Hardware-based Simulation and Collision Detection for Large Particle Systems

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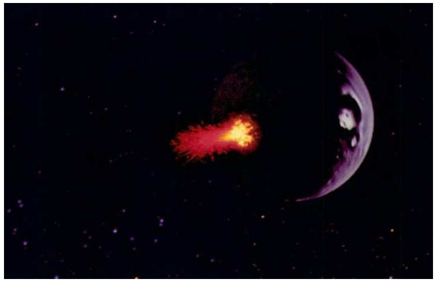
Overview

- Motivation
- Stateless PS on the GPU
- State-preserving PS on the GPU
- Collision detection
- Results
- Conclusion & future work

Motivation - History & Application

Video games:

- Spacewar (1962): Second video game ever!
- Star Trek II (1983): Planetary fire wall



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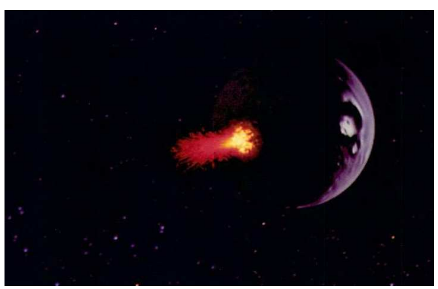
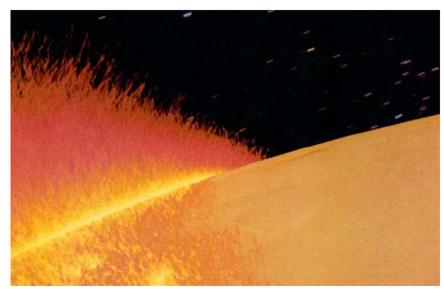
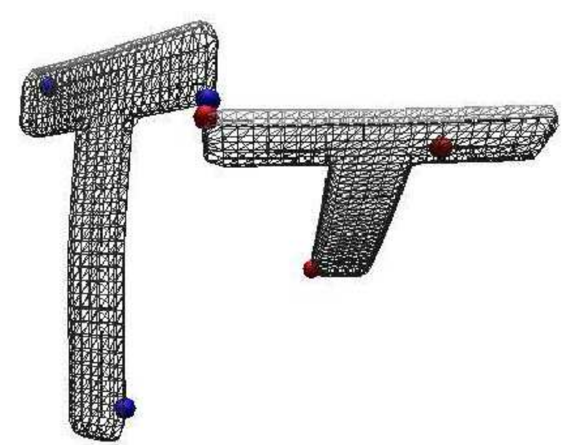
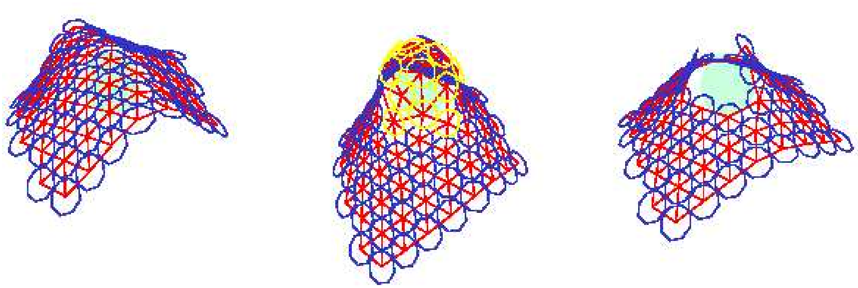
Scientific sample applications:

- Surface Modeling (Szeliski & Tonnesen ’91)
- Collision Detection (Senin etal. ’03)









Prior Work - Stateless PS on the GPU

Stateless simulation: Compute particle data by closed form functions

$\Rightarrow$ no reaction on dynamically changing environment

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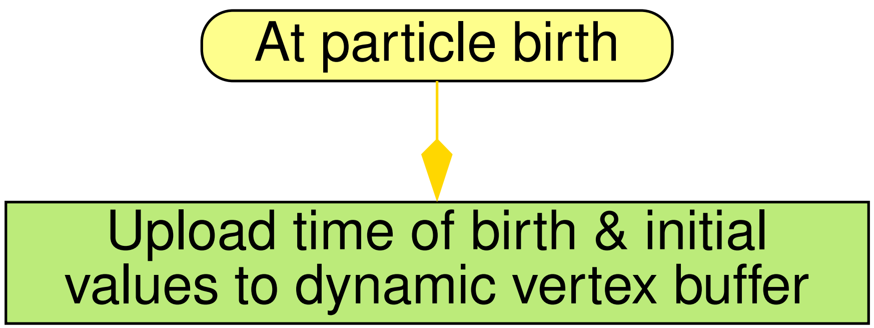

