Spatial Data Structures and Speed-Up Techniques

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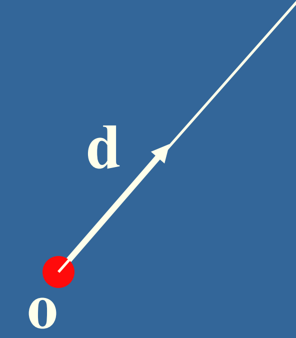
Have you done your homework ;-) ?

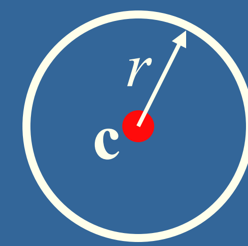
Exercises

- Create a function (by writing code on paper) that tests for intersection between:
  - two spheres
  - a ray and a sphere
  - view frustum and a sphere
  - Ray and triangle (e.g. use formulas from last lecture)
- Make sure you understand matrices:
  - Give a scaling matrix, translation matrix, rotation matrix and simple orthogonal projection matrix

Ray/sphere test



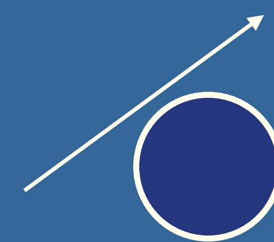
- Ray: $\mathbf{r}(t)=\mathbf{o}+t\mathbf{d}$
- Sphere center: $\mathbf{c}$, and radius r
- Sphere formula: $\|\mathbf{p}-\mathbf{c}\|=r$
- Replace $\mathbf{p}$ by $\mathbf{r}(t)$, and square it:



$$(\mathbf{o}+t\mathbf{d}-\mathbf{c})\cdot(\mathbf{o}+t\mathbf{d}-\mathbf{c})-r^2=0$$

$$t^2+2((\mathbf{o}-\mathbf{c})\cdot\mathbf{d})t+(\mathbf{o}-\mathbf{c})\cdot(\mathbf{o}-\mathbf{c})-r^2=0$$

$$ax^2+\mathrm{b}x+\mathrm{c}=0 \quad\Rightarrow\quad x=\frac{-b}{2a}\pm\sqrt{\left(\frac{\mathrm{b}}{2\mathrm{a}}\right)^2-\frac{c}{a}}$$



```
Bool raySphereIntersect(vec3f o, d, c, float r, Vec3f &hitPt) {
    float b = 2.0f*((o-c).dot(d)); // dot is implemented in class Vec3f
    float c = (o-c).dot(o-c);
    if(b*b/4.0f<c) return false;
    float t = -b/(2.0f) - sqrt(b*b/4.0f-c); // intersection for smallest t
    if (t<0) t = -b/(2.0f*a) + sqrt(b*b/4.0f-c); // larger t
    if (t<0) return false; else hitPt = o+d*t; // where * is an operator for vec mul
    return true;
}
```

Misc

- Half Time wrapup slides are available in “Schedule” on home page

- There is an Advanced Computer Graphics Seminar Course in sp 3+4, 7.5p
  - One seminar every week
    - Advanced CG techniques
  - Do a project of your choice.
  - Register to the course

Spatial data structures

- What is it?
  - Data structure that organizes geometry in 2D or 3D or higher
  - The goal is faster processing
  - Needed for most ”speed-up techniques”
    - Faster real-time rendering
    - Faster intersection testing
    - Faster collision detection
    - Faster ray tracing and global illumination
- Games use them extensively
- Movie production rendering tools always use them too
- (You may read ”Designing a PC Game Engine”. Link available on website)

TDA361 Computer Graphics

http://www.cse.chalmers.se/edu/course/TDA361/index.html

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- week 6: room HC1
- week 7: room HC3

NOTE 2: The follow-up course, DAT205 Advanced Computer Graphics, will run in study period 3+4 as usual, despite what studentportalen says.

Home page is continuously being updated

COURSE-PM

Course start: (sp2, week 1). Lectures each Wednesday 10-12, and Friday 9-12.
7,5 Högskolepoäng
Grades: U (failed), 3, 4, 5
Educational Level: Advanced
Institution: 37 - DATA- OCH INFORMATIONSTEKNIK
Teaching language: English

Teacher and Examiner: Ulf Assarsson, intern phone 1775 (031-7721775)
room 4115, floor 4, the corridor along Rännvägen, ED-huset E-mail: see above.
Course assistants: Erik Sintorn (erik dot sintorn at chalmers dot se), Ola Olsson (ola dot olsson at chalmers dot se), Markus Billeter (billeter at chalmers dot se)
Course webpage: http://www.cse.chalmers.se/edu/course/TDA361/
Course plan

Links:

- Link to home page at Studieportalen
- Seminar Course in Advanced Computer Graphics
- Links to related previous courses, now obsolete:
  - TDA361 Computer Graphics: 2010, 2009, 2008, 2007
  - TDA360 Datorgrafik 2006
  - Avancerad Datorgrafik 2006

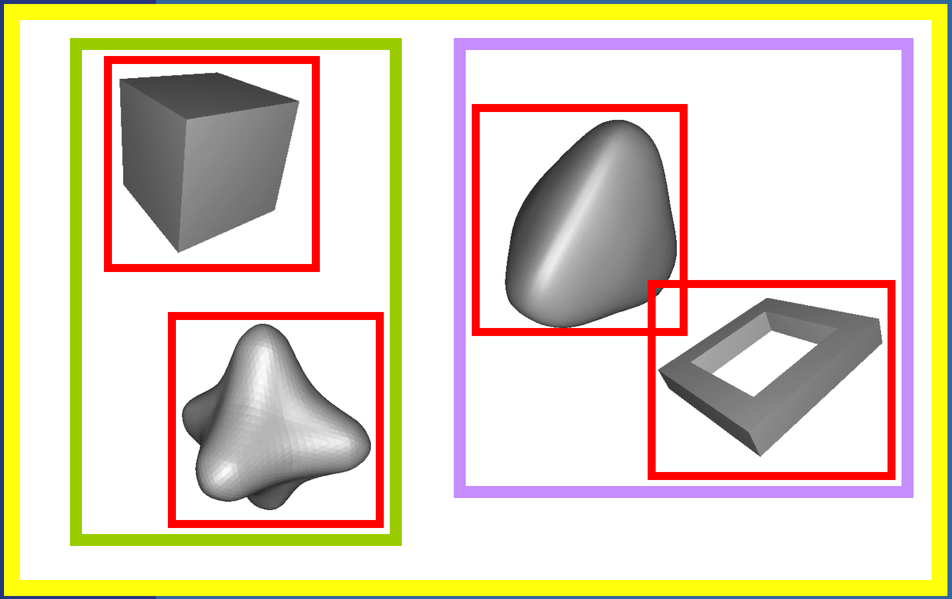
More Links:

- OpenGL Quick Reference Card.pdf
- OpenGL Reference Manual 3.0
- GLSL specification 1.30
- NVIDIA G80 OpenGL Programming.
- Sample textures for download
- Bump mapping using GLSL
- Real-Time Rendering website
- OpenGL Reference Manual - The Bluebook
- The OpenGL Programming Guide - The Redbook (html) (pdf)
- All OpenGL Manuals, including release 2.0.
- GLU Reference Manual, release 1.3.
- GLUT Reference Manual, release 3. How to open a window etc.
- OpenGL.org
- GLSL manual and quick reference guide and good GLSL Tutorial.
- Efficiency Issues for Ray Tracing, paper with optimization tricks for ray tracing.
- A Fast Voxel Traversal Algorithm for Ray Tracing, paper about grid traversal.
- MilkShape 3D, a free 3D-modeling application.
- Designing a PC Game Engine. A paper about "game engine design"
- L3DS open C++ code for loading and rendering 3ds-files.
- Cross Roads Converter between 3D formats.
- Converters for image, sound and 3D-models.
- Some 3D models.
- 3D models, converters etc.
- commandline-converter for images.
- 3D Planet - some 3D models.
- More 3D models 1
- More 3D models 2
- More 3D models 3

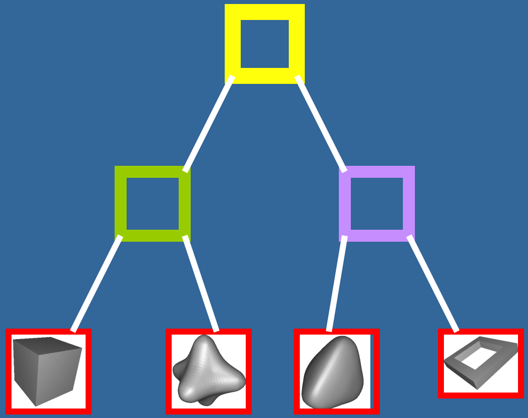
How?

- Organizes geometry in some hierarchy

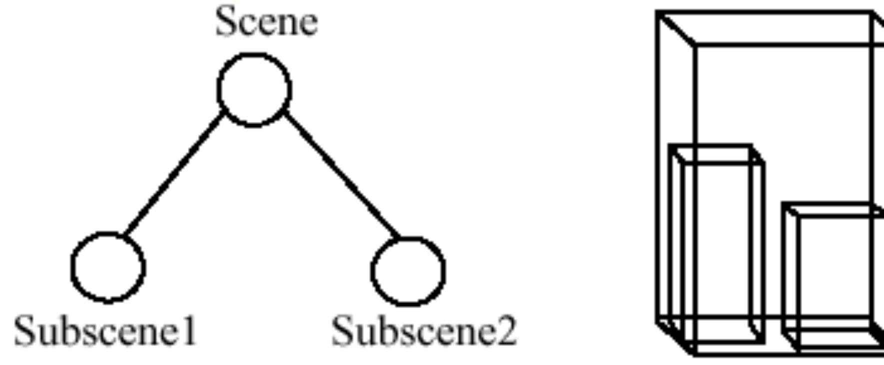
In 2D space



Data structure

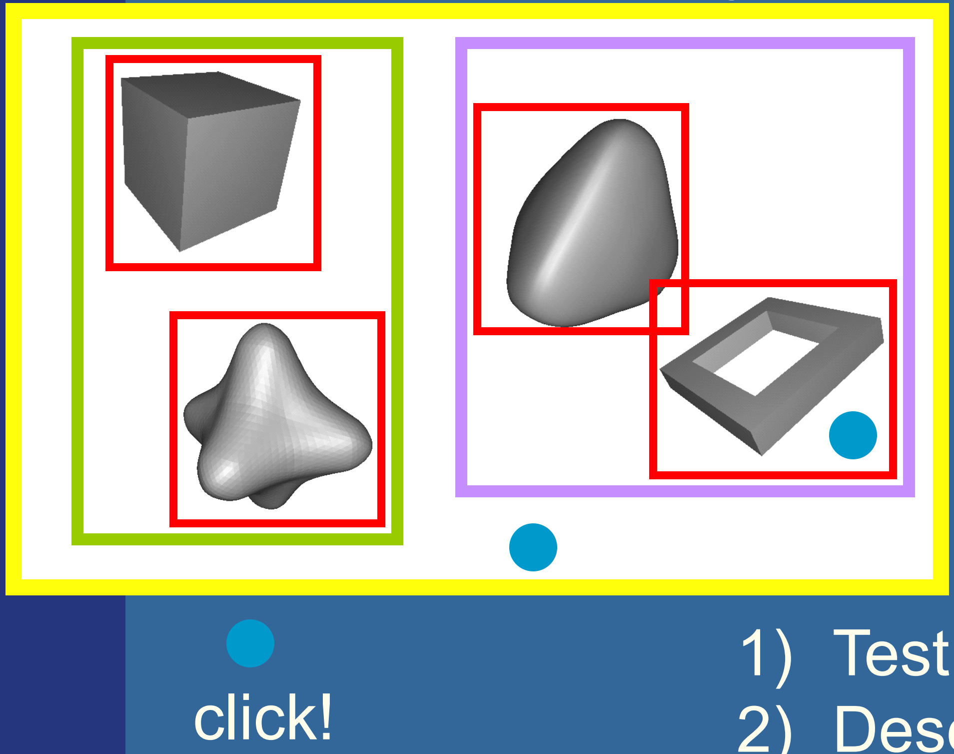


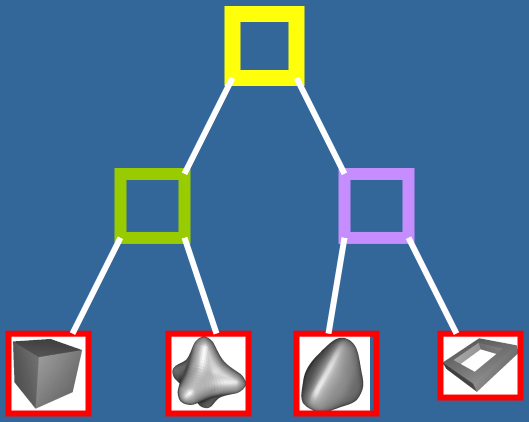
In 3D space:



What's the point?
An example

- Assume we click on screen, and want to find which object we clicked on

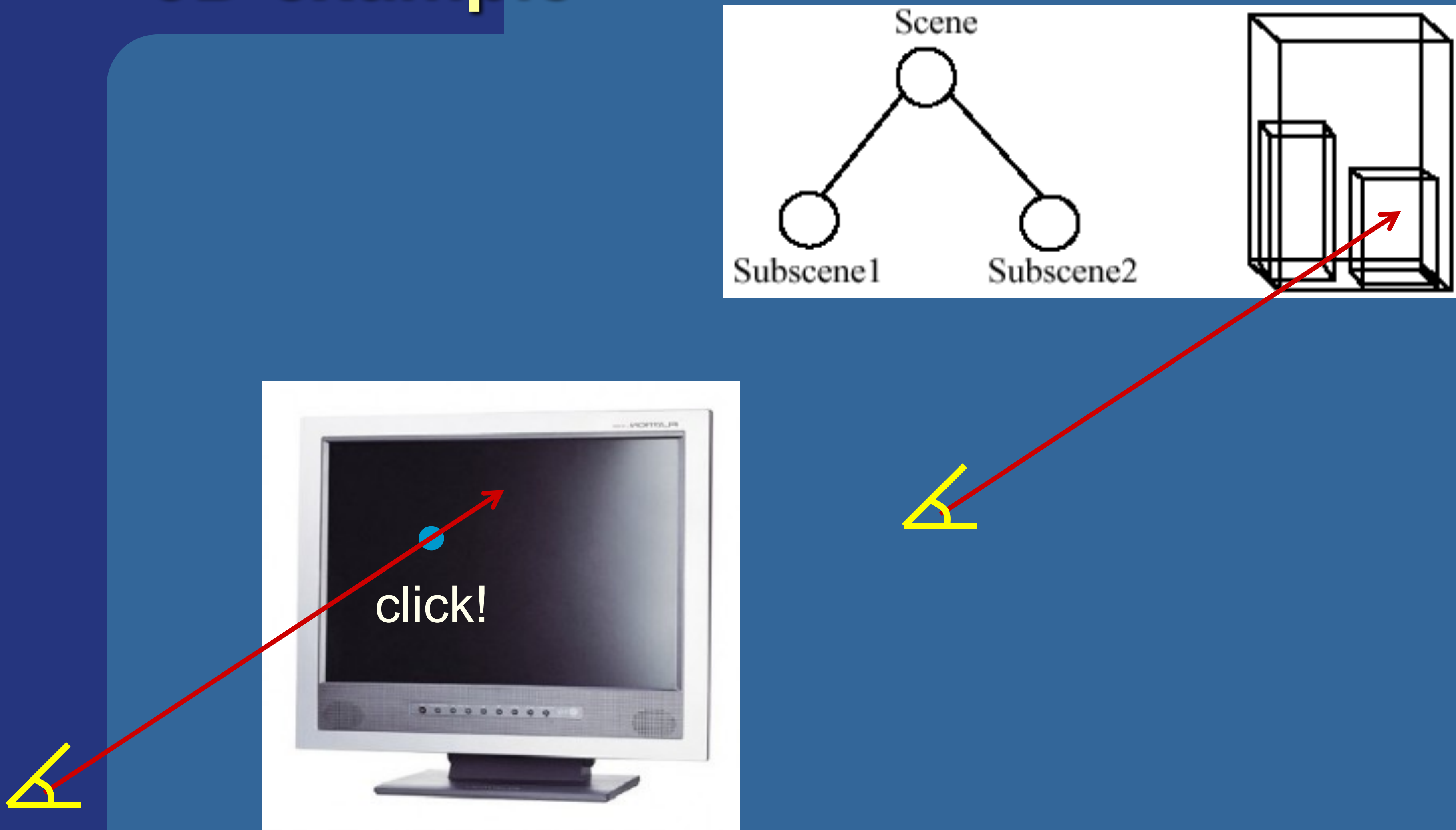




1) Test the root first
2) Descend recursively as needed
3) Terminate traversal when possible

