

KNOWLEDGE INSTITUTE OF  
TECHNOLOGY,SALEM.  
MECHANICAL ENGINEERING

*Design of Machine elements*

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# Presentation Outline

- Introduction: What is Machine Design?
- Machine Design: Research Areas
- Research Applications:
  - Gear Tooth FEM/FEA and Optimization
  - Machine Design Optimization
  - Customized Knee Implant: Design, Stress Analysis and Manufacturing

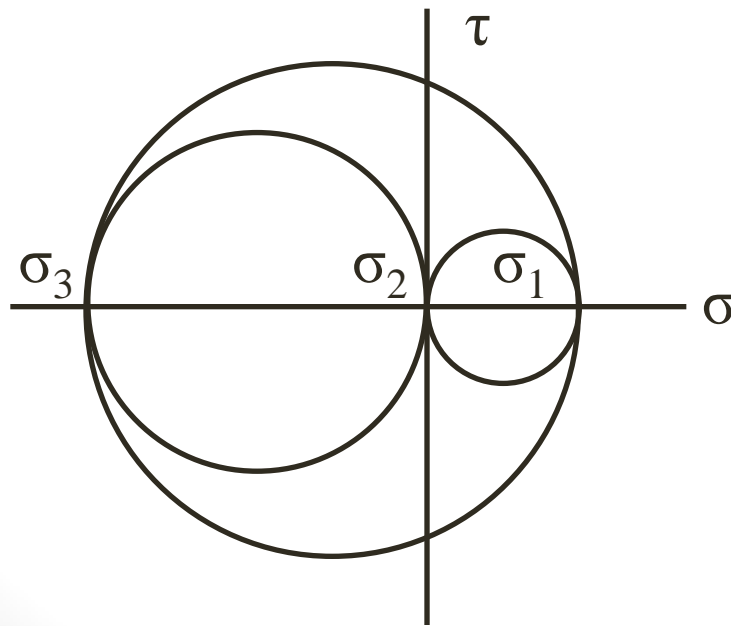
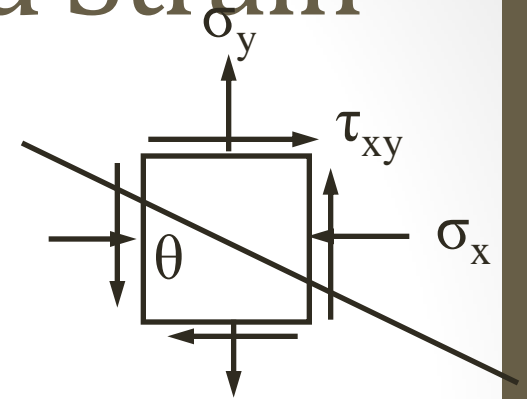
# Introduction:

## What is Machine Design?

- Core of mechanical engineering
  - Stress and strain
  - Designing for safety
  - Static failure theories
  - Fatigue failure theories
  - Machine elements
  - Mechanical material properties
- Stress Concentrations
- Fracture Mechanics
- Optimization
- Composite Materials
- Manufacturing Processes
- Computer Aided Machine Design and Analysis
- Measuring Stress and Strain

# Introduction: Stress and Strain

- Stress and strain
  - Normal stresses and strains
  - Shear stresses and strains
  - Principal stresses and strains
  - Mohr's circle and analytical relationships



$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}$$
$$\tau_{\max} = \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}$$
$$\tan(2\theta) = \frac{2\tau_{xy}}{\sigma_x - \sigma_y}$$

# Introduction: Static Failure

- Ductile Behavior

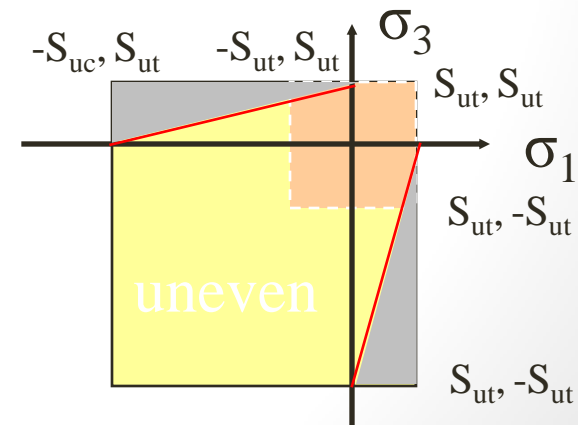
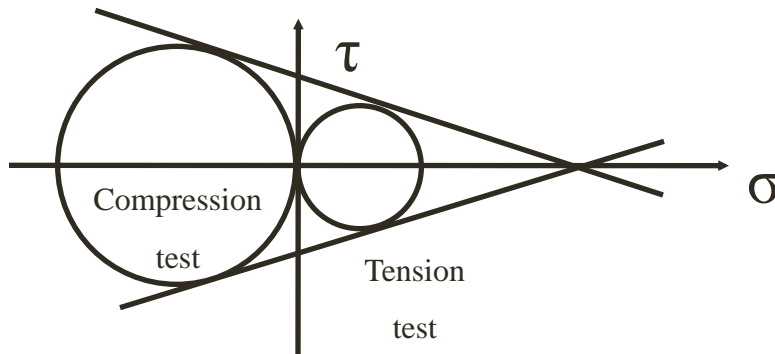
- Maximum Shear-Stress Theory (Tresca/Coulomb Theory)
- Distortion Energy Theory (von Mises)

$$\sigma_1 - \sigma_3 \leq \frac{S_y}{FS}$$

$$\sigma_{\text{eff}} = \frac{\sqrt{2}}{2} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \leq \frac{S_y}{FS}$$

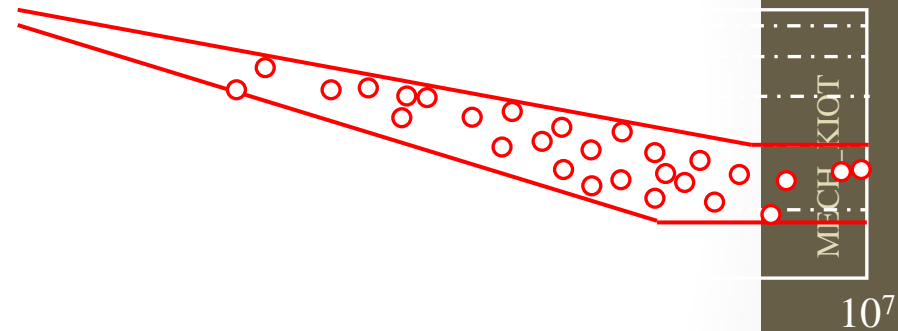
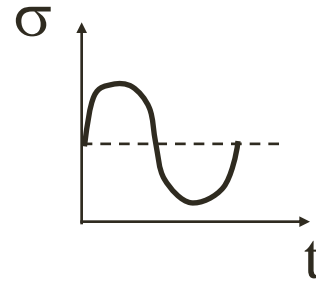
- Brittle Behavior (even and uneven materials)

- Coulomb-Mohr Theory



# Introduction: Fatigue Failure

- Alternating and mean stress
- Stress-Life Approach
  - High Cycle Fatigue Criteria
  - Load amplitude is consistent
  - Common for rotating machinery
- Strain-Life Approach
  - Low cycle fatigue ( $<10^3$ )
  - Variations in loads and high temperatures
  - Common for service machinery
- Fracture Mechanics Approach
  - Low cycle fatigue
  - Generally used to determine remaining life of a cracked part
  - Paris equation



Corrected endurance limit:

$$S_e = C_{load} C_{size} C_{surf} C_{temp} C_{reliab} S_e'$$

Corrected fatigue strength:

$$S_f = C_{load} C_{size} C_{surf} C_{temp} C_{reliab} S_f'$$

$$\frac{da}{dN} = A \cdot (\Delta K)^n$$

n, A: empirical values  
K: stress intensity factor

# Introduction: Machine Elements

- Springs
- Fasteners
- Bearings
- Shafts
- Gears



Machined



Universal  
Joint



Coiled



# Machine Design: Research Areas

- Finite Element Analysis
- Design Optimization
- Biomechanics
- Nanotechnology
- Fracture Mechanics
- Mechanical Material Properties
- Composite Materials
- Designing for Manufacturing
- Welding

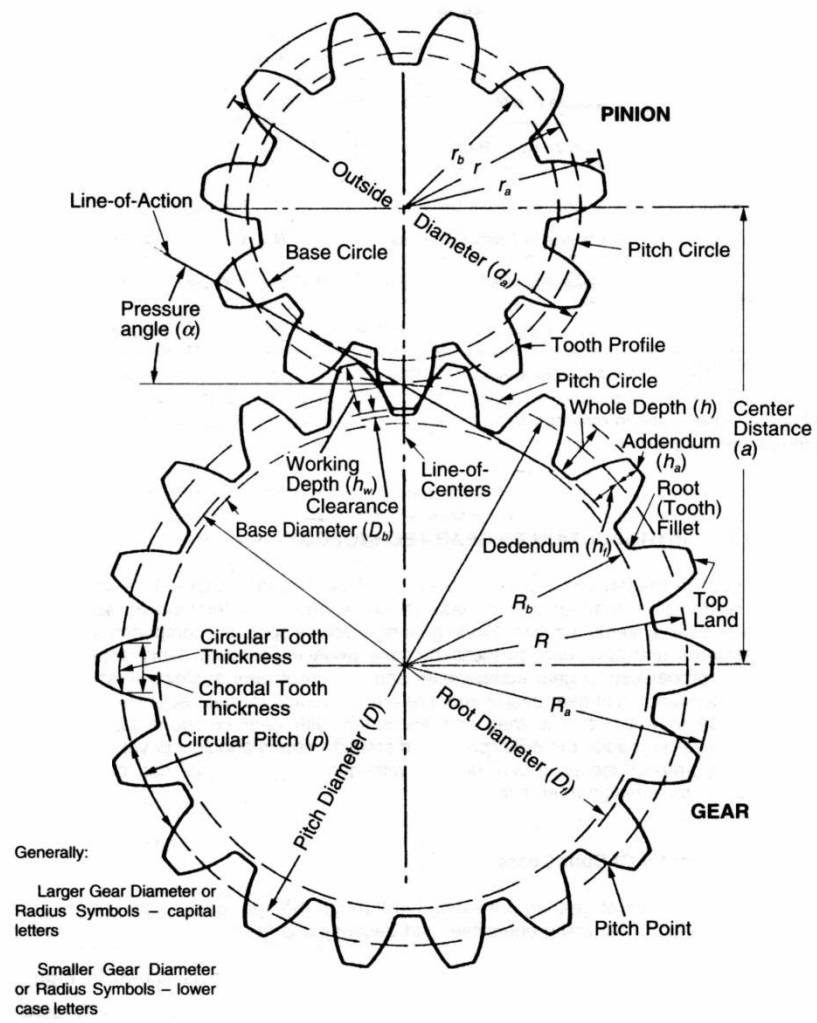
# Research Applications:

- Gear tooth stress analysis and measurement
  - Typical component studied in machine design
    - Finite element modeling and analysis
    - Stress measurement using polariscope
- Machine Design Optimization
  - Improve performance, reduce mass, stress and cost
    - Missile design
    - Optimization theory
- Customized Knee Implant:
  - Hinge joint
    - Design to even out stress, remove areas of stress concentration
    - Finite element analysis
    - Manufacturing

# Gear Tooth: Introduction

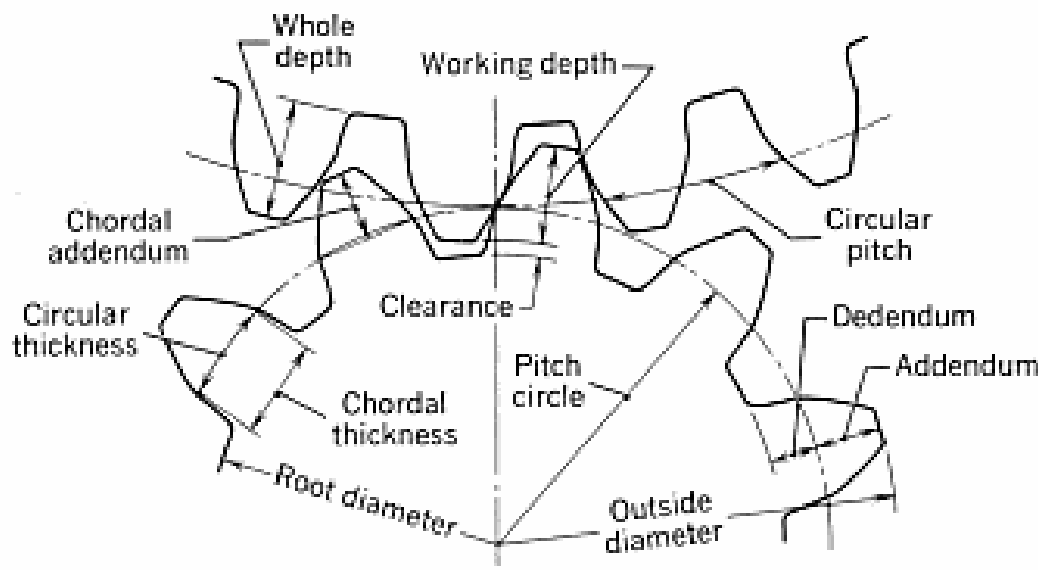
- Gear is a typical component studied in machine design
- In analyzing the stresses in gears one uses stress/strain and failure theories
- The stresses were measured using a polariscope
- Objective: minimize stress at the root of a gear tooth by introducing a stress relief hole
- Parameters: location ( $r, \theta$ ) and size of hole
- Analytical model: I-DEAS Master Series
  - Solid Model, FEA, Optimization, .stl file
- Experimental analysis to validate analytical model
  - Stereolithography model, Polariscope

