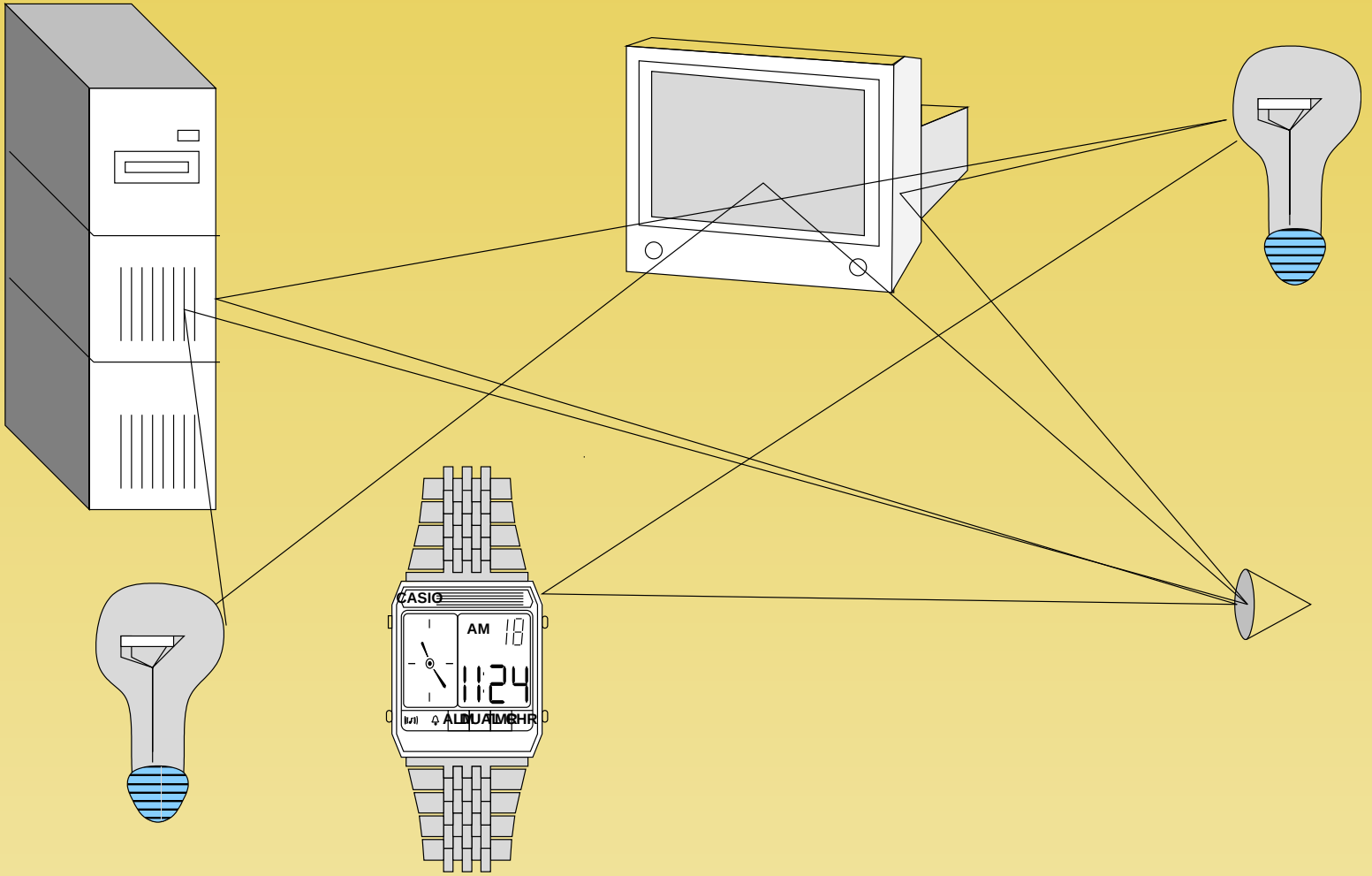
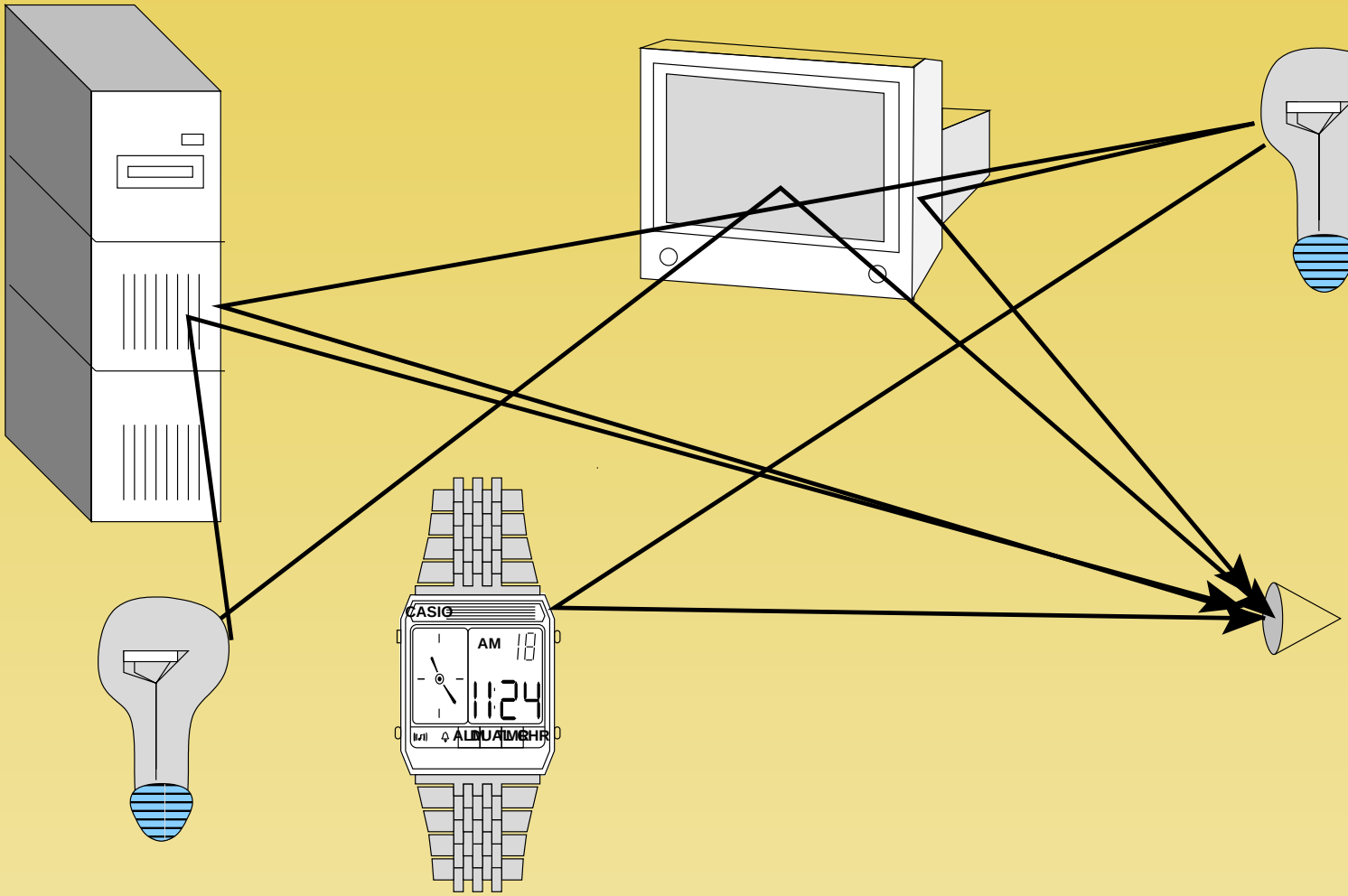
How does light get to our eyes?



