Deformable Distance Fields for Simulation of Non-Penetrating Flexible Bodies

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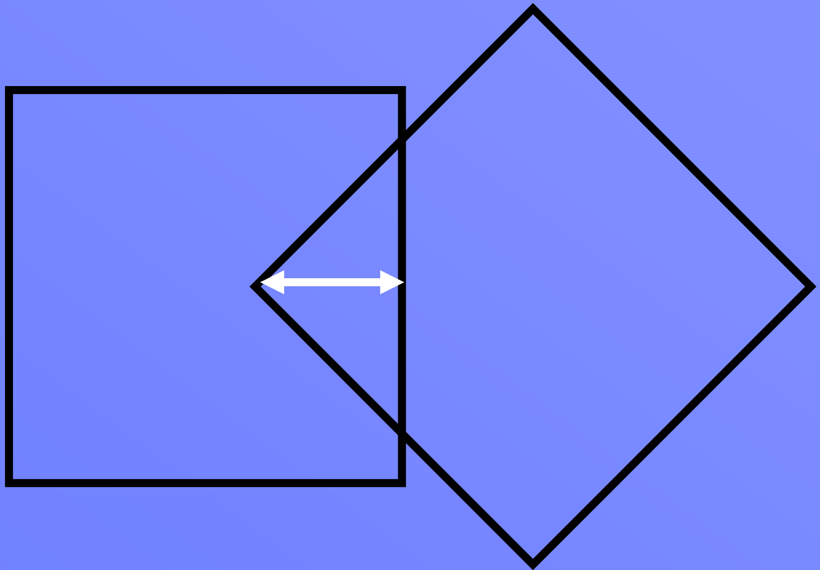
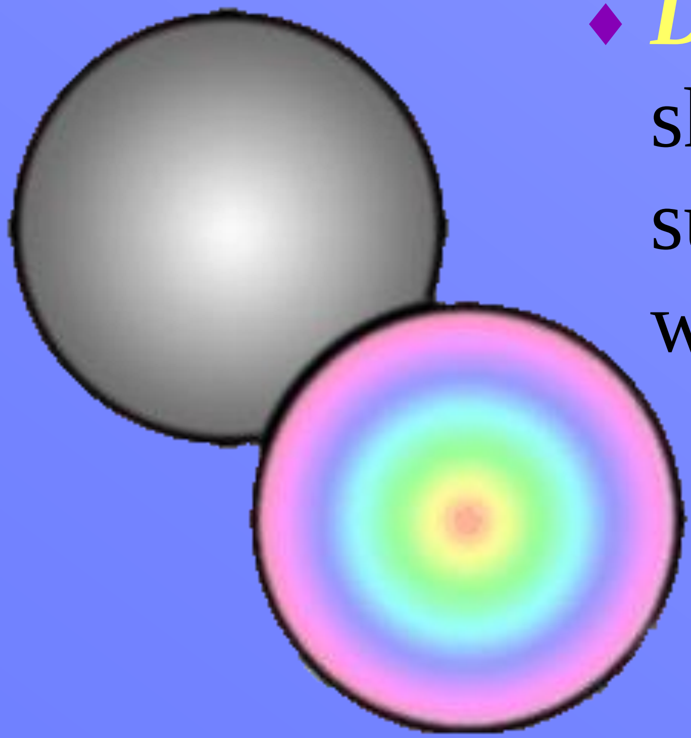
DEFINITIONS

- ***Penetration Depth*** [for rigid objects] - minimum translational distance required to separate two intersecting objects



DEFINITIONS



- ***Distance Field*** - shortest distance to the surface for any point within a 3D object
  - Can be represented with pseudocolors, or a single color gradient

MOTIVATION

- **Robotics**
  - **Virtual prototyping**
  - **Surgical planning, design of elastic tubes in medical devices**
- **Animation**
  - **Sliding contact, deforming elastic bodies**

MAIN CONTRIBUTION

A novel penetration depth estimation algorithm based on the ***deformation*** and ***partial update*** of ***distance fields*** computed using the ***fast marching level set method***

RELATED WORK

- Fast Marching Level Set Method
- Penetration Depth
- Distance Fields

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RELATED WORK

- Fast Marching Level Set Method
  - Osher and Sethian [1988], Sethian [1999]
  - Kimmel et al. [1995]
- Penetration Depth
- Distance Fields

RELATED WORK

- **Fast Marching Level Set Method**
- **Penetration Depth**
- **Distance Fields**

