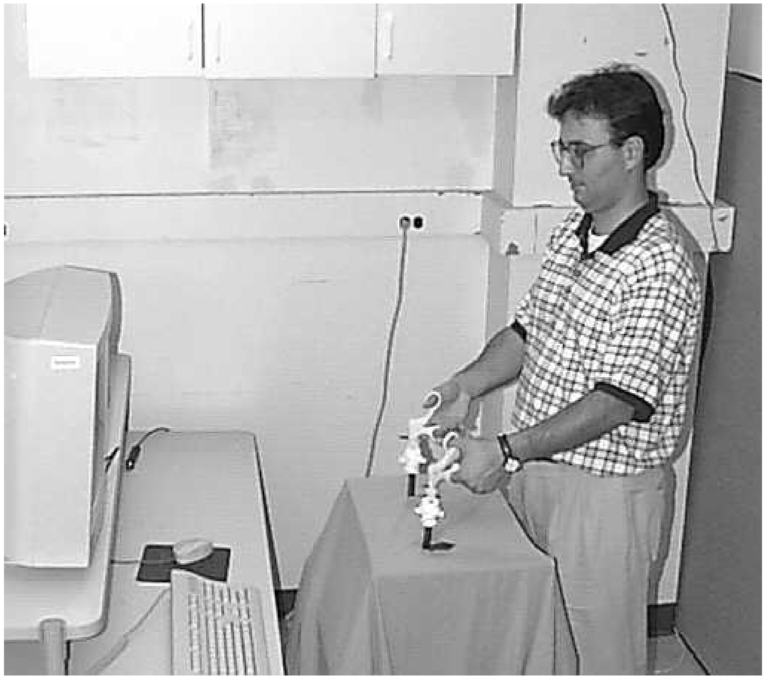
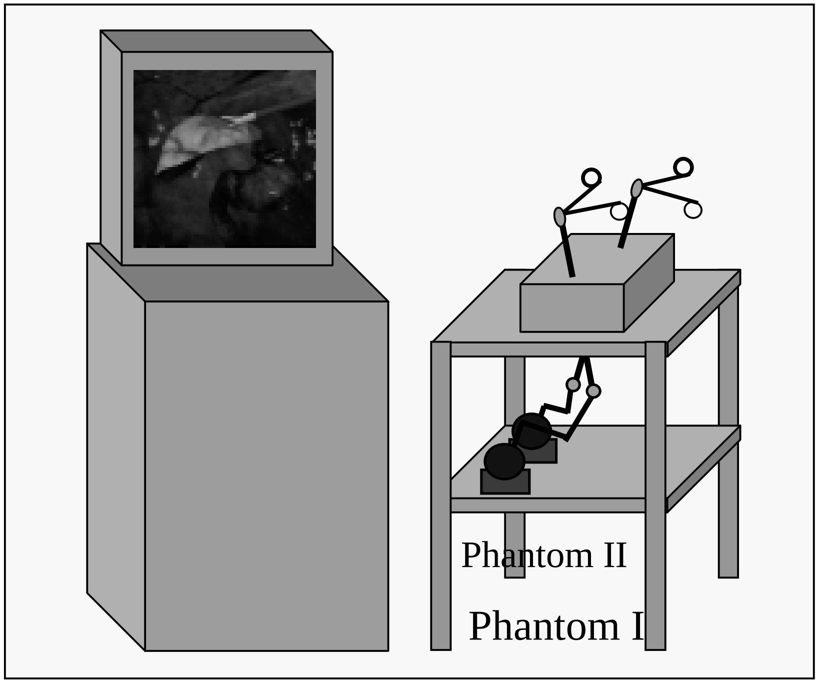
Simulation of Instrument-Tissue Interactions and System Integration





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Topics:

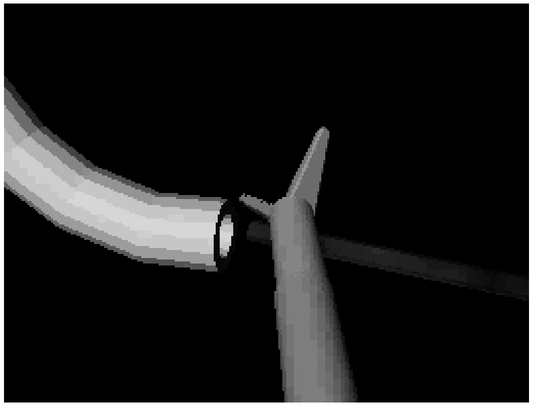
A) Collision detection and computational models of surgical instruments

B) Physically-based modeling for simulating soft tissue behavior

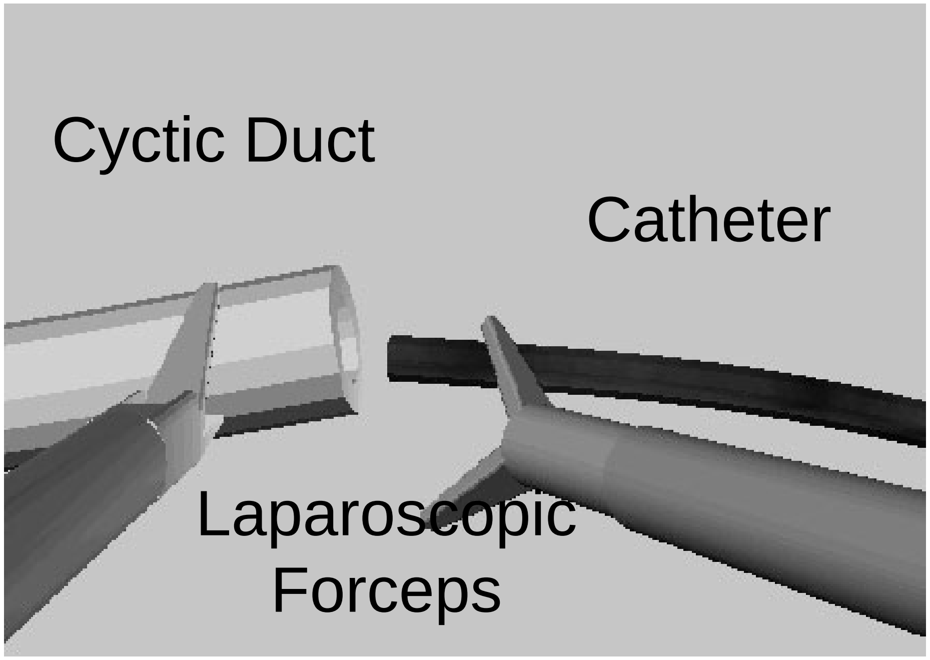
C) Haptic rendering of deformable objects

