Toward Automating Patient-Specific Stress Analysis From Medical Imaging

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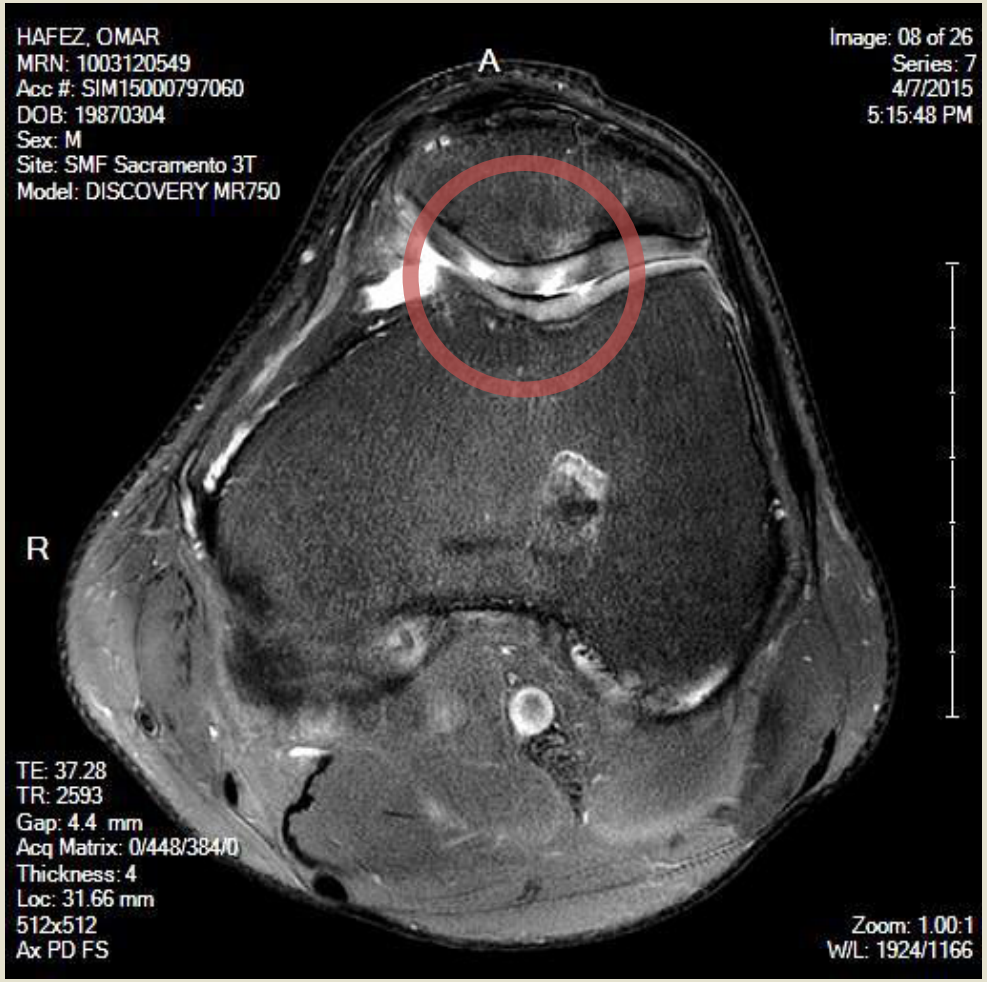
UC Davis

DOE CSGF Annual Program Review
28 July 2015 • Arlington, VA

A SHORT STORY

2009



2015

IN A NUTSHELL

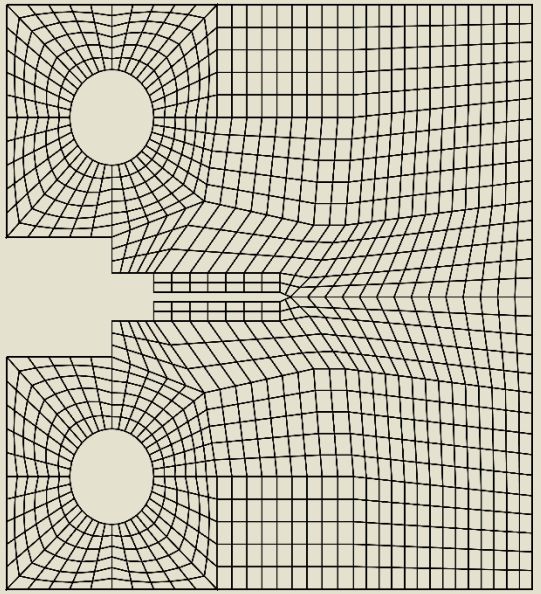
Medical Imaging

- X-ray, MRI, CT, ultrasound
- Used for diagnostics: identification of tumors, kidney stones, osteoarthritis

Physics-Based Simulation

- FEM, meshless methods, finite volumes, finite differences
- Ability to provide engineering guidance to biomechanics problems

info.blockimaging.com/bid/98700/GE-MRI-Scanner-Cost-Price-Info



THE PIPELINE

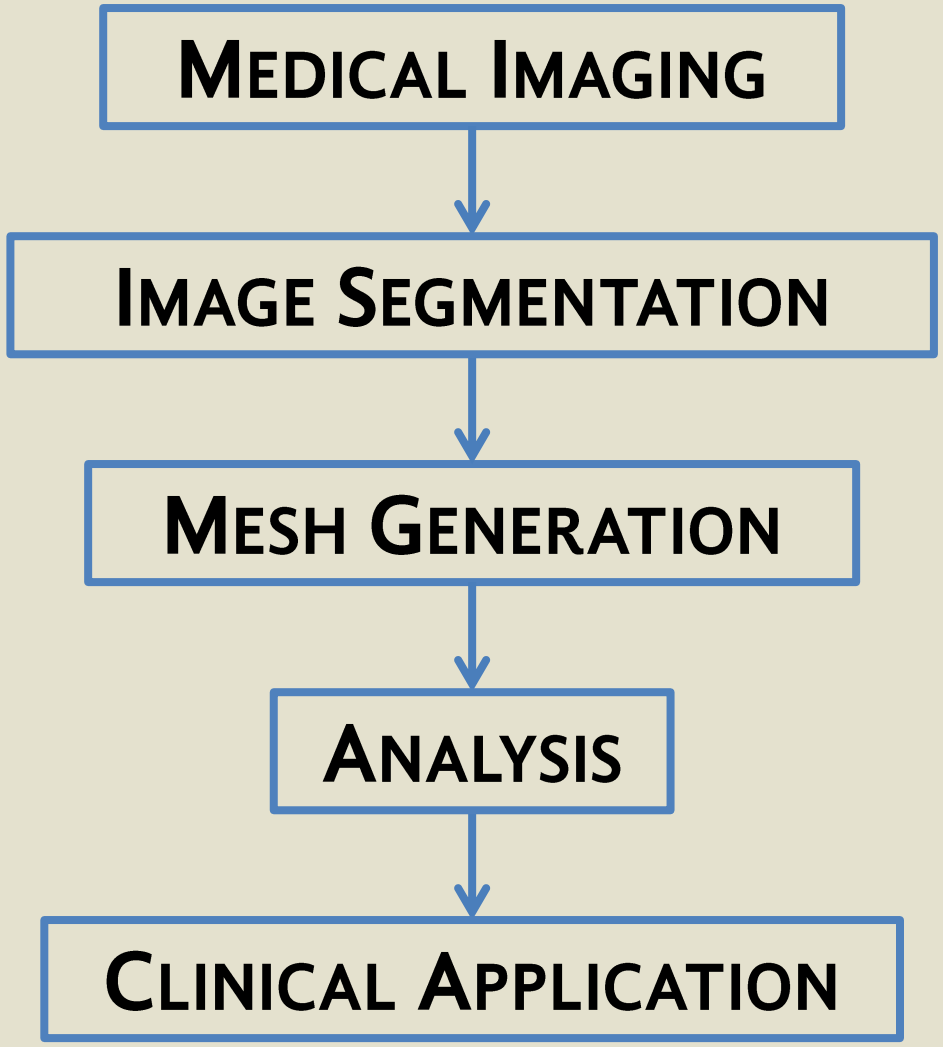


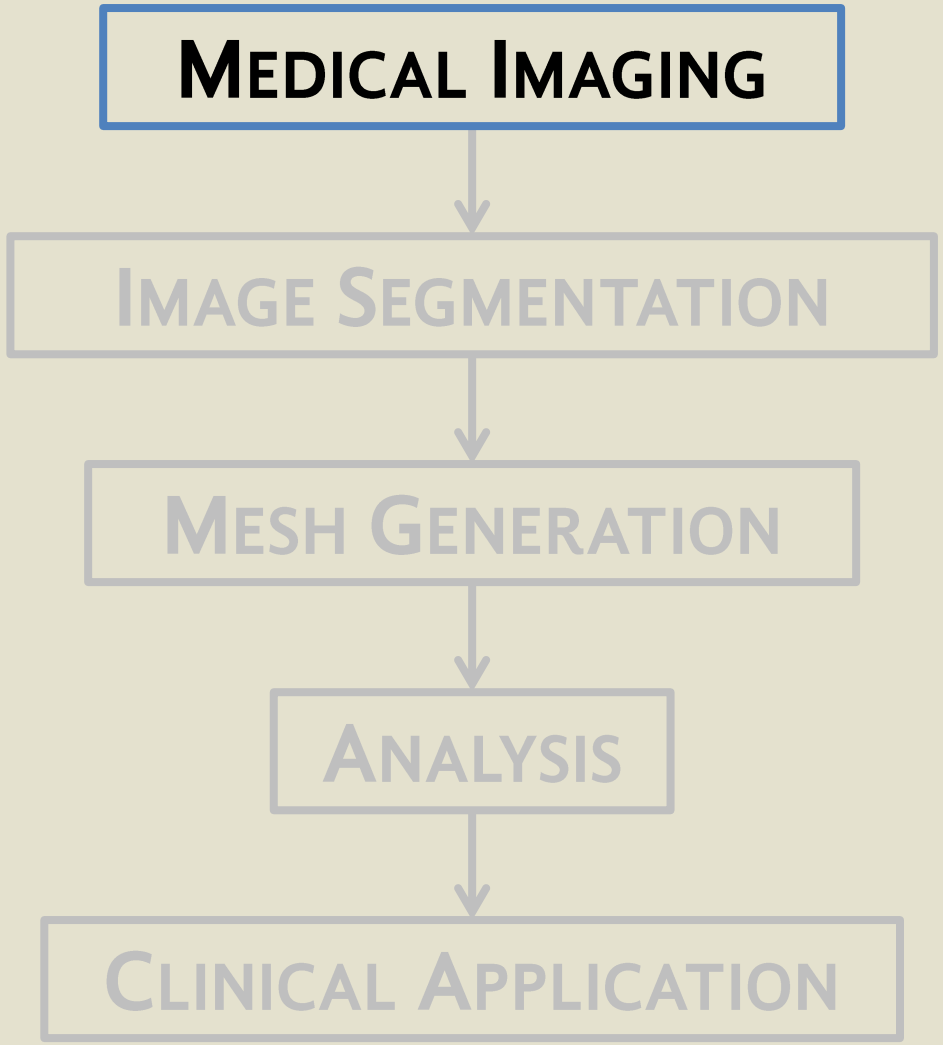
Image processing

Computational geometry

Finite Element Method
Functional Analysis

Biomechanics

THE PIPELINE

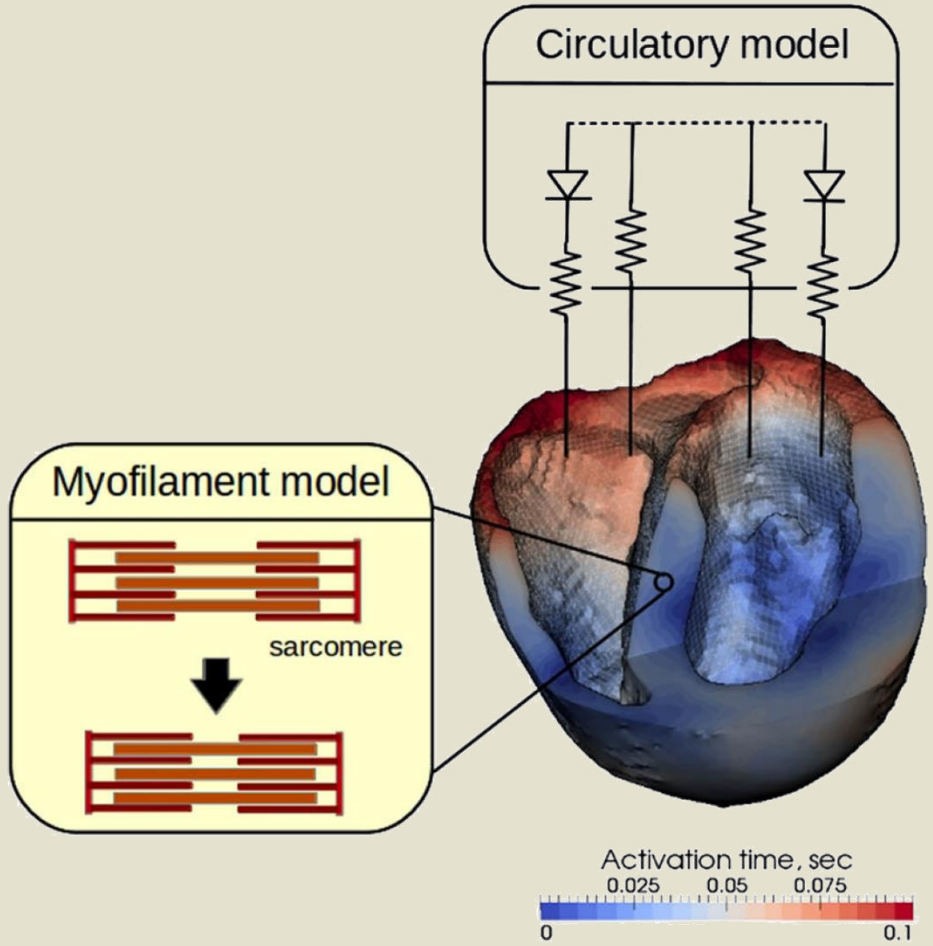


MAGNETIC RESONANCE IMAGING (MRI)

- Roughly measures the **weighted proton density** of each point in the field
- Set of 2D slices represent 3D data set
- Image resolution: ~ 0.5 x 0.5 x 3 mm
- MRI essentially provides **3D point intensity data**