RELATED WORK

- Fast Marching Level Set Method
- Penetration Depth
  - Buckley and Leifer [1985], Cameron+Culley [1986]
  - Dobkin [1993]
  - Agarwal et al. [2000]
  - Kim et al [2002, 2003]
  - Zhang & Manocha [2006, 2007]
- Distance Fields

RELATED WORK

- **Fast Marching Level Set Method**
- **Penetration Depth**
- **Distance Fields**

RELATED WORK

- Fast Marching Level Set Method
- Penetration Depth
- Distance Fields
  - Hoff et al. [1999,2001]
  - Frisken [2000]
  - Hirota, Fisher, Lin [2000]
  - Sud et al. [2006]

OUTLINE

- Introduction
- **Simulator Overview**
- Computation of Distance Field
- Update of Distance Field
- Penetration Depth Estimation
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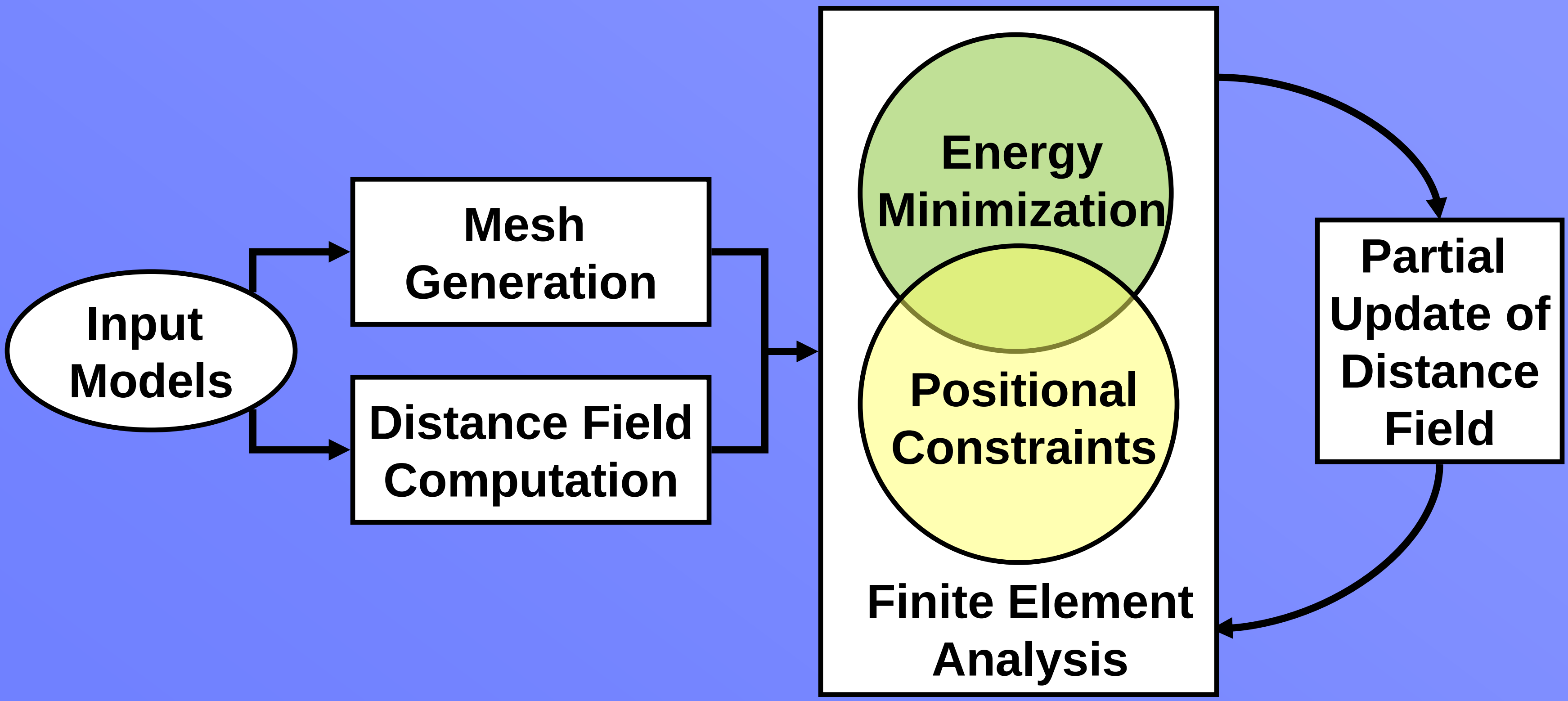
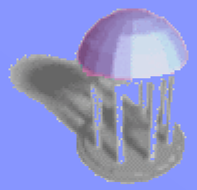
SIMULATOR OVERVIEW