# Gear Tooth: Two Gears Meshing

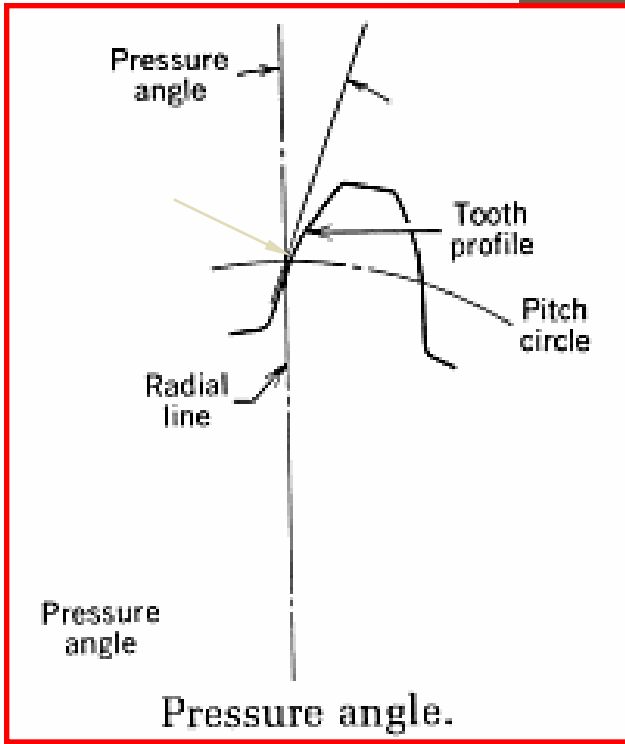


Basic Gear Geometry

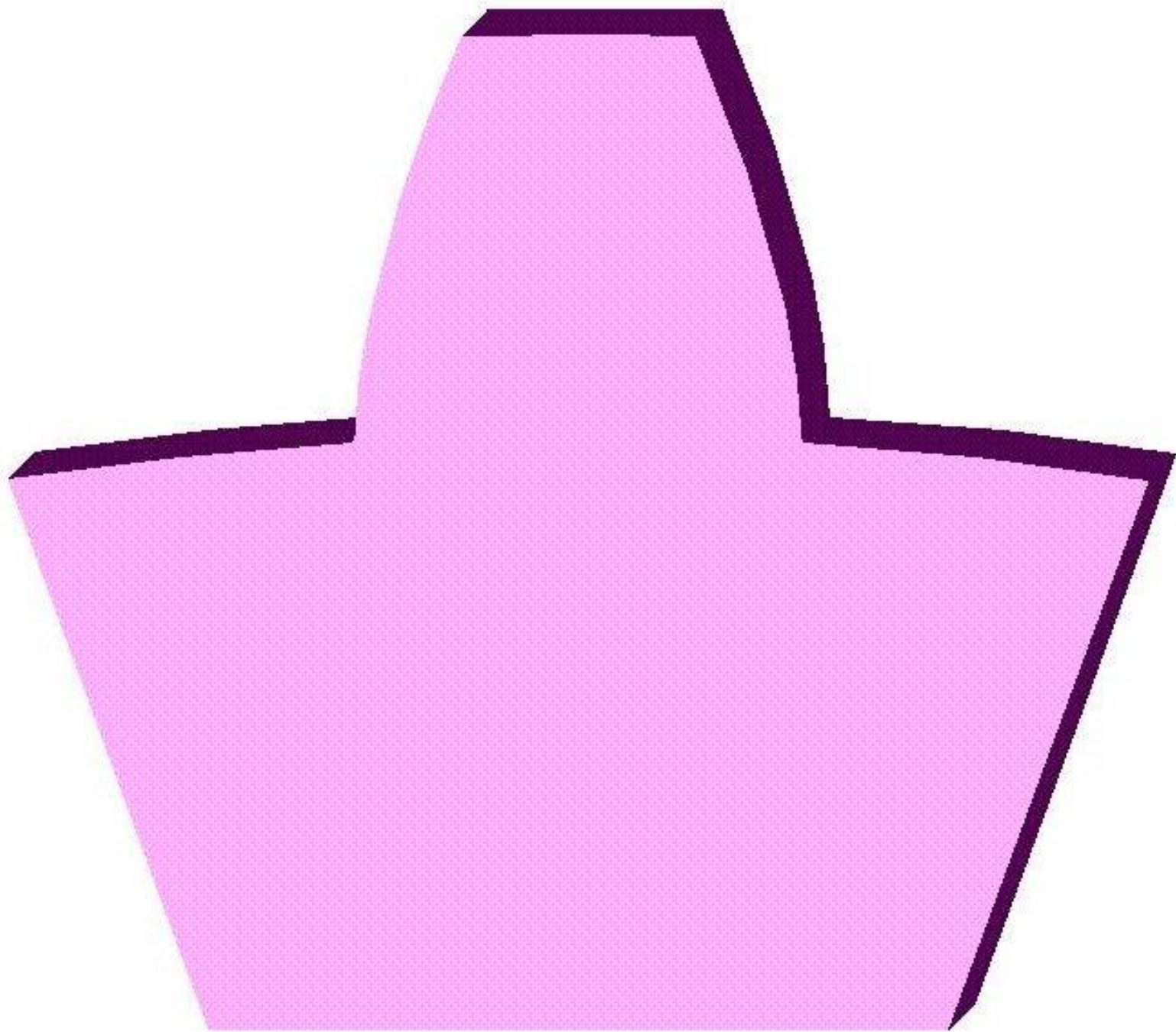
# Gear Tooth: Two Gears Meshing



Spur gear terms.

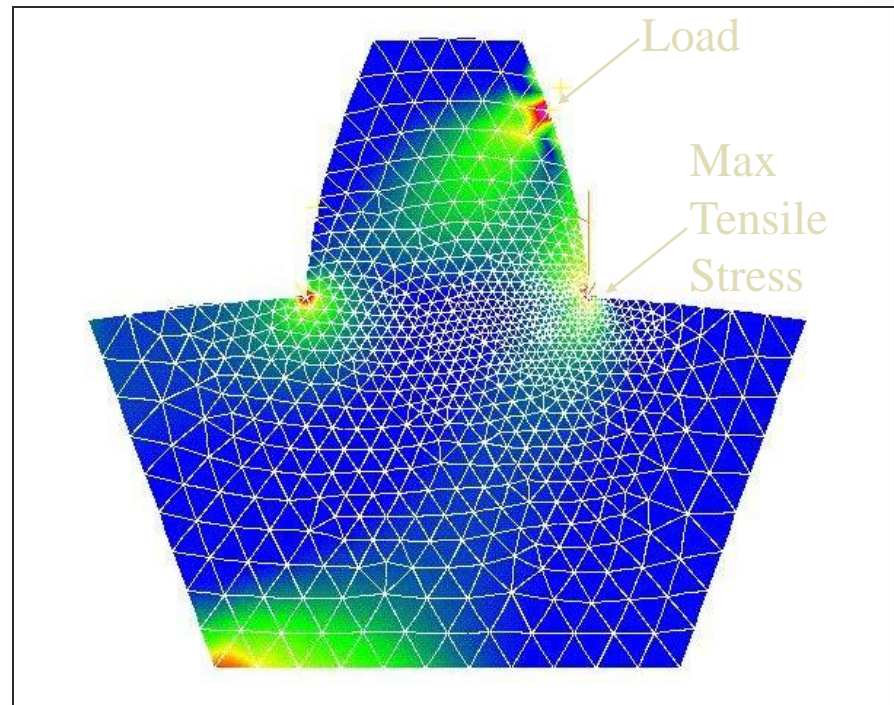


Pressure angle.



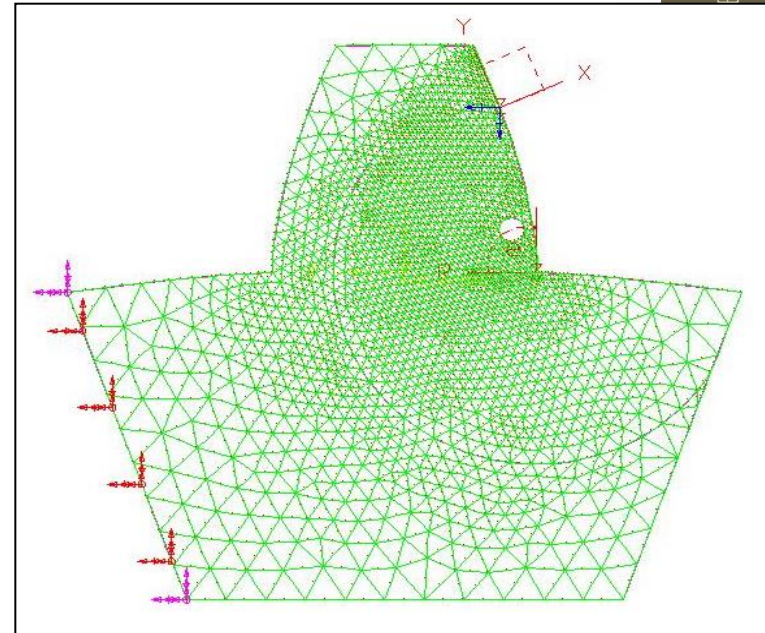
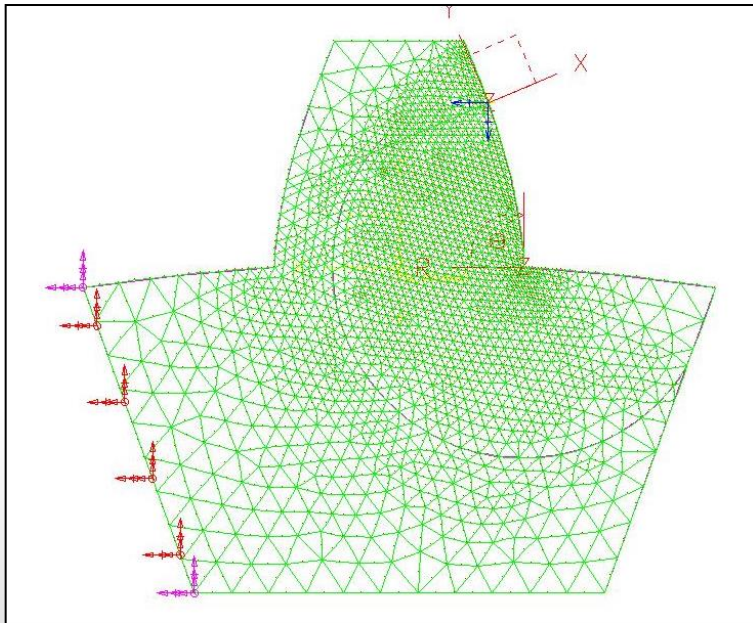
# Gear Tooth: FEA

- Results: original model
  - Band of high max principal stress
  - Max tensile stress
  - Area of concern
    - Crack propagation
    - Fatigue failure begins at a crack