CARDIOID

- Joint venture of LLNL and IBM
- Sequoia: 20 PFLOPS, 98k nodes, 1.6m processors
- Electrophysiology + mechanics of human heart → mechanisms of sudden cardiac arrest from arrhythmia
- Highly efficient and scalable code → unprecedented exploration



MECHANICS

- Passive cardiac tissue modeled as a hyperelastic, incompressible material with orthotropic properties

$$\frac{\partial}{\partial X_M}\left(T_{MN}(\mathbf{x}, p)F_{iN}(\mathbf{x})\right) + \rho g_i = 0$$
$$J = 1$$

- mixed pressure-displacement finite elements are used to enforce incompressibility

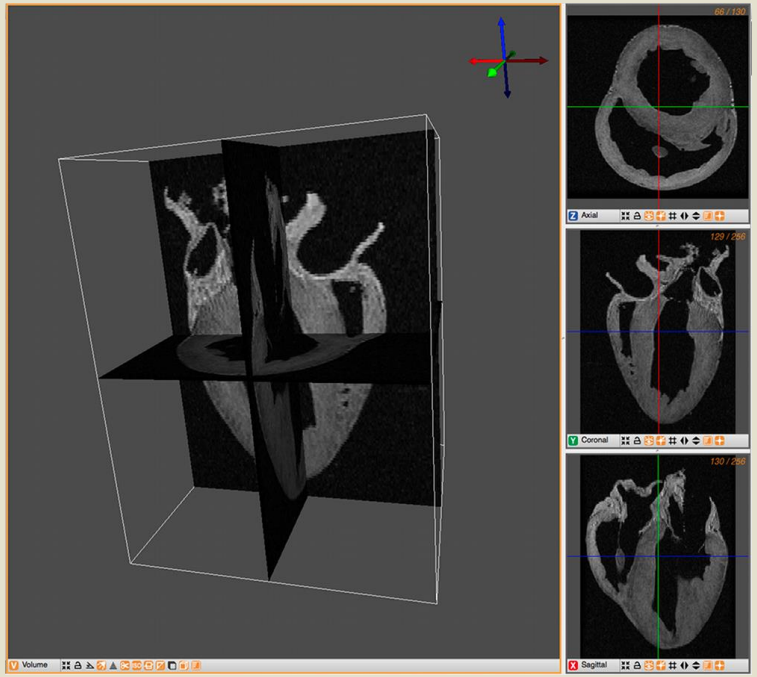
$$T^{\text{active}} = \sigma_a \mathbf{f}\mathbf{f}^{\mathrm{T}} \qquad \frac{\mathrm{d}\mathbf{w}}{\mathrm{d}t} = \mathbf{q}(\mathbf{w}; t_a, \lambda)$$
$$\sigma_a \equiv \sigma_a(\mathbf{w}; t_a, \lambda)$$

$$\begin{cases} \frac{\mathrm{d}\bar{\mathbf{w}}}{\mathrm{d}t} = \bar{\mathbf{q}}(\bar{\mathbf{w}}, t_a, \mathbf{U}) \\ K(\bar{\mathbf{w}}, \mathbf{U}, \mathbf{P}) = 0 \end{cases}$$

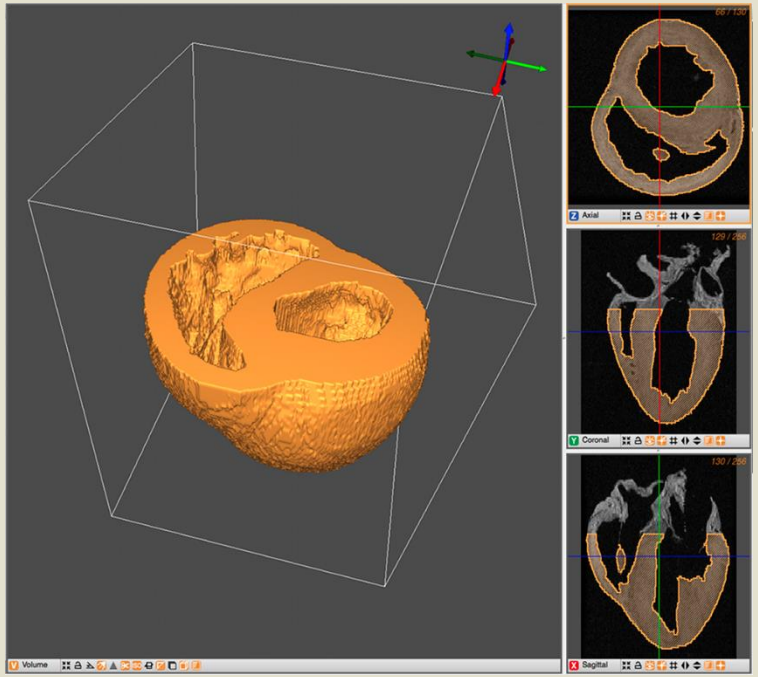
- Active stress is generated by a model with force dependence on length and velocity of muscle shortening

$$\mathcal{J}(\mathbf{U}^j_{k+1}, \mathbf{P}^j_{k+1}) \begin{bmatrix} \Delta\mathbf{U} \\ \Delta\mathbf{P} \end{bmatrix} = \begin{bmatrix} -\mathbf{r}_u(\mathbf{U}^j_{k+1}, \mathbf{P}^j_{k+1}) \\ -\mathbf{r}_p(\mathbf{U}^j_{k+1}, \mathbf{P}^j_{k+1}) \end{bmatrix}$$