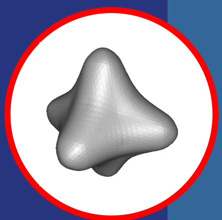
In general: get O(log n) instead of O(n)

3D example



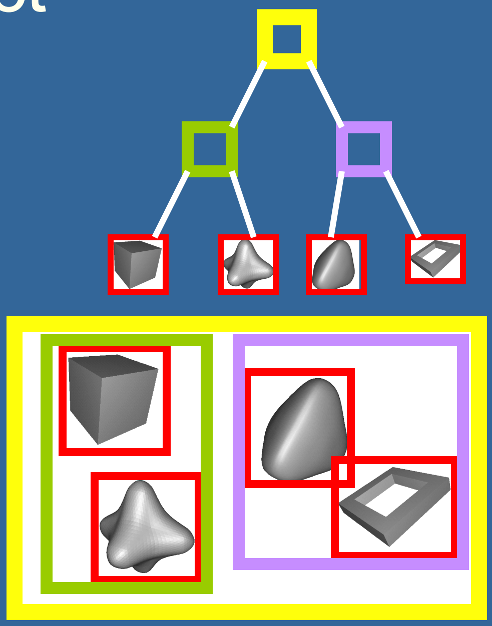
Bounding Volume Hierarchy (BVH)

- Most common bounding volumes (BVs):
  - Sphere
  - Boxes (AABB and OBB)



- The BV does not contibute to the rendered image -- rather, encloses an object

- The data structure is a *k*-ary tree
  - Leaves hold geometry
  - Internal nodes have at most *k* children
  - Internal nodes hold BVs that enclose all geometry in its subtree

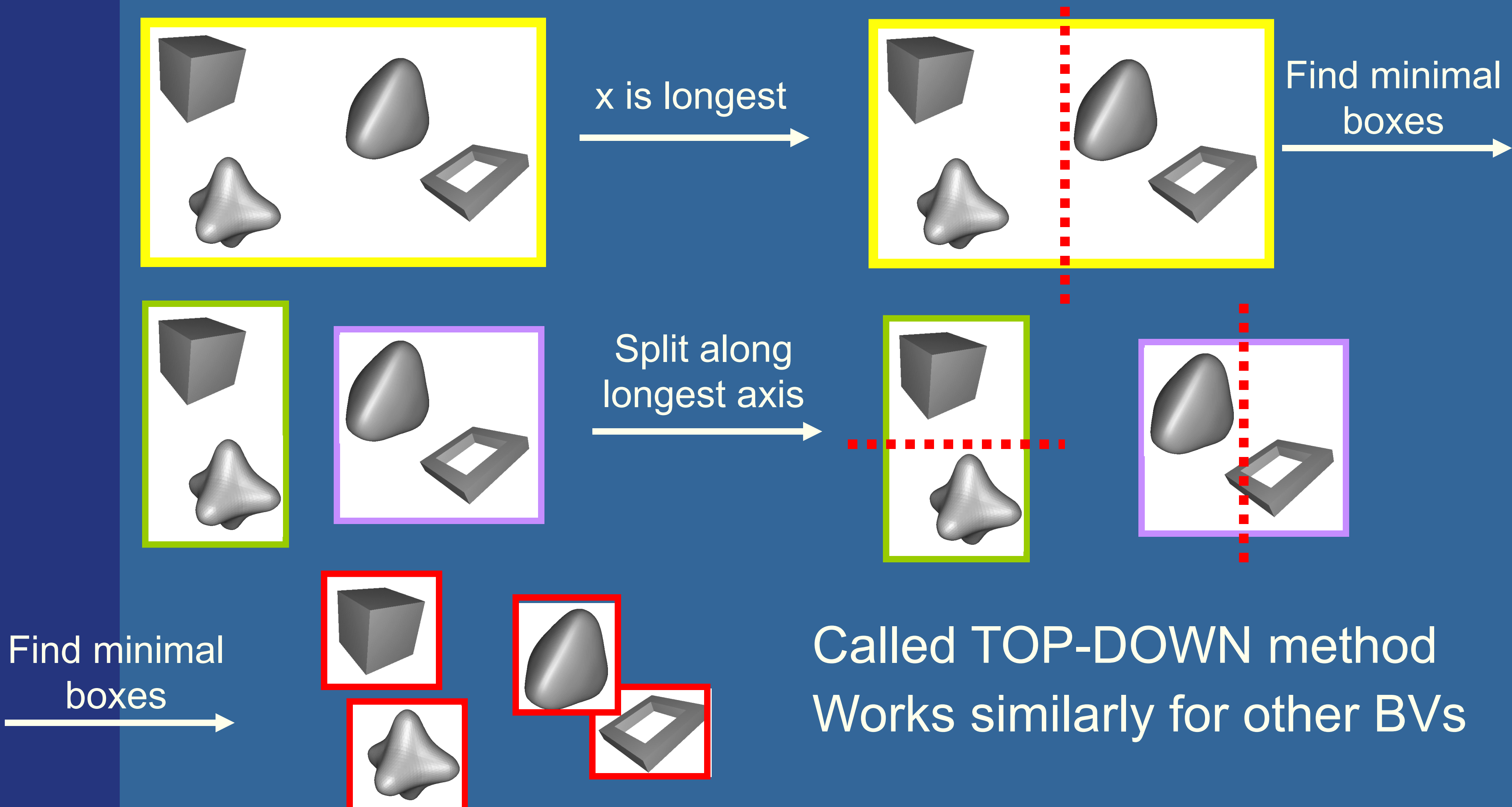


Some facts about trees

- *Height of tree, h,* is longest path from root to leaf
- *A balanced tree* is full except for possibly missing leaves at level h
- Height of <u>balanced</u> tree with n nodes: $\mathrm{floor}(\ \log_k(n)\ )$
- Binary tree (k=2) is the simplest
  - k=4 and k=8 is quite common for computer graphics as well

How to create a BVH? Example: BV=AABB

- Find minimal box, then split along longest axis



Called TOP-DOWN method

Works similarly for other BVs

Stopping criteria for Top-Down creation

- Need to stop recursion some time…
  - Either when BV is empty
  - Or when only one primitive (e.g. triangle) is inside BV
  - Or when $<n$ primitives is inside BV
  - Or when recursion level l has been reached
- Similar critera for BSP trees and octrees

Example

Killzone (2004-PS2) used kd-tree / AABB-tree based system for the collision detection

Kd-tree = Axis Aligned BSP tree

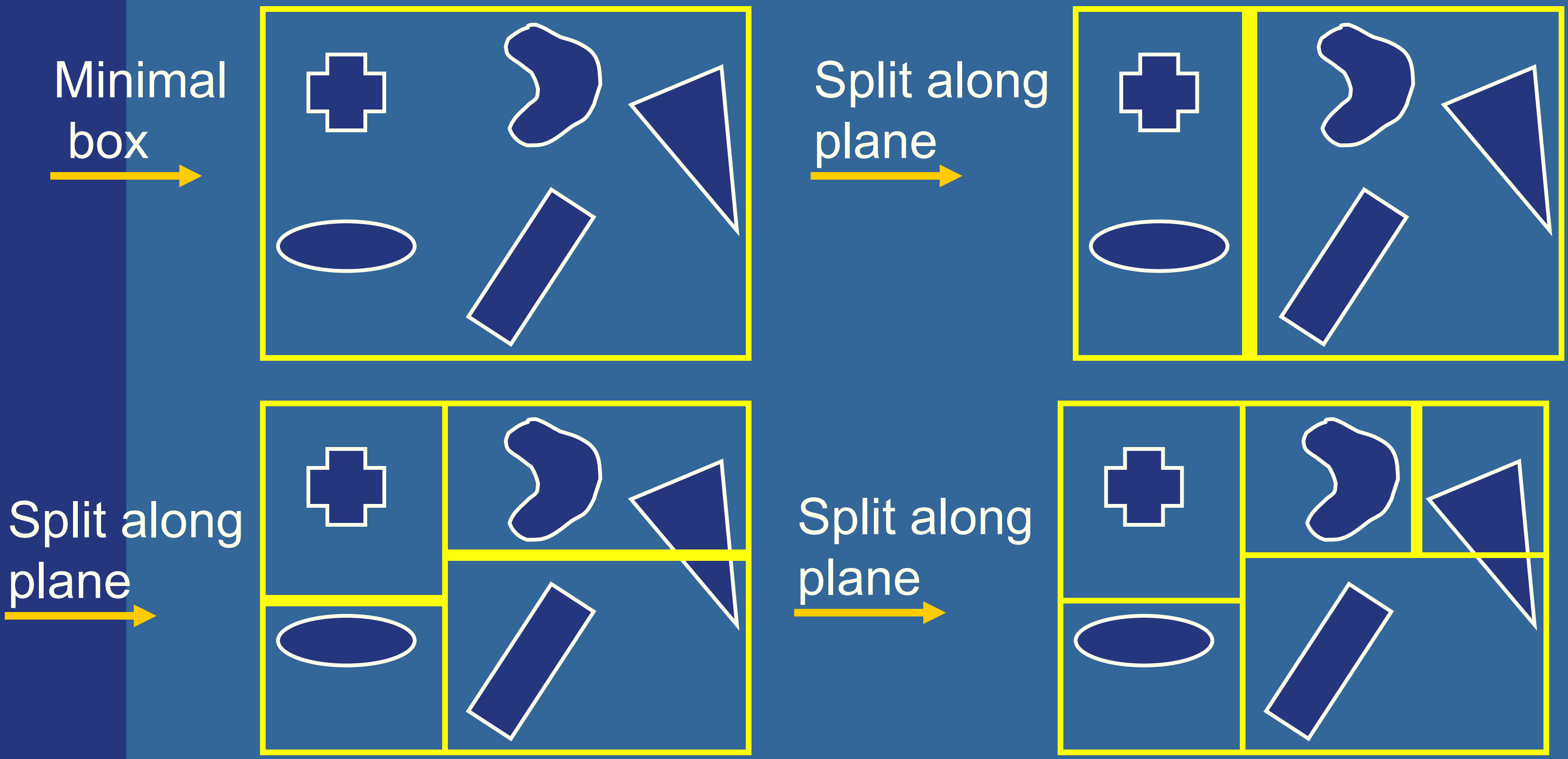
Binary Space Partitioning (BSP) Trees

- Two different types:
  - Axis-aligned
  - Polygon-aligned
- General idea:
  - Split space with a plane
  - Divide geometry into the space it belongs
  - Done recursively
- If traversed in a certain way, we can get the geometry sorted back-to-front or front-to-back w.r.t. a camera position
  - Exact for polygon-aligned
  - Approximately for axis-aligned

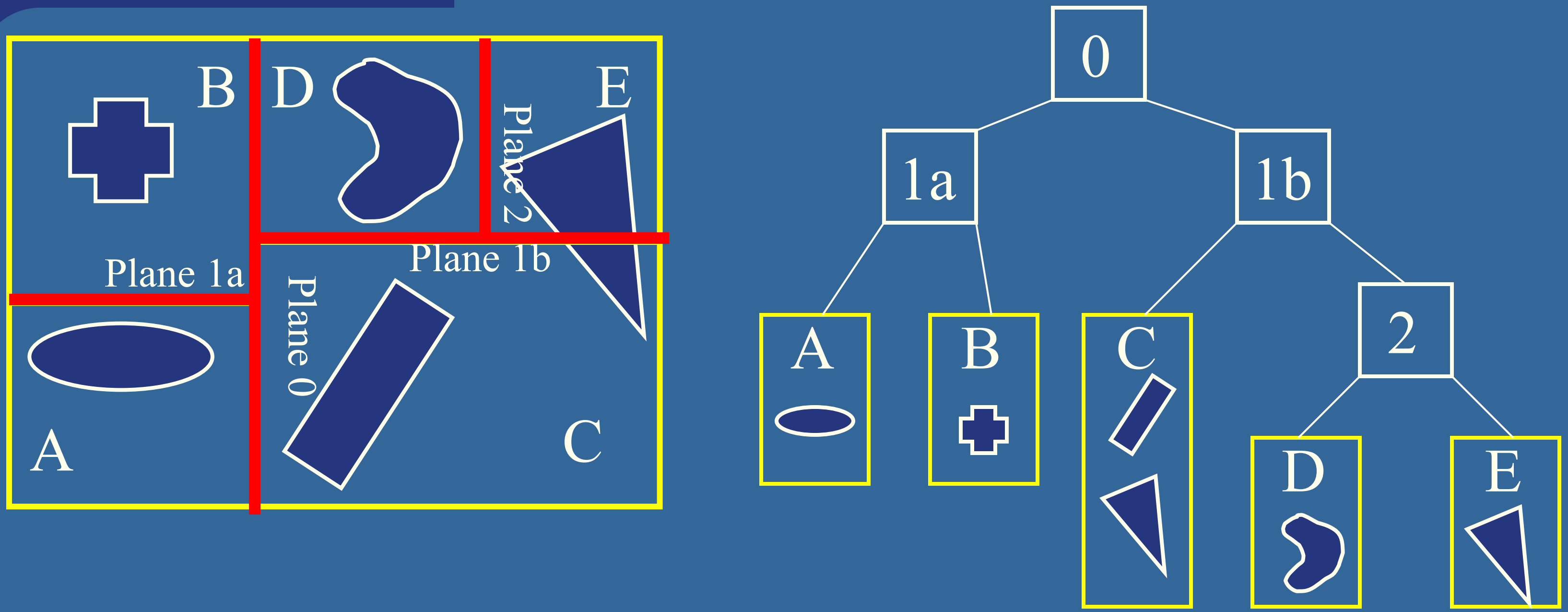
- Split space with a plane
- Divide geometry into the space it belongs
- Done recursively