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At particle birth

Upload time of birth & initial values to dynamic vertex buffer

At render time

Set global function parameter as vertex program constants

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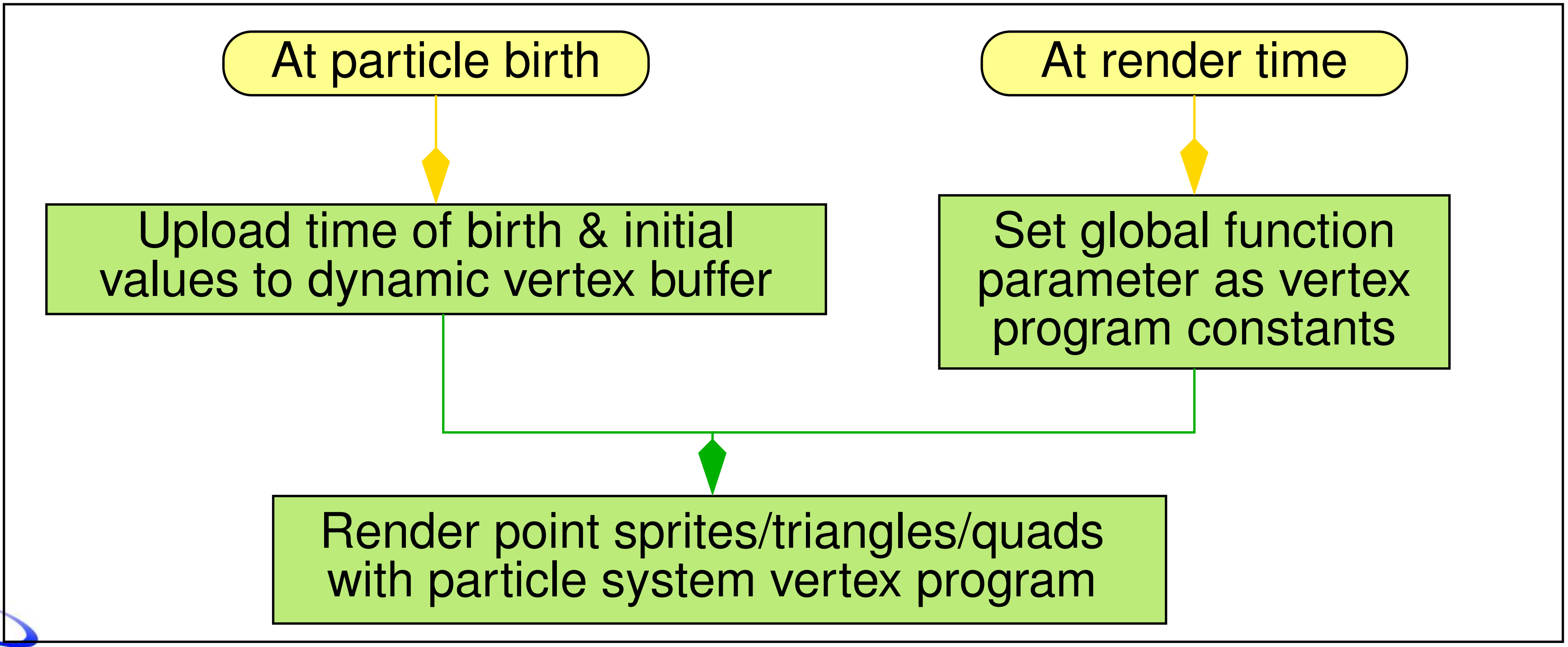

State-preserving PS on the GPU

Iterative, time-discrete simulation in fragment program

- Explicit storage of particle data (position, velocity, etc.)
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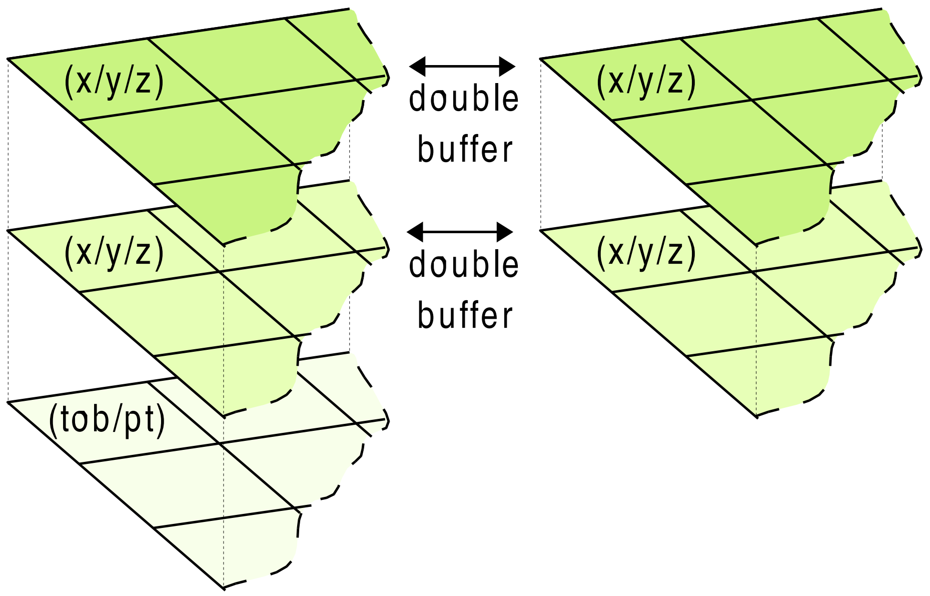
Stream processing for dynamic data (position, velocity)

- One or several textures as input stream (read-only)
- One texture as output stream/render target (write-only)

Position texture

Velocity texture

Static per particle data,
e.g. time of birth (tob)
particle type (pt), ...



Statepres. PS on the GPU - Algorithm

Algorithm for one time step

1. Process birth and death
2. Velocity operations (forces, particle-object collisions)
3. Position operations
4. Sorting for alpha blending (optional)
5. Transfer position texture to vertex data
6. Rendering

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Allocation is a serial problem $\Rightarrow$ use CPU

Heap data structure to get compact index, i.e. tex. coord. range

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Deallocation independently on CPU and GPU

- CPU: Re-add freed particle index to allocator
- GPU: Move particle out of view volume

In practice, particles fade out or “fall out of view” $\Rightarrow$ clean-up rarely needs to be done