# Gear Tooth: FEA

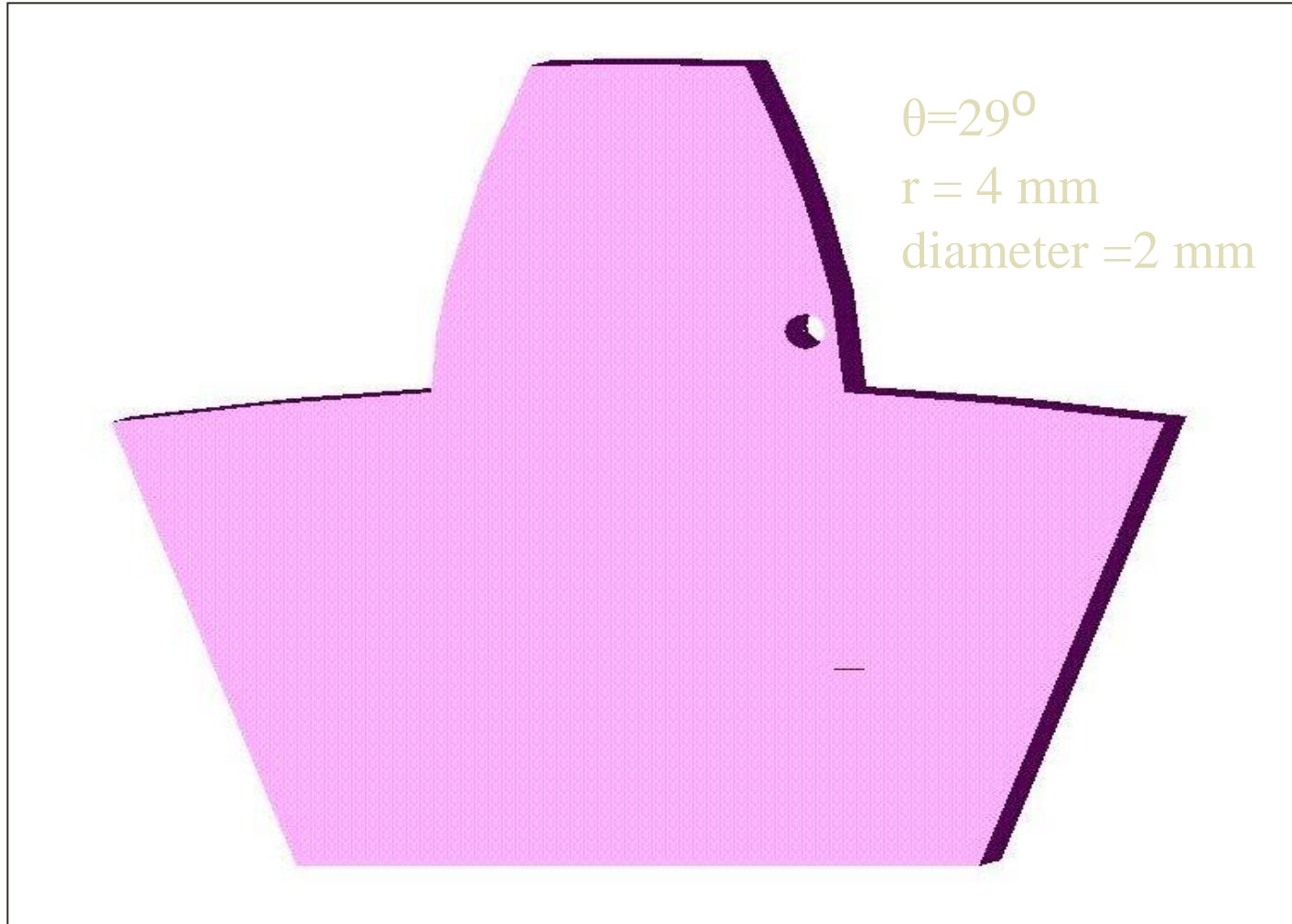
- Mesh
  - Triangular shell elements
  - With and without hole
  - Partitions
  - Free locals – mesh control
- Boundary conditions
  - Cantilever beam approx.
- Load: along  $20^\circ$  pressure line



# Gear Tooth: Optimization

- Objective: Minimize stress
- Design Variables:
  - Hole diameter
  - Angular location
  - Radial location
- Constraints
  - Displacement restraints
- Algorithm: Fletcher-Reeves optimization algorithm
  - Gradient based, improved steepest descent method
  - $\mathbf{X}^q = \mathbf{X}^{q-1} + \alpha^* \mathbf{S}^q$ 
    - Initial search direction is the steepest decent:  $-\nabla \mathbf{F}(\mathbf{X}^q)$
    - $\mathbf{S}^q = -\nabla \mathbf{F}(\mathbf{X}^q) + \beta_q \mathbf{S}^{q-1}$
    - $\beta_q = \frac{|\nabla \mathbf{F}(\mathbf{X}^q)|^2}{|\nabla \mathbf{F}(\mathbf{X}^{q-1})|^2}$

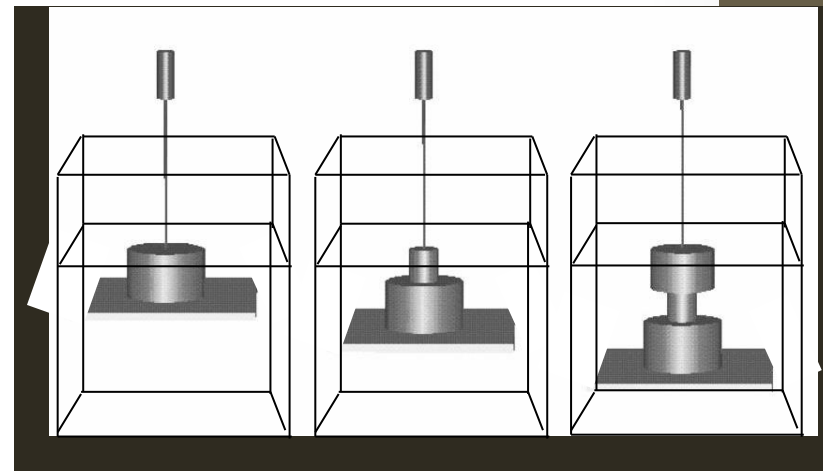
# Gear Tooth: Optimized Hole Location

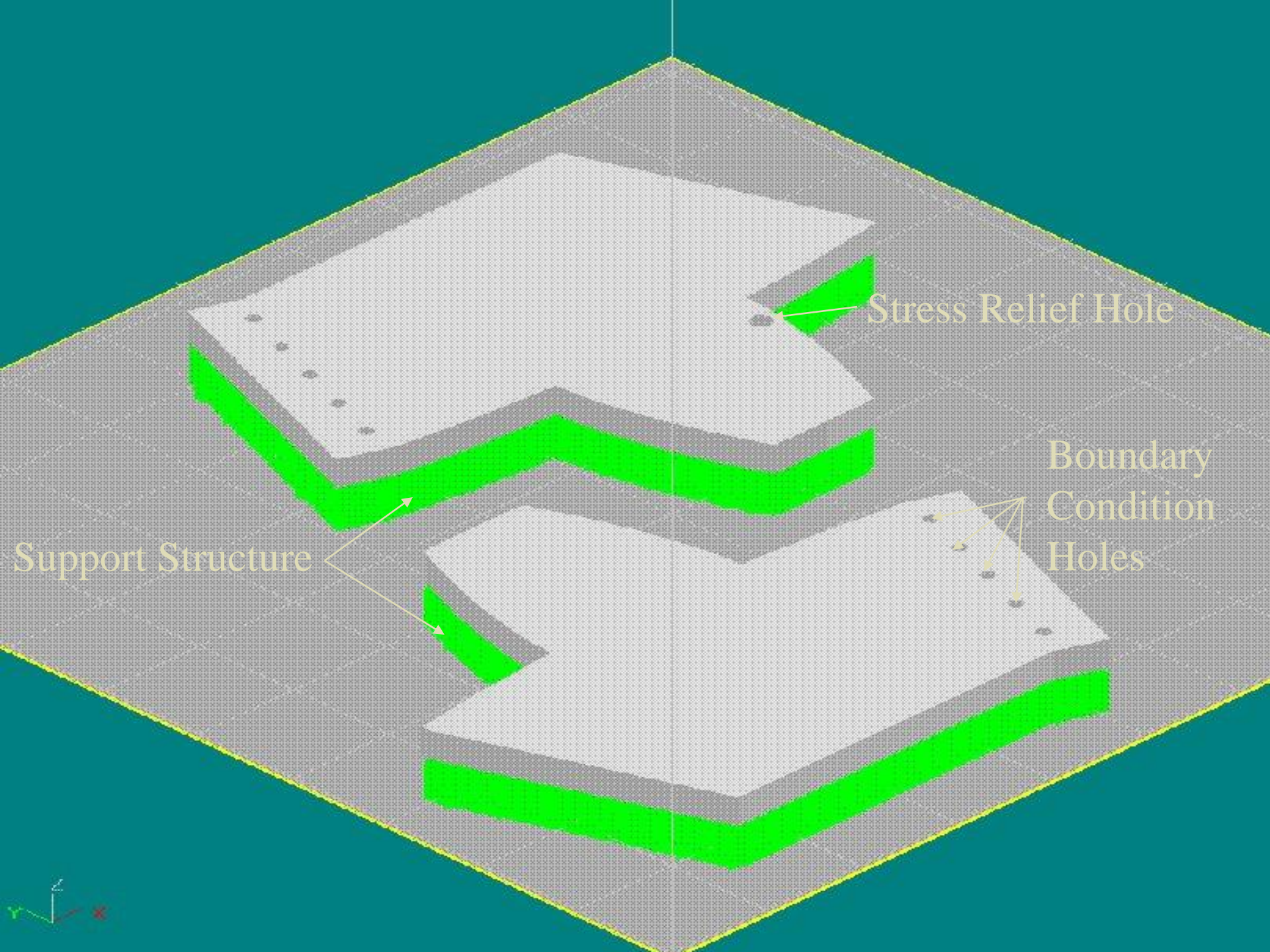


# Gear Tooth: Stereolithography Model Creation



- ◆ **Stereolithography machine SLA-250**
  - Laser cured one layer at a time
  - Thickness: 0.006 inch (103 layers)
  - Material: SL5170
  - Ultraviolet oven for 45 min
- ◆ **Models created in 15 hours**
  - With and without hole





Stress Relief Hole

Boundary Condition Holes

Support Structure



# Gear Tooth: Experimental Setup

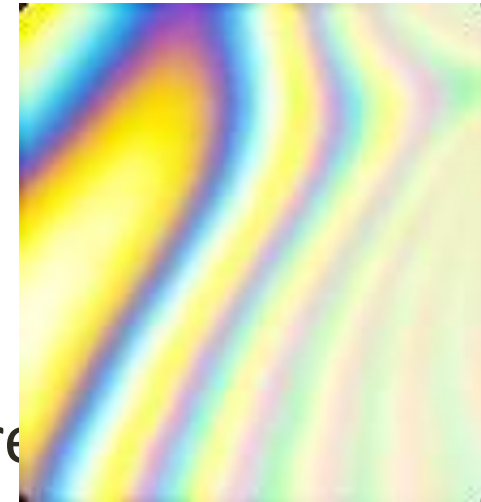
- Experimental study to verify FEA
- A flange with holes for mounting was added to the models to hold the parts in place in the polariscope
  - Compression force was applied
  - Bracket was used to distribute the force
- Circular polariscope dark field was used
  - Used to analyze stress in 2D models

# Gear Tooth: Circular Polariscope



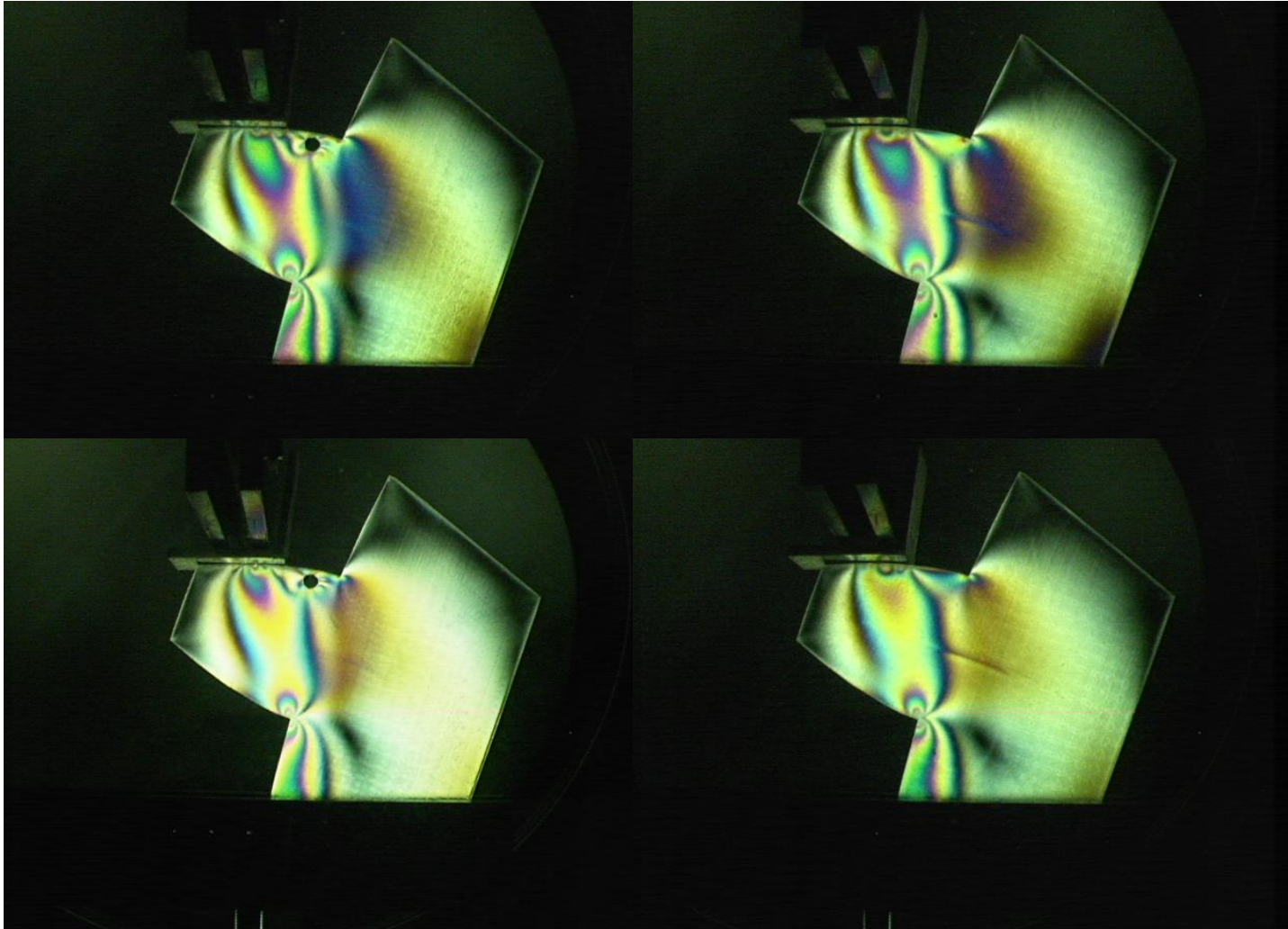
# Gear Tooth: Isochromatic Fringes

- Extinction of light of a particular wave lengths (colored light)
- Determines the magnitude of the stress difference
  - $n = hc/\lambda * (\sigma_1 - \sigma_2)$ 
    - $n$ : fringe order
    - $hc/\lambda$ : constants
    - $\sigma_1 - \sigma_2$ : stress difference

