Real-Time Collision Detection for Dynamic Virtual Environments

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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

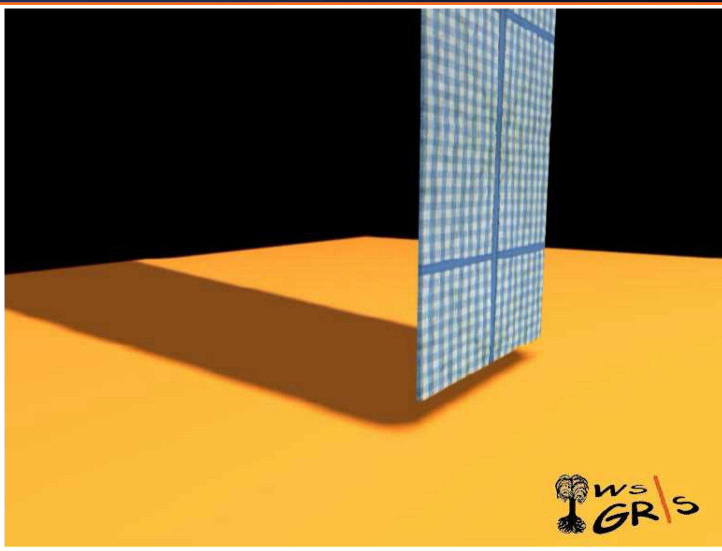
Problem of Collision Detection:

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.

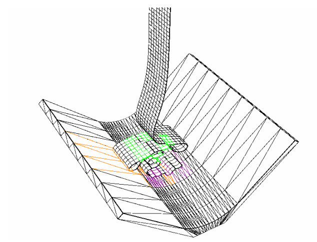
Introduction



Introduction

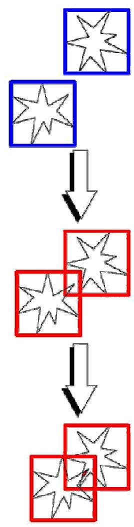
Definition of Bounding Volume Hierarchy (BVH):

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 representation 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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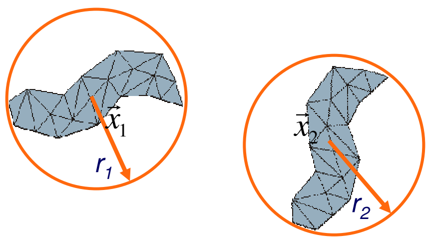
Bounding Volumes

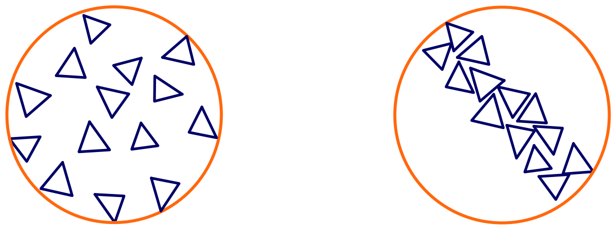
Spheres are represented by center $\vec{x}$ and radius *r*.



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:



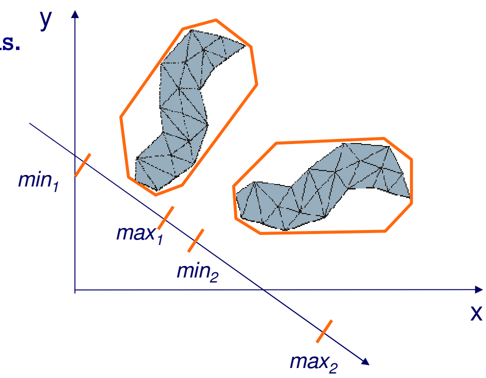
good choice   bad choice

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: $n_{k,j} \in \{0,\pm 1\}$).

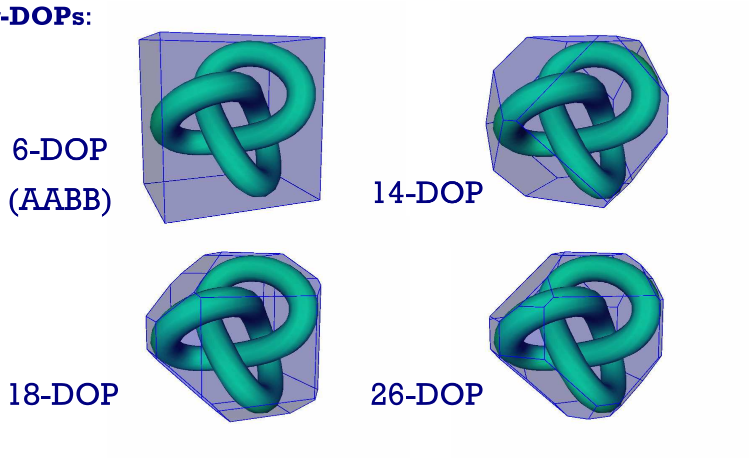
k-DOP is defined by *k*/2 pairs of *min*, *max* values in *k* directions.

