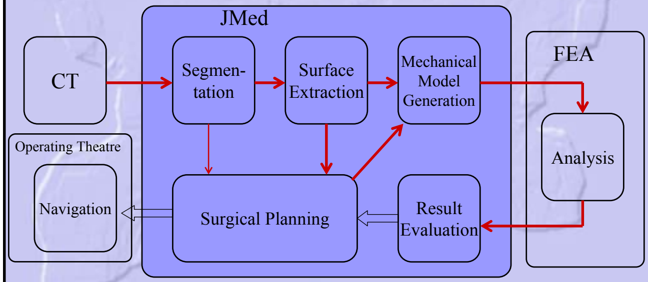
Surgical Planning and Biomechanical Analysis

Balázs Erdőhelyi[1]

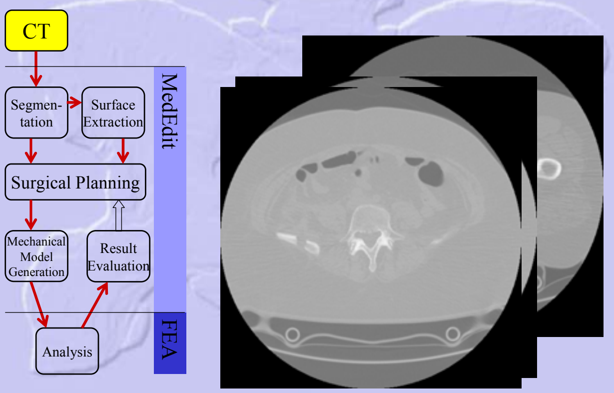
Endre Varga[2], Attila Kuba[1]

Department of Image Processing and Computer Graphics[1],
Department of Trauma Surgery[2]
University of Szeged, Hungary

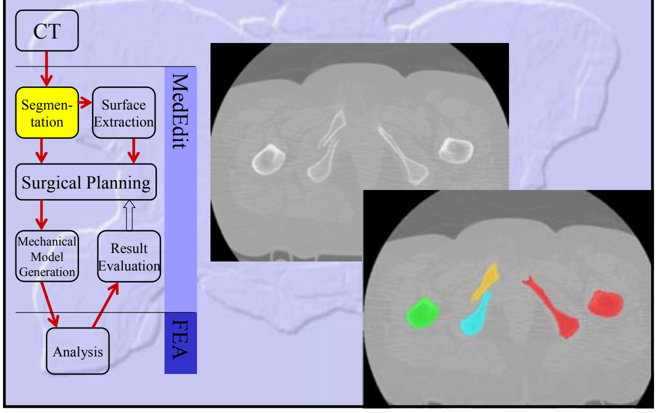
Overview



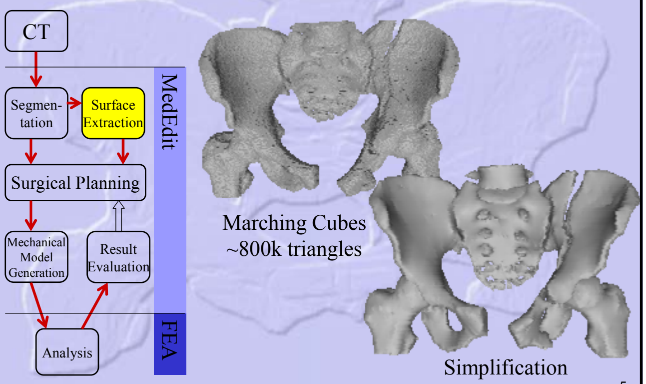
Overview - CT



System Overview - Segmentation



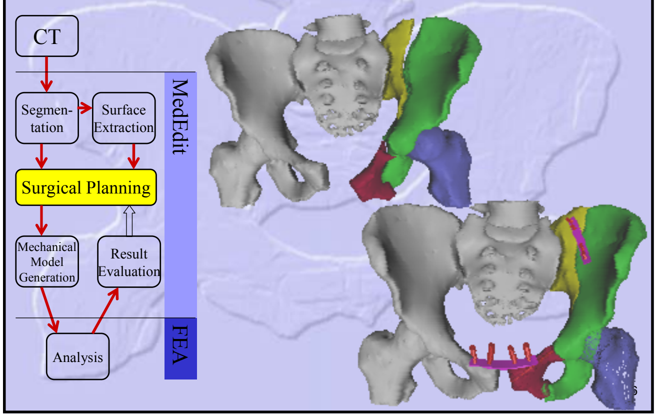
Overview – Surface Extraction



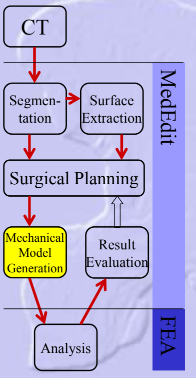
Marching Cubes
~800k triangles

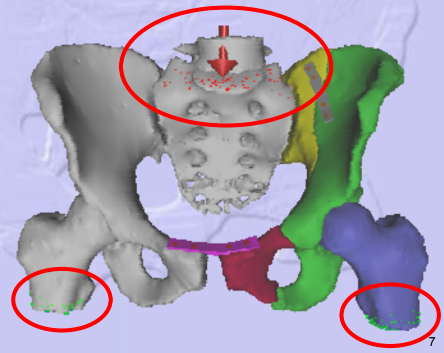
Simplification
~100k triangles

Overview – Surgical Planning

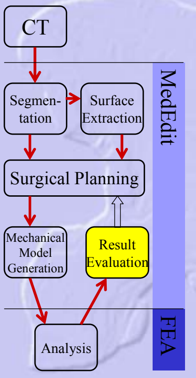


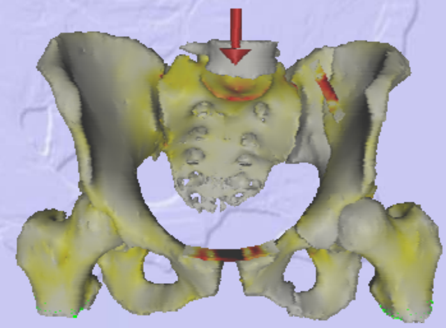
Overview – Mechanical Model



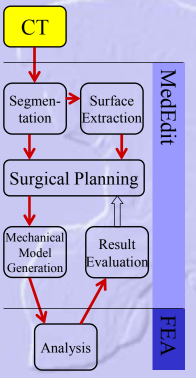


Overview – Result

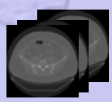




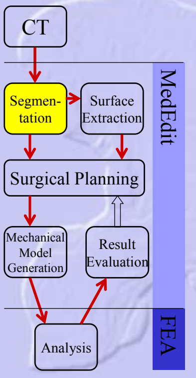
CT



- DICOM (Digital Imaging and Communications in Medicine) format
- Image size: 512 x 512 px
- Slice thickness: 0.8–15 mm
- Number of slices: 80 - 350



Segmentation



- Convert 3D grayscale to 3D binary volume
- Algorithms
  - Threshold
  - Region Growing
  - Fuzzy Segmentation

Thresholding

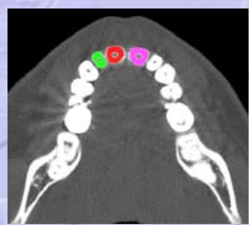

Original image


Threshold value too low


Threshold value too high

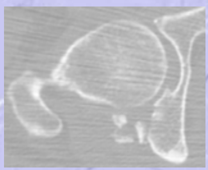
Region Growing


Original slice


Segmented

Region Growing

- Joined regions
- Undetected regions



13

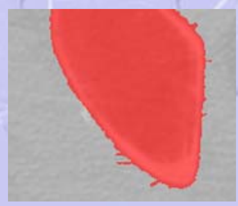
Fuzzy Connectivity

- The weakest link in the strongest path

14

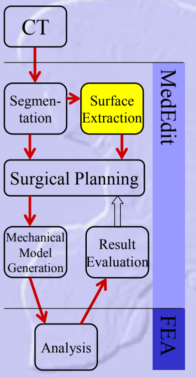
Segmentation - Post Processing

- Remove possible noise
- Fill holes
- Morphological operations
  - Dilate
  - Errode
  - Opening
  - Closing