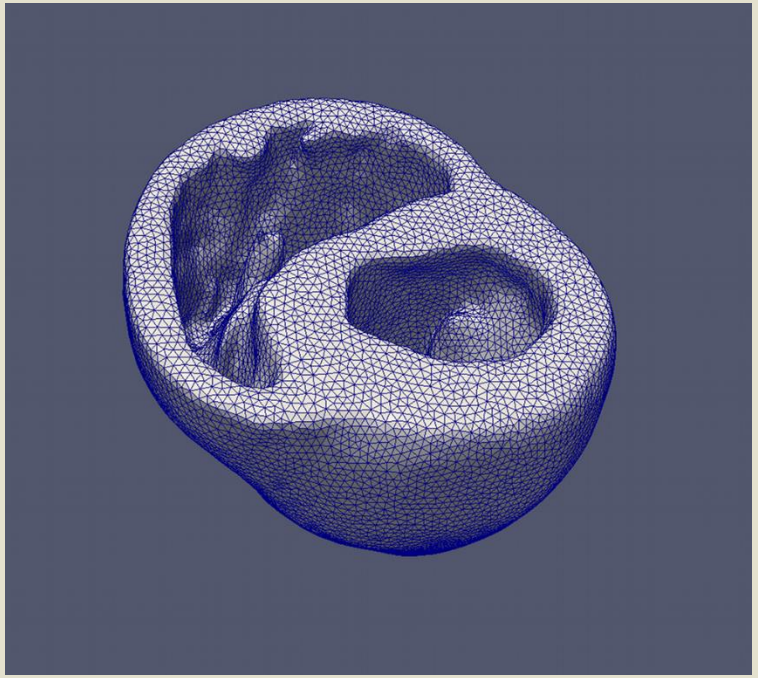
TOOLCHAIN



RAW DATA →

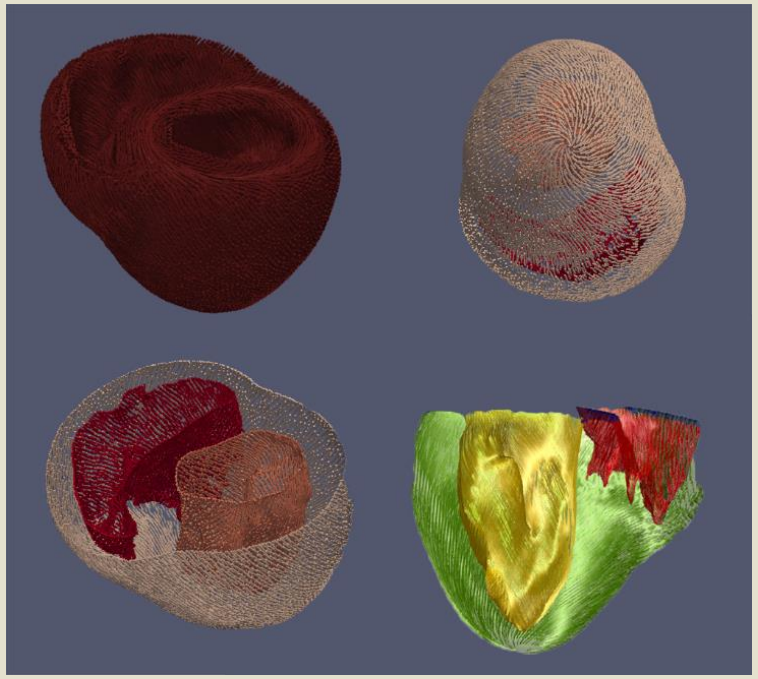


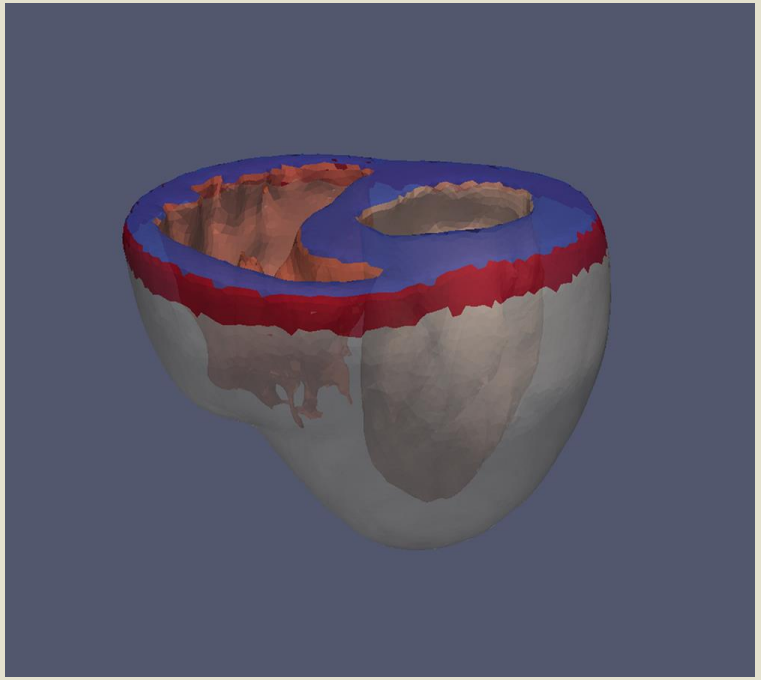
SEGMENTATION →

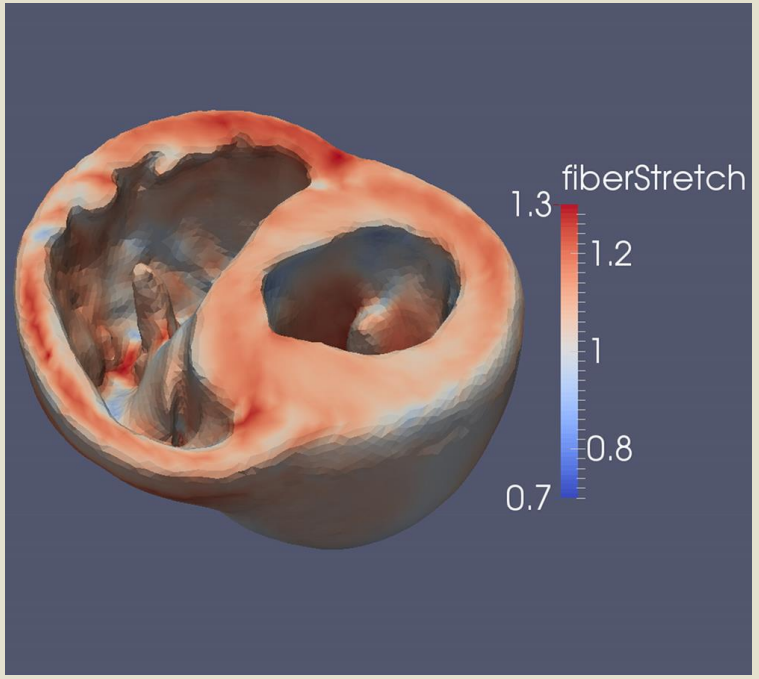


VOLUME MESH →

TOOLCHAIN

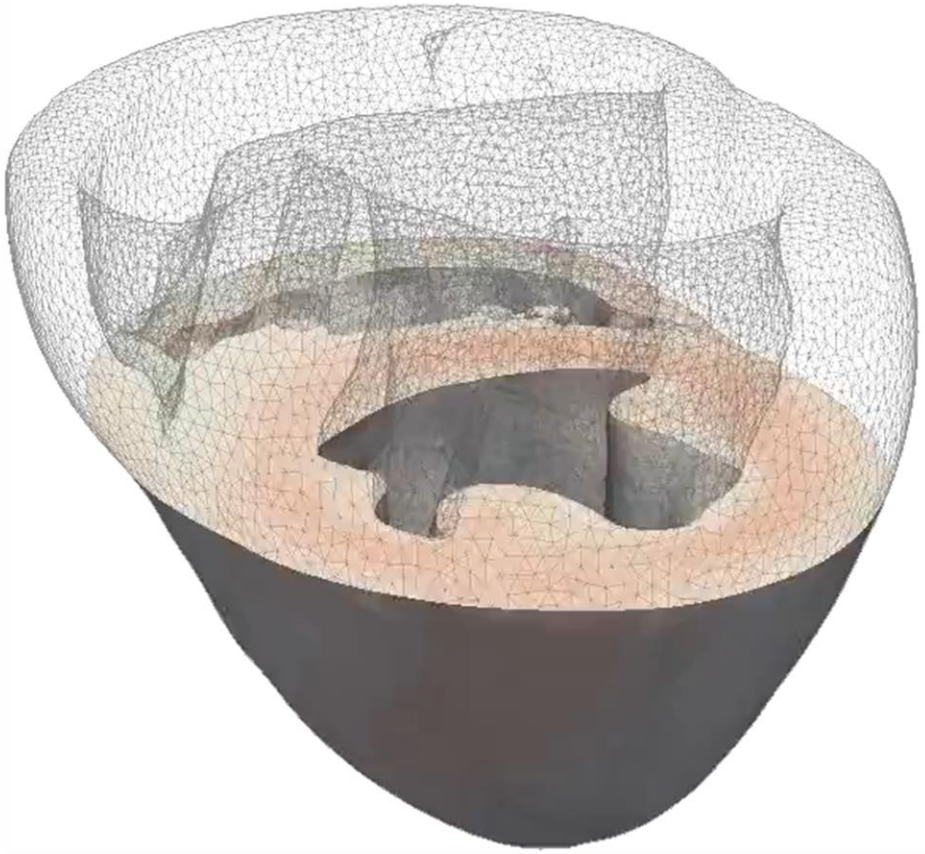


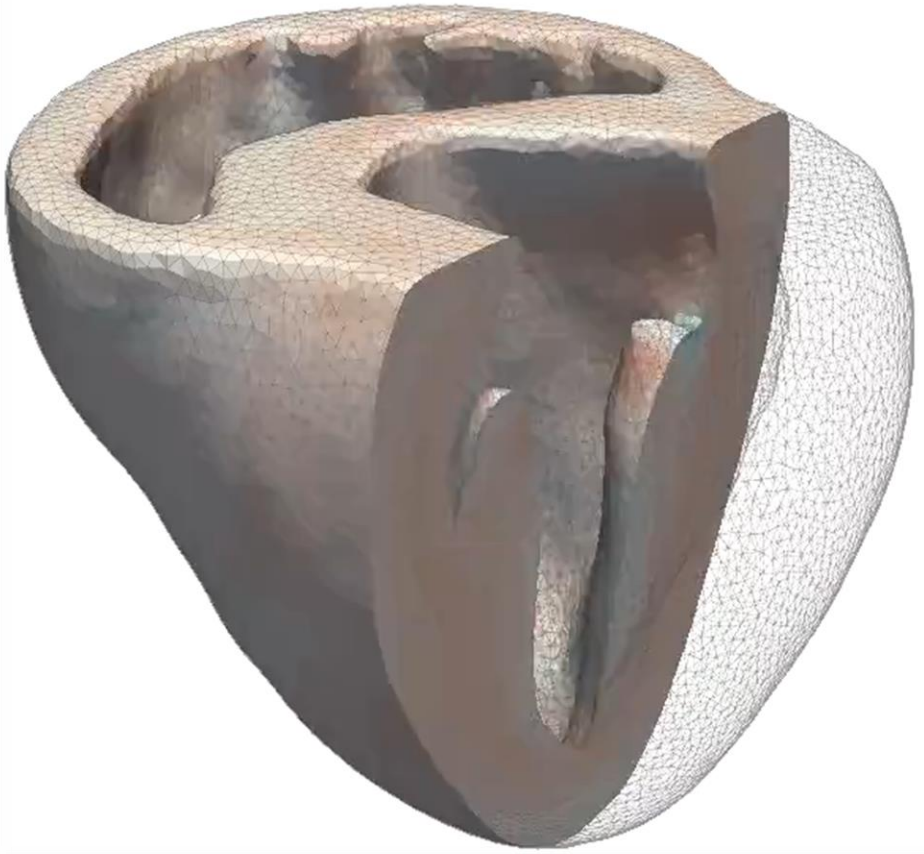




FIBER GENERATION → BOUNDARY CONDITIONS → ANALYSIS

RESULTS





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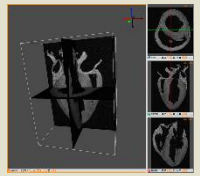
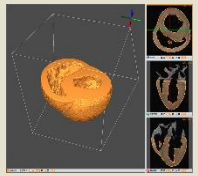
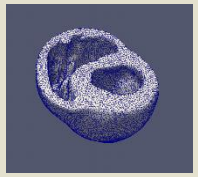
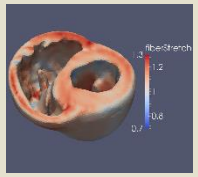








MEDICAL IMAGING

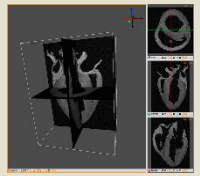
IMAGE SEGMENTATION

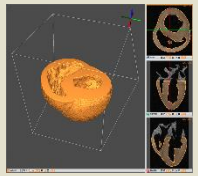
MESH GENERATION

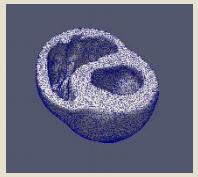
ANALYSIS

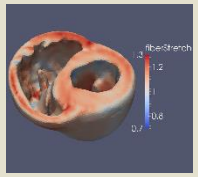
CLINICAL APPLICATION

THE PIPELINE









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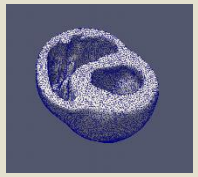


Medical Imaging

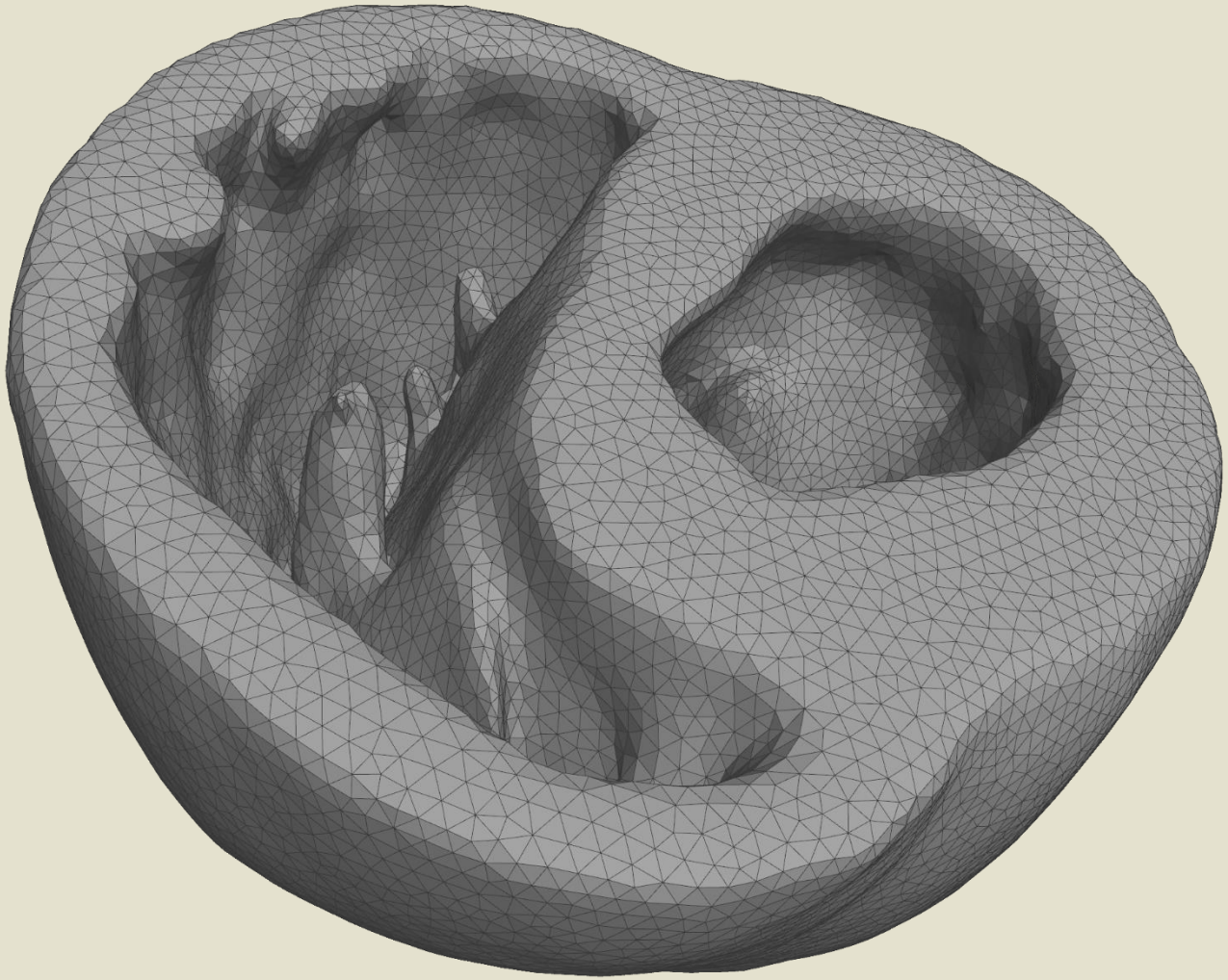
Image Segmentation

Mesh Generation

Analysis

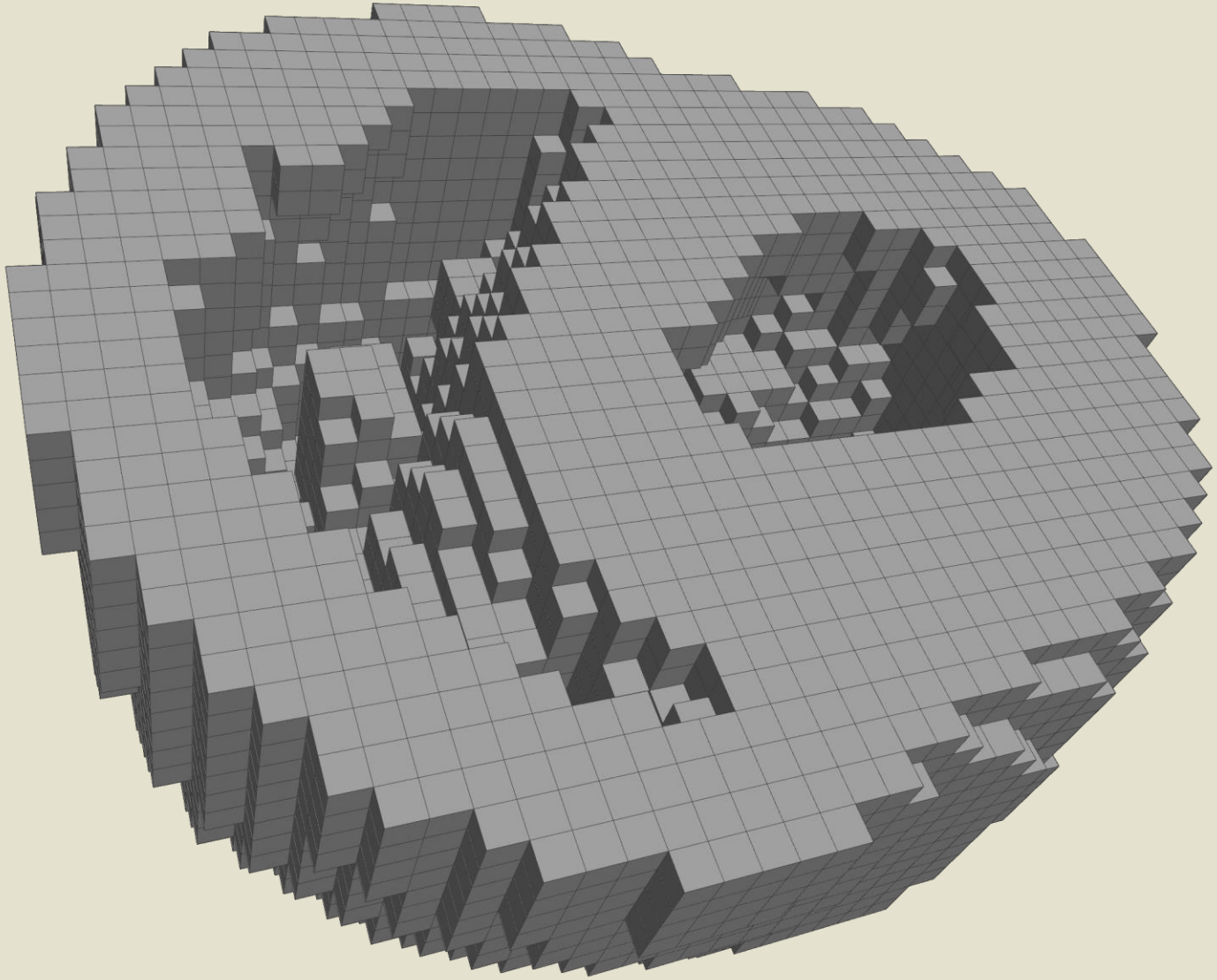
Clinical Application

AUTOMATIC MESH GENERATION



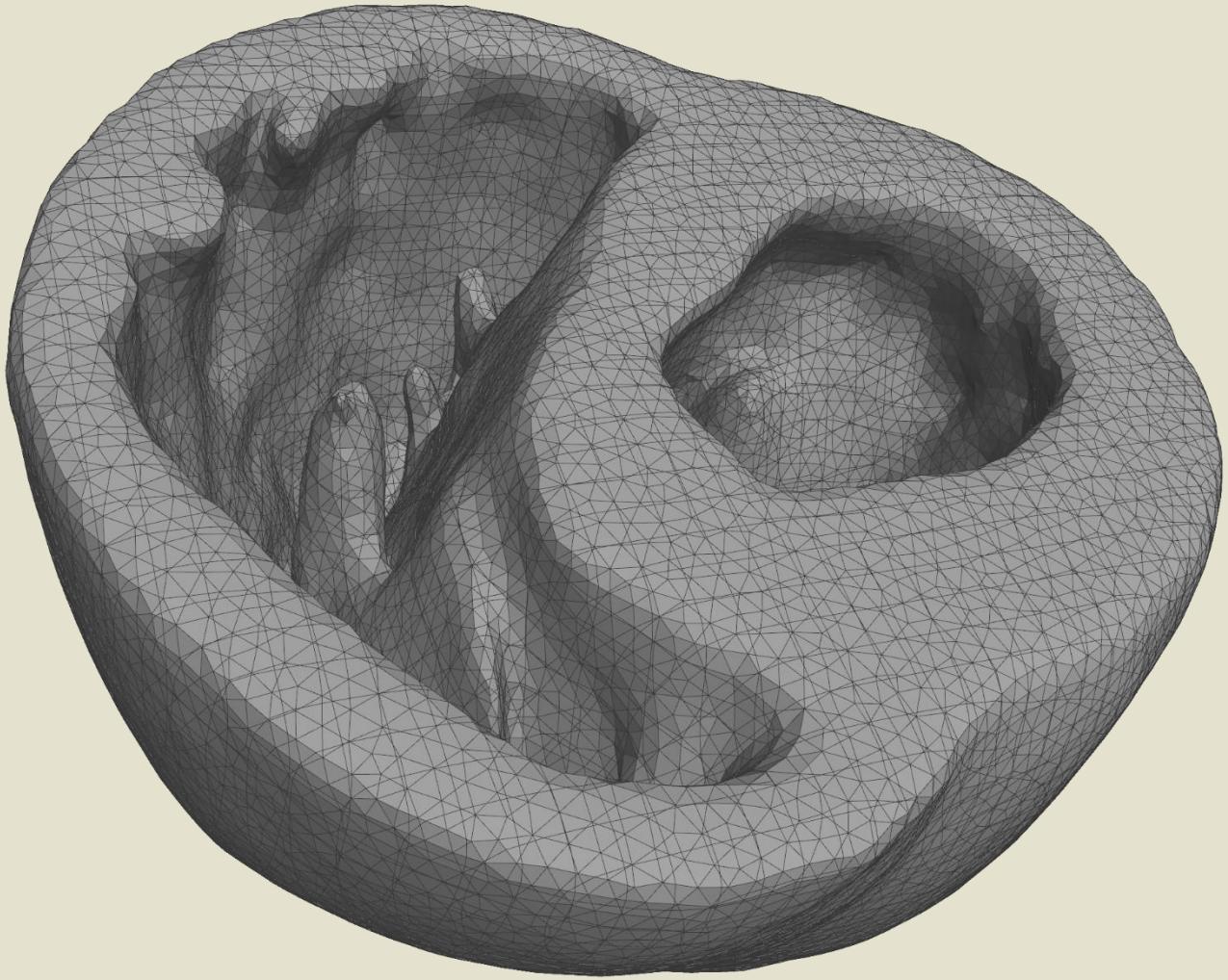
1. Given a boundary representation (b-rep) of the object