D) Software and hardware integration

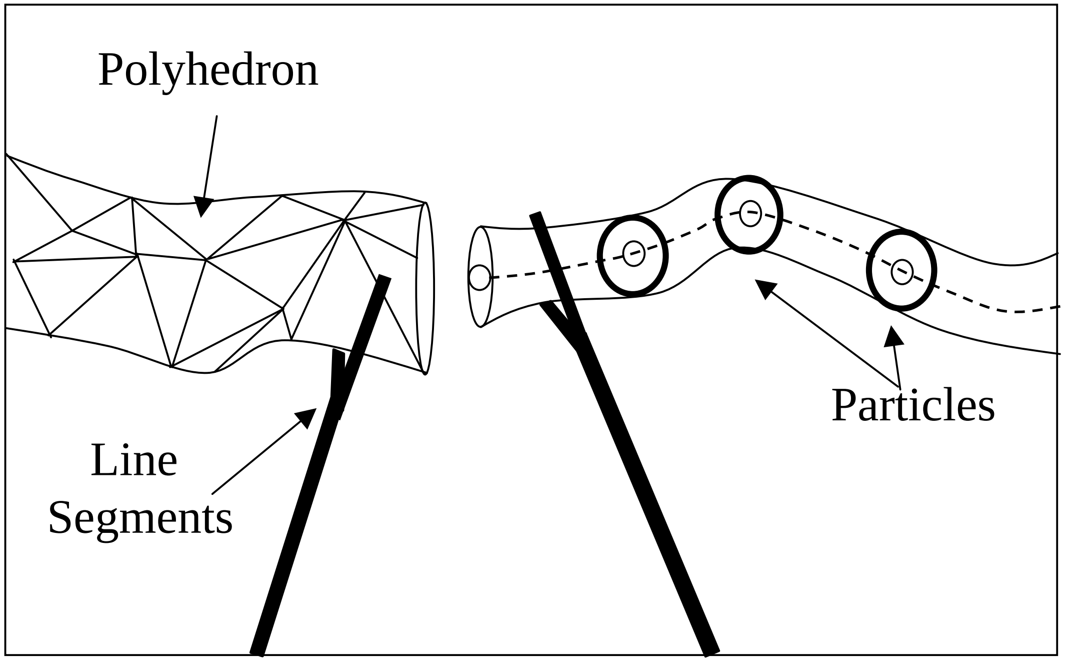
Case Study:



Simulation of Catheter Insertion into the Cyctic Duct



What you see ...



What is really happening ...

A) Collision detection and computational models of surgical instruments

- Principles of collision detection

- How to check collisions faster?

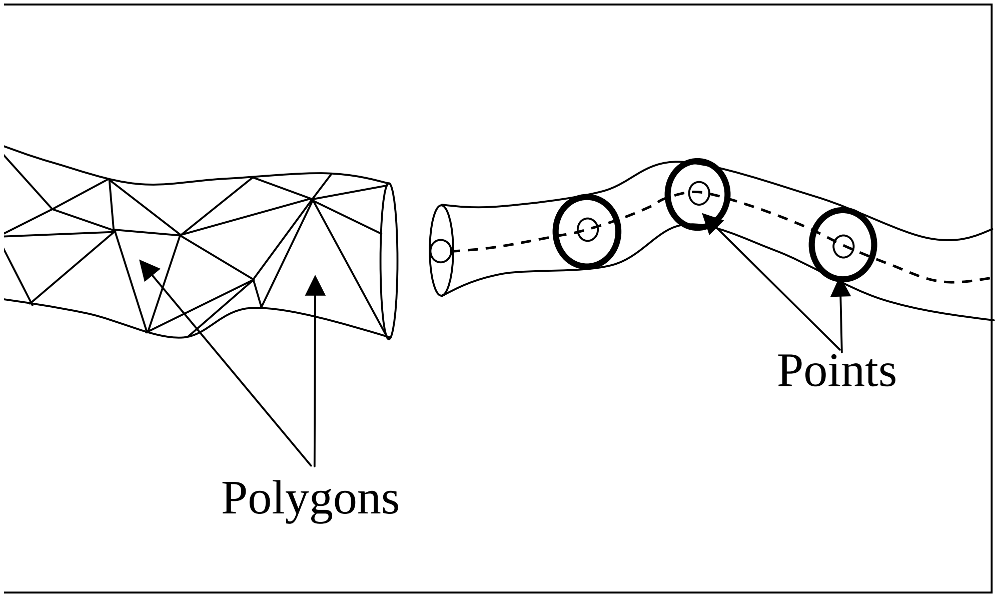
- Computational models of laparoscopic instruments

Principles of Collision Detection

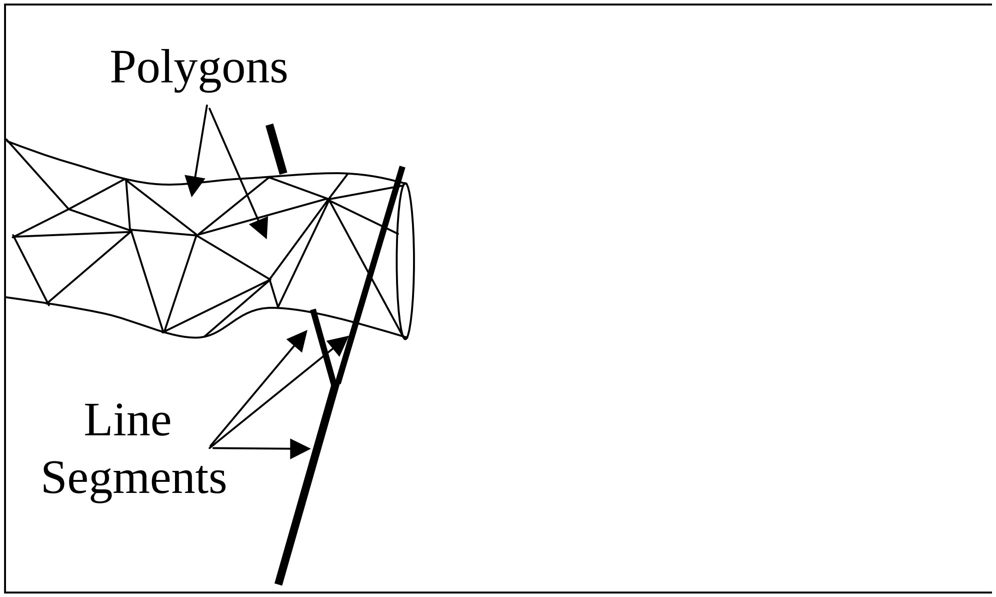
(object-object is too expensive !)