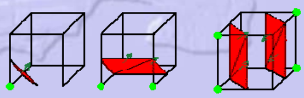

15

Surface Generation



1. Use the Segmented volume and create a triangle mesh of the surface
   - **2D**

   - 3D

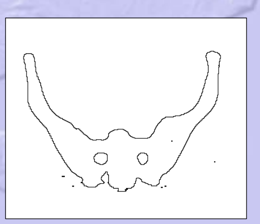


2. Simplify geometry

16

Contour following

Segmented image

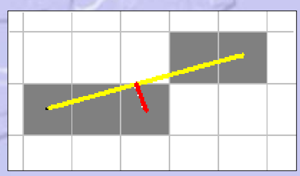


Contour points

17

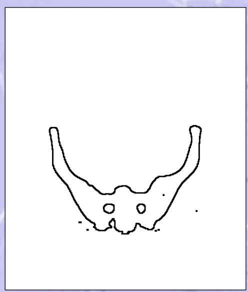
Contour Simplification

- Collinear points are deleted
- Only the first and the last is kept
- Maximum distance as parameter of the simplification

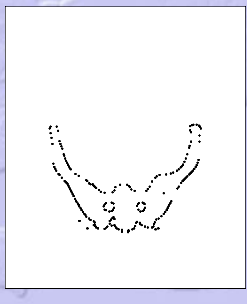


18

Contour Simplification



All contour points before simplification



After simplification

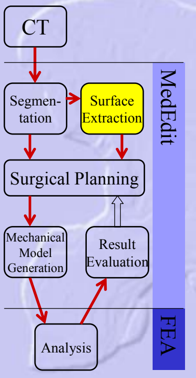
2D contour reconstruction

- Bernhard Geiger (INRIA) : NUAGES
- Input: a set of simple closed polygons on parallel planes
- Output: 3D surface

3D surface

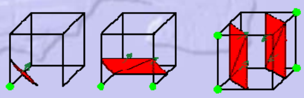
Problems:
- 2D contours
- pelvic bone is not „tubular"
- Horizontal resolution is low

Surface Generation



1. Use the Segmented volume and create a triangle mesh of the surface
   - 2D

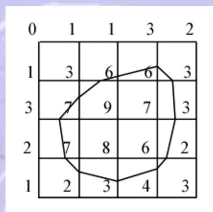
   - **3D**

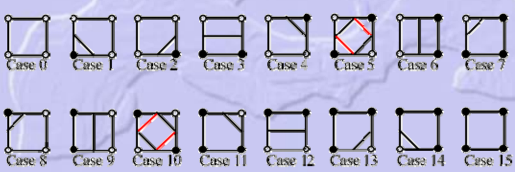


2. Simplify geometry

Marching Squares I.

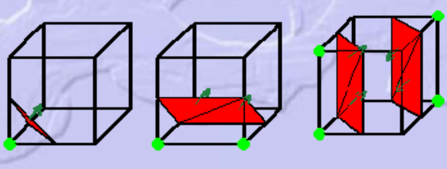
- Marching Squares (2D)
  - 16 configurations



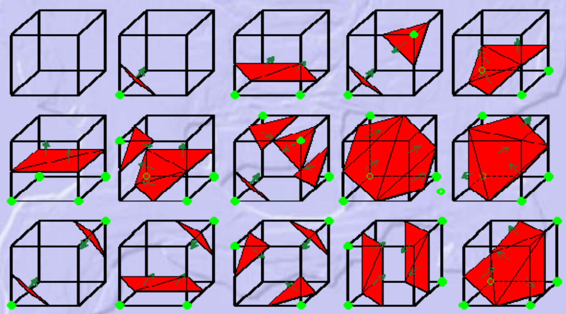


Marching Cubes

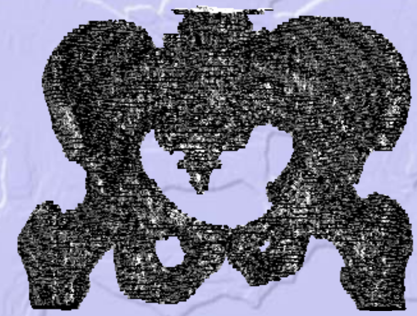
- Fully 3D
  - 256 situations
  - generalized in 15 families by rotations and symetries



Marching Cubes II.

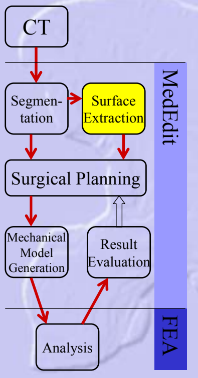


Marching Cubes

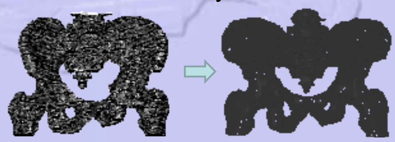


Surface generated with the marching cubes algorithm.
Number of triangles ~800.000

Surface Generation

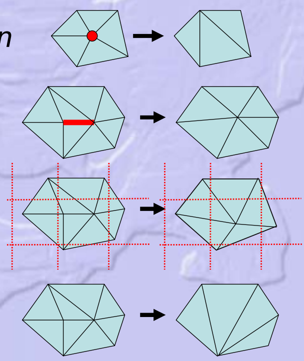


1. Use the Segmented volume and create a triangle mesh of the surface
2. **Simplify geometry**
   - Reduce rendering time
   - Reduce analysis resources



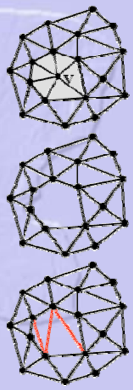
Surface Simplification Methods

- *Vertex Decimation*
- *Edge Collapse*
- *Vertex Clustering*
- *Face Merging*



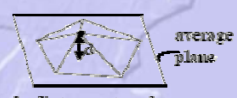
Vertex Decimation

- Schroeder et al, 92
- Based on controlled removal of vertices
- **Loop**
  - choose a removable vertex *v*
  - delete *v* and its incident faces
  - re-triangulate the hole
- **Until**
  - no more removable vertex exists or reduction rate fulfilled



Vertex Decimation

- Vertex is removable iff
  - Distance to average plane is lower than e_{max}
  - Distance to boundary is lower than e_{max}
- Properties
  - Efficient
  - Simple implementation & use
  - Works on large meshes
  - Implemented in VTK



d: distance to plane

d: distance to edge

Edge Collapse

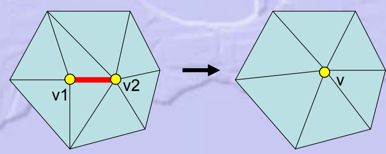
- Examine all vertex pairs
- Build queue of edges or V_1, V_2 pairs where

$$\left\|\vec{V}_1 - \vec{V}_2\right\| < t$$

- **Loop**
  - Take edge e from the queue with the least error
  - Delete e and its triangles
  - Update queue
- **Until**
  - Queue is empty or target reduction reached

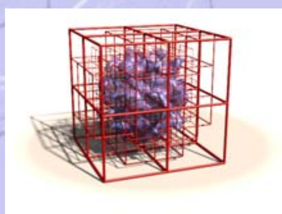
Edge Collapse

- Error of a vertex is the sum of squared distances to its planes
- Position of the new vertex is where the vertex error is minimal