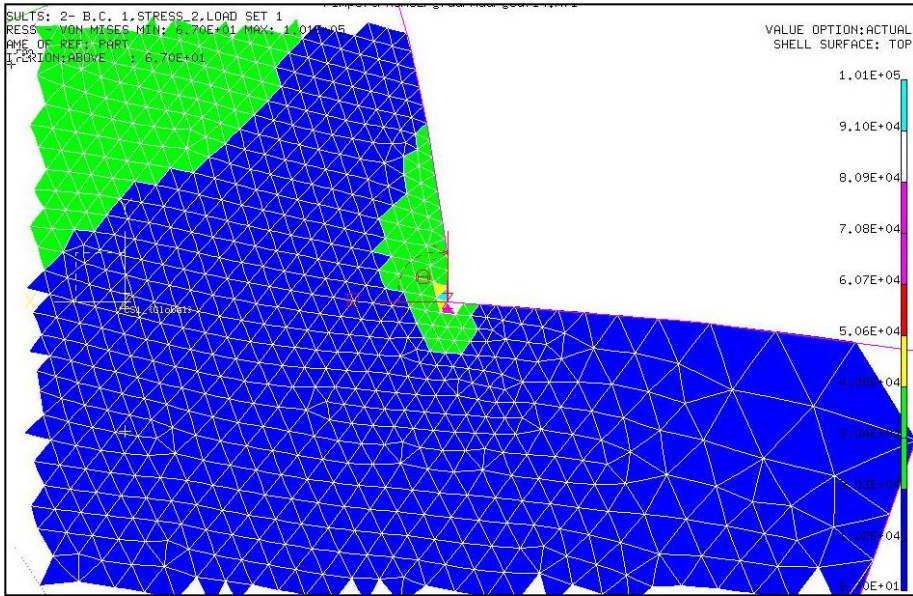


- black yellow red | blue yellow red | green yellow red | g y r | ...

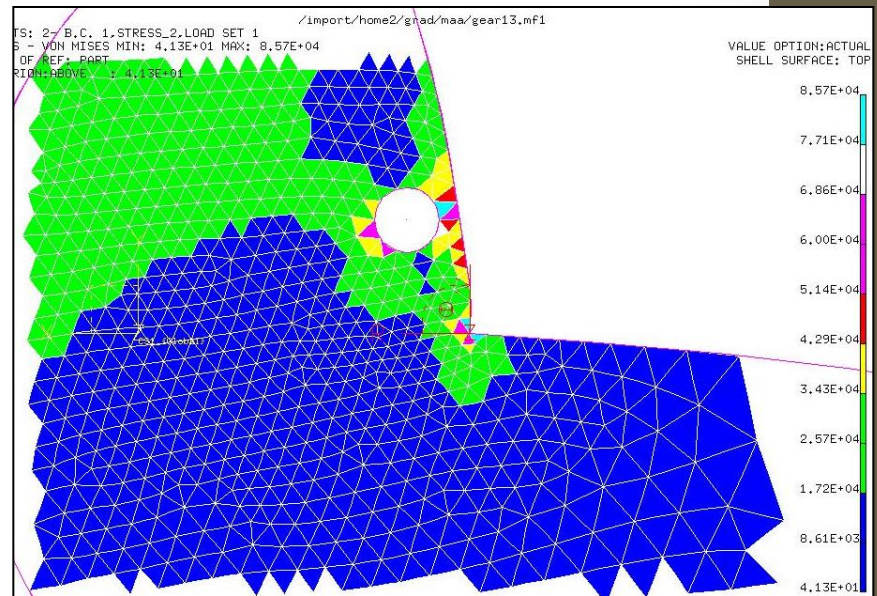
# Gear Tooth: Comparison of Fringes With and Without Hole



# Gear Tooth: Stress Results

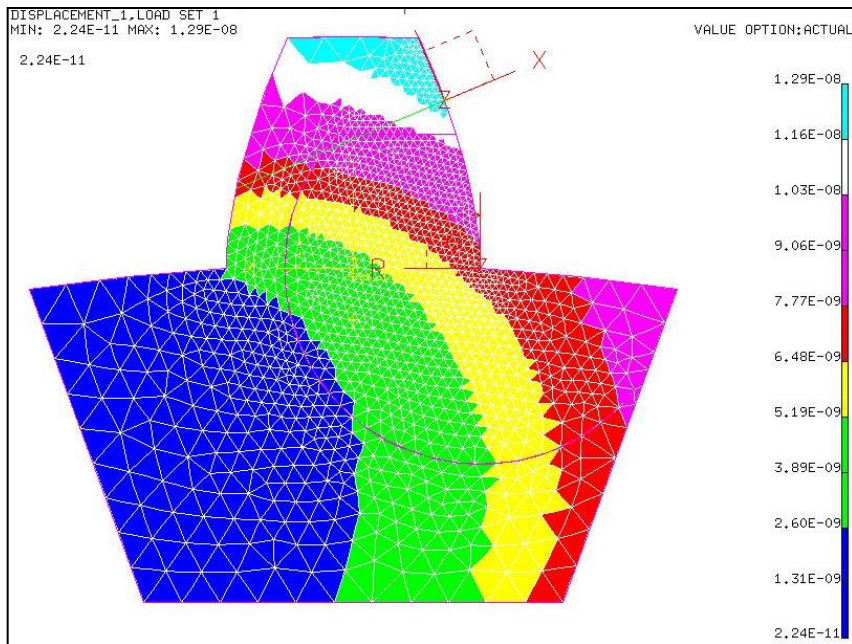


101 kPa

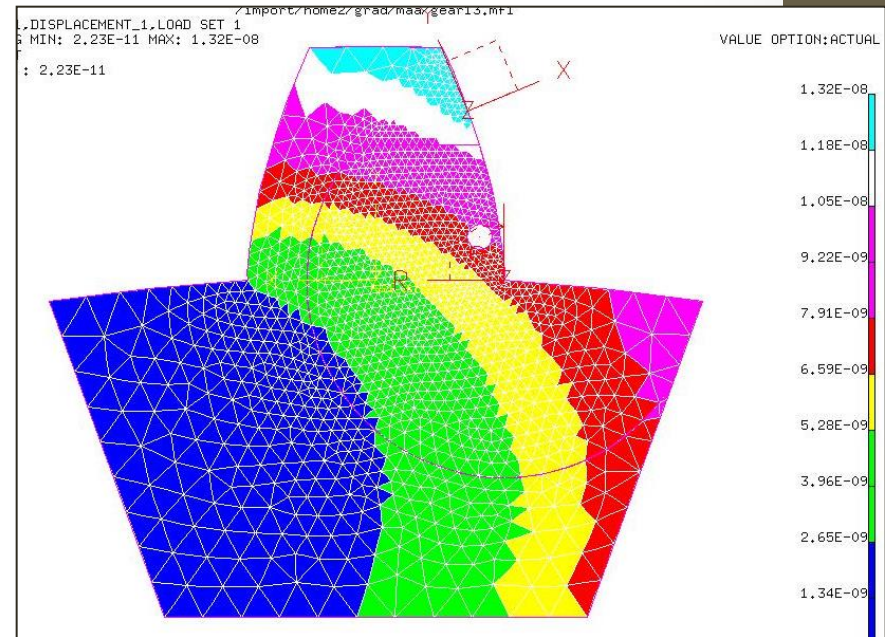


85.7 kPa  
(15% decrease)

# Gear Tooth: Deflection Results



12.9 nm



13.2 nm

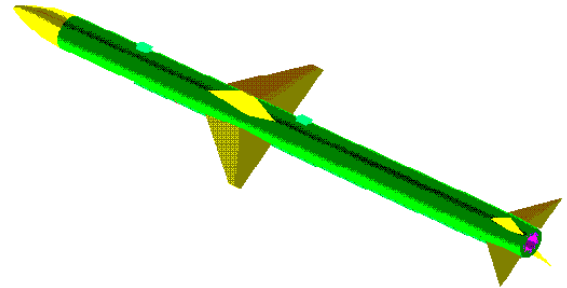
2.3% difference

# Gear Tooth: Concluding Remarks

- Stresses were analyzed and measured for a gear
  - Stresses decreased by 15%.
  - Deflection increase of 2.3% has no major effect on the kinematics and functionality of gear.
- Hole was introduced close to the corner of maximum tensile stress at an angle of 29 degrees from vertical.
- Photoelasticity results verified the analysis

# Machine Design Optimization: Optimization of a Missile

- Designing parts for performance and mass production
  - Mass reduction
  - Stress reduction
  - Cost reduction
  - Performance improvement
  - Machine design components or systems
- Missile design
  - Optimization theory and application
  - Academic vs. industrial design optimization



# Machine Design Optimization: Basics

- Optimization Vocabulary

Minimize  $F(\mathbf{X})$  Objective function

s.t.  $g_j(\mathbf{X}) \leq 0$  Inequality

$h_k(\mathbf{X}) = 0$  Equality

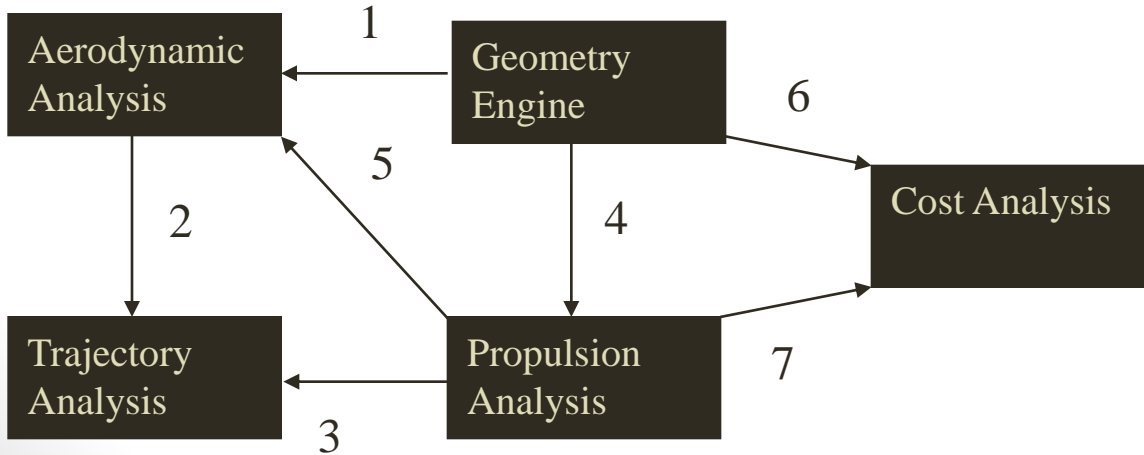
$X_i^{lower} \leq X_i \leq X_i^{upper}$  Side

$\mathbf{X}$  Design variable vector

} constraints

- Multidisciplinary Design Optimization

- Computational expense
- Organizational complexity



	Description	
1	Aerodynamic configuration mass properties CG location	
2	Aerodynamic coefficients	
3	Thrust verses time Specific Impulse Nozzle dimensions	MECH_KIOT
4	Dimensions Volume, Mass Configuration	
5	Nozzle exit diameter power on/off	
6	Geometric dimensions Propulsion dimensions, Material, Weight	
7	Single or dual pulse configuration Propellant weight	