Point-Object

Line Segment - Object



(e.g. catheter - cyctic duct)

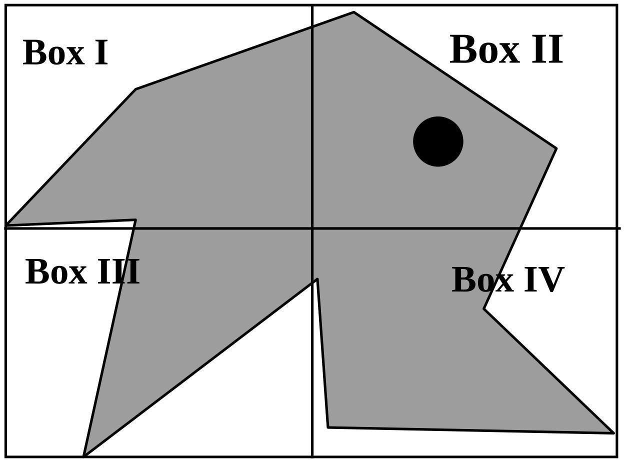


(e.g. forceps - cyctic duct)

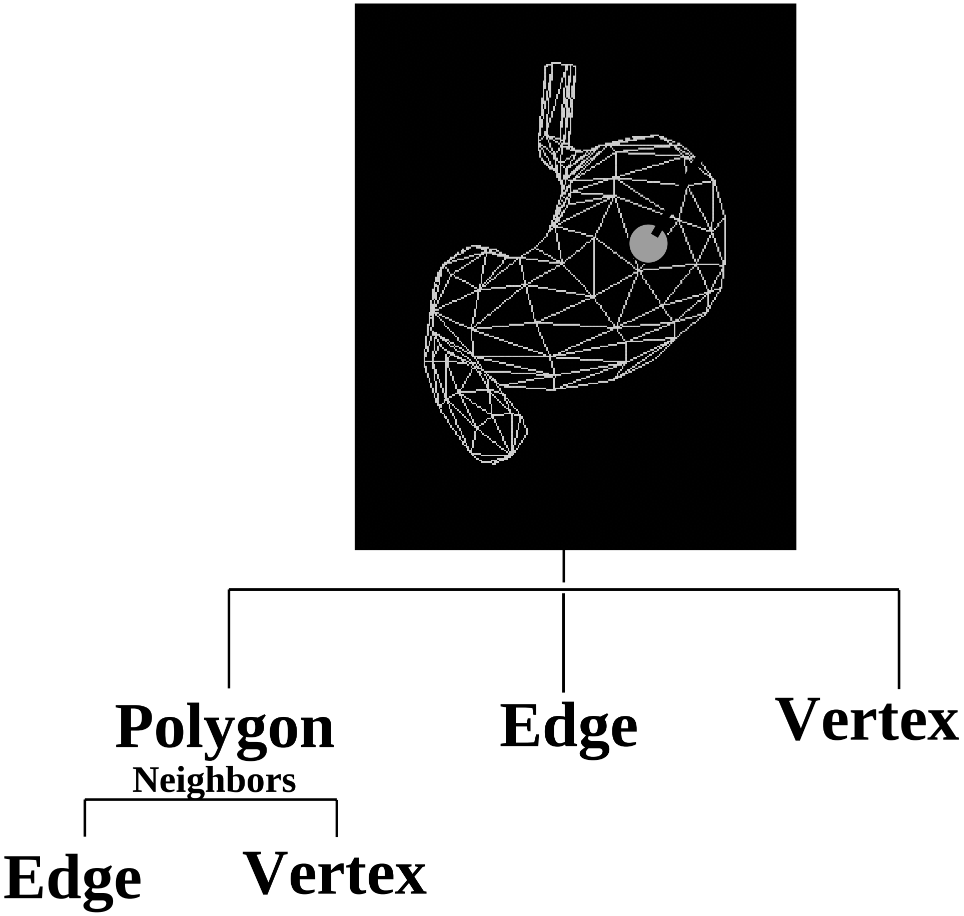
How to check collisions faster?

(Ref: "Graphics Gems, I-Collide, V-Collide,V-Clip")