FEM ATTRIBUTES



- Tetrahedral elements
- Linear shape functions
- Deformation function

  $p \rightarrow \phi(p)$
- Finite Element Analysis
  - static analysis
  - constrained minimization using constitutive law

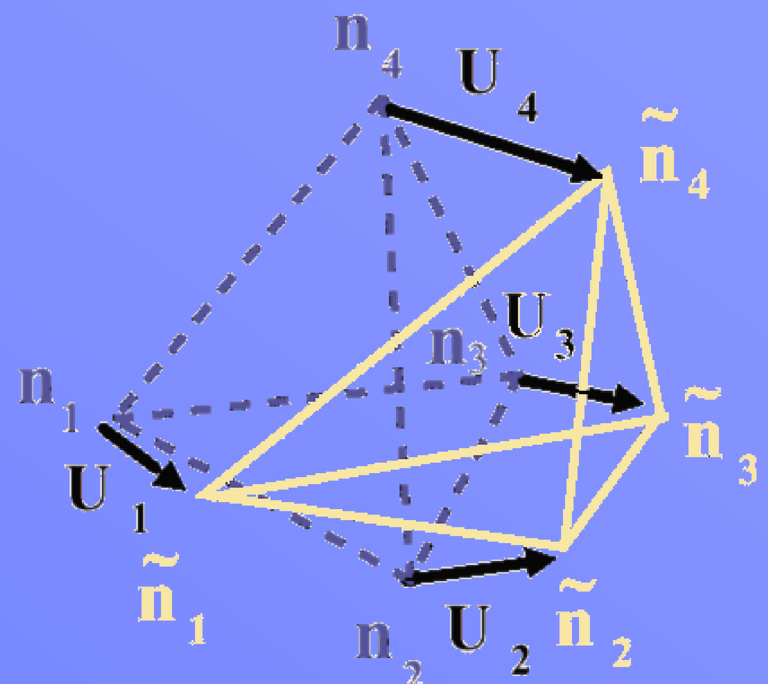


Figure 1: ϕ(p) maps four nodes of a tetrahedral element to new positions

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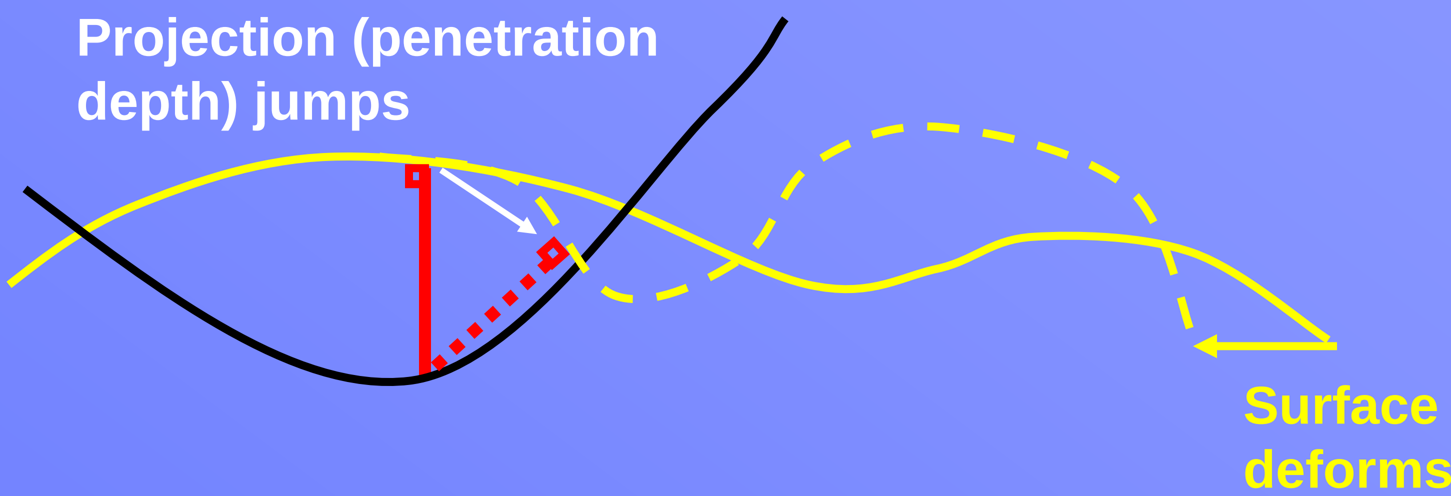
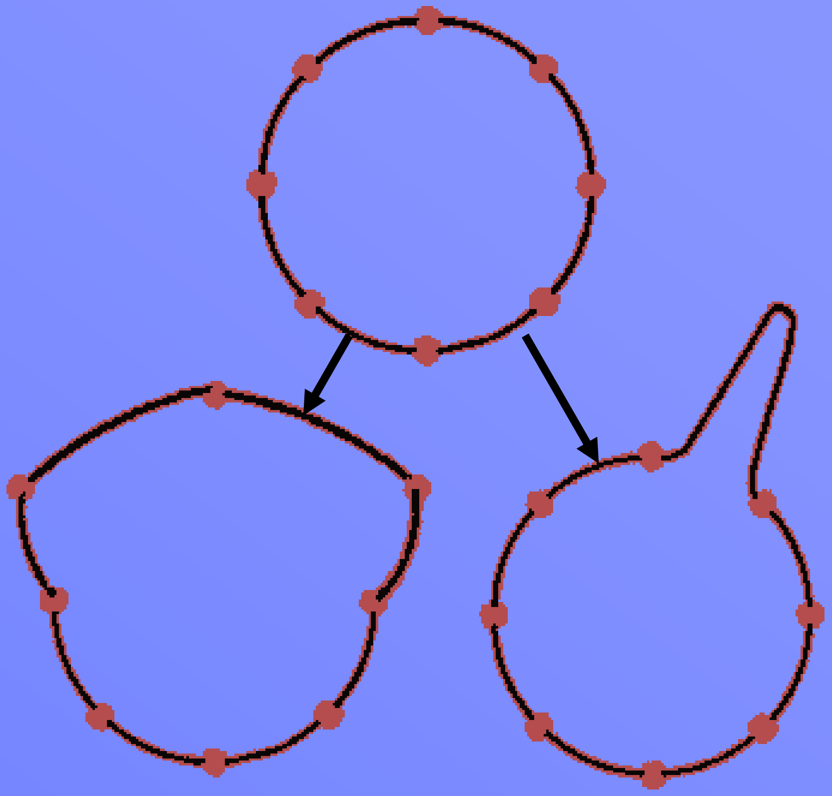
TRADITIONAL METHODS