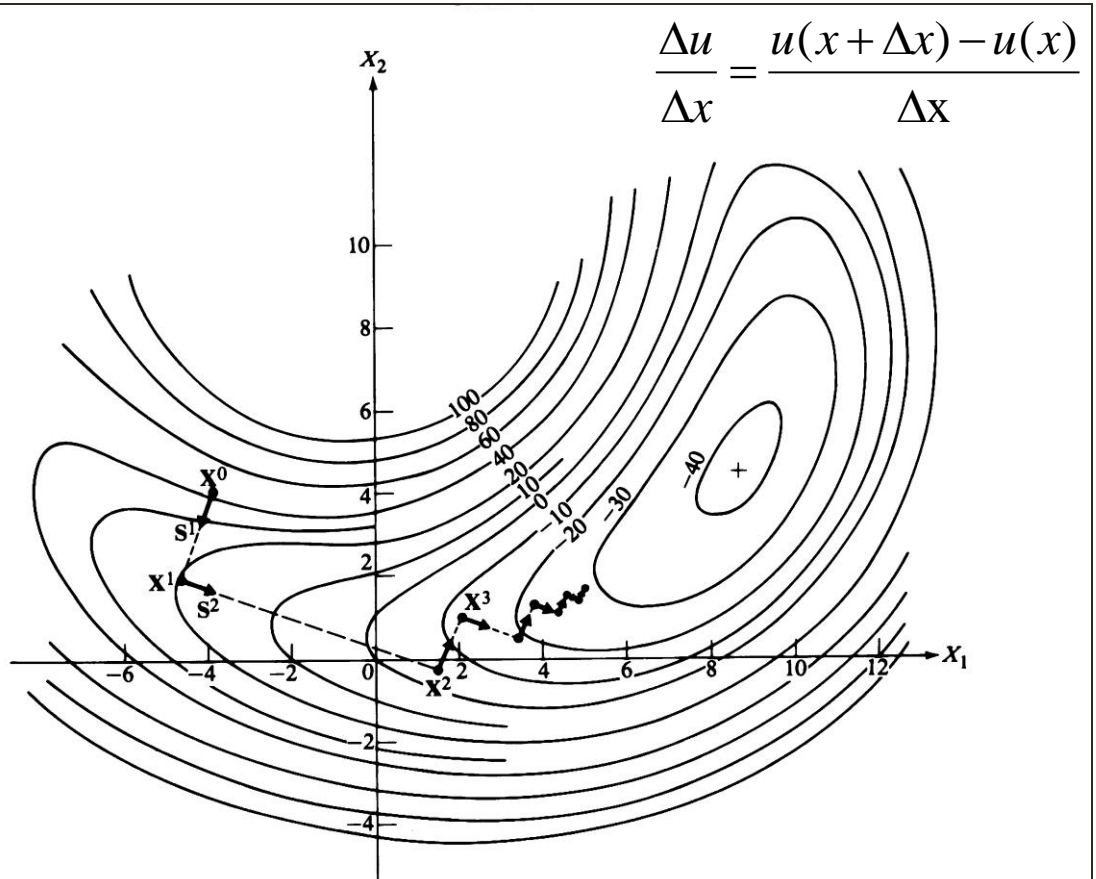
# Machine Design Optimization: Basics

- Optimization Algorithms
  - Gradient-based Algorithms
  - Genetic Algorithms
- MDO Formulations
  - Discipline communication
- Approximations
  - Artificial Neural Networks
  - Design of Experiment
  - Response Surface Approximations
  - Taylor Series Approximations

# Machine Design Optimization: Algorithms

- Gradient Based
  - Sensitivities (gradients) from finite difference

- Local minimum
- Basic concept
  - $\mathbf{X}^q = \mathbf{X}^{q-1} + \alpha^* \mathbf{S}^q$
  - X: design vector
  - q: iterate
  - S: Search direction
  - $\alpha$ : distance to move in direction S



Unconstrained problem

- Gradient is zero
- Positive definite Hessian Matrix

Constrained problem

- Khun-Tucker necessary condition

$\mathbf{X}^*$  is feasible

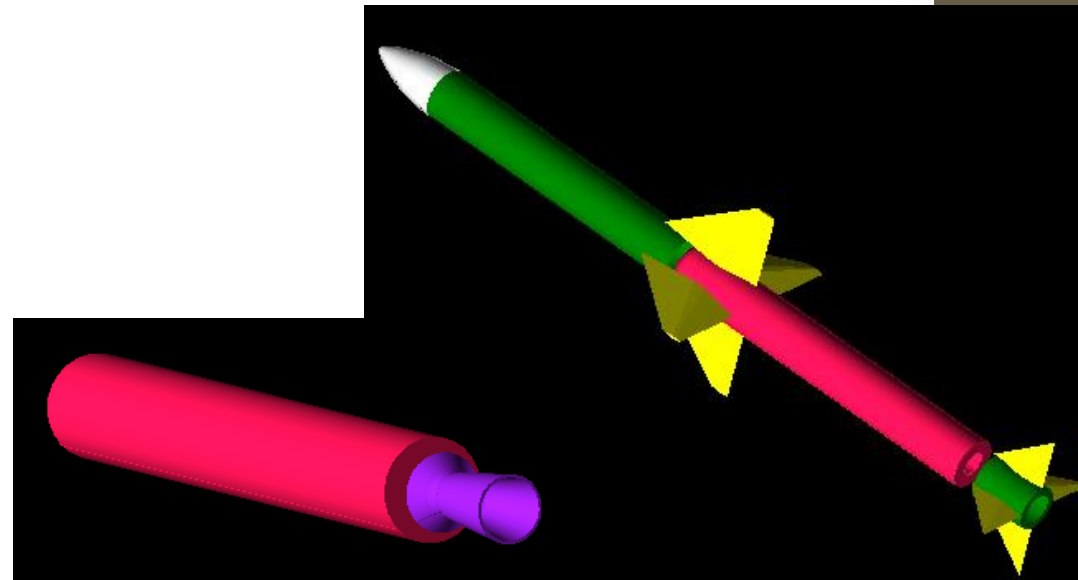
$$\lambda_j \mathbf{g}_j(\mathbf{X}^*) = 0 \quad j = 1, m \quad \lambda_j \geq 0$$

$$\nabla F(\mathbf{X}^*) + \sum \lambda_j \nabla \mathbf{g}_j(\mathbf{X}^*) + \sum \lambda_k \nabla \mathbf{h}_k(\mathbf{X}^*) = 0$$

$$\lambda_j \geq 0$$

# Machine Design Optimization: Academic vs. Industrial Problems

- Design Goal
  - Maximize range
- Key design parameters
  - Mid body diameter
  - Mid body length
  - Nose length
  - Case length
  - Web fraction (difference of the outer and inner radii to the inner radius)
  - Expansion ratio (the ratio of the exit area to the throat area of the nozzle)
  - Gamma (angle of the velocity vector)
- Constraints
  - Weight
  - Center of gravity
  - Total missile length
  - Cost
  - Nose finess ratio
  - Minimum Mach number

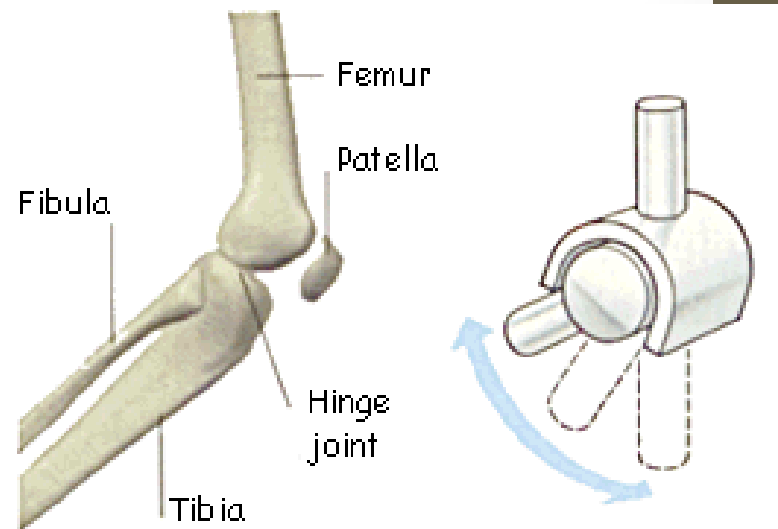
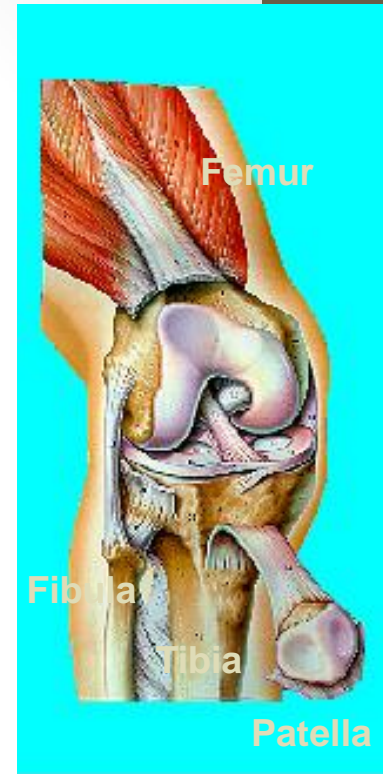


# Machine Design Optimization: Missile Concluding Remarks

- Algorithms, Formulations, Approximations and programming language were combined to remove obstacles.
- Optimization scheme was integrated and tested on a highly coupled air-to-air sparrow-like missile
  - Efficient and robust optimization scheme:
    - Reduced computational time up to 44%
    - Allows for modifications to the optimization statement
    - Covers regions in the design space for which a response cannot be computed
- Scheme can be applied to other large-scaled engineering problems

# Knee Implant Example c

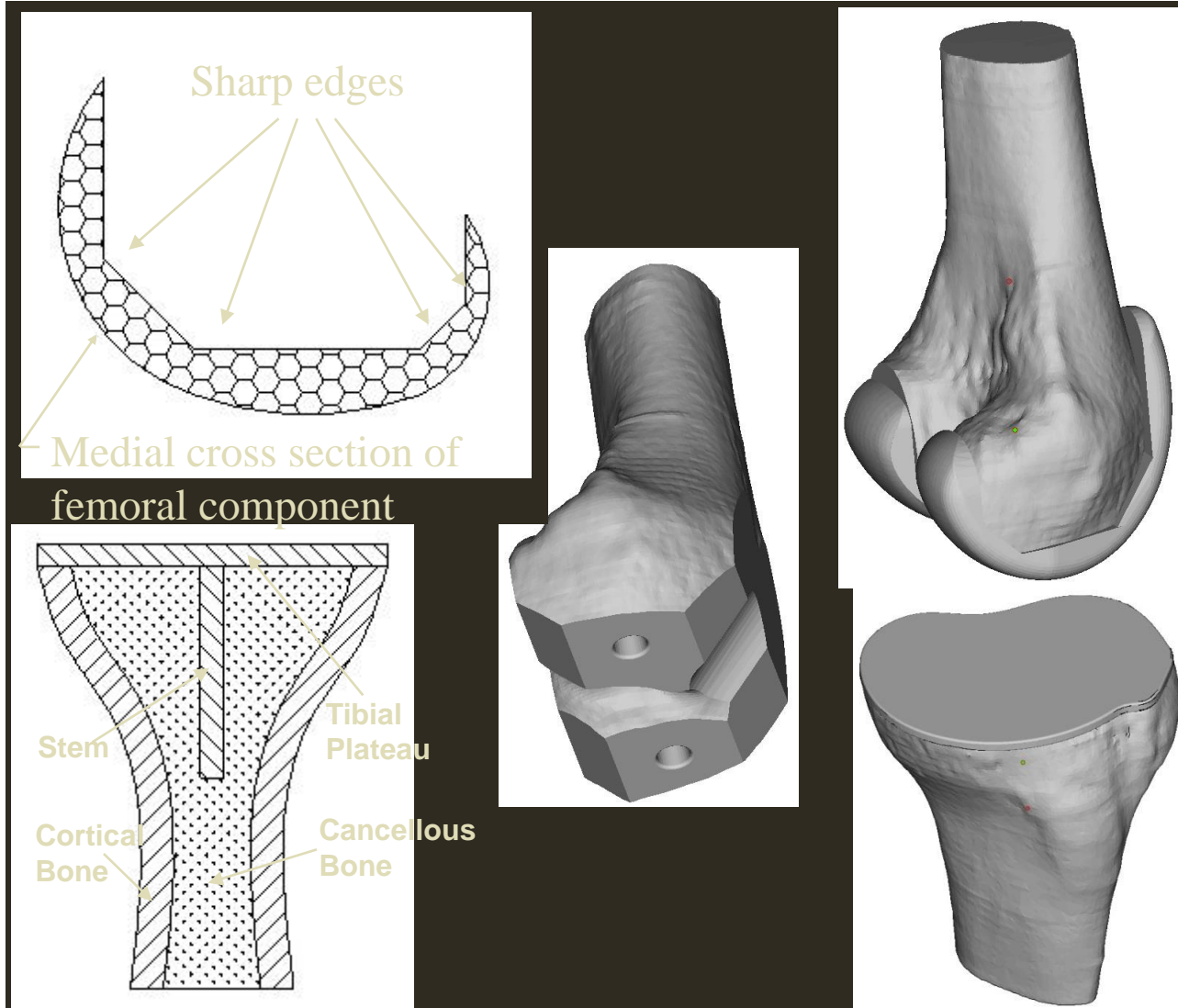
- Knee joint is a hinge joint
- Stress analysis
- Stress concentrations
- Wear of the implant
- Manufacturing
  - Rapid Prototyping
  - Investment Casting



# Knee Implant Example: Need for Customization

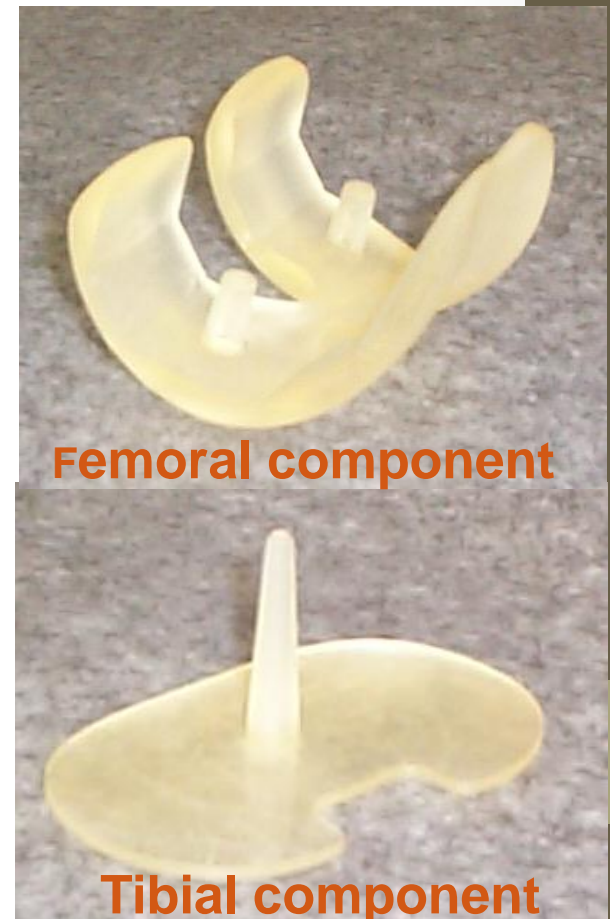
- >0.5 million orthopedic implant surgeries conducted each year in the US
  - Number increasing
    - Increasing life span
    - Higher activity level
- Problems associated with implants are proportionally increasing
  - Use of standard implants leads to removal of valuable bone material
  - Revisions are primarily due to loosening of implants
    - Poor fit – only a few types and sizes are available
    - Stress concentrations affect bone remodeling

