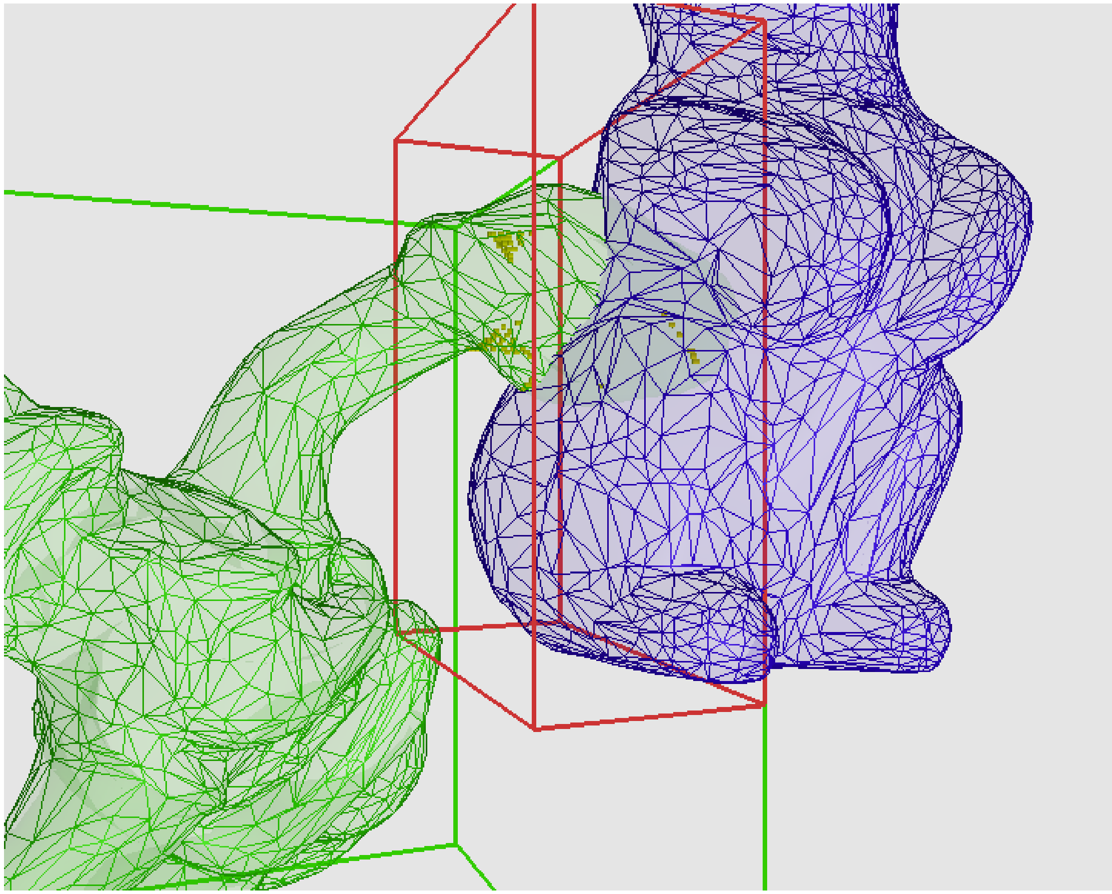
Image-Space Collision Detection



Acknowledgements

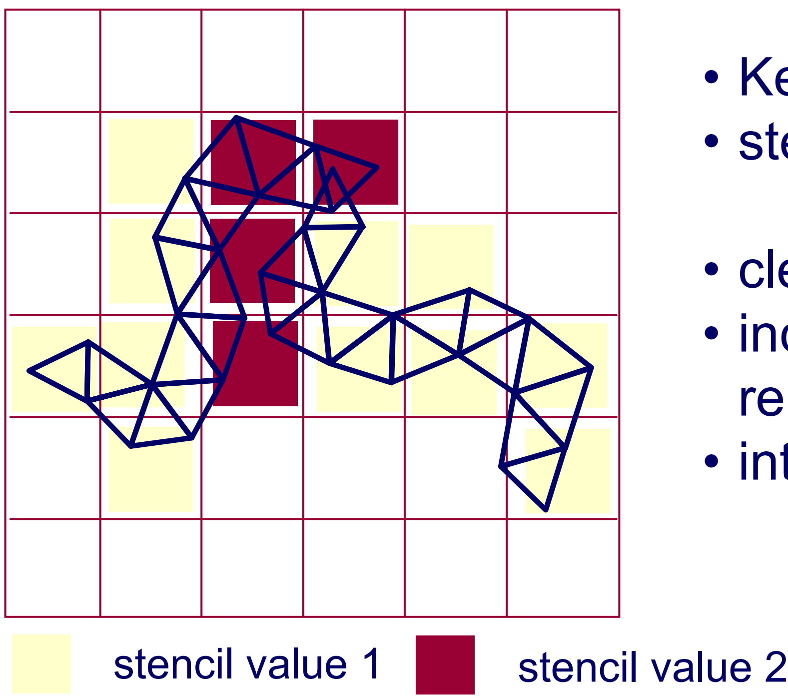
- Parts of this slide set are courtesy of Bruno Heidelberger, ETH Zurich.

Outline

- motivation
- algorithms
- performance
- application
- discussion

Graphics Hardware for 2D Collision Detection

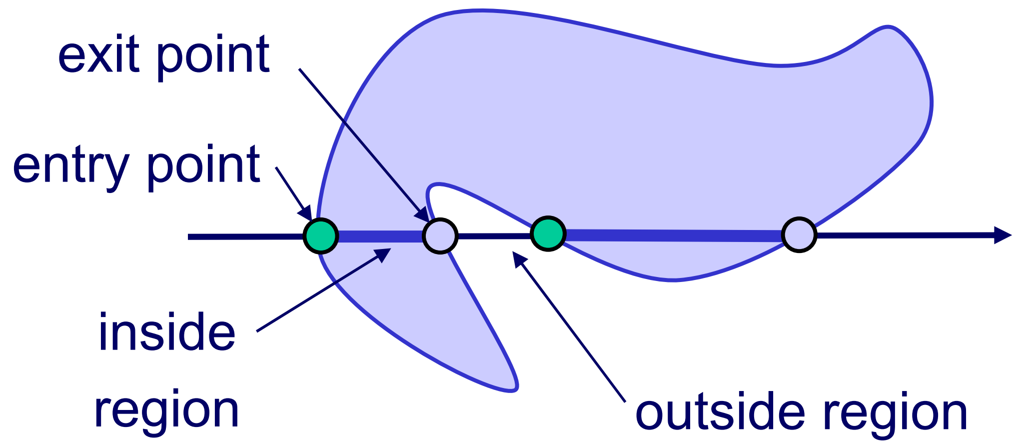
- rendering corresponds to placing all object primitives into the according cell (pixel) of a uniform rectangular 2D grid (frame buffer)
- rendering determines all pixels in a frame buffer affected by the object
- at each pixel position, information can be processed (color, depth, stencil)



- Kenneth Hoff, UNC
- stencil-buffer for collision detection

- clear stencil buffer
- increment stencil buffer for each rendered object
- intersection for stencil buffer value larger 1

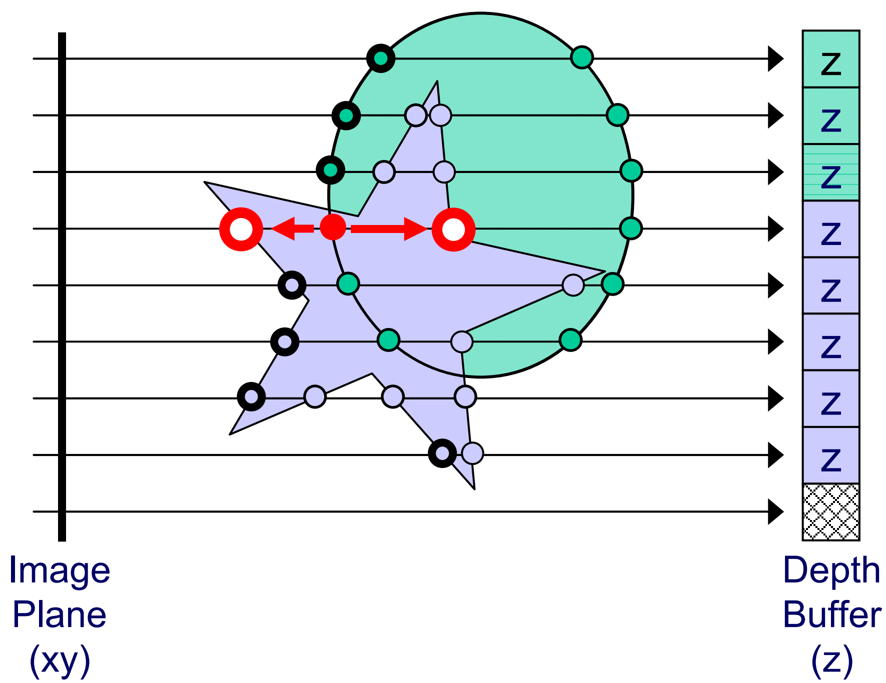
Closed Objects



- number of entry points equals the number of exit points
- in case of convex objects, one entry point and one exit point
- inside and outside are separated by entry or exit point
- entry point is at a front face
- exit point is at a back face
- front and back faces alternate

Collision Detection with Graphics Hardware

- exploit rasterization of object primitives for intersection test
- benefit from graphics hardware acceleration



Collision Detection with Graphics Hardware

Idea

- computation of entry and exit points can be accelerated with graphics hardware
- computation corresponds to rasterization of surface primitives
- all object representations that can be rendered are handled
- parallel processing on CPU and GPU

Challenges

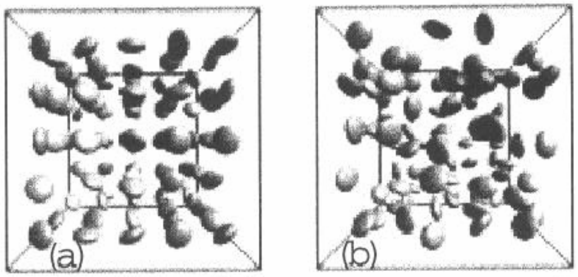
- restricted data structures and functionality

Drawbacks

- approximate computation of entry and exit points

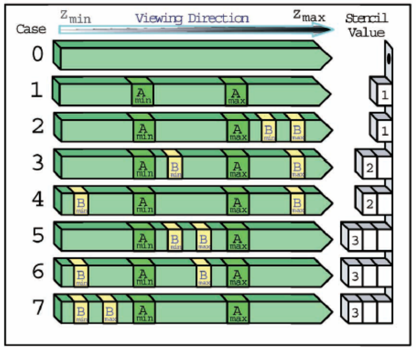
Early approaches

[Shinya, Forgue 1991]
image-space collision detection for
convex objects



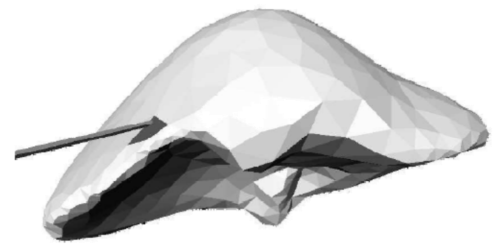
[Myszkowski, Okunev, Kunii 1995]
collision detection for *concave objects*
with limited depth complexity

[Baciu, Wong 1997]
hardware-assisted collision detection for
convex objects



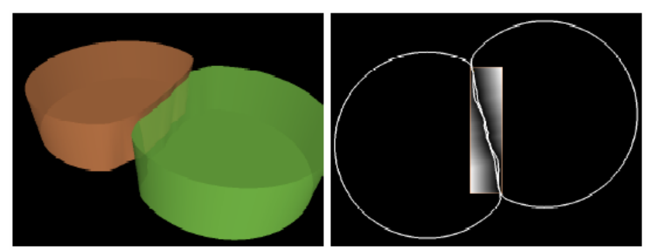
More approaches

[Lombardo, Cani, Neyret 1999]
intersection of *tool with deformable tissue*
by rendering the interior of the tool



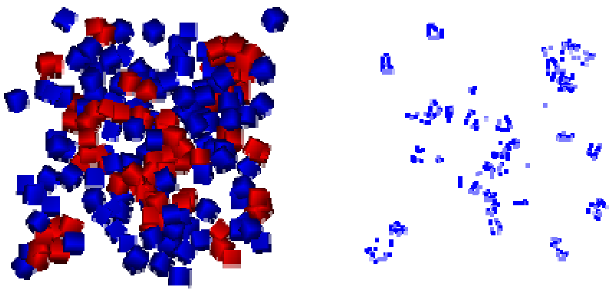
[Vassilev, Spanlang, Chrysanthou 2001]
image-space collision detection applied to
cloth simulation and *convex avatars*

[Hoff, Zaferakis, Lin, Manocha 2001]
proximity tests and penetration
depth computation, *2D*

