Tutorial:

Real-Time Collision Detection for Dynamic Virtual Environments

Bounding Volume Hierarchies

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Outline

- Introduction
- Bounding Volume Types
- Hierarchy
  - Hierarchy Construction
  - Hierarchy Update
  - Hierarchy Traversal
- Comparison Rigid-Deformable Objects
- Examples and Conclusion

Introduction

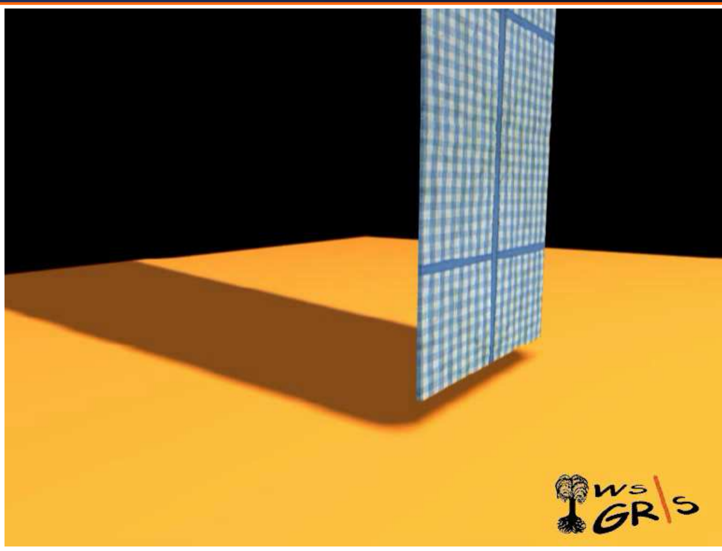
Problem of Collision Detection:

Object representations in simulation environments
do not consider impenetrability.

Collision Detection: Detection of interpenetrating objects.

The problem is encountered in
- computer-aided design and machining (CAD/CAM),
- robotics,
- automation, manufacturing,
- computer graphics,
- animation and computer simulated environments.

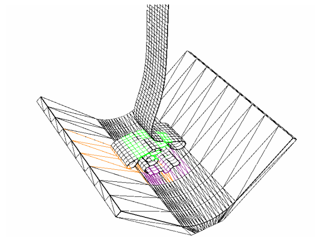
Introduction



Introduction

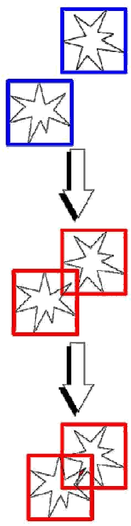
Definition of Bounding Volume Hierarchy (BVH):

Each node of a tree is associated with a subset of primitives of the objects together with a bounding volume (BV) that encloses this subset with the smallest instance of some specified class of shape.



Introduction

Use these BVs as simplified surface represen-tation for fast approximate collision detection test:



Examples of BVs:
- **Spheres**
- **Discrete oriented polytopes (k-DOPs)**
  Axis-aligned bounding boxes (AABB)
- **Object-oriented bounding boxes (OBB)**

- Check bounding volumes to get the information whether bounded objects **could** interfere.
- Avoid checking all object primitives against each other.
- Assumption that collisions between objects are rare.

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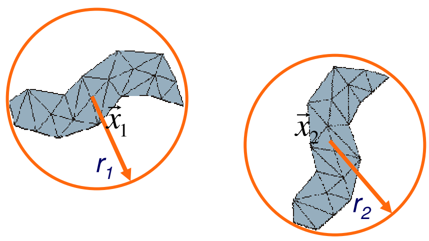
Bounding Volumes

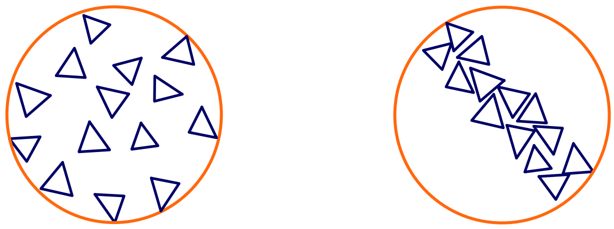
Spheres are represented by center $\vec{x}$ and radius *r*.