Statepres. PS on the GPU - Sorting

Odd-even merge sort for alpha blending

GPU-based sorting: Store particle-viewer distance in texture

Parallel sorting: Fixed number of comparisons; $\mathcal{O}(n \log_2^2(n))$

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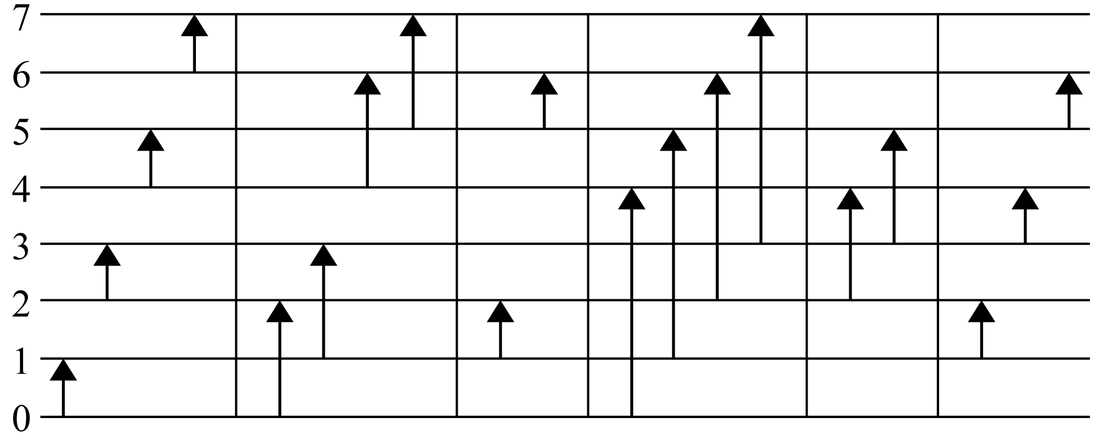

Sorting network for 8 elements

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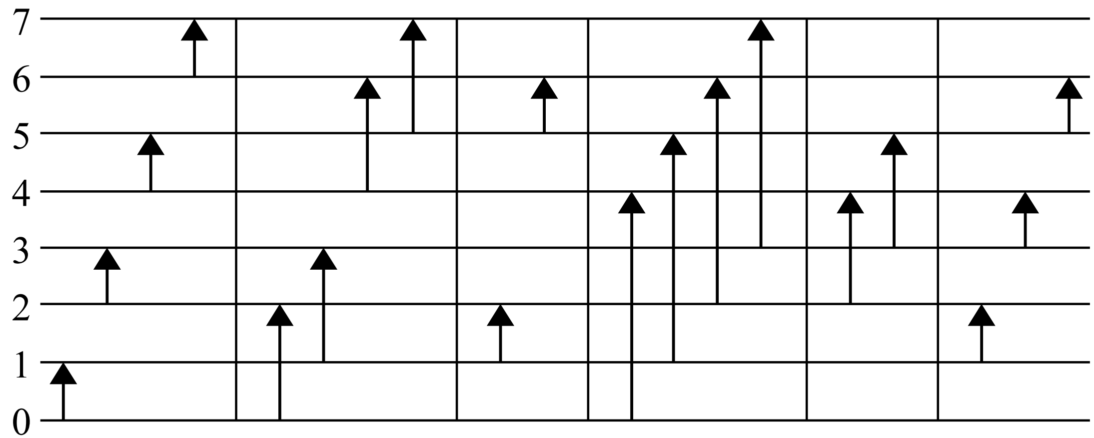

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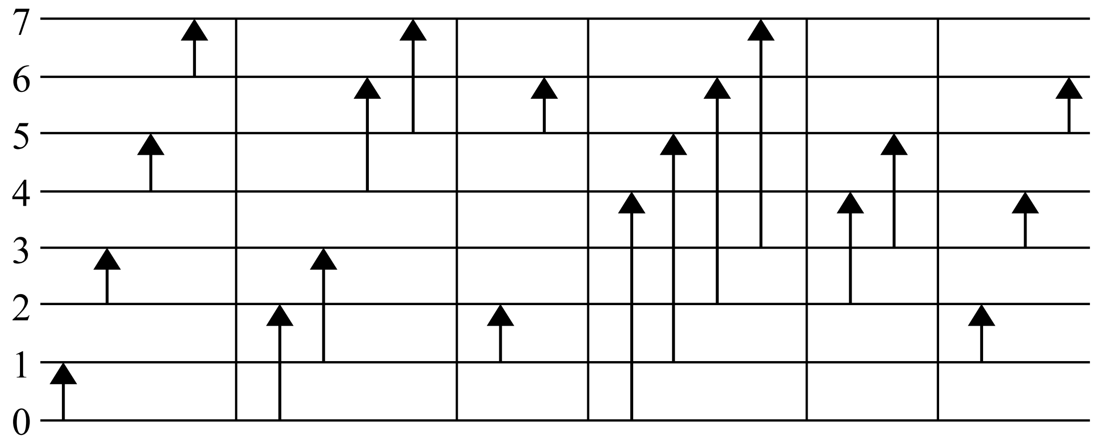

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1024^2 **particles** $\Rightarrow 210$ sorting passes $\Rightarrow$ spread over 50 frames