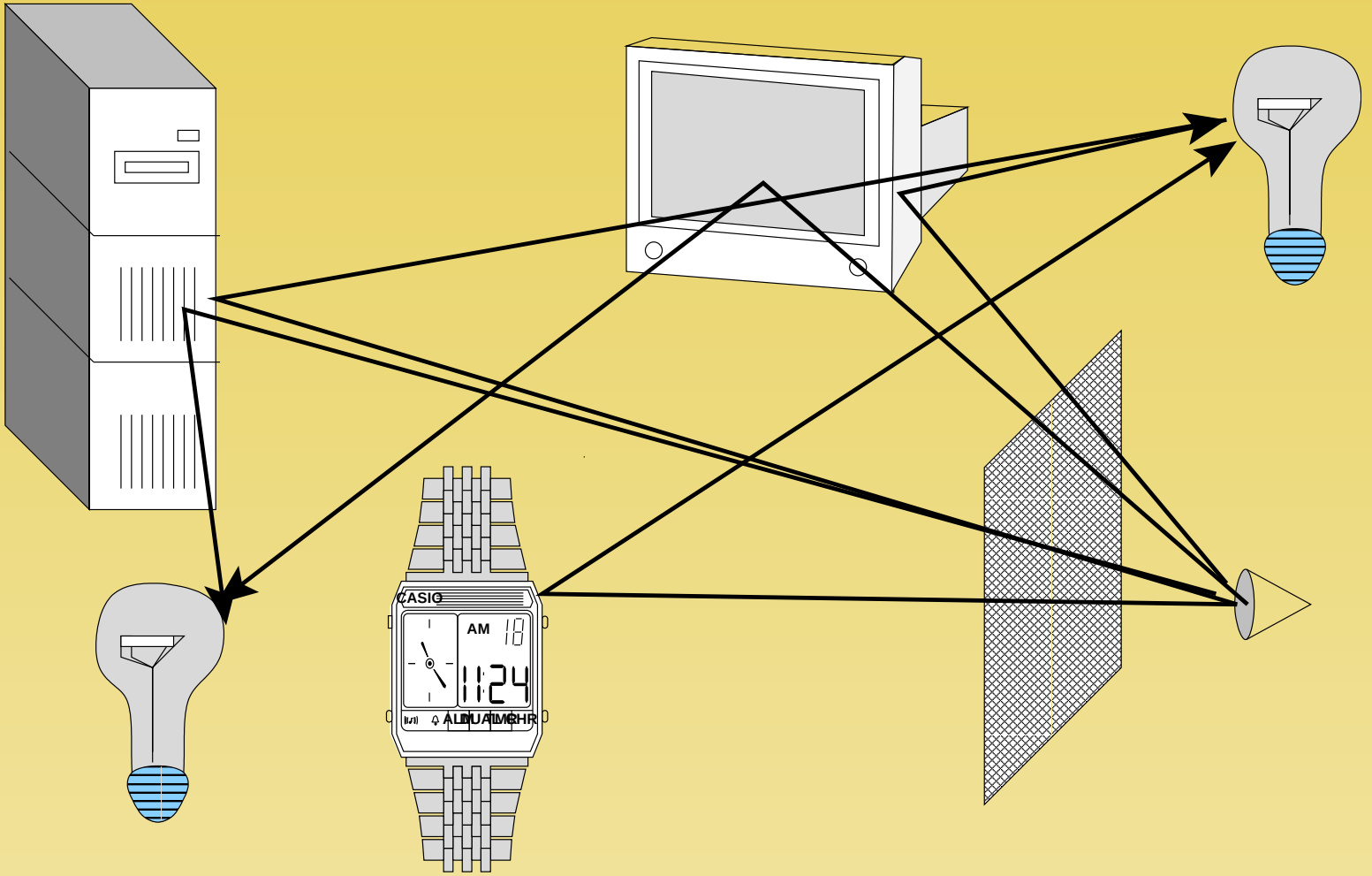
Light Comes Forward From its Source(s).



Forward Tracing

- Can this be done? Yes
- How would we do it?
  - ⋆ Well, we would have to trace all rays from all lights.
  - ⋆ If they end up hitting our eye (camera) then we add in it's contribution.
- Is this efficient? No
- Is it accurate? Yes
- What could we do instead?

Backward Tracing.



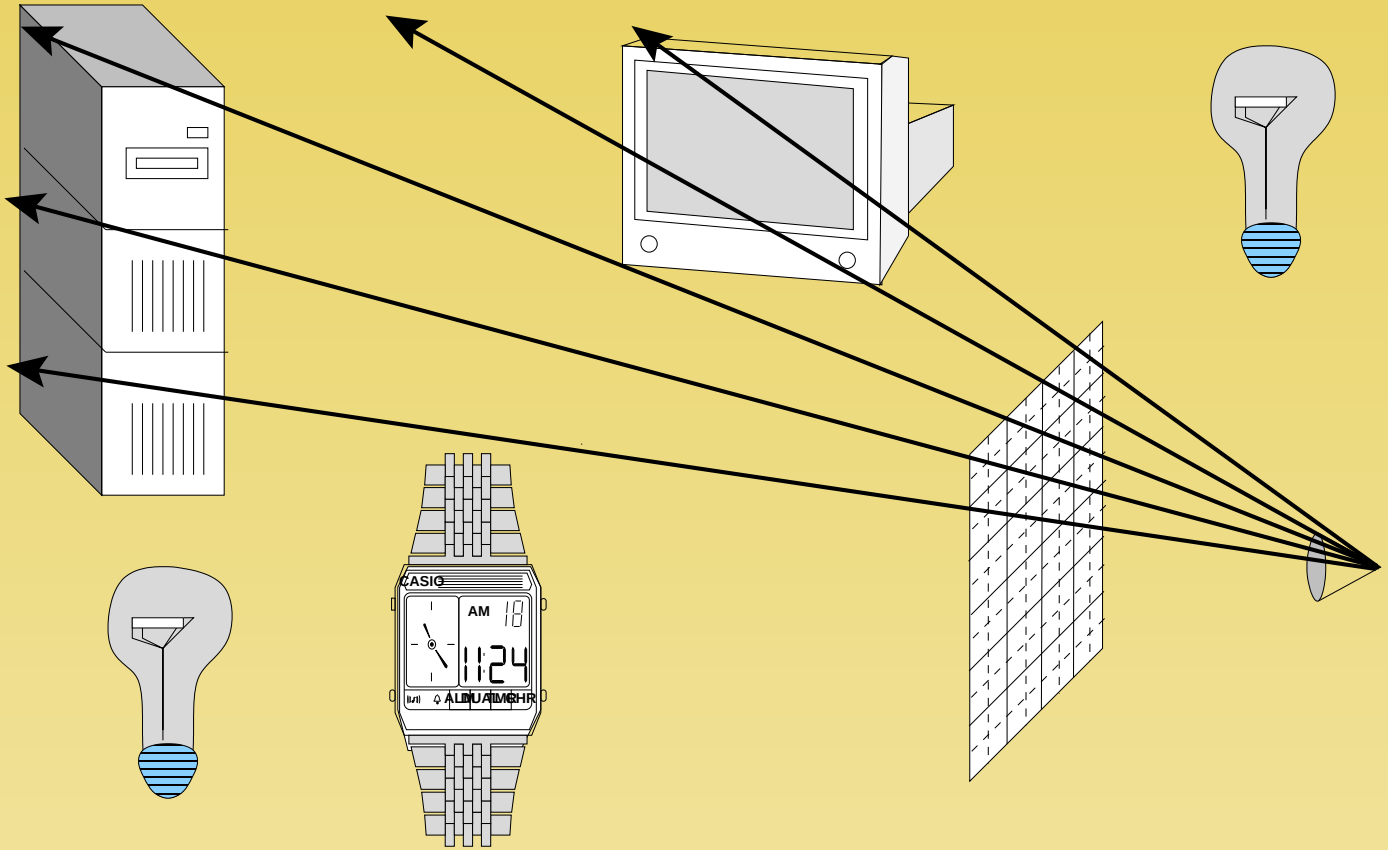
Basic Ray Casting method

$\forall$ pixels in screen

1. Shoot ray $\vec{p}$ from the eye through the pixel.
2. Find closest ray-object intersection.
3. Get color at intersection.

Basic Ray Casting method

Shoot ray $\vec{p}$ from eye through pixel.