# Knee Implant Example: Current Design



# Knee Implant Example: Current Design

- **Problems with current design:**
  - **Only 7 different sizes**
  - **Removal of bone**
  - **Doesn't fit perfectly**
  - **Not used for younger patients**
  - **Sharp edges**
  - **Stress concentrations**
  - **Bone remodeling**
  - **Loosens with time**



# Knee Implant Example: Design of Customized Implant

- Designing the customized implant
  - Implant should resemble the geometry of the original knee
  - Redistribution of stresses results in variation of bone mineral density
  - Reduce possible relative motion of tibial plate implant to the tibial bone
- Data acquisition
  - Computed Tomography data
- Modeling of bone and implant

# Knee Implant Example: Design of Customized Implant

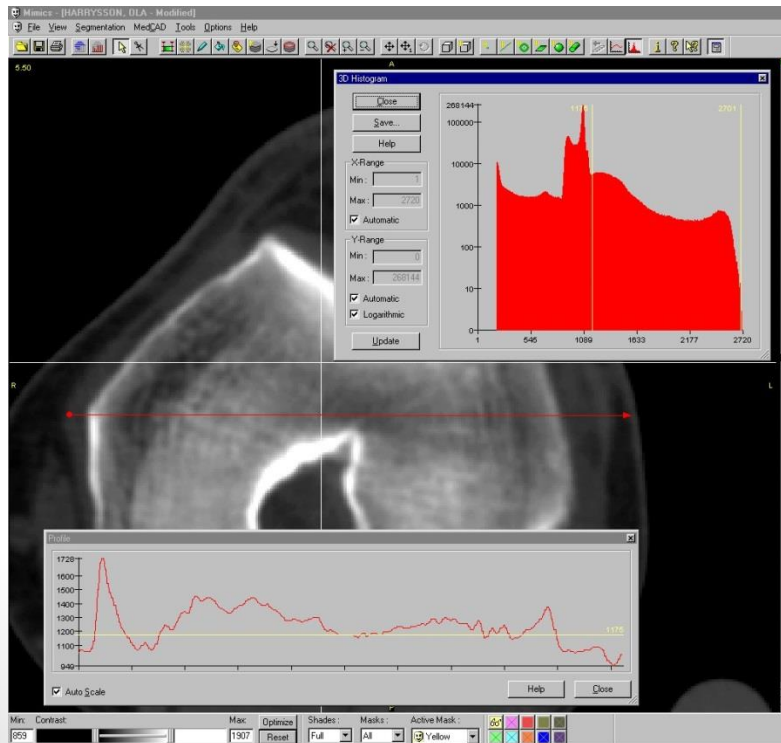
- CT-data acquisition
  - Scanning device completes a 360° revolution
  - Slices are 1 to 5 mm apart
  - Result: Matrix with gray scaled pixels based on tissue density



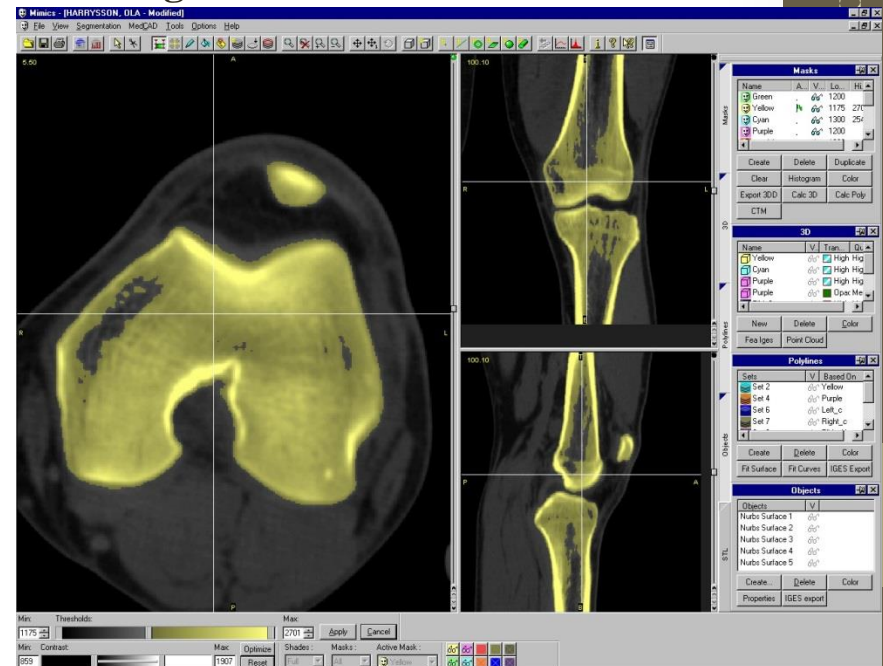
# Knee Implant Example: Design of Customized Implant

- Data conversion using Mimics from Materialise

## Density threshold



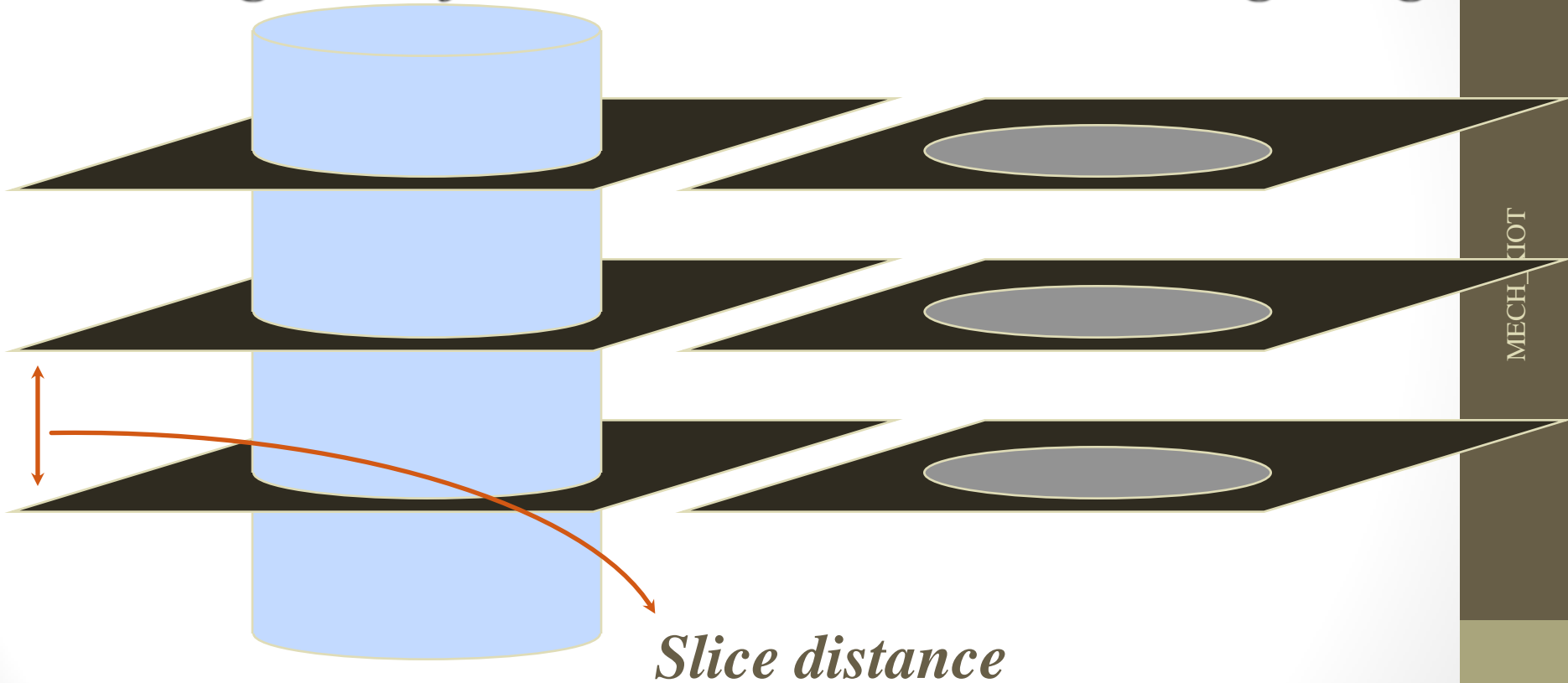
## Investigation of each scanned slice



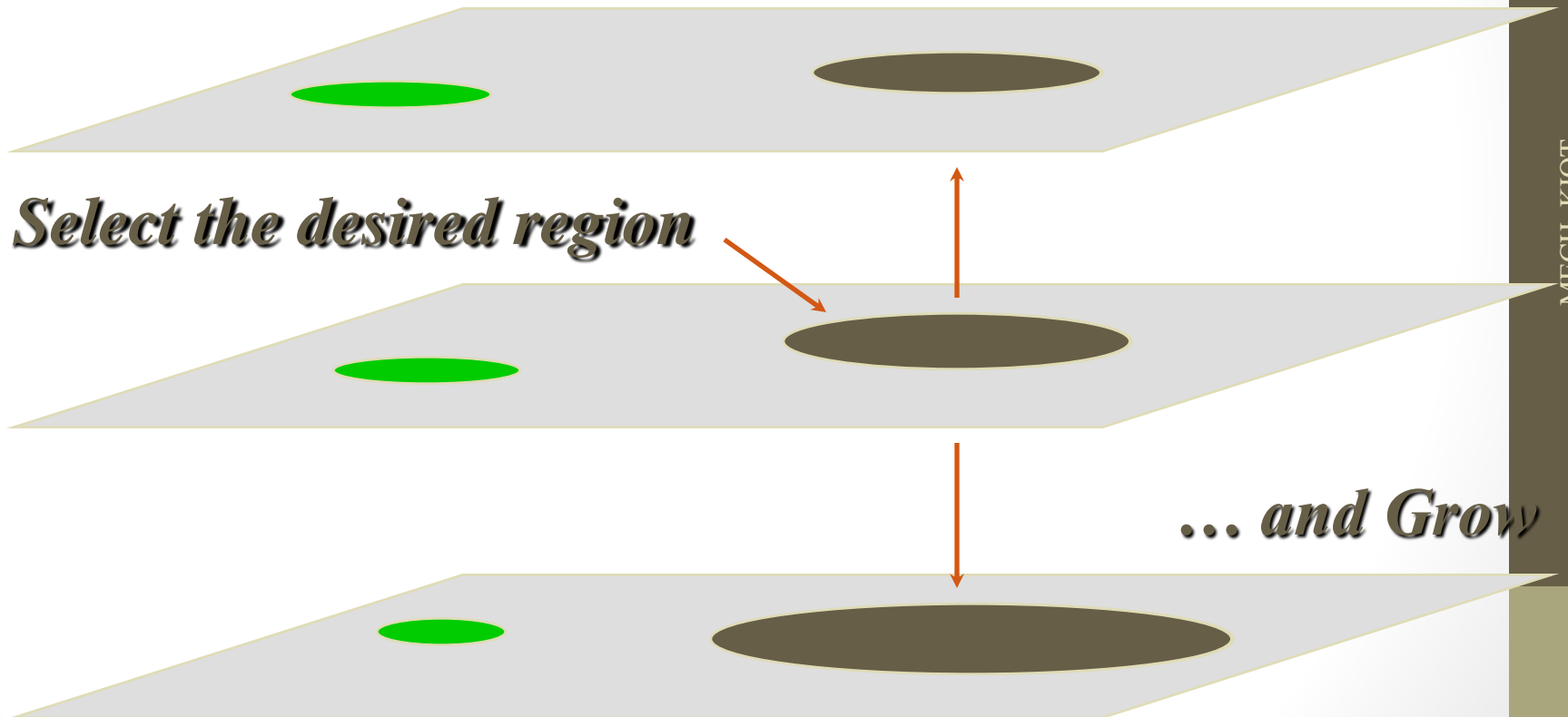
# Knee Implant Example: Design of Customized Implant