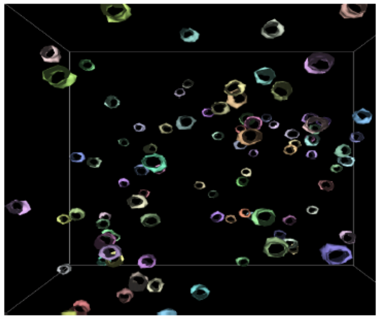


Recent approaches

[Knott, Pai 2003]
intersection of edges with surfaces



[Govindaraju, Redon, Lin, Manocha 2003]
object and sub-object pruning based on
occlusion queries



[Heidelberger, Teschner 2004]
explicit intersection volume and
self-collision detection based on LDIs

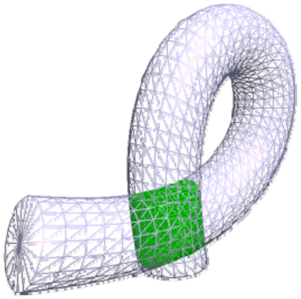


Image-Space Collision Detection [Knott, Pai 2003]

- render all query objects (e. g. edges) to depth buffer
- count the number *f* of front faces that occlude the query object
- count the number *b* of back faces that occlude the query object
- iff *f* - *b* == 0 then there is no collision

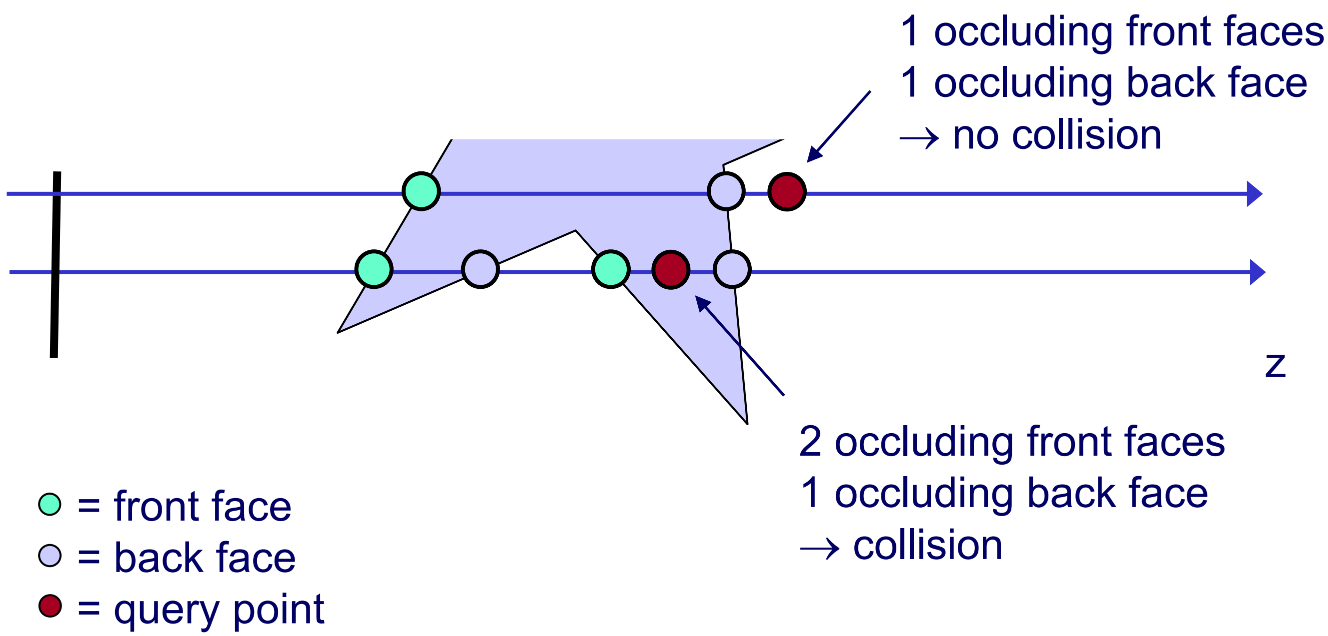


Image-Space Collision Detection

- clear depth buffer, clear stencil buffer
- render query objects to depth buffer
- disable depth update
- render front faces with stencil increment
  - if front face is closer than query object, then stencil buffer is incremented
  - depth buffer is not updated
  - result: stencil buffer represents number of occluding front faces
- render back faces with stencil decrement
  - if back face is closer than query object, then stencil buffer is decremented
  - depth buffer is not updated
  - result: stencil buffer represents difference of occluding front and back faces
- stencil buffer not equal to zero $\rightarrow$ collision

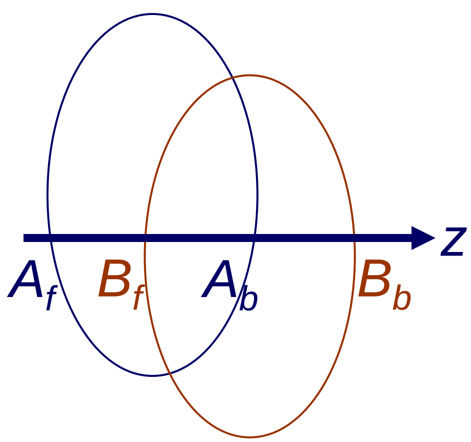
Image-Space Collision Detection

- works for objects with closed surface
- works for n-body environments
- works for query objects that do not overlap in image space
- numerical problems if query object is part of an object
  - offset in *z*-direction required

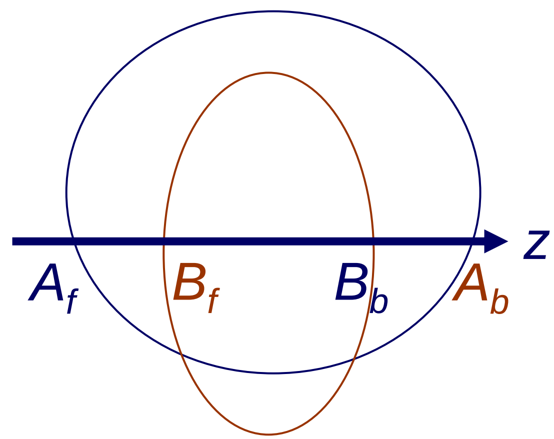
- [Video]

Image-Space Collision Detection [Baciu 2000]

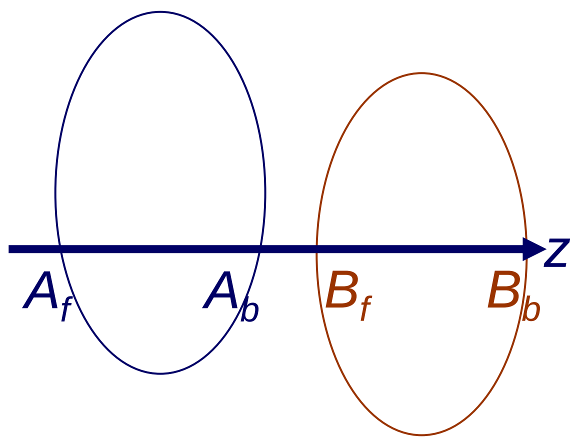
- RECODE – REndered COllision DEtection
- works with pairs of closed convex objects A and B
- one or two rendering passes for A and B
- algorithm estimates overlapping *z* intervals per pixel



collision



collision



no collision

First Rendering Pass

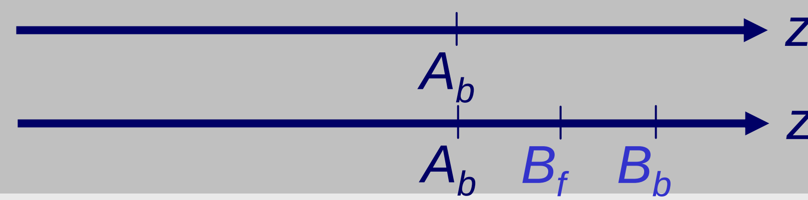
- clear depth buffer
- clear stencil buffer
- enable depth update
- render back faces of A with stencil increment
  - if nothing has been rendered $\rightarrow$ stencil=0
  - if something has been rendered $\rightarrow$ stencil=1
  - depth buffer contains depth of back faces of A
- disable depth update
- render B with stencil increment
  - if stencil==1 and B occludes back face of A $\rightarrow$ stencil+=1
  - depth buffer is not updated
  - stencil-1 = number of faces of B that occlude A

First Rendering Pass

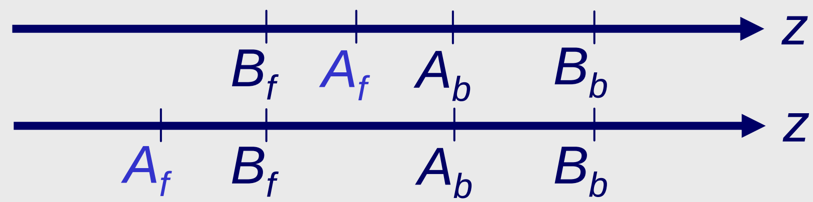
- first pass collision query

- stencil 0 → no collision

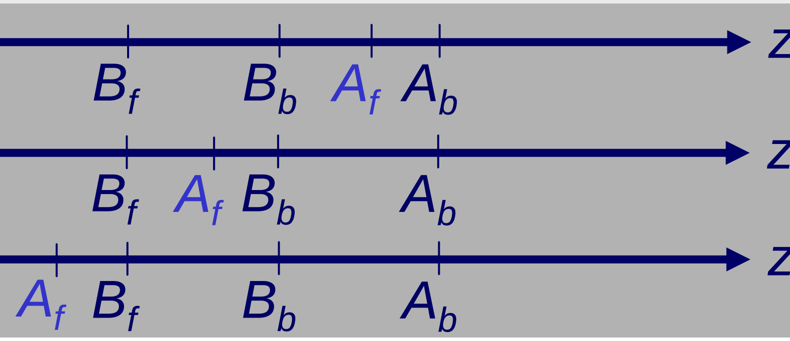
- stencil 1 → no collision
  - no fragment of B occludes back face of A (2 cases)



- stencil 2 → collision
  - front face of B occludes back face of A (2 cases)



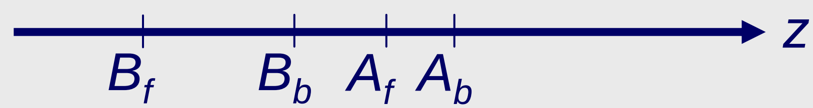
- stencil 3 → second pass
  - front and back face of B occlude back face of A (3 cases)



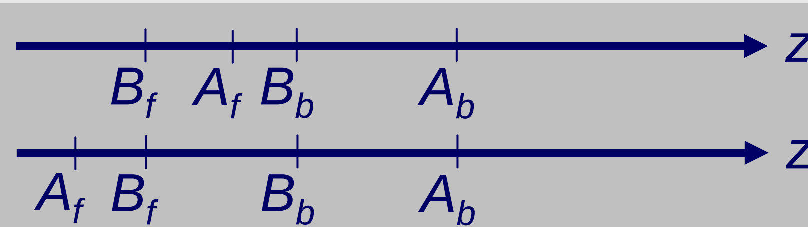
Second Rendering Pass

- render back faces of object B, count occluding faces of A
  - corresponds to first pass with A and B permuted
  - only 3 cases based on the result of the first rendering pass

- stencil 1 → no collision
  - no fragment of A occludes back face of B (1 case)



- stencil 2 → collision
  - front face of A occludes back face of B (2 cases)

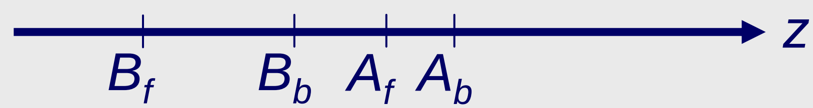


- done

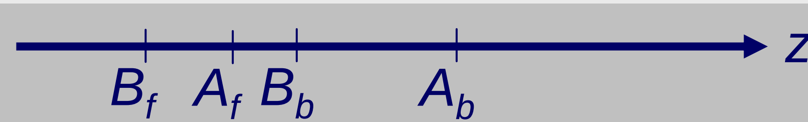
Second Rendering Pass [Myszkowski 1995]

- render front faces of object A, count occluding faces of B
  - corresponds to first pass, front faces are rendered instead of back faces
  - only 3 cases based on the result of the first rendering pass

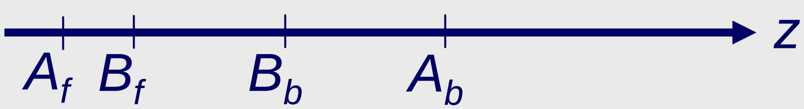
- stencil 3 $\rightarrow$ no collision
  - front and back face of B occlude front face of A



- stencil 2 $\rightarrow$ collision
  - front face of B occludes front face of A



- stencil 1 $\rightarrow$ collision
  - no fragment of B occludes front face of A



- done

Image-Space Collision Detection for Concave Objects [Myszkowski 1995]