1) Bounding-boxes



2) Hierarchical Database for Organ Geometry



Polygon

Neighbors

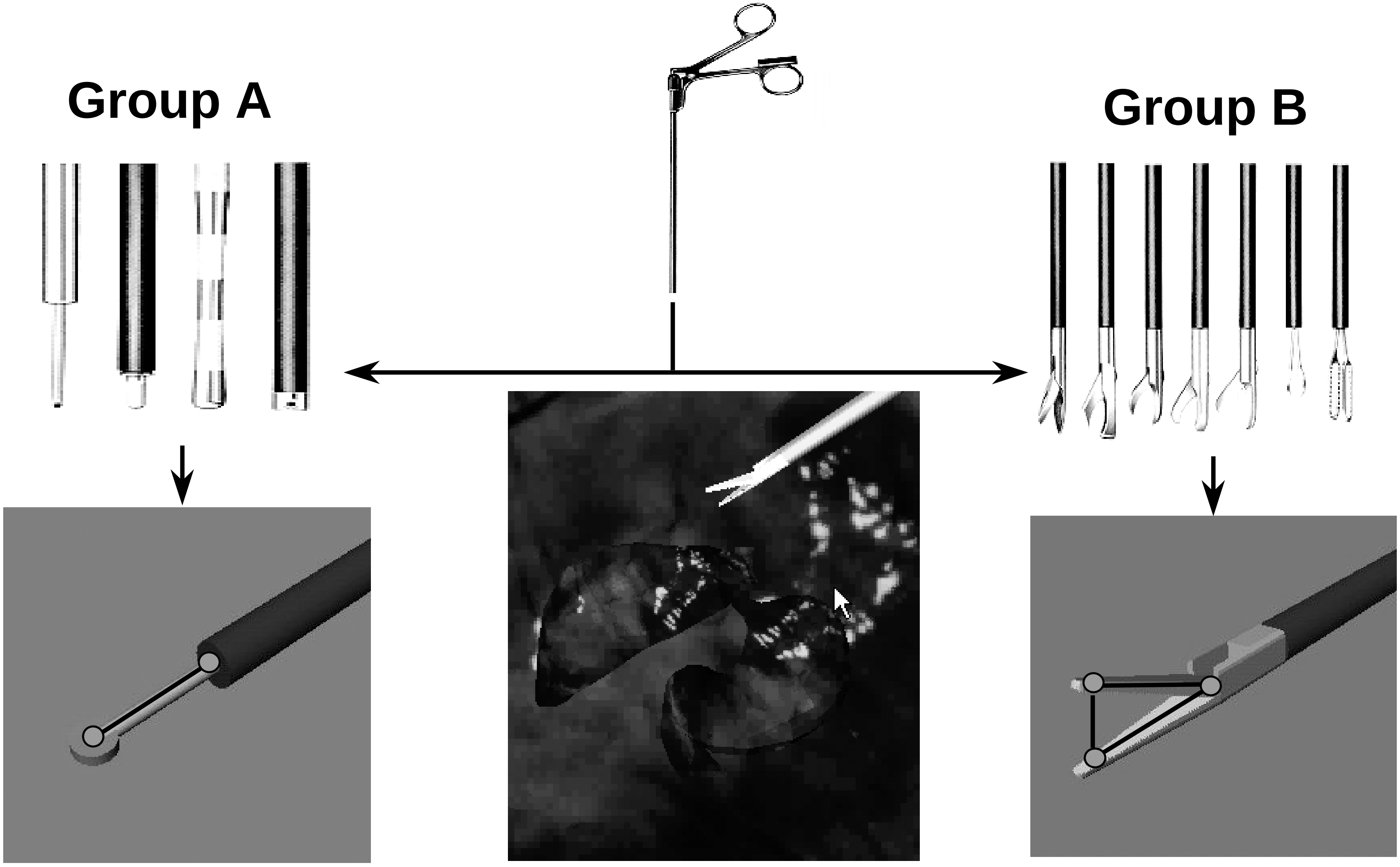
Edge

Vertex

Edge

Vertex

Computational Models of Laparoscopic Instruments



Group A

Group B

B) Physically-based modeling for simulating soft tissue behavior

- Desired properties of deformable models

- Modeling of deformable objects
  1) particle-based
  2) FEM-based

- Implementing constraints

- Problems with particle-based techniques

- Problems with FEM techniques

Desired properties of force-reflecting deformable models

- reflect stable forces
- display smooth deformations
- handle various boundary conditions and constraints
- display “physically-based” behavior in real-time

Modeling of Deformable Objects

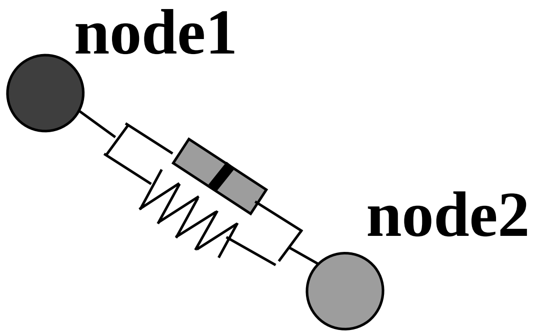
see my web-site for the details

Particle-based :

$$F = ma$$

- F_{spring}
- $F_{damping}$
- $F_{gravity}$

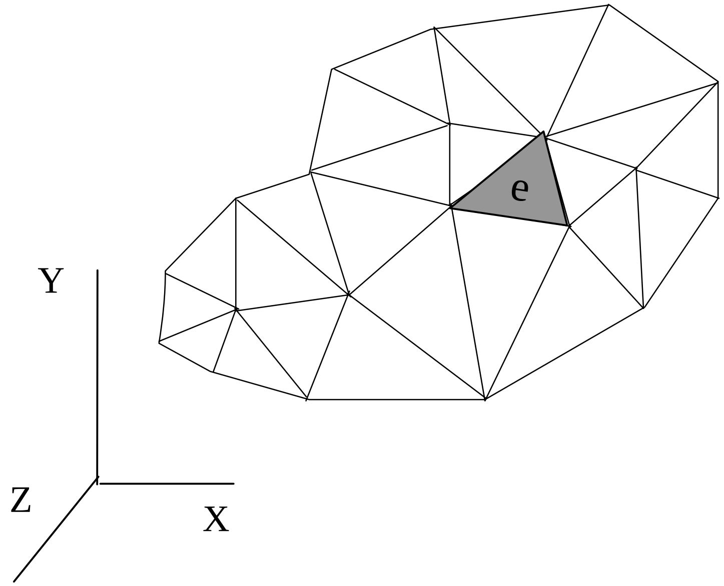
$$a(t + \Delta t) = F/m$$
$$v(t + \Delta t) = v(t) + \Delta t\, a(t + \Delta t)$$
$$p(t + \Delta t) = p(t) + \Delta t\, v(t + \Delta t)$$



FEM-based :