*Scanning the object*

*Resulting Image Set*

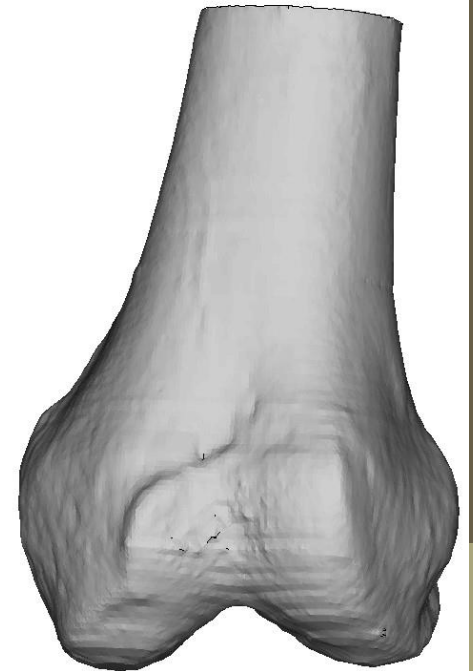
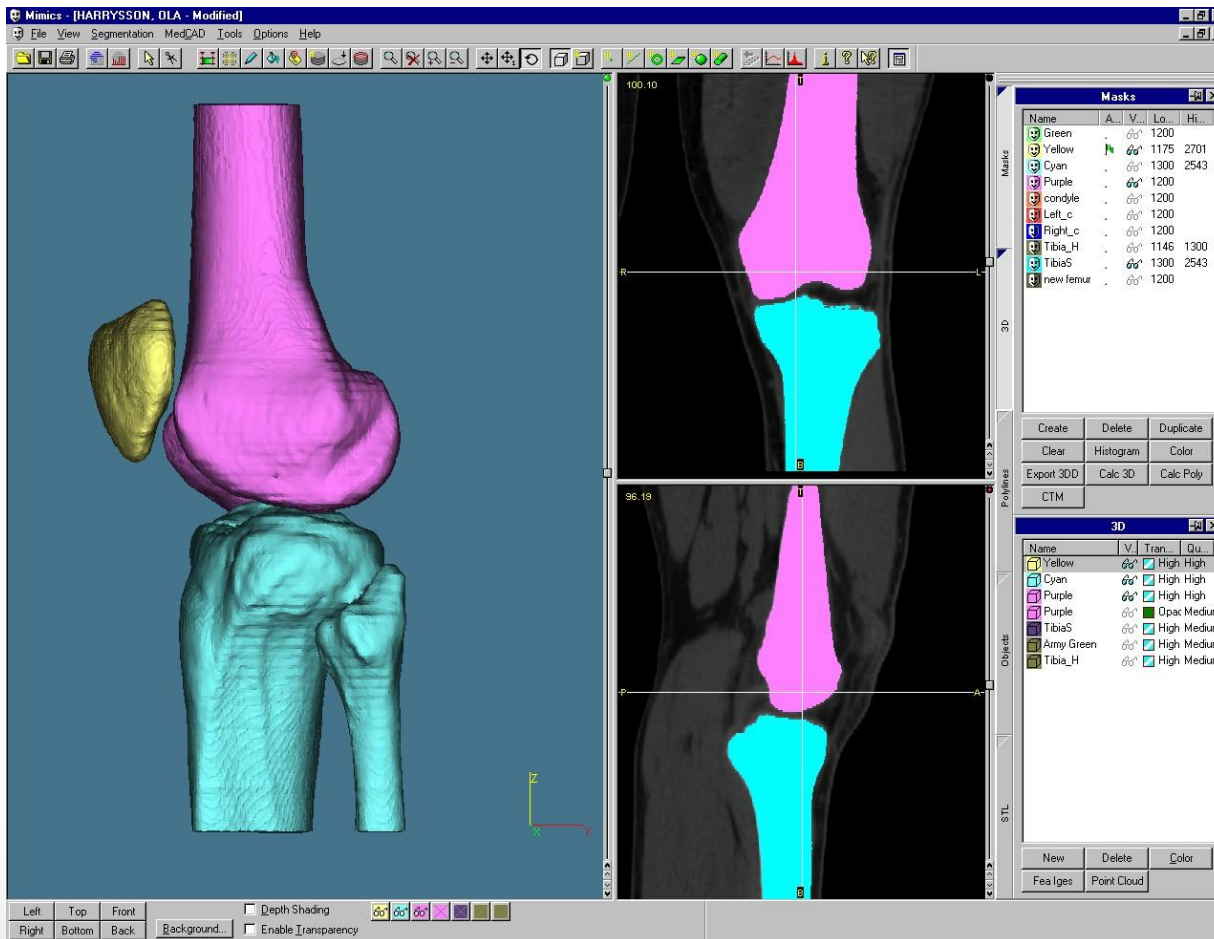


# Knee Implant Example: Design of Customized Implant



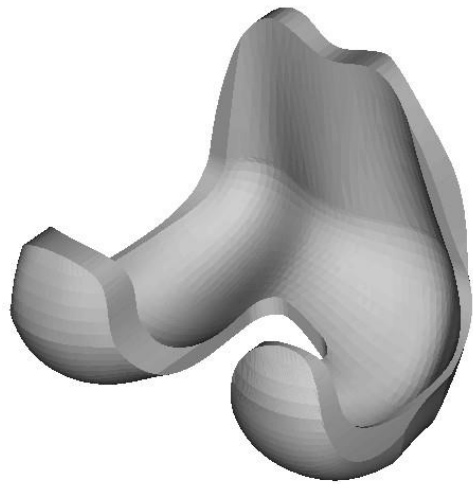
# Knee Implant Example: Design of Customized Implant