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



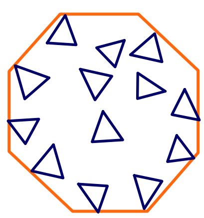
Bounding Volumes

Different ***k*-DOPs**:

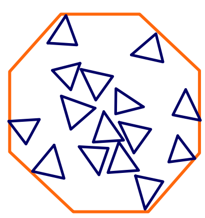


Bounding Volumes

14-DOP as bounding volume:



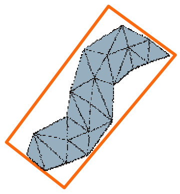
optimal choice



also good choice

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:



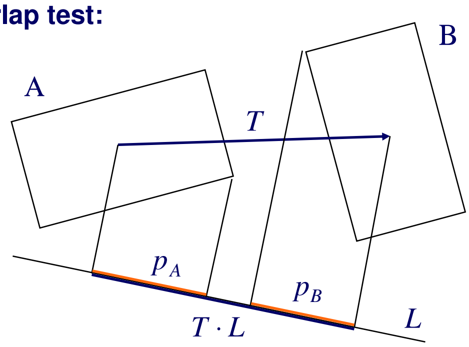
Centre of vertices $\vec{x}_i$: $\vec{\mu} = \frac{1}{n}\sum_{i=1}^{n}\vec{x}_i$

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

OBB overlap test:



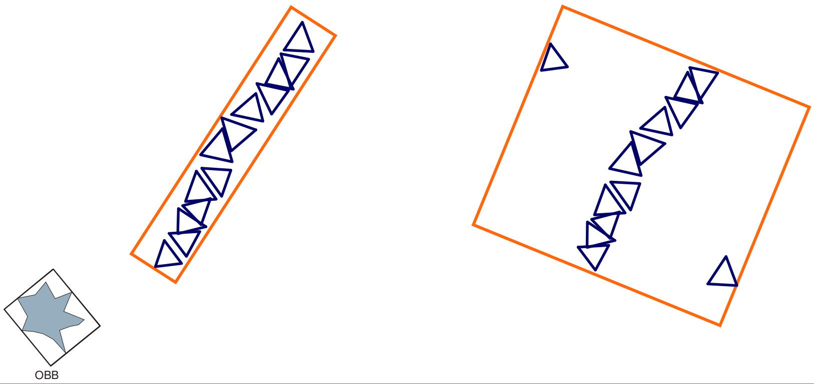
A and *B* do not overlap if: $\exists L : |T \cdot L| > p_A + p_B$

Problem: Find direction of *L*

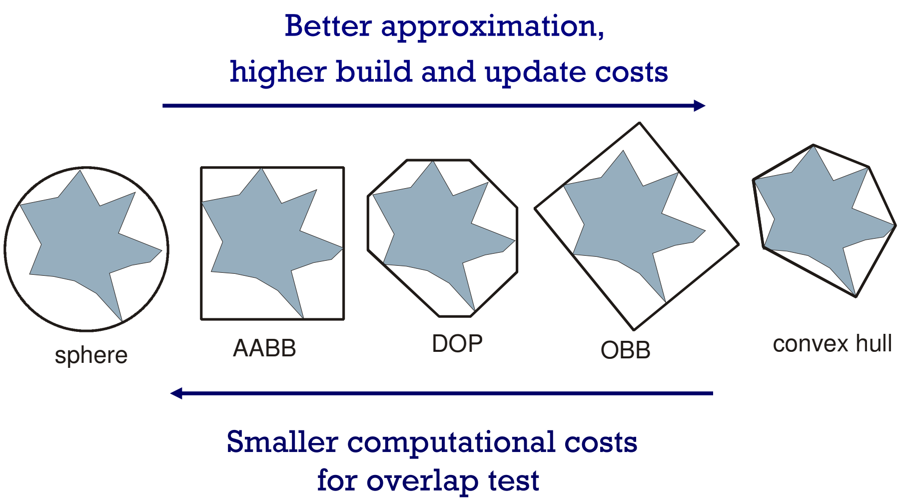
OBB

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



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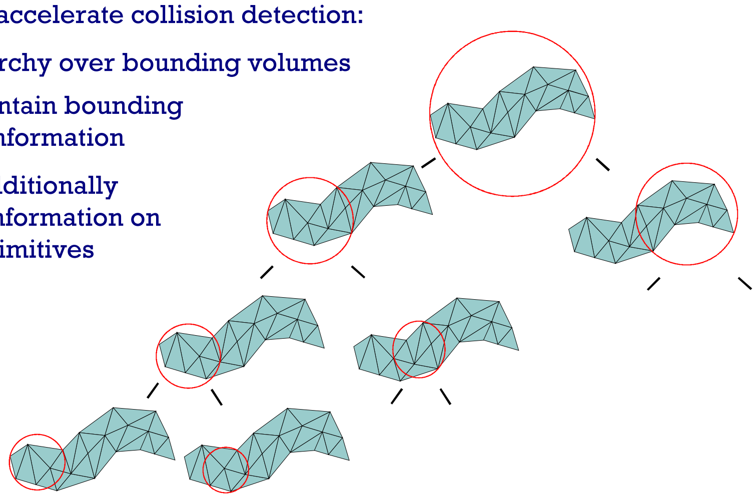
Bounding Volume Hierarchy