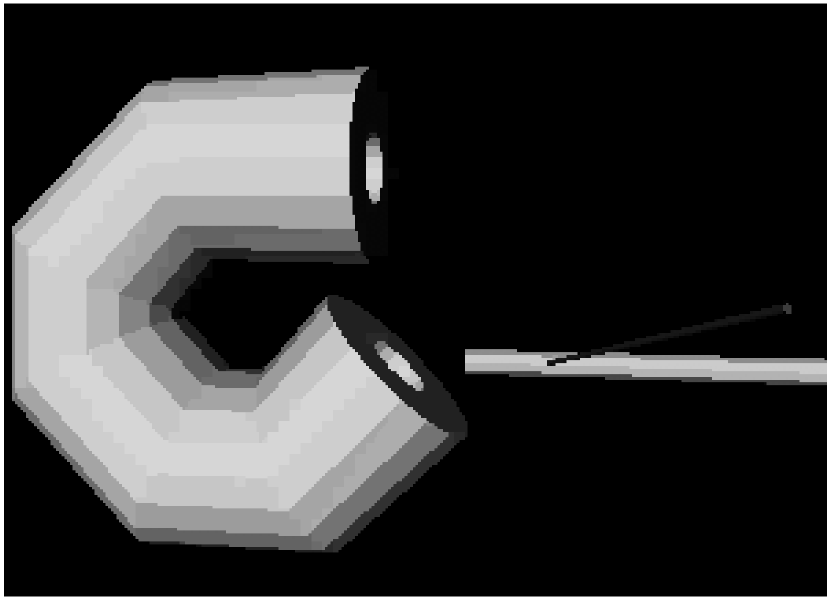
$F = KU$ (static analysis)

$F = M\ddot{U} + C\dot{U} + KU$ (dynamic analysis)



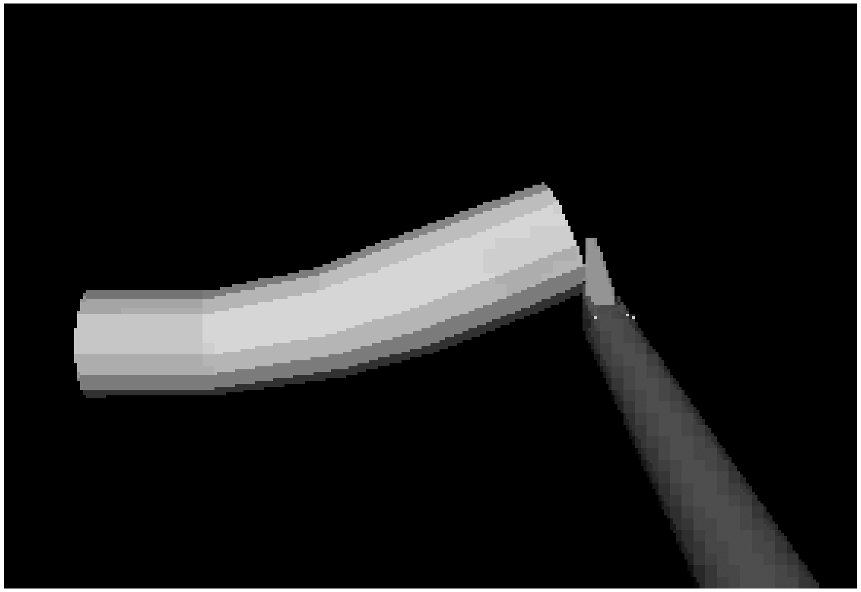
Comparison

Particle-based



easy to implement, flexible

FEM-based



comprehensive

Constraints

see my web-site for the details

Examples:

- a node is fixed in 3D space
- a node is constrained to stay on a path
- curvature constraint
- constant volume

Implementation:

1) Particle-based models (Ref: Witkin/Baraff, SIGGRAPH Notes)
    a) Penalty
    b) Lagrange multipliers
2) FEM

Problems with Particle-Based Techniques

A) Adding damping to stabilize oscillations

B) Adding constraints

C) Too many elements

→ stiffer system → $\Delta t \downarrow$ → # of iterations ↑

adaptive step size?

D) Too few elements → difficult to preserve volume

E) Non-homogeneous distribution of elements → finer adjustment of spring and damper coefficients

Problems with FEM Techniques

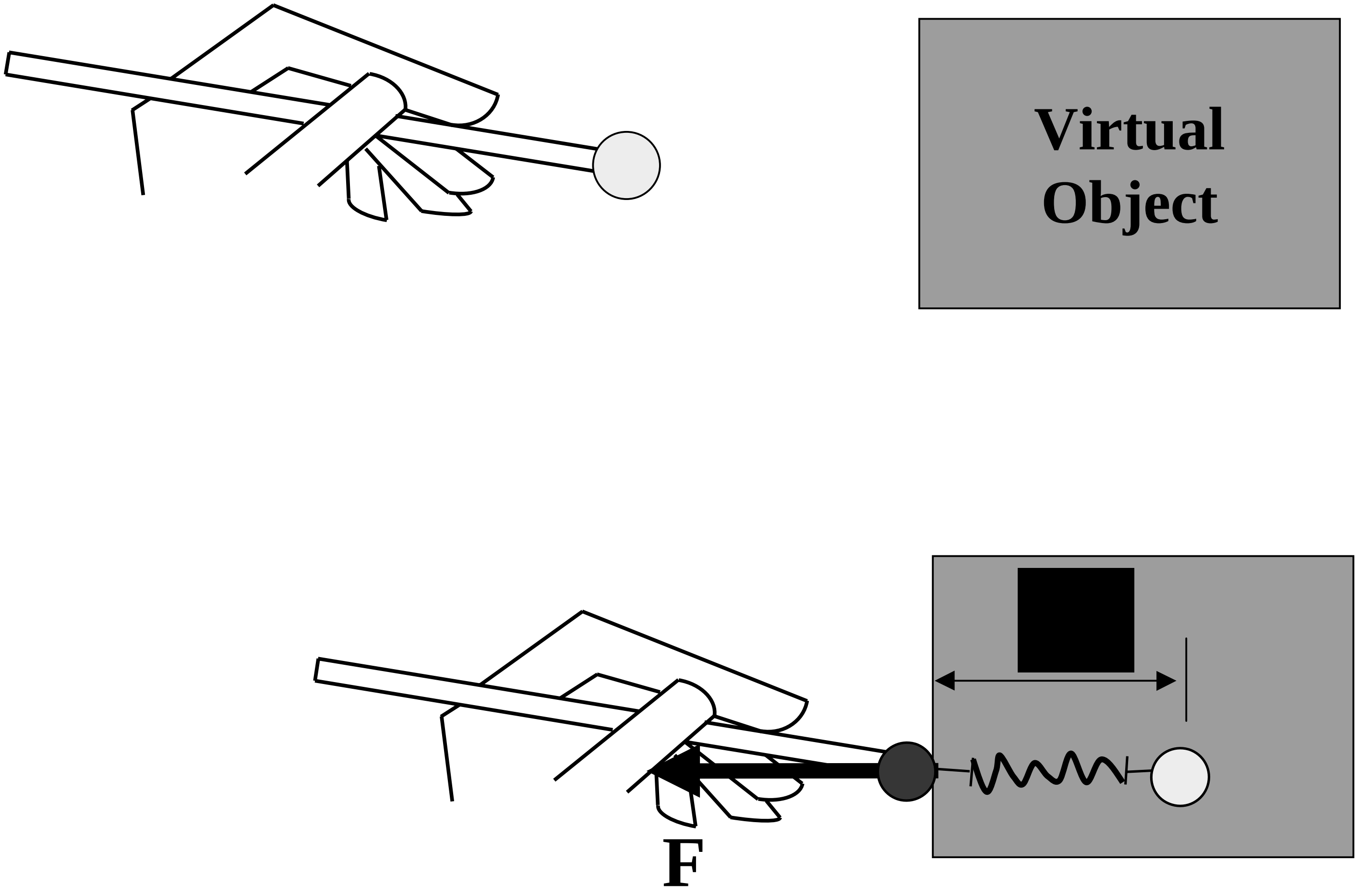
		requires	
A)	Change in topology	⇨	Re-meshing
B)	Dynamic analysis	⇨	Simplifications in the model
C)	Matrix inversion	⇨	Pre-computation
D)	Memory allocation	⇨	Simplifications in the geometry