Axis-Aligned BSP tree (1)

- Can only make a splitting plane along x,y, or z



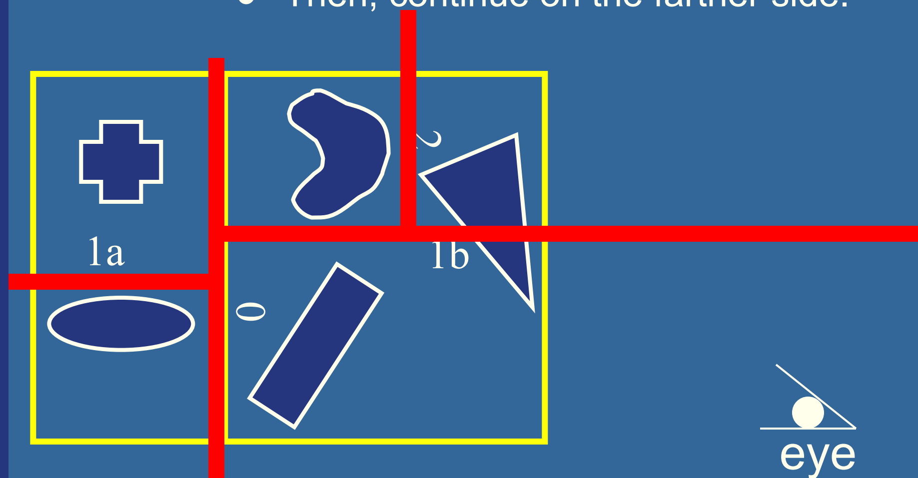
Axis-Aligned BSP tree (2)

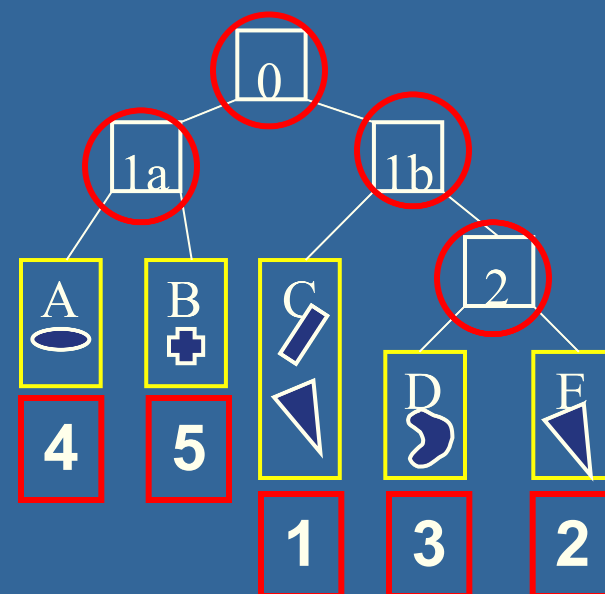


- Each internal node holds a divider plane
- Leaves hold geometry
- Differences compared to BVH
  - BSP tree encloses entire space and provides sorting
  - The BV hierarchy can have spatially overlapping nodes(no sort)
  - BVHs can use any desirable type of BV

Axis-aligned BSP tree
Rough sorting

- Test the planes, recursively from root, against the point of view. For each traversed node:
  - If node is leaf, draw the node’s geometry
  - else
    - Continue traversal on the ”hither” side with respect to the eye (to sort front to back)
    - Then, continue on the farther side.

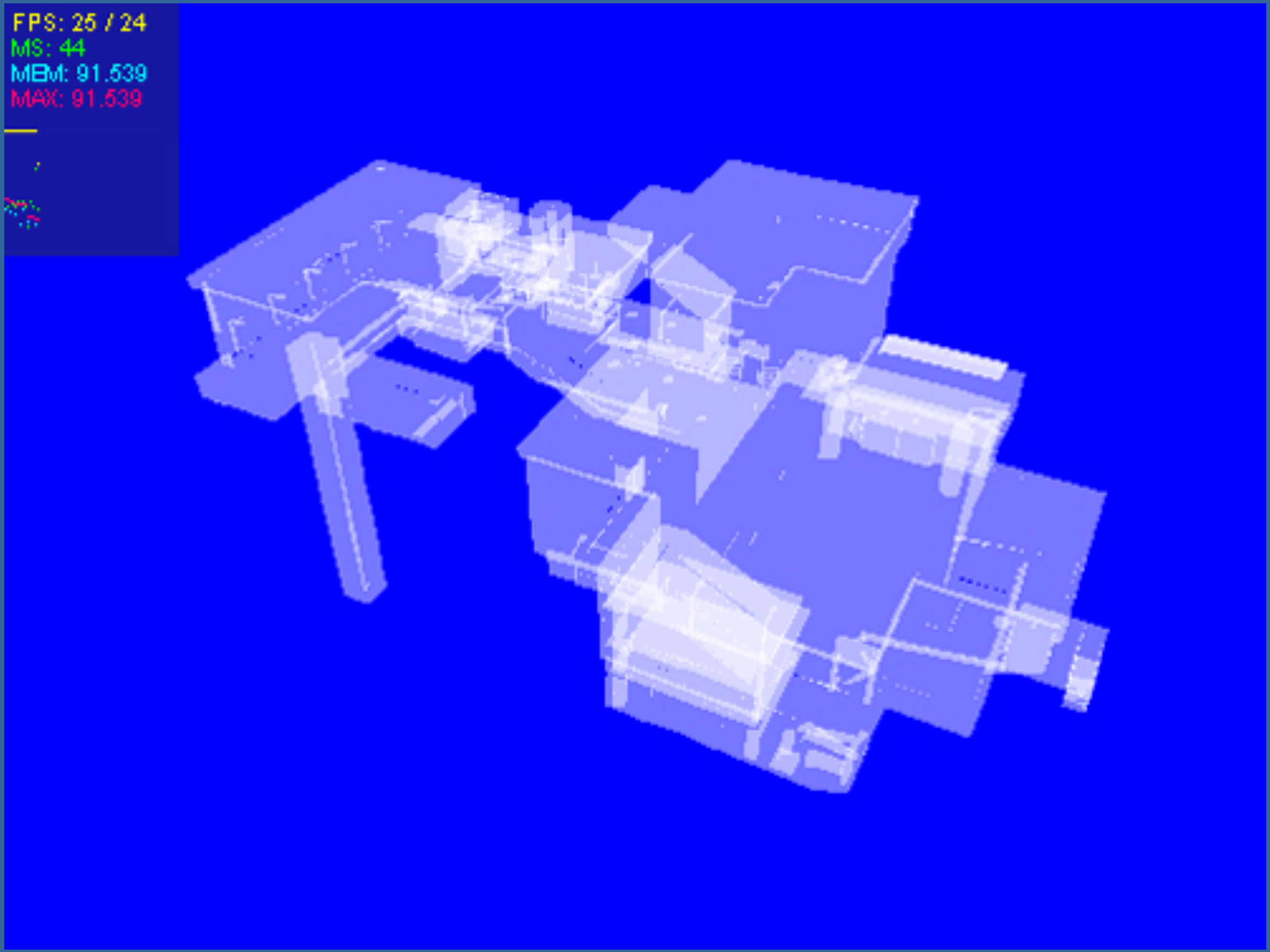




- Works in the same way for polygon-aligned BSP trees --- but that gives exact sorting

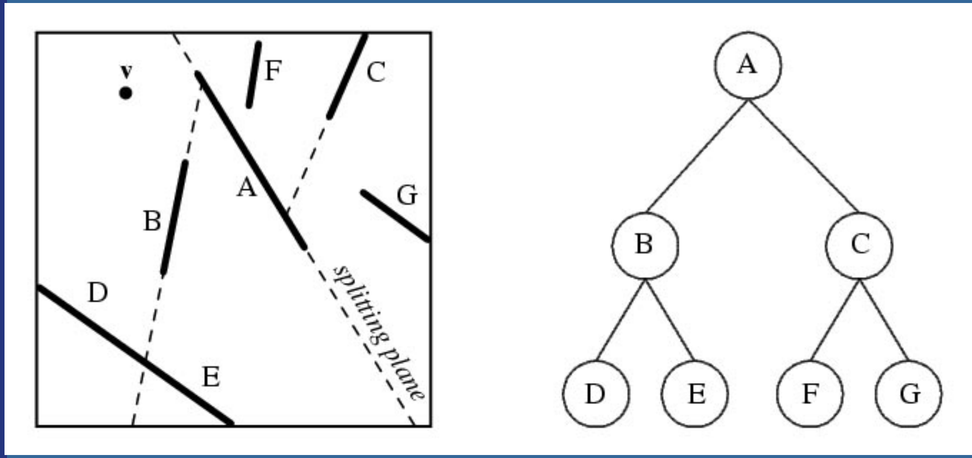
Polygon Aligned BSP tree – Quake 2

Example – Quake 2



Polygon-aligned BSP tree

- Allows exact sorting
- Very similar to axis-aligned BSP tree
  - But the splitting plane are now located in the planes of the triangles




```
Drawing Back-to-Front {
    recurse on farther side of P;
    Draw P;
    Recurse on hither side of P;
}
//Where hither and
farther are with respect
to viewpoint v
```

Algorithm for BSP trees

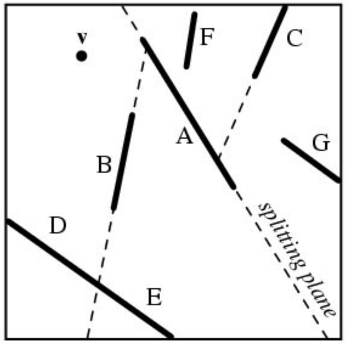
```
class BSPtree:
    Polygon P;
    BSPtree  behindP;
    BSPtree  frontOfP;
```

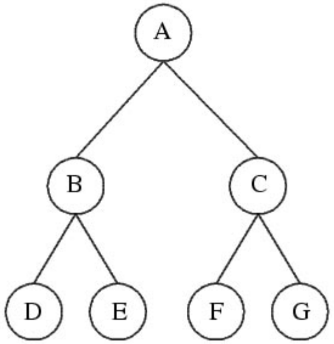
```
Tree CreateBSP(PolygonList L) {
    If L empty, return empty tree;
    Else:
        T->P = arbitrary polygon in L.
        T->behindP  = CreateBSP(polygons behind P)
        T->frontOfP = CreateBSP(polygons in front of P)
    Return T.
}
```

Drawing Back-to-Front:

```
void DrawBSP(Tree t) {
    If (t==NULL) return;
    If eye front of polygon t->P:
        DrawBSP(t->behindP);
        Draw P;
        DrawBSP(t->frontOfP);
    Else:
        DrawBSP(t->frontOfP);
        Draw P;
        DrawBSP(t->behindP);
}
```

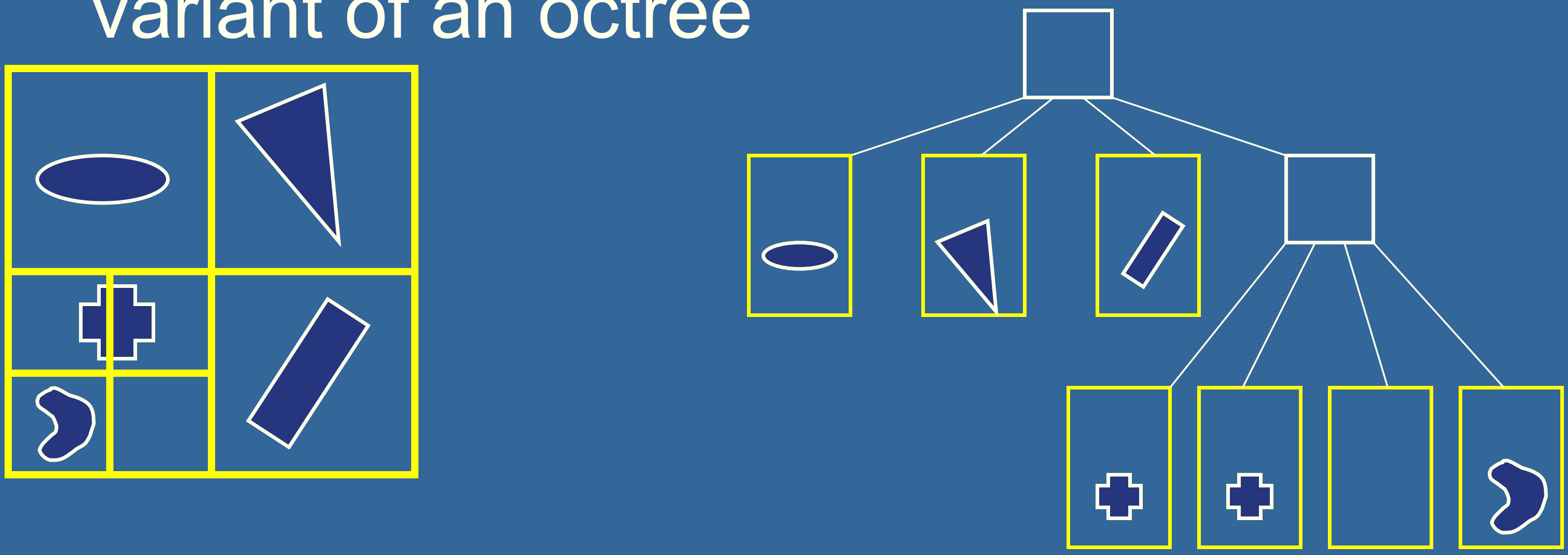
```
Drawing Back-to-Front {
    recurse on farther side of P;
    Draw P;
    Recurse on hither side of P;
}
```





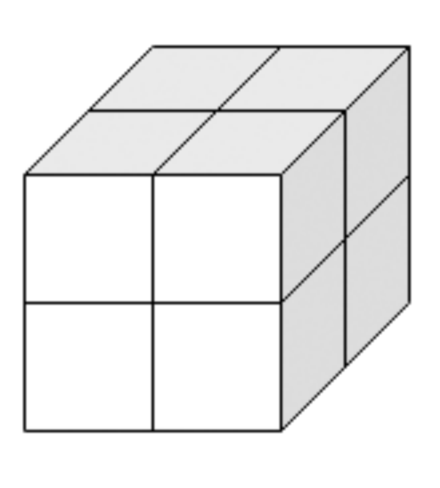
Octrees (1)

- A bit similar to axis-aligned BSP trees
- Will explain the quadtree, which is the 2D variant of an octree

