Image: Nvidia RTX ray tracer

Ray Tracing II

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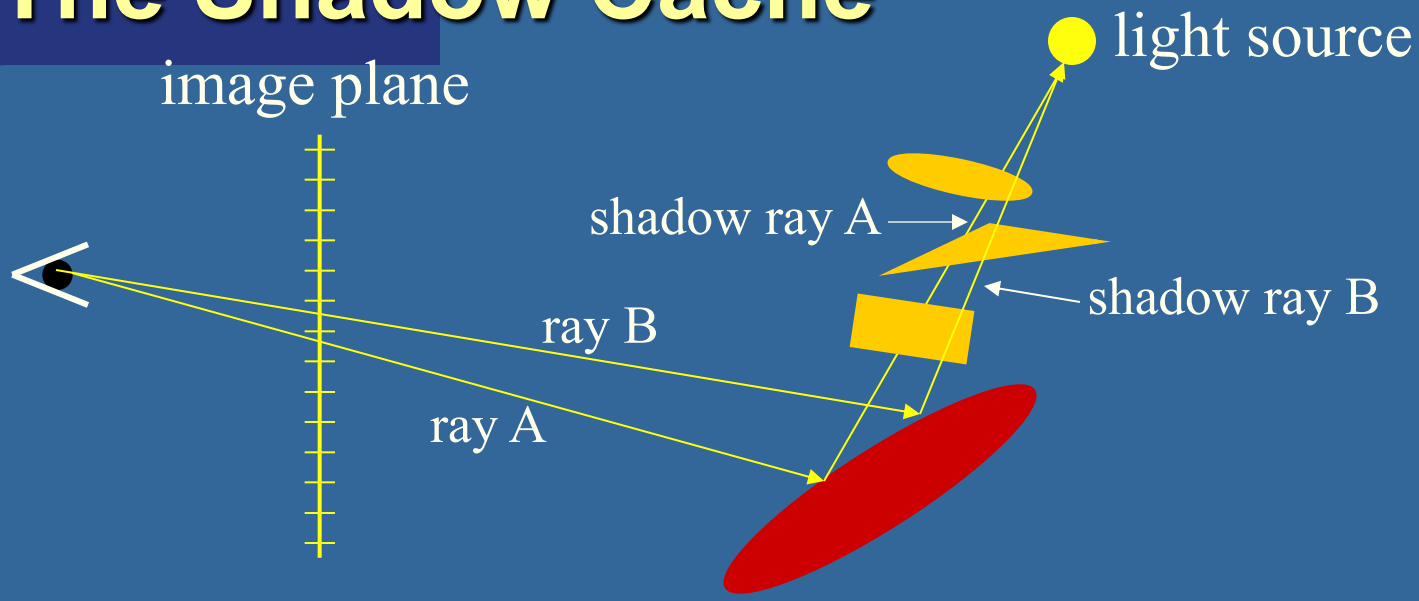
Lab 7

- YOU MUST START NOW
  - Or you may fail!
  - Purpose of Lab 7:
    - Now, you have to implement more on your own (for real), without close guidance.
      - For real-time rendering and learning to do special effects.
      - Or: Path Tracer Lab for realistic beautiful rendering!

Overview

- Shadow Cache:
  - typiccan give speedup for shadow rays if cached triangle is large (i.e., high probability of next shadow ray hitting same triangle).
- Spatial data structures and ray traversal
  - Bounding volume hierarchies (BVHs)
  - BSP trees
  - Grids
  - Cache aware coding: Shoot primary rays according to a Hilbert Curve.
- Materials
  - Fresnell Effect
  - Beer's Law
- Additional ray tracing techniques
  - Constructive Solid Geometry
  - Fractals

The Shadow Cache



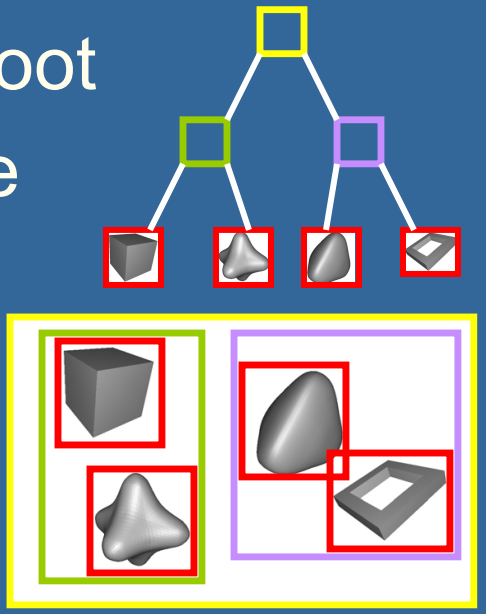
- It does not matter which object between the red ellipse and the light is detected
  - The point is in shadow if we find **one** object between
- Assume shadow ray A hits the triangle
  - store triangle in shadow cache
- For next ray B, start with testing the triangle in the shadow cache
- If high coherence, then we'll get many hits in cache
- E.g., use a cache per level of reflection-/refraction-ray recursion
- Shadow cache not popular in parallel ray tracing. (May use shadow map instead.)

Spatial data structures and Ray Tracing

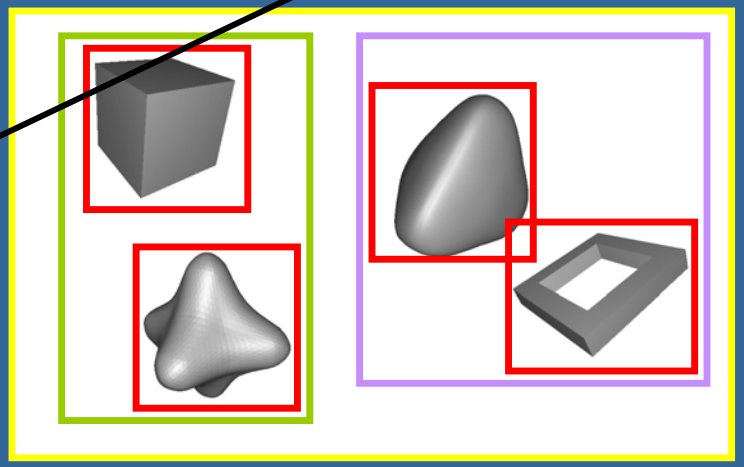
- Use spatial data structures to get faster rendering
  - Because ray tracing is often slow
  - Avoids intersection tests between the ray and each object in the scene.
    - Rather, you test a small subset
    - Typically, O(log n) instead of O(n) for each ray
- We will look at
  - Bounding volume hierarchies (BVHs)
  - BSP trees
  - Grids

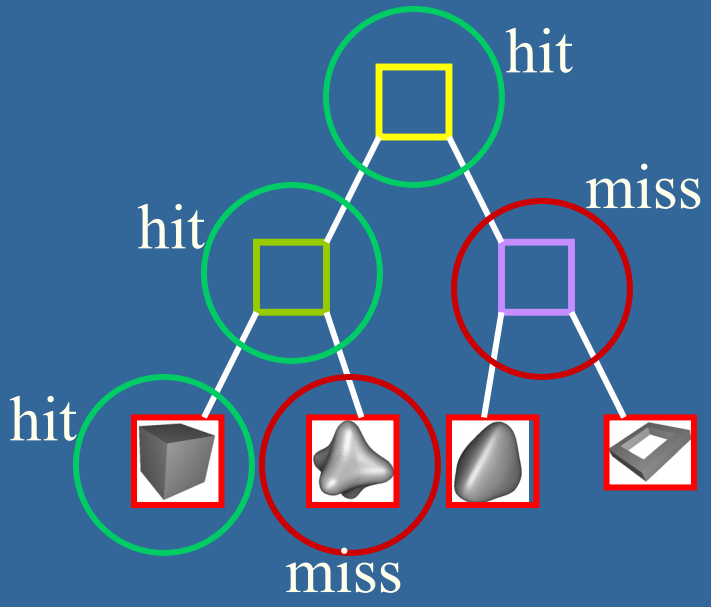
Bounding Volume Hierarchy (BVH)

- We'll use axis-aligned bounding boxes (AABBs) here
- The goal: find closest (positive) intersection between ray and all objects in the scene
- Simple: traverse the tree from the root
- If the ray intersects the AABB of the root, then continute to traverse the children
- If ray misses a child, stop traversal in that subtree



Example: ray against BVH





- Without BVH, we would test each triangle of every object against the ray
- With BVH:
  - Only test the triangles of the leaves against the ray
  - Plus some AABBs, but these are cheap

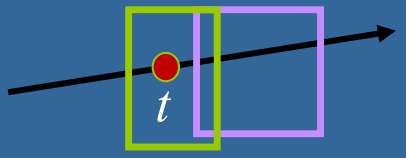
Optimizations

- Always make a reference implementation
  - And save it for benchmarking!
- Benchmarking is key here:
  - Not all ”optimizations” yield better performance
  - However, this definitely depends on what kind of scene you try to render
- Preprocessing is good
  - Use when possible

BVH traversal optimizations

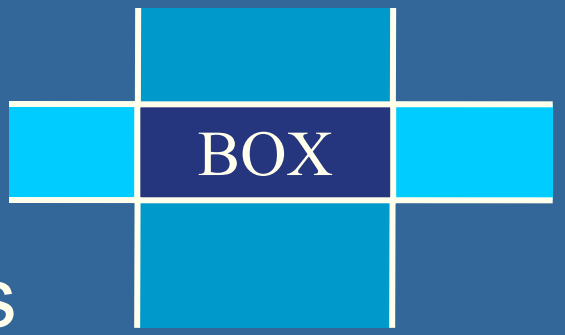
1. Use current closest intersection as an upper bound on how far the ray may ”travel”
   - Example, if a ray hits a polygon at distance t, then we don’t need to traverse a BV which is located farther than t.
2. Can also sort the BVs with respect to hit distance along ray, and only open up if necessary.
3. Shadow cache can be used for shadow rays

- Shadow cache is not efficient for small triangles and are not popular for parallel code (CPU/GPU) since parallelism breaks the assumption that the next hit is close to the previous hit. But shadow maps may be used instead.
- They are also not popular for path tracing (see next week) due to rays being incoherent.
- However, they can be good for soft shadows.



If an intersection t is found for the green box, there is no closer t in the purple box

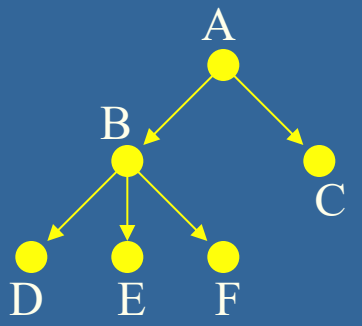
AABB hierarchy optimization

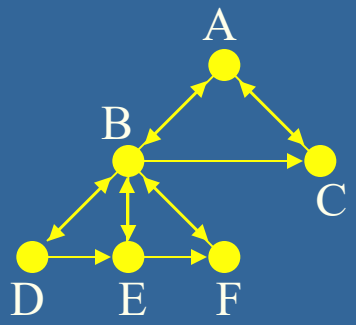


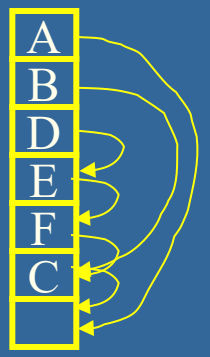
- An AABB is the intersection of three slabs (2 in 2D)
- Observation: all boxes' slabs share the same plane normals
- Exploit this for faster AABB/ray intersection!
- AABB/ray needs to compute one division per x,y, and z
  - Precompute these once per ray, and use for entire AABB hierarchy

BVH traversal… skip-pointer trees

- Standard (depth-first) traversal is slow:
  - Involves recursion
  - And memory may be allocated once per node
- Left-child, right-sibling, parent pointers avoids recursion
  - Instead follow pointers
- Store these in a clever way, with skip pointers
  - Store nodes in depth-first order
  - A skip pointer points to the place where traversal shall continue given a miss



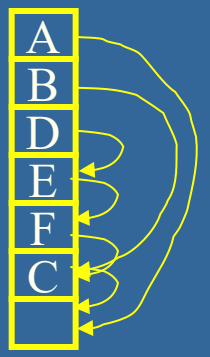




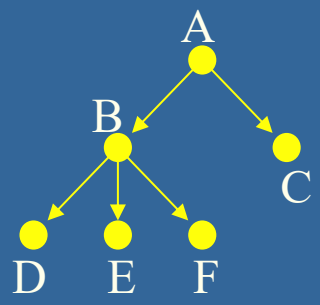
Good for single-threaded (non-parallel) code.

BVH traversal… skip-pointer trees

- If no miss, continue in depth first order
- If nodes are allocated linear in memory, then we can expect many cache hits



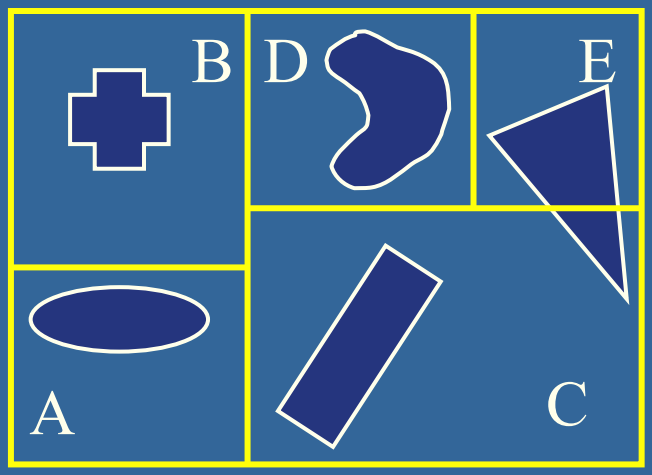
- However, a node's children cannot be accessed in any order (child n can only be reached via child 0..n-1).
  - Is a problem when first sorting the children on distance.
  - Also, for modern parallel CPUs/GPUs, you often want all of a node's children to be located adjacently in memory, so they can be efficiently fetched for testing in parallel.
    - Then, better the parent just stores one pointer to an array of all children. This also decreases the number of pointers needed to store, which significantly lowers memory usage, which increases cache coherency.



Brian Smits, "Efficiency Issues in Ray Tracing", Journal of Graphics Tools, vol. 3, no. 2. pp. 1—14, 1998.

Axis-Aligned BSP trees

- An advantage is that that we automatically traverse the space in a rough sorted order along the ray



- Pretty simple code as we will see

If we have a fixed order for the splitting dimension (e.g. x,y,z,x,y,z… or z,x,y,z,x,y… etc) this is called a kD-tree.

Axis-aligned BSP tree against ray

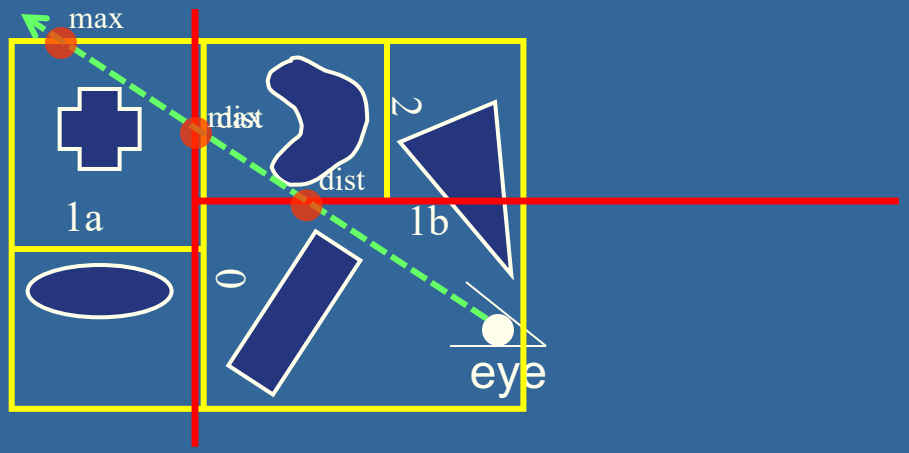
```
RayTreeIntersect(Ray, Node, min, max)
{
    if(node==NULL) return no_intersection;
    if(node is leaf)
    {
         test all primitives in leaf, discard if not between min and max;
         return closest intersection point if any;
    }
    dist = signed distance along Ray to cutting plane of Node;
    near = child of Node that contains ray origin;
    far = child of Node that does not contain ray origin;
    if(dist>0 and dist<max)          // interval intersects plane of Node
    {
         hit=RayTreeIntersect(Ray,near,min,dist);     // test near side
         if(hit) return hit;
         return RayTreeIntersect(Ray,far,dist,max);  // test far side
    }
    else if(dist>max or dist<0)      // whole interval is on near side
         return RayTreeIntersect(Ray,near,min,max);
    else                             // whole interval is on far side
         return RayTreeIntersect(Ray,far,min,max);
}
```

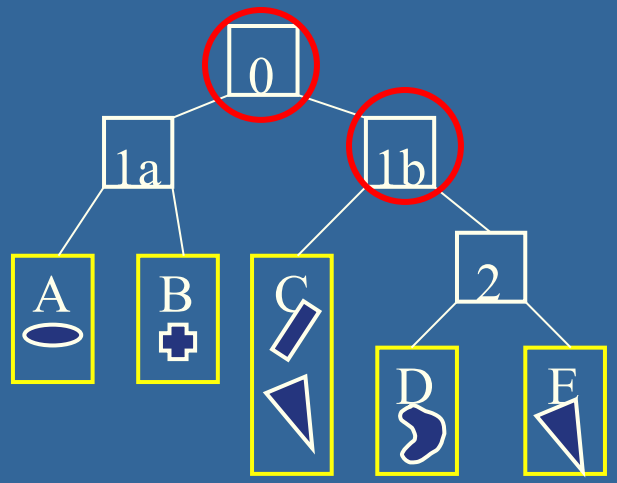
–Kelvin Sung and Peter Shirley, "Ray Tracing with the BSP Tree", Graphics Gems III, pp. 271—274, 1992.

Bonus

AA-BSP Tree Traversal

- Test the planes against the ray
- Test recursively from root
- Continue on the ”hither” side first, then farther side






```
RayTreeIntersect(Ray, Node, min, max){
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          return closest intersection point if any;
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    near = child of Node that contains ray origin;
    far = child of Node that does not contain ray origin;
    if(dist>0 and dist<max)          // interval intersects plane of Node
          hit=RayTreeIntersect(Ray,near,min,dist);    // test near side
          if(hit) return hit;
          return RayTreeIntersect(Ray,far,dist,max);  // test far side
    else if(dist>max or dist<0)                          // whole interval is on near side
          return RayTreeIntersect(Ray,near,min,max);
    else    return RayTreeIntersect(Ray,far,min,max);  // whole interval is on far side
}
```
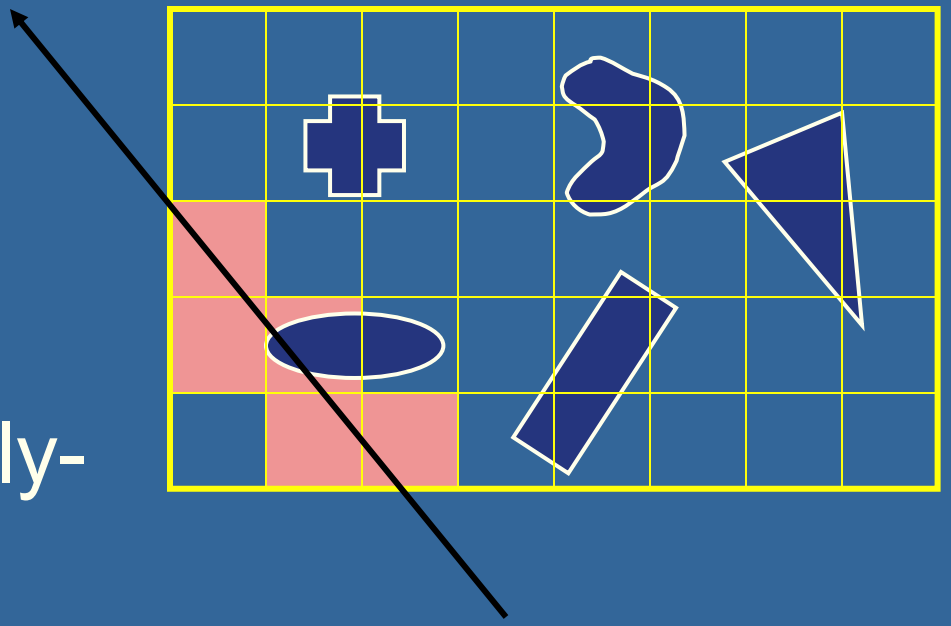

Kelvin Sung and Peter Shirley, ”Ray Tracing with the BSP Tree”, Graphics Gems III, pp. 271—274, 1992.