- collision detection for pairs of concave objects
  A and B with limited depth complexity (number of entry/exit points)
- faces have to be sorted with respect
  to the direction of the orthogonal projection (e. g. BSP tree)

- objects are rendered in front-to-back or back-to-front order
- alpha blending is employed:

$$\text{color}_{\text{framebuffer}} = \text{color}_{\text{object}} + \alpha \cdot \text{color}_{\text{framebuffer}}$$

- color of A is zero, color of B is 2^{k-1},
  k is the number of bits in the frame buffer,
  $\alpha = 0.5$

Image-Space Collision Detection for Concave Objects

- example: $k = 8$
- color A = 0, color B = 2^7
- sequence of faces B_1 A_1 A_2 B_2 B_3 B_4 rendered back to front:
  - $c_{fb} = 00000000_2$
  - render B_4: $c_{fb} = 2^7 + \alpha \cdot c_{fb} = 10000000_2 + 0.5 \cdot 00000000_2 = 10000000_2$
  - render B_3: $c_{fb} = 10000000_2 + 0.5 \cdot 10000000_2 = 11000000_2$
  - render B_2: $c_{fb} = 10000000_2 + 0.5 \cdot 11000000_2 = 11100000_2$
  - render A_2: $c_{fb} = 00000000_2 + 0.5 \cdot 11100000_2 = 01110000_2$
  - render A_1: $c_{fb} = 00000000_2 + 0.5 \cdot 01110000_2 = 00111000_2$
  - render B_1: $c_{fb} = 10000000_2 + 0.5 \cdot 00111000_2 = 10011100_2$
- resulting bit sequence represents order of faces of A (0) and B (1)
- odd number of adjacent zeros or ones indicates collision

Image-Space Collision Detection for Concave Objects

- example:

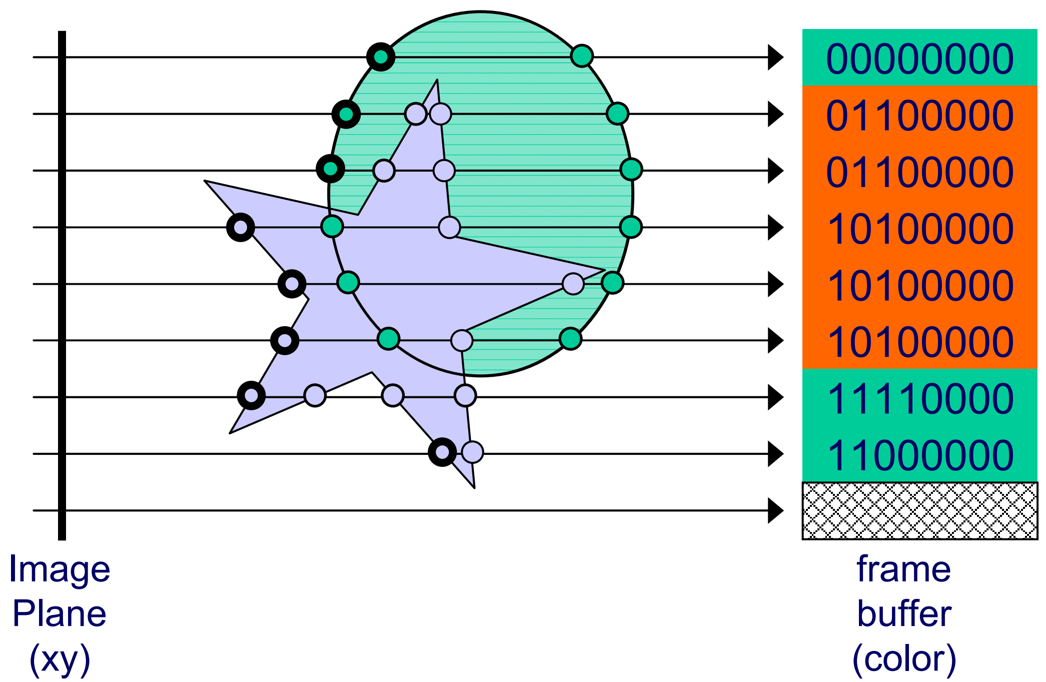
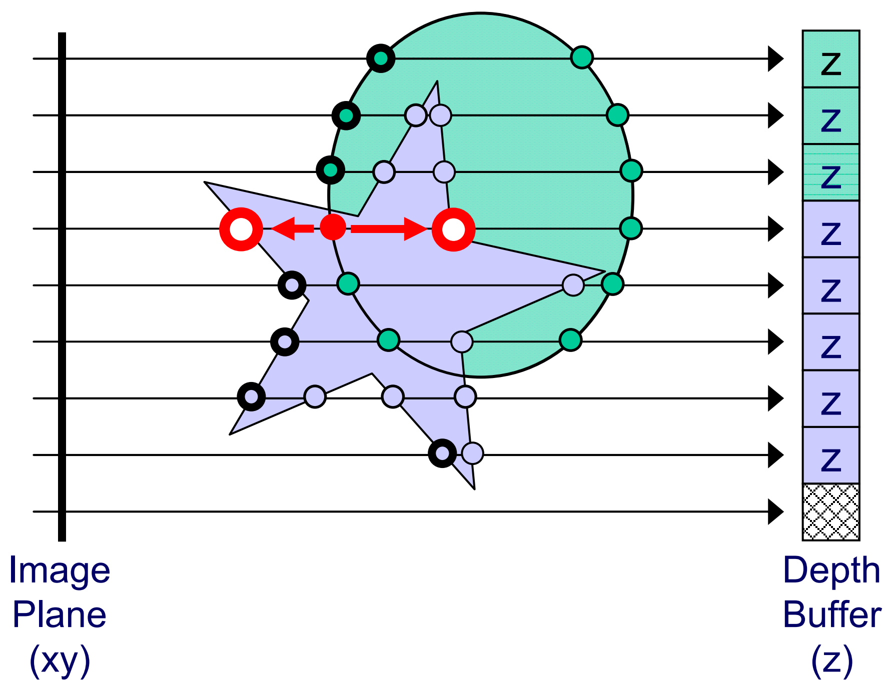


Image-Space Collision Detection [Heidelberger 2003]

- works with pairs of closed arbitrarily-shaped objects
- three implementations
  - *n+1* hardware-accelerated rendering passes
    where n is the depth complexity of an object
  - *n* hardware-accelerated rendering passes
  - 1 software rendering pass
- three collision queries
  - intersection volume (based on intersecting *z* intervals)
  - vertex-in-volume test
  - self-collision test
- basic idea and implementation for convex objects
  has been proposed by Shinya / Forgue in 1991

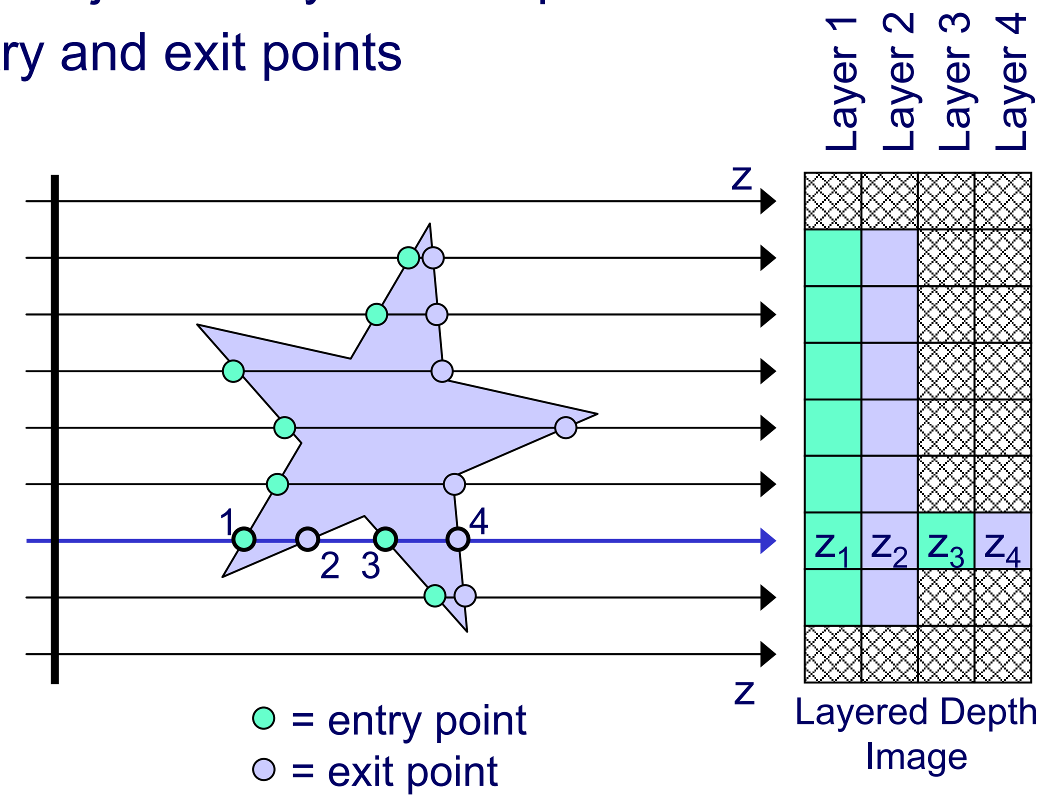
Collision Detection with Graphics Hardware

- exploit rasterization of object primitives for intersection test
- benefit from graphics hardware acceleration



Layered Depth Image

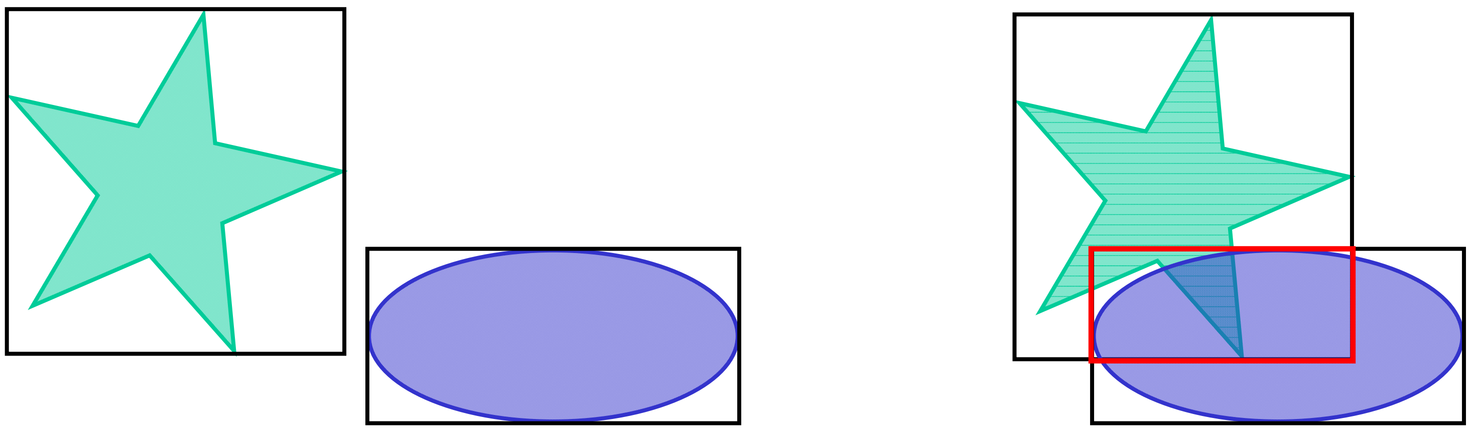
- compact, volumetric object representation [Shade et al. 1998]
- represents object as layers of depth values
- stores entry and exit points



Algorithm Overview

Algorithm consists of 3 stages:

Stage 1: Check for bounding box intersection

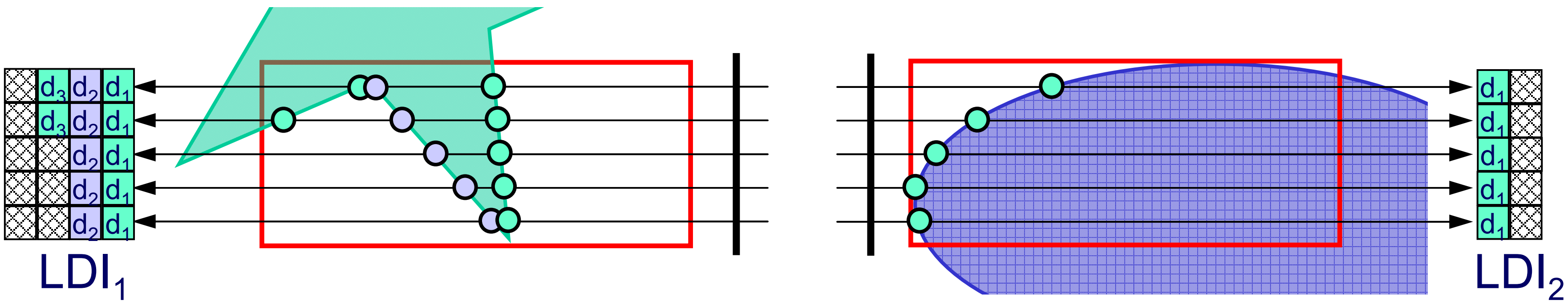


a) Very fast detection of trivial “no collision” cases

b) Overlapping area defines volume of interest (VoI) for step 2 & 3

Algorithm Overview

Stage 2: Generate the layered depth images (LDI)