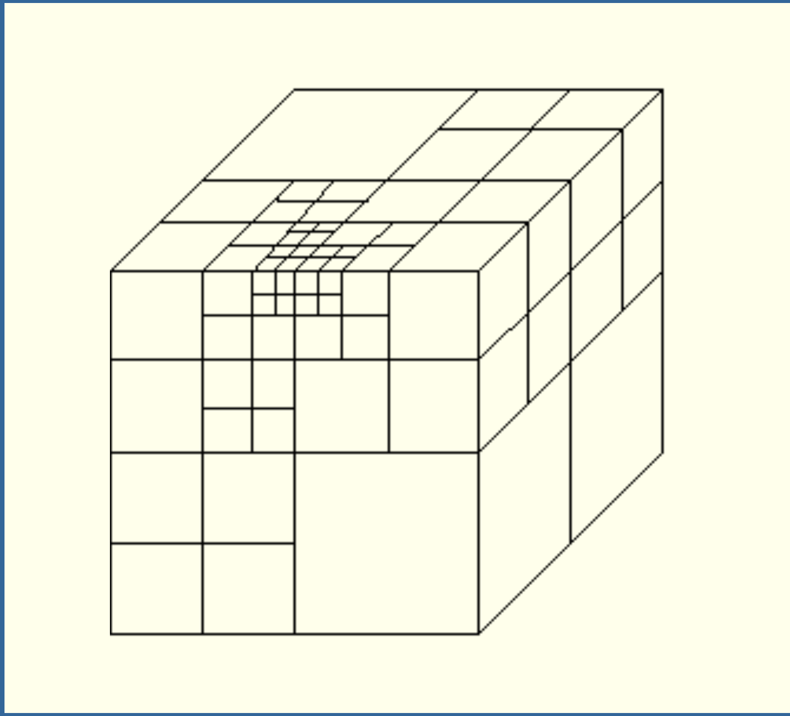


- In 3D, each square (or rectangle) becomes a box, and 8 children

Example of Octree



Recursively split space in eight parts – equaly along x,y,z dimension simultaneously for each level



Example of octree

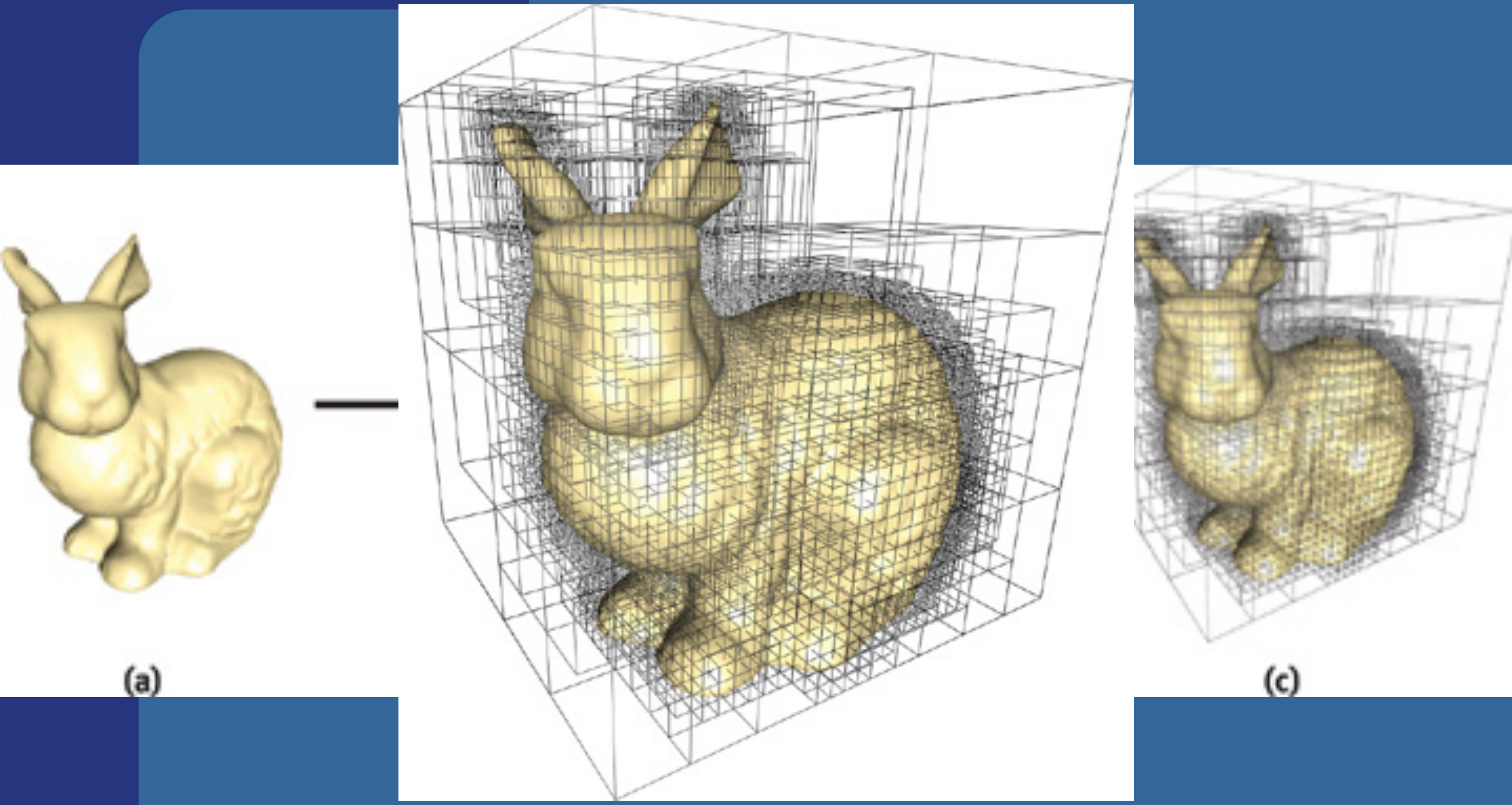


Image from Lefebvre et al.

Example of octree

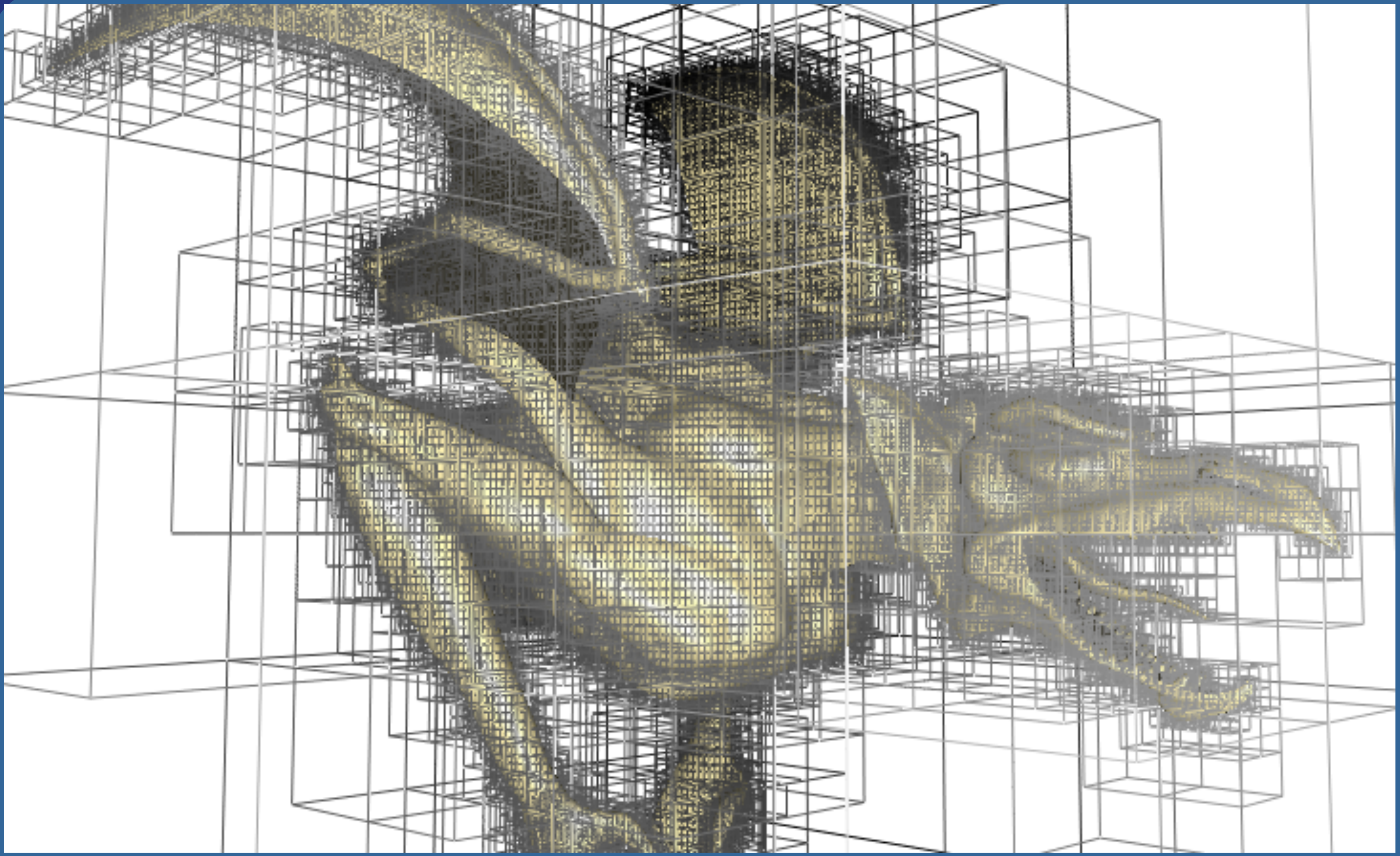


Image from Lefebvre et al.

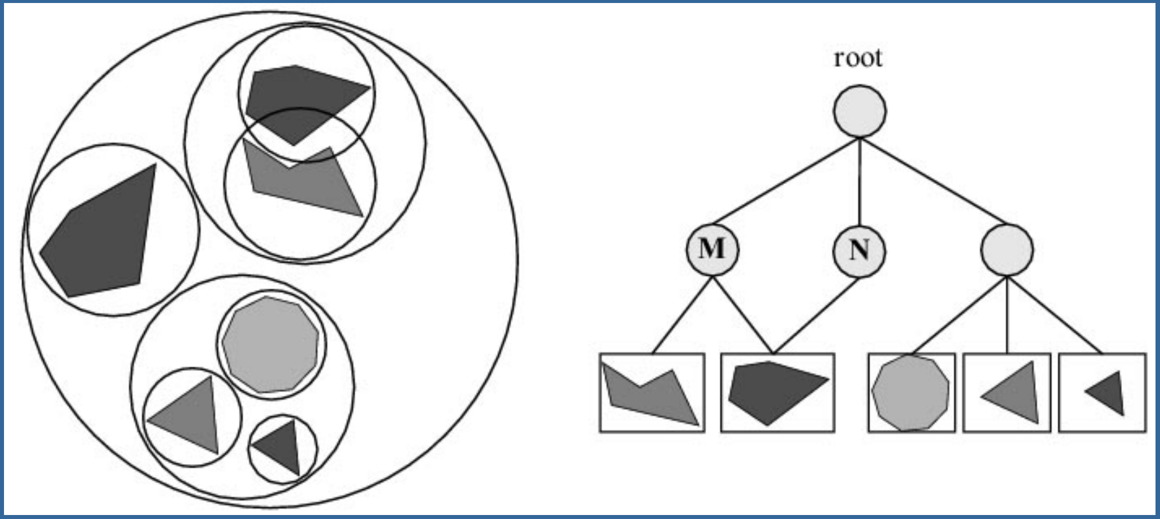
Octrees (2)

- Expensive to rebuild (BSPs are too)
- (loose octrees, page 656, 3:rd ed.)
  - A relaxation to avoid problems

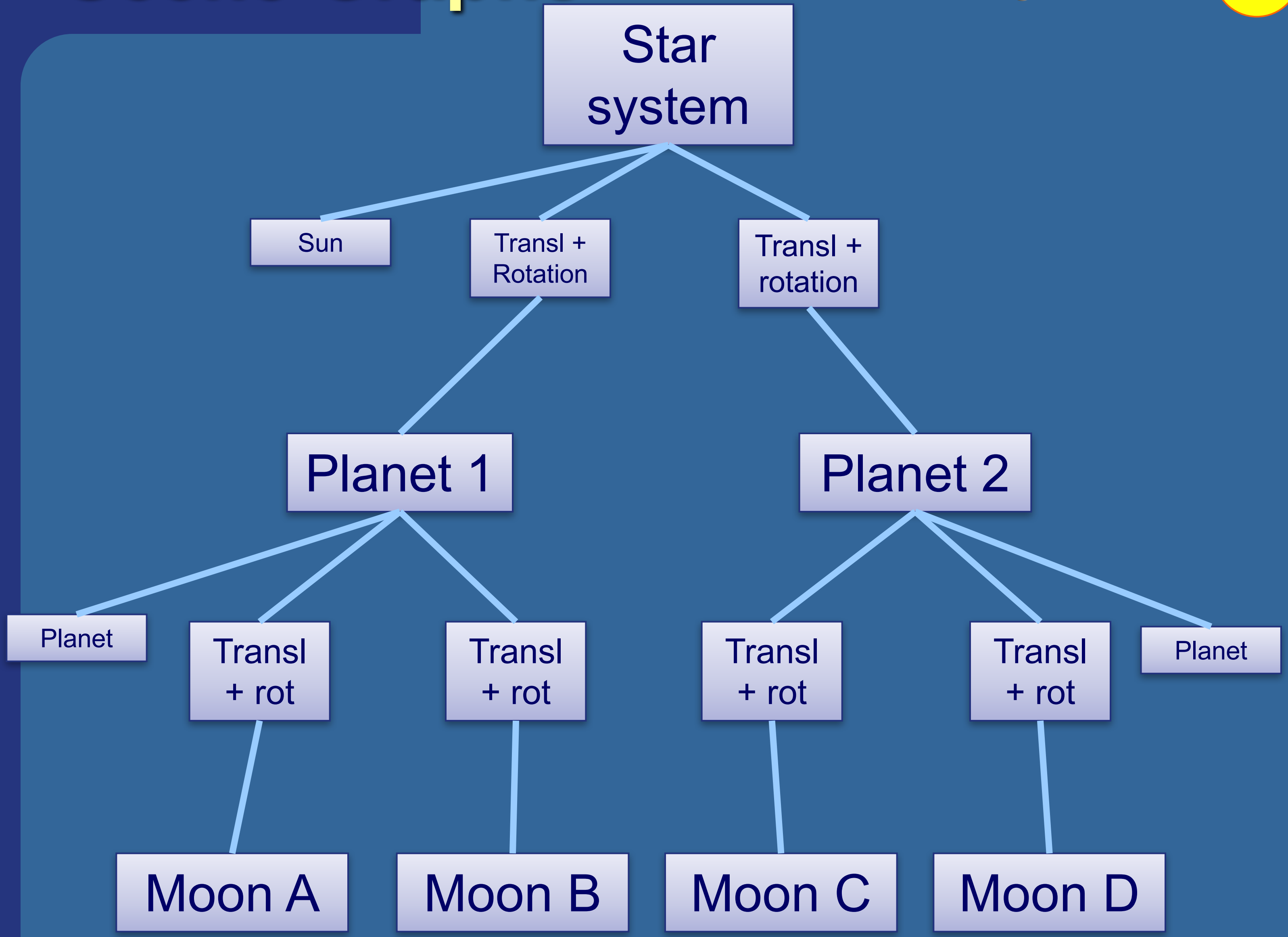
- Octrees can be used to
  - Speed up ray tracing
  - Faster picking
  - Culling techniques
  - Are not used that often in real-time contexts
    - ~~An exception is loose octrees~~