Two spheres do not overlap if $(\vec{x}_1 - \vec{x}_2)\cdot(\vec{x}_1 - \vec{x}_2) > (r_1 + r_2)^2$

Bounding Volumes

Sphere as bounding volume:

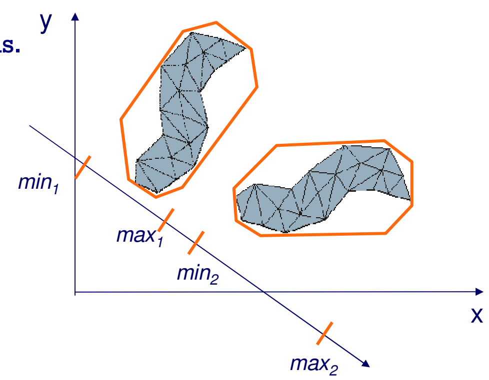


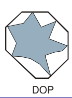
Bounding Volumes

Discrete oriented polytopes (*k*-DOP) are a generalization of axis aligned bounding boxes (AABB) defined by *k* hyperplanes with normals in **discrete** directions (n_k: $n_{k,j} \in \{0,\pm 1\}$).

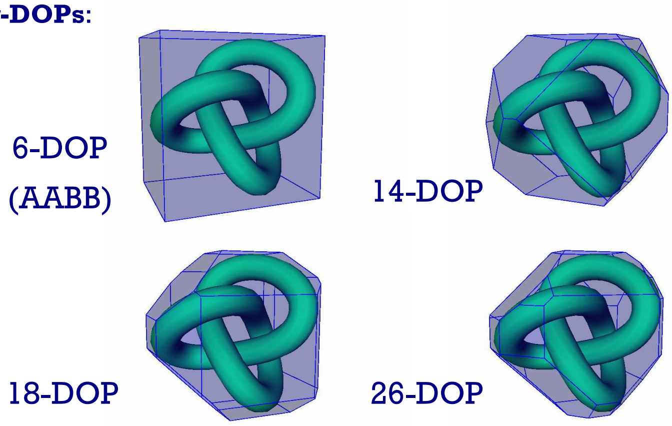
k-DOP is defined by *k*/2 pairs of *min*, *max* values in *k* directions.

Two *k*-DOPs do not overlap, if the intervals in one direction do not overlap.

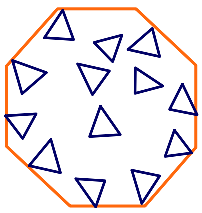




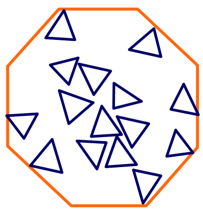
Different ***k*-DOPs**:



14-DOP as bounding volume:



optimal choice

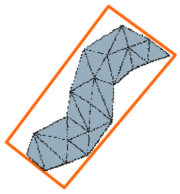


also good choice

Bounding Volumes

Object oriented bounding boxes (OBB) can be represented by the principal axes of a set of vertices. These axes have **no discrete orientation**. They move together with the object.

The axes are given by the Eigenvectors of the covariance matrix:



Centre of vertices $\vec{x}_i$: $\vec{\mu} = \frac{1}{n}\sum_{i=1}^{n} \vec{x}_i$

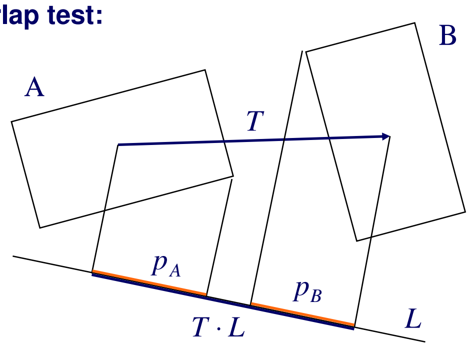
Covariance matrix: $C_{jk} = \frac{1}{n}\sum_{i=1}^{n} \bar{x}_{ij}\bar{x}_{ik}$ $\quad j,k = 1..3$