C) Haptic Rendering of Deformable Objects

- Principles of haptic rendering
- Key components of a haptic rendering algorithm
- Computational Architecture

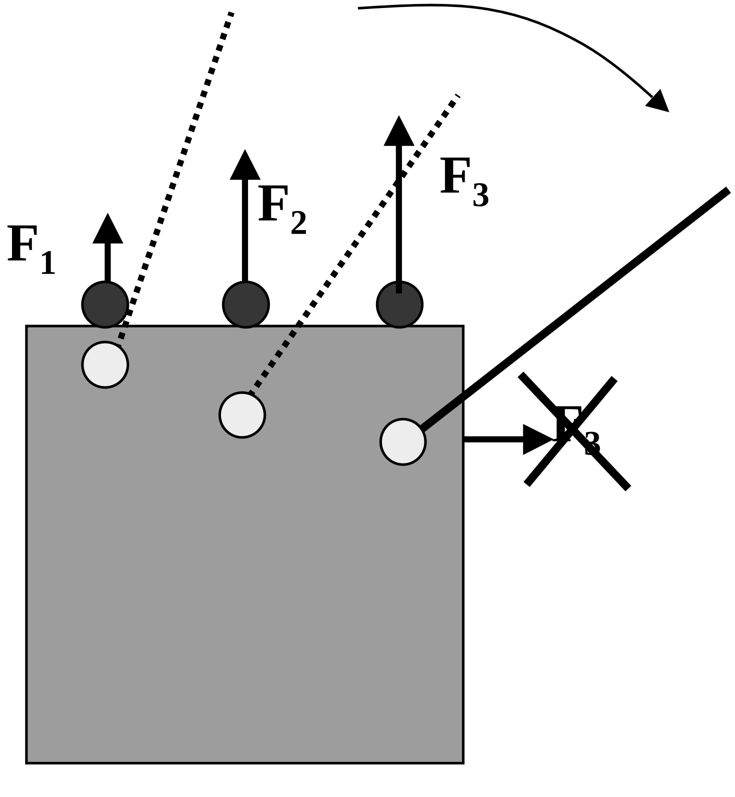
Principles of Haptic Rendering

see my web-site for the details



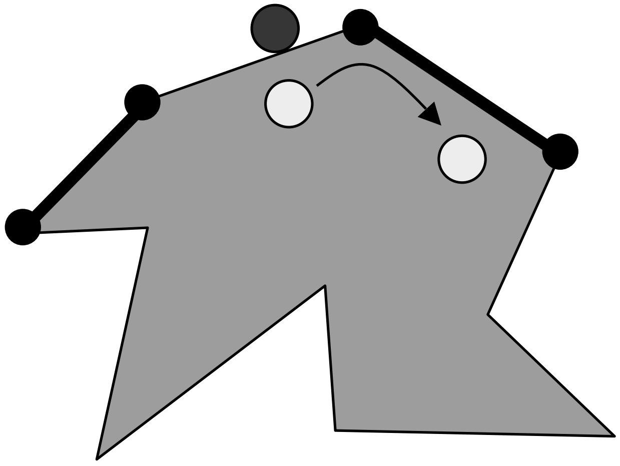
$$F = k\,\Delta x$$

Key Components of a Haptic Rendering Algorithm

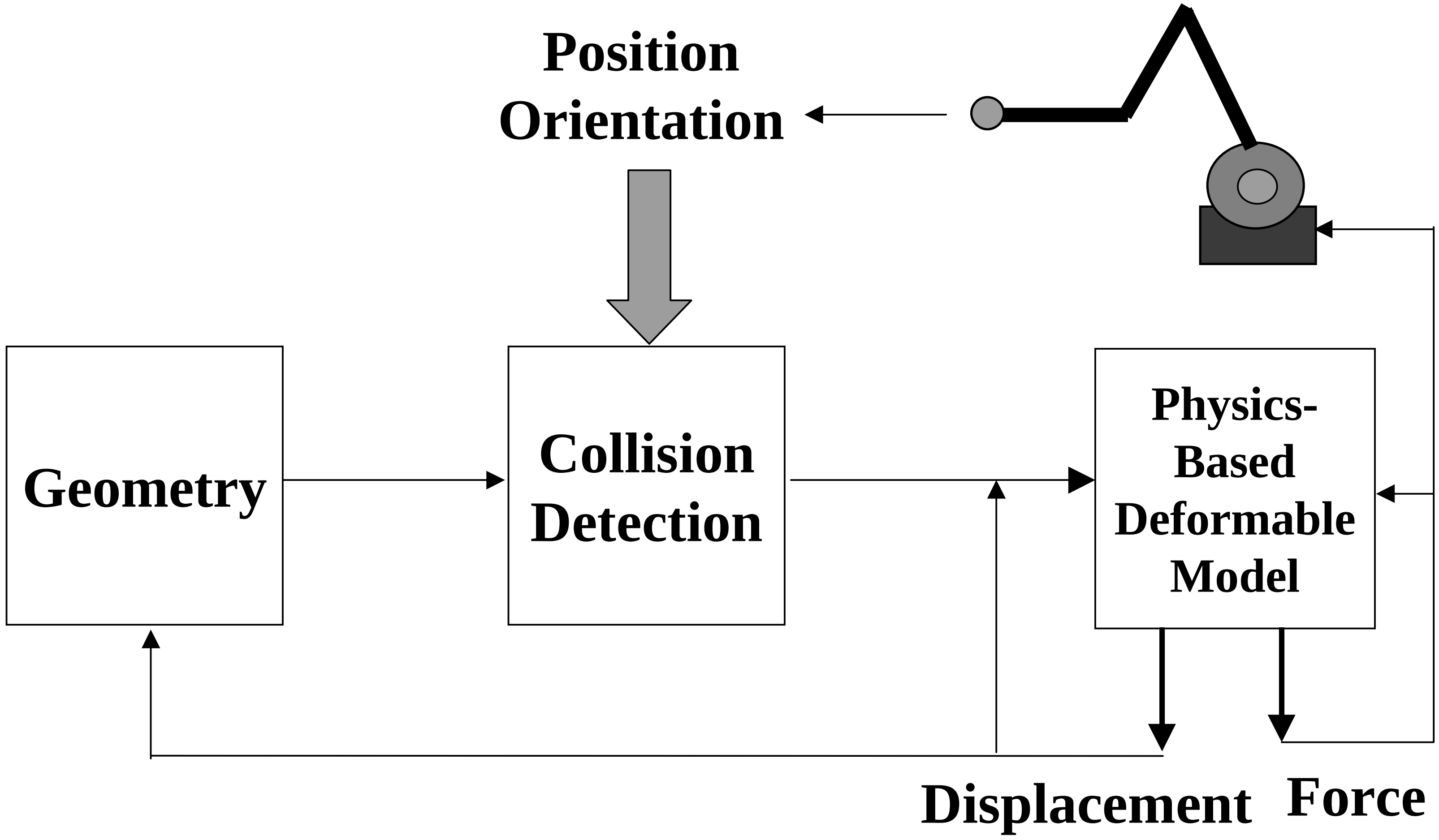


1) Contact history

2) Local coherence



Computational Architecture

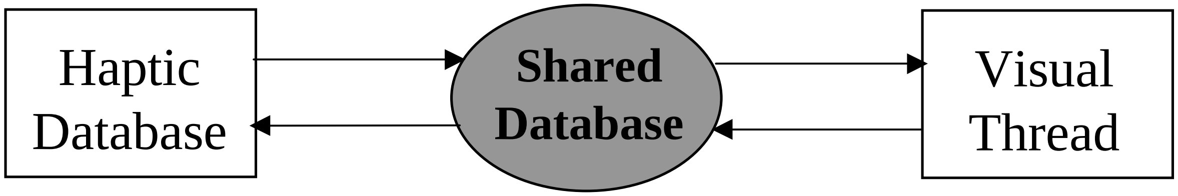