Basic Ray Casting method

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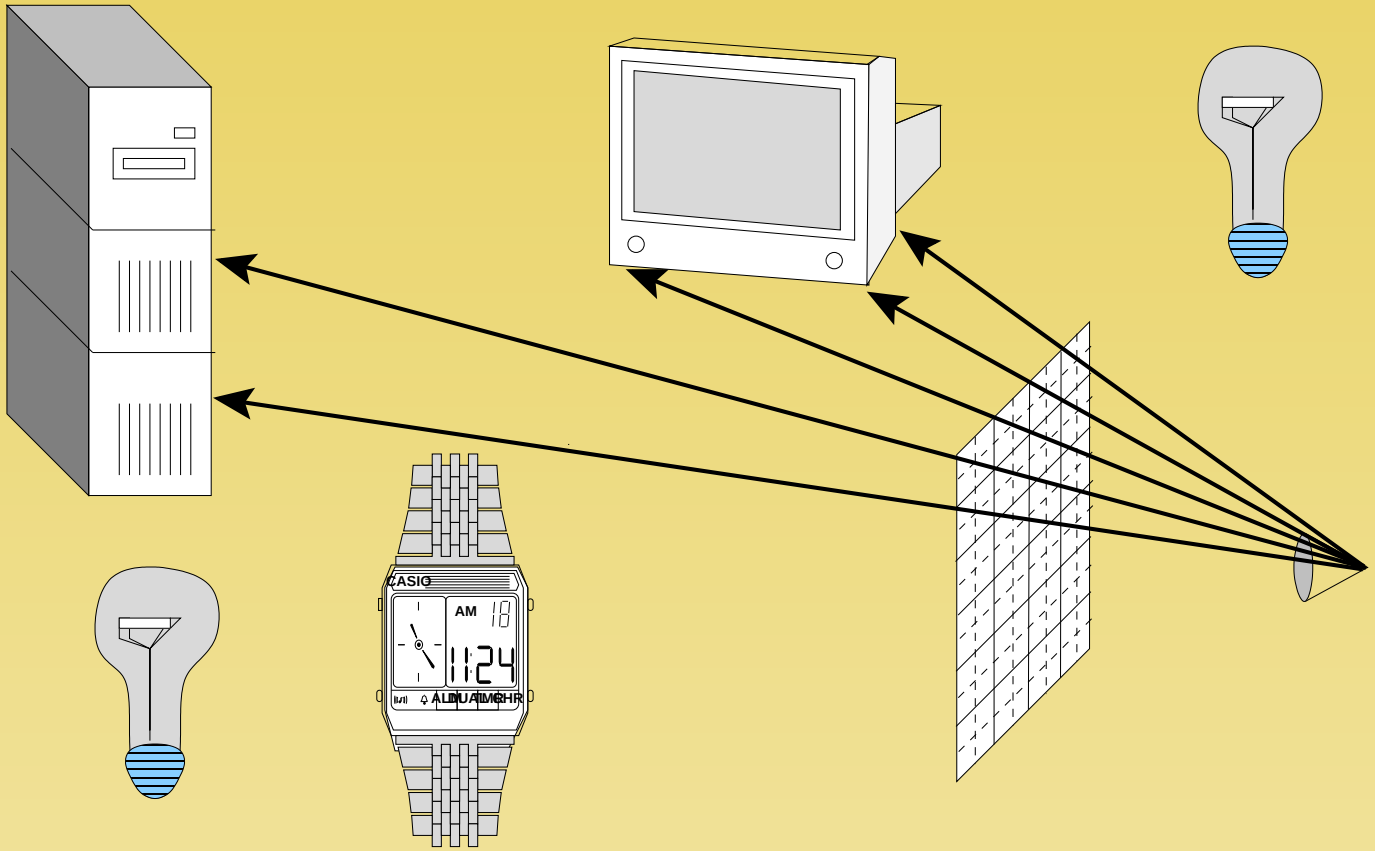

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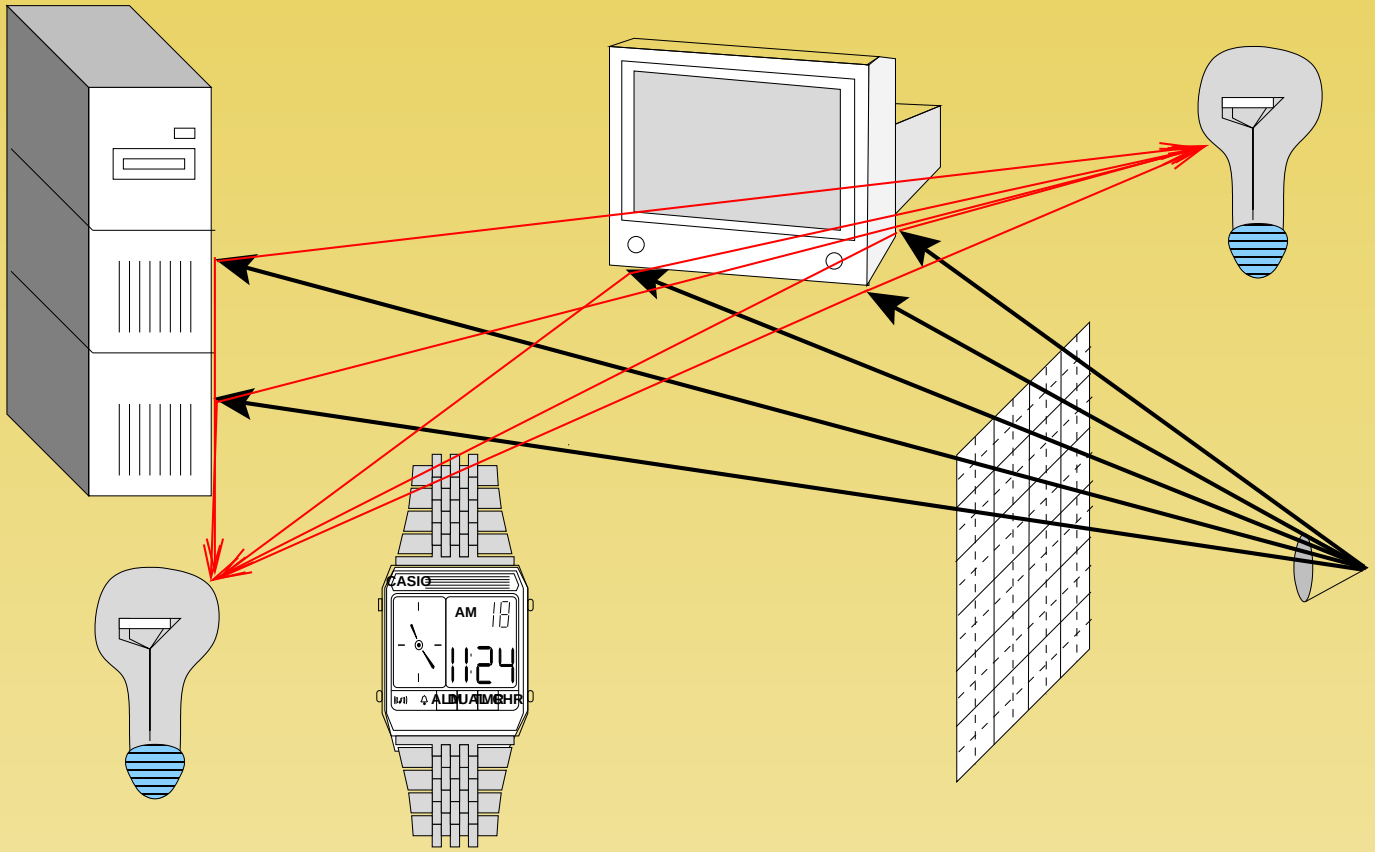
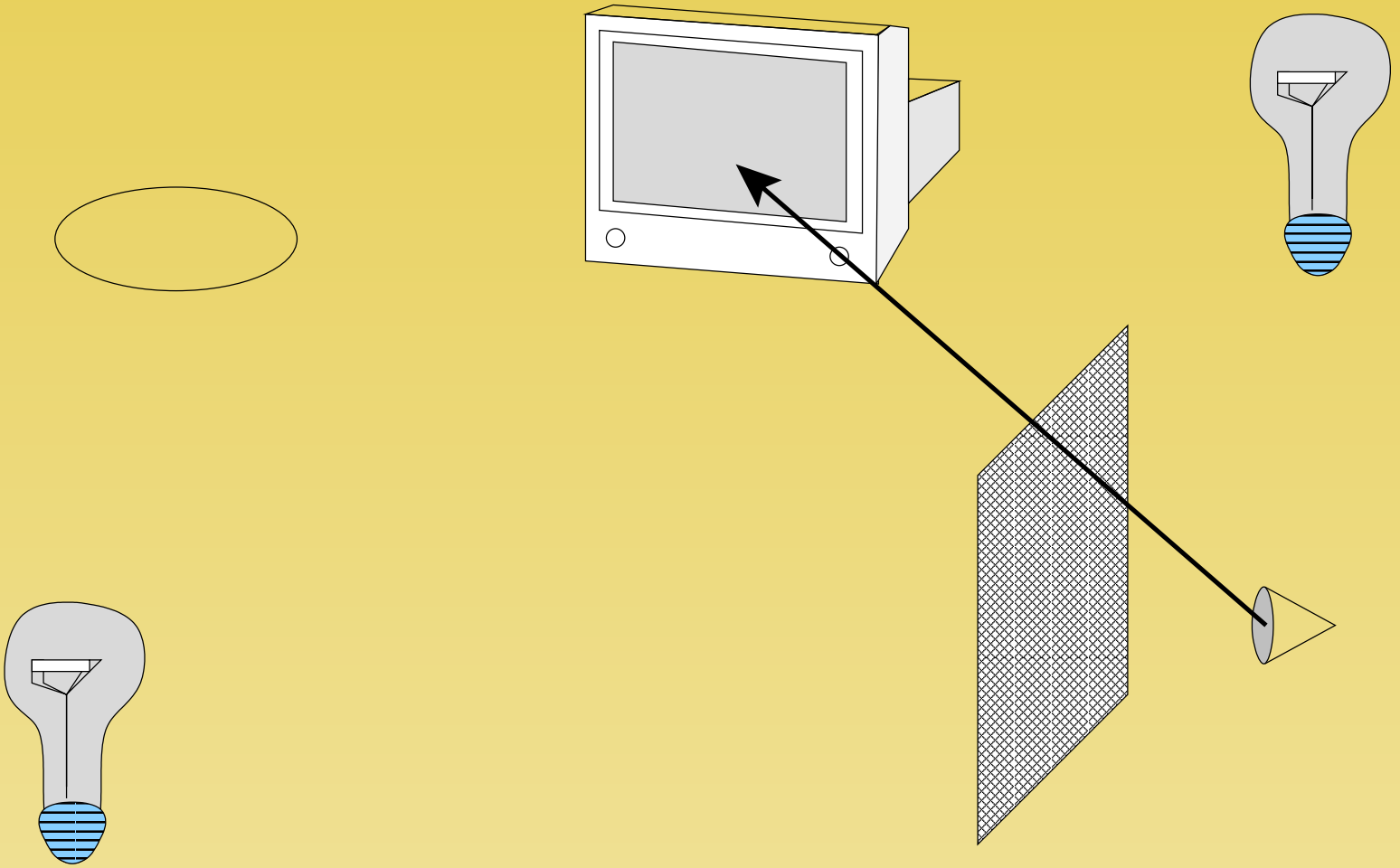