Vertex Clustering

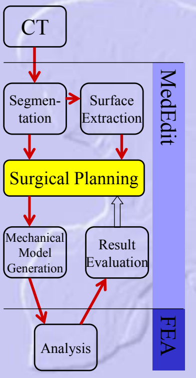
- Object's bounding box is subdivided into a grid
- All vertices inside a cell are clustered to one representative vertex
- Layout of the grid controls the simplified model
- Properties
  - Very fast
  - Poor quality
  - No direct controll of reduction rate



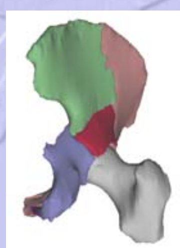
Co-planar face merging

- Kalvin, Taylor '96
  - Partitions the surface into connected disjoint co-planar regions
  - Regions are replaced by a polygon
  - Polygon boundary is simplified
  - Boundary retriangulated

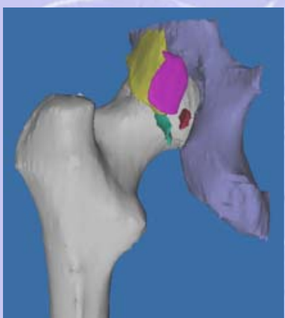
Overview – Surgical Planning



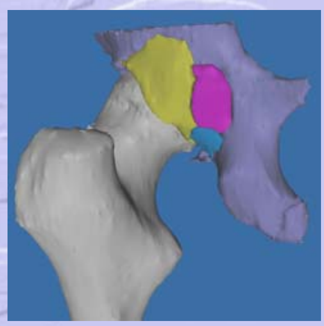
- **Repositioning**
- Implants



Repositioning

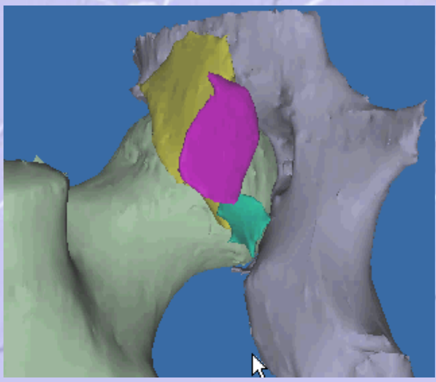


As found on CT



After repositioning

Repositioning with the Mouse

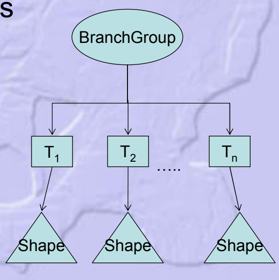


Repositioning - Heptic device

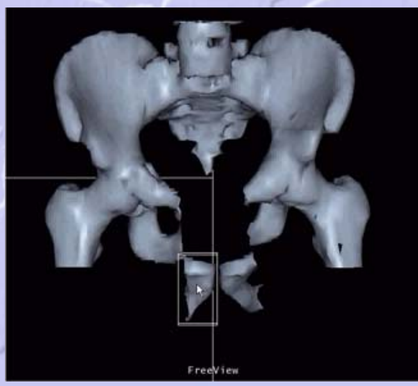
http://www.sensable.com/index.htm

Surgical Planning

- Treat bone surfaces as objects in 3D space
- Transformations
  - Translation
  - Rotation
- Implants
  - Screw
  - Fixation Plate



Collision Detection



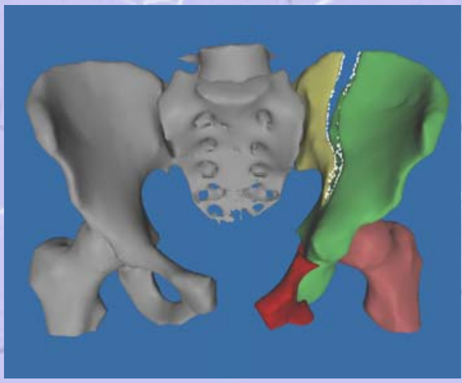
Surgical Planning

- 3D object positioning requires learning
- The model is 3D but the screen and the mouse is 2D
- Collision detection can help
- Automatic tool is needed

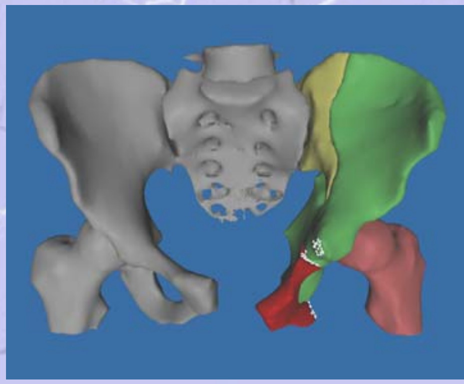
Repositioning using Registration

- Semi-automatic: user selects surface pairs
- Do registration on every pair one-by one
- Cost function: sum of distances to the nearest neighbours
- Search in 6 dim. space for the minimum of cost function
- EA optimization

Example

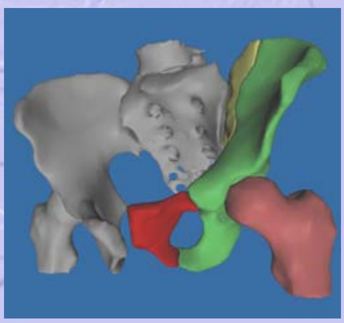


Example

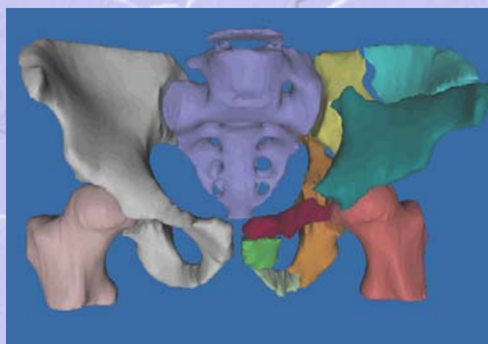


Properties

- With constraints: good matching of points
- Fast: 5-8 seconds
- BUT: possible errors
  - Segmentation
  - Simplification
  - User input
- Errors accumulate in complex cases