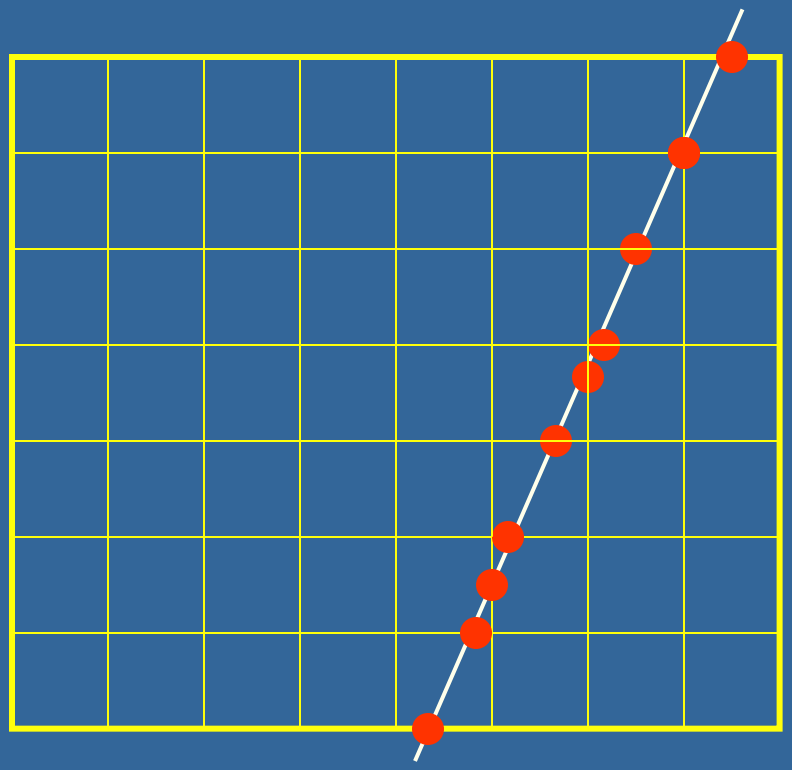
Grids



- A large box is divided into a number of equally-sized cells
- Each grid cell stores pointers to all objects that are inside it
- During traversal, only the cells that the ray intersect are visited, and objects inside these cells are tested

Grid Traversal Algorithm

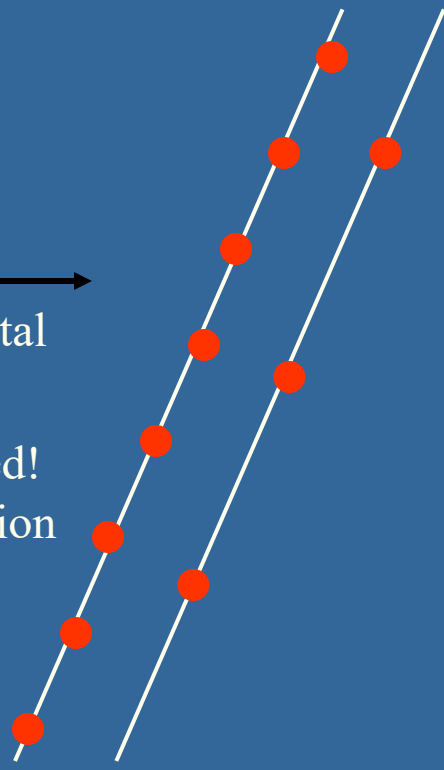
- A modified line generating algorithm can be used
  - Bresenham or DDA
- But easier to think in geometrical terms
  - Red circles mark where ray goes from one grid box to the next



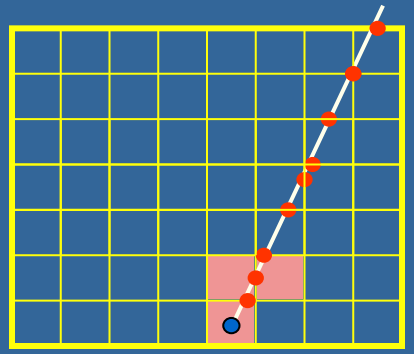
Intersection points appear with irregular spacing

But, look first at only intersection with horizontal lines, then vertical

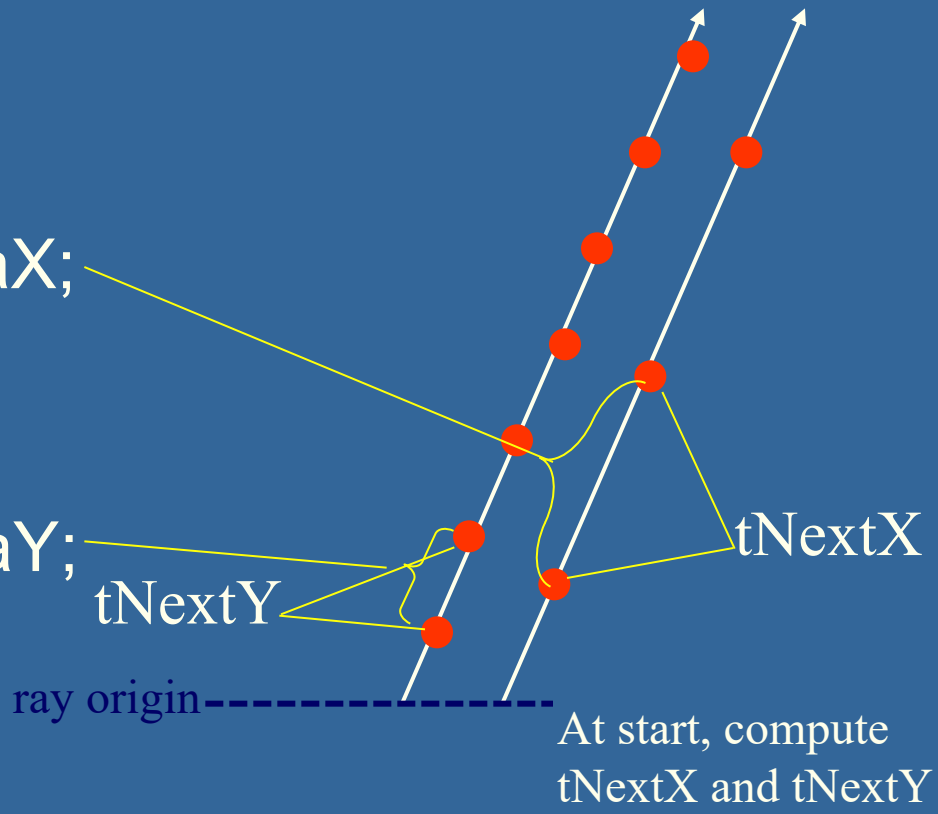
These are regular spaced! Use that in implementation



Traversal example



```
loop
    if(tNextX < tNextY)
        X= X + stepX;
        tNextX += tDeltaX;
    else
        Y= Y + stepY;
        tNextY += tDeltaY;
    VisitVoxel(X,Y);
```



tNextX = t-value at next step in x

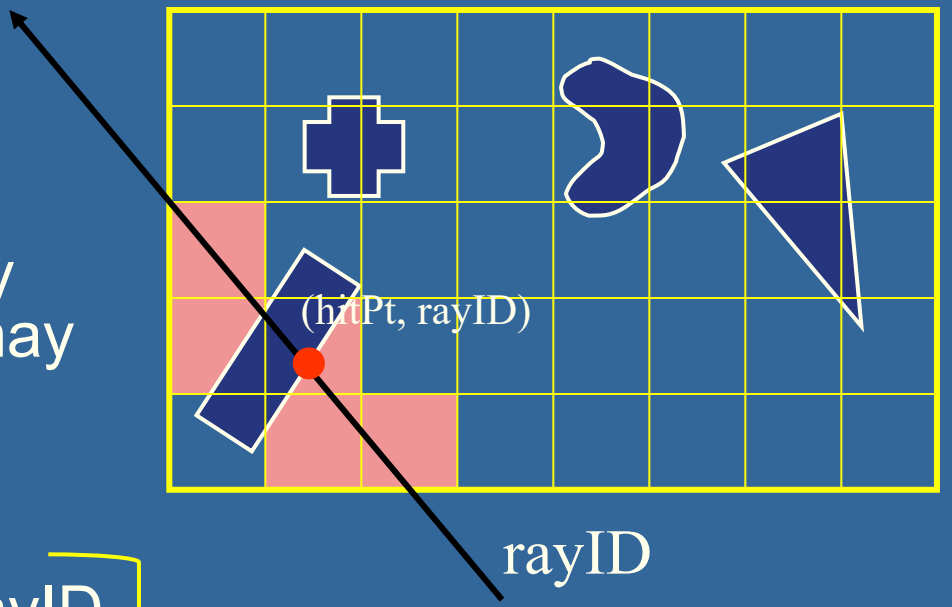
tNextY = t-value at next step in y

stepX/Y = ± 1 depending on ray's slope

Grid Traversal (2)

- Easy to code up,
- Check out the following paper (for those who want to implement in their path tracer):
  - Amantindes and Woo, ”A Fast Voxel Traversal Algorithm for Ray Tracing”, Proc. Eurographics '87, Amsterdam, The Netherlands, August 1987, pp 1-10.
- Available on course website

Testing the same object more than once in grids



- If an object intersects more than one grid box, and a ray traverses these, then you may test the same object twice (waste of performance).

- Solution: assign a unique rayID to each ray. For each tested object, store the {hitPt,rayID} with the object.
- If rayID of ray and object are the same, then we have already tested the object.

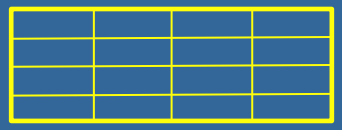
This is called mailboxing

So then just fetch the hitpoint, stored with the object

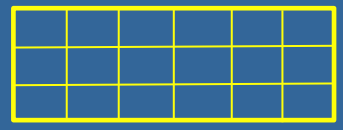
Choose a good grid resolution

- Assume n objects in scene, g is grid resolution

$$g = \sqrt[3]{n}$$



4^2



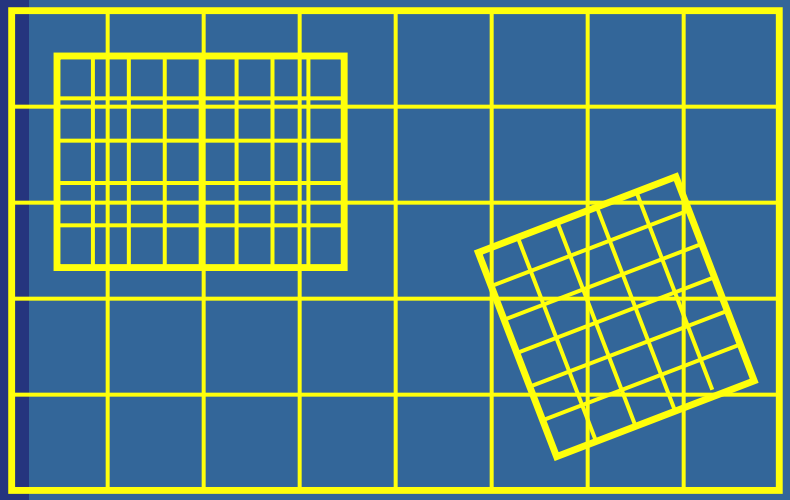
3x6

- Only good for cubes!

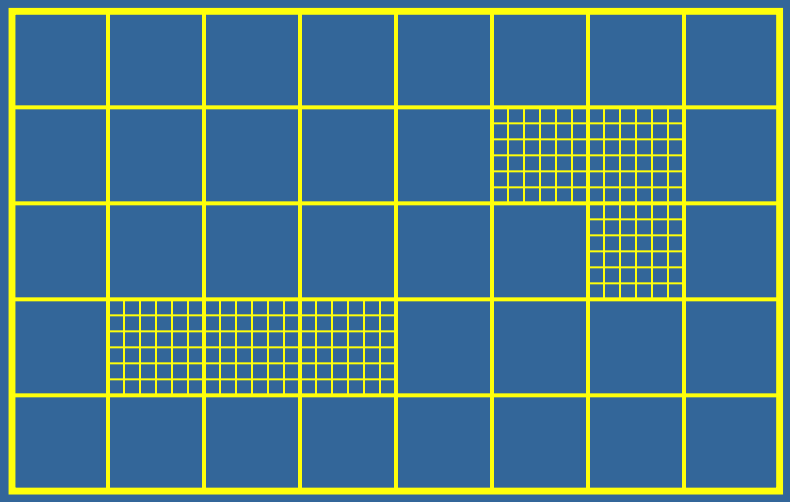
- Better to have different number of grid boxes per side
- Let the number of grid boxes per side be proportional to the length of the box side
- See Klimaszewkski and Sederberg, in IEEE Computer Graphics & Applications, Jan-Feb, 1997, pp. 42—51.

Hierarchical and Recursive Grids

- We often use hierarchies in CG, so we can do that now as well
- When a grid box (voxel) contains many primitives, introduce a smaller grid in that grid box

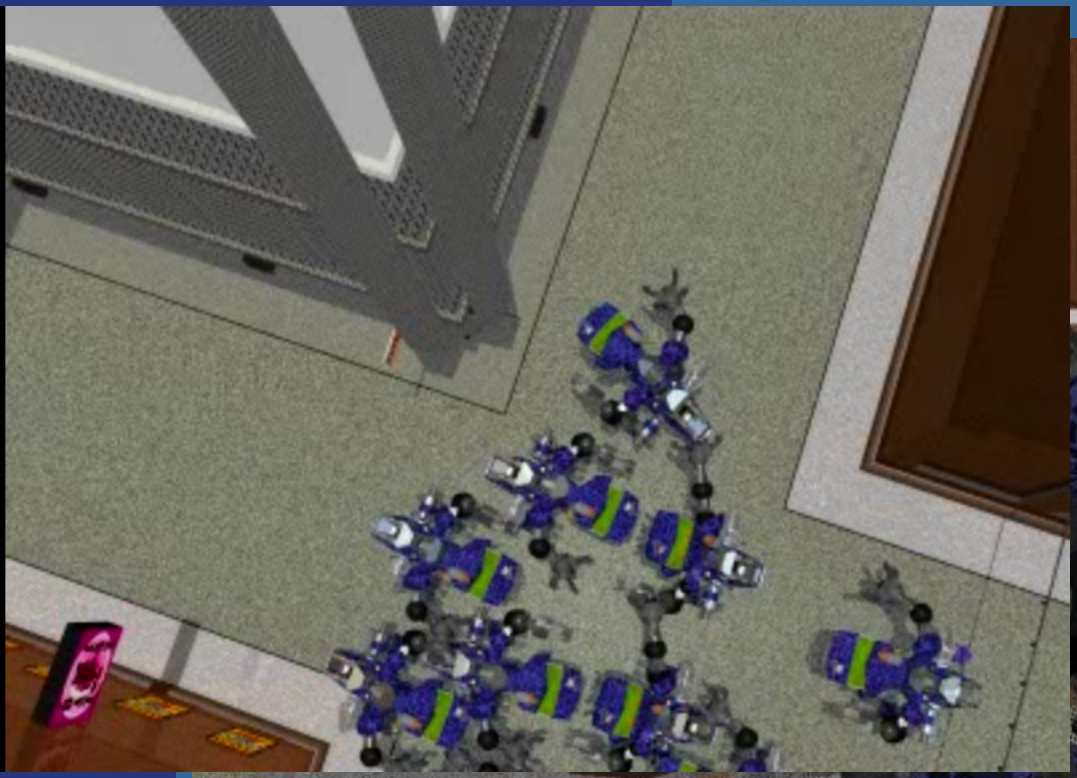


Hierarchical grid



Recursive grid

Hierarchies to avoid the “Teapot in a stadium" problem

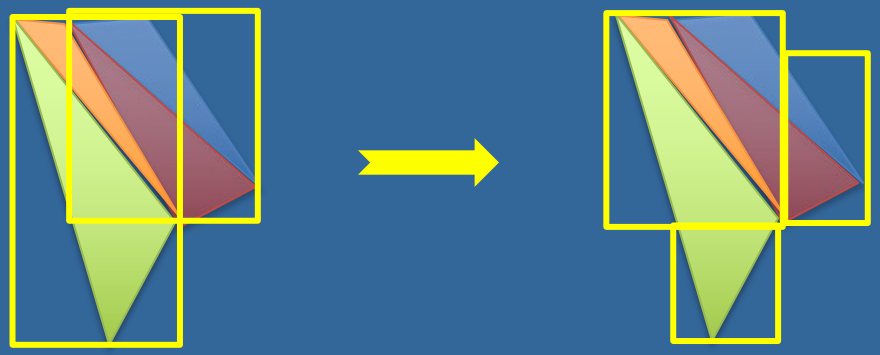


Which spatial data structure is best?

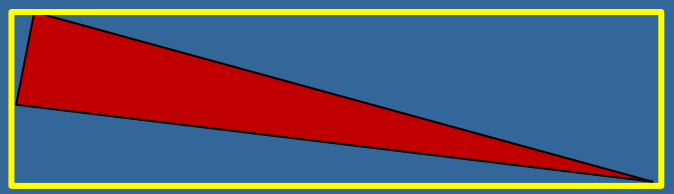
- Depends on implementation, the type of scene, how complex shading, etc, etc.
- Kd-trees:
  - Fastest to traverse, little memory, slow to build
- AABB-hierachies:
  - Fast to build, slower to traverse (not automatically in order along ray. Fast to update for moving rigid objects.
  - CPU ray tracing: SBVHs currently the winner
- Grids
  - Fast to build, middle fast to traverse, typically needs to be hierarchial/recursive
  - Hierarchical grids can be fast to update for moving rigid objects.

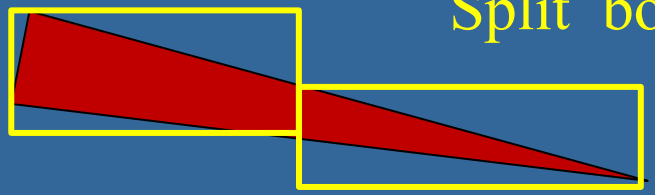
Split BVHs

- SBVH – typically AABB hierarchies but allowing triangles to be part of several BV:s, to minimize empty volume and overlaps: E.g:
  - A bit complicated. Requires careful analysis. See papers, Google on best ways or see Intel's Embree
  - Popular for CPU ray tracing but not real-time GPU ray tracing.



Clip and split boxes. Add triangles to boxes if necessary.