D) Software and Hardware Integration: tips and tricks

- **Programming tips to speed up your computations**
- **Modeling tips to speed up your computations**
- **Simulation set-up**

Programming tips to speed up your computations

- Synchronize your haptic and graphic loops through a shared database

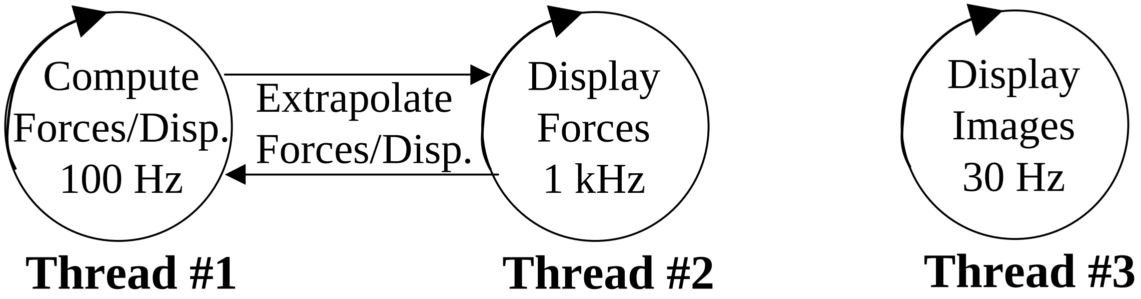


Haptic Database

Shared Database

Visual Thread

- Construct a multi-layered computing structure



Compute Forces/Disp. 100 Hz

Extrapolate Forces/Disp.