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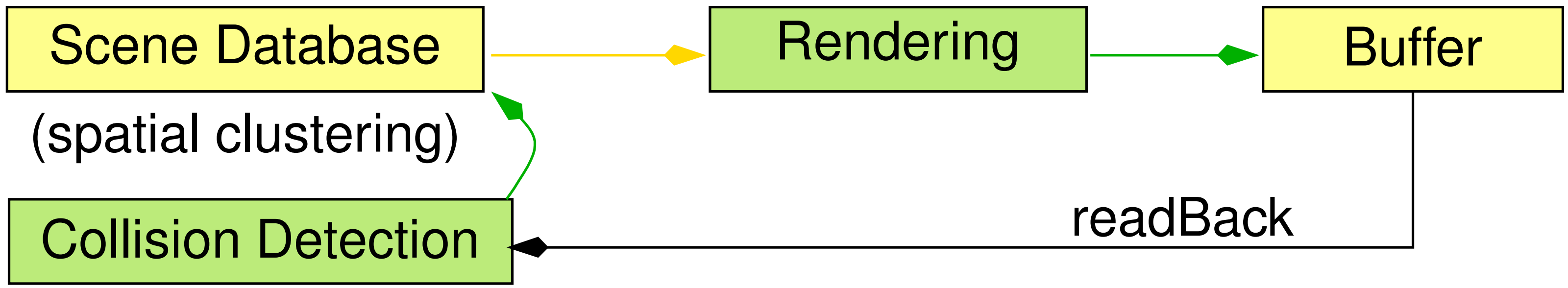
Vertex texture as alternative approach

- Access textures from vertex shaders
- Vertex shader actively reads particle positions
- Conceptually available in DirectX (VS3.0) and OpenGL (`ARB_vertex_shader/GLSL`)

Collision Detection (CD) - HW Approaches

Depth buffer & stencil buffer, e.g. Baciu & Wong ’03



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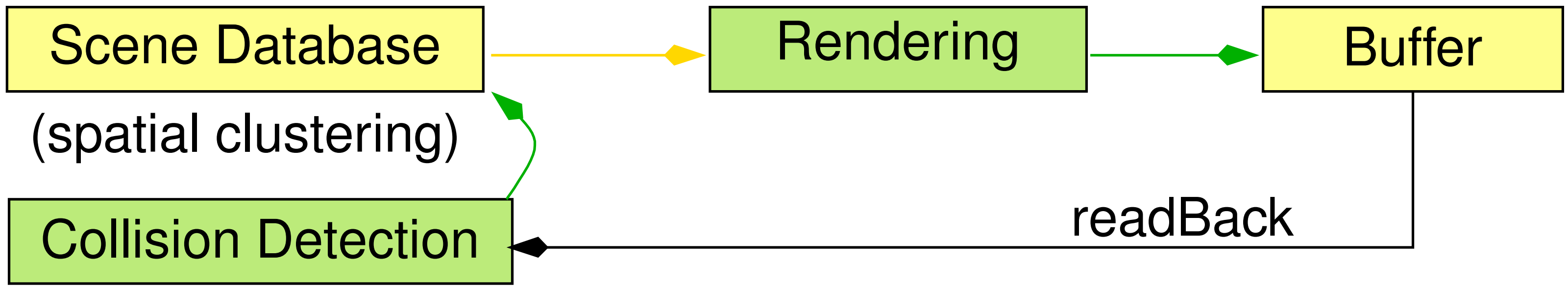

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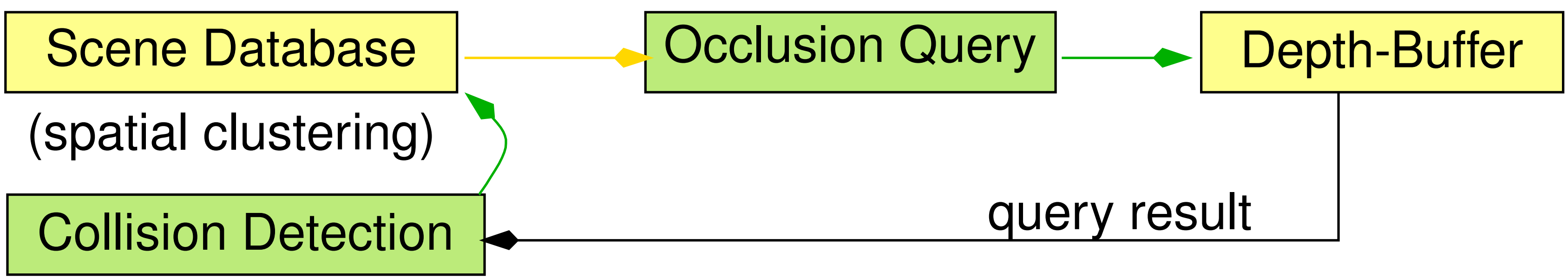

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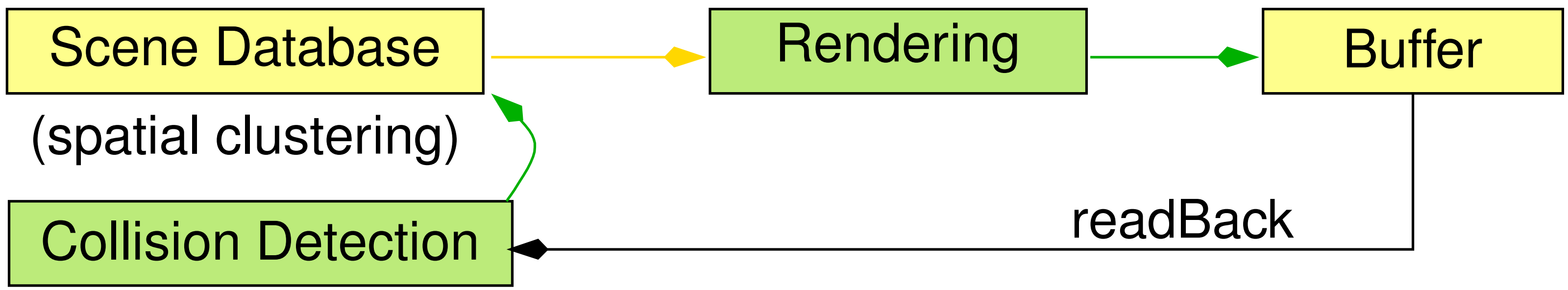