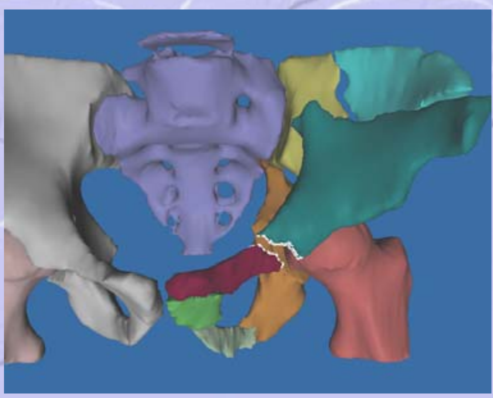


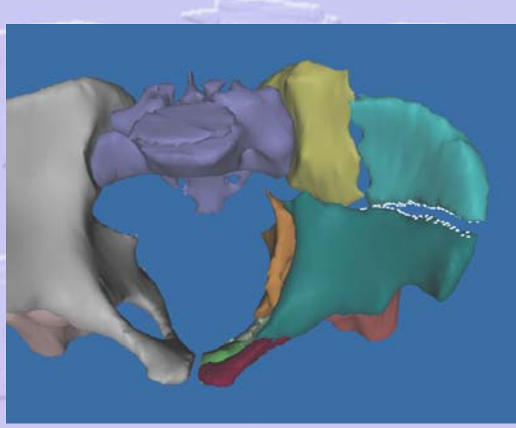
Complex Fracture

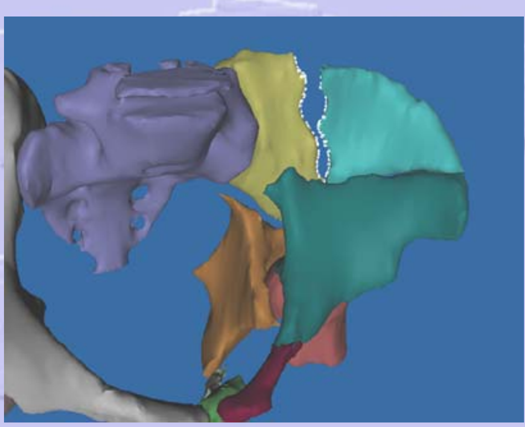


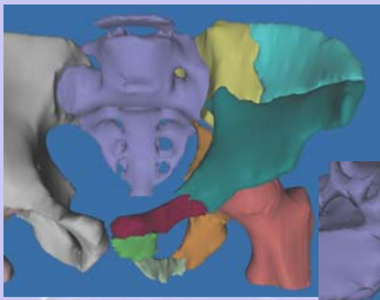
Male, 40Y, 7 fragments

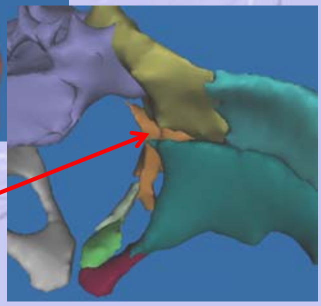
Pairwise Surface Registration







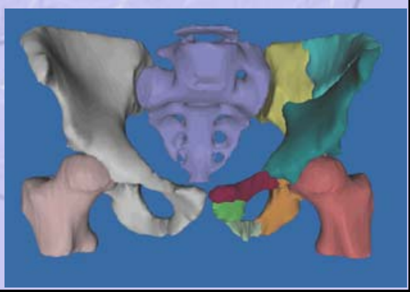




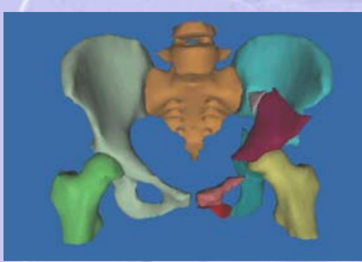
Global optimization
is needed!

Global Optimization

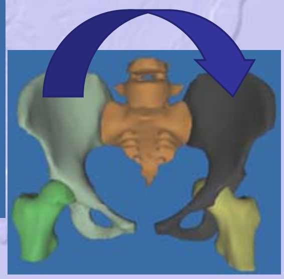
- All surface pairs are considered simultaneously
- Search space is `(n-1)*6` dim.
- Stronger constraints
- Improves overall result



Global Positioning

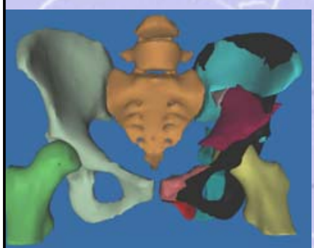


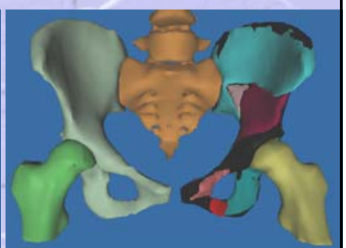
Original fracture
Female, 52Y, 6 fragments



Healthy bone mirrored and translated

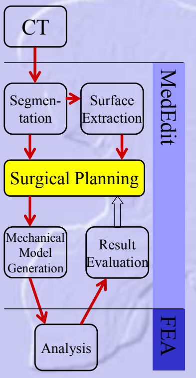
Global Positioning



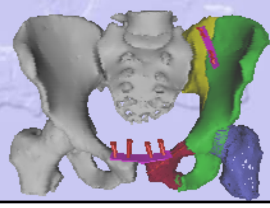


- Model contains 12k points
- Points used for registration 2k-6k
- Slow

Overview – Surgical Planning

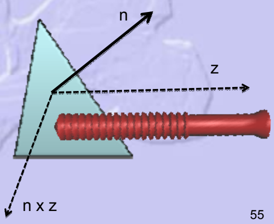


- Repositioning
- **Implants**
  - **Screws**
  - **Plates**



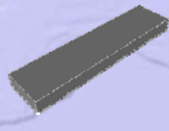
Surgical Planning – Fixation Screw

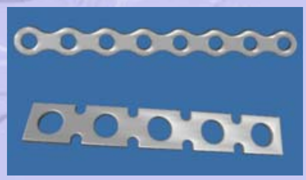
- Screw parameters
  - Length
  - Insertion depth
  - Shank diameter
  - Tip length
  - Head length/diameter
  - Thread length
  - Major / minor diameters
  - Pitch



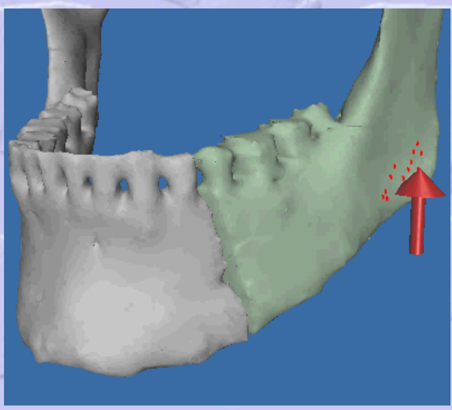
Surgical Planning – Fixation Plate

- Fixation plate
  - Width
  - Height
  - Length
  - Follow surface

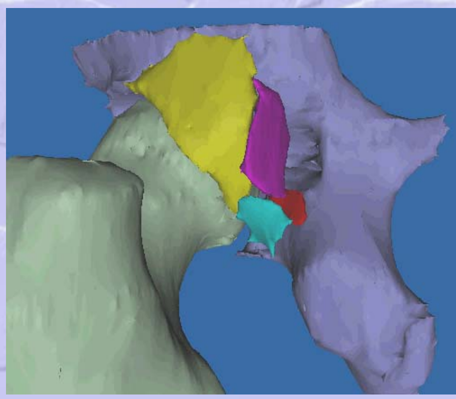




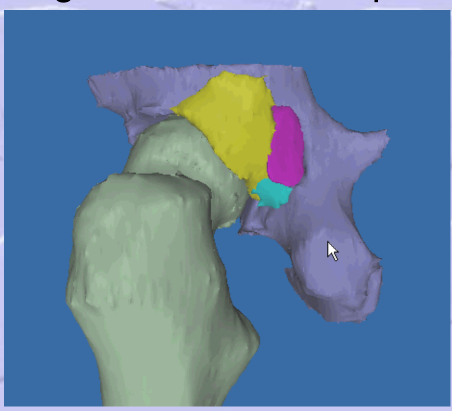
Surgical Planning



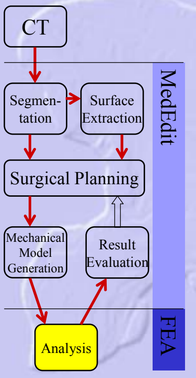
Surgical Plan – Example II.



Surgical Plan – Example II.



Finite Element Analysis

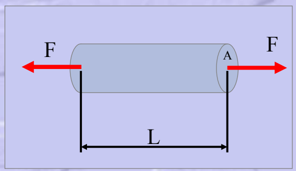


- History
- Basic concept
- Material properties
- Mesh, element library
- How an enginier works

Stress

- Stress is a measure of the internal distribution of force per unit area within a body that balances and reacts to the loads applied to it.