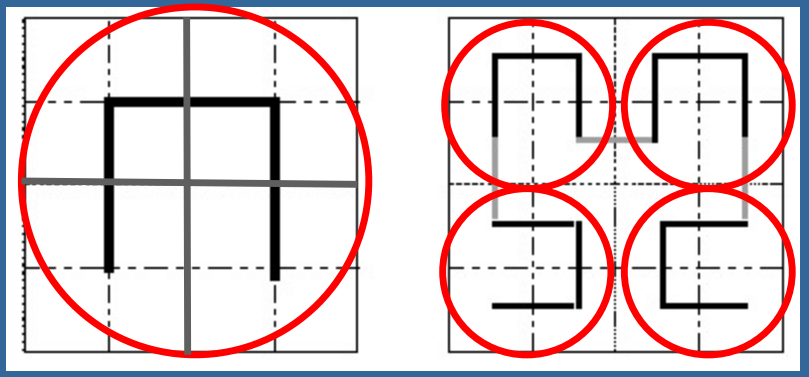


Split boxes.

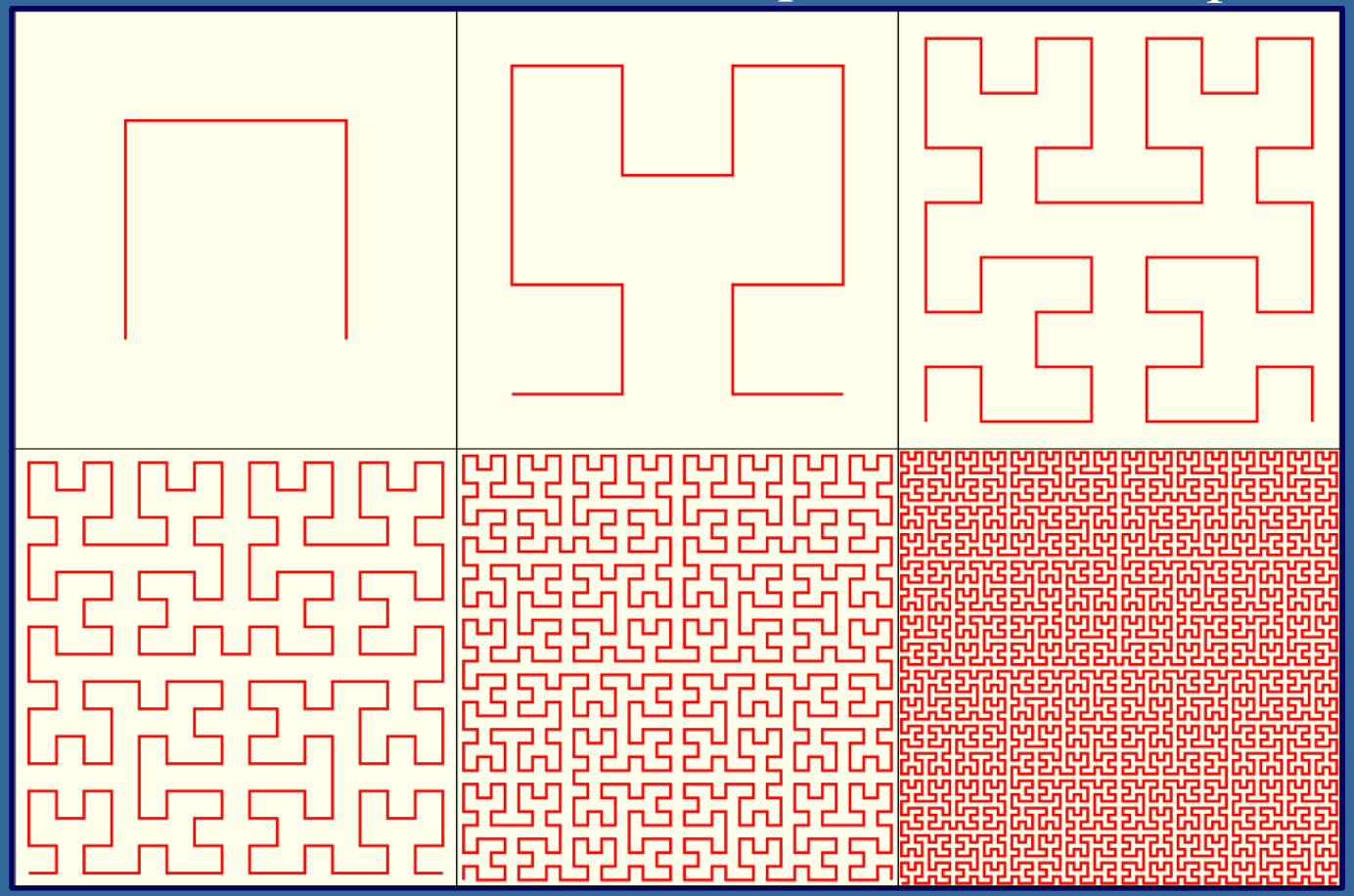
Cache awareness

- To maximize cache locality, you can utilize that the next ray likely will access roughly the same memory locations since it will traverse roughly the same part of the tree and geometrical objects.
  - To maximize spatial locality, shoot the primary rays according to a Hilbert curve, instead of sequentially scanline by scanline….

Hilbert Curve



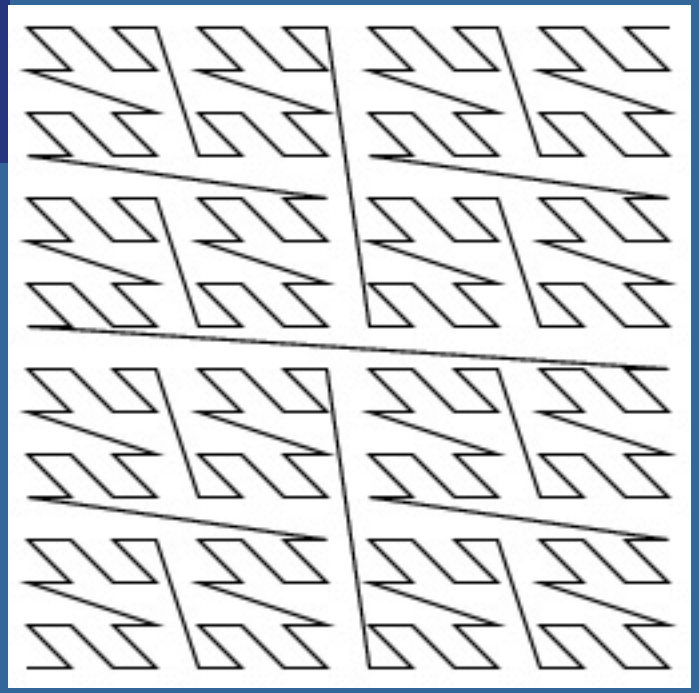
2x2 pixels 4x4 pixels



For code, see: https://en.wikipedia.org/wiki/Hilbert_curve

Z-curve

or "Morton order"



Recipe to shoot primary rays in a Z-curve order:

For primary ray n:

- the screen-x coord is every 2nd bit of n, starting with bit 0.
- the screen-y coord is every 2nd bit of n, starting with bit 1.

Shoot rays r = 0..w*h

Assume ray is the n:th ray, and n's binary value is:

$n = \ldots y_3\ x_3\ y_2\ x_2\ y_1\ x_1\ y_0\ x_0$

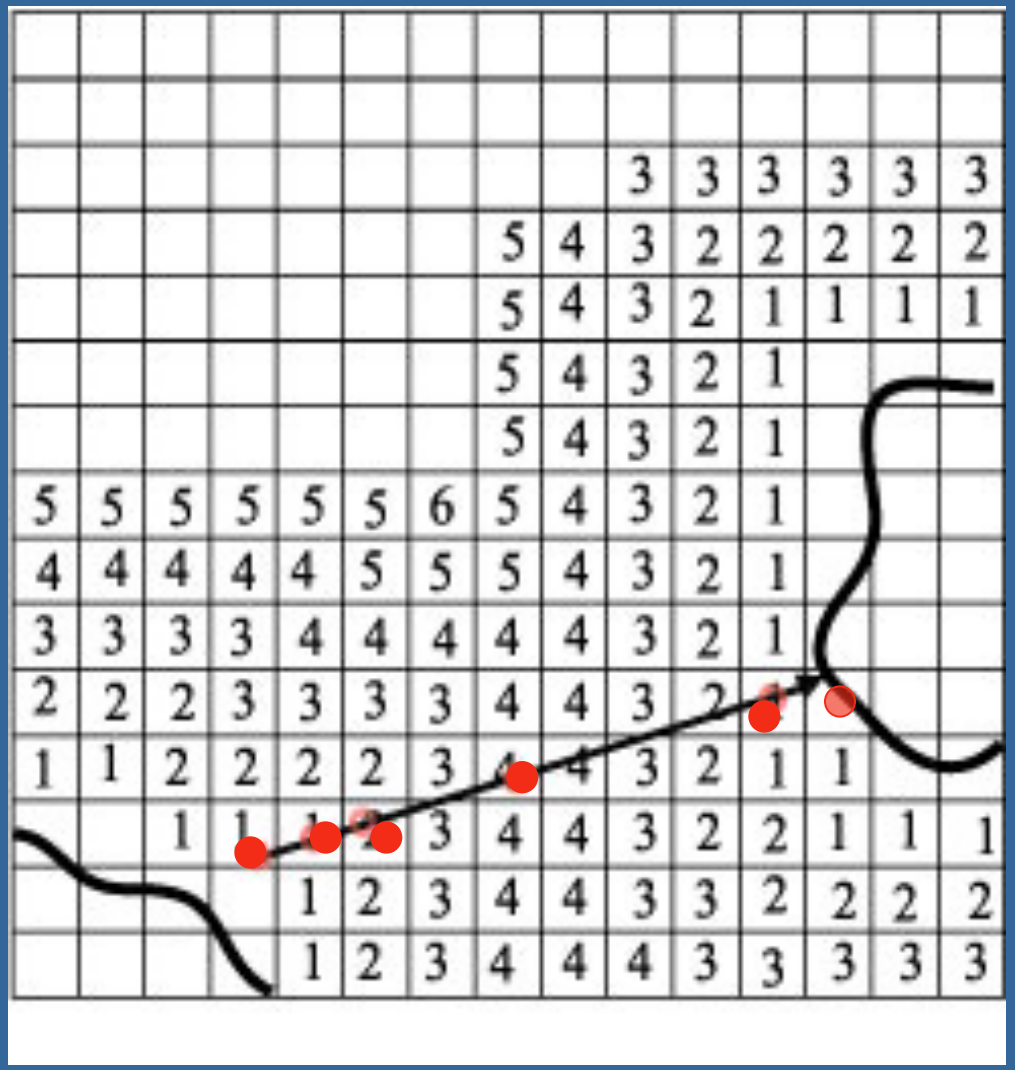
e.g., n = 1 1 0 1 0 1 1 0 = 214

Then, the ray's x and y coordinates are:

$x\_coord = \ldots x_3\ x_2\ x_1\ x_0 = 1\ 1\ 1\ 0 = 14$

$y\_coord = \ldots y_3\ y_2\ y_1\ y_0 = 1\ 0\ 0\ 1 = 9$

Faster Grid Traversal using Proximity Clouds/Distance Fields



"Proximity Clouds – An Acceleration Technique for 3D Grid Traversal", Daniel Cohen and Zvi Sheffer

Demo
using SSE

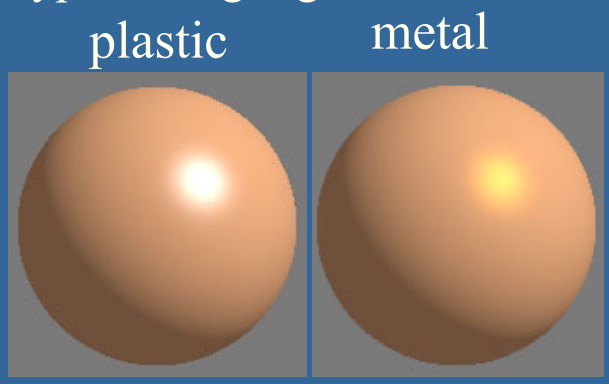
MATERIALS

- Types of material, and how light interacts
  - Glass, plastic... (dielectrics)
  - Metal (conductive)

Smooth Metal
(slät metall)

- Often used material, and well-understood in computer graphics
- We'll present a good approximation here
- Metals obey three "laws":
  - The highlight often has the same color as the diffuse
  - Law of reflection (and reflections are typically strong)
  - The Fresnel equations:
    How much is reflected and how much is absorbed
    - Though, Fresnel effect for metals is subtle
    - Higher for dieletric materials

Smooth metals (2)



- Highlight
- The law of reflection
- If the metal is smooth, we can say that it reflects perfectly in the reflection direction
- Fresnel equations depend on
  - Incident angle of the light
  - Index of refraction (e.g., chromium oxide: 2.7)
- Can compute polarized, and unpolarized values for the light (in CG, we ignore polarization, often)

- At some places, the reflection is saturated (almost white), but mostly, it is clearly modulated by the copper color
  - Plastic adds the pure reflection color
  - Metal adds a modulated reflection color

Fresnel

- F describes the reflectance at a surface at various angles (n=index of refraction)

$$F = \frac{1}{2}\frac{(g-c)^2}{(g+c)^2}\left(1+\frac{[c(g+c)-1]^2}{[c(g-c)+1]^2}\right)$$

$$g = \sqrt{n^2 + c^2 - 1}$$

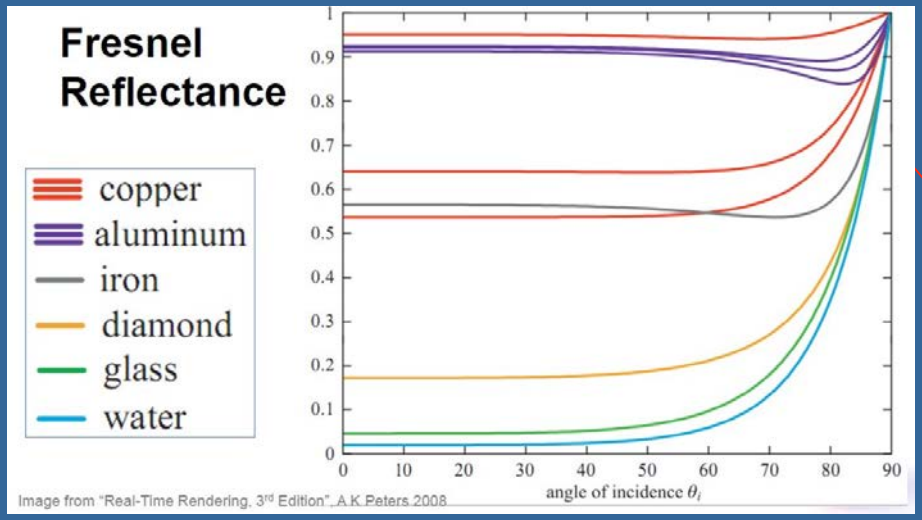
$c = \mathbf{l} \bullet \mathbf{n}$ =angle

Or $c = \mathbf{v} \bullet \mathbf{n}$

Or if you use the half vector instead of normal:

$c = \mathbf{v} \bullet \mathbf{h}$

$\mathbf{h} = \mathbf{v}+\mathbf{l}/||\mathbf{v}+\mathbf{l}|$



An approximation to Fresnel
(by Schlick)

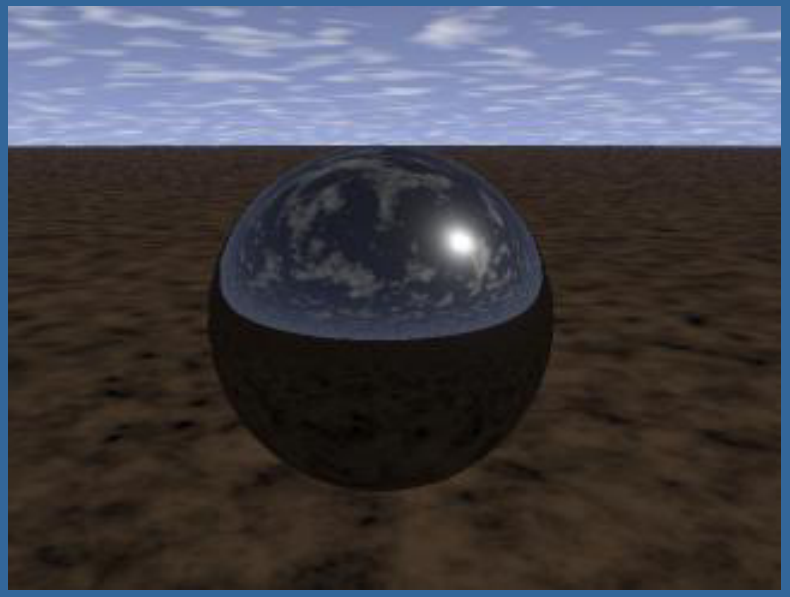
$$F \approx R_0 + (1 - R_0)(1 - \mathbf{v} \cdot \mathbf{n})^5$$

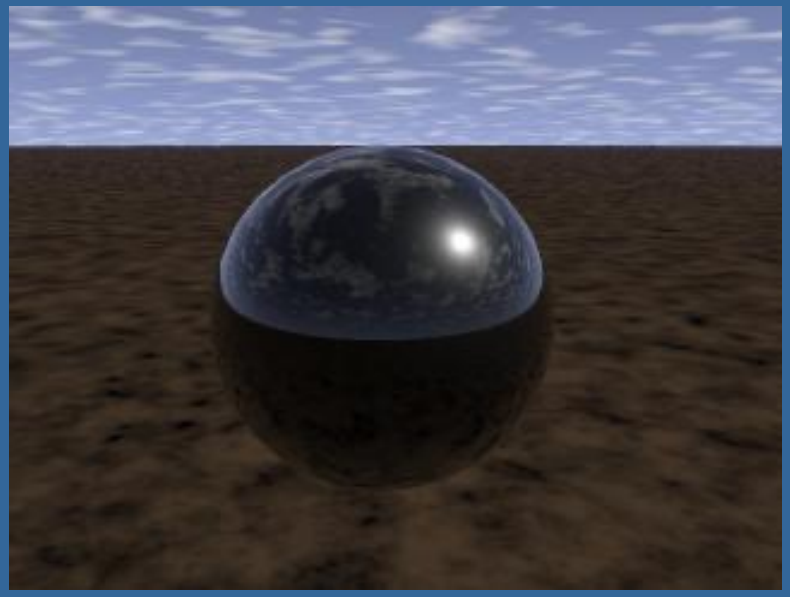
- $\mathbf{v}$ is the vector from the point on the surface to the eye
- $\mathbf{n}$ is the surface normal
- R_0 is the reflectance when $\mathbf{v} \cdot \mathbf{n} = 1$
- Works well in practice

- Use F for your reflection rays in shading:
  - F^*`trace`(reflection_vector)
  - Can be used for rasterization too (e.g. when applying result from cubemaps)

Fresnel, example

- What does it look like
- A black dielectric sphere (glass or plastic)
  - in computer graphics, glass can be black
- Which has the Fresnel effect?