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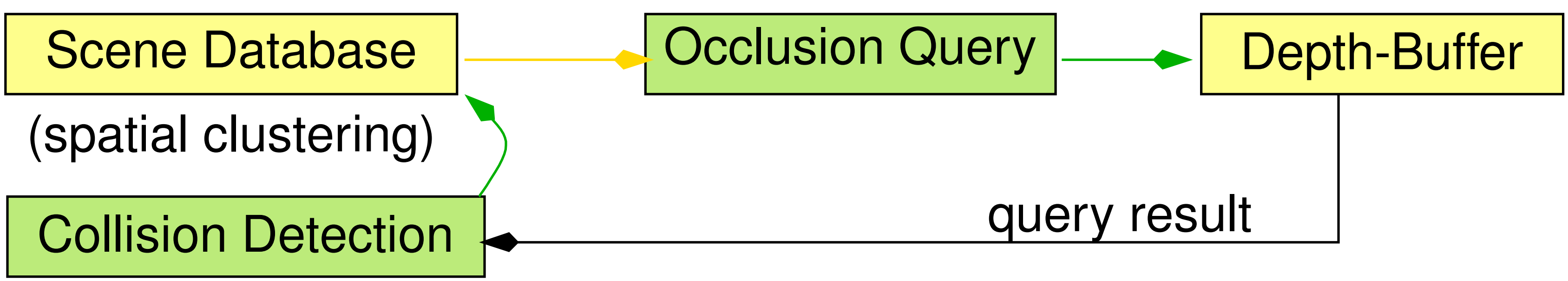

Collision detection on the GPU?

CD - Implicit Model Representation

Basic concept

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Implicit model: 3D scalar-valued function $f(\mathbf{P})$:

- f specifies distance to object's outer boundary
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- Represent object in depth map textures
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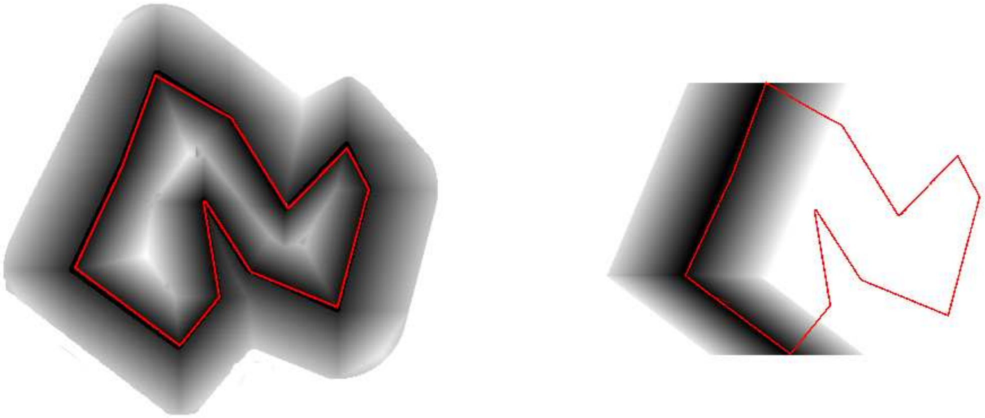

Exact distance map (left) and approximation using one orthogr. projection (right)

CD - Implicit Model Representation (Cont'd)

Depth Maps (DM)

Collider object information from rendering contains

1. $dist(x, y)$: distance to object w.r.t. projection direction
2. Normal vector $\hat{\mathbf{n}}(x, y)$ at the relevant object surface point
3. $T_{OC \to DC}$ transforms from object- to DM coordinates
4. z_{scale} to compensate for possible z-scaling by $T_{OC \to DC}$

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Distance measuring for point $\mathbf{P} \in \mathbb{R}^3$ (in case of orthographic projection):

Map to DC: $\mathbf{P}' = (p'_x, p'_y, p'_z)^T = T_{OC \to DC}\mathbf{P}$

Distance value: $f(\mathbf{P}) = z_{scale} \cdot \left(dist(p'_x, p'_y) - p'_z\right)$

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Several DMs better approximate the object boundary

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Several DMs better approximate the object boundary

Resulting distance value from values $f_1(\mathbf{P}), f_2(\mathbf{P}), \ldots$

$$f(\mathbf{P}) = \begin{cases} \max\{f_i(\mathbf{P})\} & \text{if } f_i(\mathbf{P}) < 0 \; \forall i \\ \min\{f_i(\mathbf{P}) : f_i(\mathbf{P}) > 0\} & \text{else} \end{cases}$$

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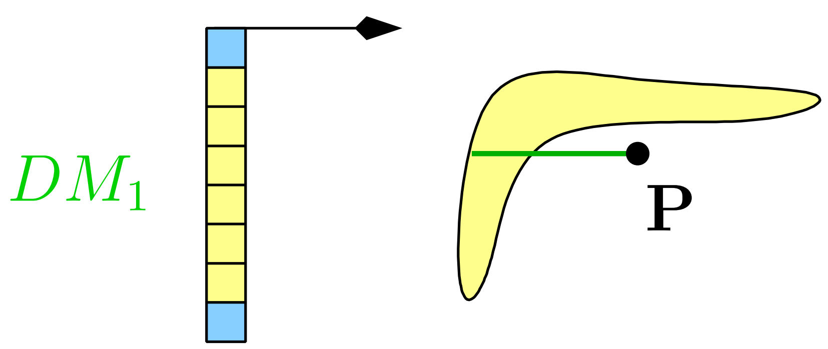