Step 3: Perform the collision tests

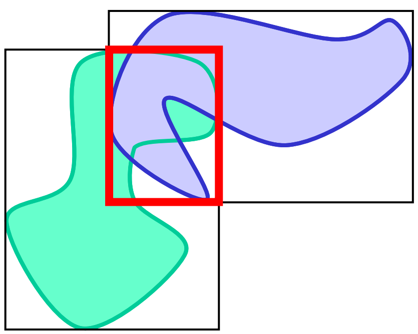
a) test object primitives of one object against LDI of the other

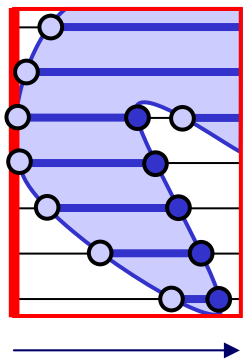
b) combine both LDI to get overlapping volume

c) self-intersection test

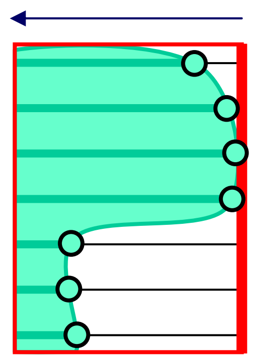
Algorithm Overview

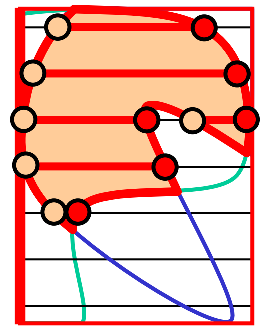
Stage 1	**Stage 2**	**Stage 3**
Volume-of-interest	LDI generation	Collision query



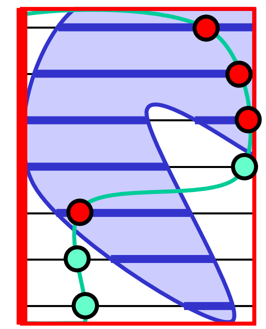


viewing direction

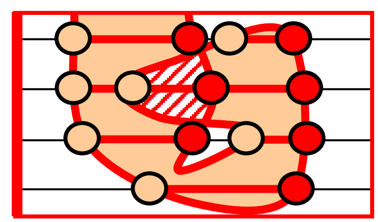




a) LDI intersection

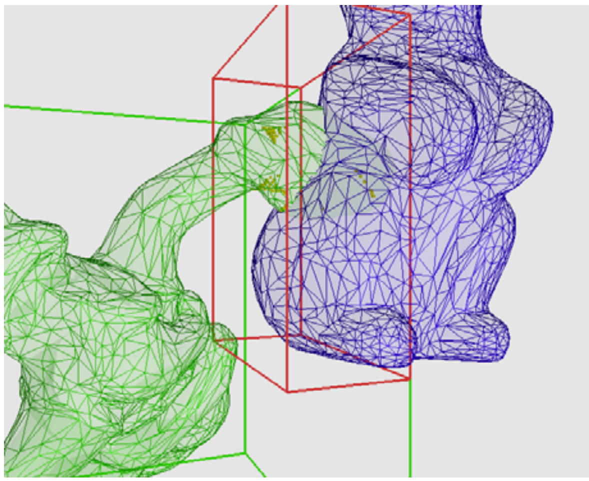


b) Vertex-in-volume

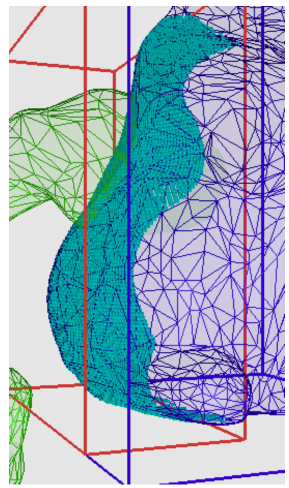


c) Self-collision

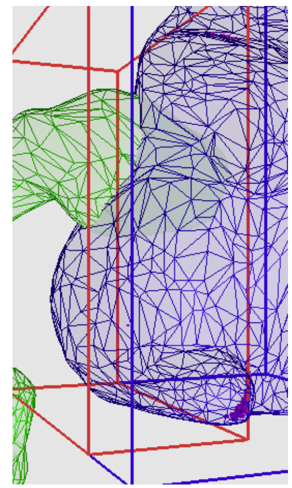
Algorithm Overview



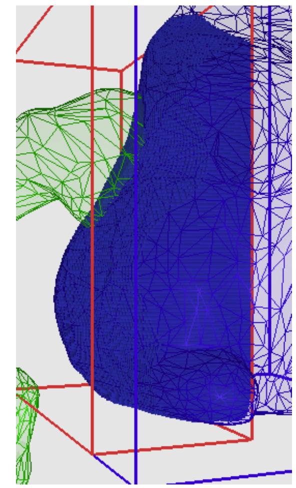
volume of interest VoI



layer 1



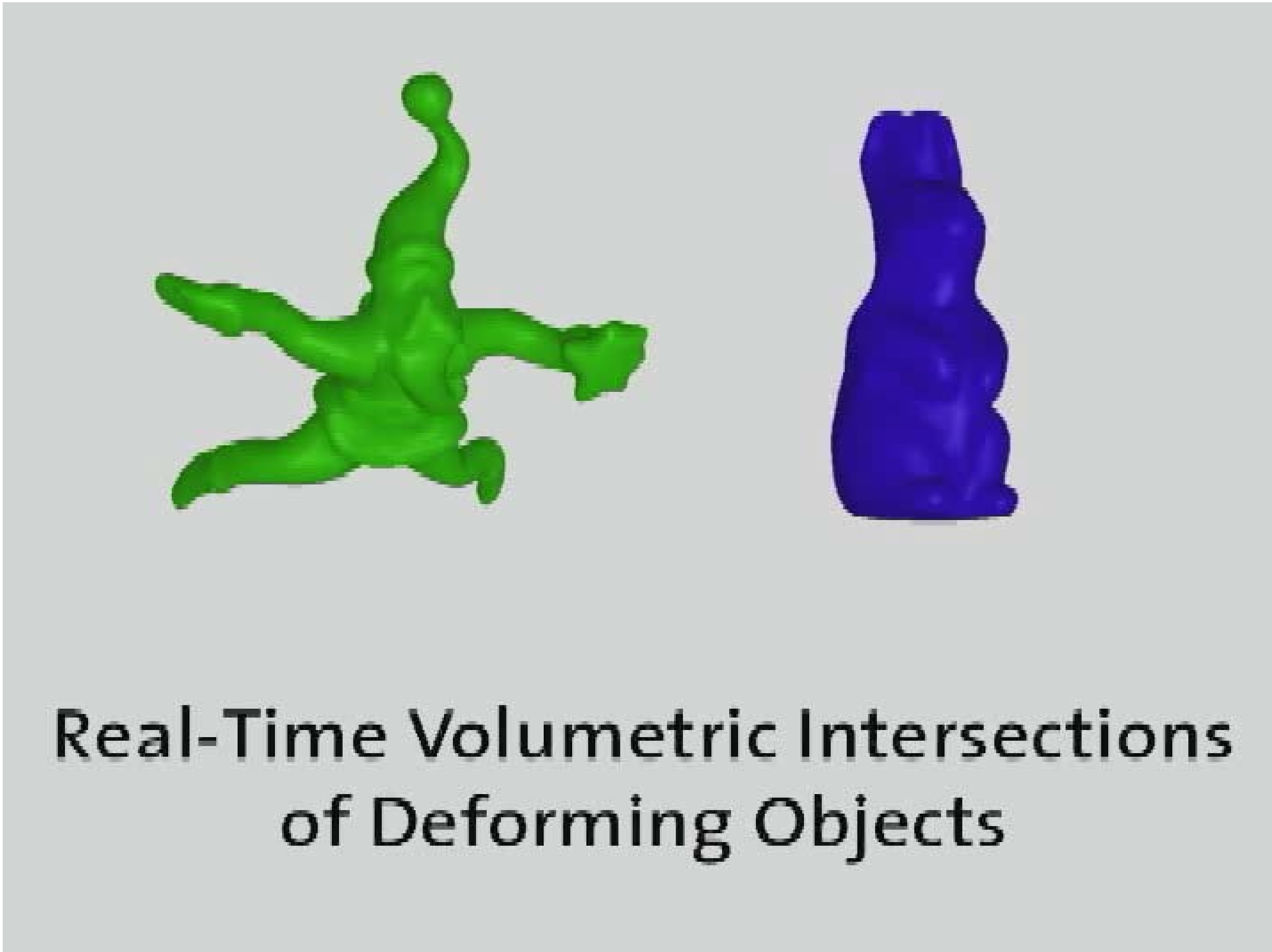
layer 2



volume

collision
queries

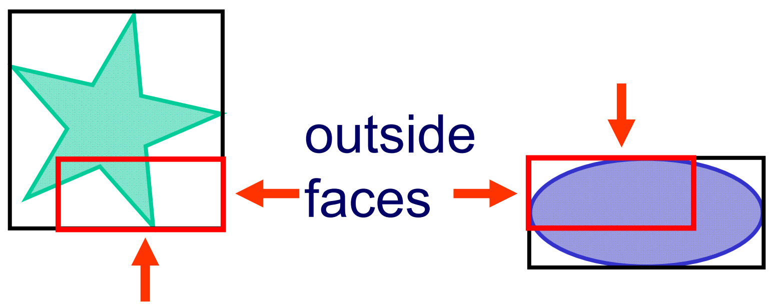
Algorithm Overview



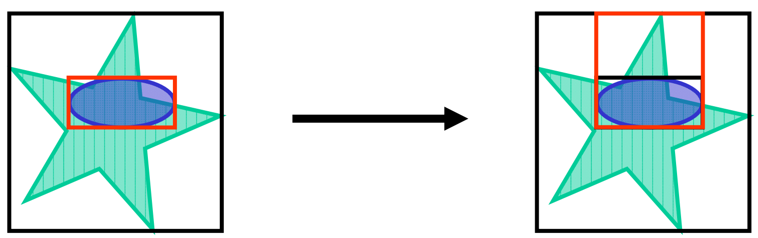
Volume of Interest

VoI = BoundingBox(Object 1) ∩ BoundingBox(Object 2)

1. evaluation of trivial rejection test: VoI == Ø → no collision!
2. choice of *opposite* render directions for LDI generation



possible enlargement of VoI to guarantee valid directions



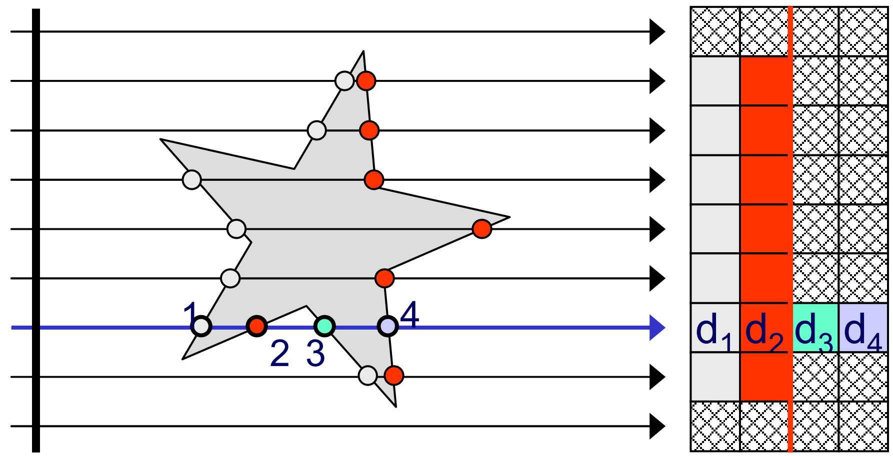
outside faces are outside the object

-> guarantees that first intersection point is an entry point

LDI Generation on the GPU Depth Peeling

- object is rendered once for each layer in the LDI
- two separate depth tests per fragment are necessary:
  - fragment must be farther than the one in the previous layer (**d_2**)
  - fragment must be the nearest of all remaining fragments (**d_3** & **d_4**)

example: *pass #3*



→ second depth test is realized using shadow mapping
extended depth-peeling approach [Everitt 2001]