- Traditional projection search methods provide a ***discontinuous*** solution

MARKER METHODS

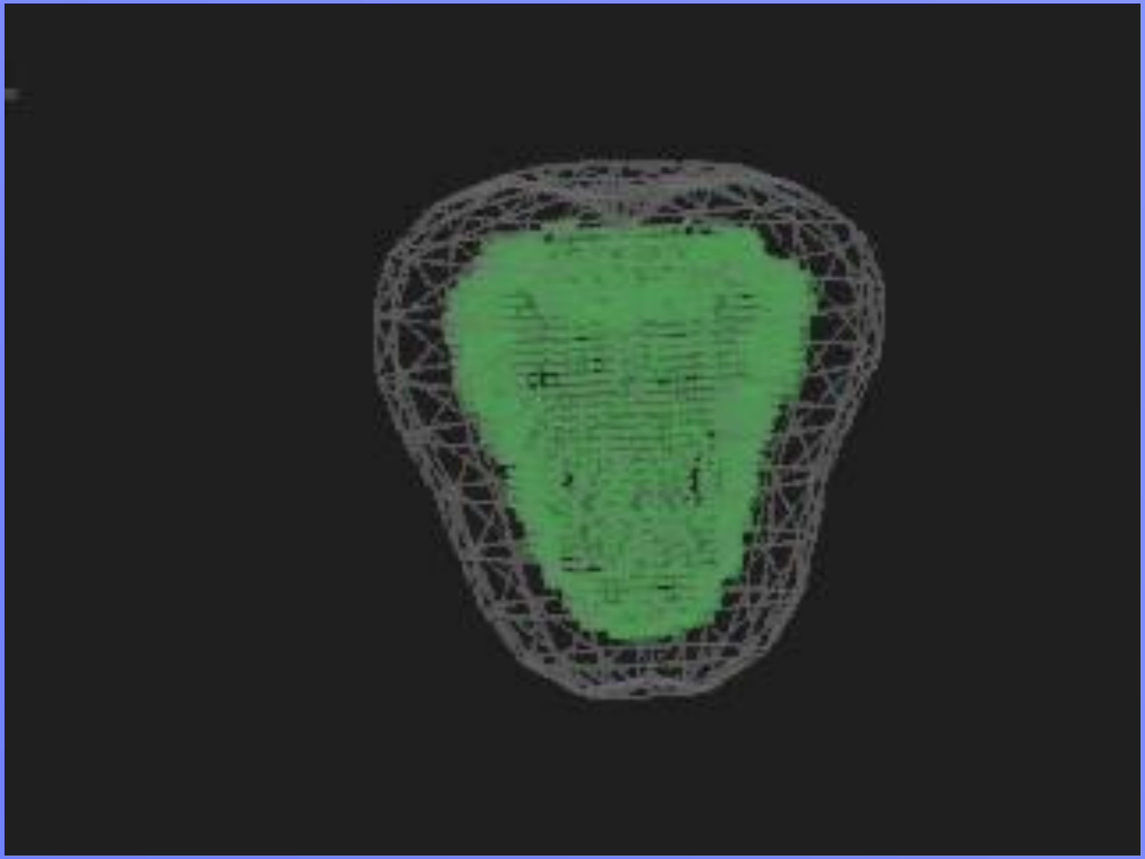
- Markers can get stretched out
- Sharp cusps are *not* preserved