AUTOMATIC MESH GENERATION



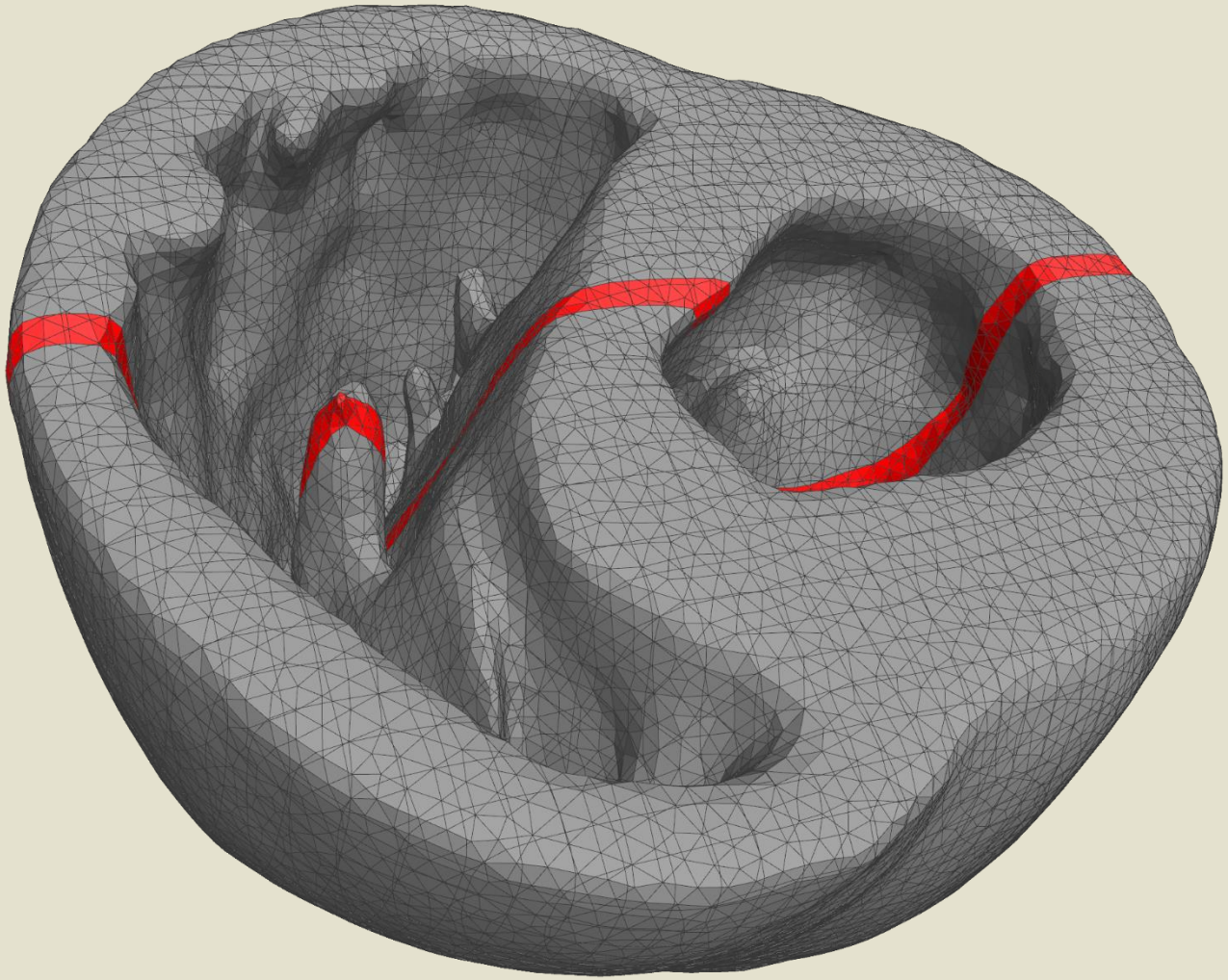
2. Create bounding hex mesh

AUTOMATIC MESH GENERATION



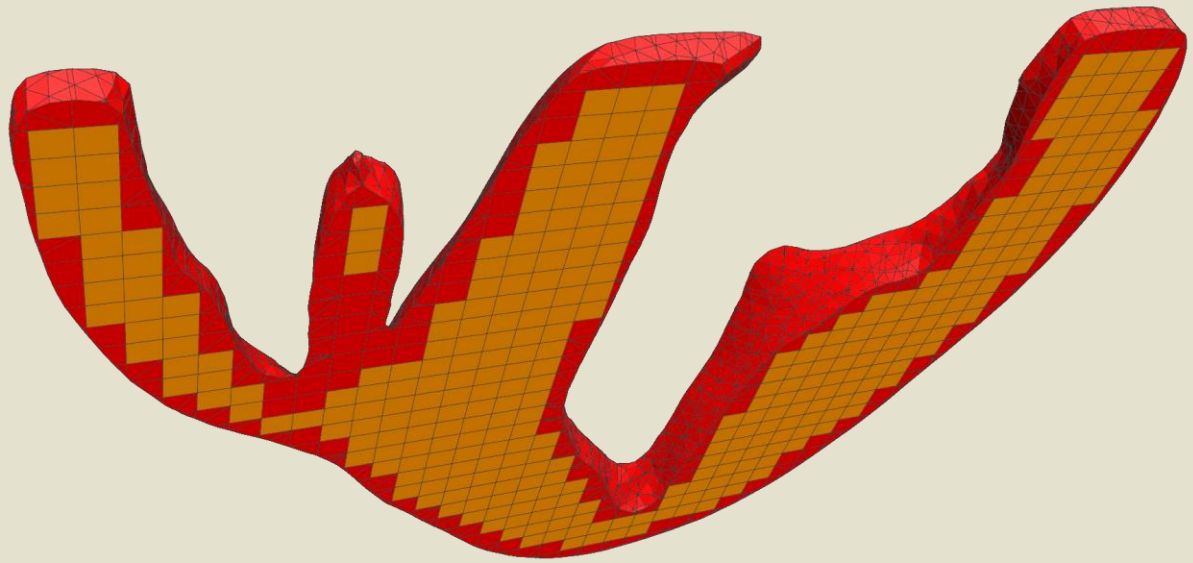
3. “Sculpt” the hex mesh with the b-rep

AUTOMATIC MESH GENERATION



Arbitrary polyhedral elements result

AUTOMATIC MESH GENERATION



Arbitrary polyhedral elements result

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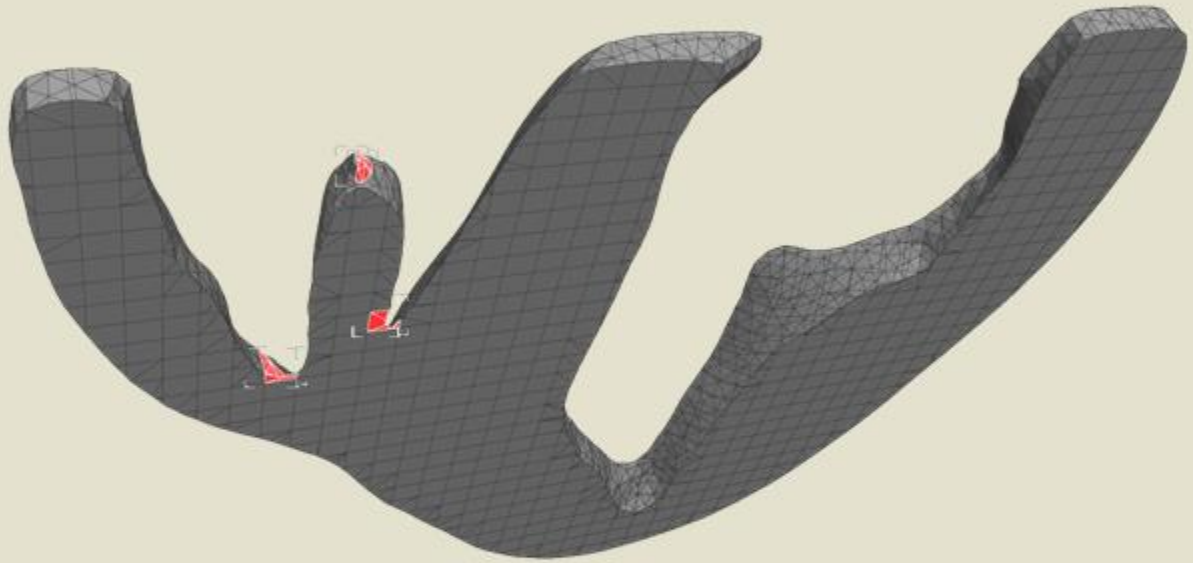

Arbitrary polyhedral elements result

AUTOMATIC MESH GENERATION

Arbitrary polyhedral elements result

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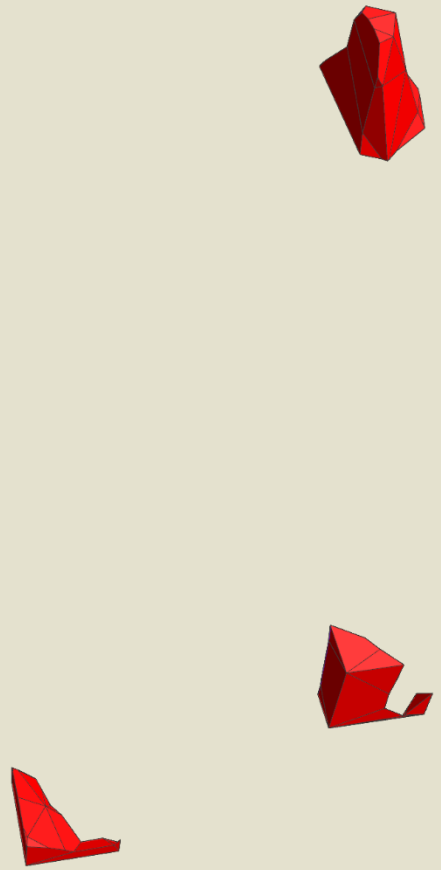

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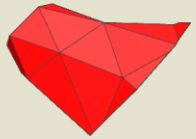

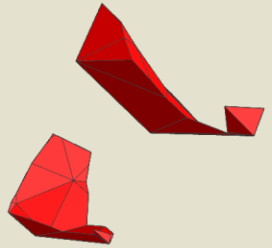

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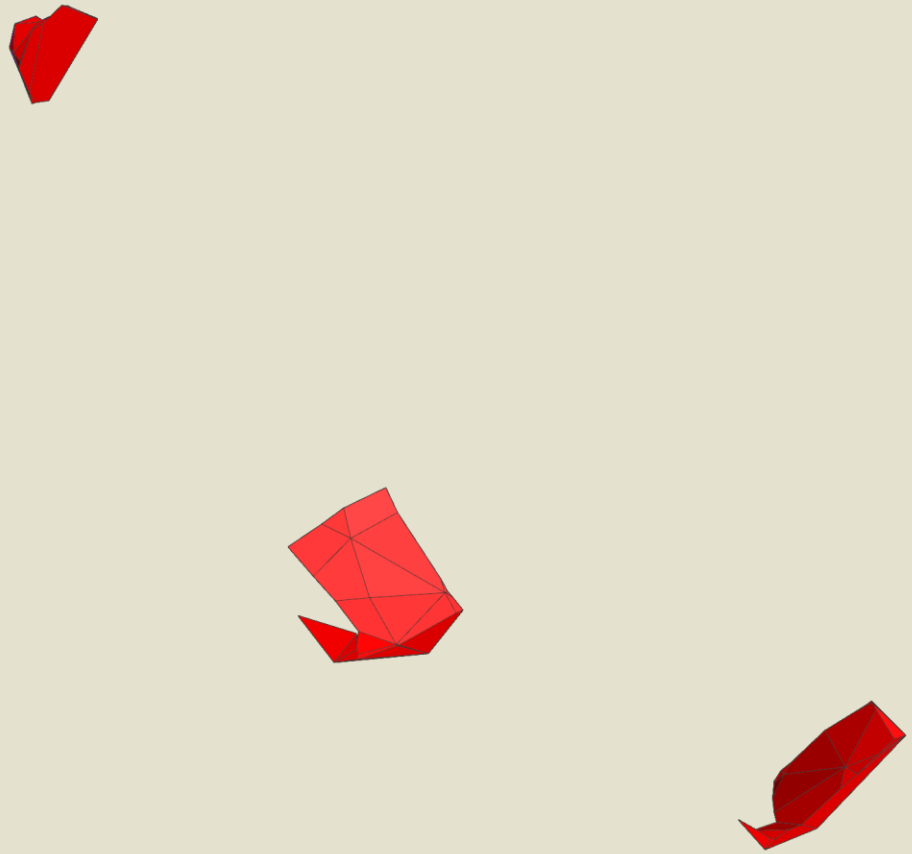