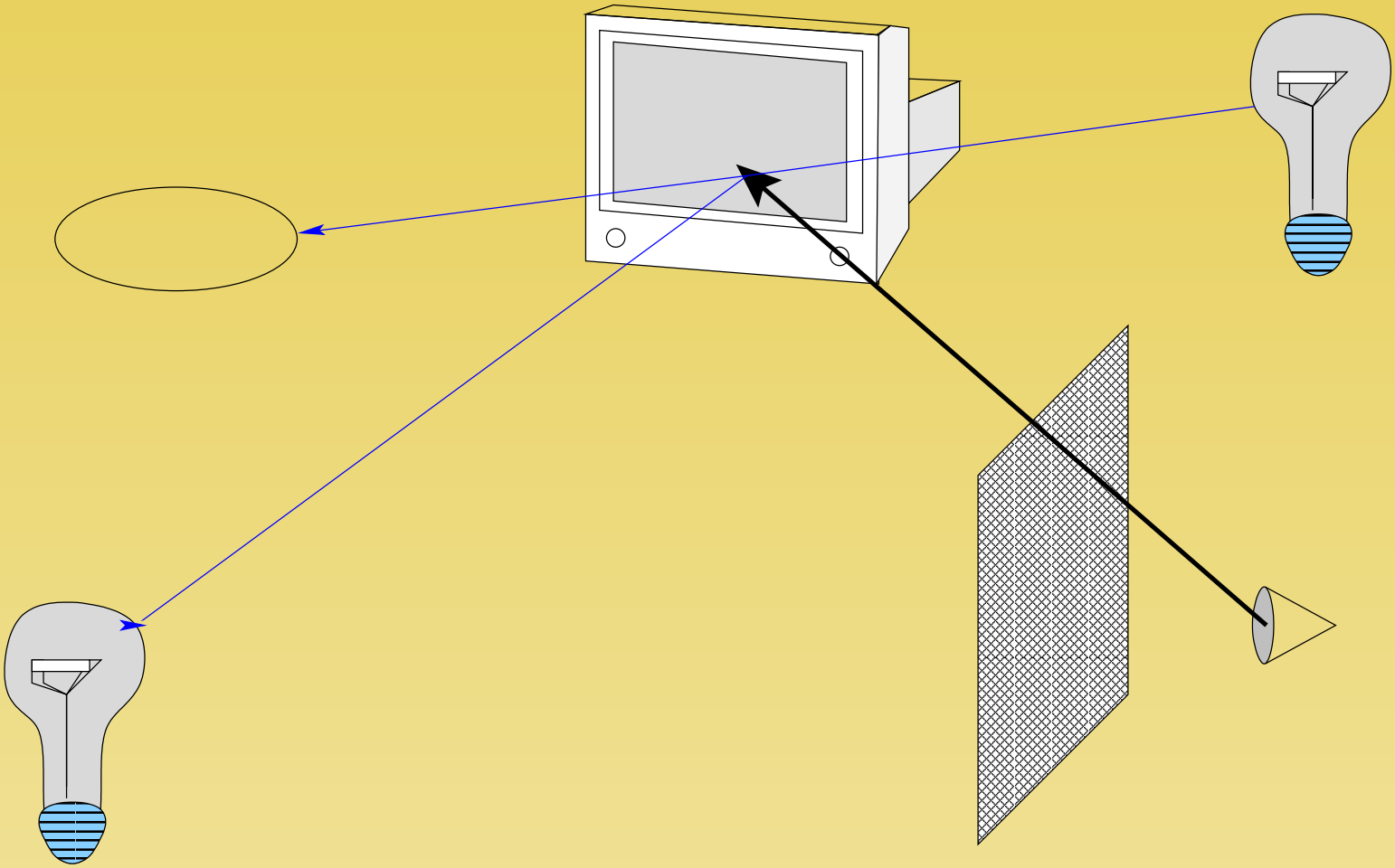
Ray Genealogy

- Primary rays spawn off 3 rays. Two of those can spawn of 3 more, etc.
- When do you stop?
  - ⋆ When ray leaves the scene.
  - ⋆ When the contribution is small enough - after each bounce the contribution is attenuated by the k's in the illumination model. So we set a recursion level.