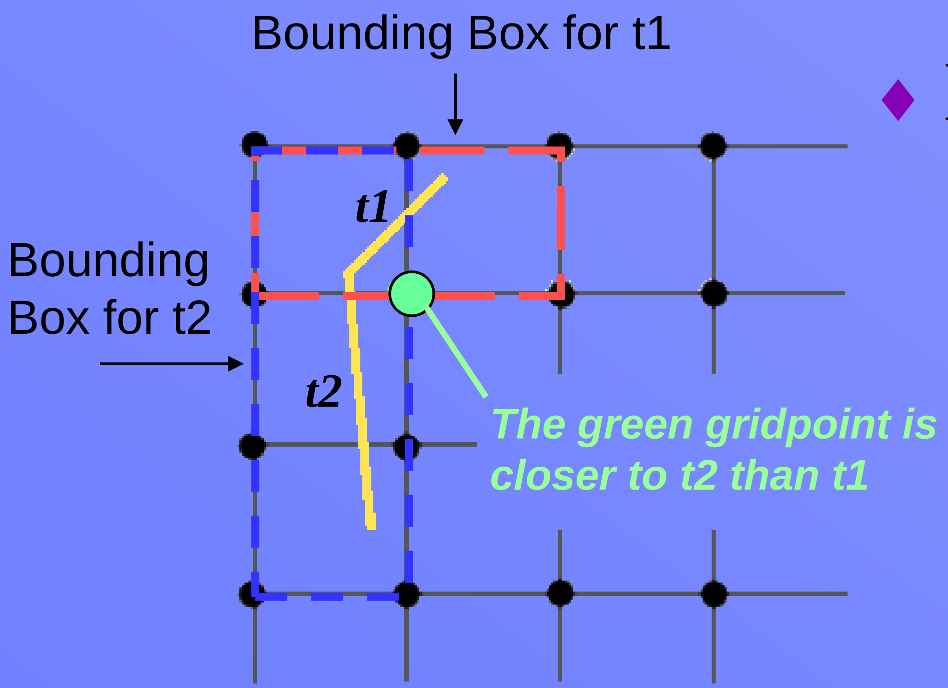
LEVEL SET METHODS

- Provides a *continuous* solution
- Avoids reparameterization due to control markers spreading apart
- Can handle sharp corners and cusps
- Requires no specialized hardware

EXAMPLE



COMPUTING THE FIELD

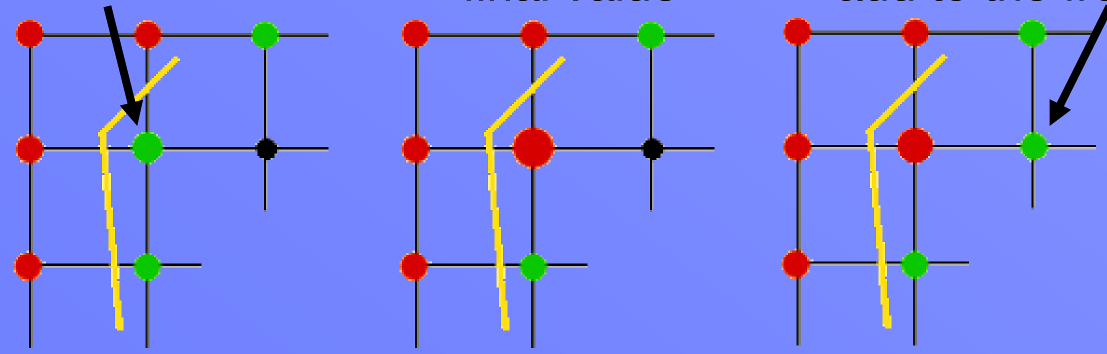


- Initialize
  - walk through each triangle, computing exact distance for gridpoints within its AABB
  - if two AABB's overlap, the smaller value is used