AUTOMATIC MESH GENERATION

AUTOMATIC MESH GENERATION

COMPARISON

- Quadratic tetrahedra: 856k DOF
- Comparable polyhedral elements: 106k DOF
- Generally get order of magnitude reduction in system compared to tets!
- Heterogeneous conventional meshes can have their own (stability related) issues

THE PIPELINE

MEDICAL IMAGING

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IMAGE SEGMENTATION

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MESH GENERATION

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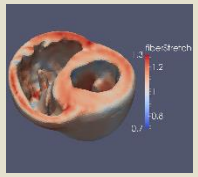

ANALYSIS

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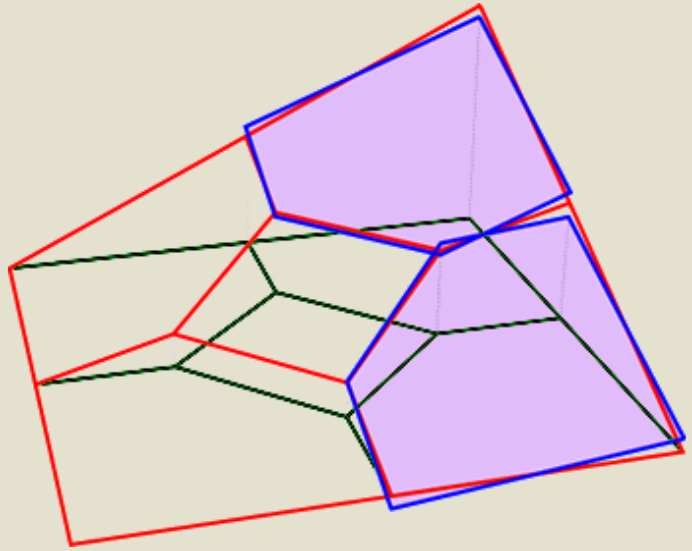
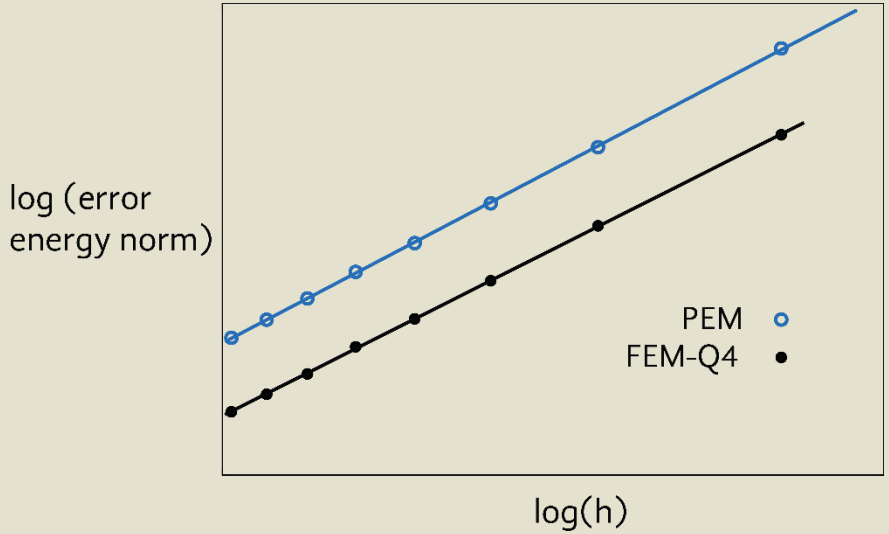
CLINICAL APPLICATION

THE PARTITIONED ELEMENT METHOD

- A new, FE-like method that accommodates essentially arbitrary polyhedral elements
- Allows for fast, robust meshing – no longer a bottleneck
- Shape functions are discrete discontinuous, piecewise linear functions over partitions of physical element
- Converges at the same rate as FEM
- PEM enjoys FEM-like BC enforcement and quadrature efficiency, without the strict topological restrictions on elements





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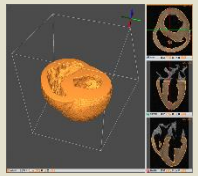

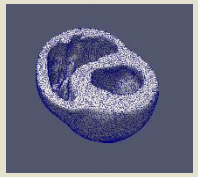

Medical Imaging

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Image Segmentation

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Mesh Generation

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Analysis

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Clinical Application

THE PIPELINE

Medical Imaging

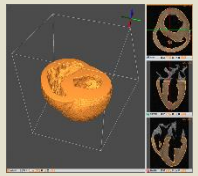
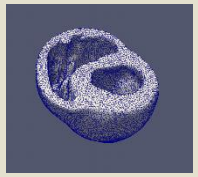


Image Segmentation

B-rep generation



Mesh Generation

Analysis

Clinical Application

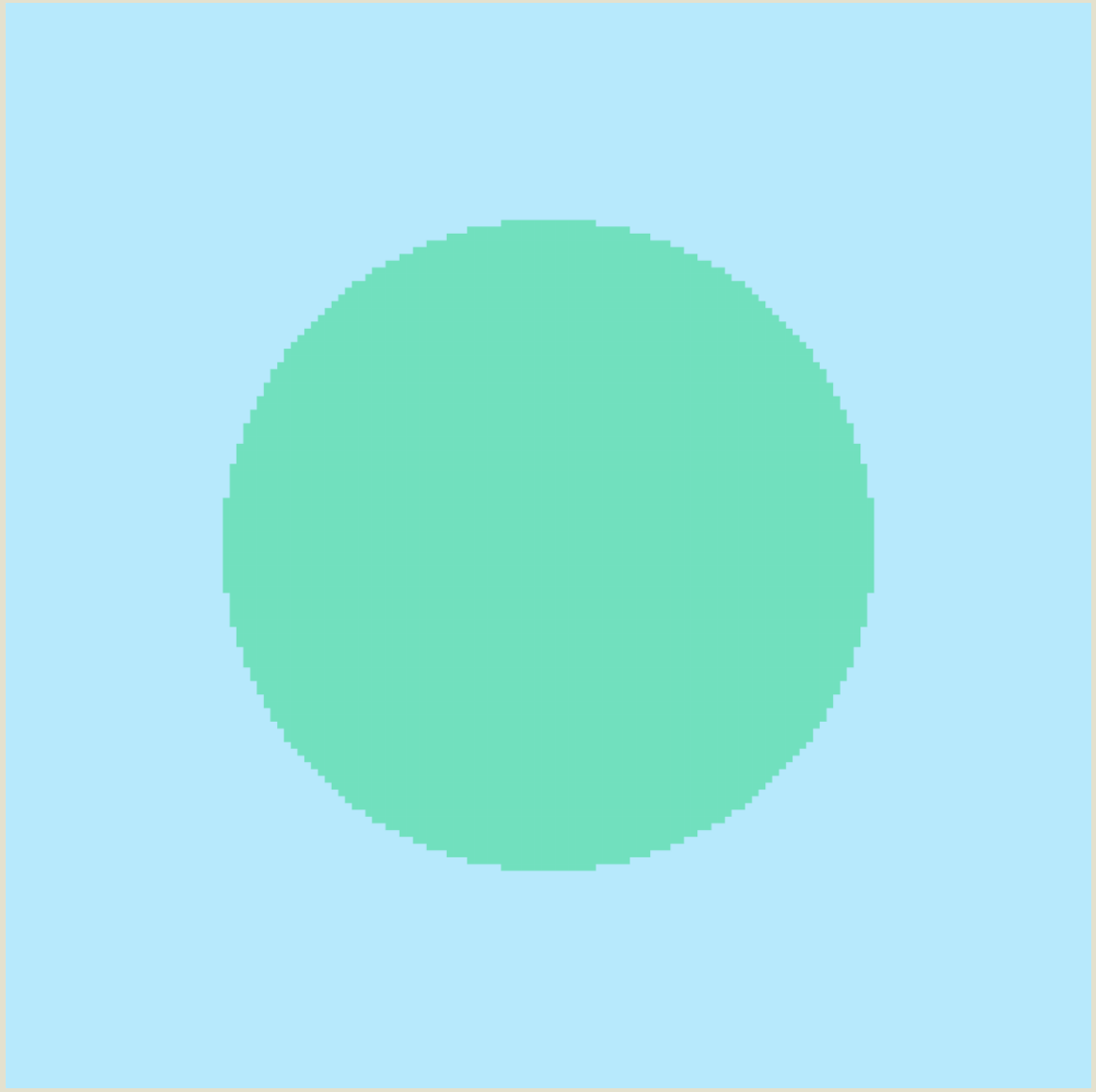
OBJECTIVES

- Given 3D point intensity values, seek to
  - identify the different materials in a scan (**segmentation**) and
  - define their facetized boundaries (**b-rep generation**)

- Seek to:
  1. Minimize user interaction
  2. Produce an explicit definition of a facetized, watertight boundary representation
  3. Robust and reproducible

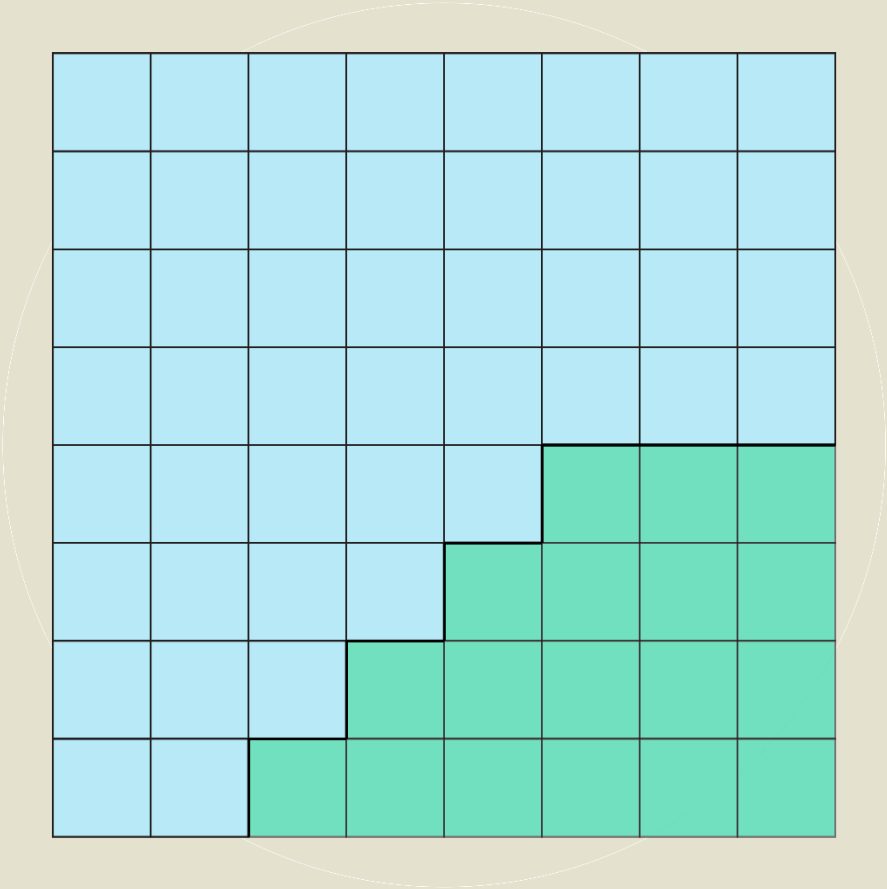
- For now, assume segmentation as input (manual, level sets, etc.)

VORONOI-BASED B-REP GENERATION



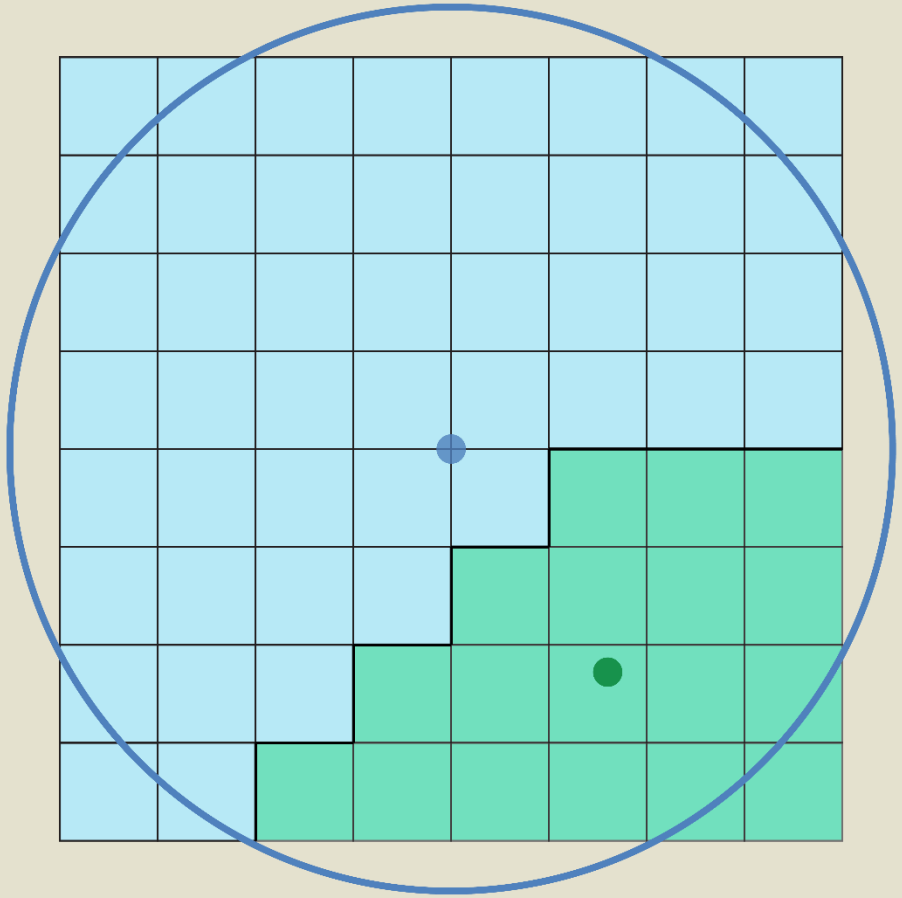
Use segmented image as input – each voxel assigned a region