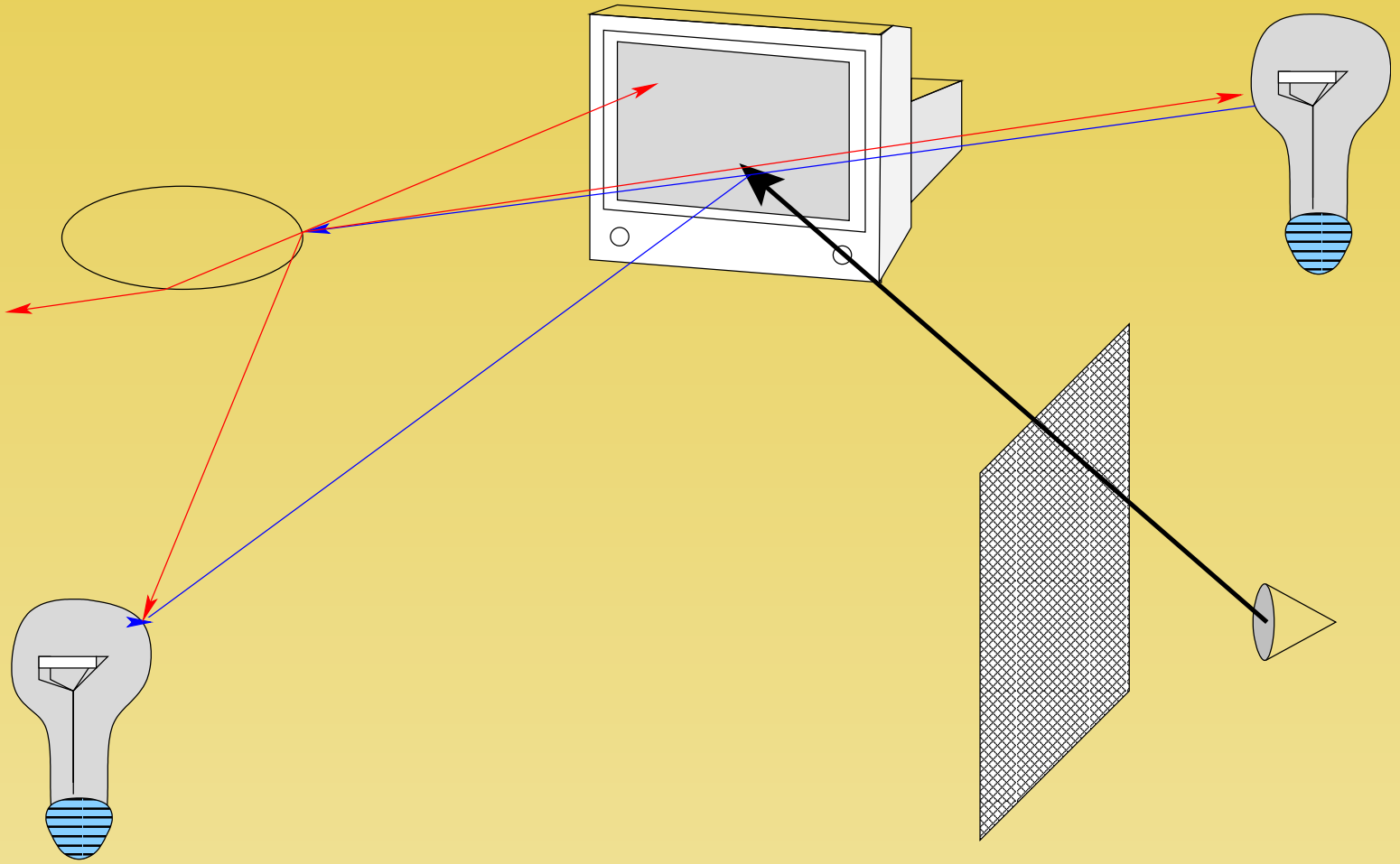
Ray Genealogy



Ray Genealogy



Ray Genealogy



Ray Genealogy

- 1 Ray/pixel at $1k \times 1k$ image $= 1M$ rays.
- Say on average 6 secondary rays.$\rightarrow 7M$ rays
- $100k$ objects; 10 ops/intersection $\rightarrow 7,000,000M$ ops
- 2GHz processor 5 cycles per op $\rightarrow 400MFLOPS$
- How long to render? $70000/4 = 17500s \approx 5hr$
- Will this image look really good for our 5hrs?

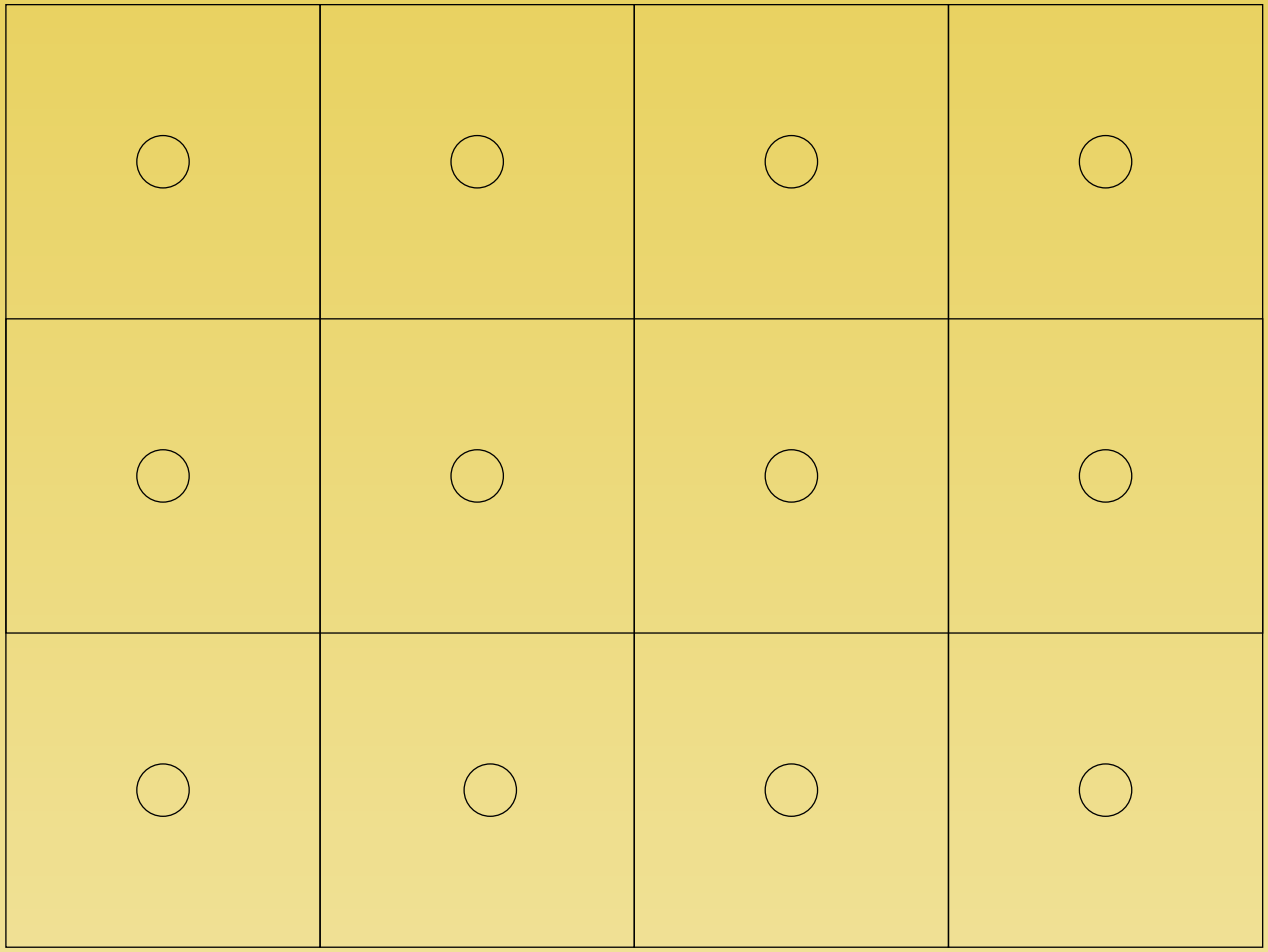
Anti-aliasing

- The pixels represent discrete samples of our image.
- Since we don’t have enough samples, higher frequencies get aliased (renamed) to lower ones.
- How can we remove the aliasing?