Scene graphs

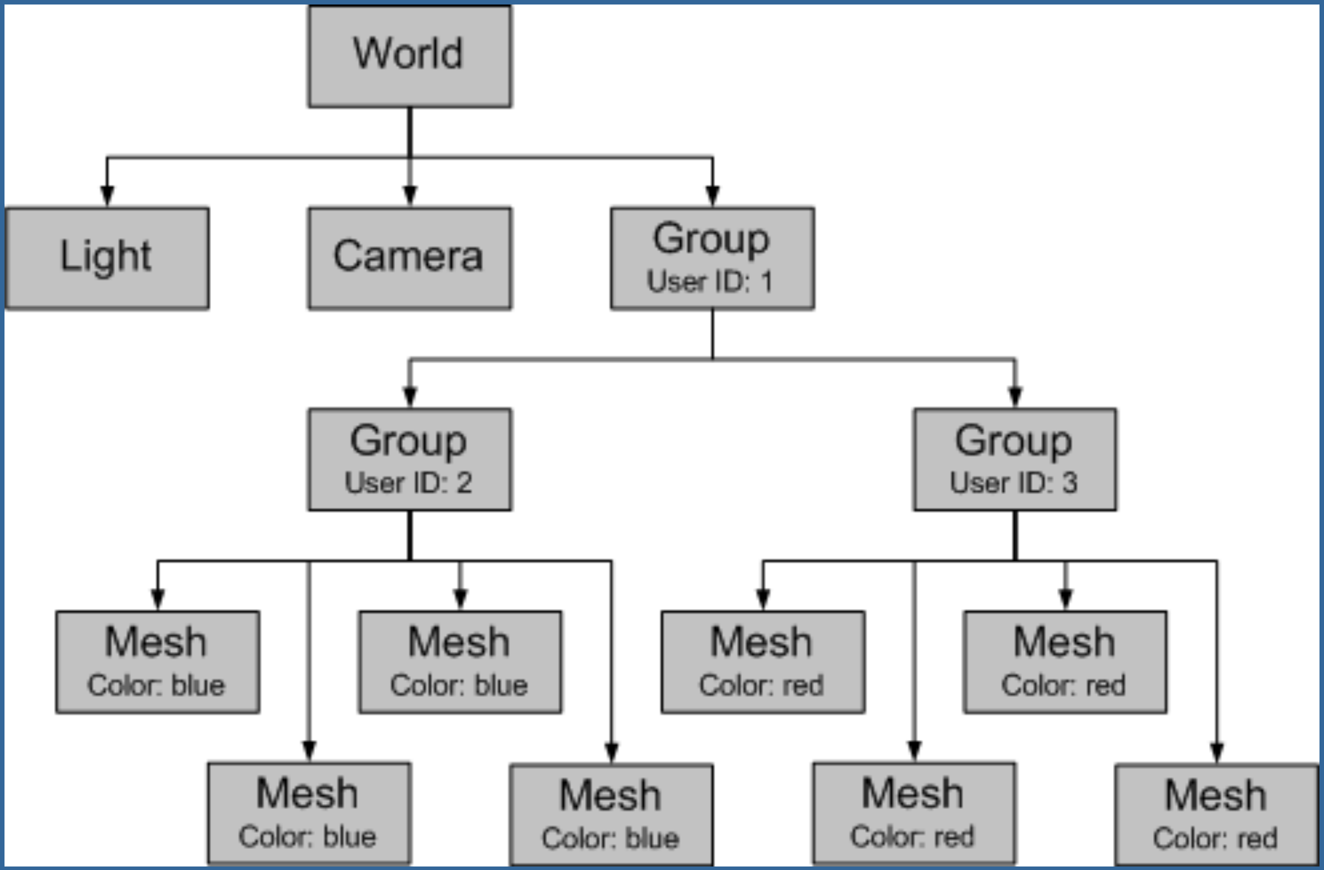
- BVH is the data structure that is used most often
  - Simple to understand
  - Simple code
- However, it stores just geometry
  - Rendering is more than geometry
- The scene graph is an extended BVH with:
  - Lights
  - Materials
  - Transforms
  - And more
  - Typically the logical structure



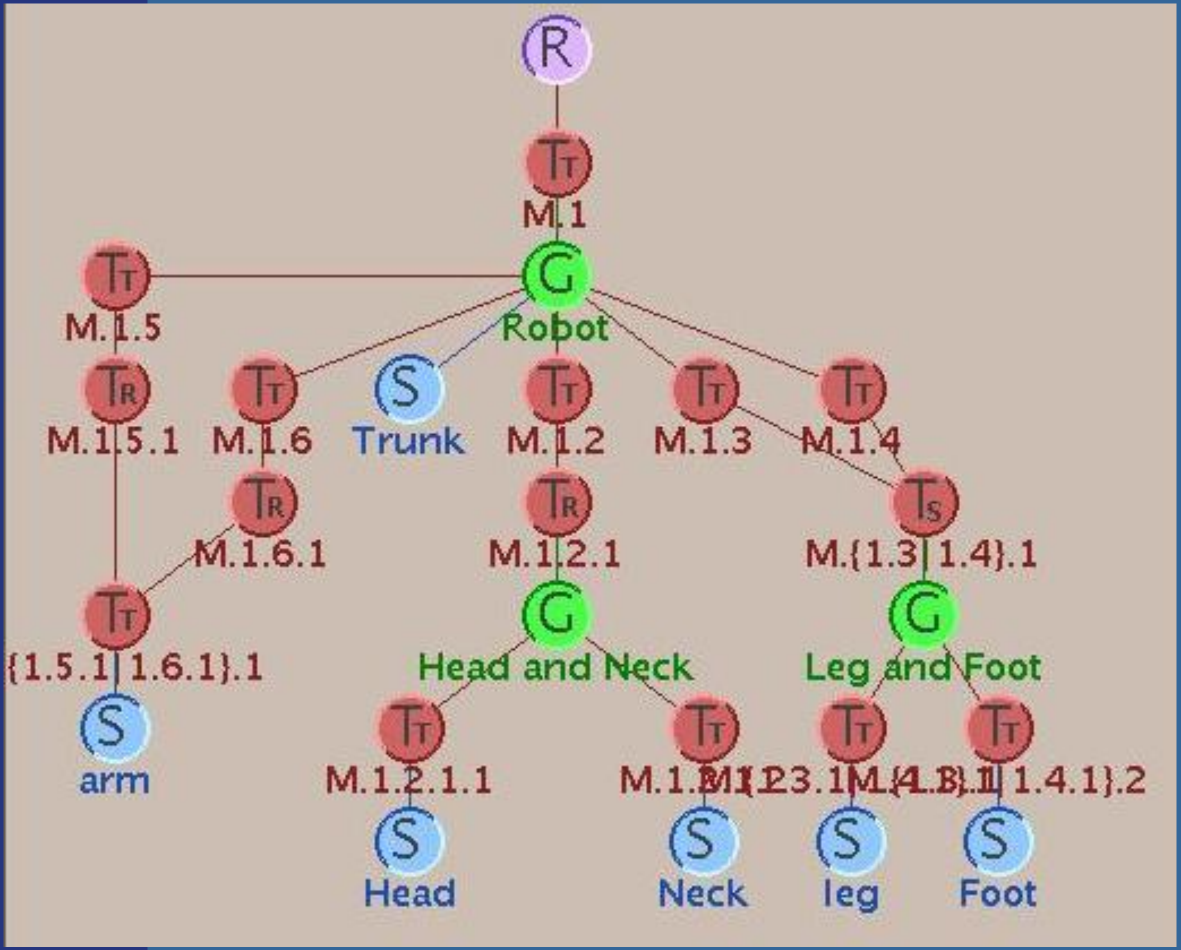
Scene Graphs

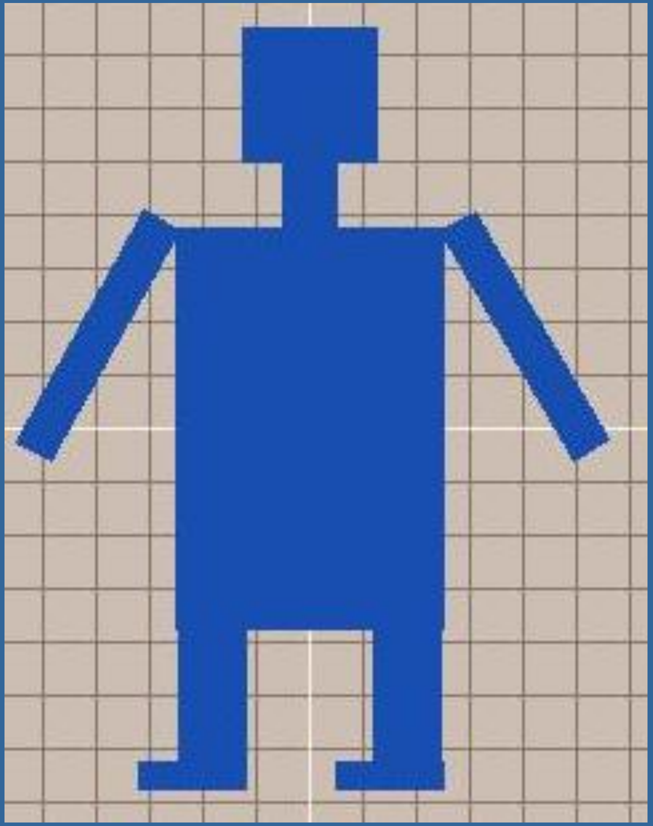


Scene Graphs



Scene Graphs





Speed-Up Techniques

- Spatial data structures are used to speed up rendering and different queries

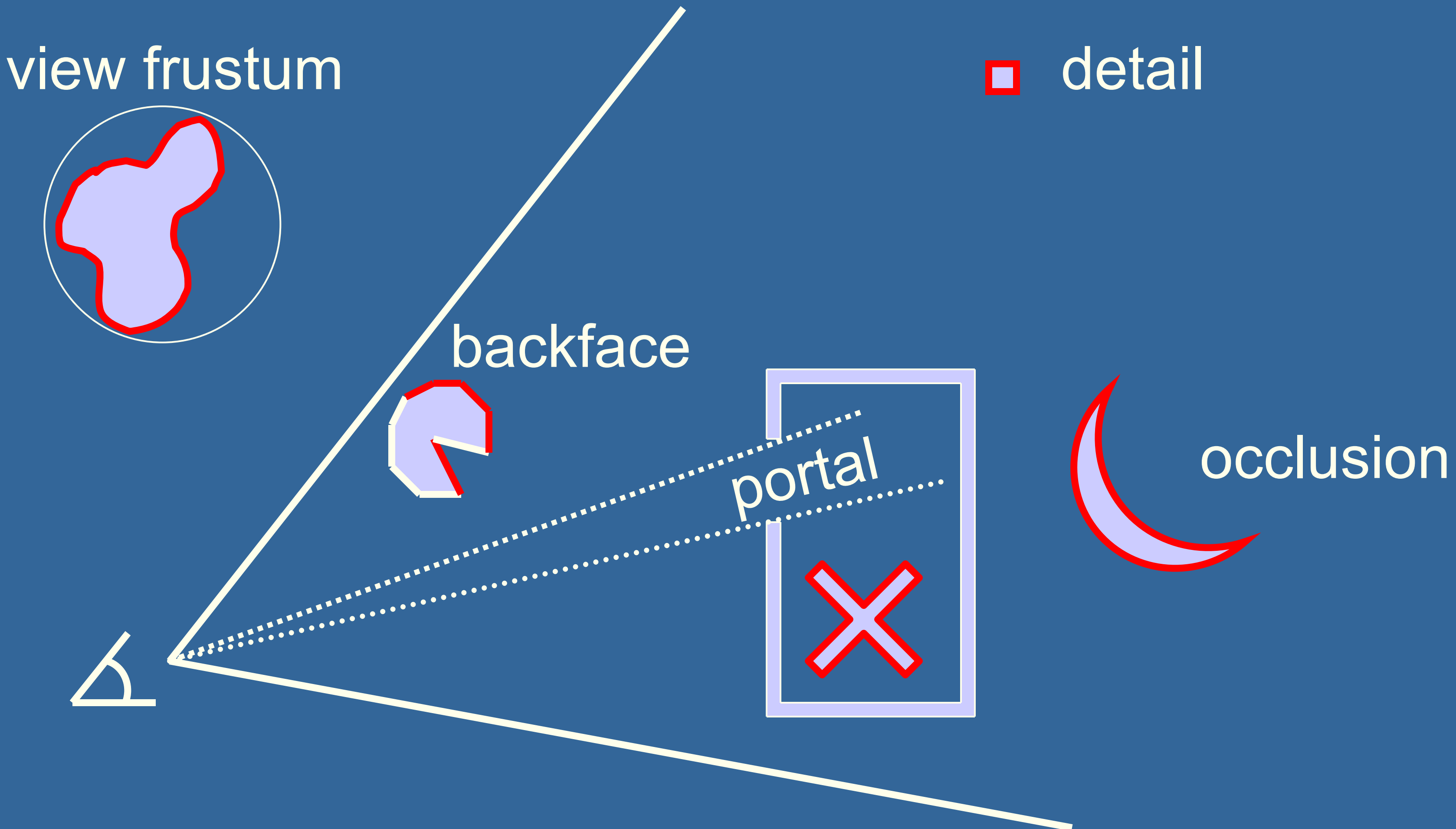
- Why more speed?
- Graphics hardware 2x faster in 6-12 months!
- Wait… then it will be fast enough!
- NOT!
- We will never be satisfied
  - Screen resolution: angular resolution in “gula fläcken” ~0.001 degree (eye sweeps scene)
    - Apple’s retina screen: 2880 x 1800
  - Realism: global illumination
  - Geometrical complexity: no upper limit!