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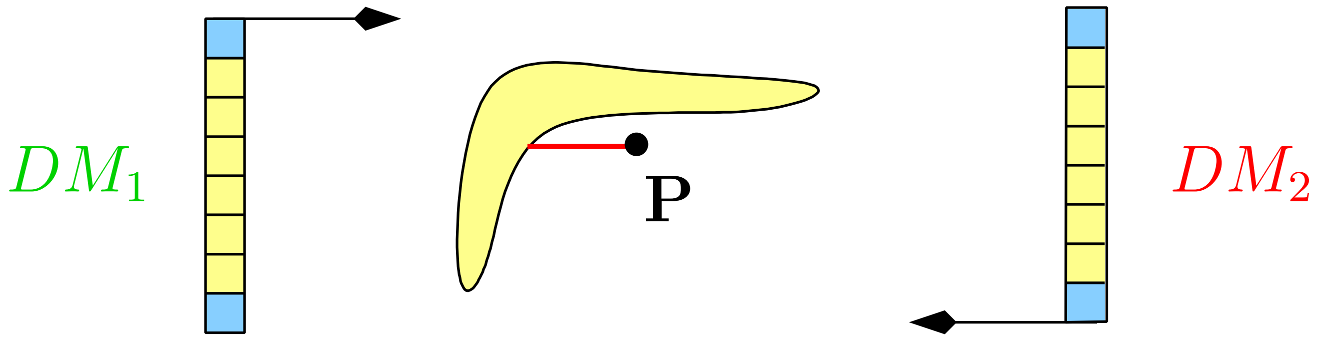

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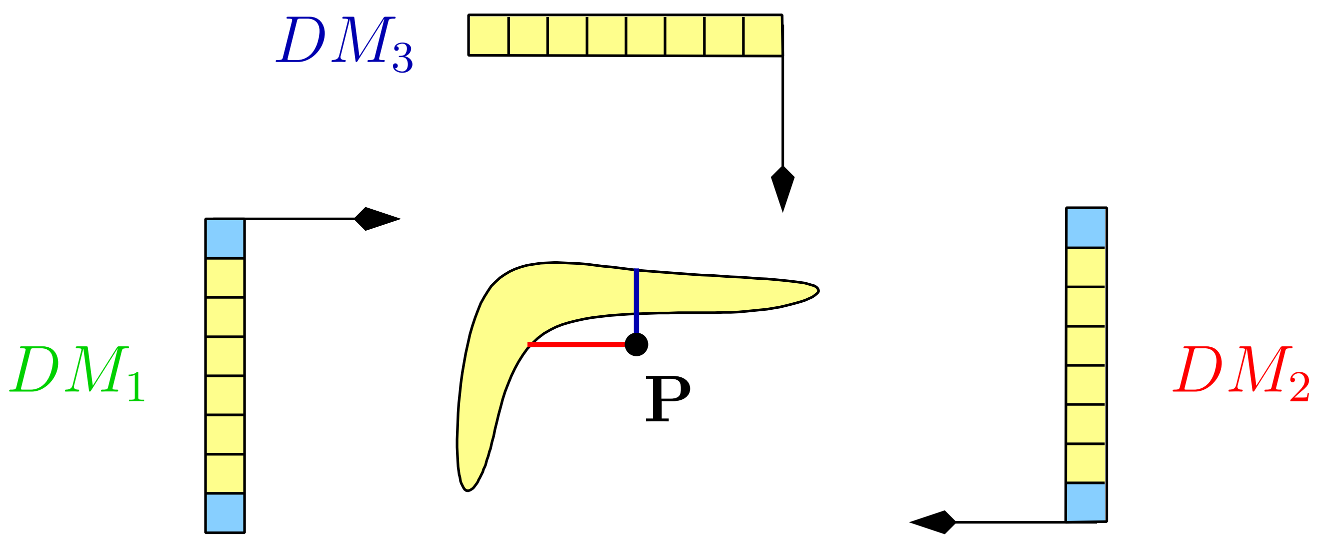

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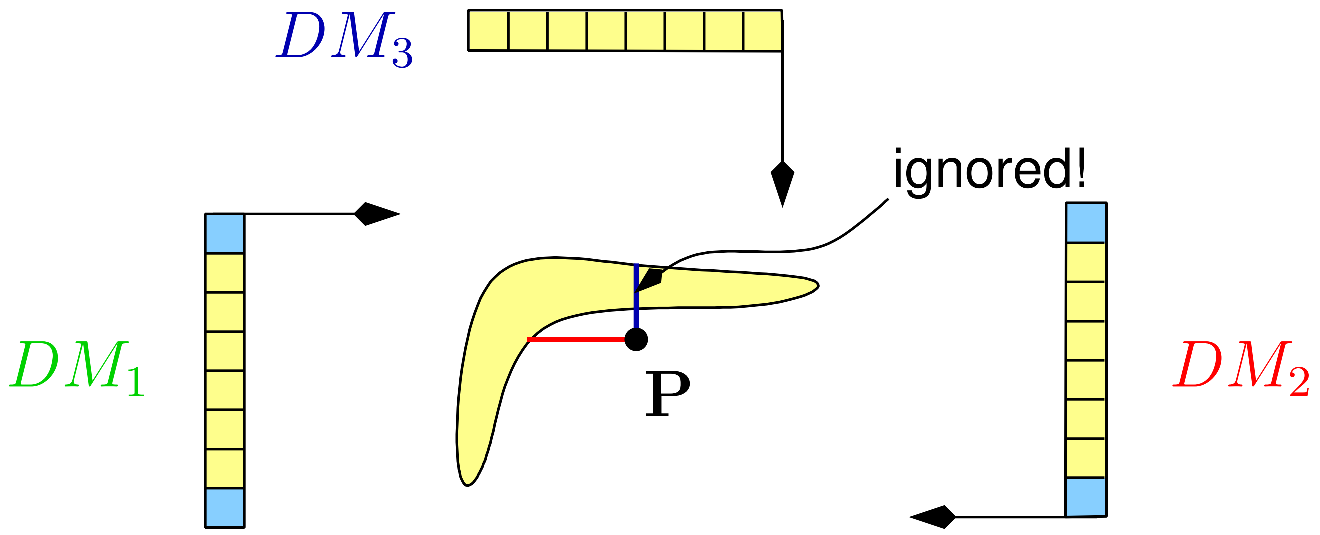