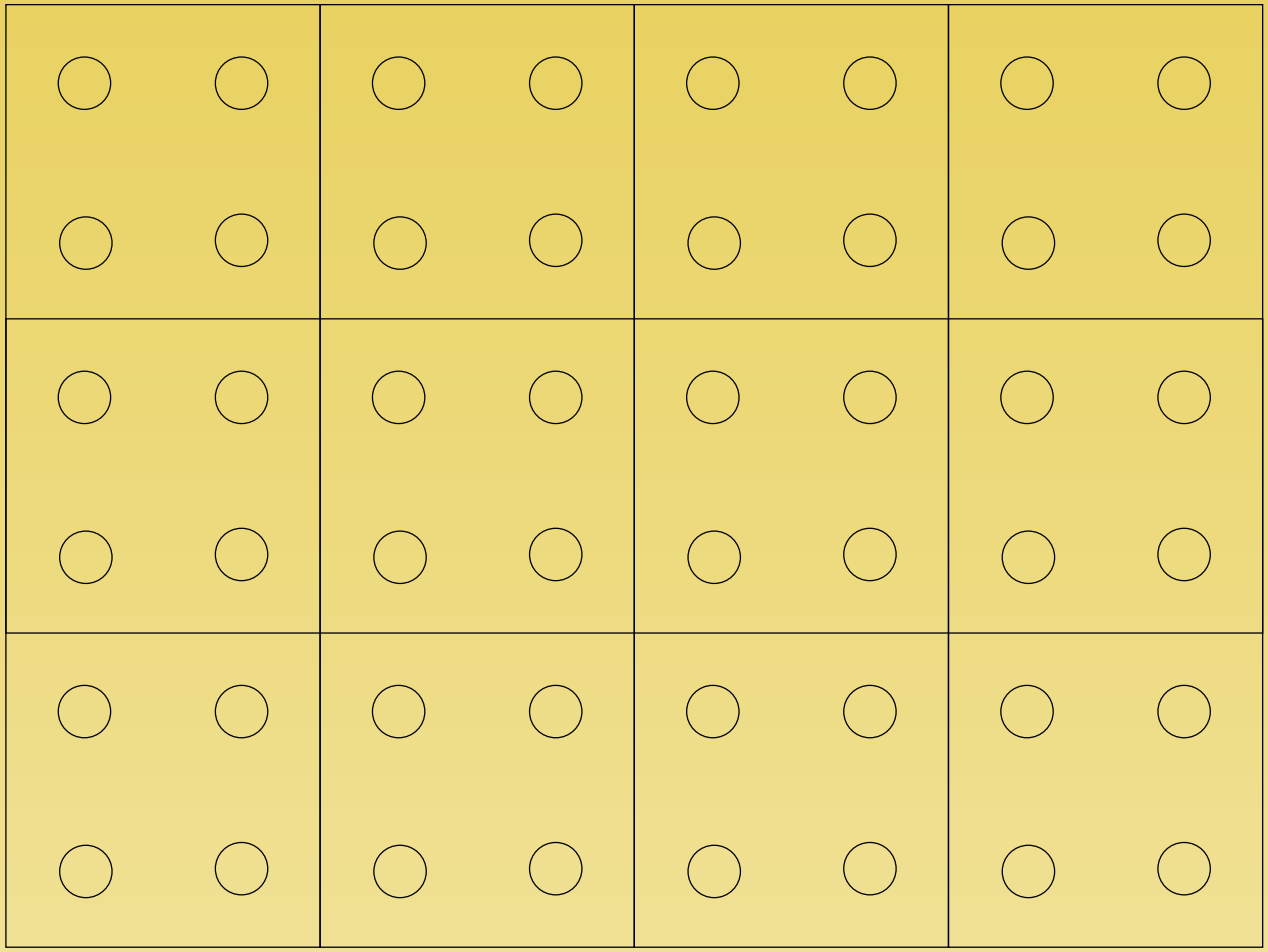
Super-sampling

- A simple method is to shoot more than one ray per pixel and average the values.

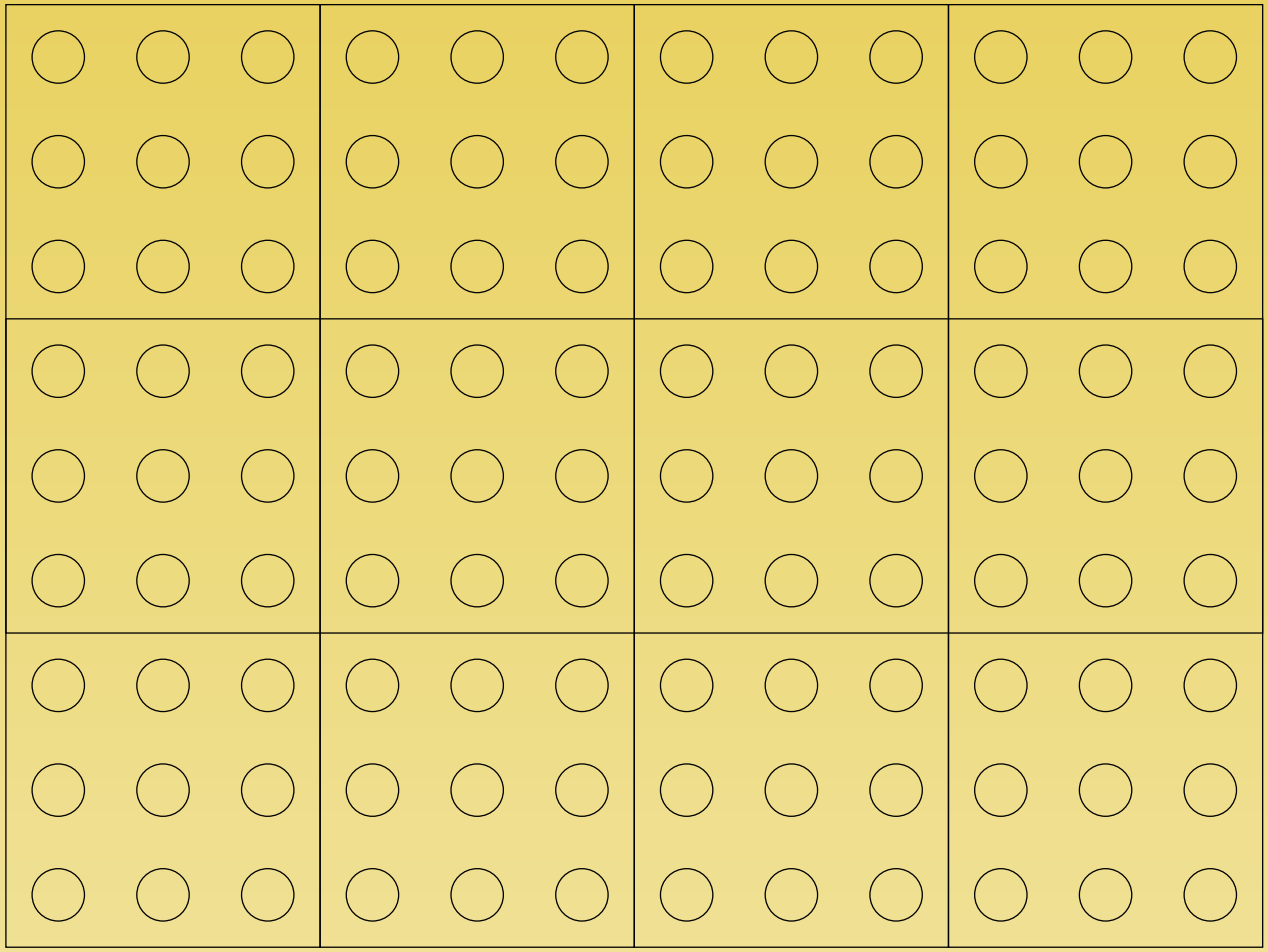
Super-sampling



Super-sampling



Super-sampling



Super-sampling

- We can do this forever.
- Can fire many many rays and still have aliasing.
- Now what?

Ray Genealogy

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- If we shoot 9 rays/pixel that gives us $45hr$.

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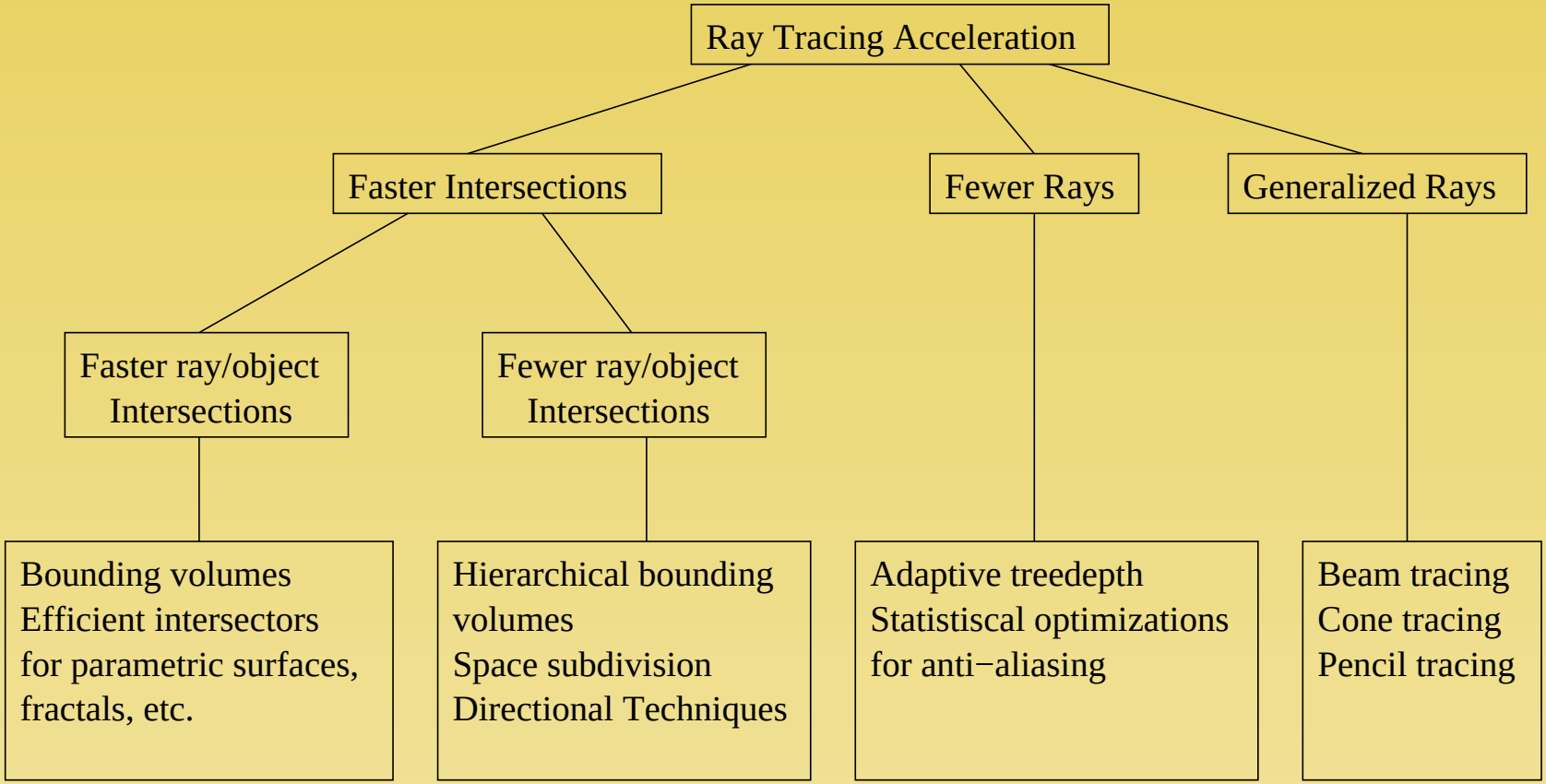
- Will this image look really good for our 5hrs?
- If we shoot 9 rays/pixel that gives us $45hr$.
- So where are we spending the time?