$\bar{x}_i = \vec{x}_i - \vec{\mu}$

OBB

Bounding Volumes

OBB overlap test:



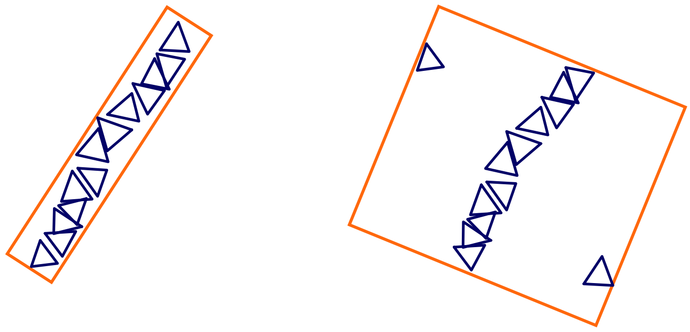
A and *B* do not overlap if: $\exists L : |T \cdot L| > p_A + p_B$

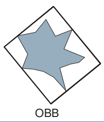
Problem: Find direction of *L*

OBB

Bounding Volumes

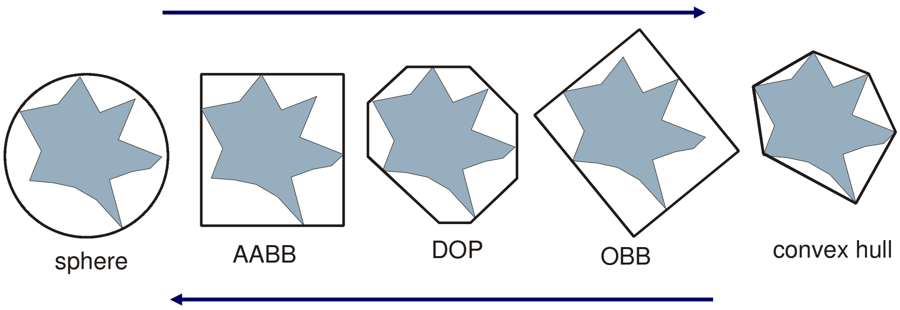
- Principal axes of an object are not always a good choice for the main axes of an OBB!
- Inhomogeneous vertex distribution can cause bad OBBs.





Bounding Volumes

Better approximation,
higher build and update costs



Smaller computational costs
for overlap test

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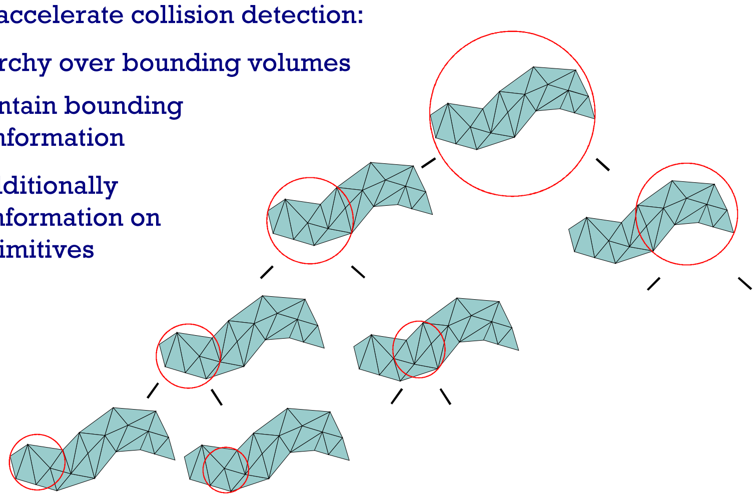
Bounding Volume Hierarchy

To further accelerate collision detection:

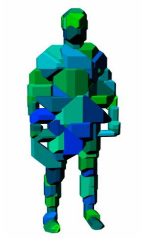
- use hierarchy over bounding volumes
- nodes contain bounding volume information
- leaves additionally contain information on object primitives