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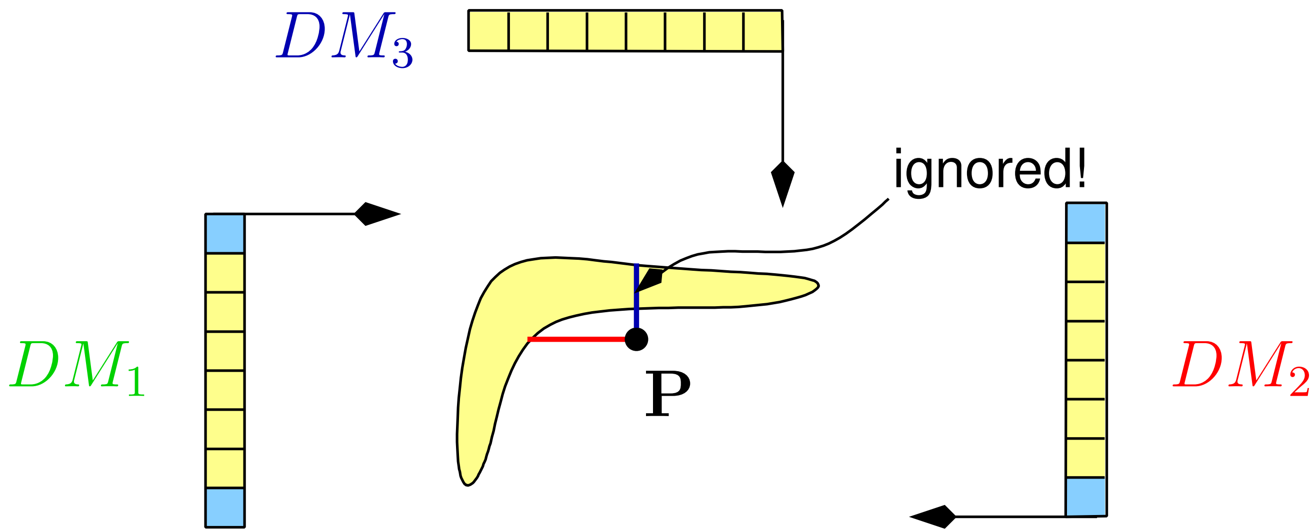

Update rule: $\left\{ \vee \begin{matrix} (f(\mathbf{P}) < 0 \wedge f_i(\mathbf{P}) > f(\mathbf{P})) \\ (f_i(\mathbf{P}) > 0 \wedge f_i(\mathbf{P}) < f(\mathbf{P})) \end{matrix} \right\} \Rightarrow (f(\mathbf{P}) \leftarrow f_i(\mathbf{P}))$

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- space efficient storage (only unit vectors needed!)

  $\boxed{\Rightarrow \text{ use indexing technique into normal-texture}}$

- utilize complete normal-texture
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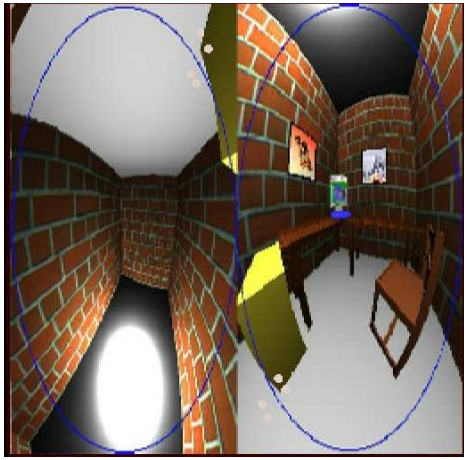
HW-based approaches

1. Cube maps: 3D-index!
2. Parabolic maps: Hemi-sphere & texture partially used

Environmental Cube map



Environmental dual parabolic map

CD - Normal Vector Representation (Cont'd)

L_1-parameterization:

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L_1-parameterization:

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l_1(s,t) = \begin{cases} \begin{pmatrix} s \\ t \\ 1-|s|-|t| \end{pmatrix} & \text{if } |s|+|t| \leq 1 \\ \begin{pmatrix} \operatorname{sgn}(s)(1-|t|) \\ \operatorname{sgn}(t)(1-|s|) \\ 1-|s|-|t| \end{pmatrix} & \text{if } |s|+|t| > 1 \end{cases}
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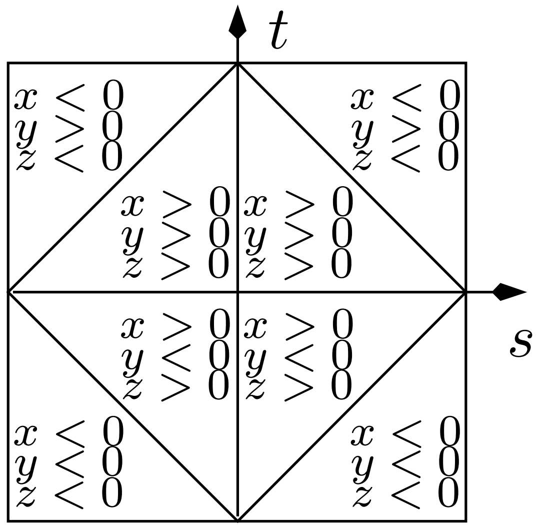