Images courtesy of Steve Westin, Cornell University

Smooth dielectric materials

- A dielectric is a transparent material
- Refracts light
- Filters light (due to impurities in material)
- Examples (index of refraction):
  - Glass = 1.5
  - Plastic = ~1.5
  - Diamond = 2.4
  - Water = 1.33
  - Air = 1.0

Smooth Dielectric

- Low reflectance (water, glass, plastic, etc. ~5%)
- Refracted light continues inside the material, being scattered by impurities until it is absorbed or re-exits the surface

From Advanced Real-Time Reflectance, by Dan Baker, Naty Hoffman & Peter-Pike Sloan

Glossy reflecton

From Advanced Real-Time Reflectance, by
Dan Baker, Naty Hoffman & Peter-Pike Sloan

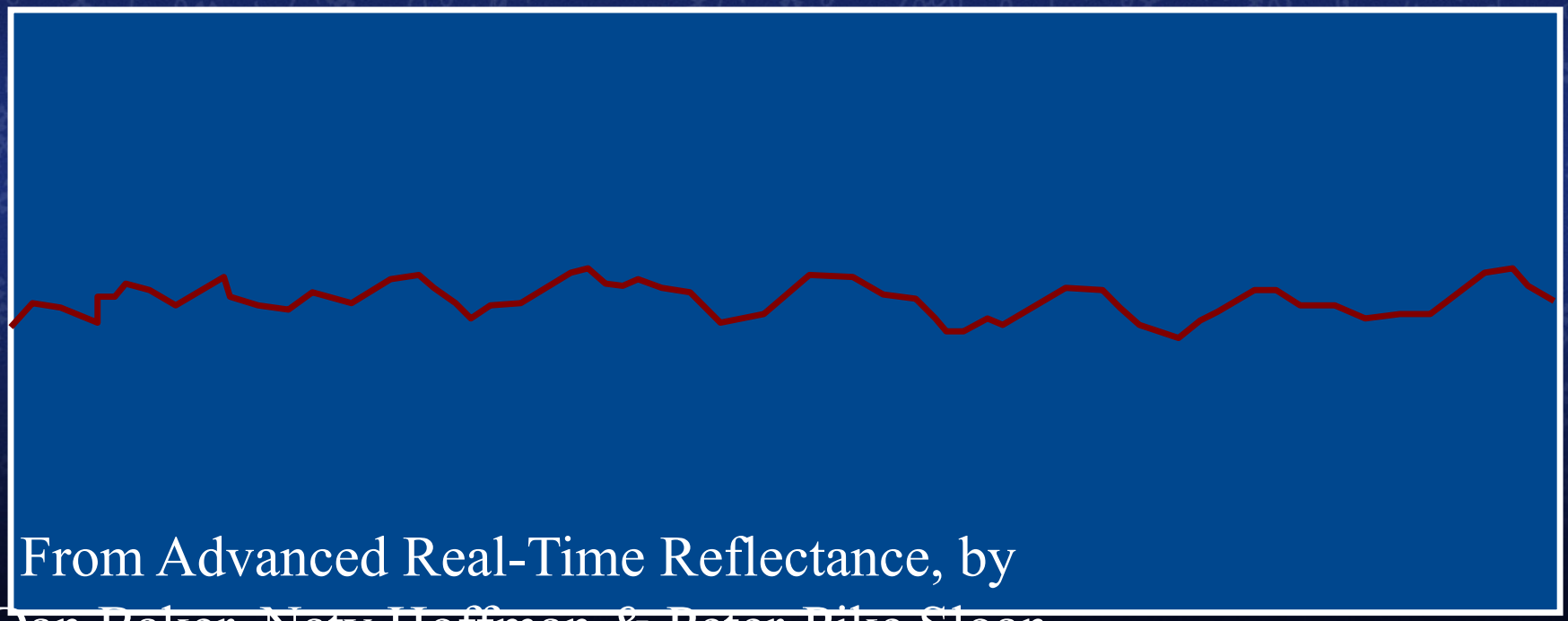
Semi-Rough (Glossy)

- Most surfaces are not flat at all scales

From Advanced Real-Time Reflectance, by Dan Baker, Naty Hoffman & Peter-Pike Sloan

Semi-Rough (Glossy)

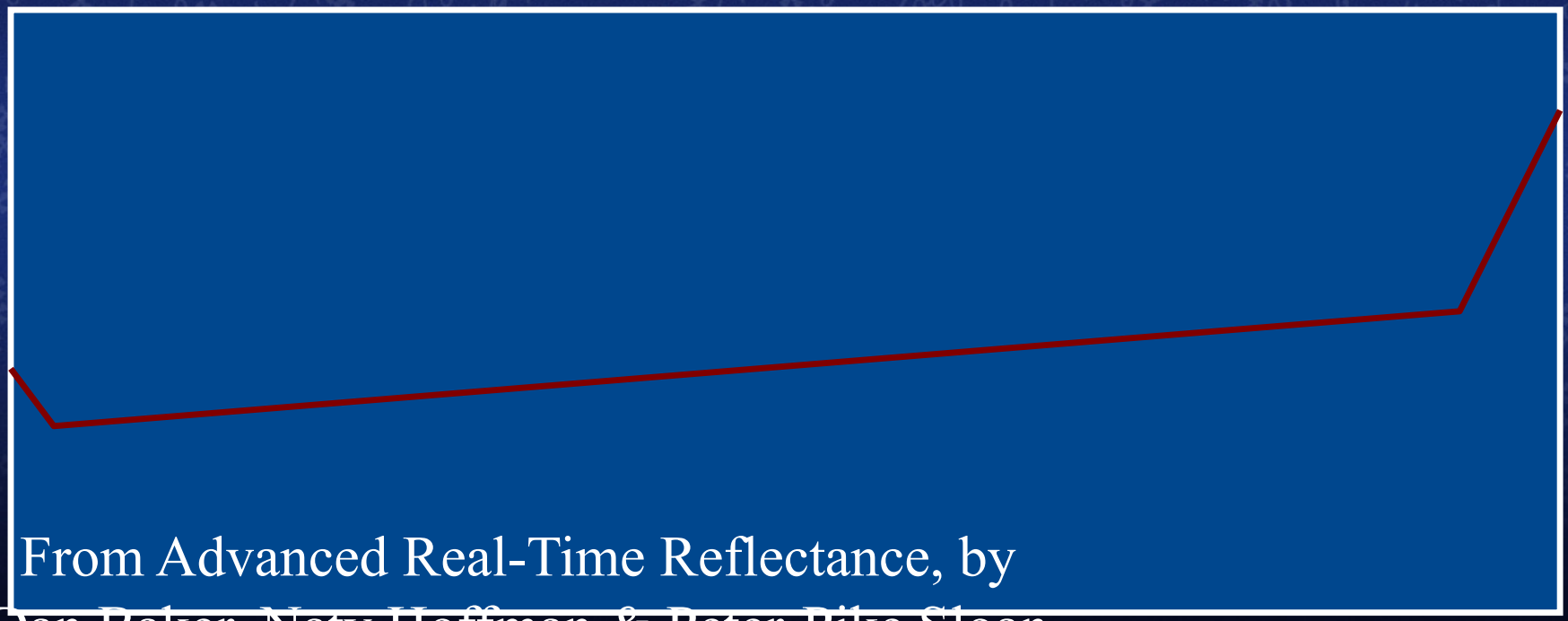
- Most surfaces are not flat at all scales
  - Many surfaces which appear flat at visible scales have complex *microscale* structure



From Advanced Real-Time Reflectance, by Dan Baker, Naty Hoffman & Peter-Pike Sloan

Semi-Rough (Glossy)

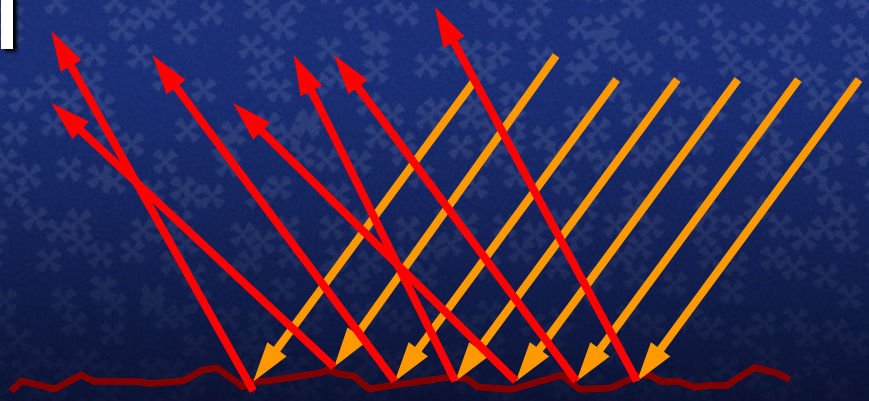
- Most surfaces are not flat at all scales
  - Many surfaces which appear flat at visible scales have complex *microscale* structure
  - At the smallest scale we can often treat the surface as flat again



From Advanced Real-Time Reflectance, by Dan Baker, Naty Hoffman & Peter-Pike Sloan

Semi-Rough (Glossy)

- A surface patch contains micro-facets with continuously distributed normals
- Light reflects off facets, ‘spreads out’
- In ‘semi-rough’ surfaces distribution of micro-normals biased to macro-normal



From Advanced Real-Time Reflectance, by Dan Baker, Naty Hoffman & Peter-Pike Sloan

Semi-Rough (Glossy)

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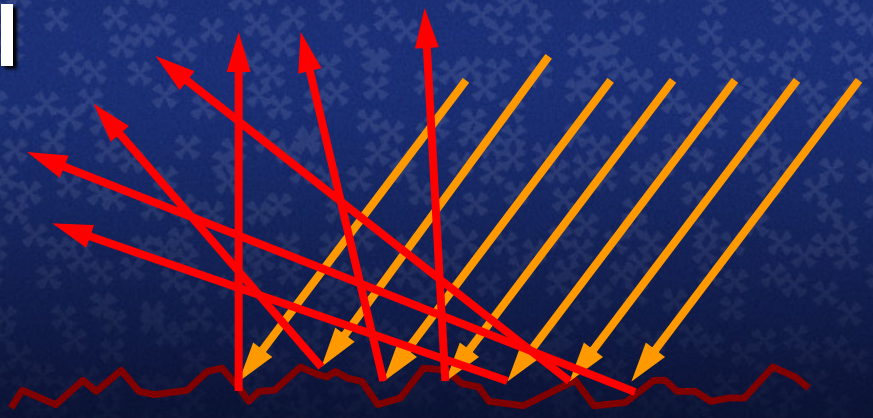

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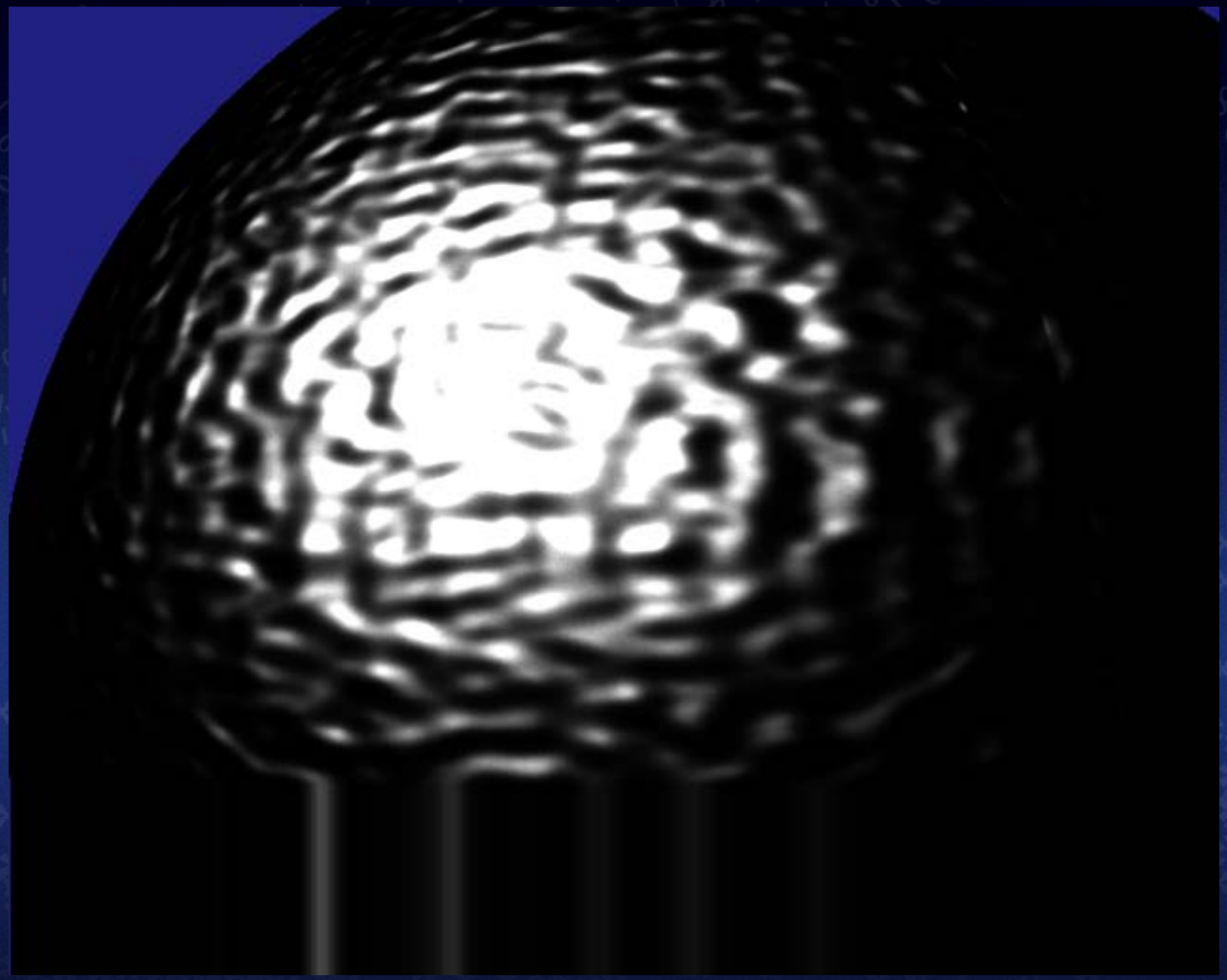
Semi-Rough (Glossy)



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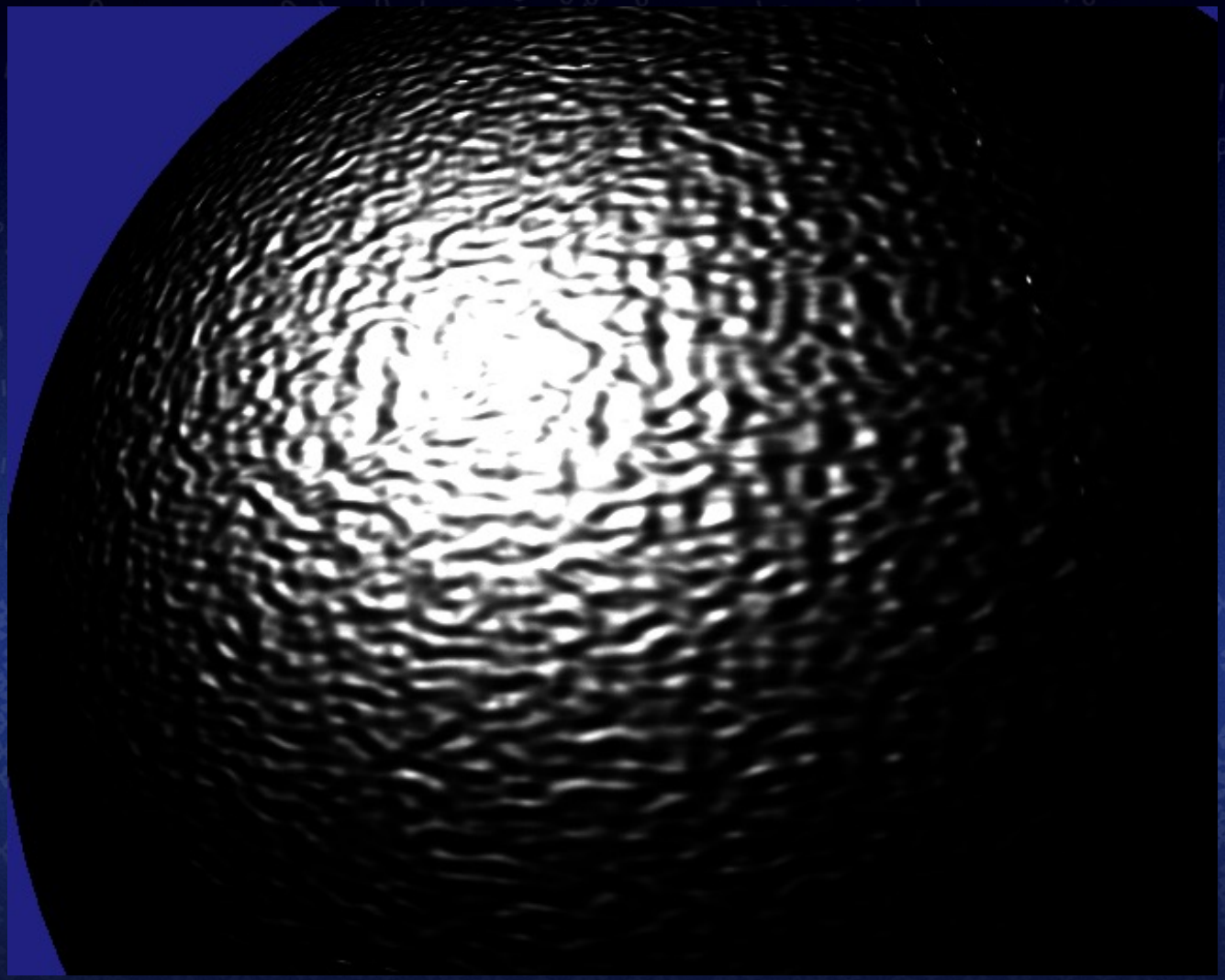
Semi-Rough (Glossy)