Hierarchy Construction

Parameters

- Bounding volume
- Type of tree (binary, 4-ary, k-d-tree, …)
- Bottom-up/top-down
- Heuristic to subdivide/group object primitives or bounding volumes
- How many primitives in each leaf of the BV tree



Goals

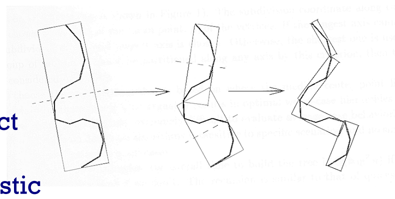
- Balanced tree
- Tight-fitting bounding volumes
- Minimal redundancy (primitives in more than one BV per level)

Hierarchy Construction

Bottom-Up

- Start with object-representing primitives
- Fit a bounding volume to given number of primitives
- Group primitives and bounding volumes recursively
- Stop in case of a single bounding volume at a hierarchy level

Top-Down

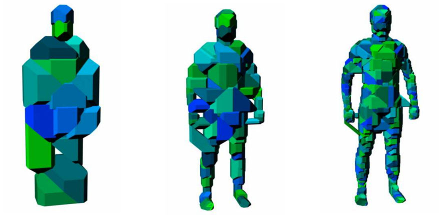


- Start with object
- Fit a bounding volume to the object
- Split object and bounding volume recursively according to heuristic
- Stop, if all bounding volumes in a level contain less than *n* primitives

Hierarchy Construction

Top-Down Node-split:

- Split *k*-DOP using heuristic:
  - Try to minimize volume of children (Zachmann VRST02).
  - Split along the longest side of the k-DOP (Mezger et al. WSCG03).

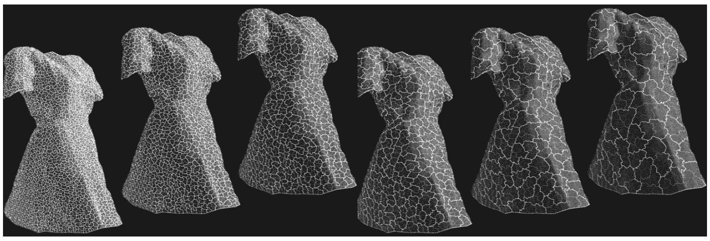


- The splitting continues until n single elements remain per leaf.

Hierarchy Construction

Bottom-Up Node-grouping:

- Group nodes using heuristic:
  - Try to get round-shaped patches by improving a shape factor for the area (Volino et al. CGF94).



- Group until all elements are grouped and the root node of the hierarchy is reached.

Hierarchy Update

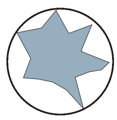
Updating is necessary in each time step due to movement/deformation of simulated object.

Difference between rigid and deformable objects:

- For rigid objects: transformations can be applied to complete object.
- For deformable objects: all BVs need to be updates separately.
  - Update is possible top-down or bottom-up.
  - To avoid a complete update of all nodes in each step, different update strategies have been proposed.

Hierarchy Update

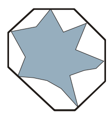
Some object transformations can be simply applied to all elements of the bounding-volume tree:



sphere

Spheres

- Translation, rotation



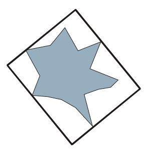
DOP

Discrete Orientation Polytopes

- Translation, no rotation
  (discrete orientations of *k* hyperplanes for all objects)

Object-Oriented Bounding Boxes

- Translation, rotation
  (box orientations are not fixed)



OBB

Hierarchy Update

Larsson and Akenine-Möller (EG 2001):

- If many deep nodes are reached, bottom-up update is faster.
- For only some deep nodes reached, top-down update is faster.