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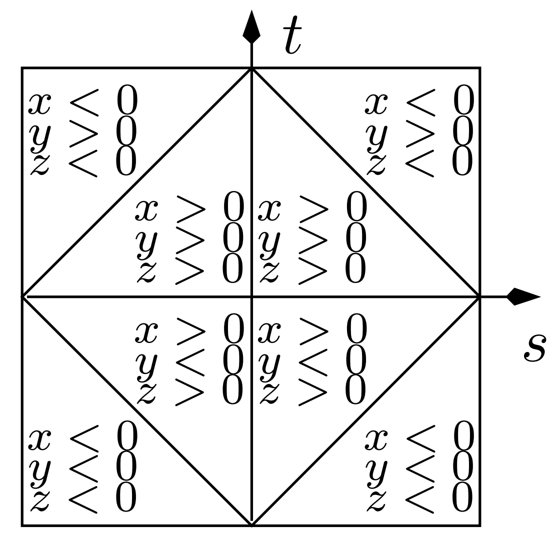
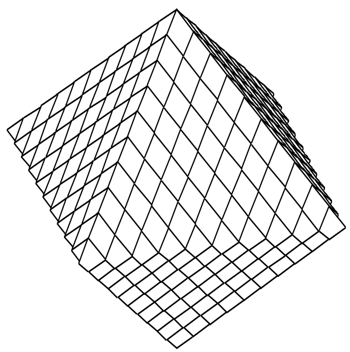
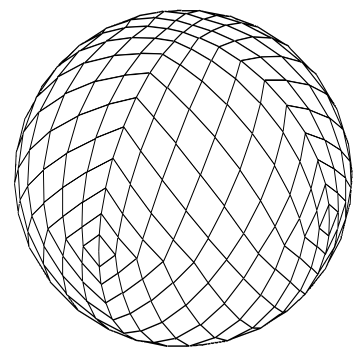


maps $[-1,1]^2$ to L_1-unit sphere (octahedron)



Applying l_1 to $[-1,1]^2$



Sampling of directions in 3D

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8**-bit fixed depth cube:**

- utilize cube map lookup $\Rightarrow$ omni-directional depth map
- perspective projection w.r.t. cube center
- $T_{OC \to DC}$ maps view volume to unit cube $[-1, 1]^3$
- determine distance w.r.t. view volume extends s_x, s_y, s_z:

$$f(\mathbf{P}) = \left(1 - \frac{dist(p'_x, p'_y, p'_z)}{\|\mathbf{P}'\|}\right) \left\| \begin{pmatrix} s_x \cdot p'_x \\ s_y \cdot p'_y \\ s_z \cdot p'_z \end{pmatrix} \right\|, \quad \mathbf{P}' = T_{OC \to DC}\mathbf{P}$$

Results

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Performance on NVIDIA Geforce FX 5900 XT

- Only particle simulation: 1024^2 particles, 10 fps

\+ depth sorting & one depth cube: 512^2 particles, 15 fps

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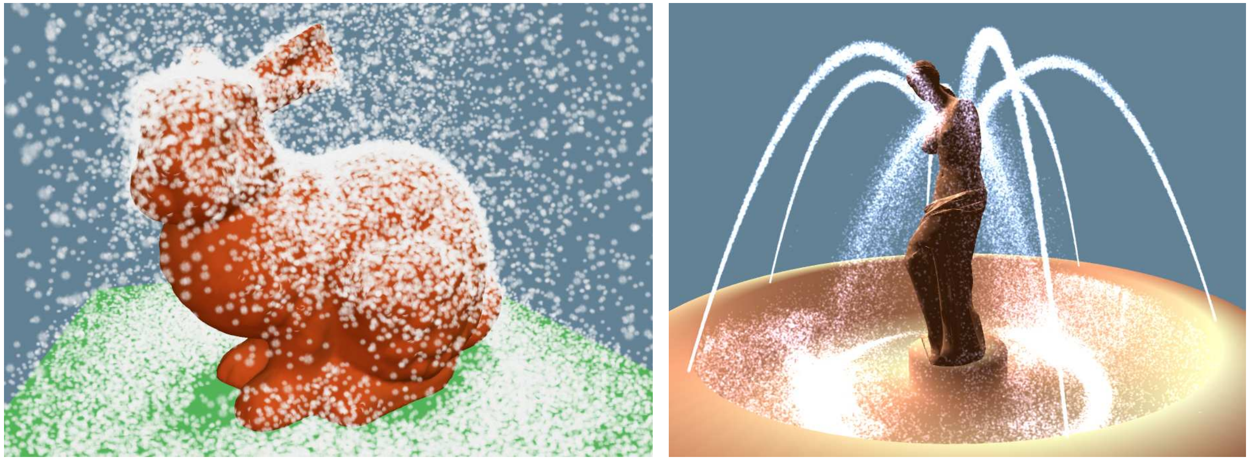
Bunny in the snow at 15 fps: 512^2 particles, depth sorting, one depth cube, one 16-bit fixed front & back DM

Venus fountain at 10 fps: 512^2 particles, three 16-bit fixed front & back, one 8-bit fixed DM



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Other functionality like

- improved integer arithmetic
- improved modulo operators

would help, e.g. for parallel sorting

Conclusion & Future Work

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  - “stream processing” paradigm for state-preserving PS
  - simulation and collision reaction
  - parallel sorting for non-commutative blending
- collision detection based on implicit models
  - DM with orthographic & perspective projection
  - various formats for efficient DM storage
  - L_1 parameterization to represent normals

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Future Work

- applying L_1-parameterization, e.g. as reflection map
- handling linked particles
- GPU based collision detection between (complex) objects