VORONOI-BASED B-REP GENERATION



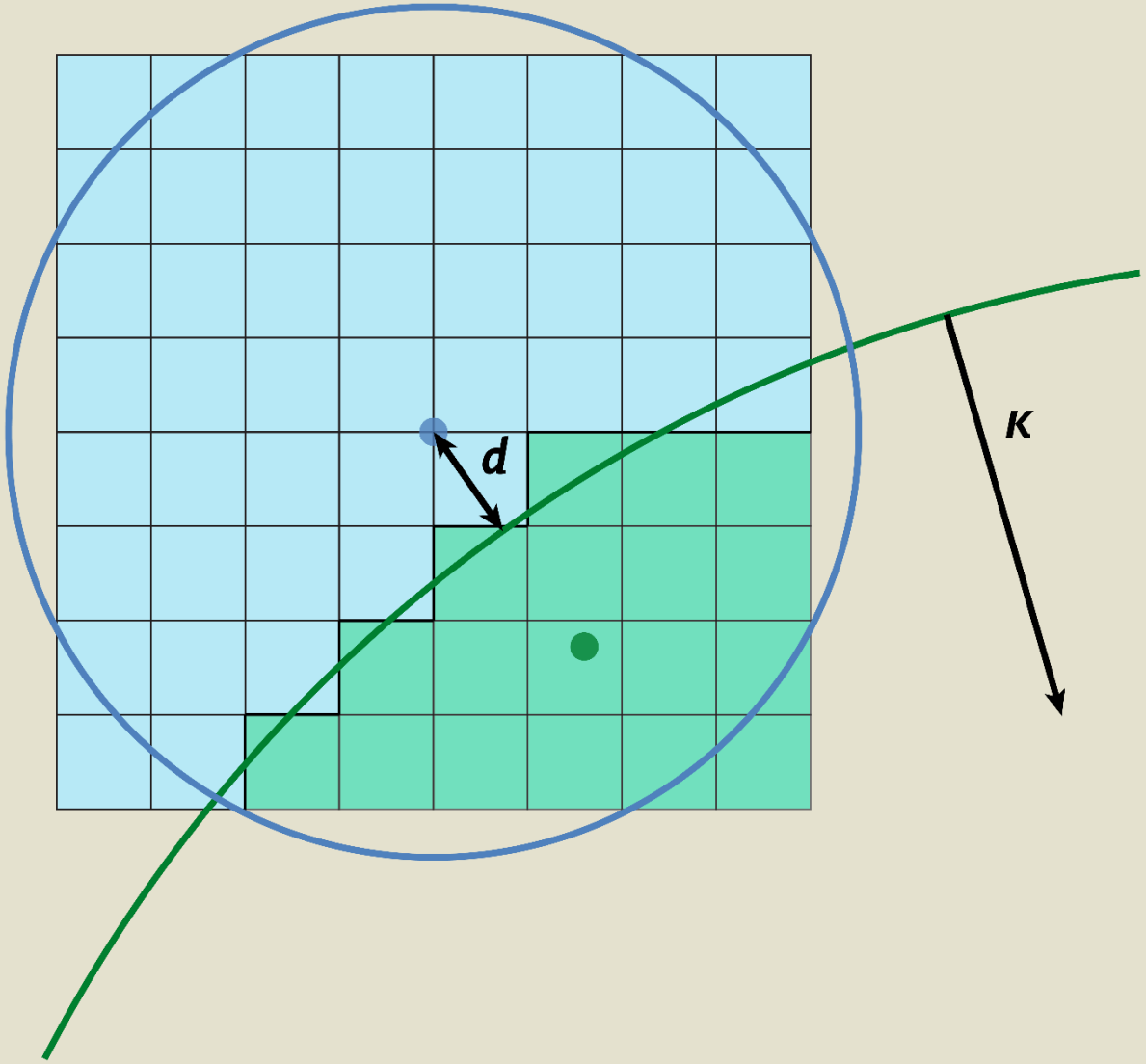
Consider a window in the segmented image

VORONOI-BASED B-REP GENERATION



Identify a disc that shares the same area and centroid of the entire window

VORONOI-BASED B-REP GENERATION

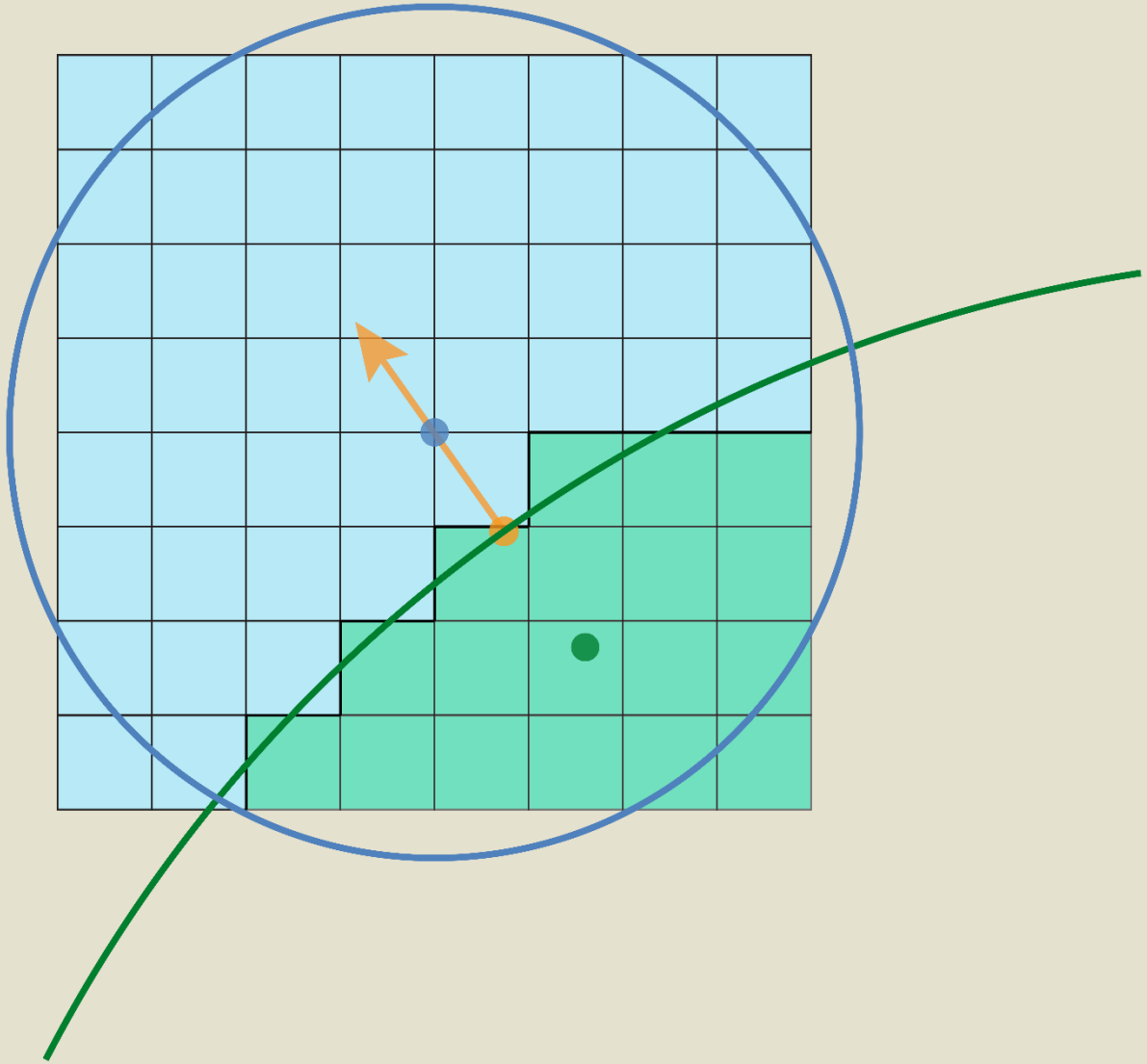


Approximate interface with circular arc

Match the area and centroid of material with the area and centroid of the intersecting disc.

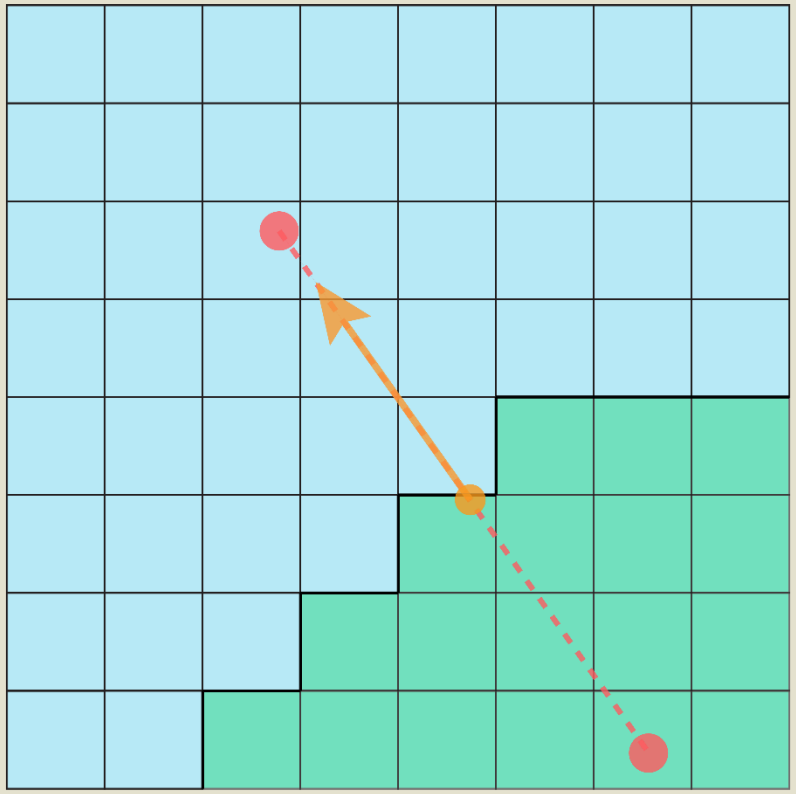
Results in nonlinear system of equations in ***d*** and ***K***.

VORONOI-BASED B-REP GENERATION



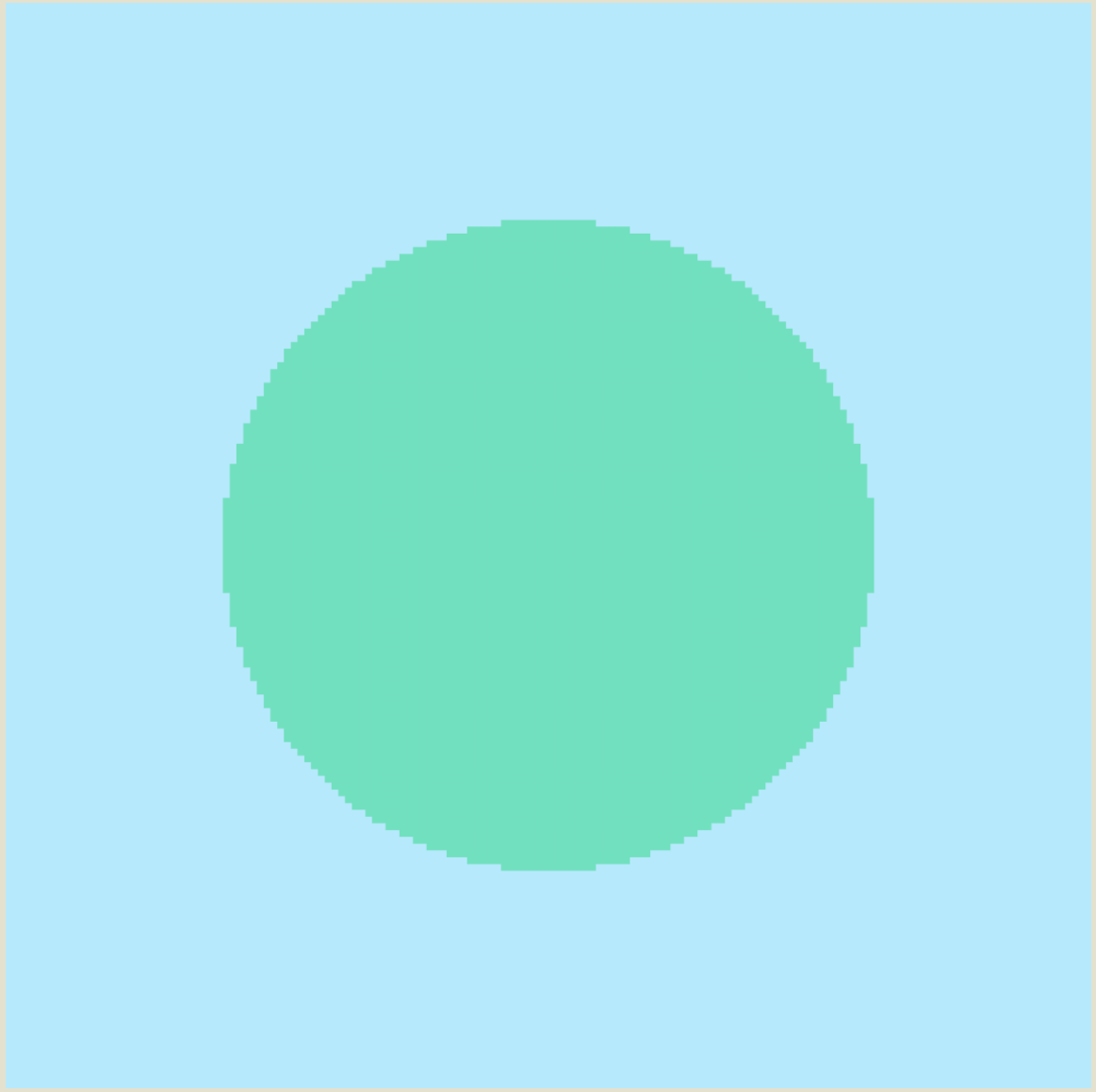
Identify the discrete point-direction pair defined by these geometric constructs