-> Update top half of hierarchy bottom-up

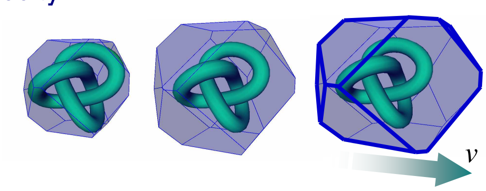
-> only if non-updated nodes are reached update them top-down.

- Reduction of unnecessarily updated nodes!
- Leaf information of vertices/faces has to be stored also in internal nodes -> higher memory requirements.

Hierarchy Update

Mezger et al. (WSCG 2003):

- Inflate bounding volumes by a certain distance depending on velocity.



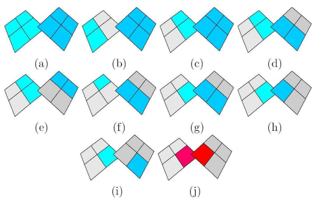
Update is only necessary if enclosed objects moved farther than that distance.

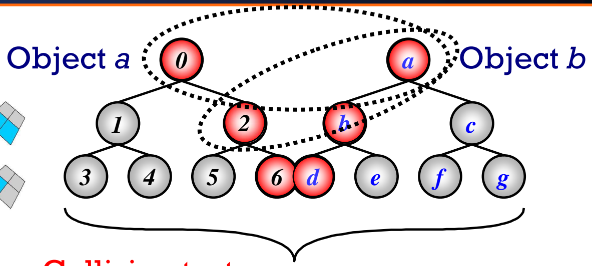
-> Fewer updates necessary.

-> More false positive collisions of BVs.

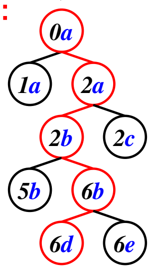
Hierarchy Traversal

Binary trees:





Collision test:

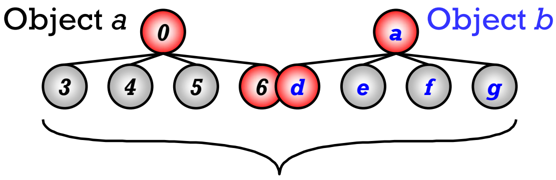


Minimize probability of intersection as fast as possible:

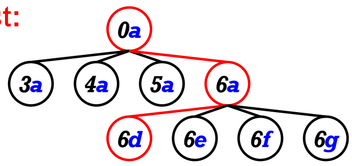
- Test node with smaller volume against the children of the node with larger volume.

Hierarchy Traversal

4-ary Trees:



Collision test:



Higher order trees:

- Fewer nodes
- Total update costs are lower
- Recursion depth during overlap tests is lower, therefore lower memory requirements on stack

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Comparison – Collision Detection for Rigid and Deformable Objects

Rigid Objects:

- use OBBs as they are usually tighter fitting and can be updated by applying translations and rotations.
- update complete BVH by applying transformations
- usually small number of collisions occur

Deformable Object:

- use DOPs as update costs are lower than for OBBs
- update by refitting or rebuilding each BV separately (top-down, bottom-up)
- high number of collisions may occur
- Self-collisions need to be detected
- use higher oder trees (4-ary, 8-ary)

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Example

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Interactive Cutting
and Sewing

Conclusions

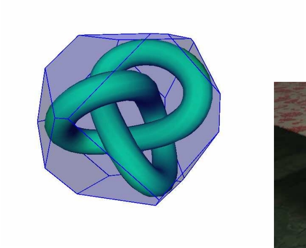
- BVHs are well-suited for animations or interactive applications, since updating can be done very efficiently.

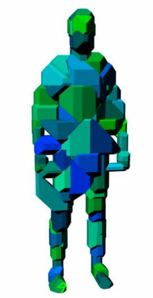
- BVHs can be used to detect self-collisions of deformable objects while applying additional heuristics to accelerate this process.

- BVHs work with triangles or tetrahedrons which allow for a more sophisticated collision response compared to a pure vertex-based response.

- Optimal BVH and BV dependent on application (collision or proximity detection) and type of objects (rigid / deformable object)

Thank you!





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