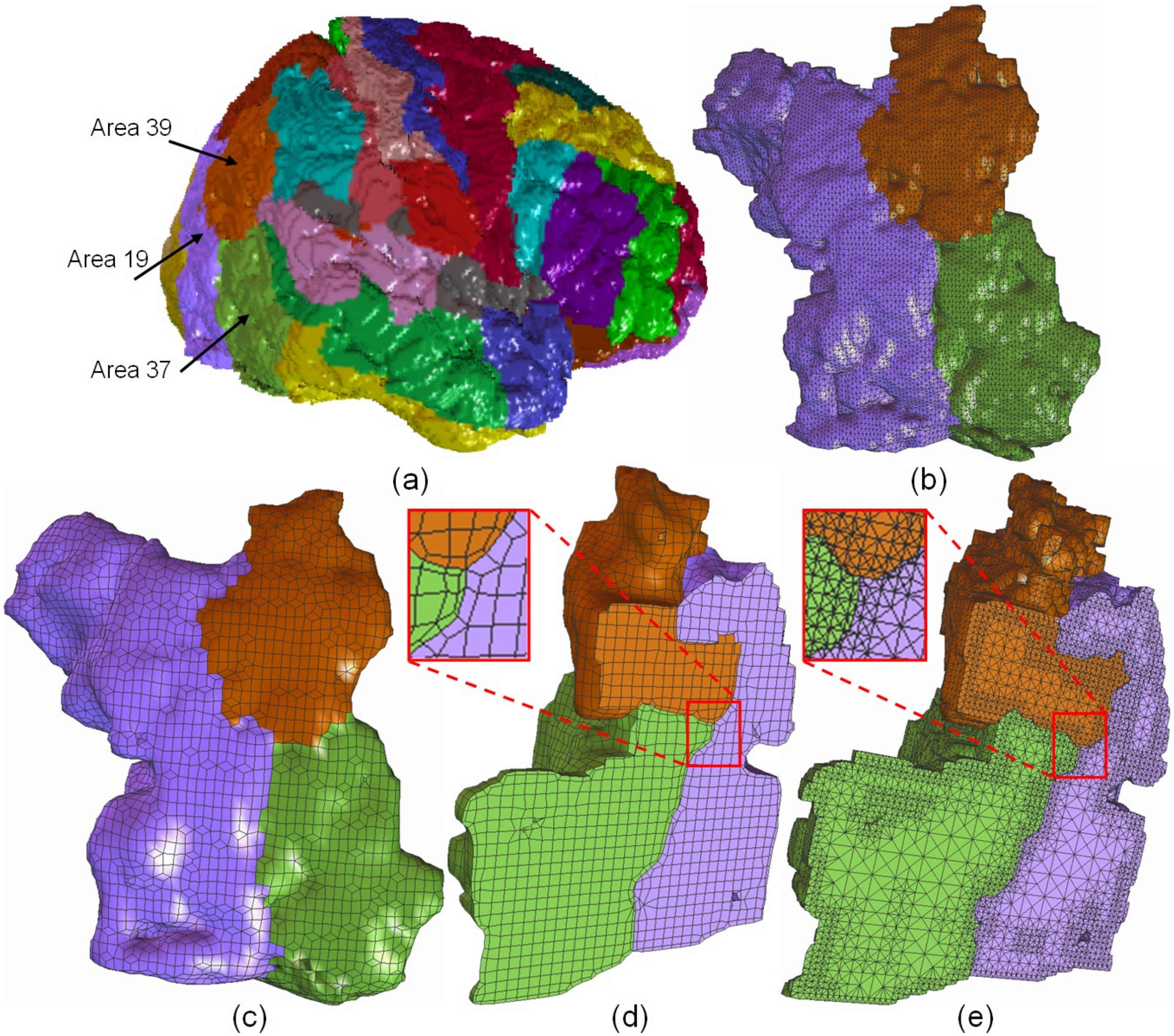
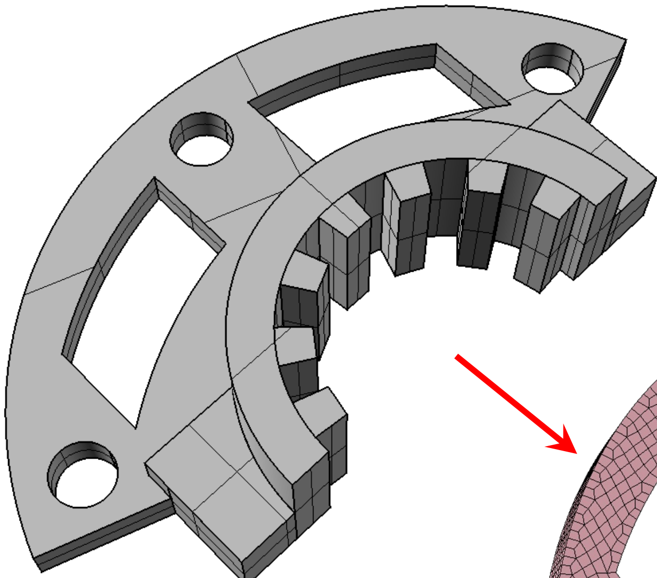
Brodmann Brain Atlas