F: force,
A: crossectional area



$\sigma = F / A$

- Unit: N / m^2 = Pa

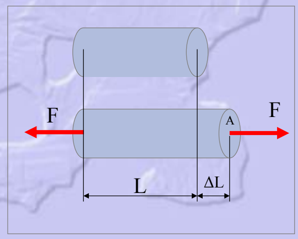
Strain

Strain is the geometrical expression of deformation caused by the action of stress

$\varepsilon = \Delta L / L$

L: original length
ΔL : change in length

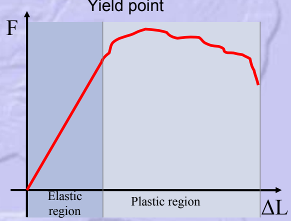
Unit: no unit

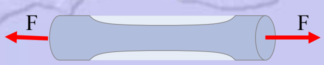


Strain

Deformation

- Elastic region: the deformation is proportional to the force
- Plastic region: the material undergoes a non-reversible change



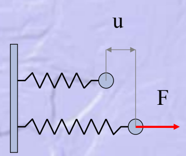


non-reversible change

Hooke's law

- *Hooke's law (1676): F*, is proportional to *u* by a constant factor, *k*

F = ku



Where, k is the spring constant, u stretching distance

- Elastic materials: *E* is the elastic modulus.
  $\sigma = E\varepsilon$

Hooke's law

- Generalised to 3D by Cauchy

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \sigma_{yz}\\ \sigma_{zx}\\ \sigma_{xy}\end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16}\\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26}\\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36}\\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46}\\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56}\\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66}\end{bmatrix} \begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \varepsilon_{yz}\\ \varepsilon_{zx}\\ \varepsilon_{xy}\end{bmatrix}$$

Stress　　Stiffness matrix　　Strain

Hooke's law

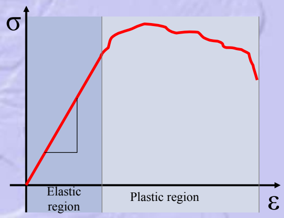
- *Izotropic material*: the material properties are independent of direction (2 elastic constants)

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \sigma_{yz}\\ \sigma_{zx}\\ \sigma_{xy}\end{bmatrix} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0\\ \nu & 1-\nu & \nu & 0 & 0 & 0\\ \nu & \nu & 1-\nu & 0 & 0 & 0\\ 0 & 0 & 0 & 1-2\nu & 0 & 0\\ 0 & 0 & 0 & 0 & 1-2\nu & 0\\ 0 & 0 & 0 & 0 & 0 & 1-2\nu\end{bmatrix} \begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \varepsilon_{yz}\\ \varepsilon_{zx}\\ \varepsilon_{xy}\end{bmatrix}$$

- *Ortotropic material: 2-3 orthogonal planes of symmetry, where material properties are independent of direction within each plane*
- Anisotropyc (21 elastic constants)

Young's modulus

- Modulus of elasticity
- The slope of the stress-strain curve
  $E = \sigma / \varepsilon$
- SI unit: Pa

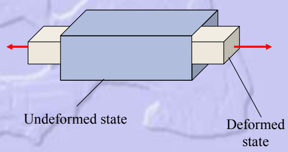


Material	E (GPa)
Diamond	1200
Steel	210
Iron	196
Aluminium	69

Bone	1.1
Cancelous bone	0.01
Rubber	0.01

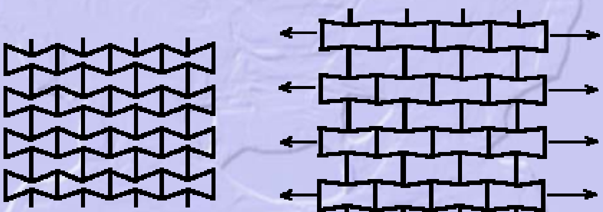
Poisson's ratio

- Defined as the ratio of the contraction strain normal to the applied load divided by the extension strain in the direction of the applied load
- $n = - \varepsilon_{trans} / \varepsilon_{longitud}$
- $-1 <= n < 0.5$



Rubber	0.495
Steel	0.28
Bone	0.3
Cork	0.0

Negative Poisson's Ratio Materials



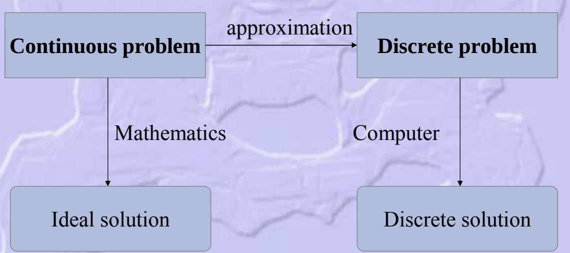
Finite Element Method

- If we can not solve the original problem, let's brake it into smaller, but well known pieces and solve it that way!

$K = 2r\pi$ $K_n = nK_{ij}$ $K_{ij} = K_{45} = 2r \sin(\pi/n)$

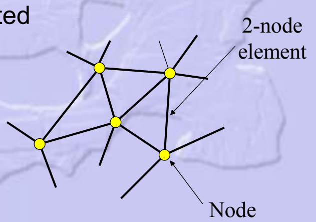
$\pi_n = K_n/2r = n$

FEA theory



Finite Element Mesh

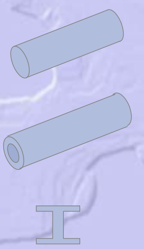
- The model is a mesh of springs
  - **Nodes** define the geometry
  - **Elements** define which nodes are connected



Element library I.

- Primitive elements

Real



Rod element

Pipe element

Arbitrary profil

Discrete

Element library II.

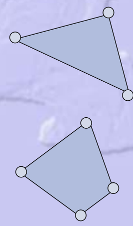
- Shell elements: 2D, but with thickness

Real

Triangle

Quadrangle

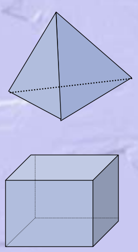
Discrete



Element library III.