- Data conversion using Mimics from Materialise

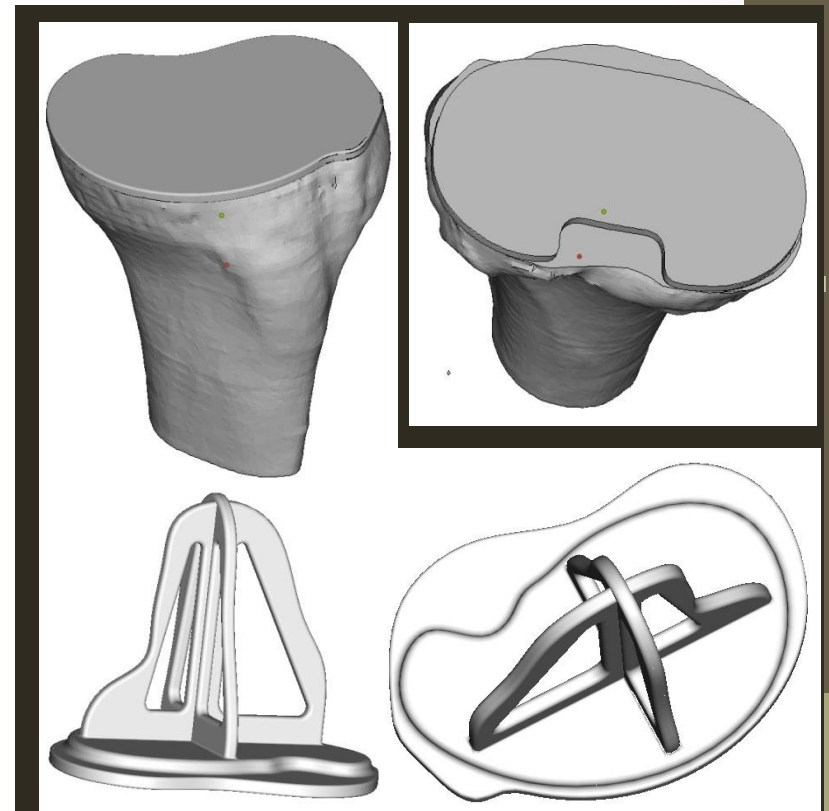


# Knee Implant Example: Design of Customized Implant

**Femoral Component**



**Tibial Component**

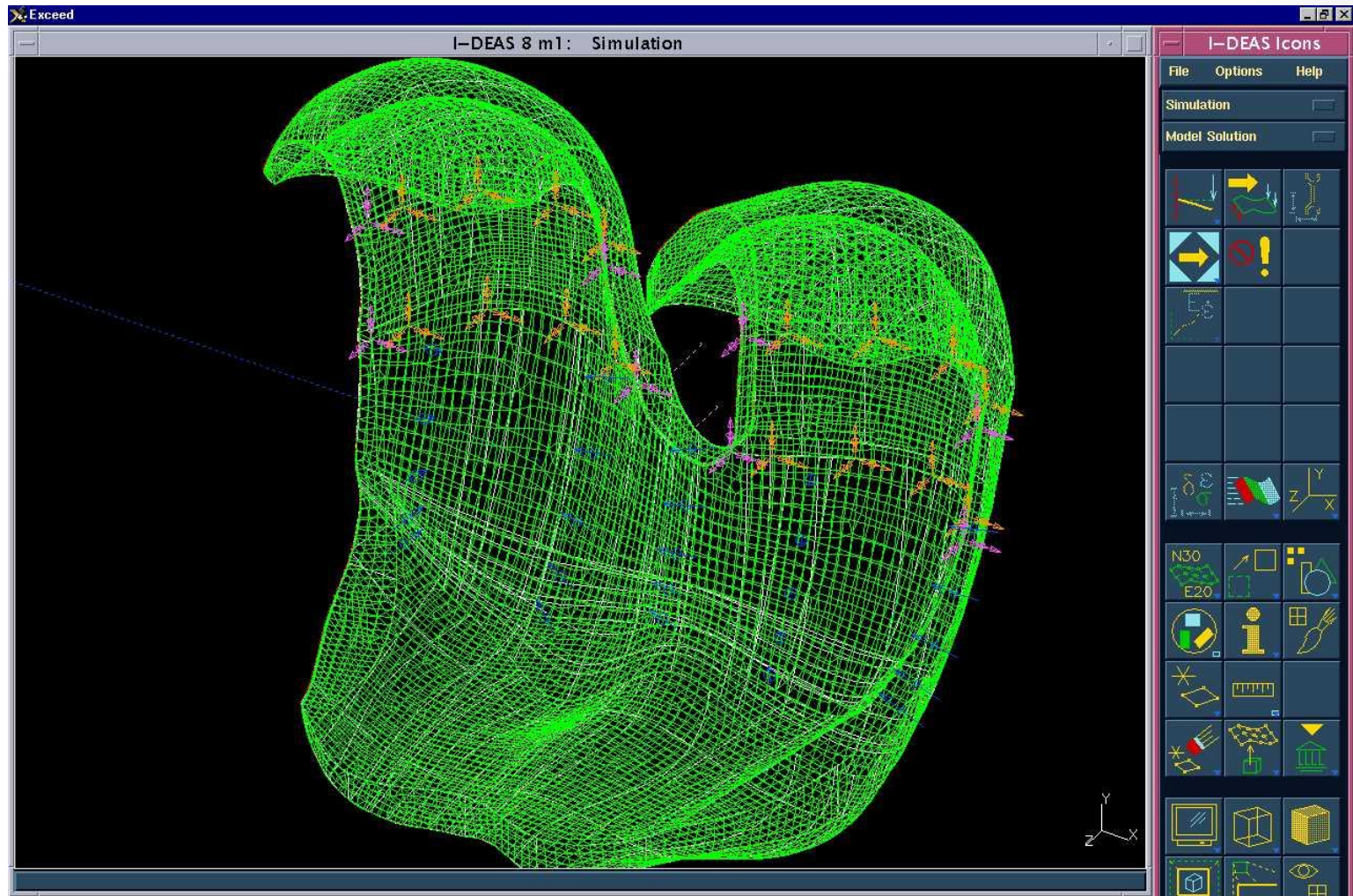


# Knee Implant Example: Initial Stress Analysis of Implant

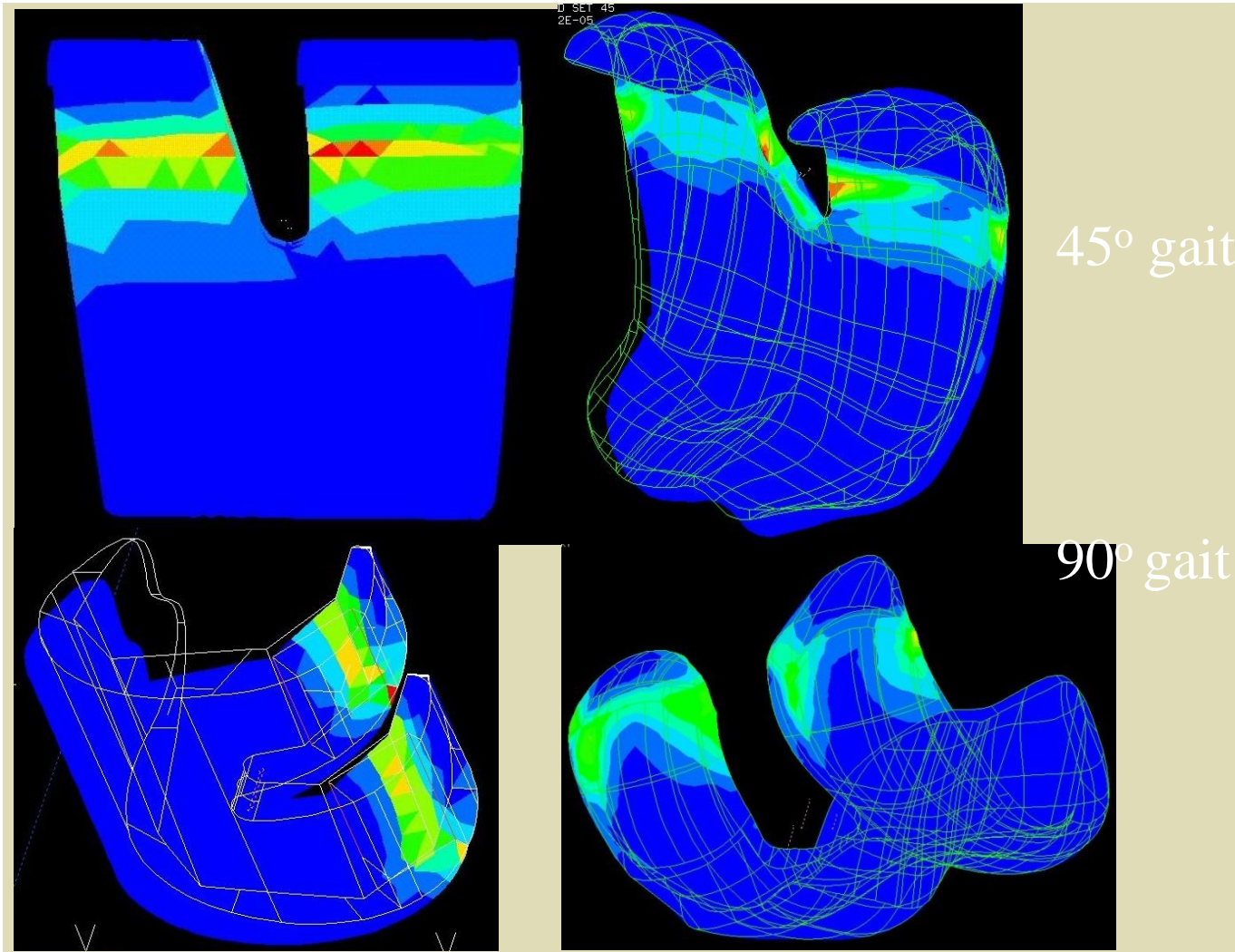
- Finite Element Analysis
  - $0^\circ$ ,  $45^\circ$ ,  $90^\circ$  gait angle
  - Load 3,5,10 times the body weight



# Knee Implant Example: Initial Stress Analysis of Implant



# Knee Implant Example: Initial Stress Analysis of Implant



# Knee Implant Example: Initial Stress Analysis of Implant

<b>Implant Design (<math>\sigma</math> in MPa)</b>				
Type of Implant	X*body weight (85kg * 9.81m/s <sup>2</sup> )	0° gait angle	45° gait angle	90° gait angle
Old	3	186	150	154
New	3	158	115	130
Old	5	311	250	257
New	5	263	191	217
Old	10	622	500	514
New	10	525	383	435

# Knee Implant Example: Manufacturing



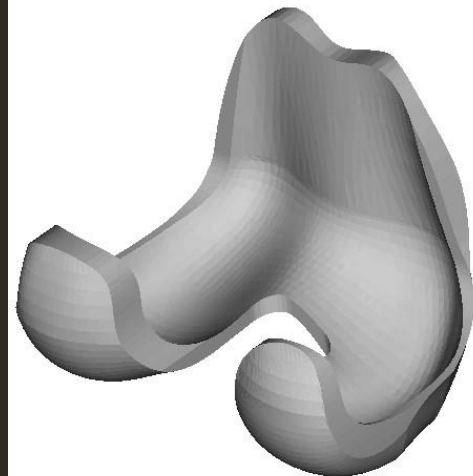
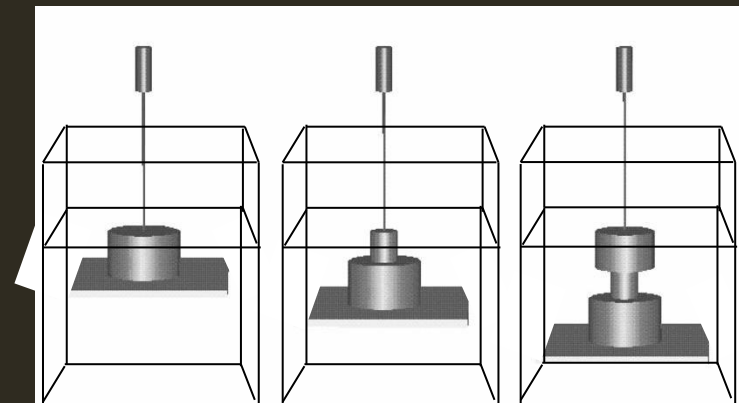
## ◆ Rapid Prototyping

- Laser cures one layer at a time
- Thickness: 0.006 inch

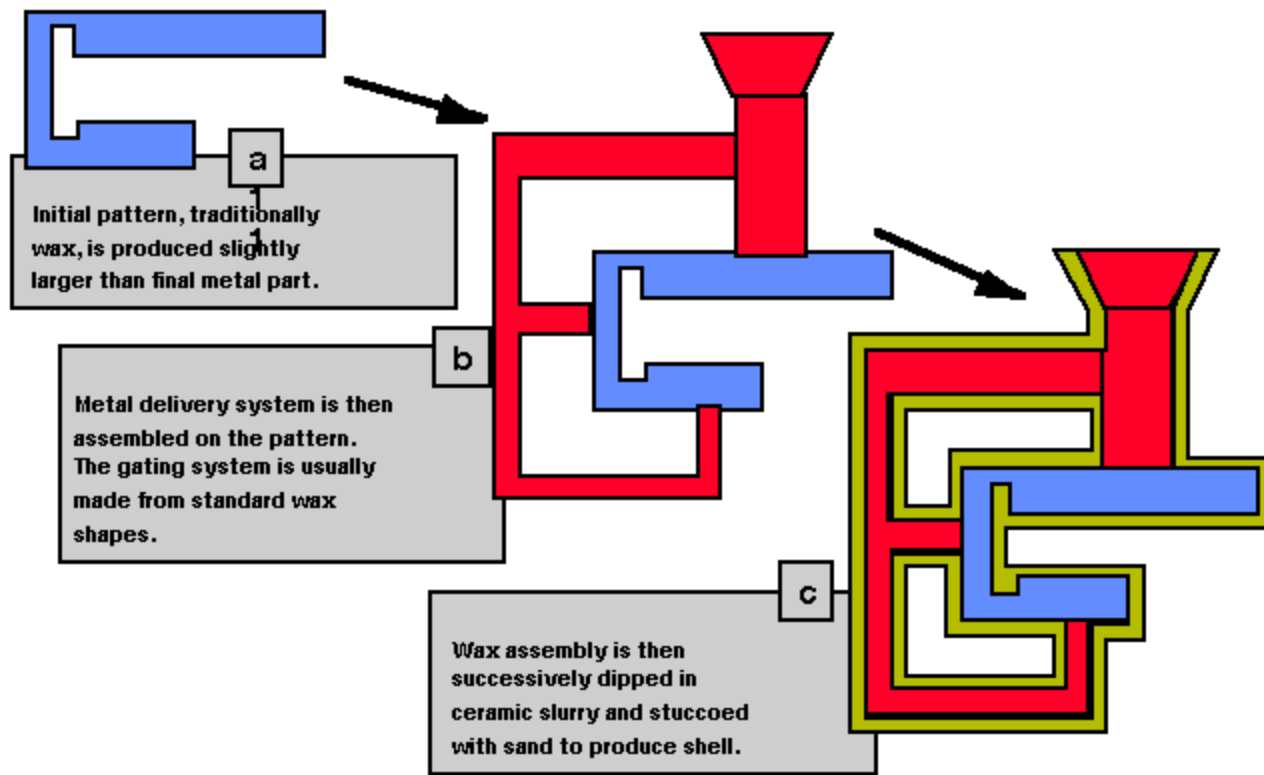
## ◆ Investment Casting

**CAD model to stereolithography model.**

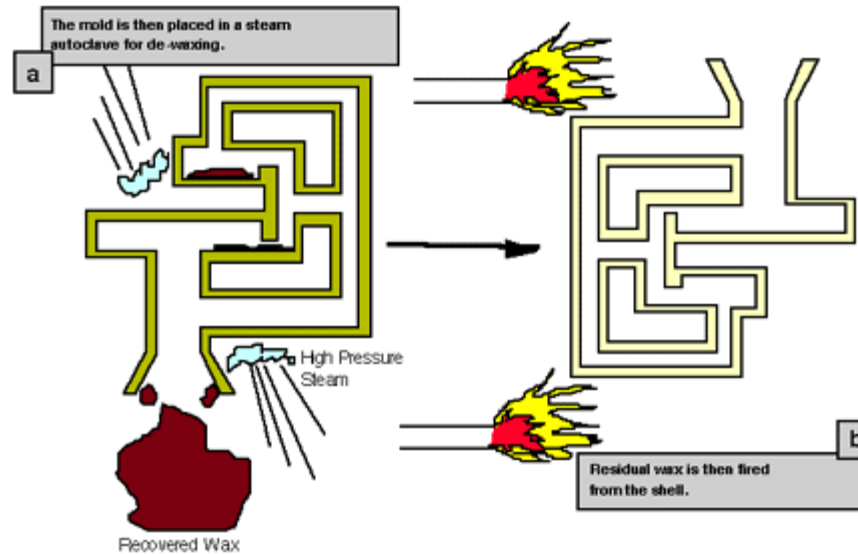
- Eliminates costly low-production-run wax pattern tooling.



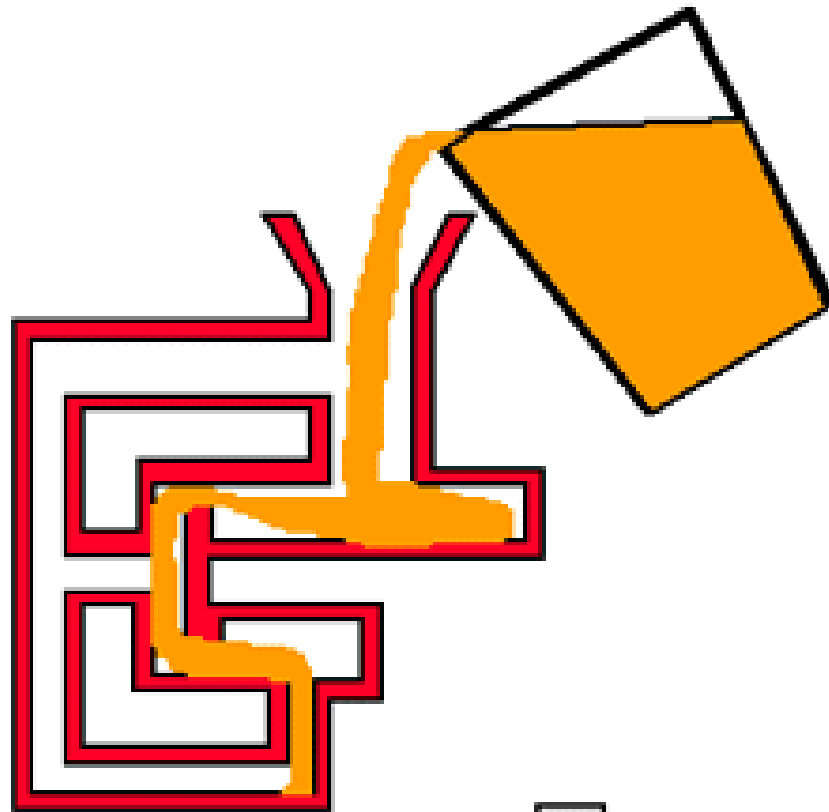
# Knee Implant Example: Manufacturing – Investment Casting



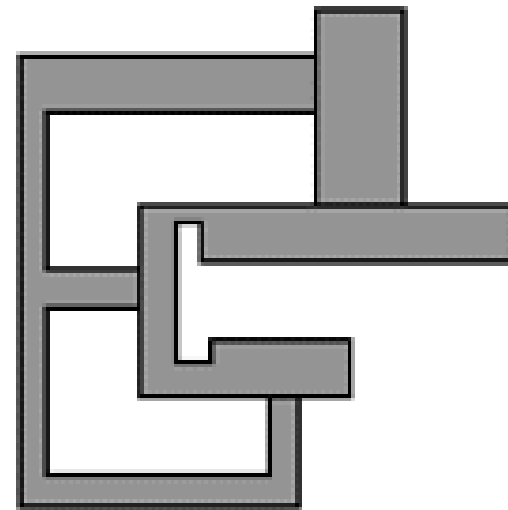
# Knee Implant Example: Manufacturing – Investment Casting



# Knee Implant Example: Manufacturing – Investment Casting



Mold is preheated, and molten metal is poured into the mold cavity.



After cooling, the ceramic shell is chipped or blasted off, and the metal part attached to gating system remains.

# Knee Implant Example:

## Concluding Remarks

- An implant design has been studied and redesigned to increase life of the implant
- Initial stress analysis have been performed.
  - Results are favorable for the new implant
- Manufacturing of implant
  - Rapid prototype model
  - Investment casting model
- Future work:
  - Improve finite element model and analysis
  - Parameterize and optimize
- Machine design:
  - Hinge joint, stress analysis, stress concentration, wear, manufacturing

# Overall Conclusion

- Machine Design Overview
- Research Areas and Applications
  - Gear Tooth FEM/FEA and Optimization
  - Machine Design Optimization
  - Customized Knee Implant: Design, Stress Analysis and Manufacturing
- Research Mission at UNF