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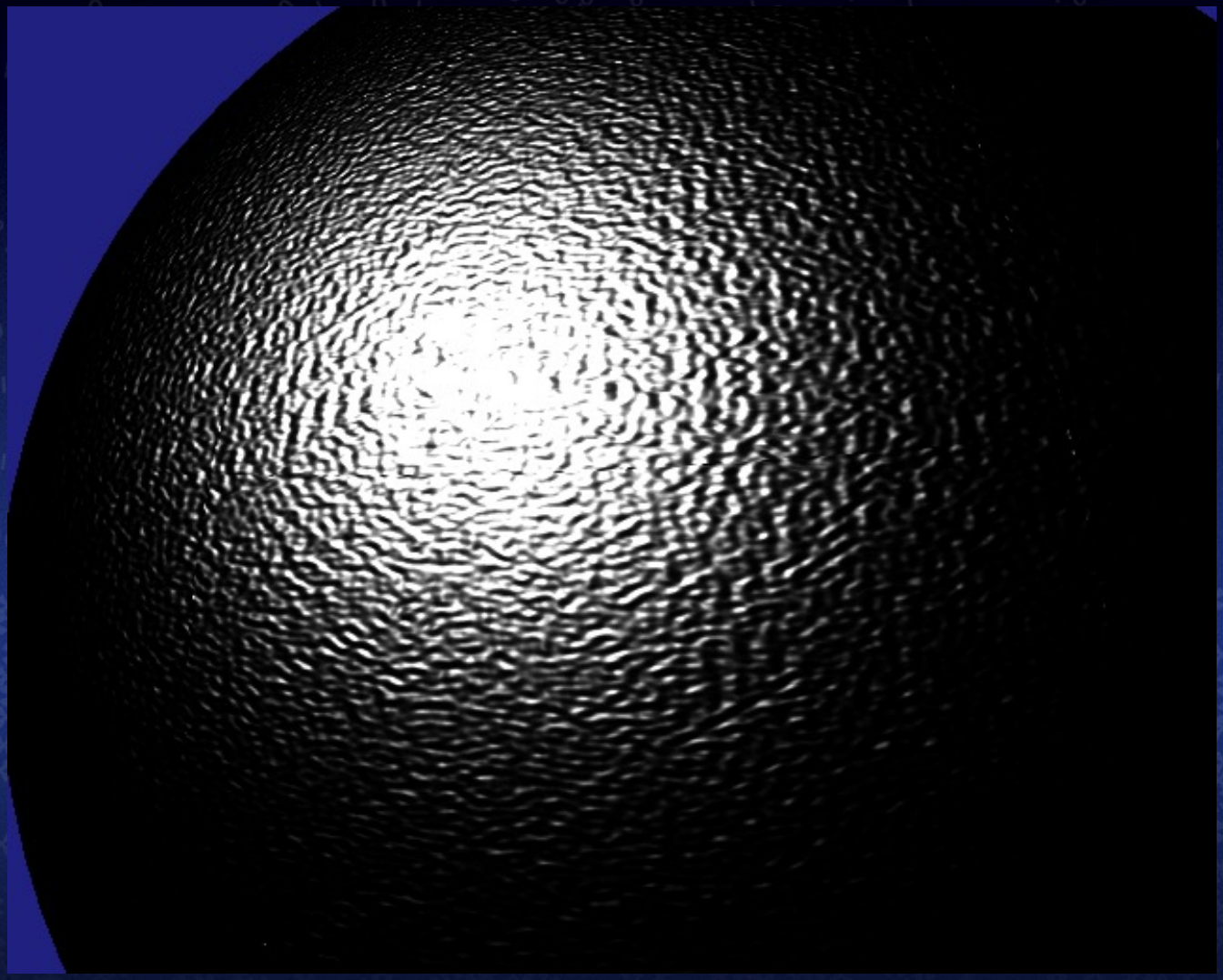
Semi-Rough (Glossy)



From Advanced Real-Time Reflectance, by
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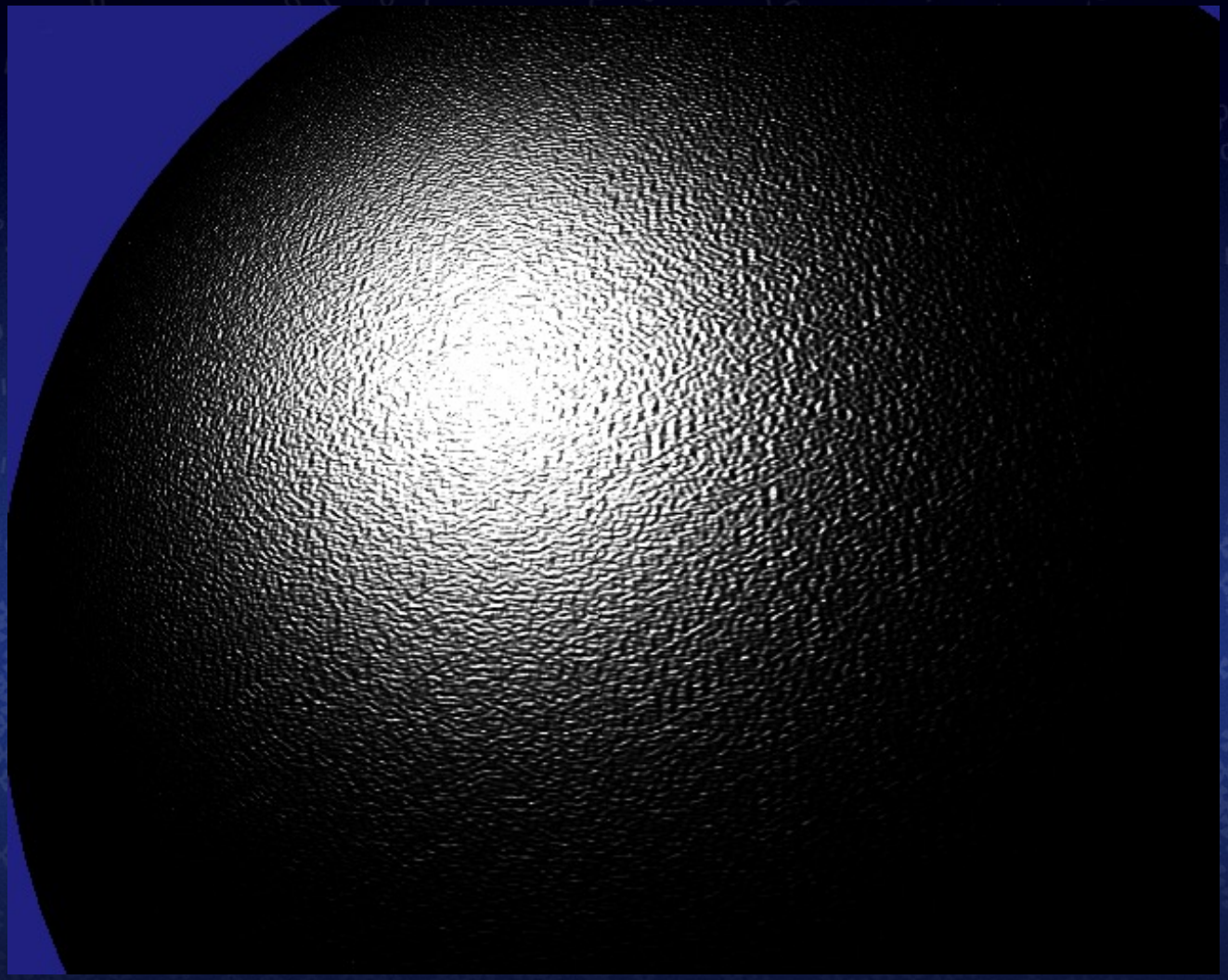
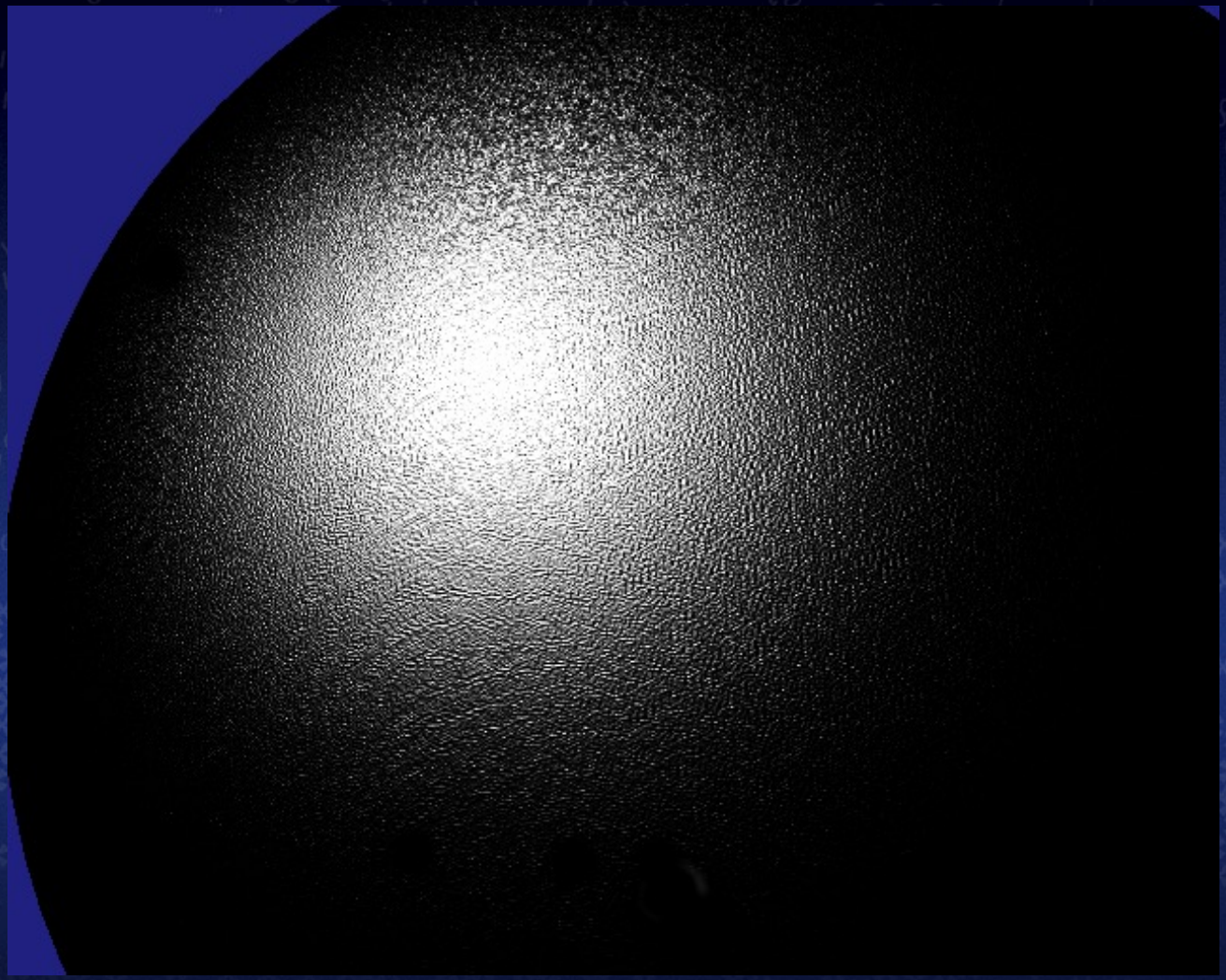
Semi-Rough (Glossy)



From Advanced Real-Time Reflectance, by
Dan Baker, Naty Hoffman & Peter-Pike Sloan

Semi-Rough (Glossy)



From Advanced Real-Time Reflectance, by
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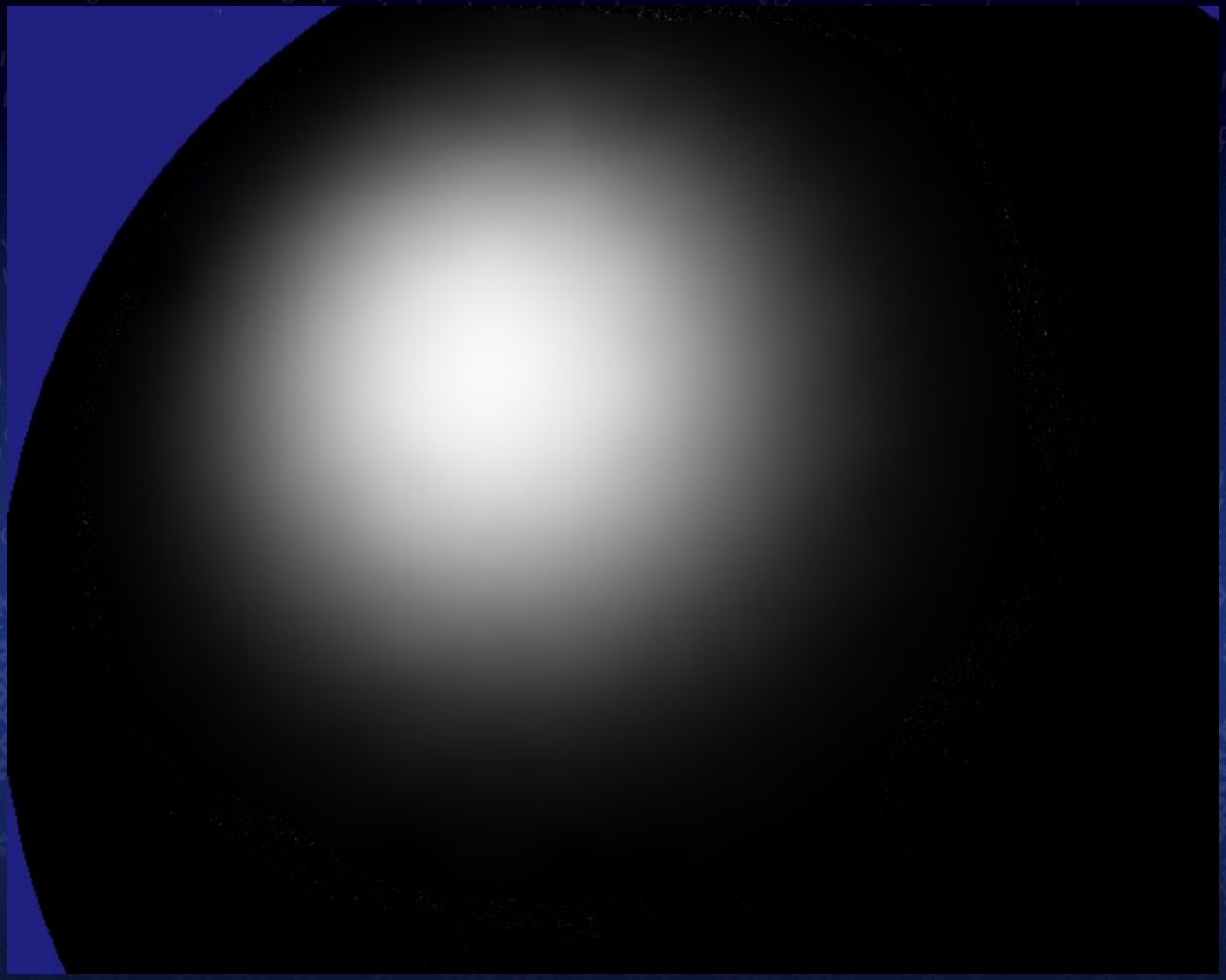
Semi-Rough (Glossy)



From Advanced Real-Time Reflectance, by
Dan Baker, Naty Hoffman & Peter-Pike Sloan

Rough Dielectric

- Normal distribution is extremely random
- Almost uniformly diffuse with some retroreflection

From Advanced Real-Time Reflectance, by Dan Baker, Naty Hoffman & Peter-Pike Sloan

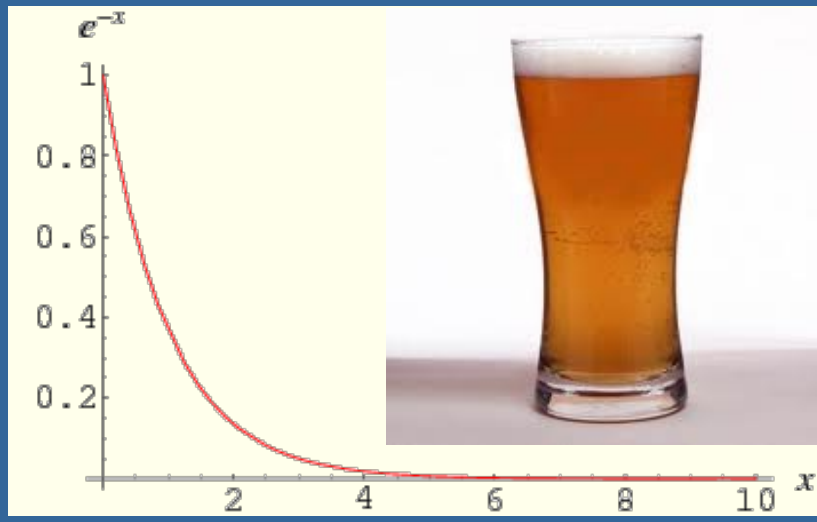
Smooth dielectric materials (2)
Homegeneous impurities

E.g. Water, transparent plastic, glass…

- Light is attenuated with Beer's law
- Looses intensity with: $dI=-C\,I\,ds$
- $I(s)=I(0)e^{-Cs}$
- Compute once for each RGB
- Also, use the Fresnel equations for these materials

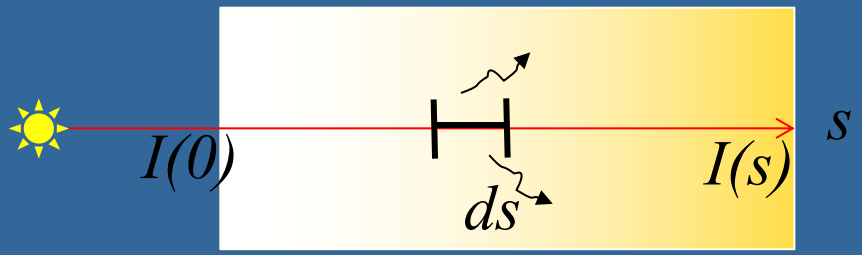
Beer's Law

Constant intensity decrease at greater distance due to out-scattering and absorption.



$$dI = -CIds$$

$$I(s) = I(0)e^{-C*s}$$



Beer's law

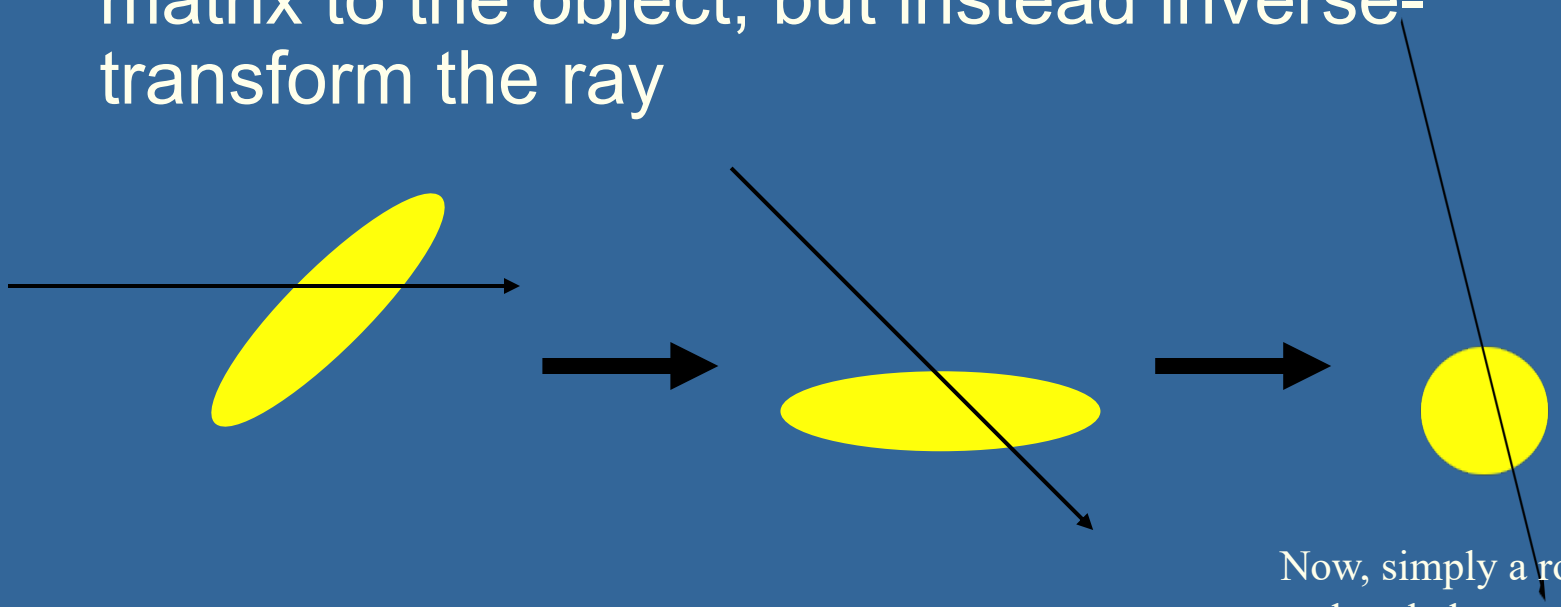
The taller the glass, the darker the brew,
The less the amount of light that comes through