- 3D elements

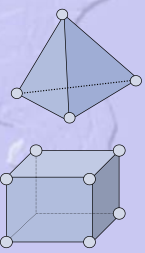
Real



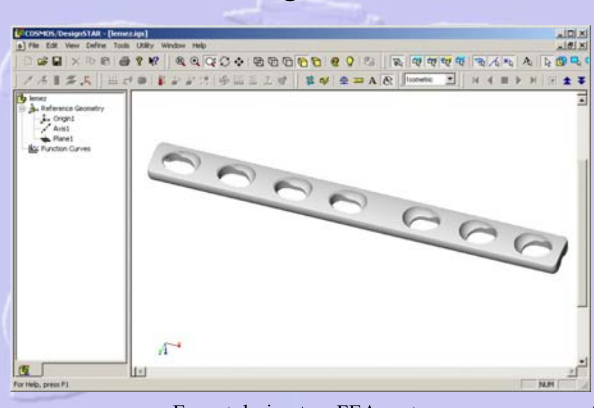
Tetrahedron

Hexahedron

Discrete

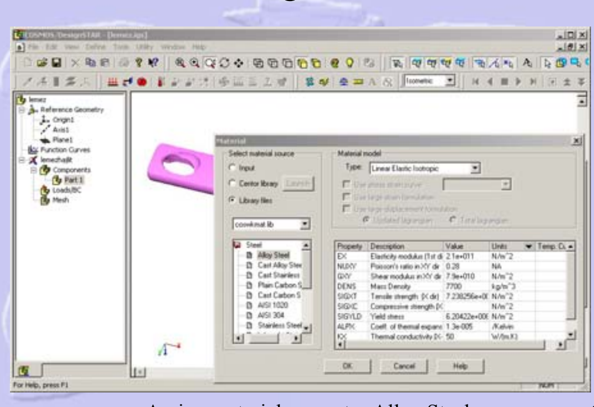


How an engineer works



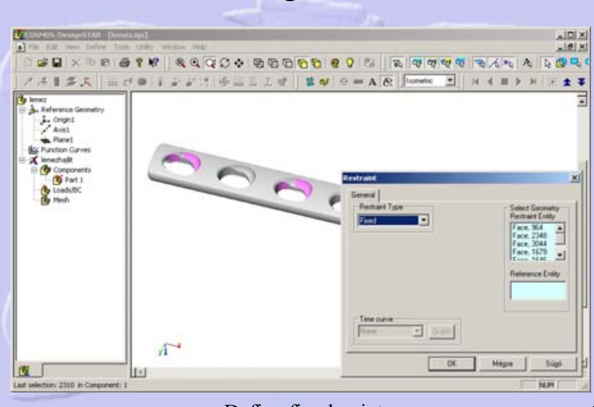
Export design to a FEA system

How an engineer works



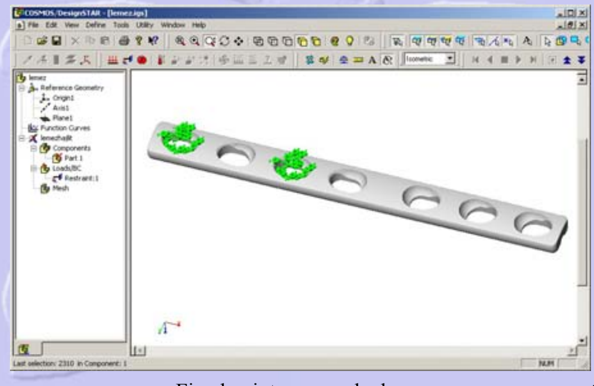
Assign material property: Alloy Steel

How an engineer works



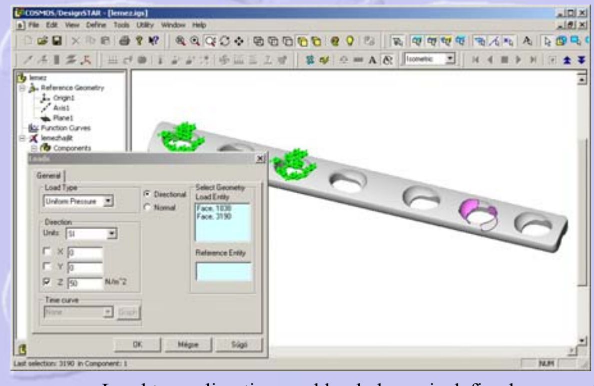
Define fixed points

How an engineer works



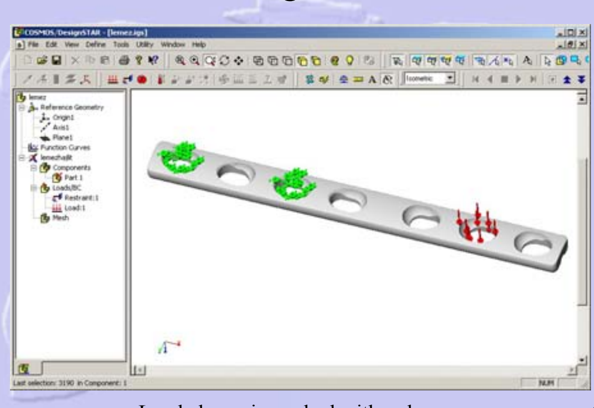
Fixed points are marked green

How an engineer works



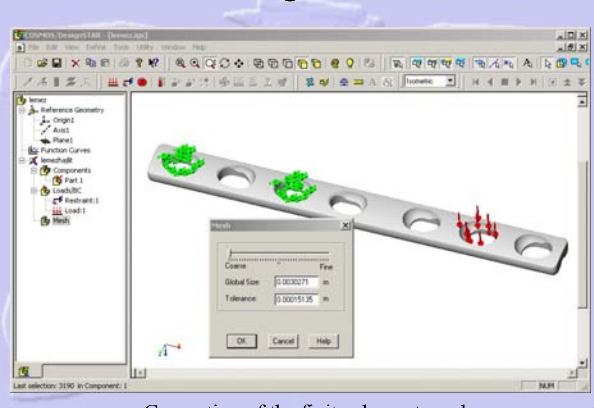
Load type, direction, and loaded area is defined

How an engineer works



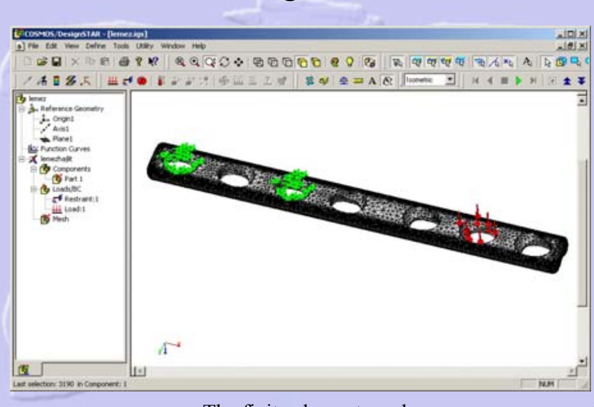
Loaded area is marked with red arrows

How an engineer works



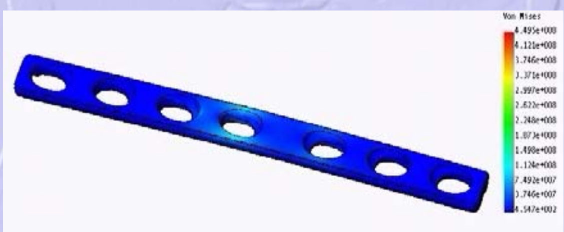
Generation of the finite element mesh

How an engineer works



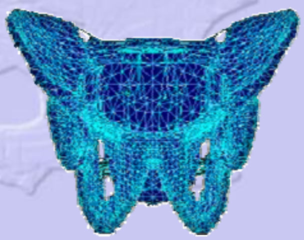
The finite element mesh

How an engineer works



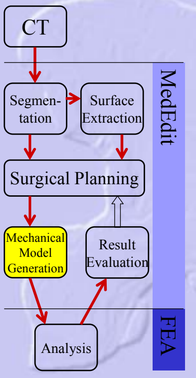
Irregular objects

- There is no CAD model of the patients broken bone
- **No automatic mesh generation**
- Fixed points and loaded areas

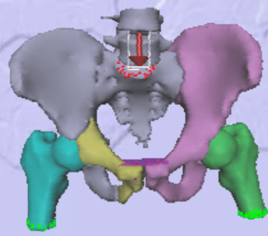


CAD-pelvis

Mechanical Model Generation



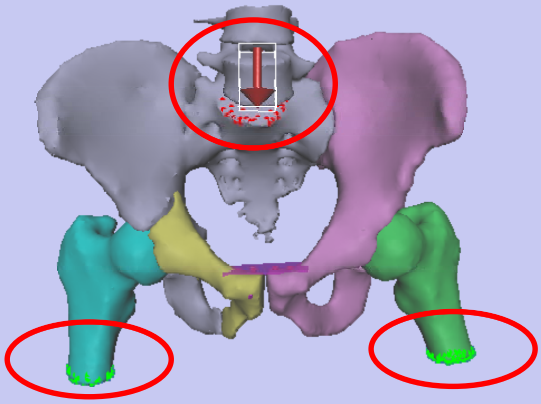
- UI for Load and boundary conditions
- Direct mesh generation



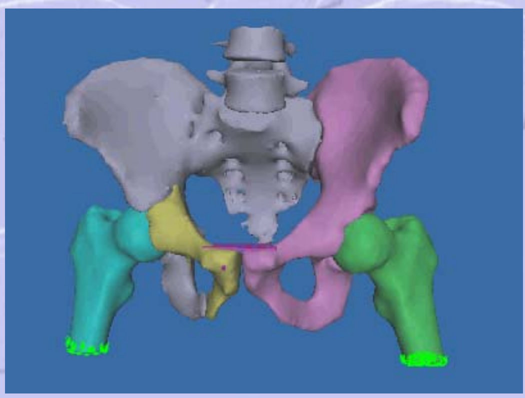
Mechanical Model

- Geometrical model
  - Nodes
  - Finite elements (shell, tetra, hexa)
  - Material properties (Young's modulus, Poisson' ratio)
  - Load
  - Boundary conditions
  - Connections between objects