Shadow Mapping

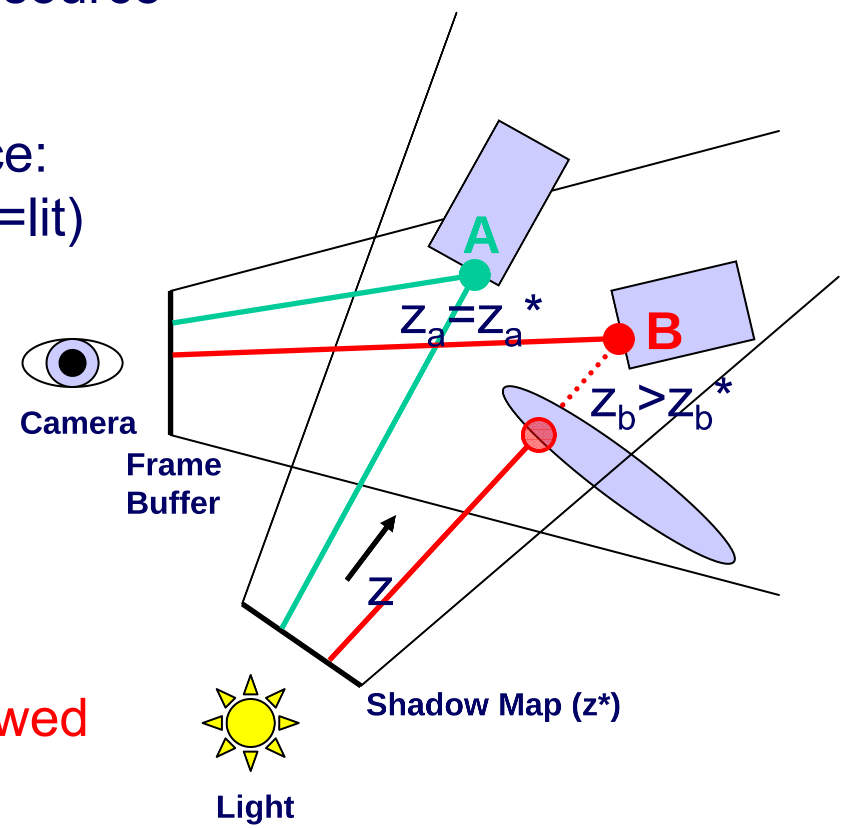
Idea:

– for each fragment to be rendered:
  check if it is visible from the light source

Algorithm:

– render scene from the light source:
  store all distances to the visible (=lit) fragments in a “shadow map”
– render scene from the camera:
  compare the distance *z* of each fragment to the light with the value *z** in the shadow map:

  z = z* → fragment is lit
  z > z* → fragment is shadowed



Shadow Mapping as Depth Test

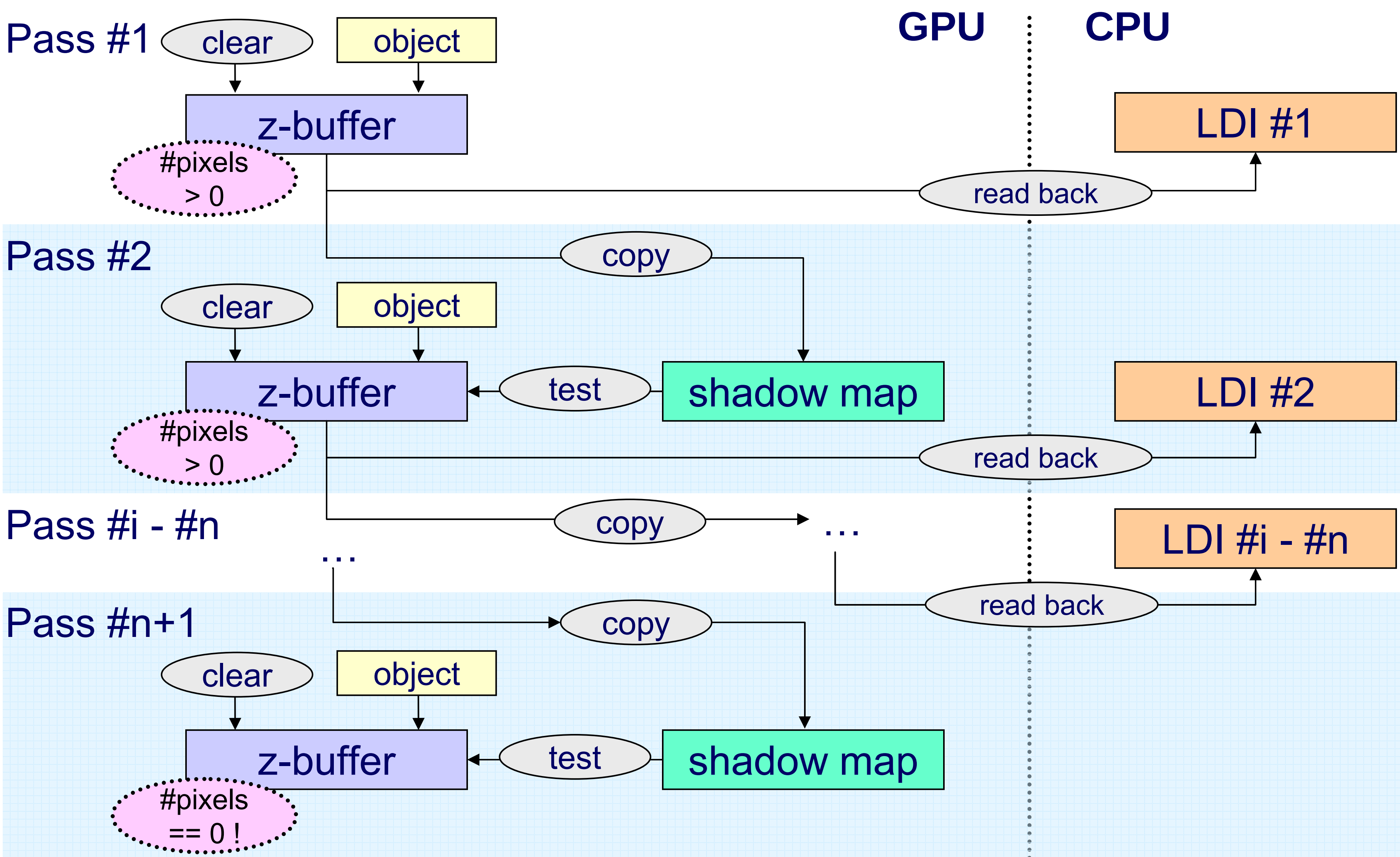
Differences to regular depth test:

- shadow mapping depth test is not tied to camera position
- shadow map (depth buffer) is *not writeable during depth test*
- shadow mapping *does not discard fragments*

Depth test setup for LDI generation:

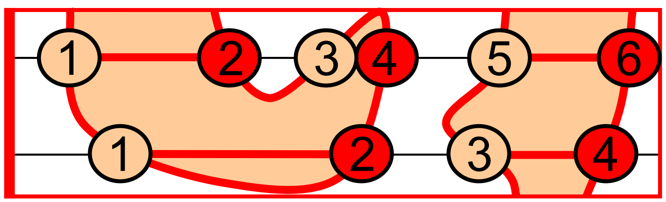
- fragment must be farther away than fragment in previous depth layer → shadow map test
- fragment must be the nearest of all remaining fragments → regular depth test

Multipass LDI Generation



Result of LDI Generation

- multipass LDI generation results in
  an ordered LDI representation of the VoI



VoI

1	2	3	4	5	6
1	2	3	4		

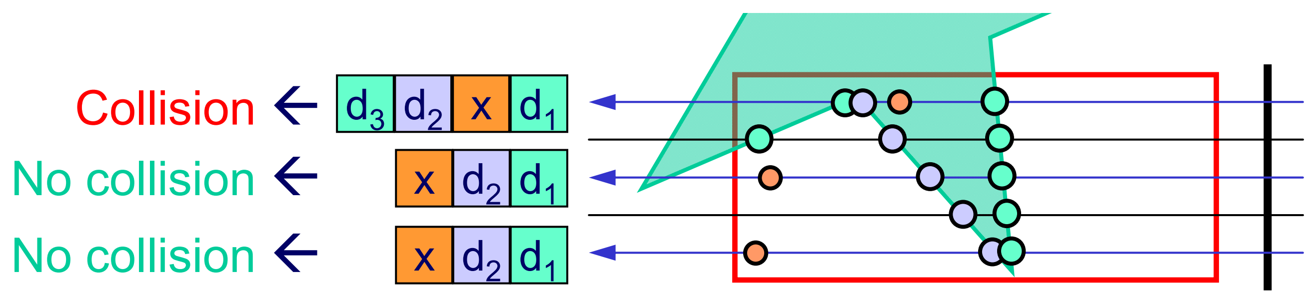
ordered LDI

- requires one rendering pass per depth layer
- requires shadow mapping functionality

Collision Detection Test

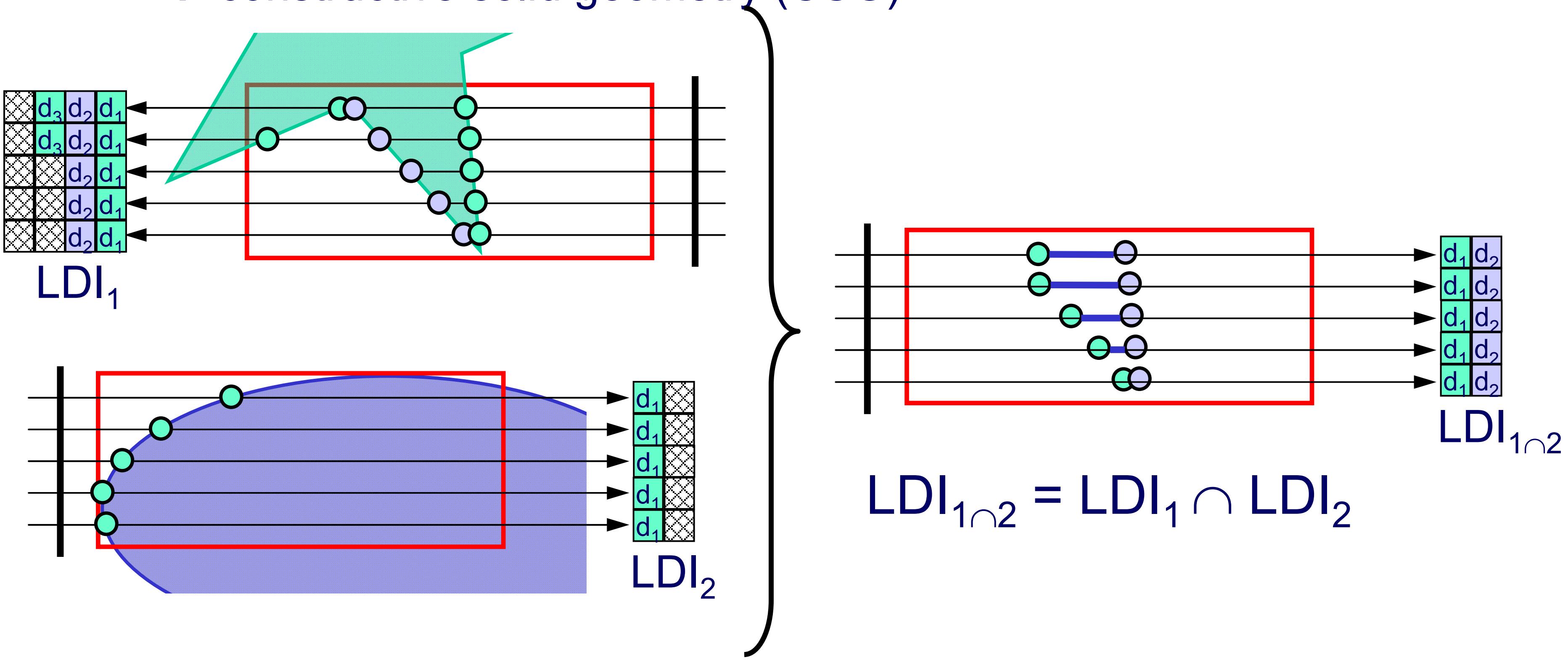
- test object primitives of one object against LDI of the other object (and vice versa)
- vertex-in-volume test

example:



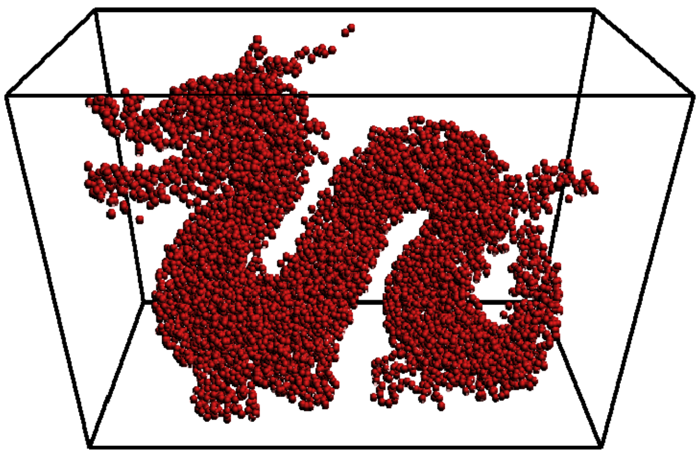
LDI Combination

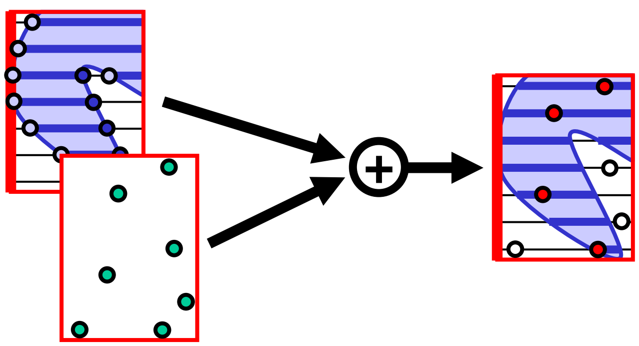
- intersect both LDI to get the overlapping volume
- provides an explicit intersection volume
- other boolean operations (union, difference) are also possible
  → constructive solid geometry (CSG)