DISTANCE FIELD

- Marching
  - Extract minimum valued gridpoint on the front, and recompute its value
  - Update other neighbors *on the front*
  - Add any remaining neighbors to the front

1. Select minimum point on front
2. Assign a final value
3. Update neighbors, add to the front



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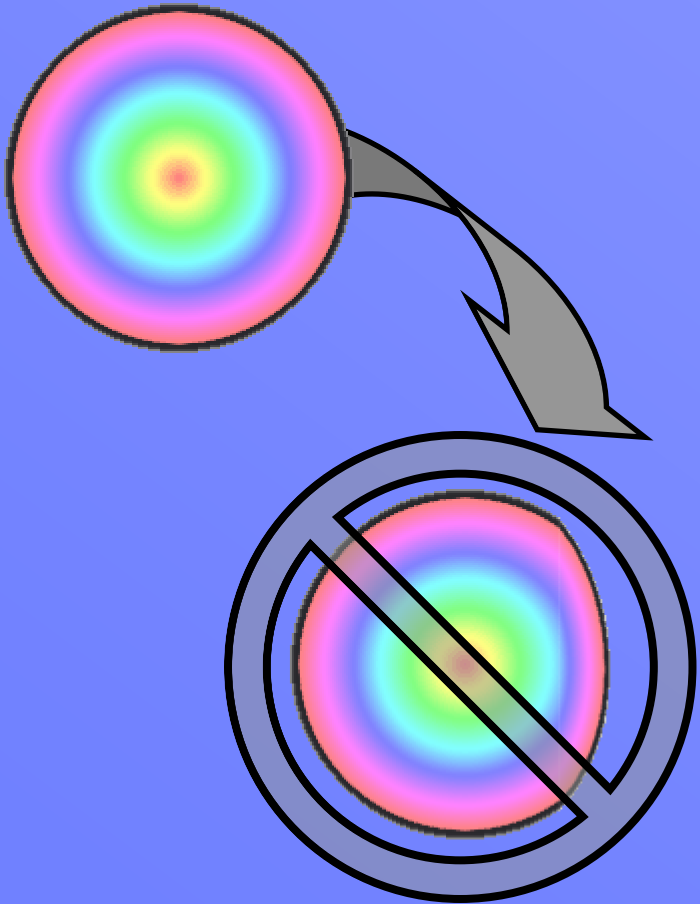
WHY UPDATE?



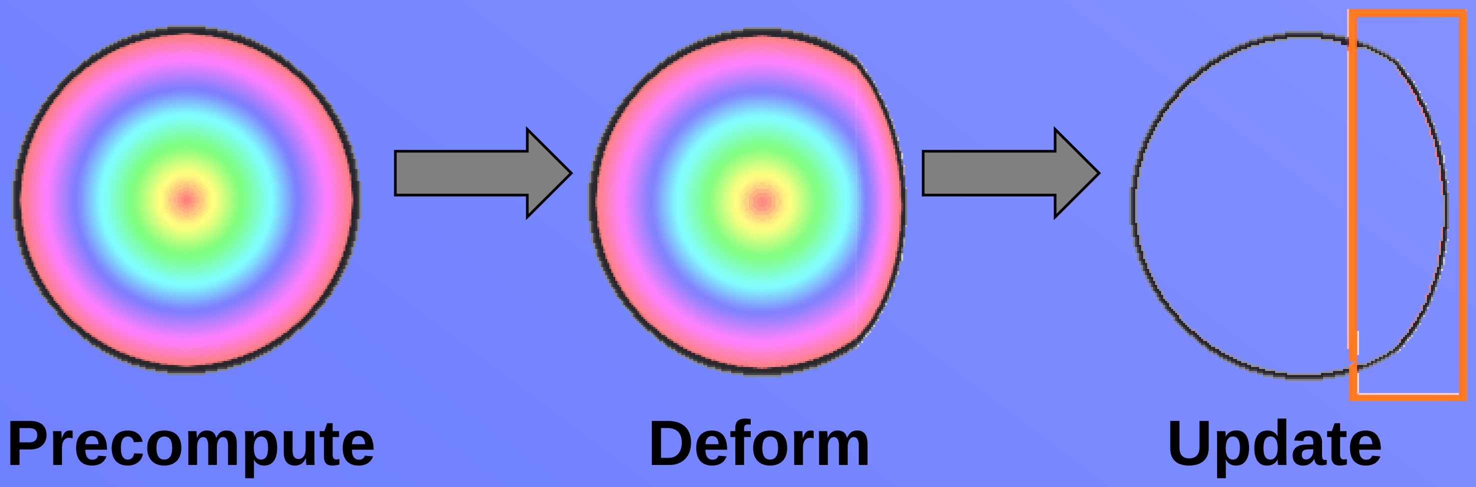
- Penetration depth computed based on pre-assigned distance values
- After deformation, affected elements may have incorrect distance values