What we’ll treat now

- Culling techniques
- Level-of-detail rendering (LODs)

- “To cull” means “to select from group”
  - ”Sort out”, ”<u>remove</u>”, ”cut away”, something picked out and put aside as inferior.
- In graphics context: do not process data that will not contribute to the final image

Different culling techniques
(red objects are skipped)

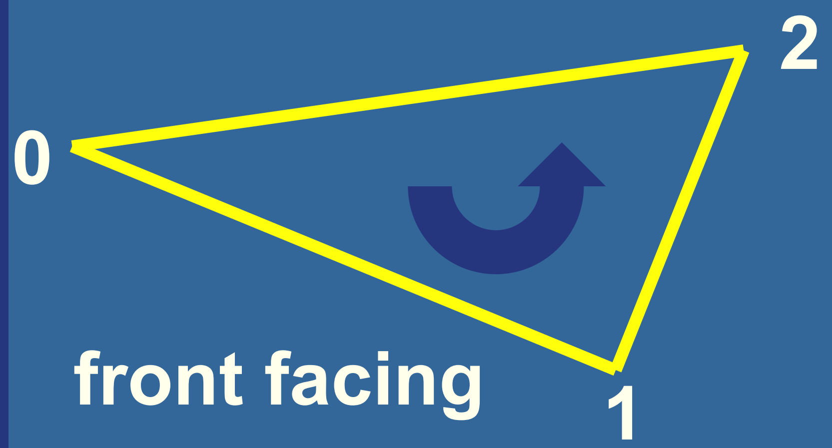


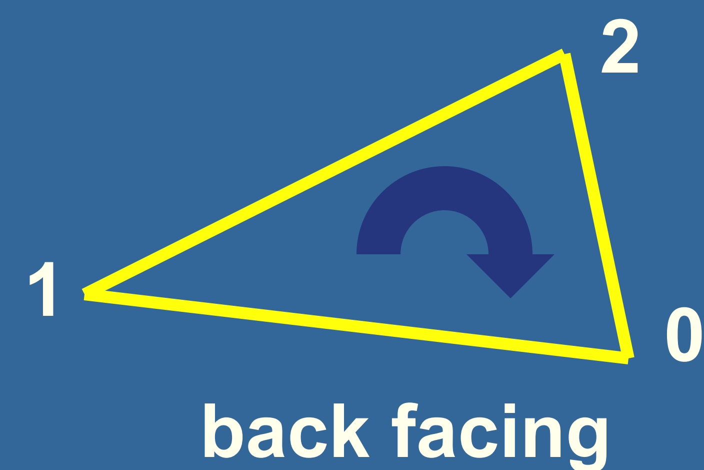
Backface Culling

- Simple technique to discard polygons that faces away from the viewer
- Can be used for:
  - closed surface (example: sphere)
  - or whenever we know that the backfaces never should be seen (example: walls in a room)
- Two methods (screen space, eye space)
- Which stages benefits?
  - Rasterizer stage

Backface culling (cont’d)

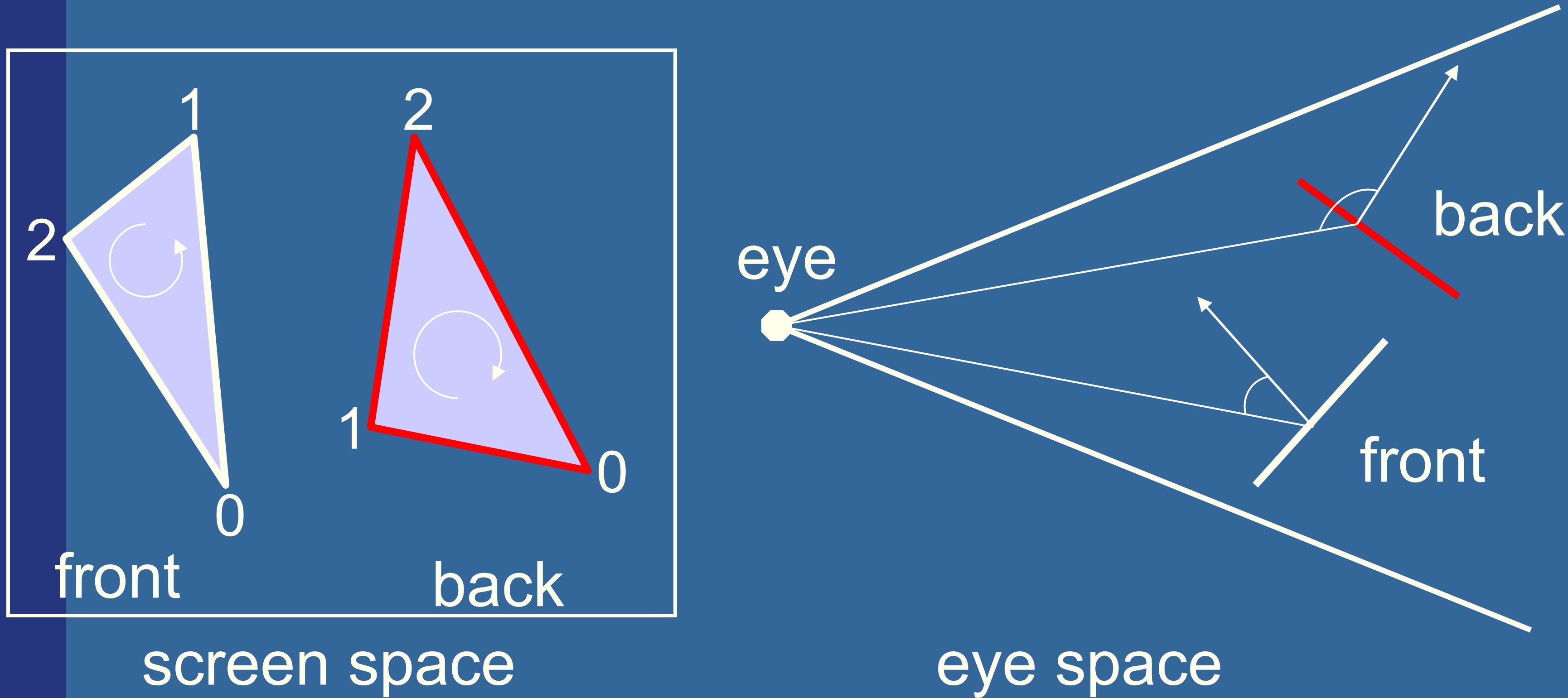
- Often implemented for you in the API
- OpenGL:
  - `glCullFace(GL_BACK);`
  - `glEnable(GL_CULL_FACE);`
- How to determine what faces away?
- First, must have consistently oriented polygons, e.g., counterclockwise





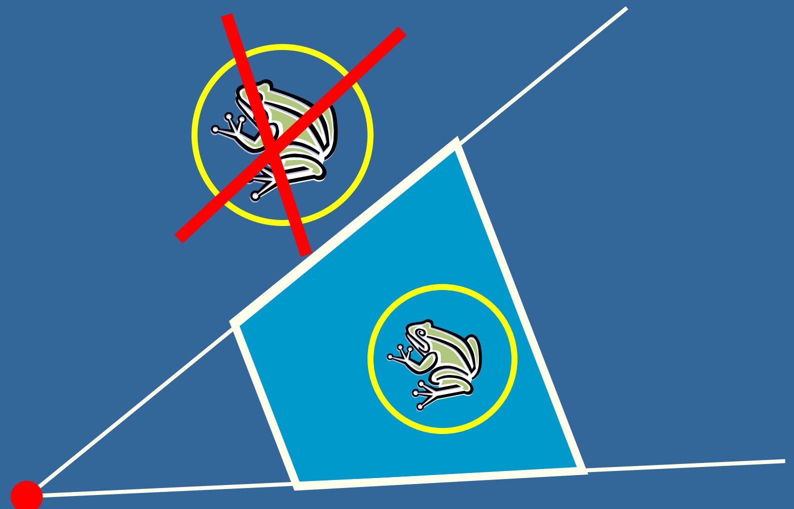
How to cull backfaces

- Two ways in different spaces:



View-Frustum Culling

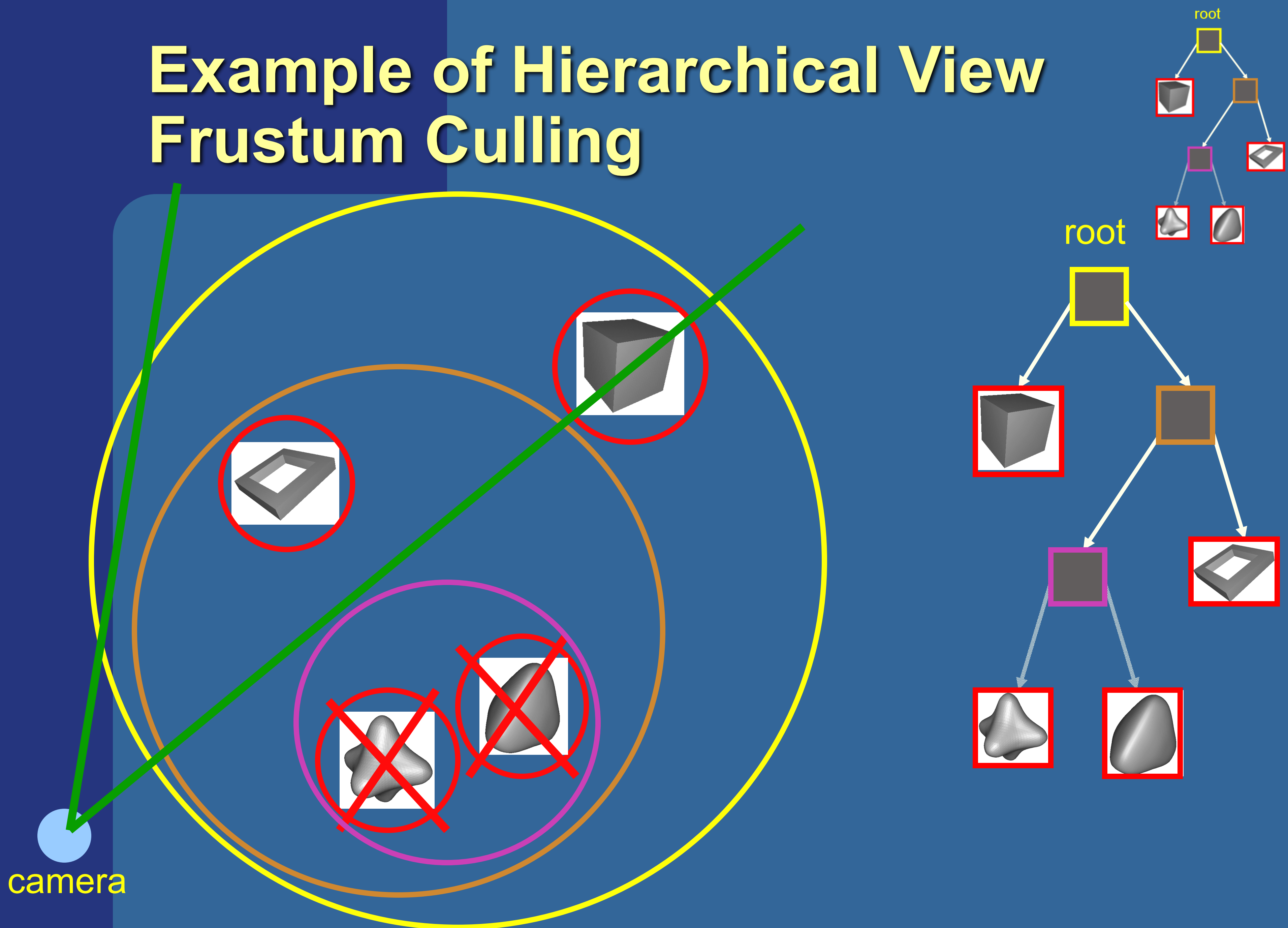
- Bound every “natural” group of primitives by a simple volume (e.g., sphere, box)
- If a bounding volume (BV) is outside the view frustum, then the entire contents of that BV is also outside (not visible)



Can we accelerate view frustum culling further?

- Do what we always do in graphics…
- Use a hierarchical approach, e.g., a spatial data structure (BVH, BSP)
- Which stages benefits?
  - Geometry and Rasterizer
  - Possibly also bus between CPU and Geometry

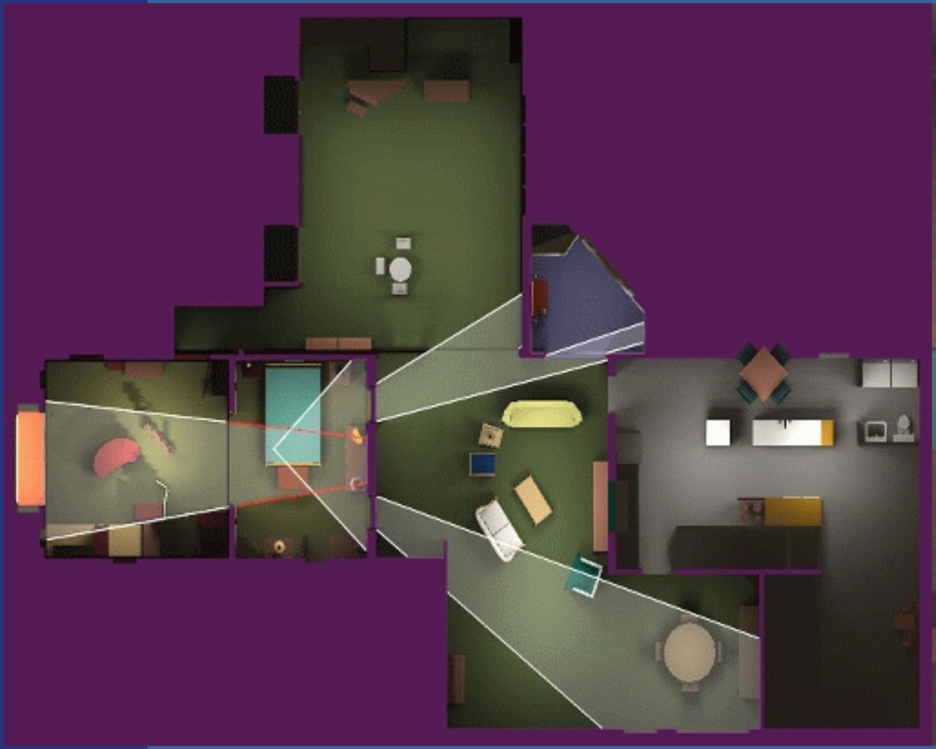
Example of Hierarchical View Frustum Culling