RAY TRACING ADDITIONALS

- Geometrical objects
  - Ray intersections: transform ray into object space
  - Constructive Solid Geometry
  - Blobs
- Procedural textures
  - Fractals from noise
- Optics
  - E.g., depth-of-field

Geometry

- Object-oriented programming
  - Makes it simple to add new geometrical objects from simpler ones. E.g., elipsoid from scaled sphere.
- Just add a transform (TRS)
- The standard trick is not to apply the transform matrix to the object, but instead inverse-transform the ray

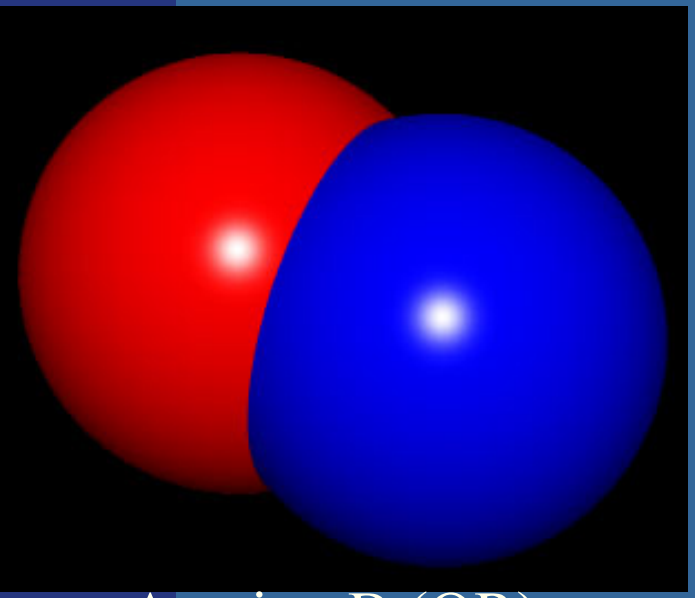


Geometry: Constructive Solid Geometry (CSG)

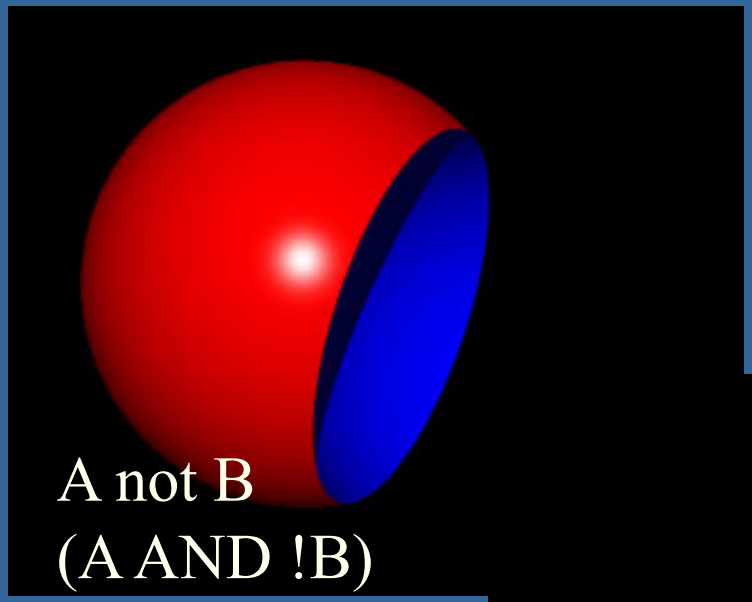
- Boolean operations on objects
  - Union (or)
  - Subtraction (A not B)
  - Xor
  - And
- Simple to implement
- Must find *all* intersections with a ray and an object
- Then do this for involved objects, and apply operators to found interval

Geometry: Constructive Solid Geometry (CSG)

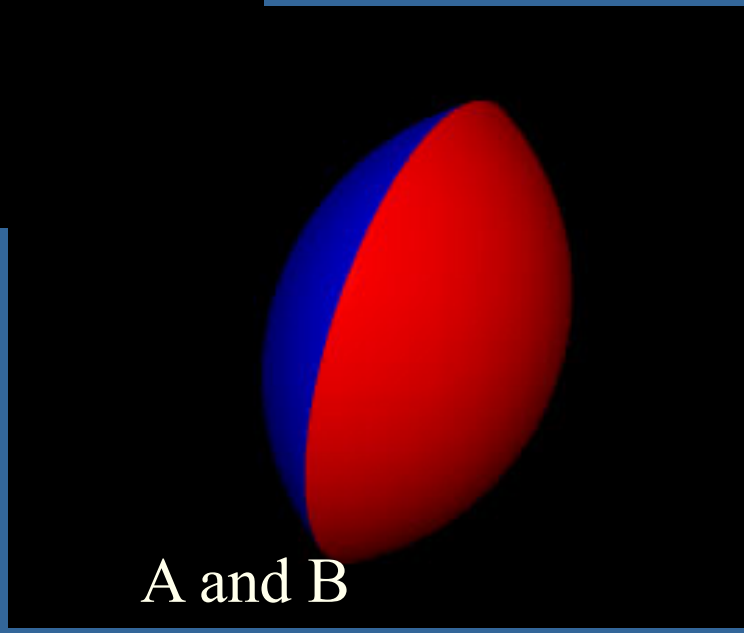
- Examples, operators:



A union B (OR)



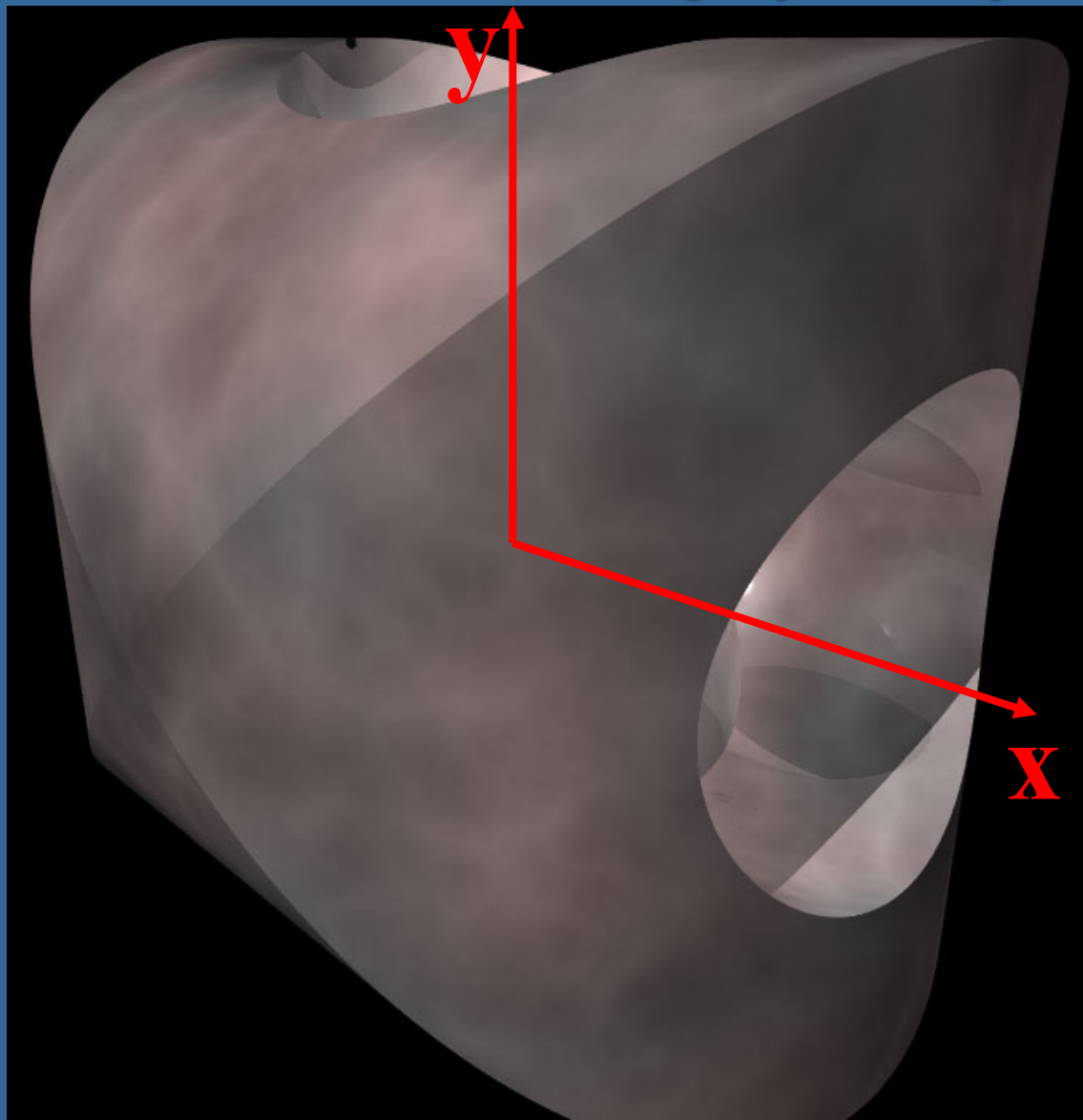
A not B
(A AND !B)



A and B

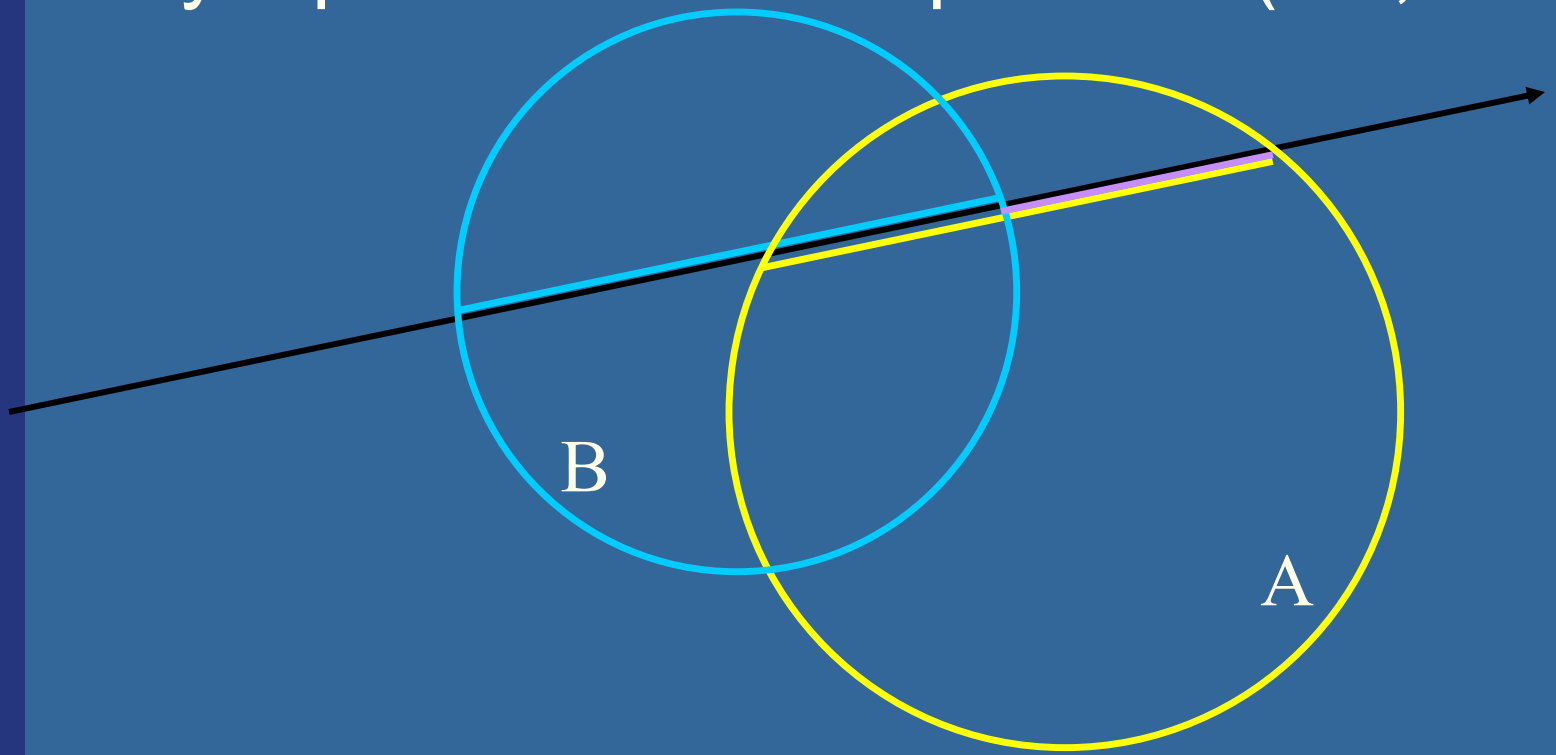
Geometry: Constructive Solid Geometry (CSG)

- Another example
- Done with 4 cylinders



Constructive Solid Geometry (CSG) How to implement

- Try: sphere A minus sphere B (i.e., A not B)



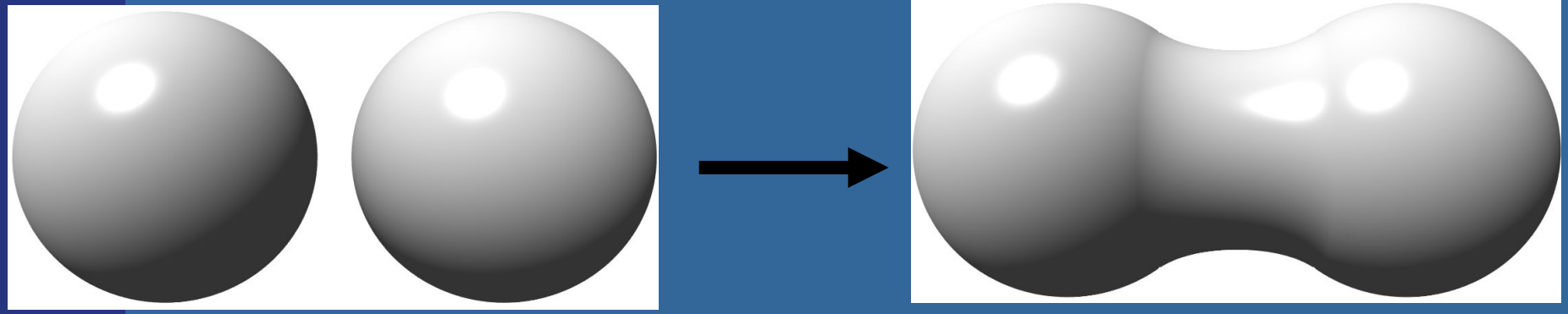
- In summary: find both entry and exit points on both spheres. Such two points on a sphere is an interval (1D). Apply the operator on these intervals

CSG

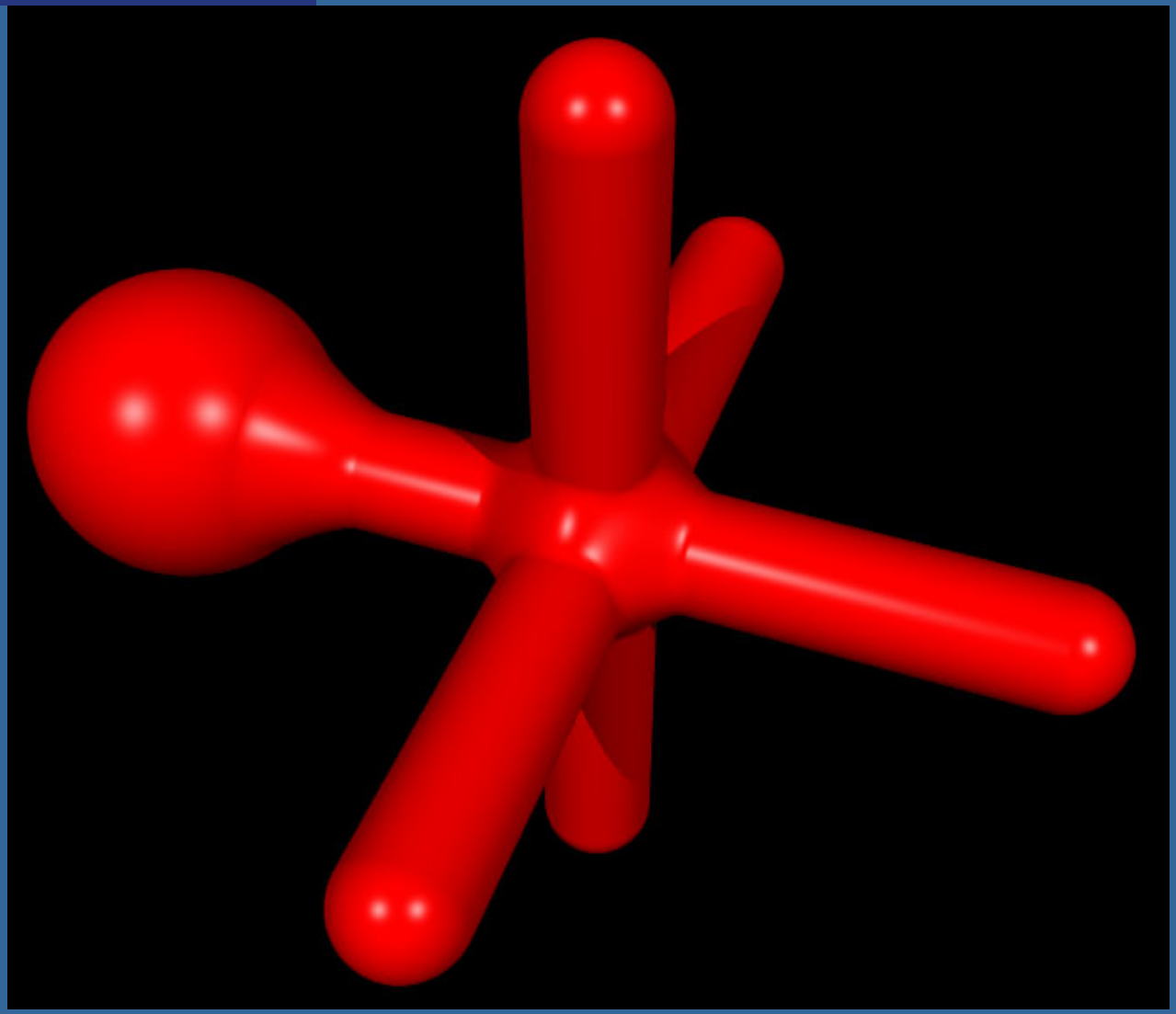
- Works on any geometrical object, as long as you can find **all** intersection point along a line
  - So, be careful with optimizations…
- And objects should be closed
  - Example: put caps on cylinder.