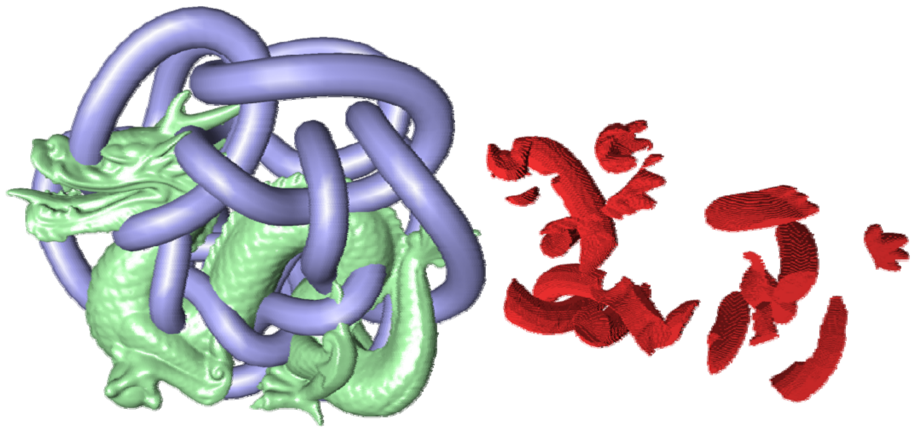
Collision queries

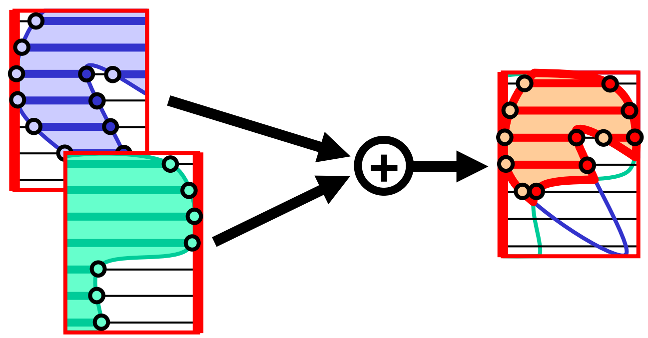
Vertex-in-volume test





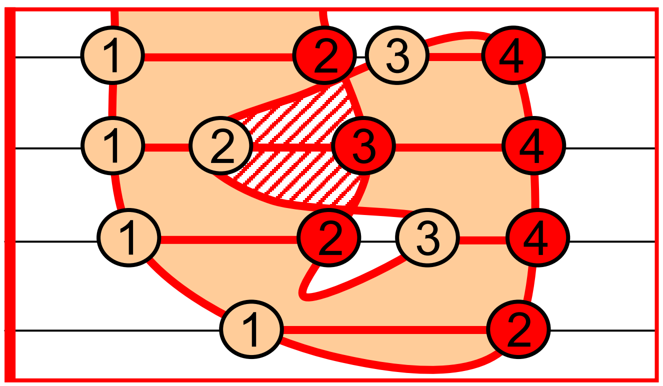
Explicit intersection volume





Self-collision query

- check for incorrect ordering of front and back faces
- if front and back faces do not alternate -> self collision



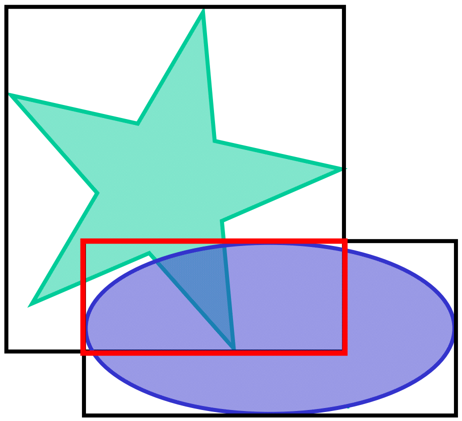
VoI

1	2	3	4
1	2	3	4
1	2	3	4
1	2		

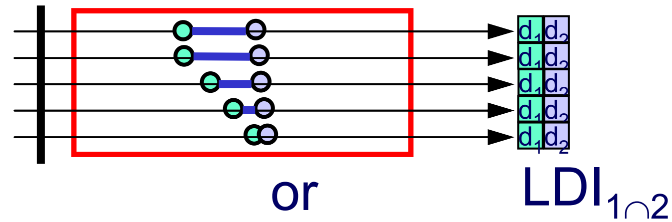
LDI

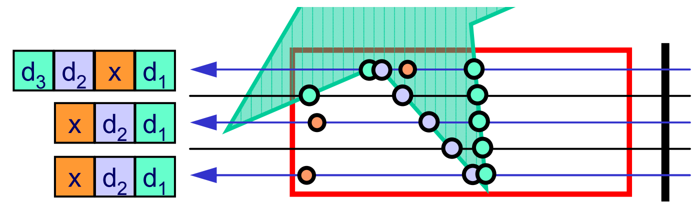
Algorithm Summary

(1) Volume of interest



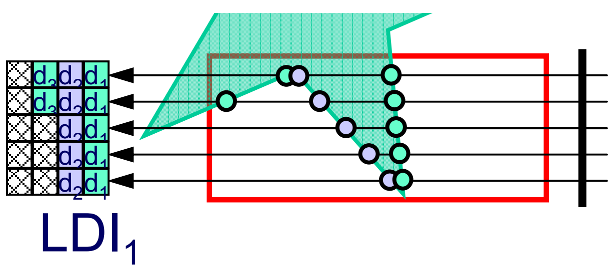
(3) Collision detection test

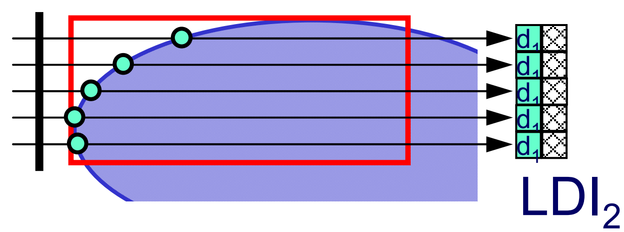




or self-collision

(2) LDI generation

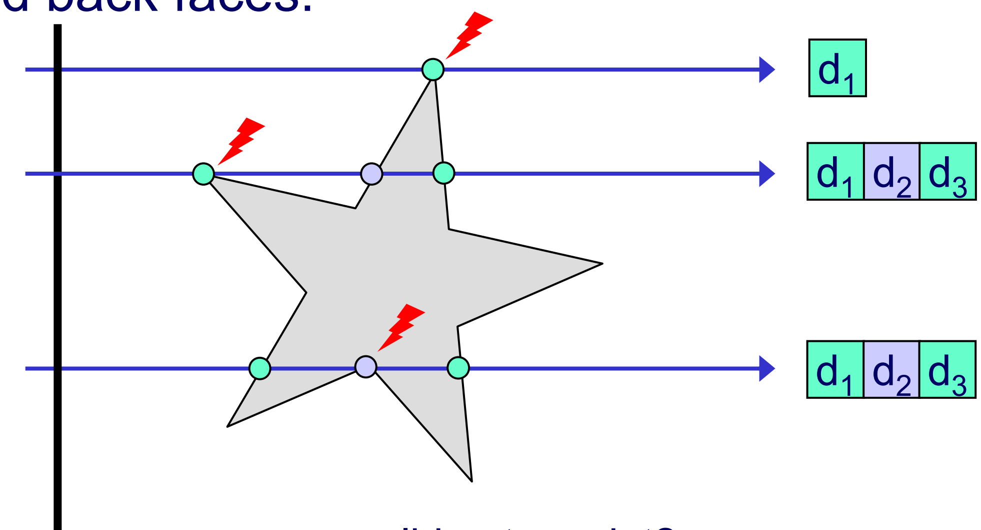




Problems

- object can not be rendered to shadow map (see differences to depth buffer) → additional copy process necessary
- limited precision of depth buffer leads to singularities near edges between front and back faces:

example:



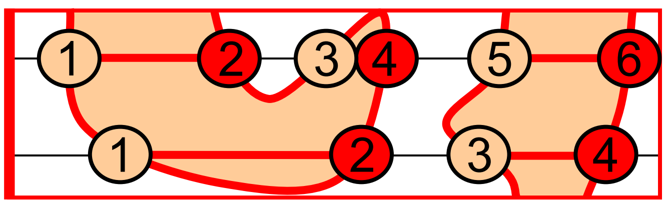
● = valid entry point?
● = valid leaving point?

No! → corrupt LDI!

→ handle front and back faces in separate passes

Unordered LDI Generation

- alternative method for LDI generation
- GPU generates unsorted LDI
  - fragments are rendered in the same order in each rendering pass
  - stencil buffer is used to get n-th value in the n-th pass
- CPU generates ordered LDI
  - depth complexity is known for each fragment
    (how many values are rendered per pixel)



VoI

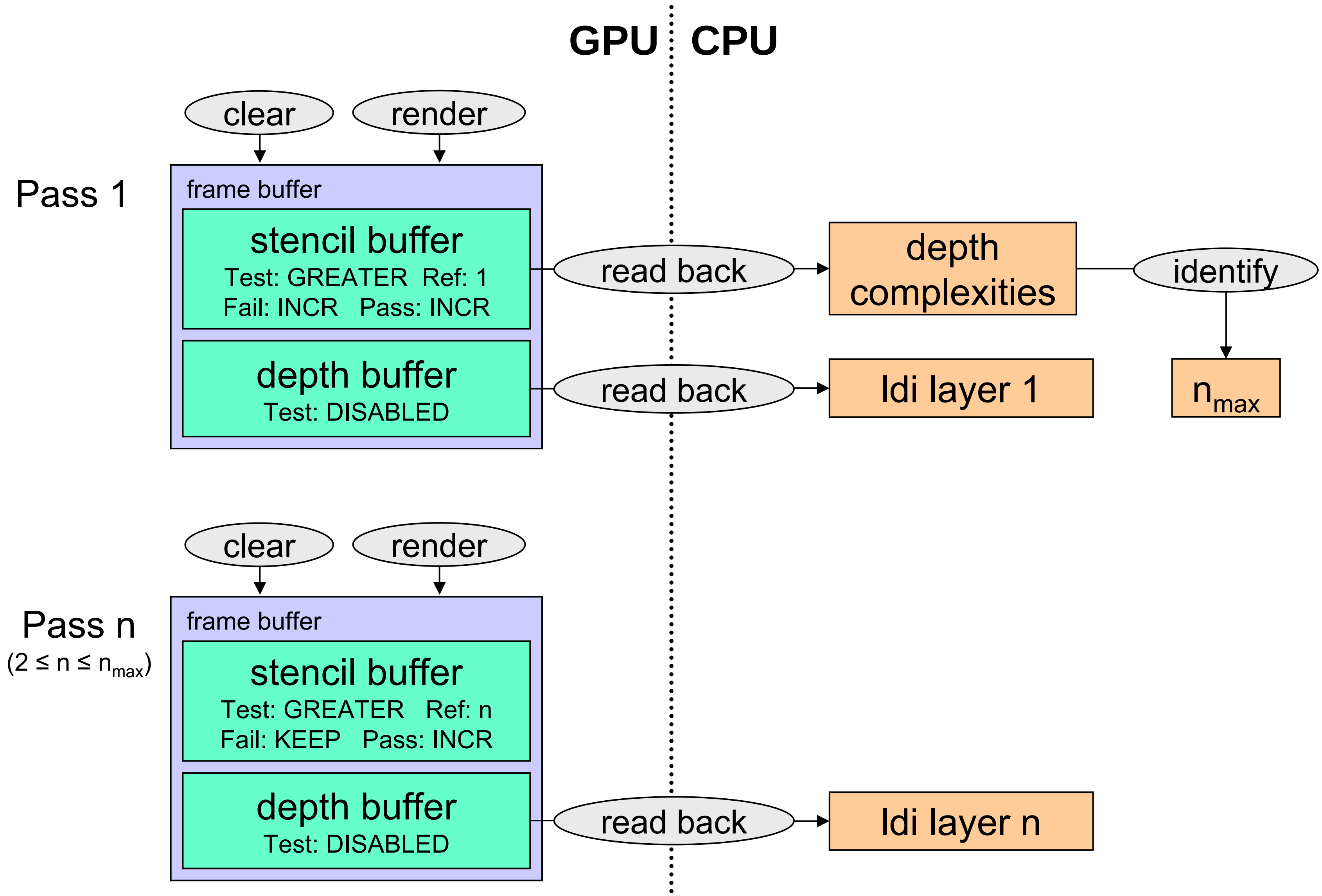
5	3	2	1	4	6
4	1	3	2	2	2

unsorted LDI (GPU)