COLLISION DETECTION

- Need to identify region of change
  - Hierarchical Sweep and Prune when NURBS representations are available
  - Lazy evaluation of possible intersection using Bounding Volume Hierarchies (AABB)

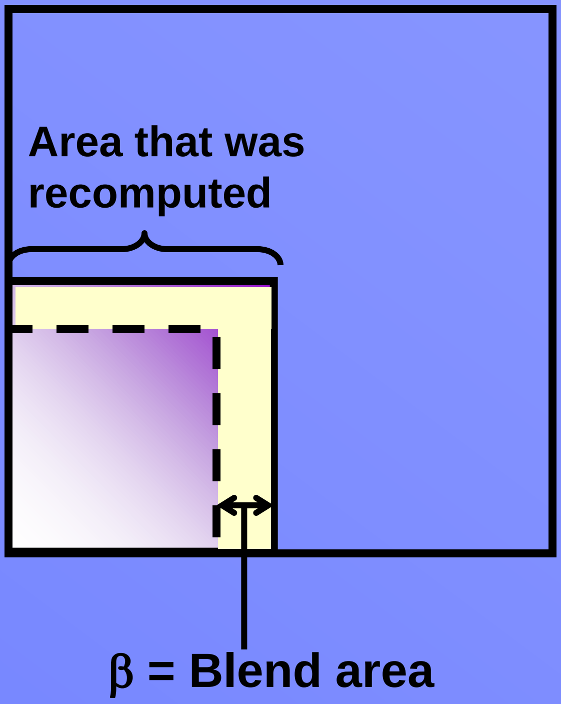
DISTANCE FIELD UPDATE

- Bounding box is expanded to insure continuity
- Within this expanded bounding box, the same algorithm is applied



DISTANCE FIELD UPDATE

- New distance values are used, but are blended with the old at the edges
- Blend region size is a user parameter



DISTANCE FIELD UPDATE

- Values are blended in each dimension successively

Blend area, β gridpoints

Old field, A_x	●	●	●		●
	1	**2**	**3**	**…**	**β**
New field, B_x	●	●	●		●
Resulting field, C_x	**$(1-1/\beta)a_1+$ $(1/\beta)b_1$**	**$(1-2/\beta)a_2+$ $(2/\beta)b_2$**	**$(1-3/\beta)a_3+$ $(3/\beta)b_3$**		**$(1-((\beta -1)/\beta))a_B+$ $((\beta -1)/ \beta)b_B$**

DISTANCE FIELD UPDATE

- C1 continuity is verified by checking first derivatives
- For discontinuous cases, there are two options:
  1. Expand bounding box of region of change and recompute
  2. Recompute entire field
- *In practice, the two fields always provided a continuous solution*

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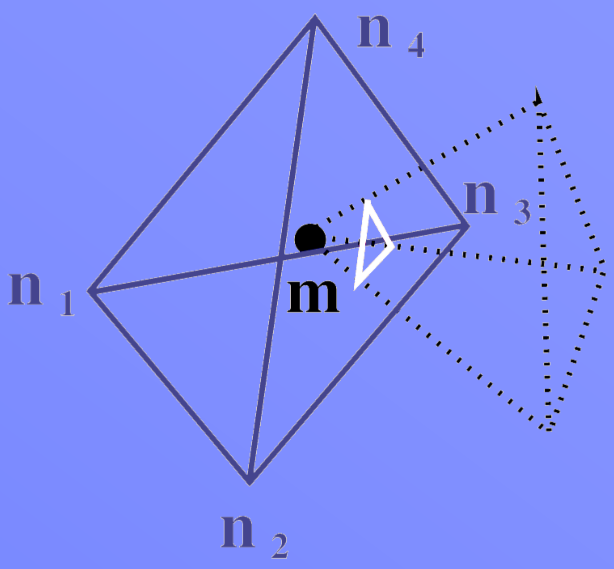
PENETRATION DEPTH