Ray Tracing Acceleration Classification



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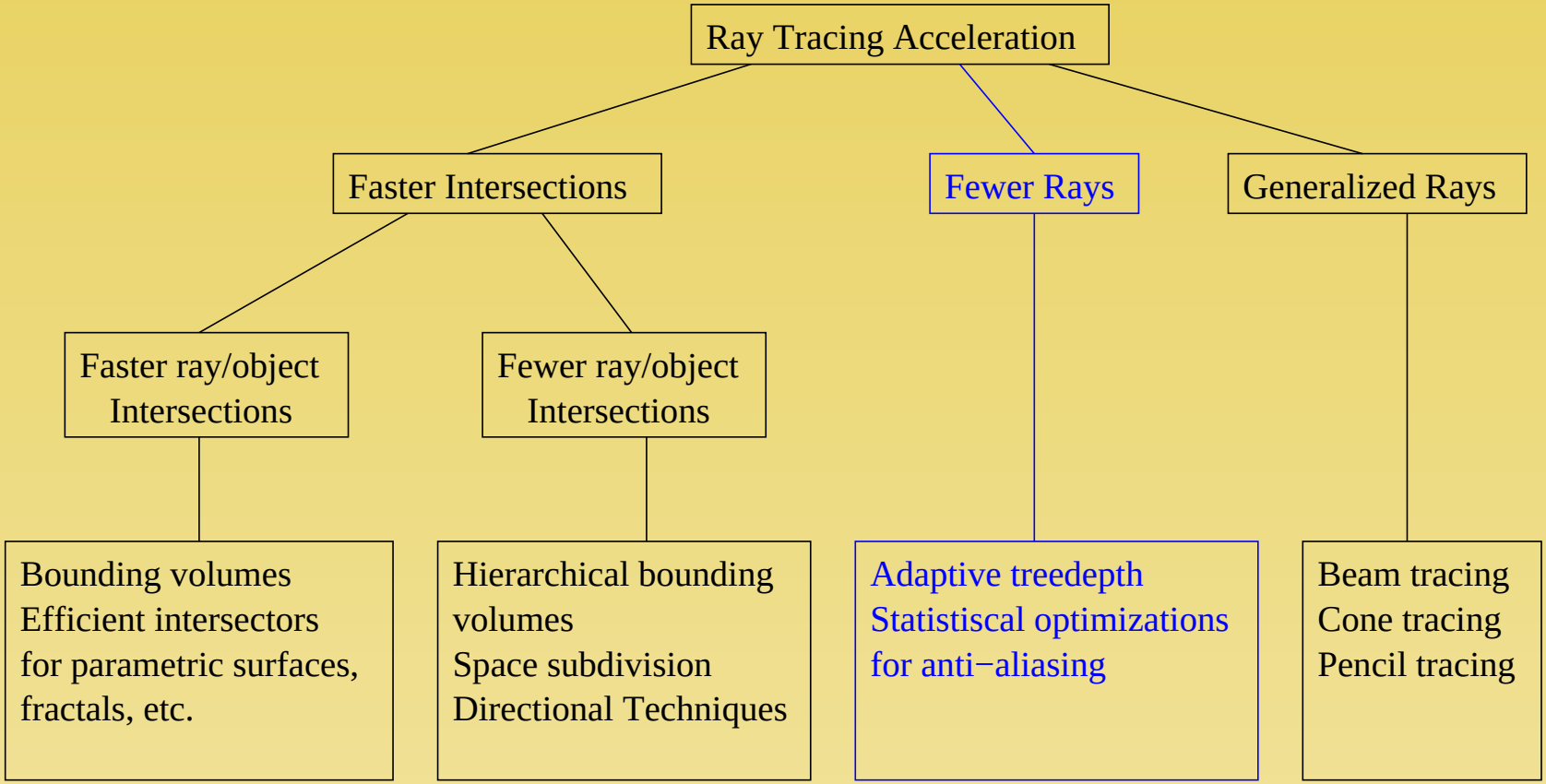
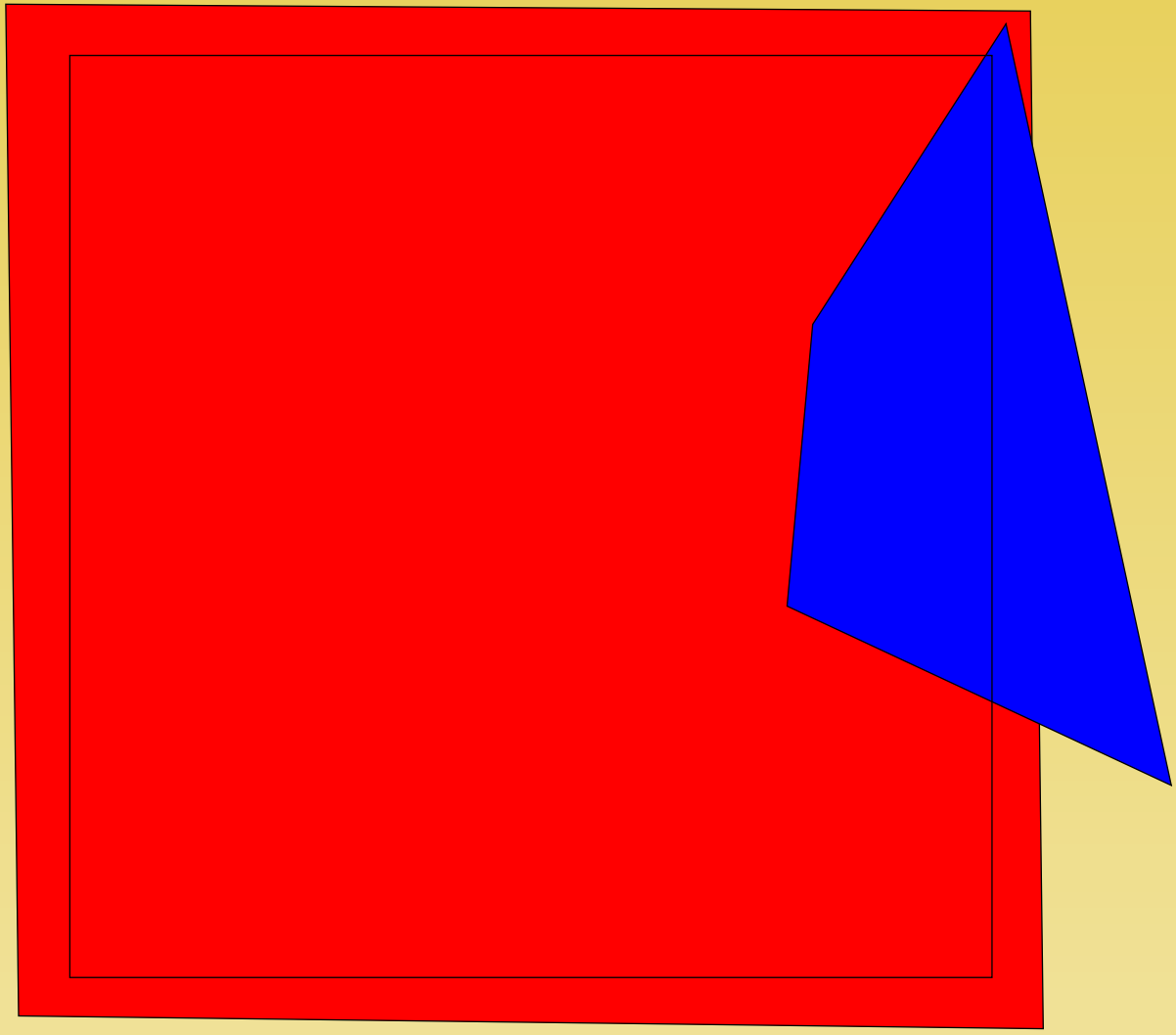