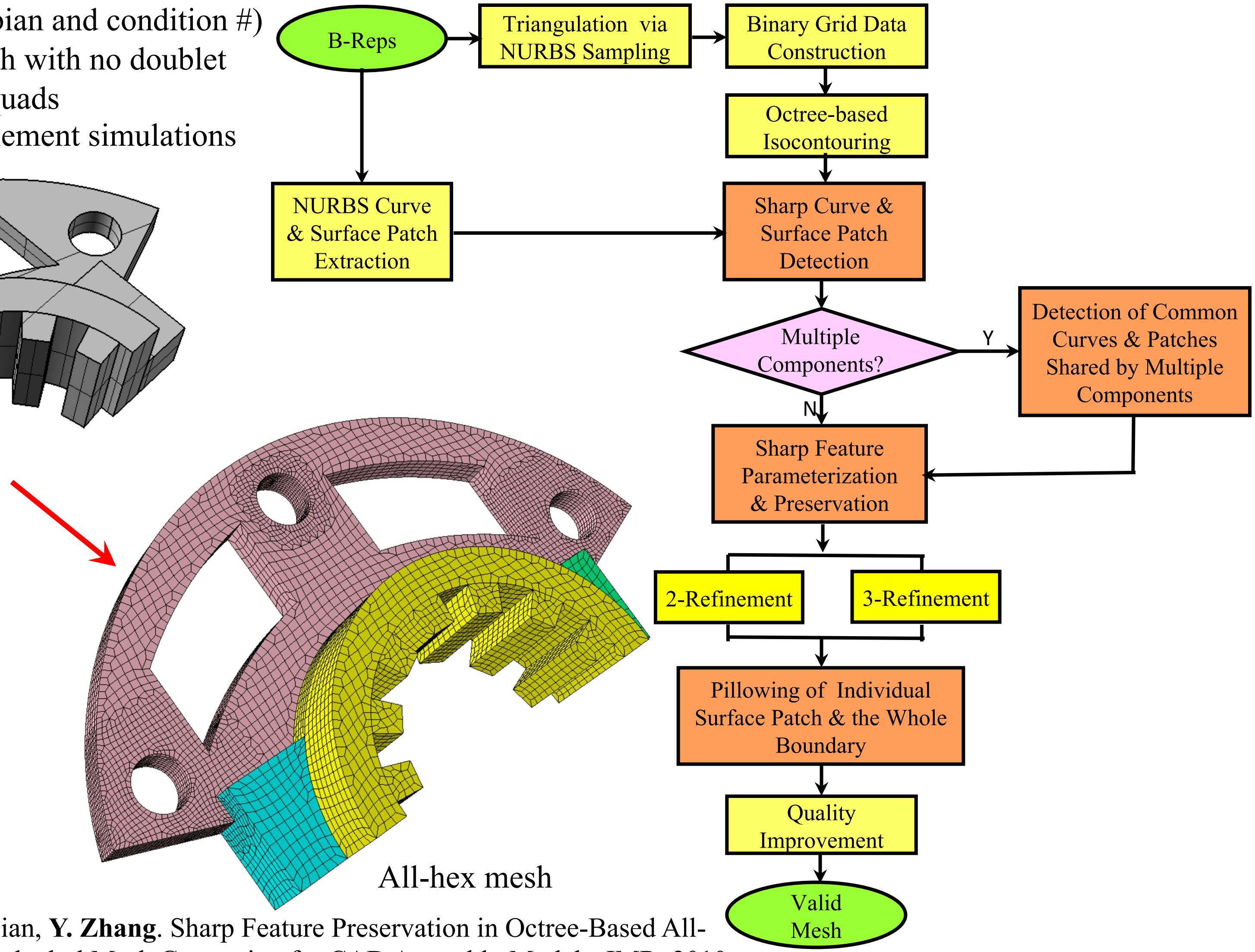
From CAD to All-Hex Meshing: Sharp Feature Preservation

To develop an automatic and robust method to generate conformal hex meshes with sharp feature preservation for single-component models and multiple-component assemblies.

- Conformal to the CAD model or assembly
- Good quality (Jacobian and condition #)
- "Fundamental" mesh with no doublet or triangle-shaped quads
- Suitable for finite element simulations



CAD model



All-hex mesh

J. Qian, **Y. Zhang**. Sharp Feature Preservation in Octree-Based All-Hexahedral Mesh Generation for CAD Assembly Models. IMR, 2010.