Display Forces 1 kHz

Display Images 30 Hz

Thread #1

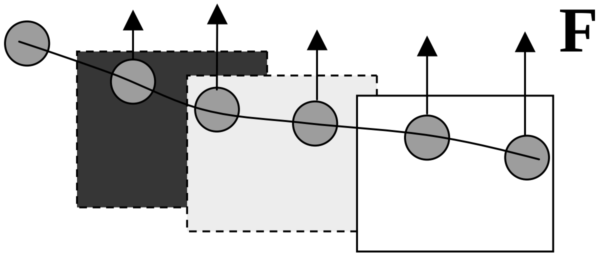
Thread #2

Thread #3

- Construct a hierarchical data structure
- Update your geometric coordinates less frequently

Δt_{haptic} = 0.001 sec (display forces)

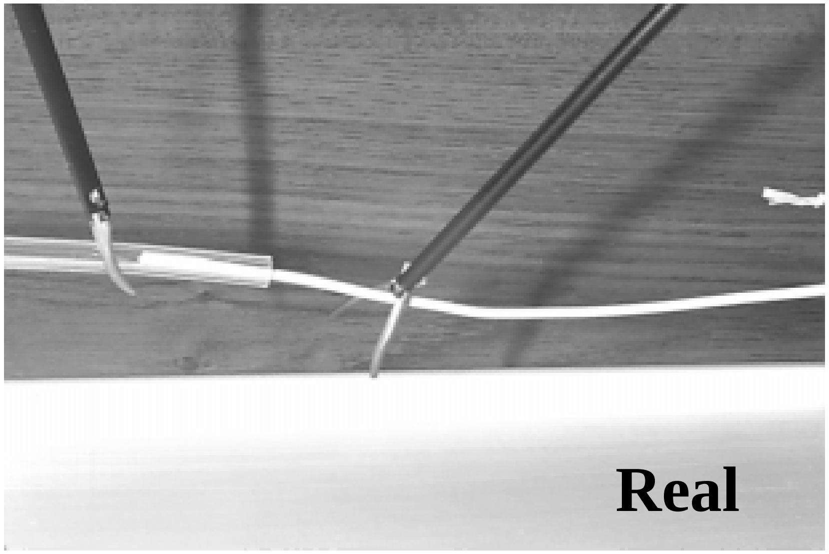
$\Delta t_{\text{iteration}}$= 0.01 sec (update coordinates)

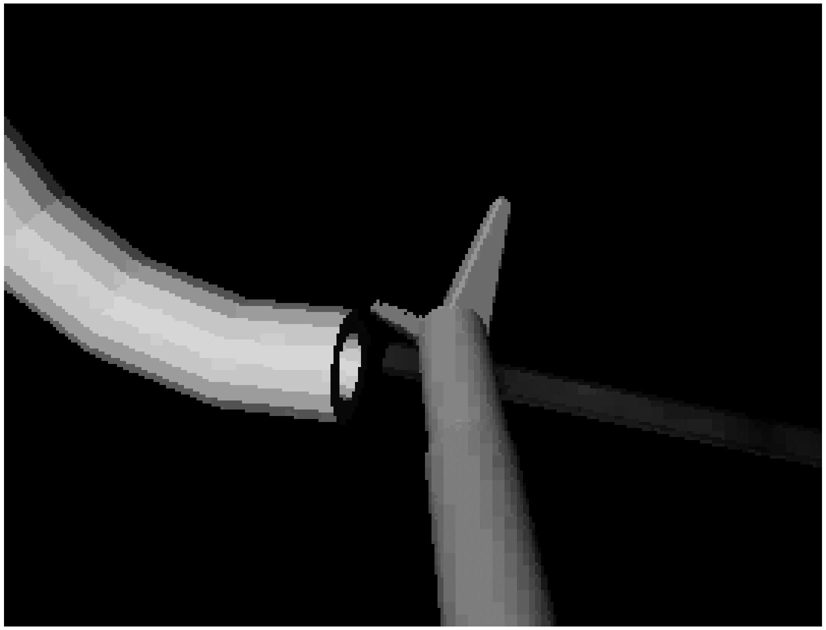


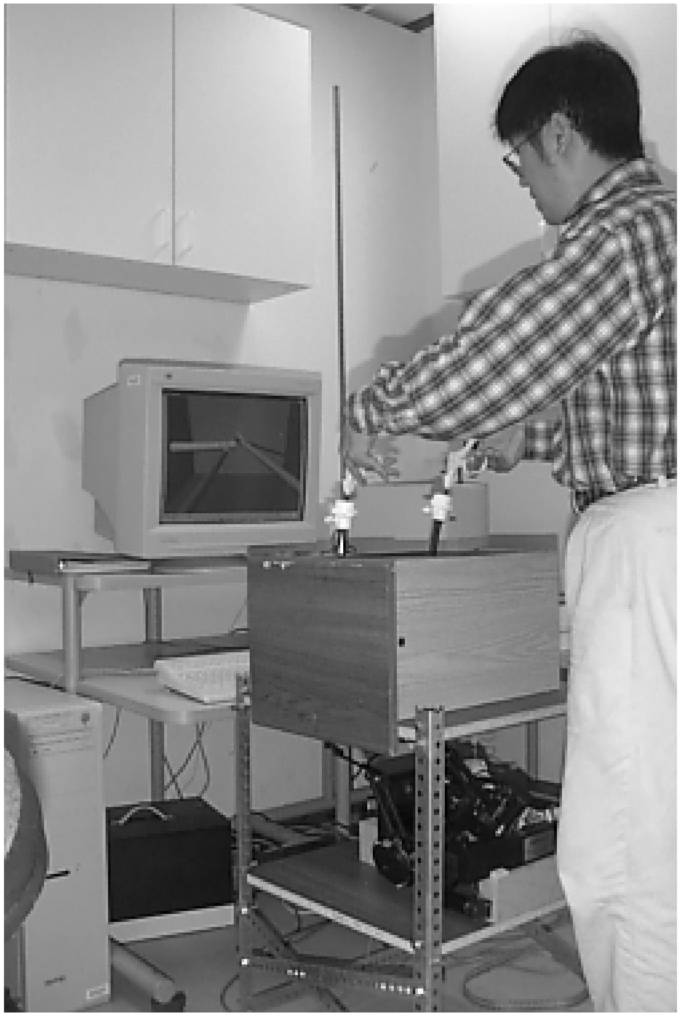
Modeling tips to speed up your computations

- deform your objects locally
- take advantage of single point interactions
- condense your matrices in FEM
- transform your coordinates to modal coordinates (for dynamic analysis)
- pre-compute (matrices, unit displacements/force)
- loosely couple your force and deformation model
- adaptive meshing
- take advantage of human perceptual limitations

Simulation of Catheter Insertion







Simulation Set-Up

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Ela Ben-Ur
Jim Westwood

tutorial notes will be available online:

http://eis.jpl.nasa.gov/~basdogan