- Linear interpolation provides the penetration depth:

$$m = u_1 n_1 + u_2 n_2 + u_3 n_3$$
$$+(1 - u_1 - u_2 - u_3) n_4$$



The distance from m to the white triangle is the penetration depth

FRAMEWORK

- This work is a general algorithm which can be used in other simulation frameworks, not just FEM
  - FDM (Finite Difference Method)
  - Spring-Mass Network

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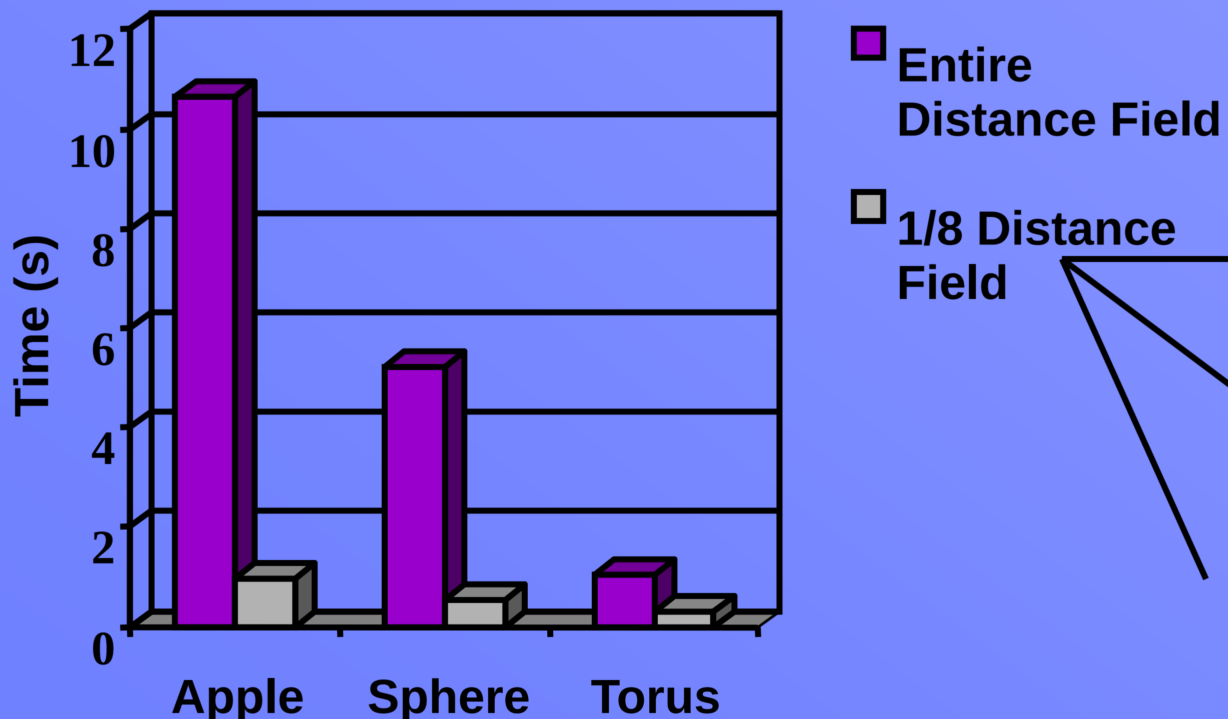
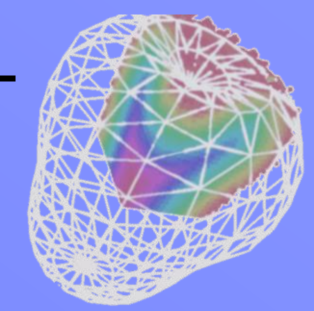
RESULTS

- 50 x 50 x 50 grid resolution





Example: 1/8 of the apple's distance field

RESULTS - MPEGS

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SUMMARY

Fast, adaptive method to estimate penetration depth for deformable objects

- Versatile input format
- Handles self collisions and inter-object collisions in an uniform manner
- Can trade off speed for accuracy

RECENT WORK

- GPU to compute 3D distance fields and update it on the fly. See Sud et al. [2006]

http://gamma.cs.unc.edu/gvd

FUTURE WORK

- Quantify effect of grid resolution on accuracy of simulation
- Explore continuity issues if adaptive grids are used to compute the distance fields

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