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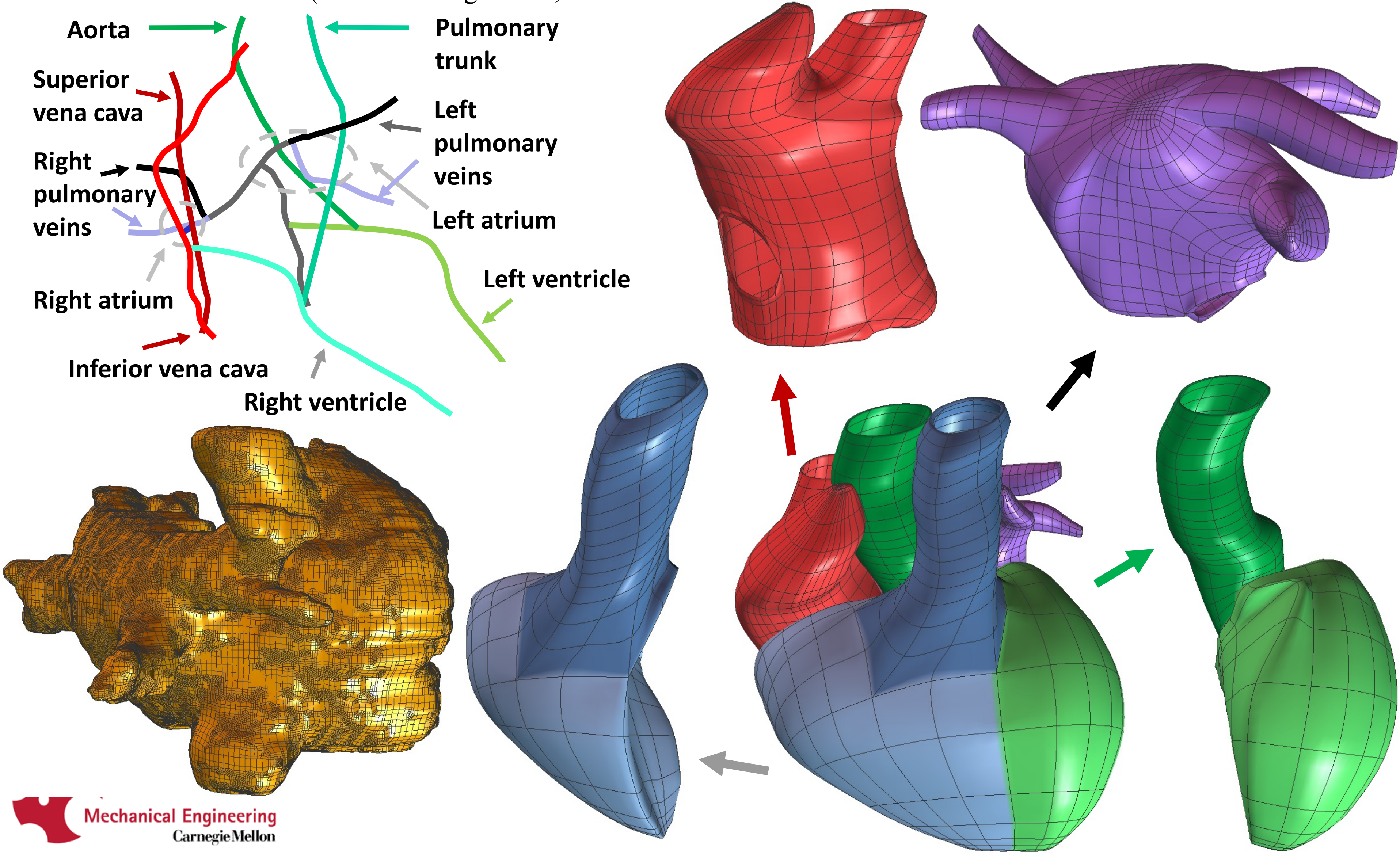
Collaborators: Prof. Andrew McCulloch (UCSD)

Cardiac Hermite Model Construction from Imaging Data

* To develop a NURBS based geometry pipeline for constructing 3D cubic Hermite finite element meshes of the human heart from volumetric imaging data, taking into account the details of the heart structure, including the four main chambers (the left and right atria, ventricles)



Topic 5: Computational Mechanics

- Computational Mechanics has been used in a lot of research fields:
  - Mechanical Engineering
  - Biomedical Engineering
  - Biology, Chemistry, Physics
  - Civil Engineering and Architecture
  - Materials Science
  - Geological Engineering
  - Petroleum Engineering
  - Electrical Engineering, Computer Sciences, etc.

Cardiovascular Blood Flow Simulations

- The human cardiovascular system is comprised of the heart of blood vessels, and supply each organ with blood.
- The amount of the blood provided to each organ may vary depending on physiologic conditions and organ demands.

Movie

Simulating Patient-specific Nanoparticulate Drug Delivery for the Treatment of Vulnerable Plaques

http://youtu.be/wHQY0o8RdS4

References

- Y. J. Zhang. Geometric Modeling and Mesh Generation from Scanned Images. CRC Press, Taylor & Francis Group. 2016 (available free online through CMU Library)
- http://en.wikipedia.org/wiki/Breast_cancer
- http://www.nlm.nih.gov/medlineplus/ency/imagepages/8856.htm
- C.A. Taylor, T.J.R. Hughes and C.K. Zarins, "Finite element modeling of blood flow in arteries," Computer Methods in Applied Mechanics and Engineering, Vol. 158, 158-196 (1998).

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