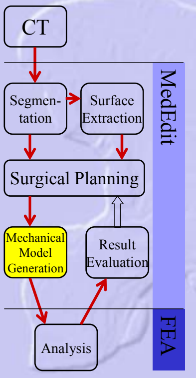
Load and boundary conditions



Load



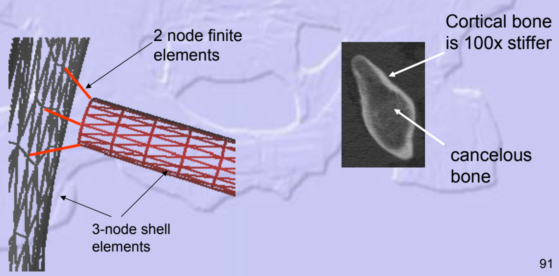
Mechanical Model Generation



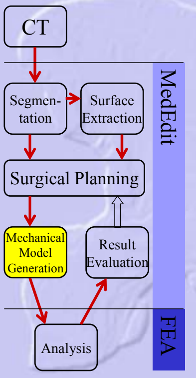
- UI for Load and BC
- Mesh generation
  - **Shell elements**
  - Solid (tetra-, hexahedron) elements
    - Quadtree / Octree
    - Advancing Front
    - Delaunay

Mechanical Model
Shell Elements

- Based on the geometry → 3-node shell el.
- Relation between objects → 2-node el.

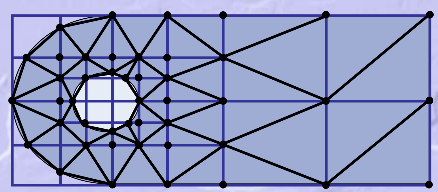


Mechanical Model Generation



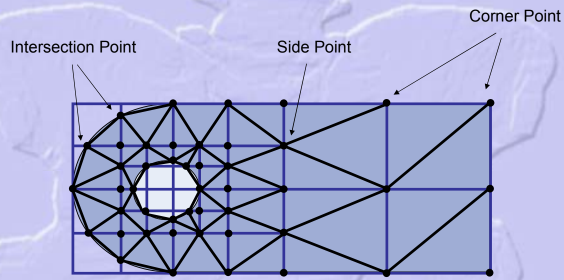
- UI for Load and BC
- Mesh generation
  - Shell elements
  - Solid (tetra-, hexahedron) elements
    - **Quadtree / Octree**
    - Advancing Front
    - Delaunay

Octree/Quadtree



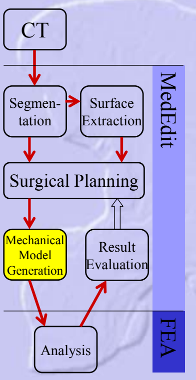
- Start with bounding box
- Recursively build quadtree

Octree/Quadtree



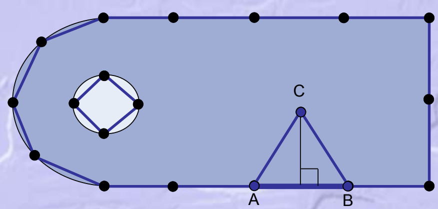
- Triangulate Intersection, Side, and Corner Points

Mechanical Model Generation



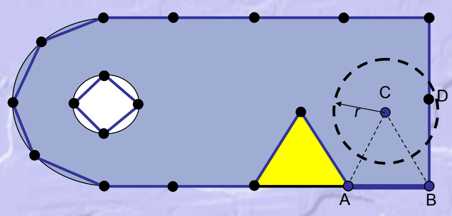
- UI for Load and BC
- Mesh generation
  - Shell elements
  - Solid (tetra-, hexahedron) elements
    - Quadtree / Octree
    - **Advancing Front**
    - Delaunay

Advancing Front



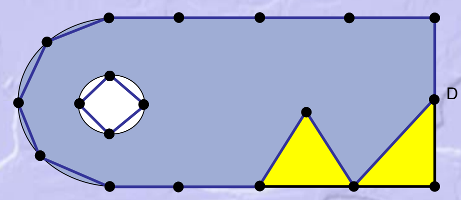
- Bundary is the initial *front*
- Process front segments
- Calculate ideal position for triangle

Advancing Front



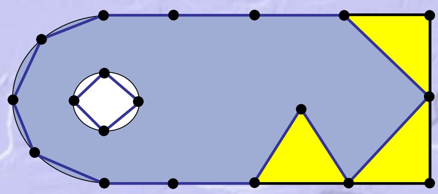
- Check radius around optimal node for existing front nodes

Advancing Front



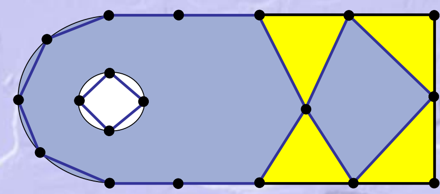
- Delete orig. front elements and insert new ones
- Continue while front exists

Advancing Front



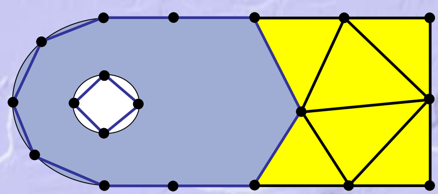
- Delete orig. front elements and insert new ones
- Continue while front exists

Advancing Front



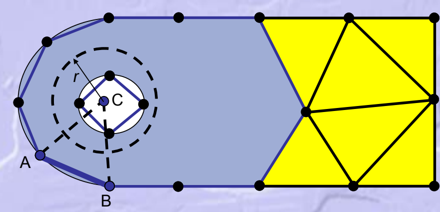
- Delete orig. front elements and insert new ones
- Continue while front exists

Advancing Front



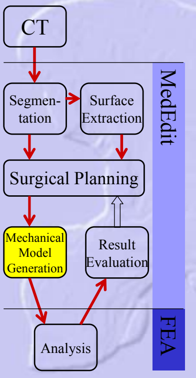
- Delete orig. front elements and insert new ones
- Continue while front exists

Advancing Front



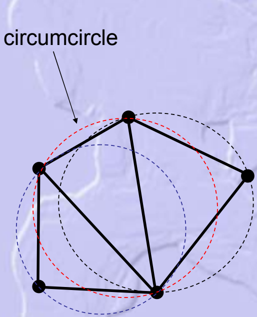
- In case of multiple possibilities, chose best quality

Mechanical Model Generation



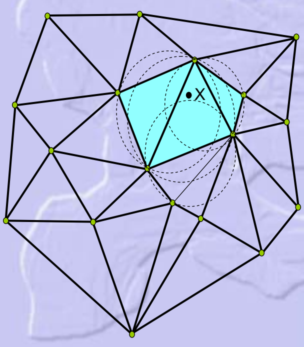
- UI for Load and BC
- Mesh generation
  - Shell elements
  - Solid (tetra-, hexahedron) elements
    - Quadtree / Octree
    - Advancing Front
    - **Delaunay**

Delaunay Triangle



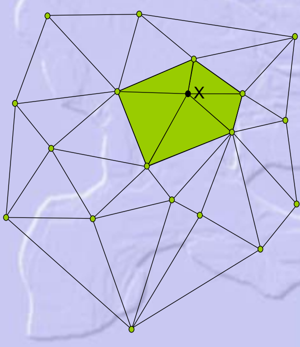
- **Delaunay Triangularization (DT)**: All triangles satisfy the empty circle property
- **Empty circle property**: No other vertex is contained within the circumcircle of any triangle

Bowyer-Watson algoritmusa



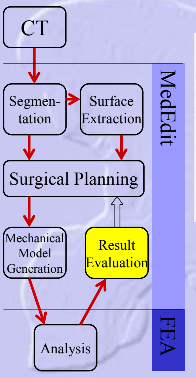
Iteratively insert new points:
1. Find all triangles whose circumcircle contains the new node.
2. Remove edges interior to these triangles
3. Connect nodes of this empty space to new node.