VORONOI-BASED B-REP GENERATION



Introduce Voronoi site pair based on point-direction pair

VORONOI-BASED B-REP GENERATION



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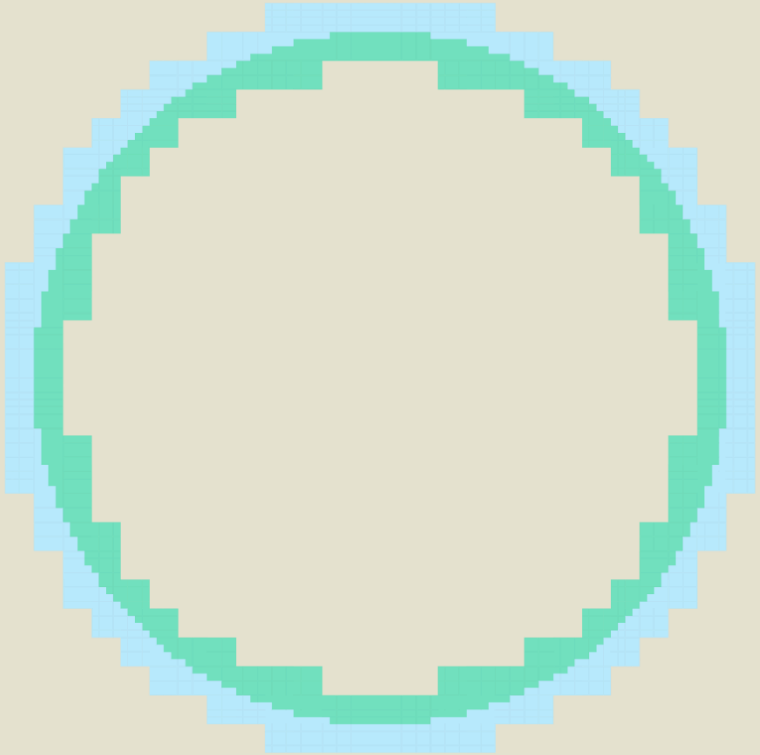
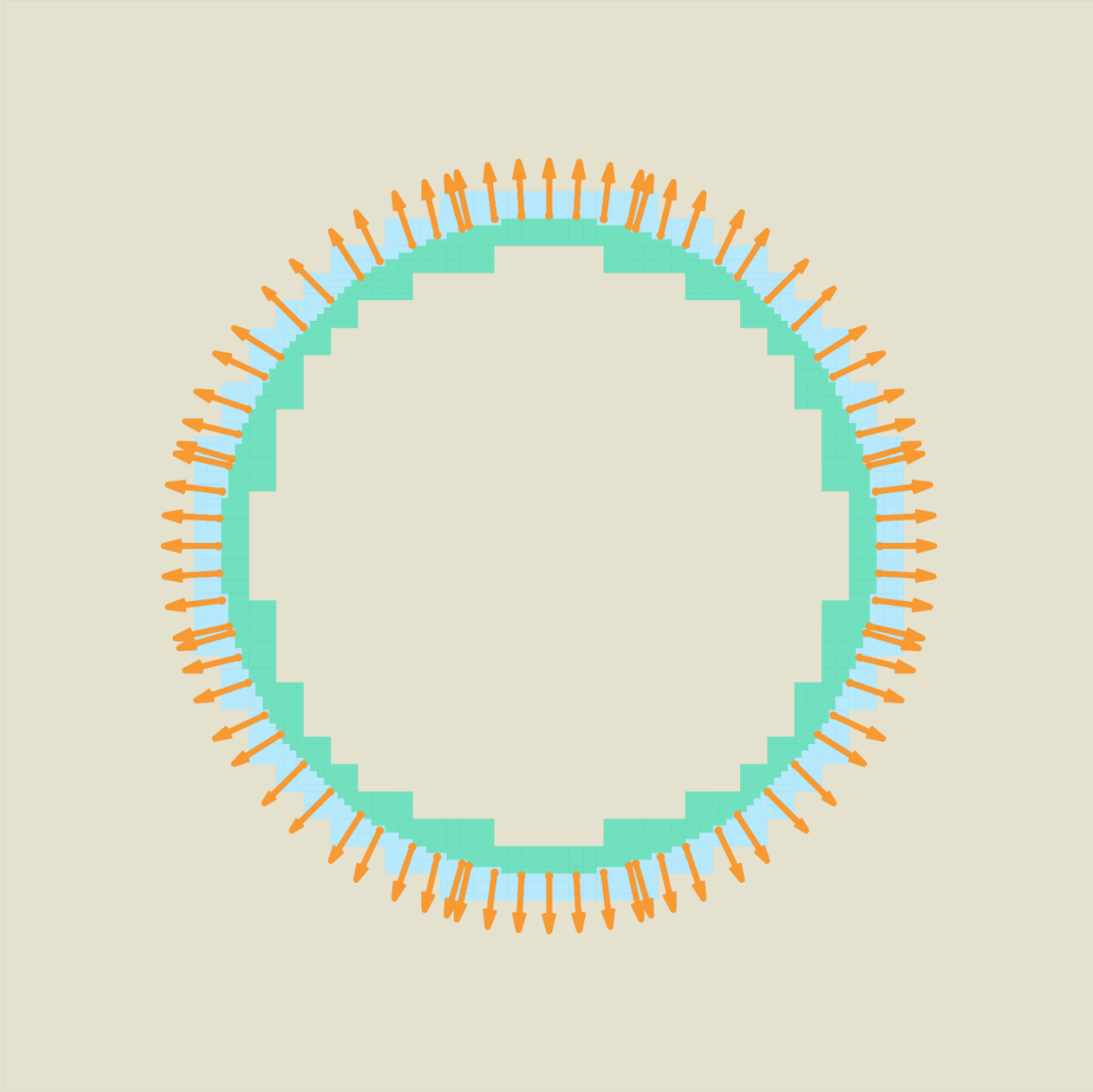


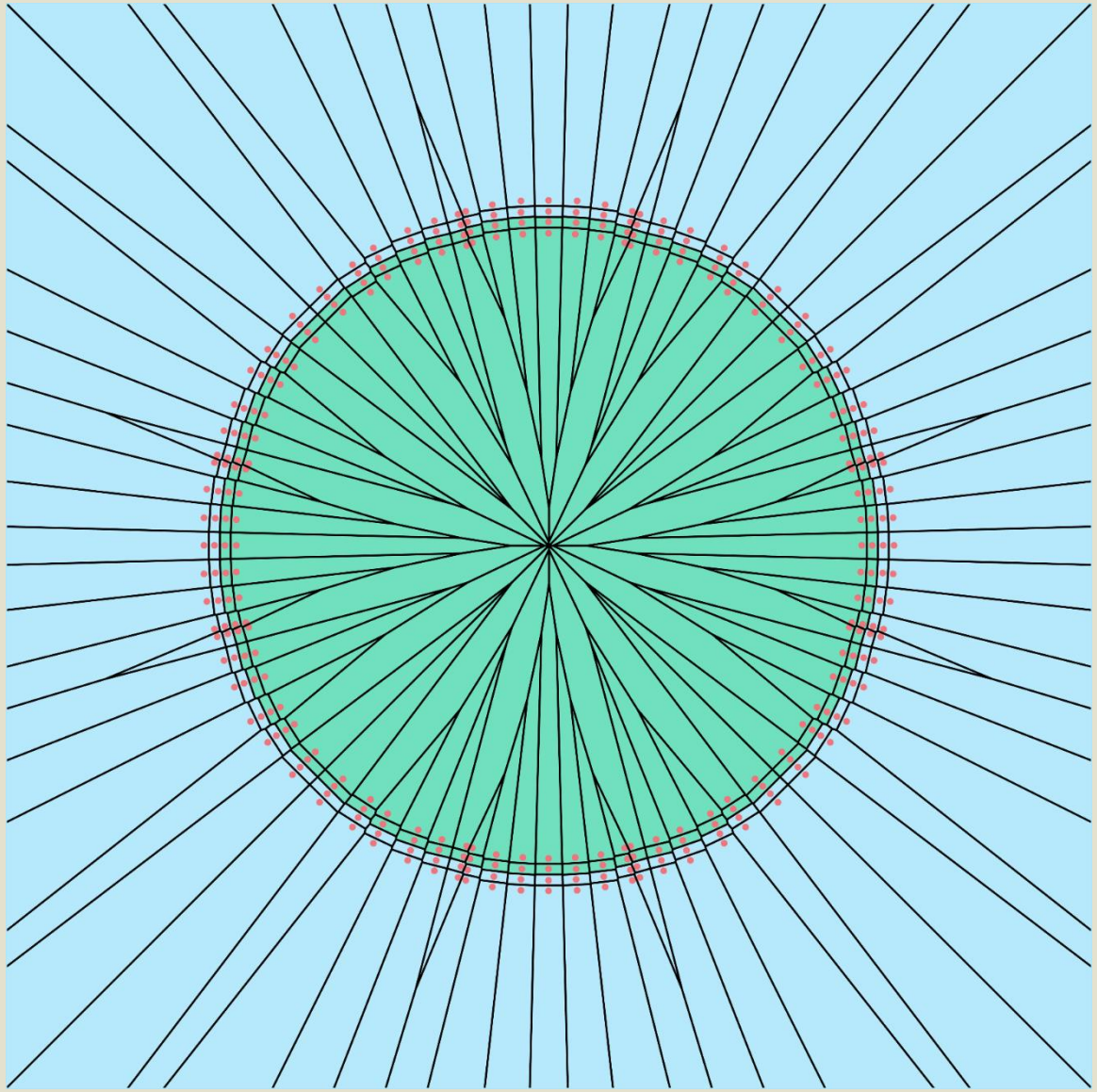
Identify windows that have multiple materials

VORONOI-BASED B-REP GENERATION



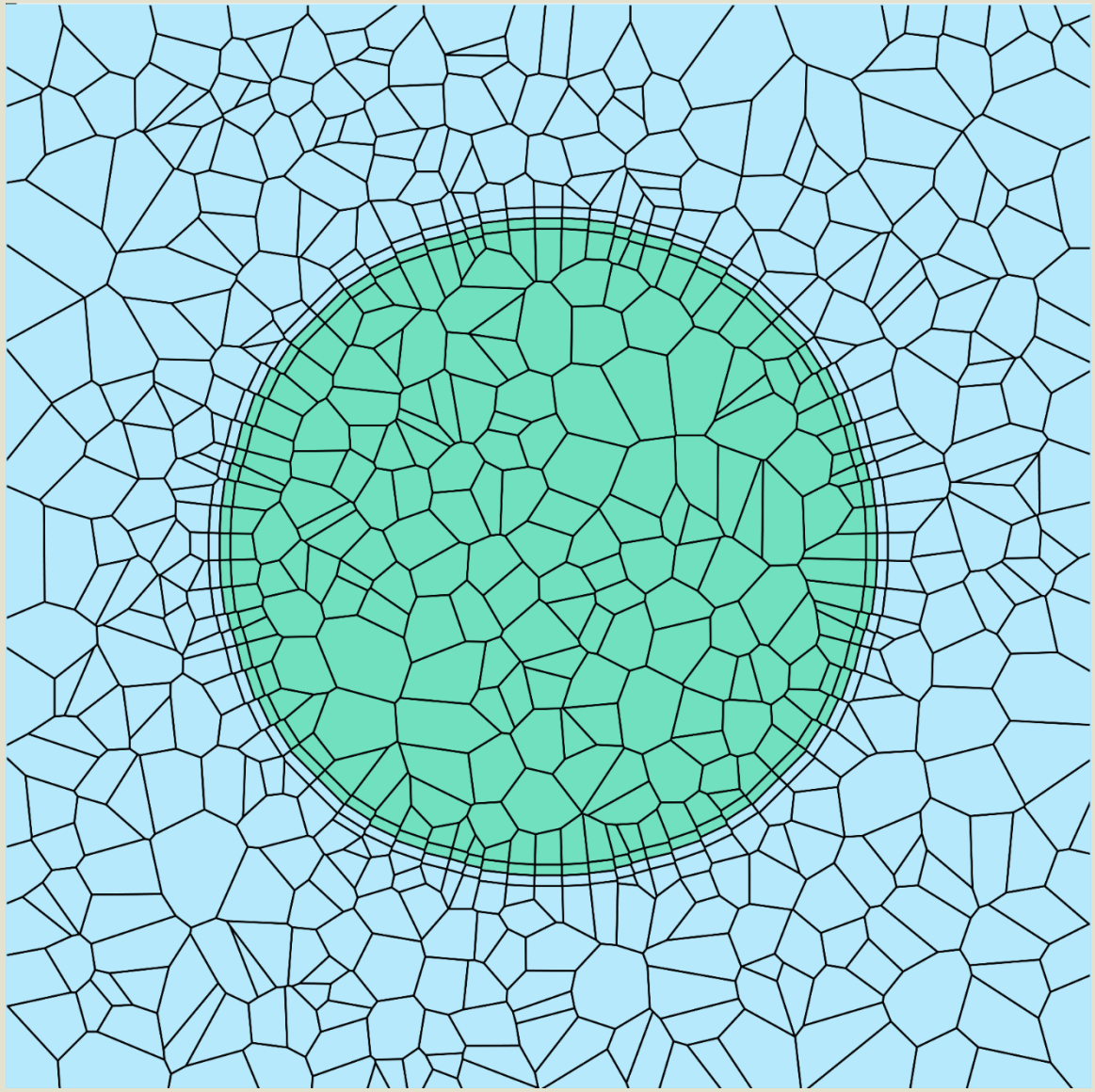
Compute discrete point-direction pair for each window