Refined view frustum culling: frustum gets smaller for each door

Portal Culling

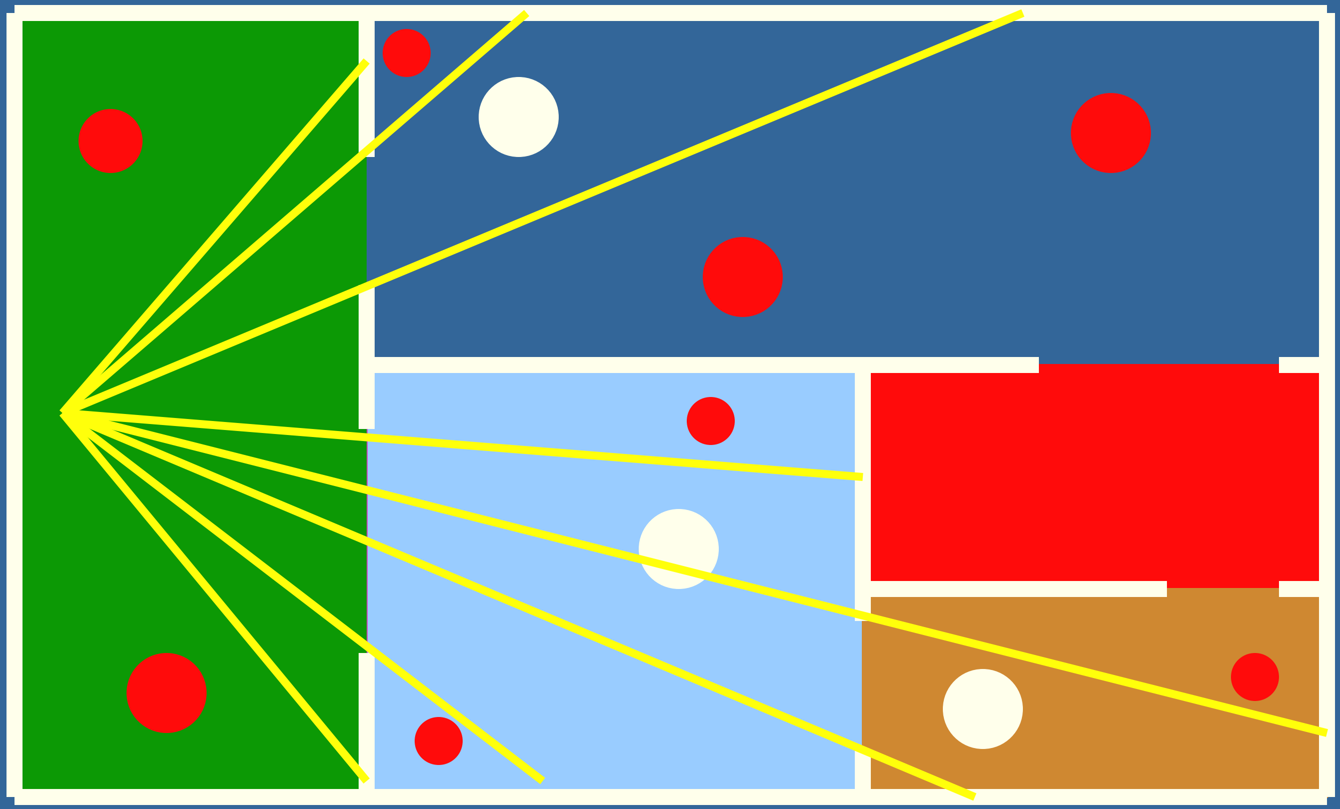
Images courtesy of David P. Luebke and Chris Georges



- Average: culled 20-50% of the polys in view
- Speedup: from slightly better to 10 times

Portal culling example

- In a building from above
- Circles are objects to be rendered



Portal Culling Algorithm (1)

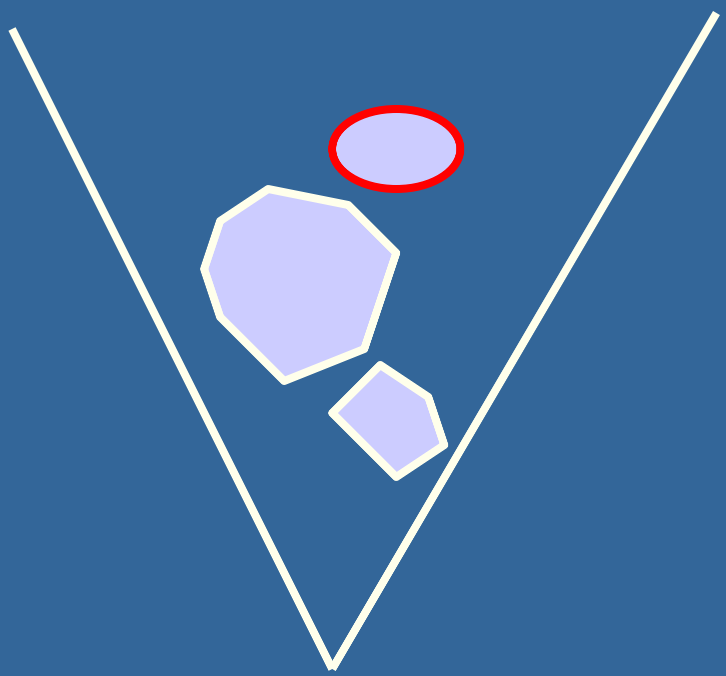
- Divide into cells with portals (build graph)
- For each frame:
  - Locate cell of viewer and init 2D AABB to whole screen
  - * Render current cell with View Frustum culling w.r.t. AABB
  - Traverse to closest cells (through portals)
  - Intersection of AABB & AABB of traversed portal
  - Goto *

Portal Culling Algorithm (2)

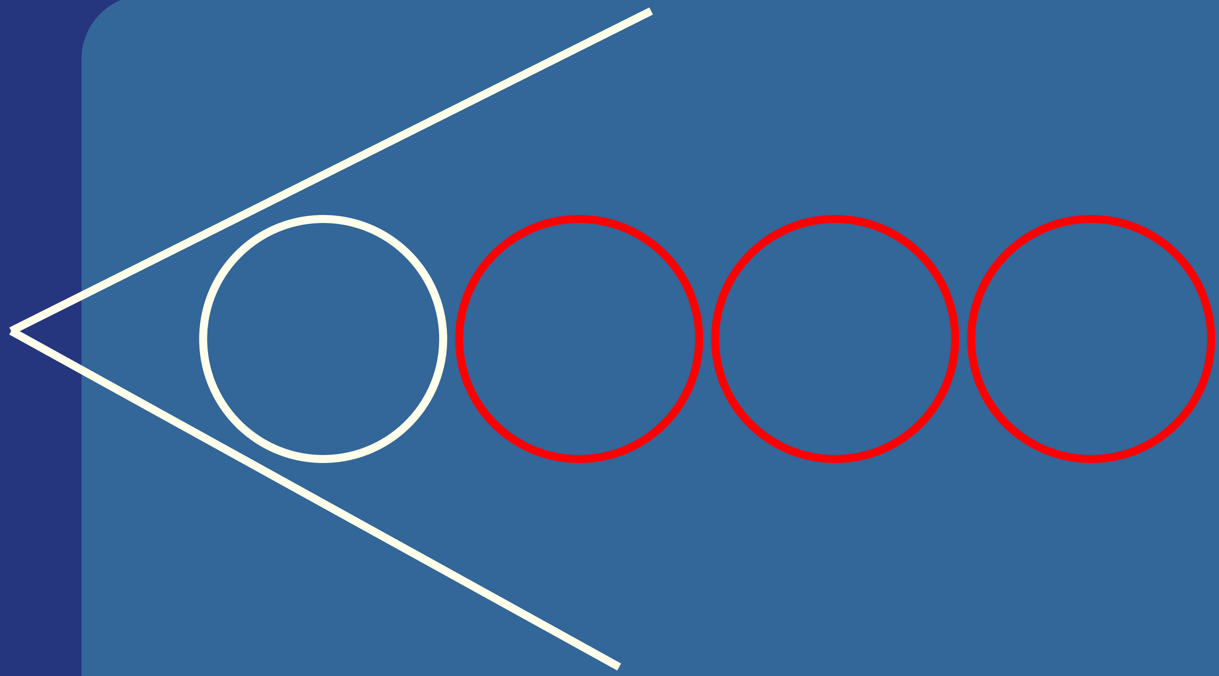
- When to exit:
  - When the current AABB is empty
  - When we do not have enough time to render a cell (“far away” from the viewer)
- Also: mark rendered objects

Occlusion Culling

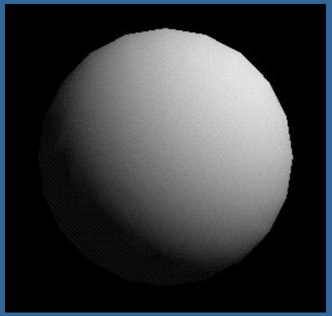
- Main idea: Objects that lies completely “behind” another set of objects can be culled
- Hard problem to solve efficiently
- Has been lots of research in this area
  - OpenGL: “Occlusion Queries”



Example



final image



- Note that “Portal Culling” is type of occlusion culling

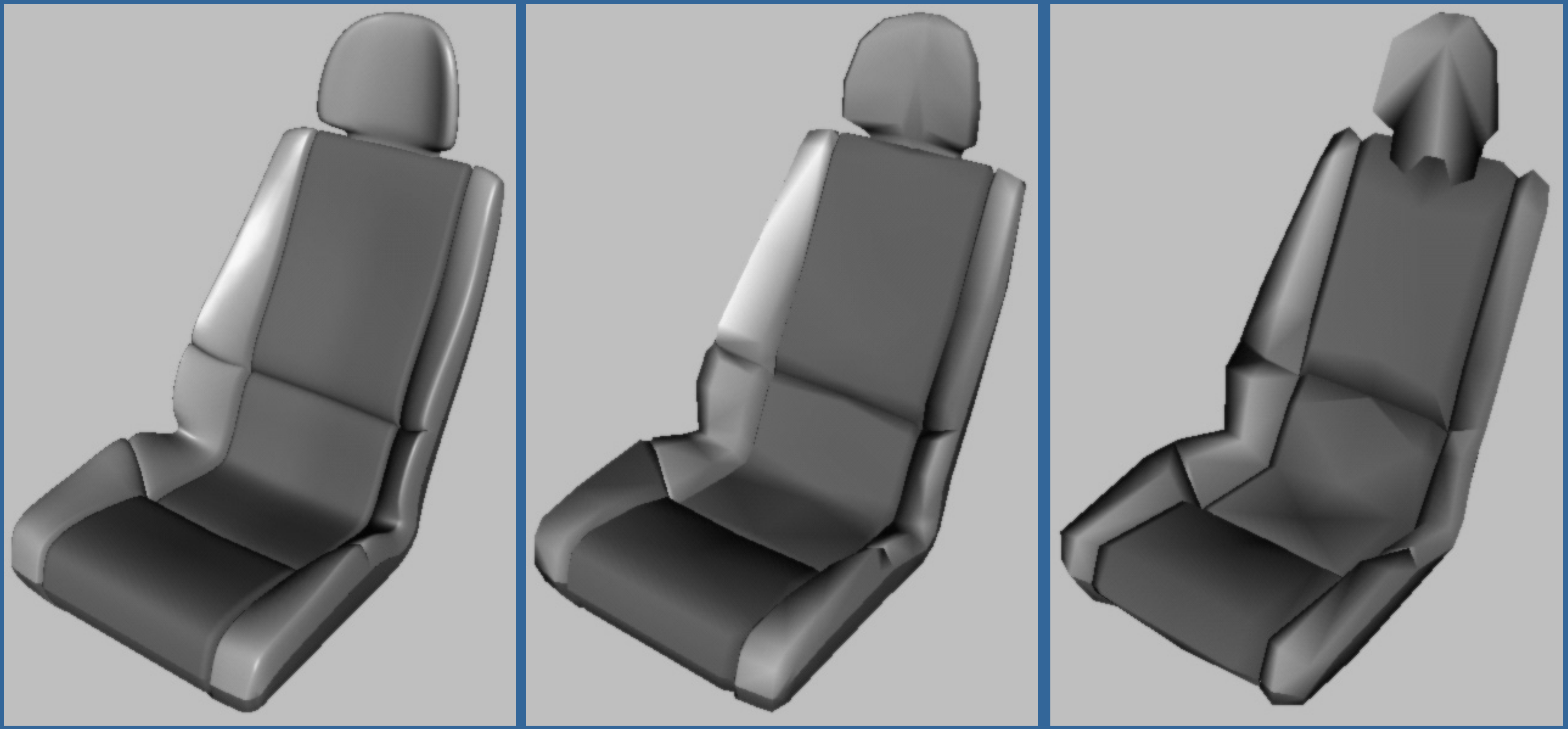
Occlusion culling algorithm

Use some kind of occlusion representation O_R

```
for each object g do:
   if( not Occluded(O_R ,g))
      render(g);
      update(O_R ,g);
   end;
end;
```

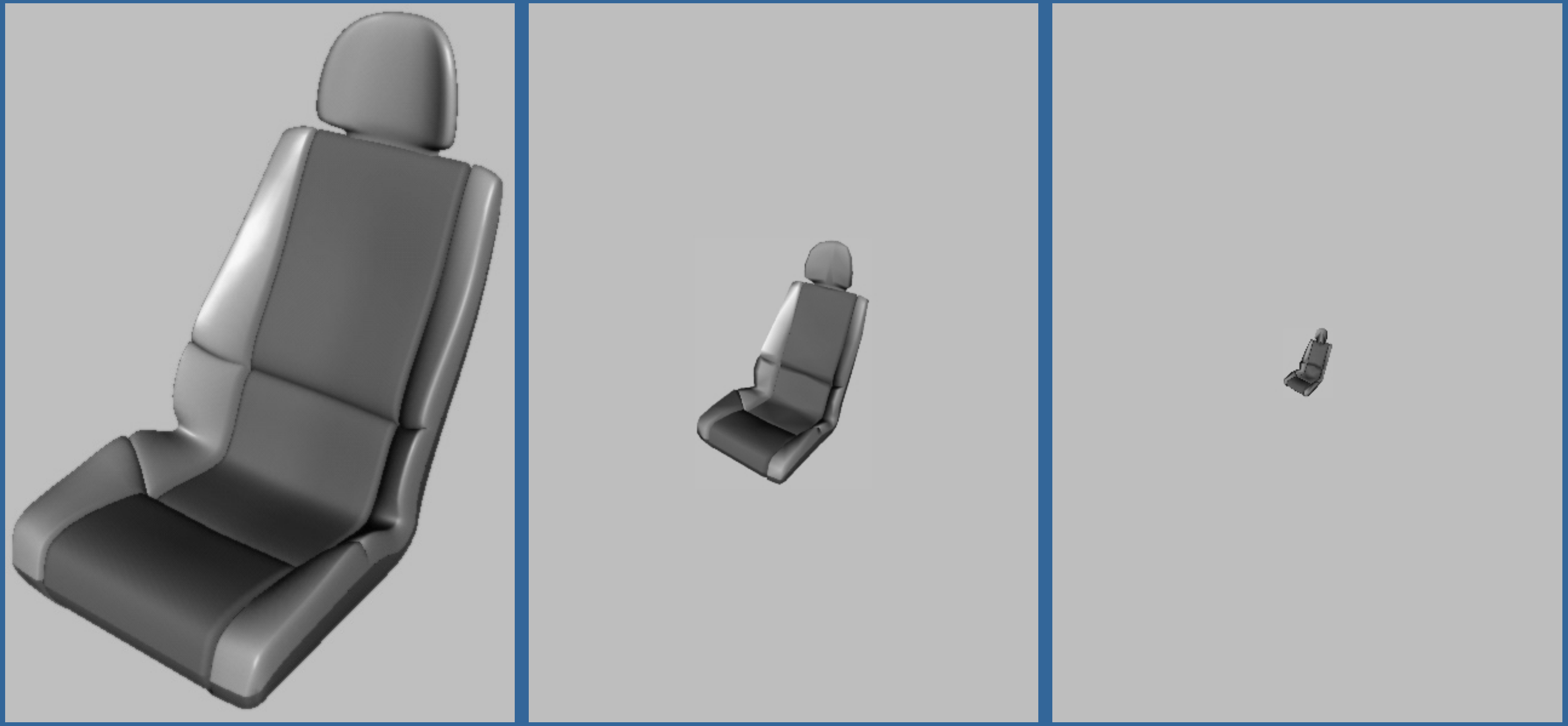
Level-of-Detail Rendering

- Use different levels of detail at different distances from the viewer
- More triangles closer to the viewer