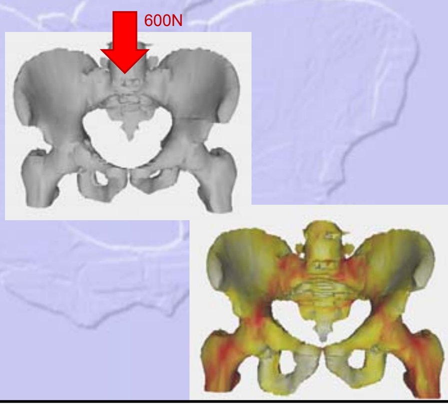
Bowyer-Watson algoritmusa



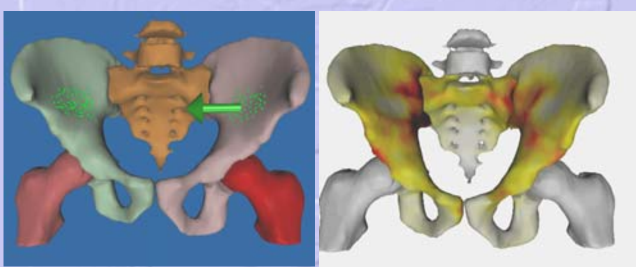
Iteratively insert new points:
1. Find all triangles whose circumcircle contains the new node.
2. Remove edges interior to these triangles
3. Connect nodes of this empty space to new node.

Mechanical Model Generation

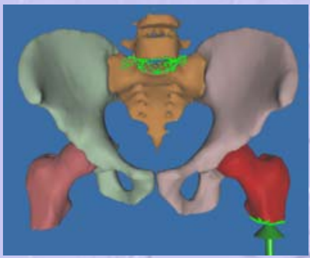




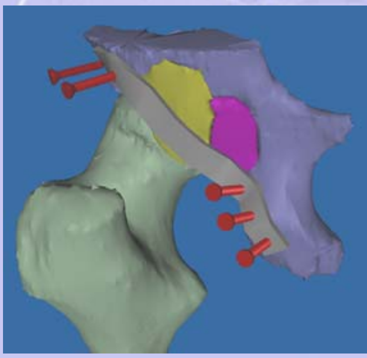
Lateral Compression

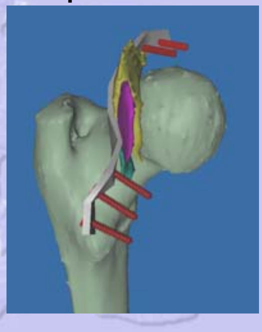


Vertical Shear

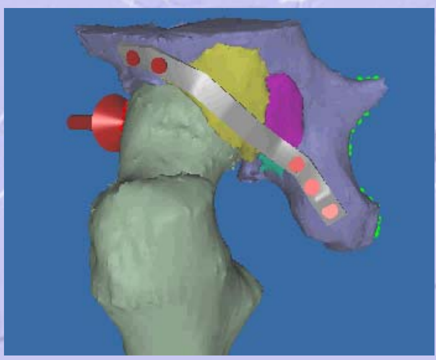


Example I. - Hip

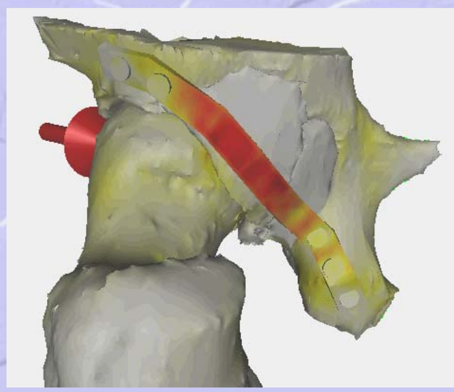




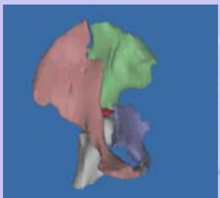
Example I.

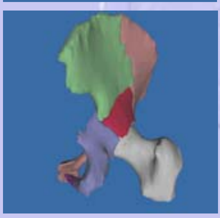


Example I.



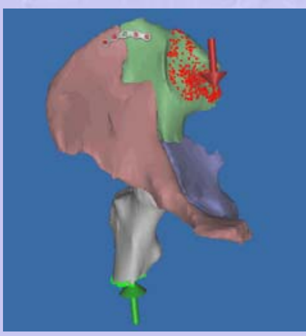
Example II. - Pelvis

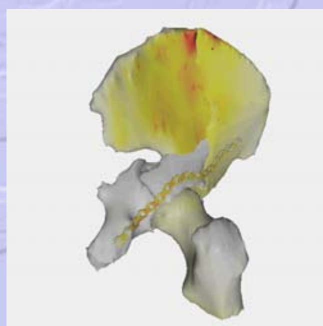




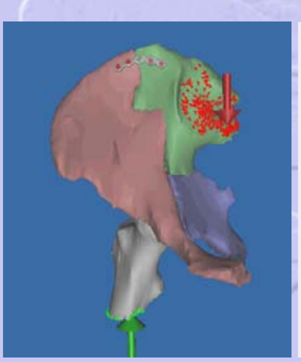
- Female, 50Y
- Monday:
  - Fall from a ladder
  - CT
- Tuesday:
  - Preparations
  - Surgical planning
- Wednesday
  - Operation

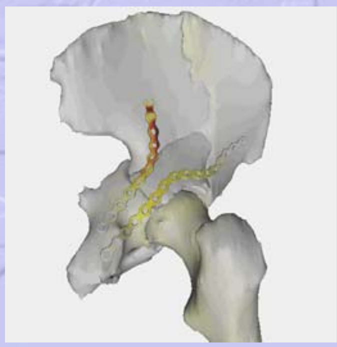
Example II. - Pelvis



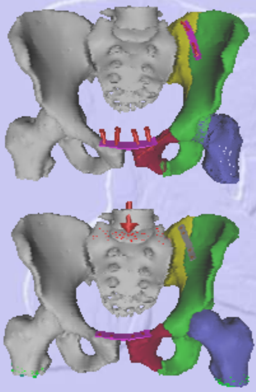


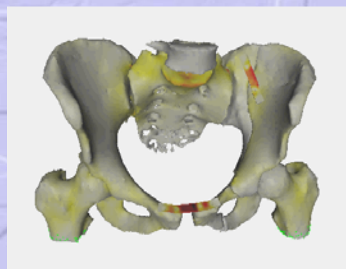
Example II. - Pelvis





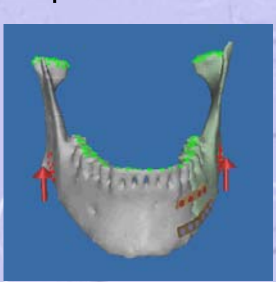
Example III. - Pelvis



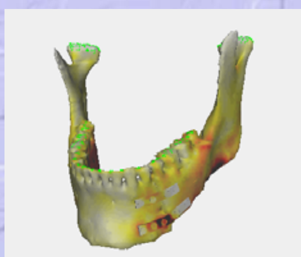


Example IV. - Jaw

Preoperative Plan



Biomechanical simulation



Conclusion

- Results match to the clinical expectations
- Quantitative comparative measurements still pending
- Possible Applications
  - Clinical practice
  - Education
  - Navigation
  - Research