Geometry: Blobs

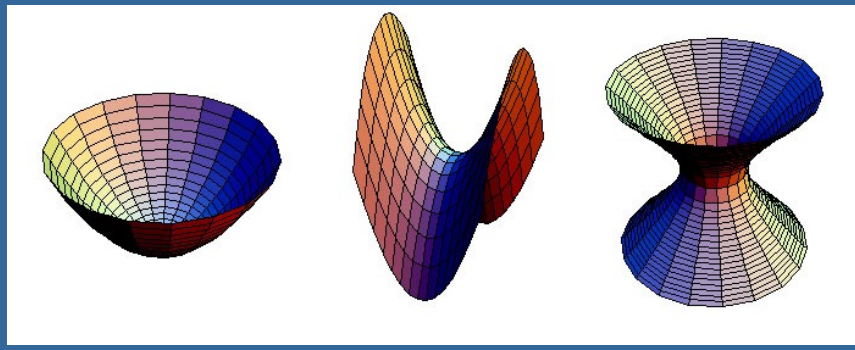
- A method for blending implicit surfaces (e.g., spheres, $x^2+y^2+z^2=1$)
- After blend, you get a higher order surface
- Need a numerical root finder



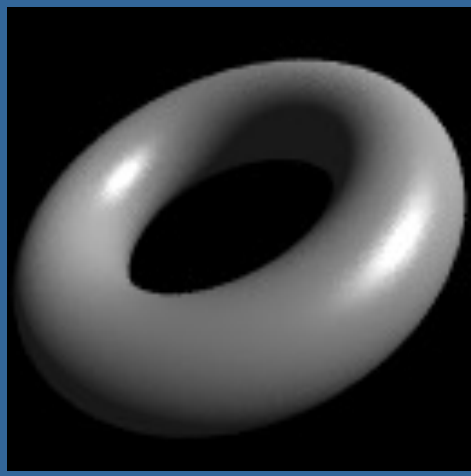
Blob example

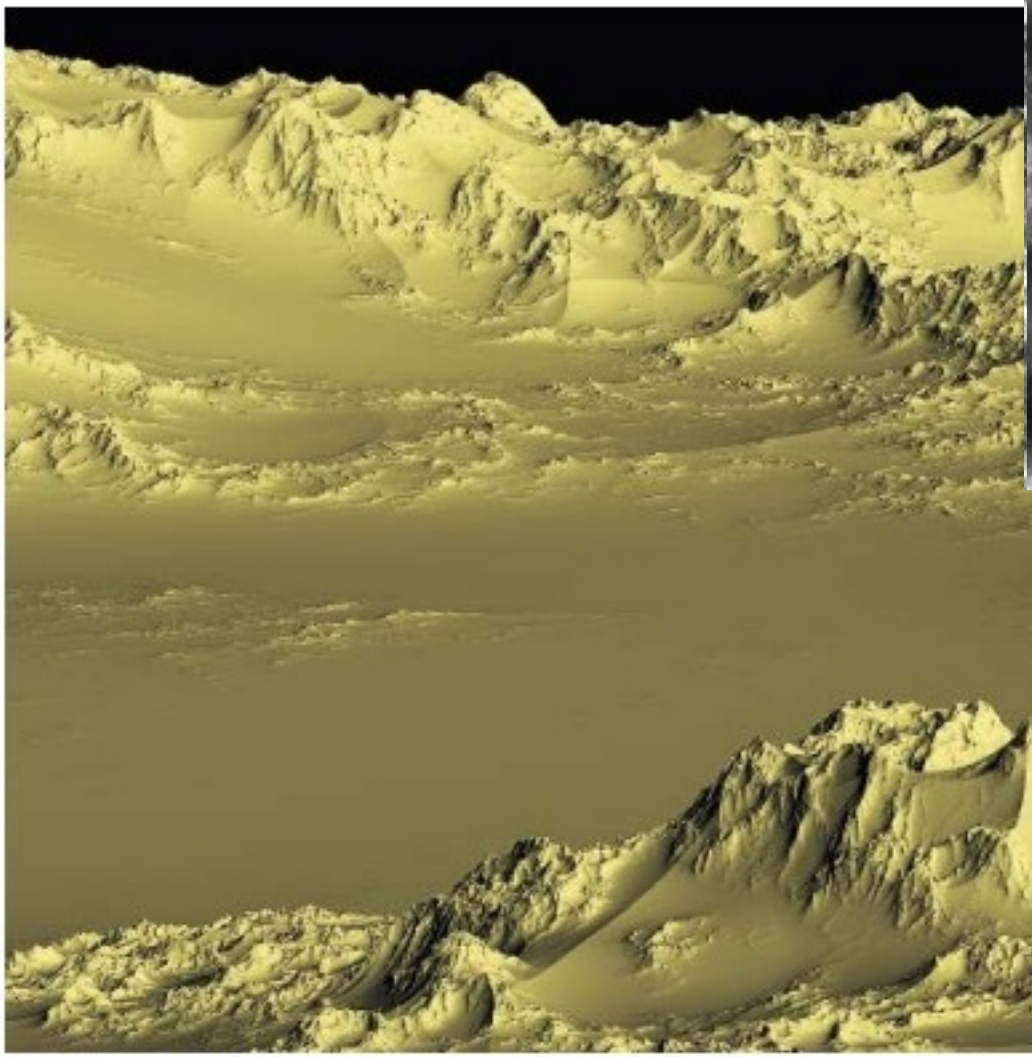


Geometry



- Quadrics (2:a-gradsytor)
  - Cone, cylinder, paraboloids, hyperboloids, ellipsoids, etc.
- Higher order polynomial surfaces
  - Example: torus, 4th degree
- Fractal landscapes
  - Pretty simple, fast algorithm exist





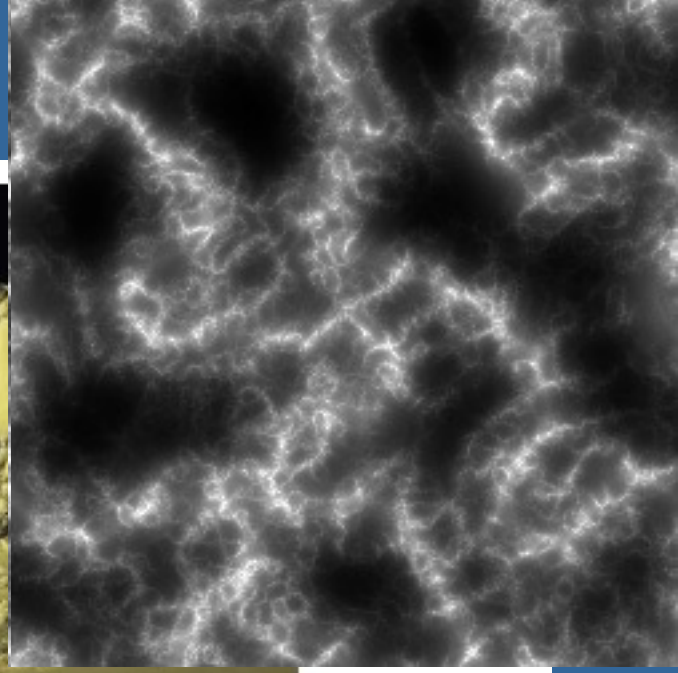
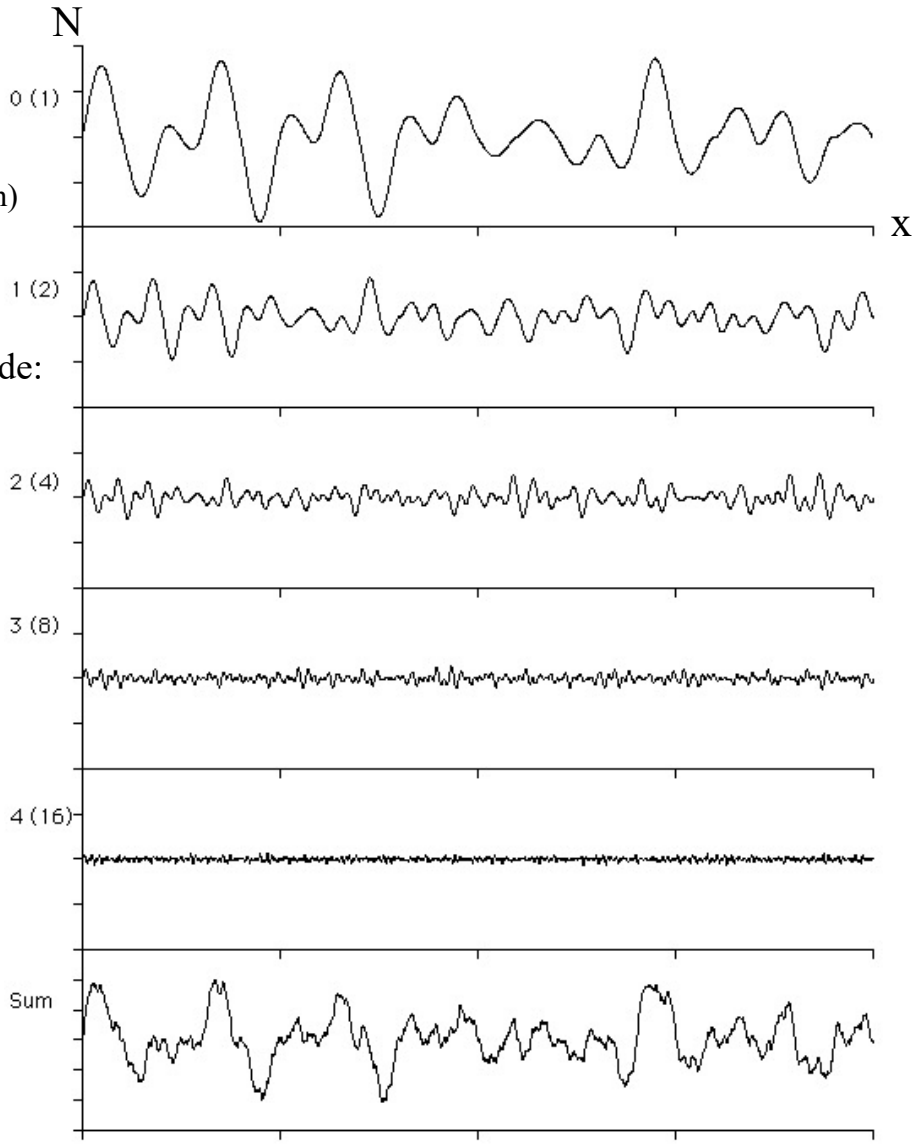


FIGURE 17.4 The very first QAEB-traced terrain. The terrain model is the "ridged multifractal" function described in Chapter 16. Copyright © F. Kenton Musgrave.

Perlin Noises in 1-D

Noise signal with certain frequency and amplitude:
(E.g., use random-number generator and spline interpolation)

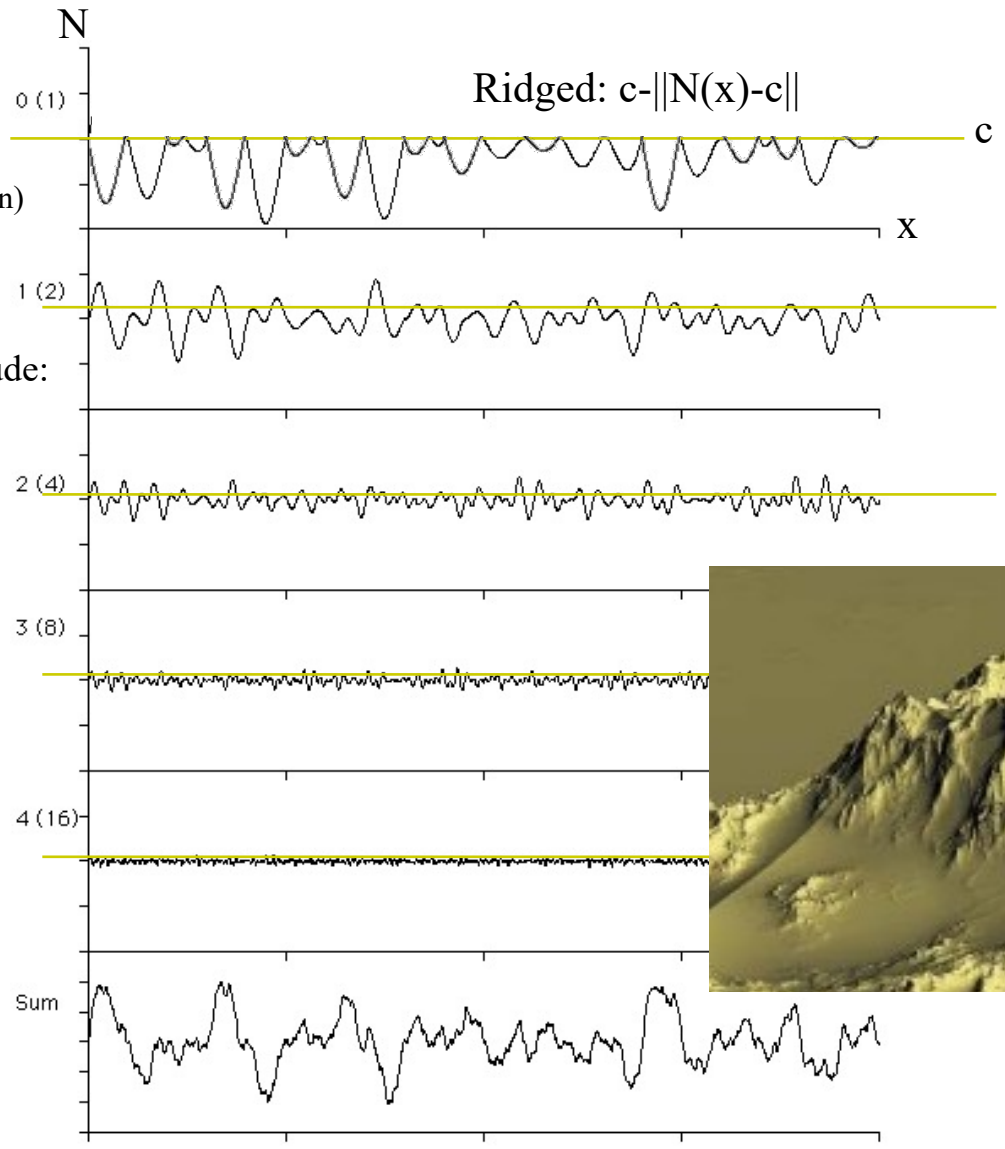


Next octave: ~double frequency, ~half amplitude:

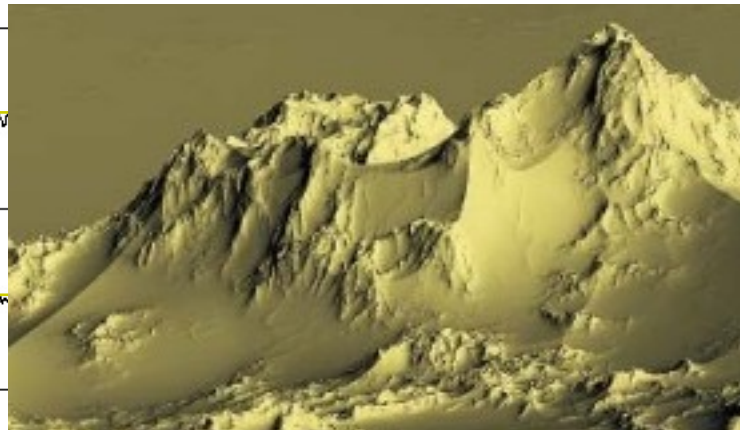
Adding gives Fractal Noise:

Perlin Noises in 1-D

Noise signal with certain frequency and amplitude:
(E.g., use random-number generator and spline interpolation)

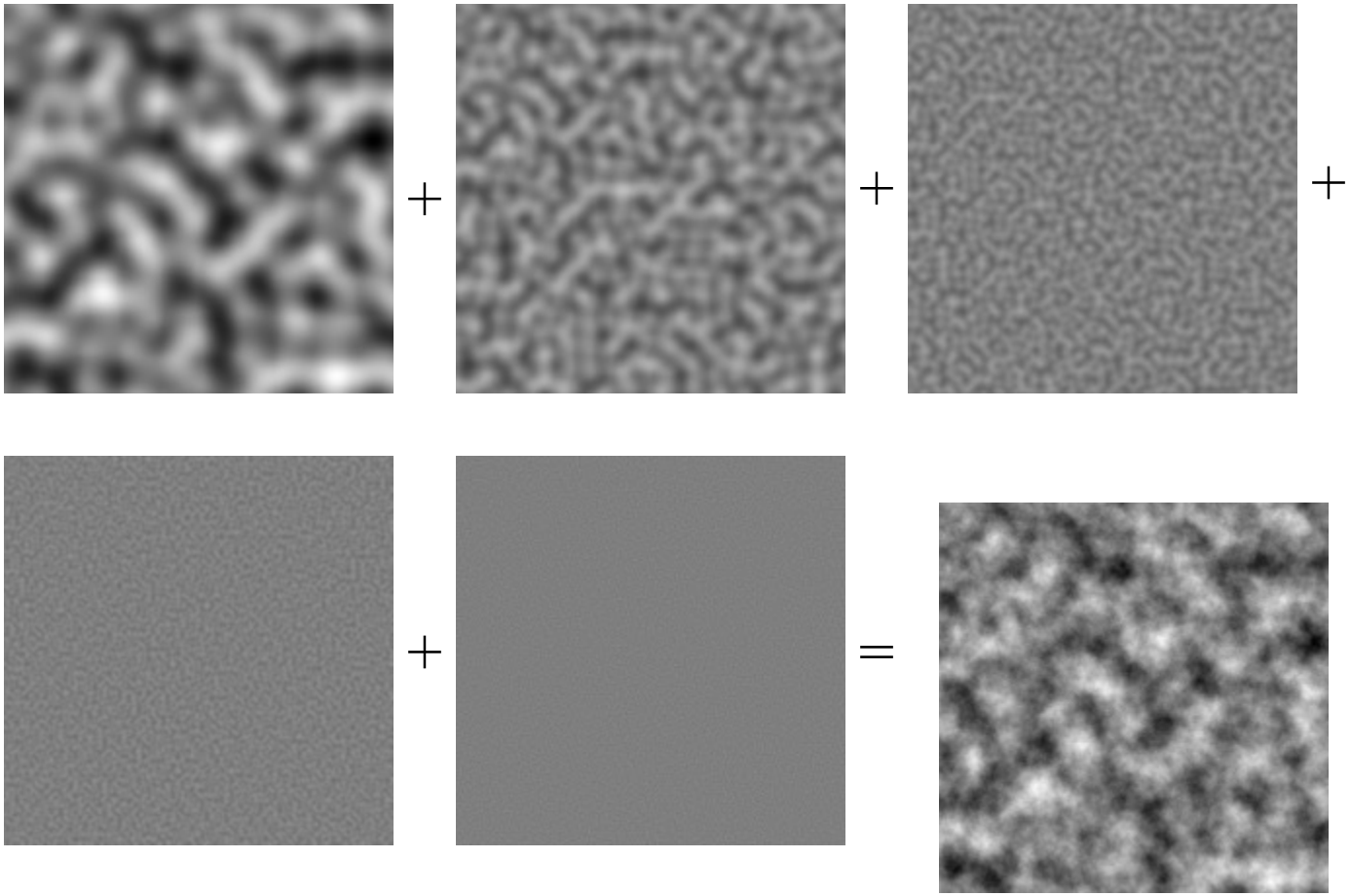


Next octave: ~double frequency, ~half amplitude:



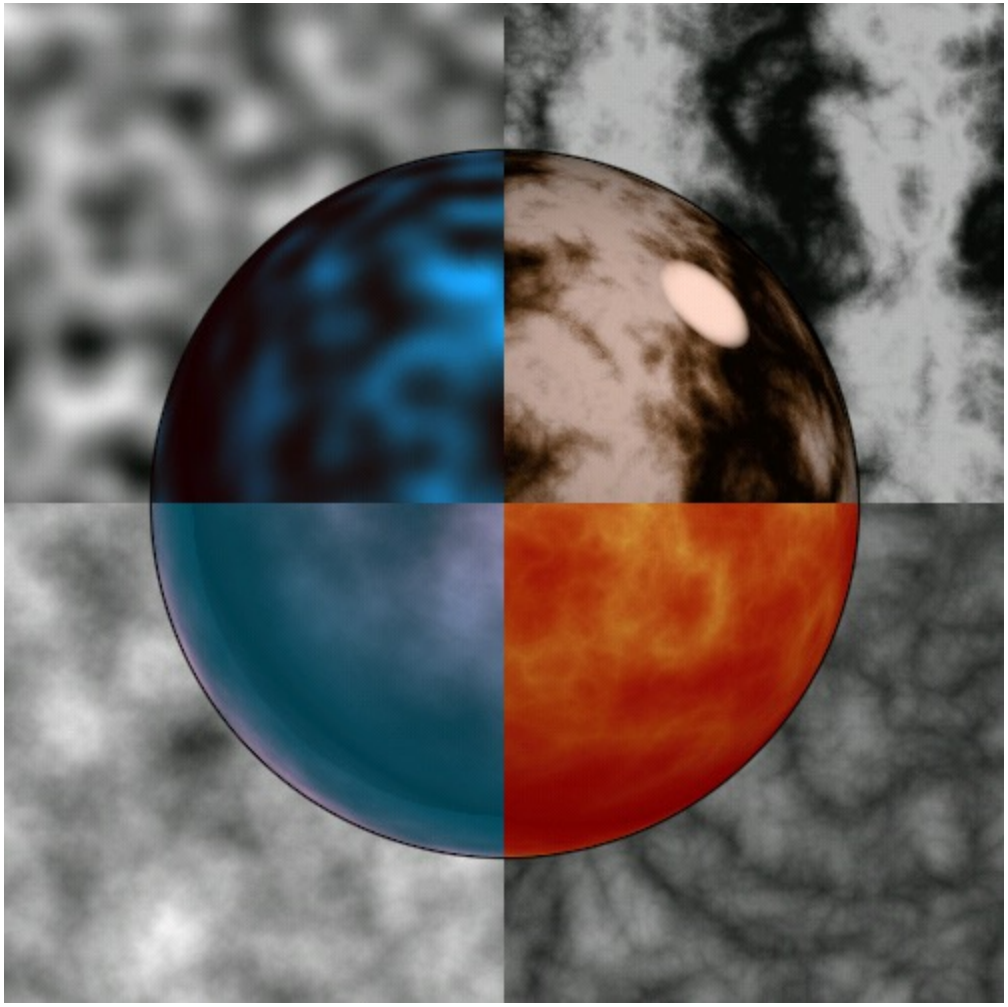
Adding gives Fractal Noise:

Perlin Noises in 2-D



Weighted Sums

Noise (1 octave):
-Worn metal
-Water wave



Sin(x + Sum[1/f *|noise|]):
-Turbulent flows
-Fire
-Marble

Sum[1/f * noise]:
-Rock
-Mountains
-Clouds

Sum[1/f * |noise|]:
-Turbulent flows
-Fire
-Marble
-Clouds

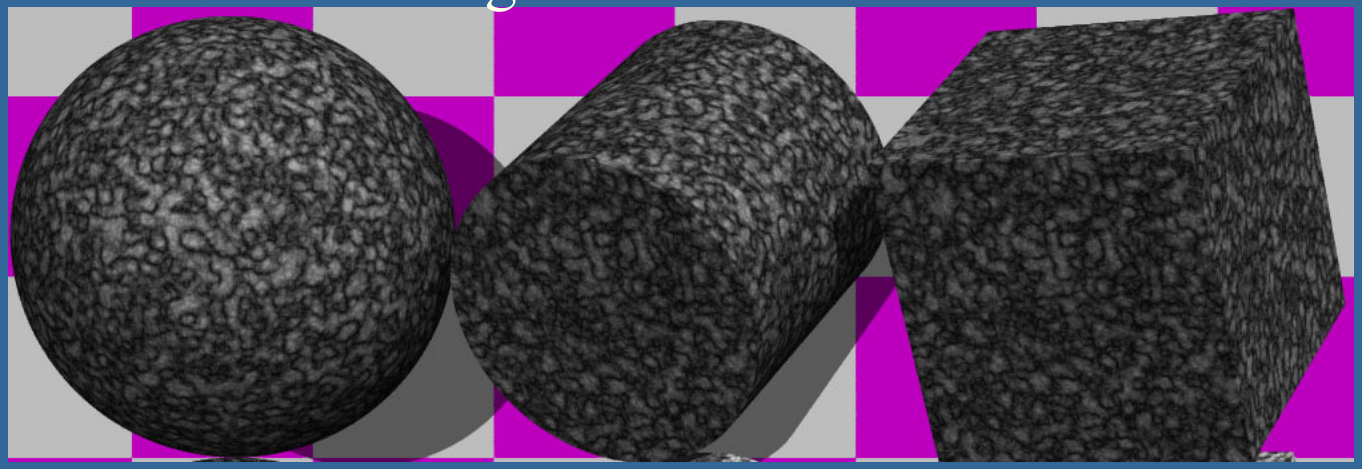
K. Perlin

More fractal examples…

WebGL examples:

- https://www.shadertoy.com/view/MdfGRX
- Ladybug (fully procedural, open in Chrome): https://www.shadertoy.com/view/4tByz3

Procedural texturing:



Texturing and Modeling – a procedural approach, by Perlin, Musgrave, Ebert…

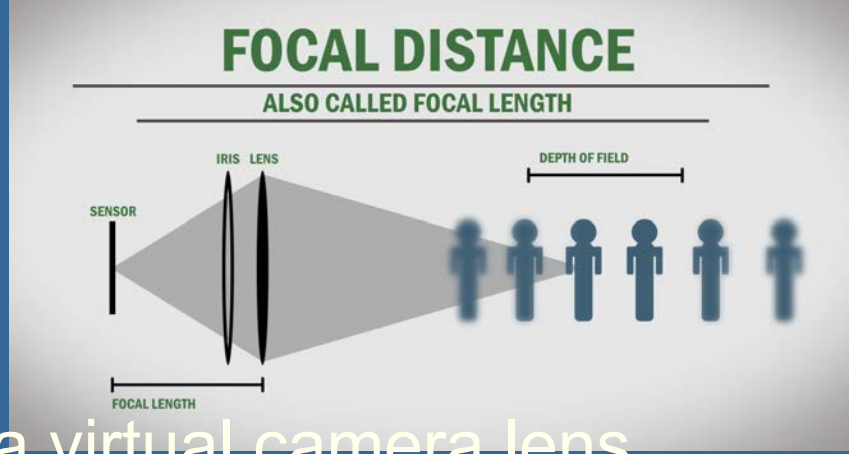
Optics

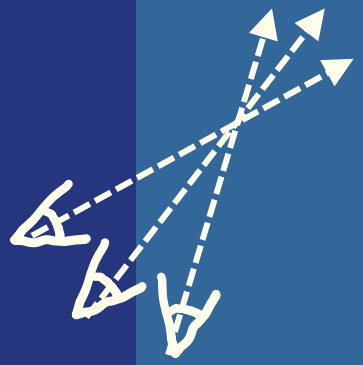
- You can add
  - Fog
  - Light fall off : $1/d^2$
  - Fresnel equations
  - Depth of field
  - Motion blur
  - …

Participating media

Optics

- Depth-of-field
  - Add more samples on a virtual camera lens



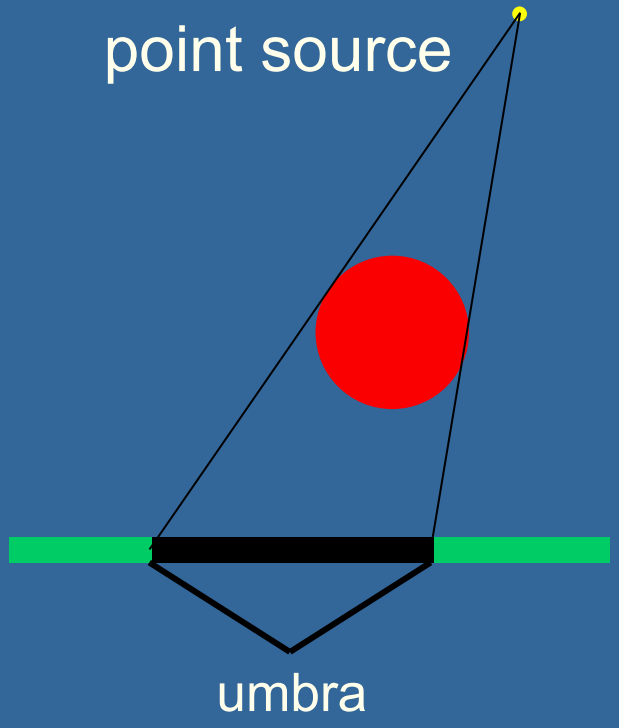


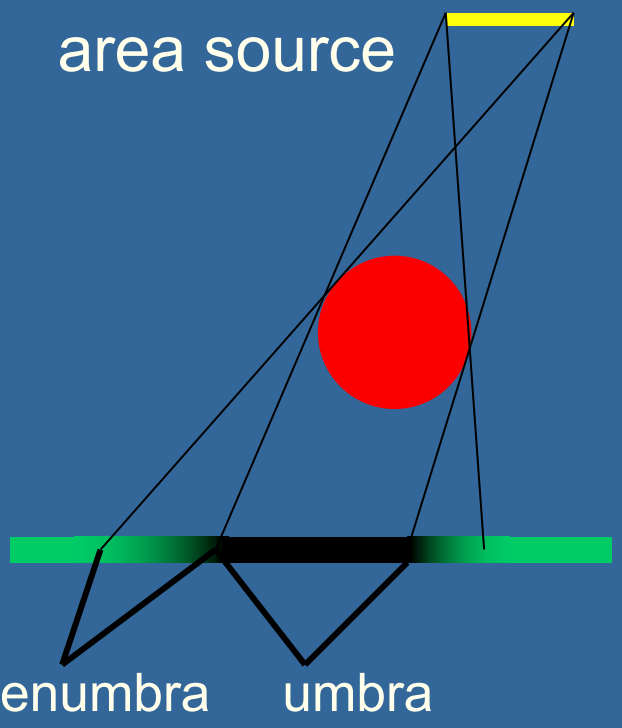
Soft shadows

- Soft shadows are typically more realistic than hard shadows
- Examples:

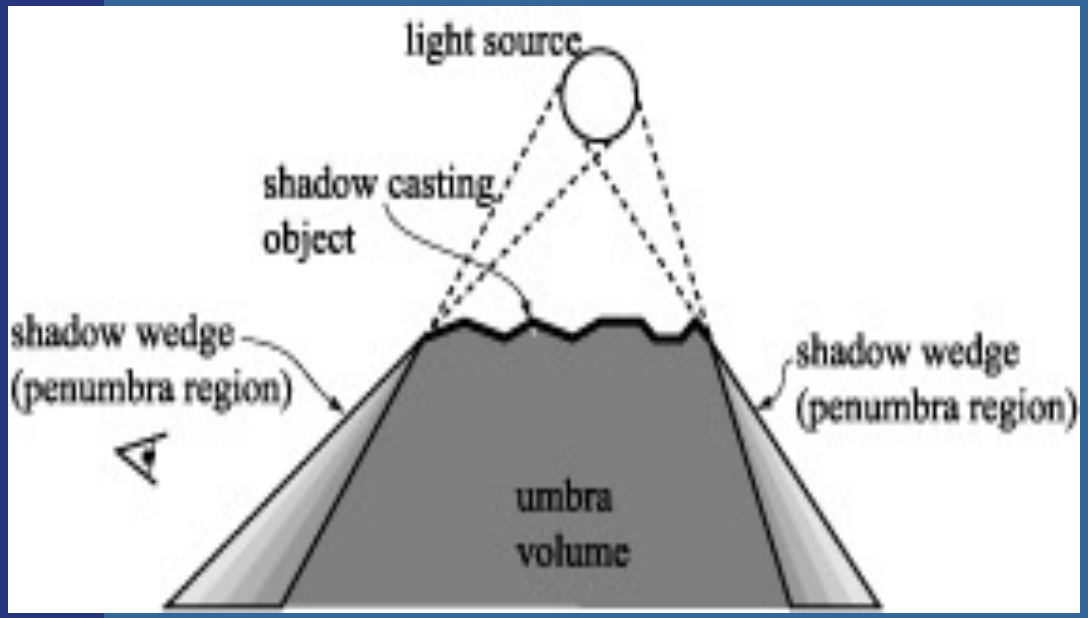
Soft shadows

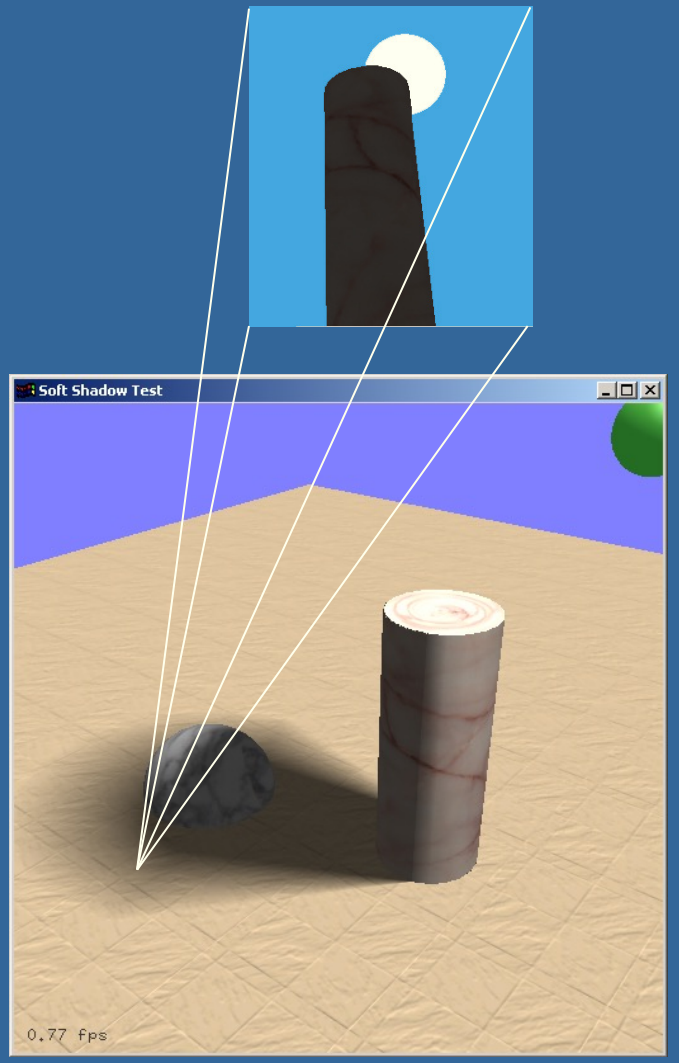
- Why do they appear?
- Because light sources have an area or volume (seldom point lights)





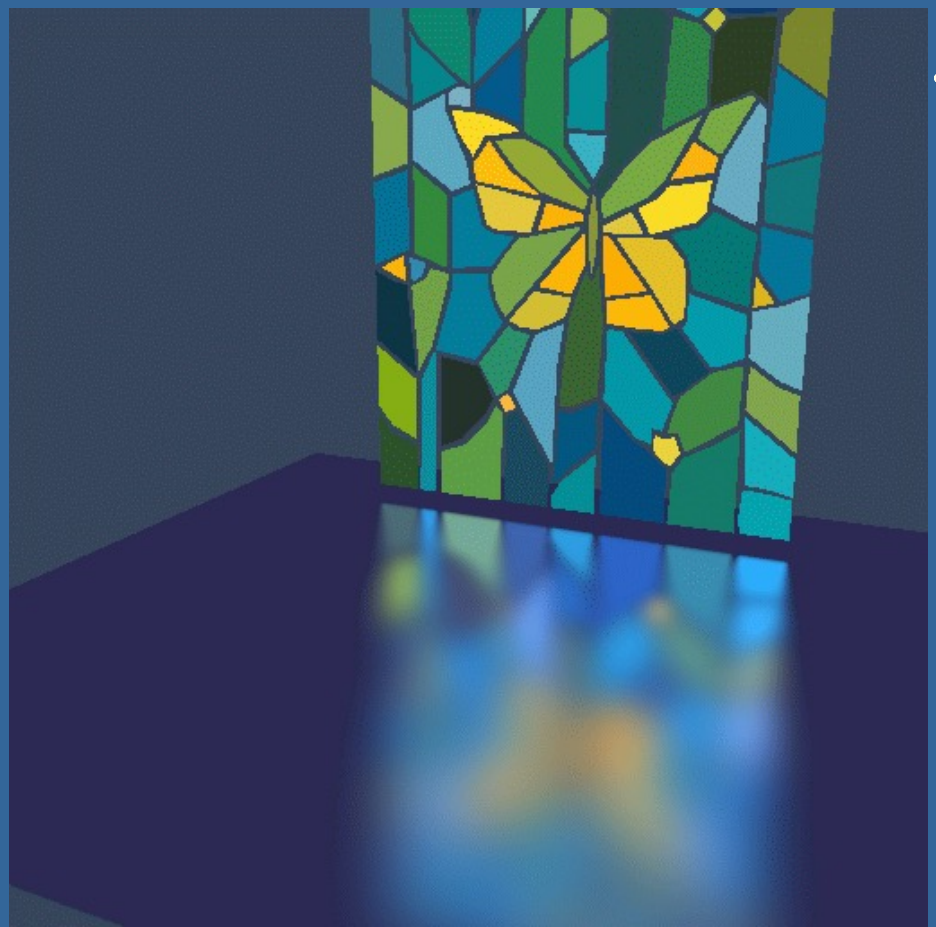
Example

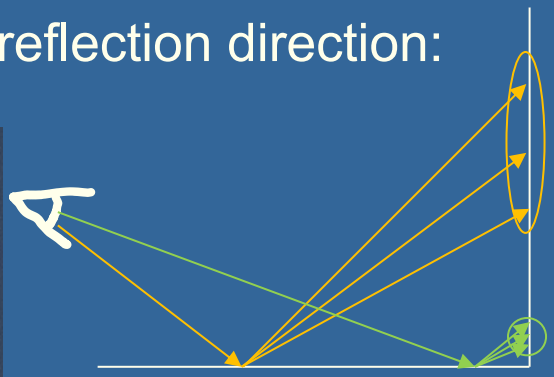

light source
shadow casting object
shadow wedge (penumbra region)
shadow wedge (penumbra region)
umbra volume


Soft Shadow Test
0.77 fps

Glossy (blurry) reflections

- Trace many reflection directions
  - Each perturbed slightly from the main reflection direction:





Do the same with the transmission vectors

Speed-up techniques

- For eye rays:
  - Render scene with OpenGL
  - Let each triangle or object have a unique color
  - Then read back color buffer
  - For each pixel, the color identifies the object
  - You need fast rendering in order to gain from this
    - the primary rays (eye rays) are typically so few compared to all other secondary rays, so often not worth optimizing.

Typical Exam Questions
– what you need to know

- Draw grid (plain/hierarchical/recursive)
  - Mailboxing.
- Draw all our other spatial data structures:
  - Octree/quadtree, AABSP-tree (kd-tree), polygon-aligned BSP tree, Sphere/AABB/OBB-tree,
- What's a
  - skip-pointer tree?
  - Shadow cache?
  - Kd-tree? (=AABSP with fixed split-plane order)
- Descibe ray/BVH intersection test
- The Fresnel-effect: metal vs dielectrics)
  - How does glass/water/air behave?
  - How does metal behave?
- Describe how to implement ray/object intersection for Constructive Solid Geometry