1	2	3	4	5	6
1	2	3	4	2	2

sorted LDI (CPU)

Unordered LDI Generation



Limitations

- performance is dependent on:
  - depth complexity of objects in volume of interest
  - read back delay for simple objects
  - rendering speed for complex objects
- requires graphics hardware

Ordered LDI Generation on CPU

Motivation

- buffer read-back from GPU
  can be performance bottleneck
- GPU requires multiple passes
- CPU can store fragments directly into LDI

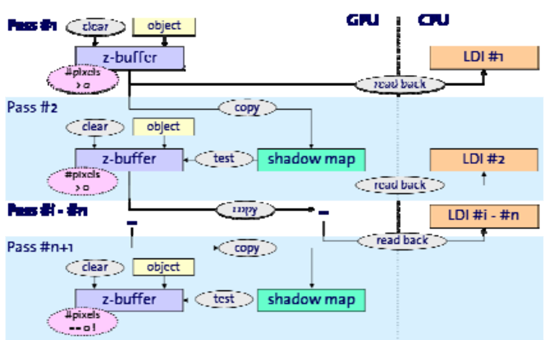
Simplified software-renderer

- rasterization of triangle meshes
- frustum culling
- face clipping
- orthogonal projection

LDI Generation - Summary

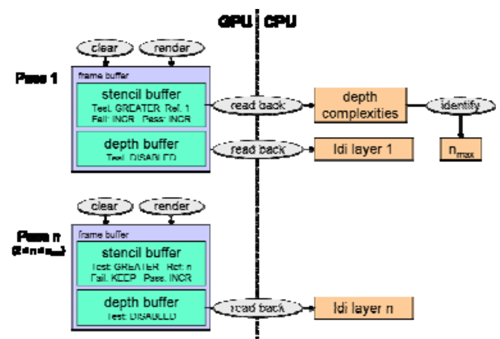
Ordered LDI (GPU)	***Unordered LDI (GPU)***	***Ordered LDI (CPU)***

Ordered LDI (GPU)



- n+1 passes
- complex setup
- two depth tests
- shadow map
- OpenGL extensions

Unordered LDI (GPU)



- n passes
- simple setup
- no depth test
- stencil buffer
- plain OpenGL 1.4

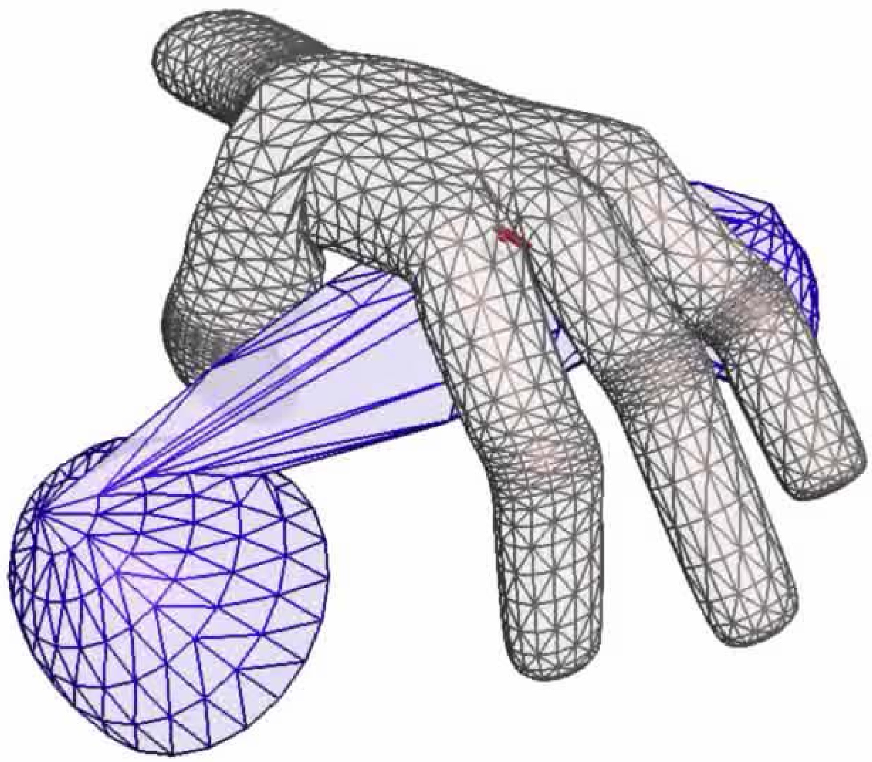
Ordered LDI (CPU)

rasterize

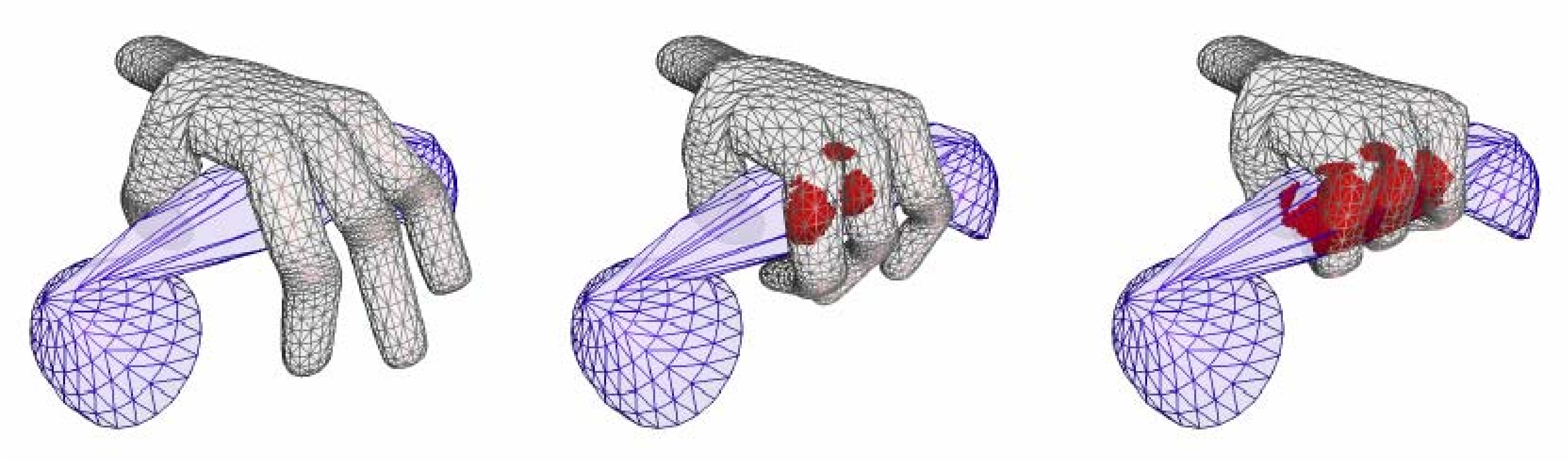
- 1 pass
- simple setup
- no depth test

Performance - Intersection Volume

- hand with 4800 faces
- phone with 900 faces
- two LDIs
- intersection volume for collision detection
- analysis of front / back face ordering for self-collision



Performance – Intersection Volume



method	collision min / max	self collision min / max	overall min / max
ordered (GPU)	28 / 37	40 / 54	68 / 91
unordered (GPU, CPU)	9 / 12	12 / 18	21 / 30
software (CPU)	3 / 4	5 / 7	8 / 11

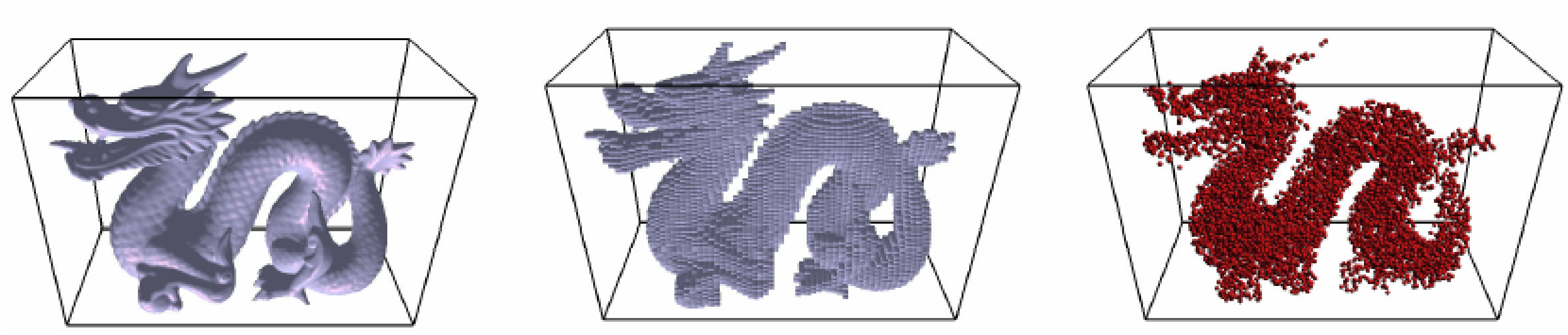
3 GHz Pentium 4, GeForce FX Ultra 5800

hand with 4800 faces
phone with 900 faces
measurements in ms

Performance – Vertex-in-Volume

- santa with 10000 faces
- 20000 particles
- one LDI
- test vertices against inside regions of the LDI

Performance – Vertex-in-Volume



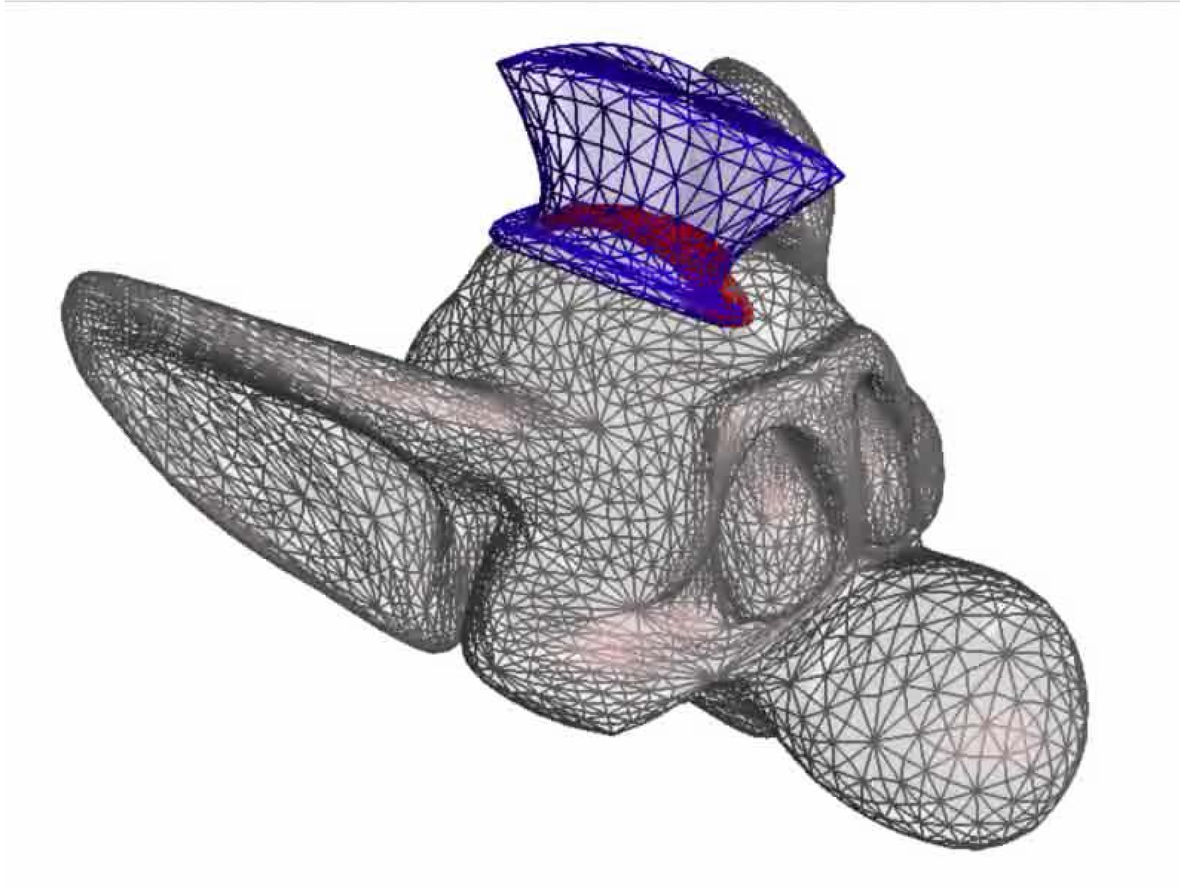
method	520k faces 100k particles	150k faces 30k particles	50k faces 10k particles
ordered (GPU)	450	160	50
unordered (GPU, CPU)	225	75	25
software (CPU)	400	105	35