To further accelerate collision detection:

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



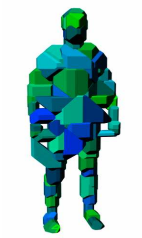
Hierarchy Construction

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)



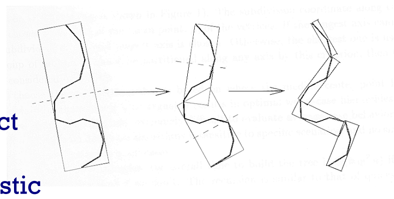
Hierarchy Construction

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

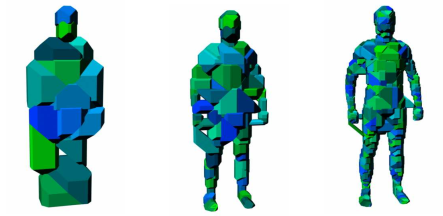
- Start with object
- Fit a bounding volume to the object
- Split object and bounding volume recursively according to heuristic
- Stop, if all bounding volumes in a level contain less than *n* primitives



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).

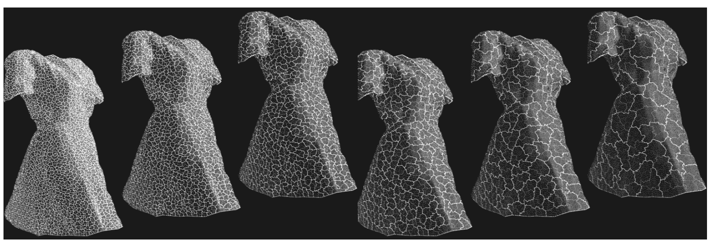


- The splitting continues until n single elements remain per leaf.

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

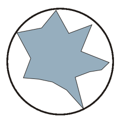
Updating is necessary in each time step due to movement/deformation of simulated object.

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

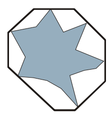
Some object transformations can be simply applied to all elements of the bounding-volume tree:



sphere

Spheres

- Translation, rotation



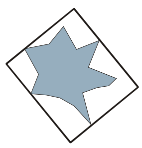
DOP

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

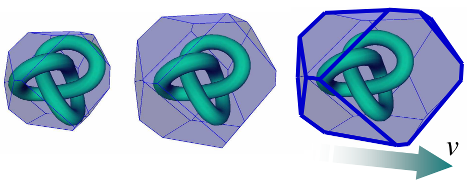
-> only if non-updated nodes are reached update them top-down.

- 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.



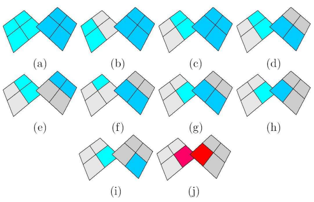
Update is only necessary if enclosed objects moved farther than that distance.

-> Fewer updates necessary.

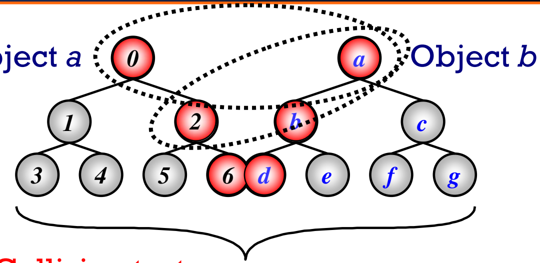
-> More false positive collisions of BVs.

Hierarchy Traversal

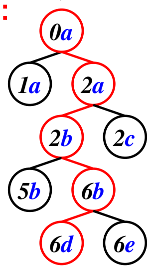
Binary trees:



Object *a* Object *b*



Collision test:



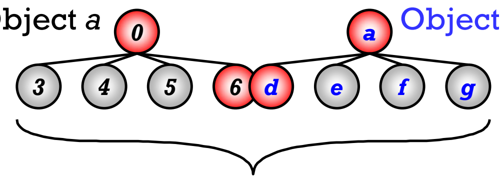
Minimize probability of intersection as fast as possible:

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

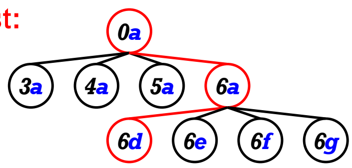
Hierarchy Traversal

4-ary Trees:

Object *a* Object *b*



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

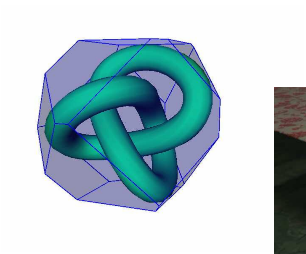
Interactive Cutting
and Sewing

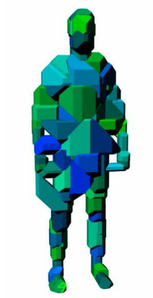
Conclusions

- 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 ...

Thank you!





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