VORONOI-BASED B-REP GENERATION



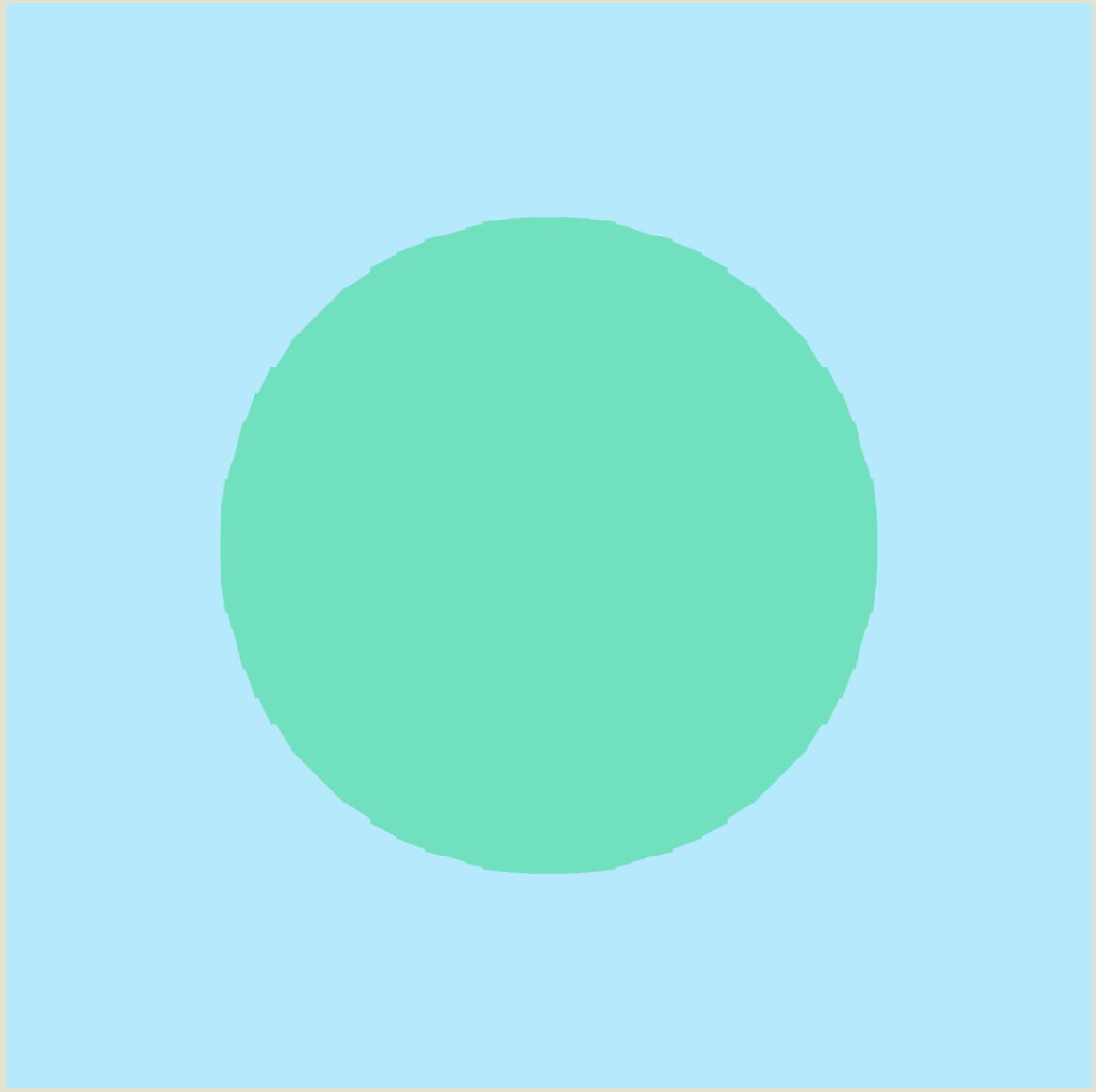
Introduce site pairs

VORONOI-BASED B-REP GENERATION



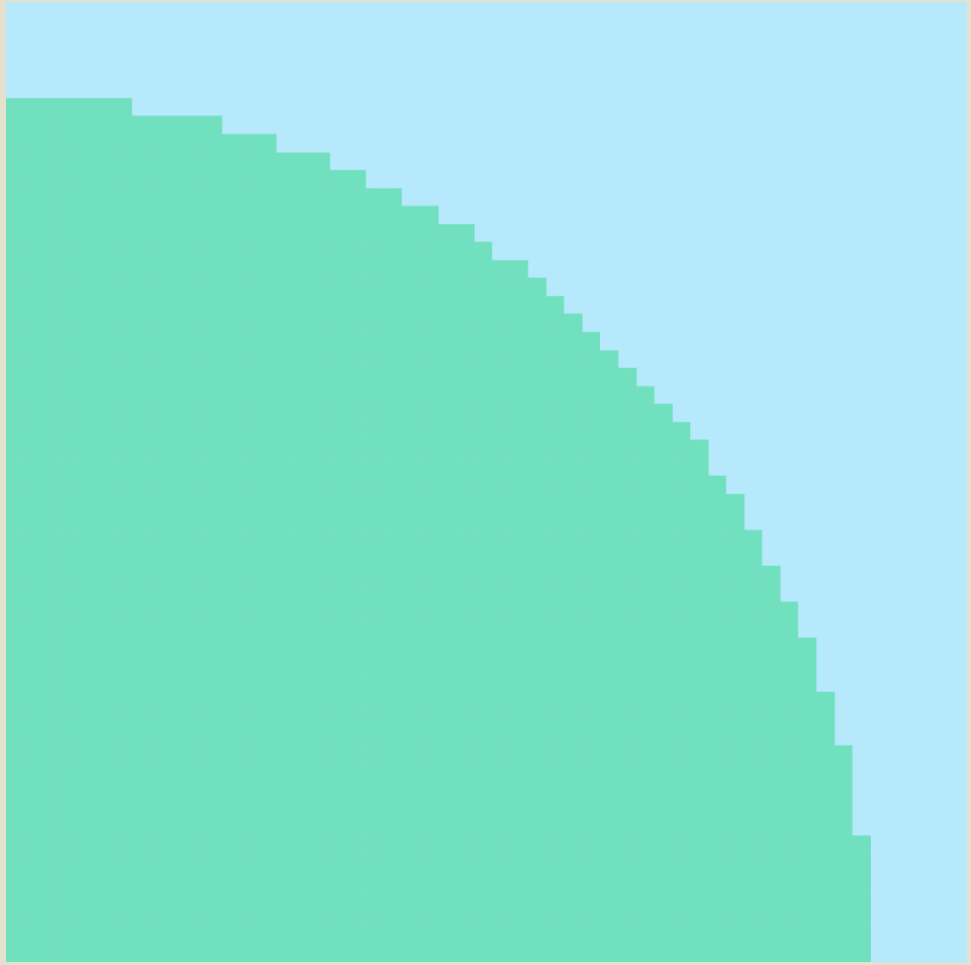
Introduce additional sites and perform Voronoi partition

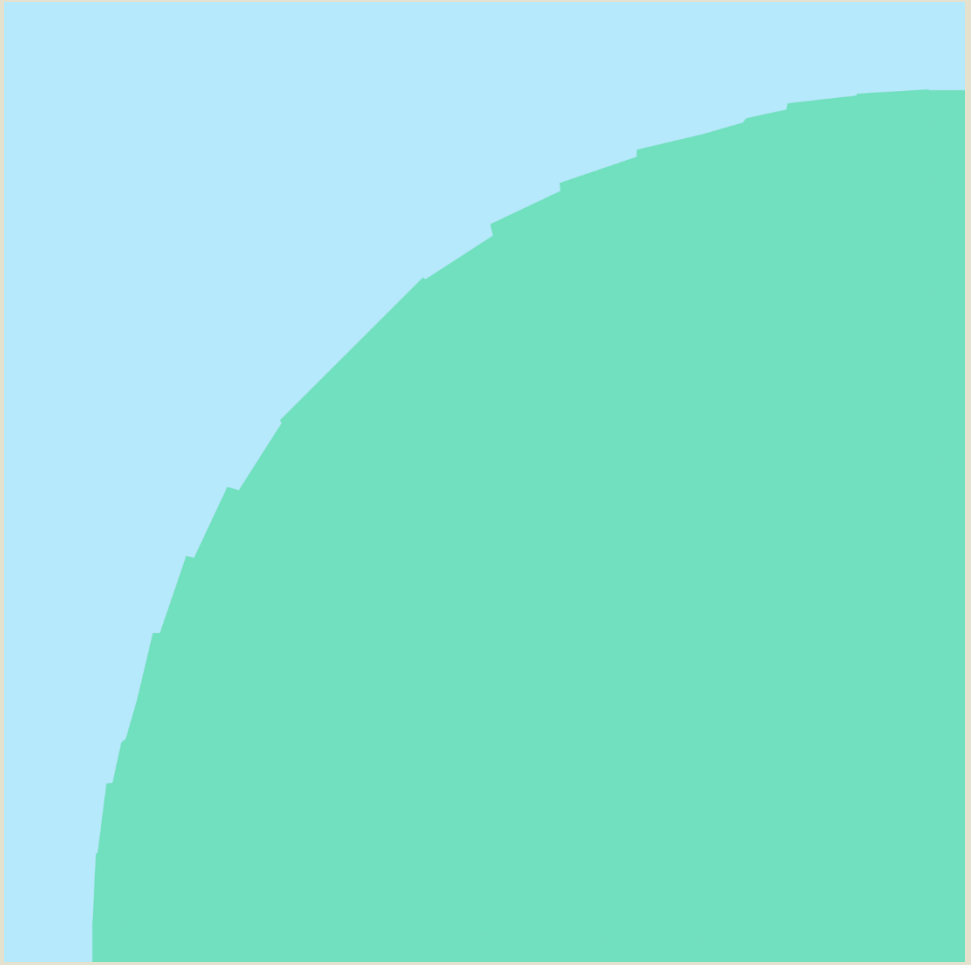
VORONOI-BASED B-REP GENERATION



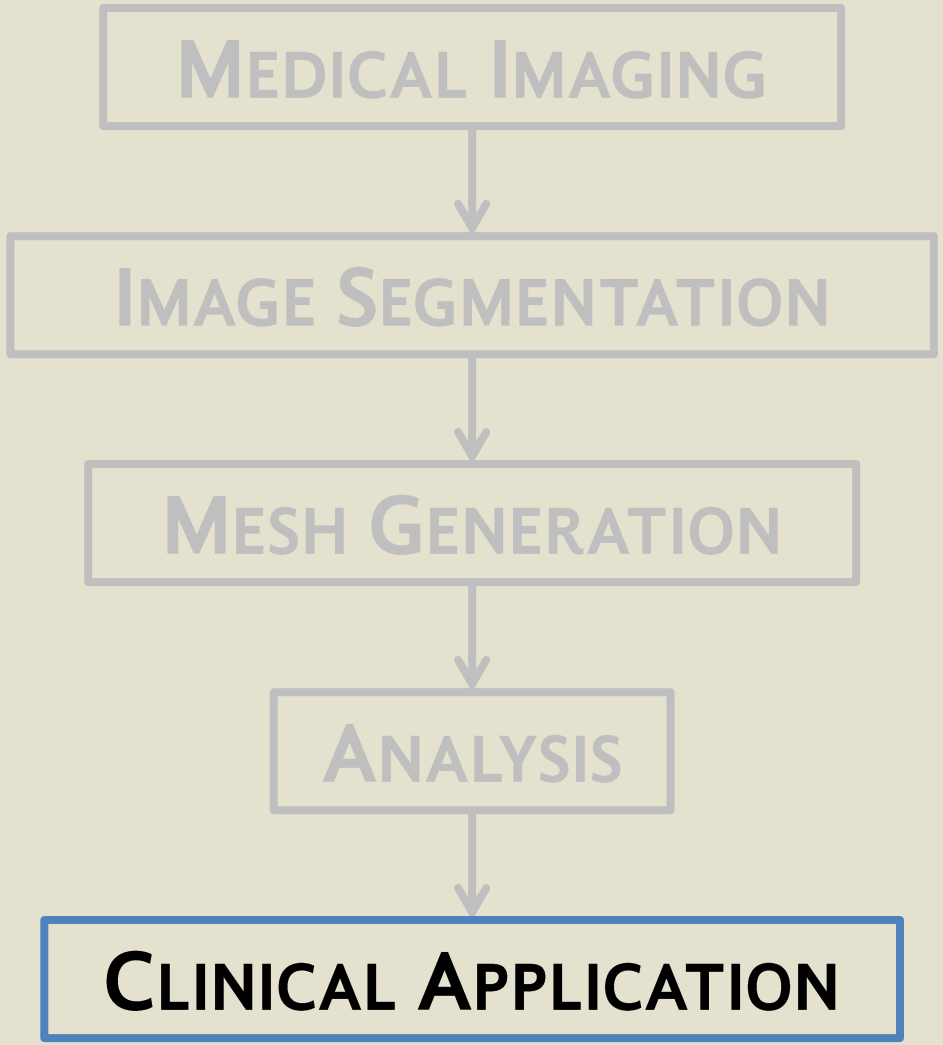
Resulting material labeling from Voronoi partition

VORONOI-BASED B-REP GENERATION



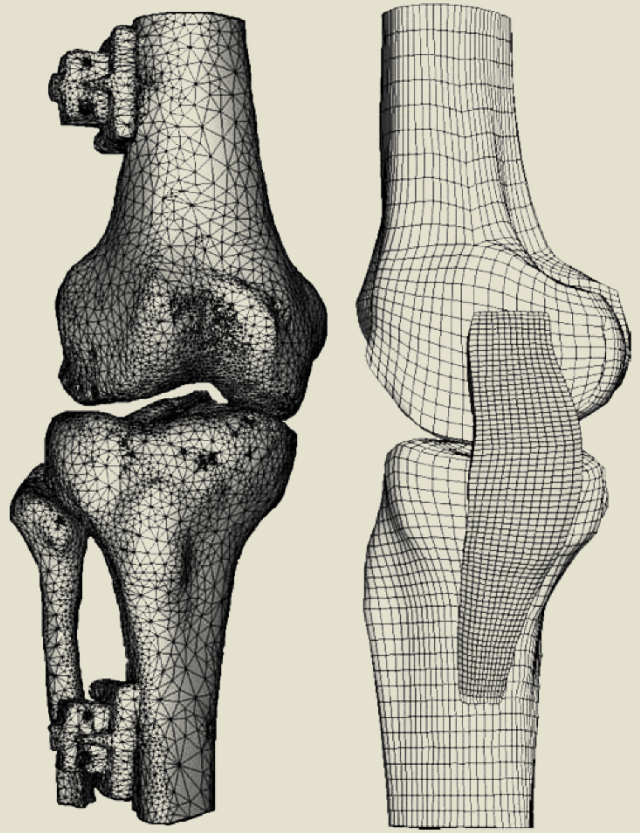


THE PIPELINE



CLINICAL APPLICATION

- Potential for to play important analytic and predictive role in medical applications
  - Improved diagnosis and treatment
  - Identify causes of pathology
  - Surgical design/planning
  - Computer-assisted surgery (real-time)
  - Haptic technologies/surgeon training



Gardiner JC, Weiss JA. *Subject-specific finite element analysis of the human medial collateral ligament during valgus knee loading*. Journal of Orthopaedic Research, vol. 21, pp. 1098-1106, 2003

“CLINICAL COMPUTATION”

- An automated, patient-specific process provides the means to run lots of simulations quickly, and get lots of data
- Clinical trials via simulation
- Additional considerations needed:
  - Material properties
  - Boundary conditions
  - UQ, V&V
  - HPC

One day:

“With a 95% confidence level, changing the drilling angle by 3% for an ACL graft reduces the average patellofemoral stress 10-15%”

Thank You

UNIVERSITY OF CALIFORNIA, DAVIS

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TOO MANY TO LIST!

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