3 GHz Pentium 4, GeForce FX Ultra 5800

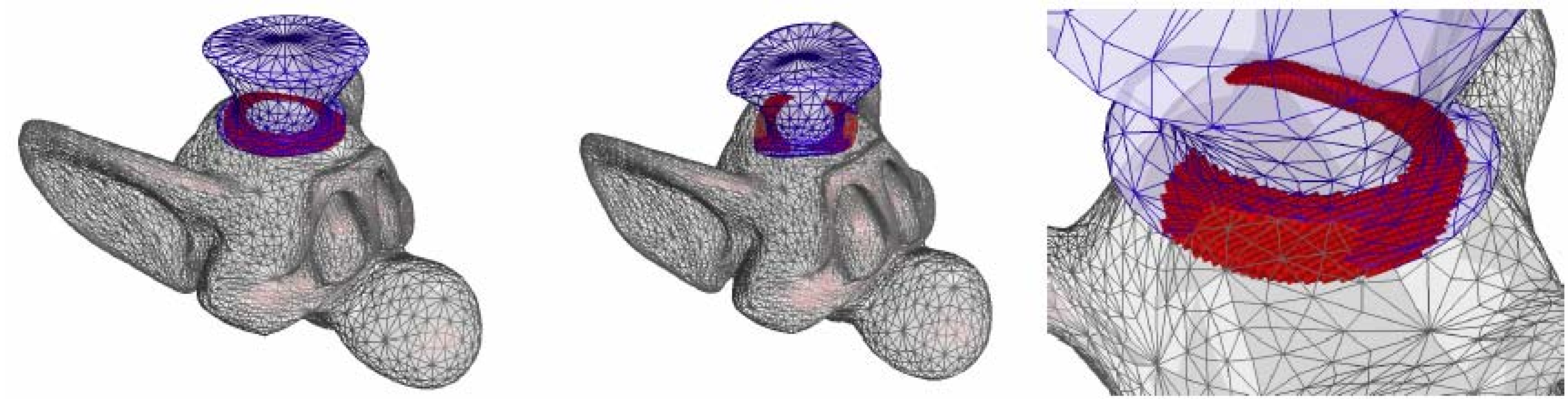
LDI resolution 64 x 64
measurements in ms

Performance – LDI resolution

- mouse with 15000 faces
- hat with 1500 faces
- two LDIs
- intersection volume for collision detection



Performance – LDI resolution



method	32 x32	64 x 64	128 x128
ordered (GPU)	24	26	51
unordered (GPU, CPU)	8	9	17
software (CPU)	2	3	6

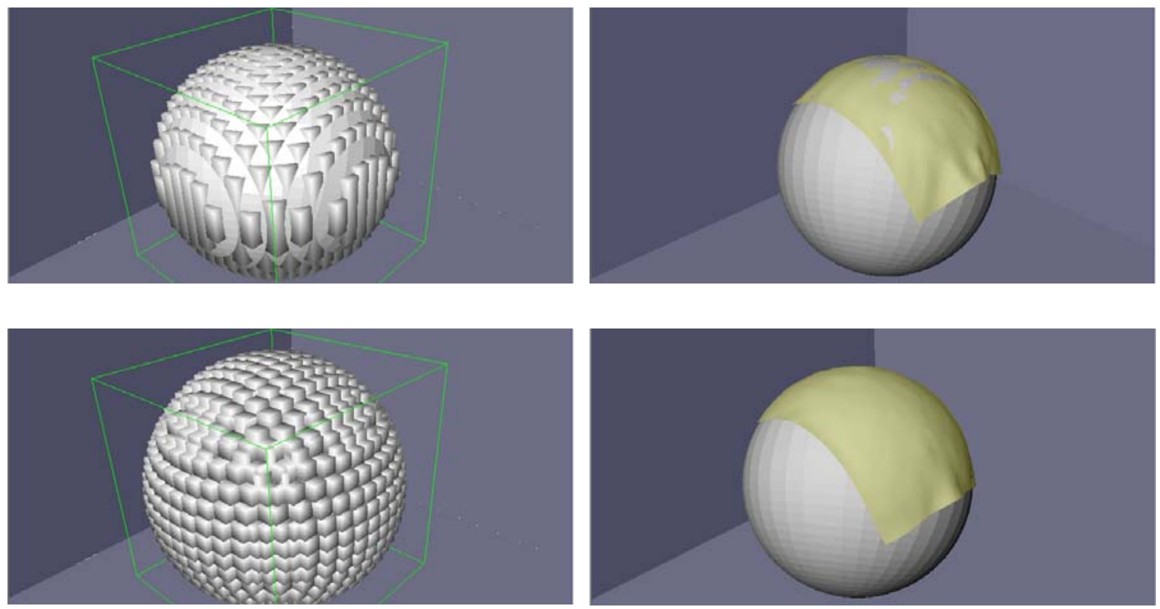
3 GHz Pentium 4, GeForce FX Ultra 5800

mouse with 15000 faces
hat with 1500 faces
measurements in ms

Applications – Cloth Modeling

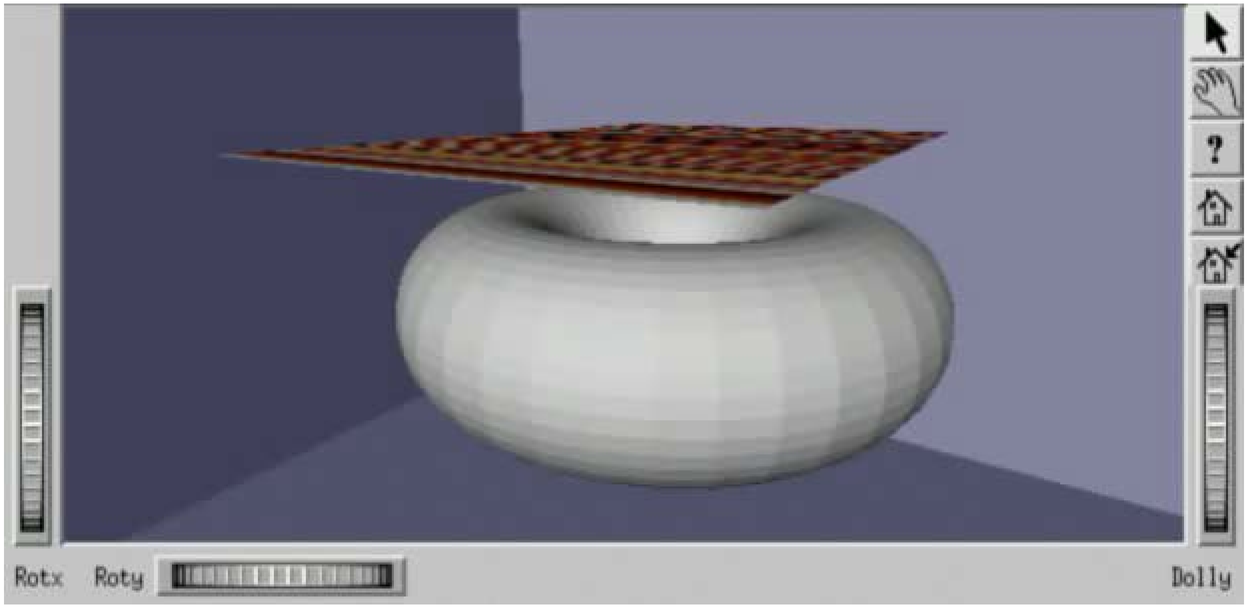
LDI

3 orthogonal
dilated LDIs



Real-Time Cloth Simulation with Collision Handling

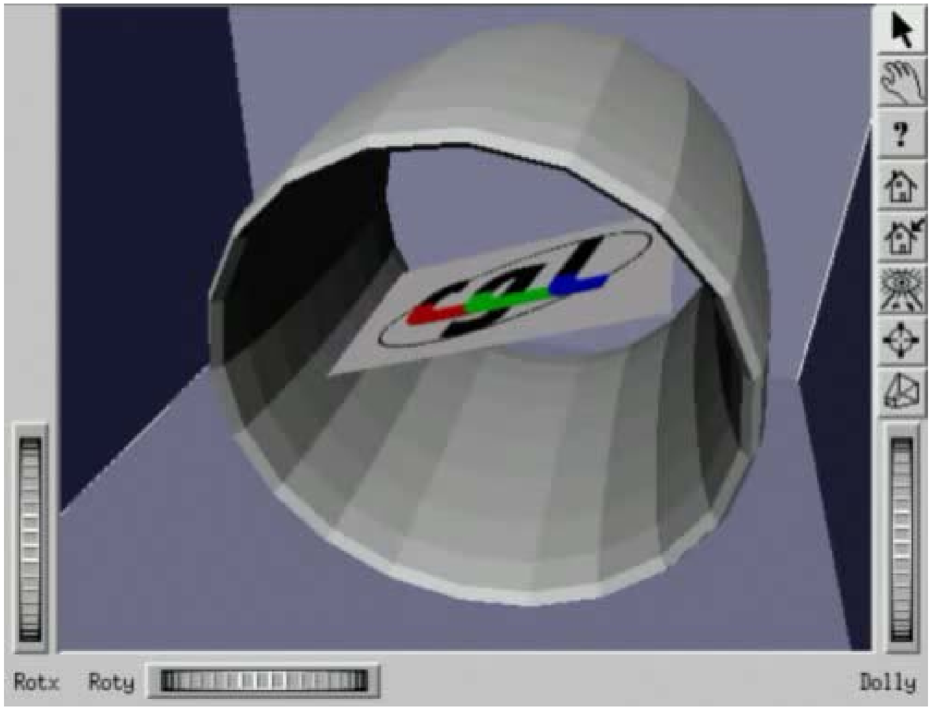
real-time movie
3GHz Pentium 4



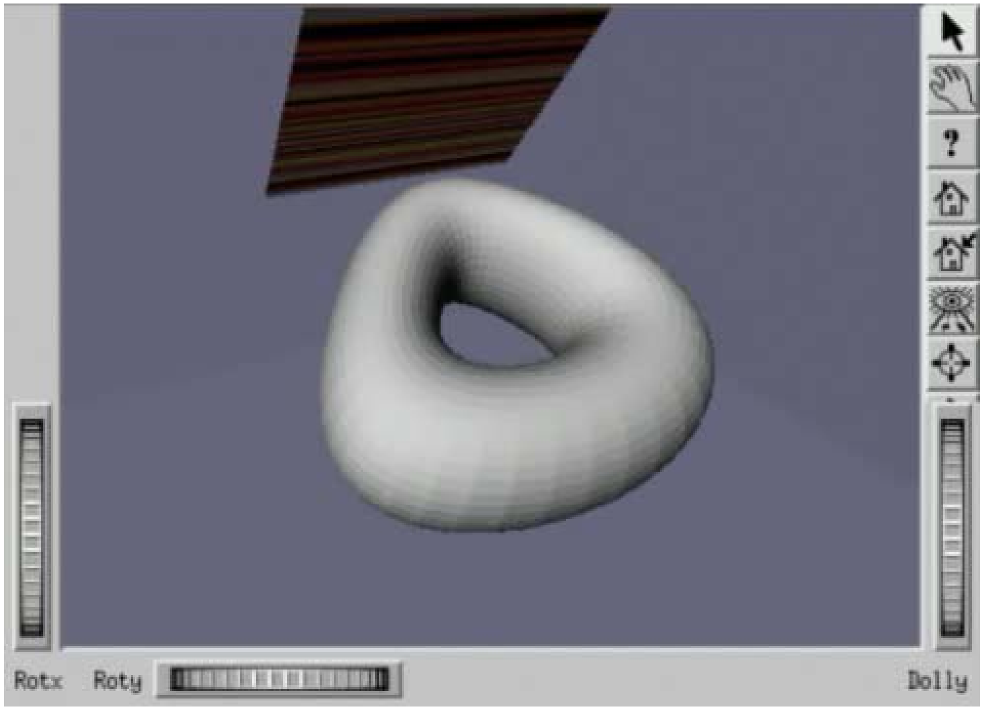
stable collision handling

Real-Time Cloth Simulation with Collision Handling

real-time movies
3GHz Pentium 4



concave transforming object



concave deforming object

Summary

- image-space technique
- detection of collisions and self-collisions
- handling of rigid and deformable closed meshes
- no pre-processing
- CPU: 5000 / 1000 faces at 100 Hz
- GPU: 520000 faces / 100000 particles at 4 Hz
- application to cloth simulation
- limitations
  - closed meshes
  - accuracy
  - collision information for collision response

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