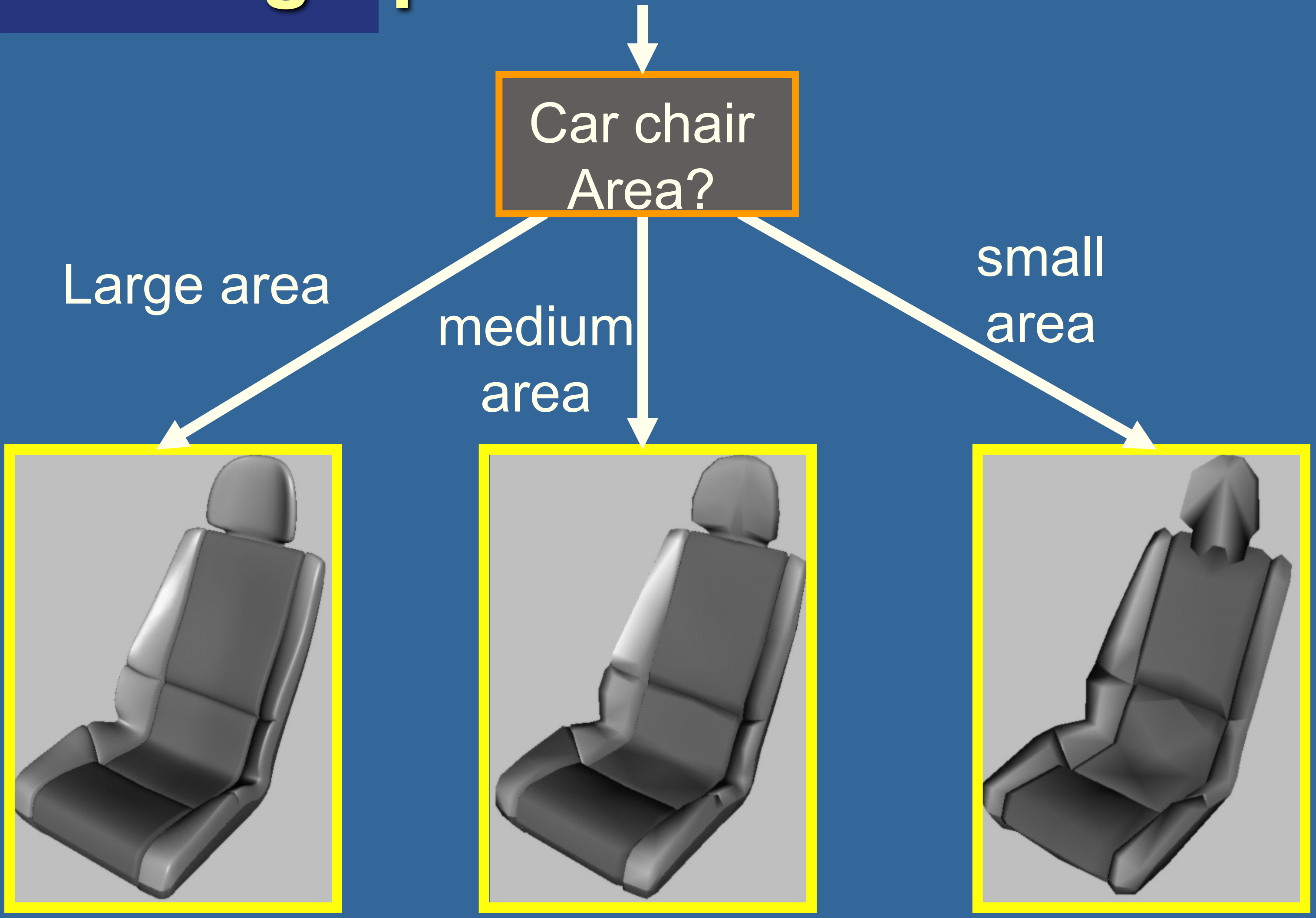
LOD rendering

- Not much visual difference, but a lot faster



- Use area of projection of BV to select appropriate LOD

Scene graph with LODs



Far LOD rendering

- When the object is far away, replace with a quad of some color
- When the object is ***really far away***, do not render it (called: detail culling)!
- Use projected area of BV to determine when to skip

Misc

- Half Time wrapup slides will be available in “Schedule” on home page
- There is an Advanced Computer Graphics Seminar Course in sp 3+4, 7.5p
  - One seminar every week
    - Discussing advanced CG papers and techniques
  - Do a project of your choice.
  - Register to the course

THE END

Exercise

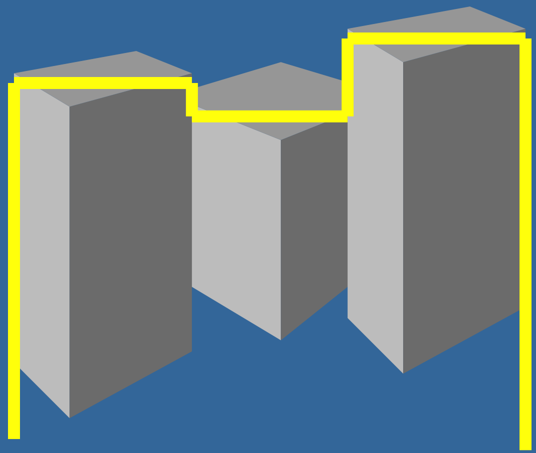
- Create a function (by writing code on paper) that performs hierarchical view frustum culling
  - void hierarchicalVFC(node* sceneGraphNode)

What you need to know

- Top-down construction of BVH, AABSP-tree,
- Construction + sorting with AABSP and Polygon-Aligned BSP
- Octree/quadtree (skip loose octrees)
- Scene Graphs (briefly)
- Culling – VFC, Portal, Detail, Backface, Occlusion
  - Backface culling – screenspace is robust, eyespace non-robust.
- What is LODs
- Describe how to build and use BVHs, AABSP-tree, Polygon aligned BSP-tree.
- Describe the octree/quadtree.

THE END

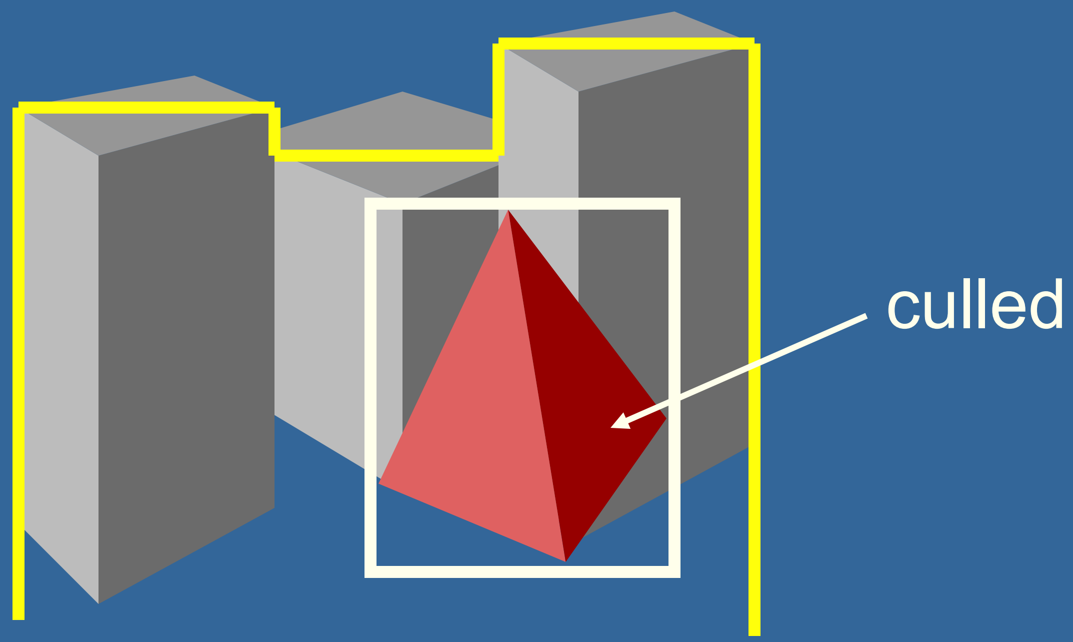
BONUS MATERIAL Occlusion Horizon



- Target: urban scenery
  - dense occlusion
  - viewer is about 2 meters above ground
- Algorithm:
  - Process scene in front-to-back using a quad tree
  - Maintain a piecewise constant horizon
  - Cull objects against horizon
  - Add visible objects’ occluding power to the horizon

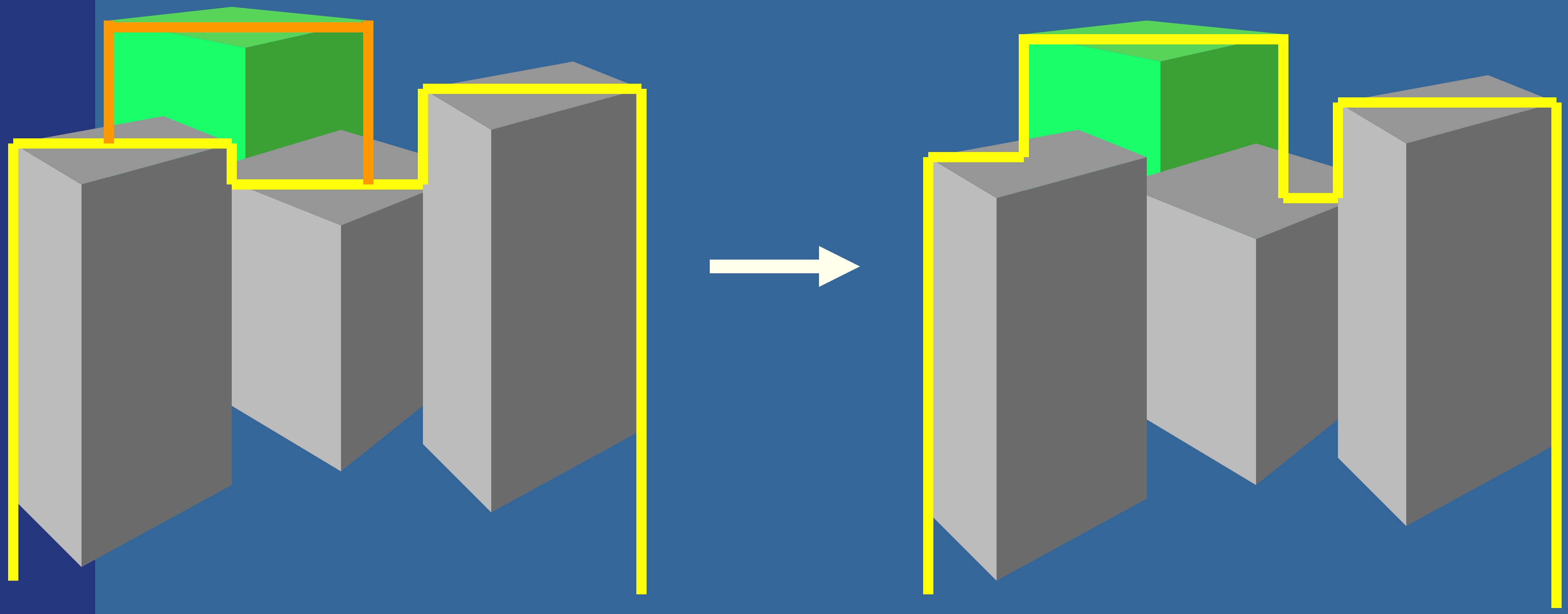
Occlusion testing with occlusion horizons

- To process tetrahedron (which is behind grey objects):
  - find axis-aligned box of projection
  - compare against occlusion horizon

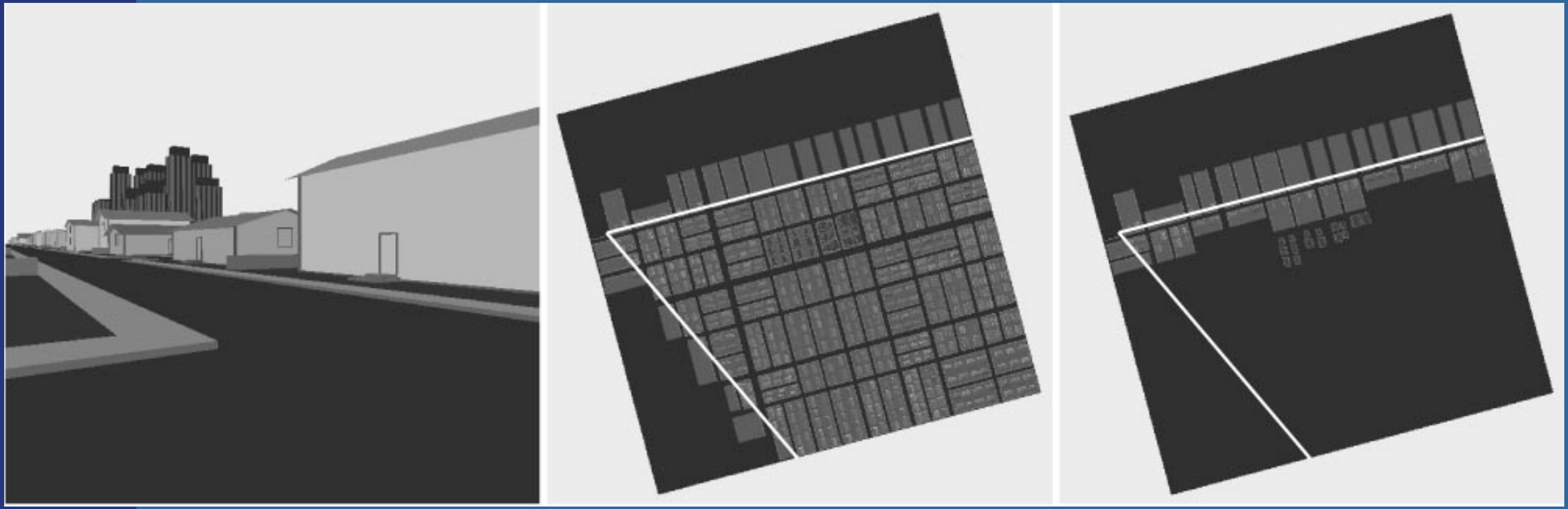


Update horizon

- When an object is considered visible:
- Add its “occluding power” to the occlusion representation



Example:



- Read about the details in paper on website (compulsory material!)