Adaptive Super-sampling



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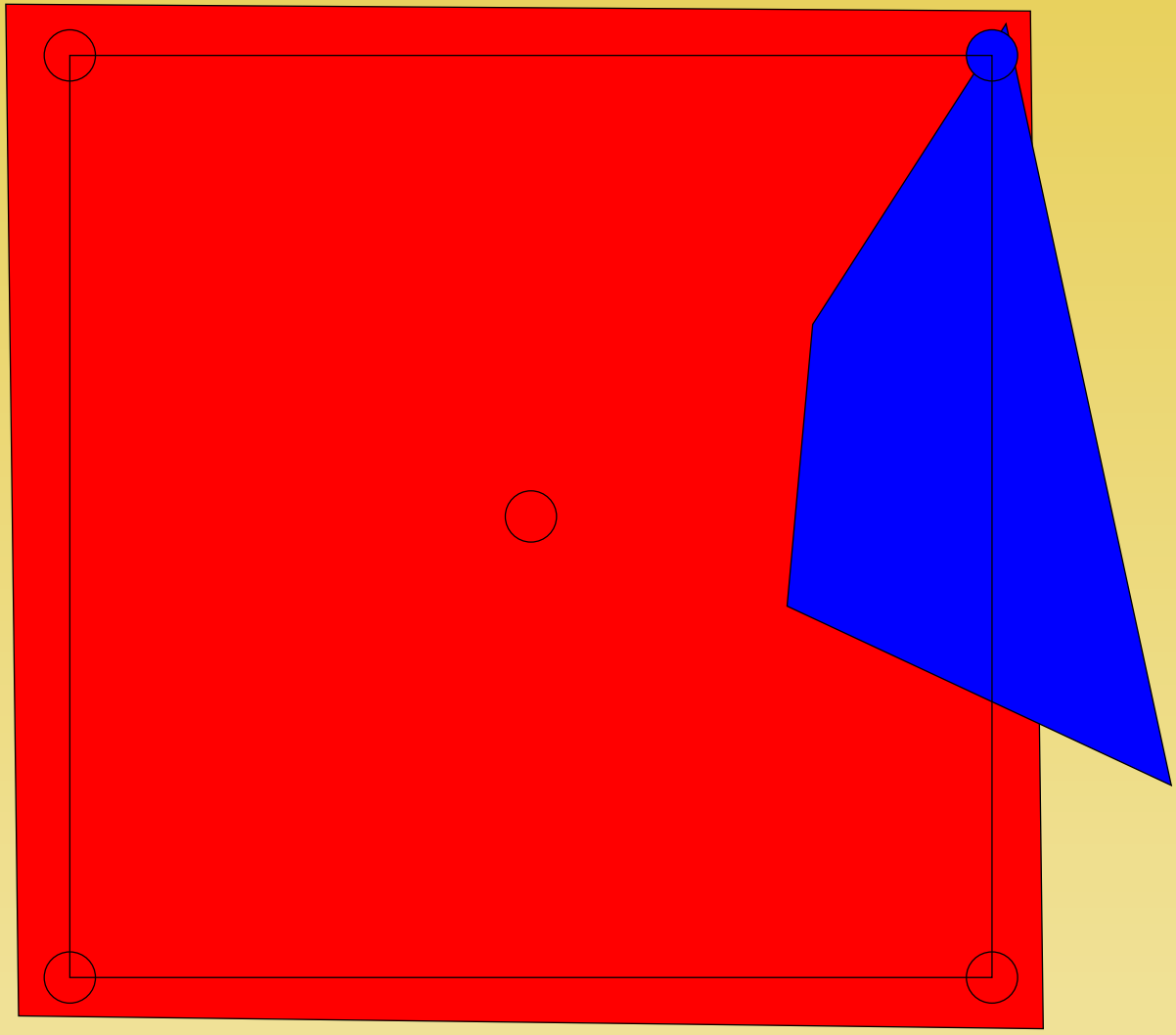

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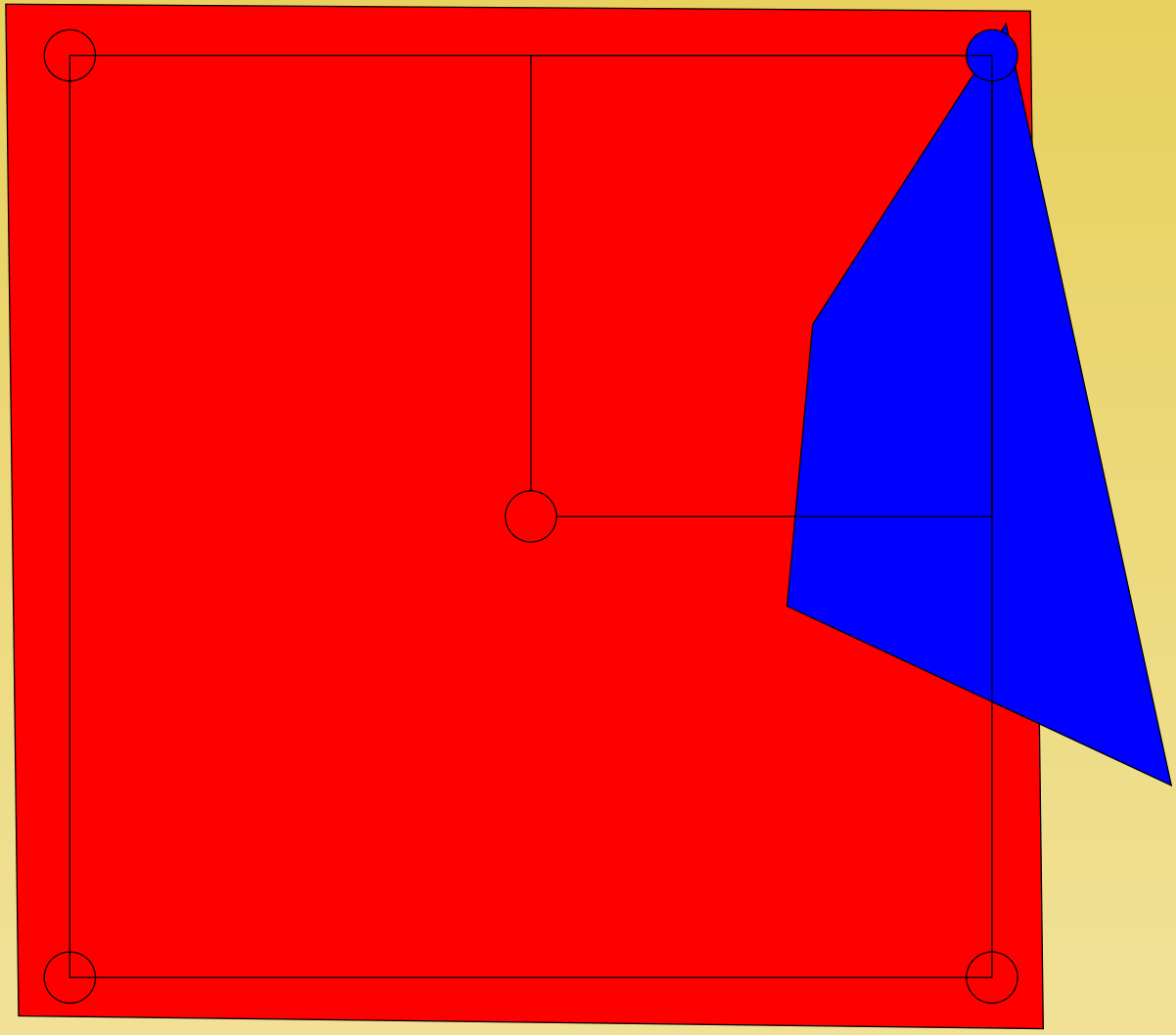

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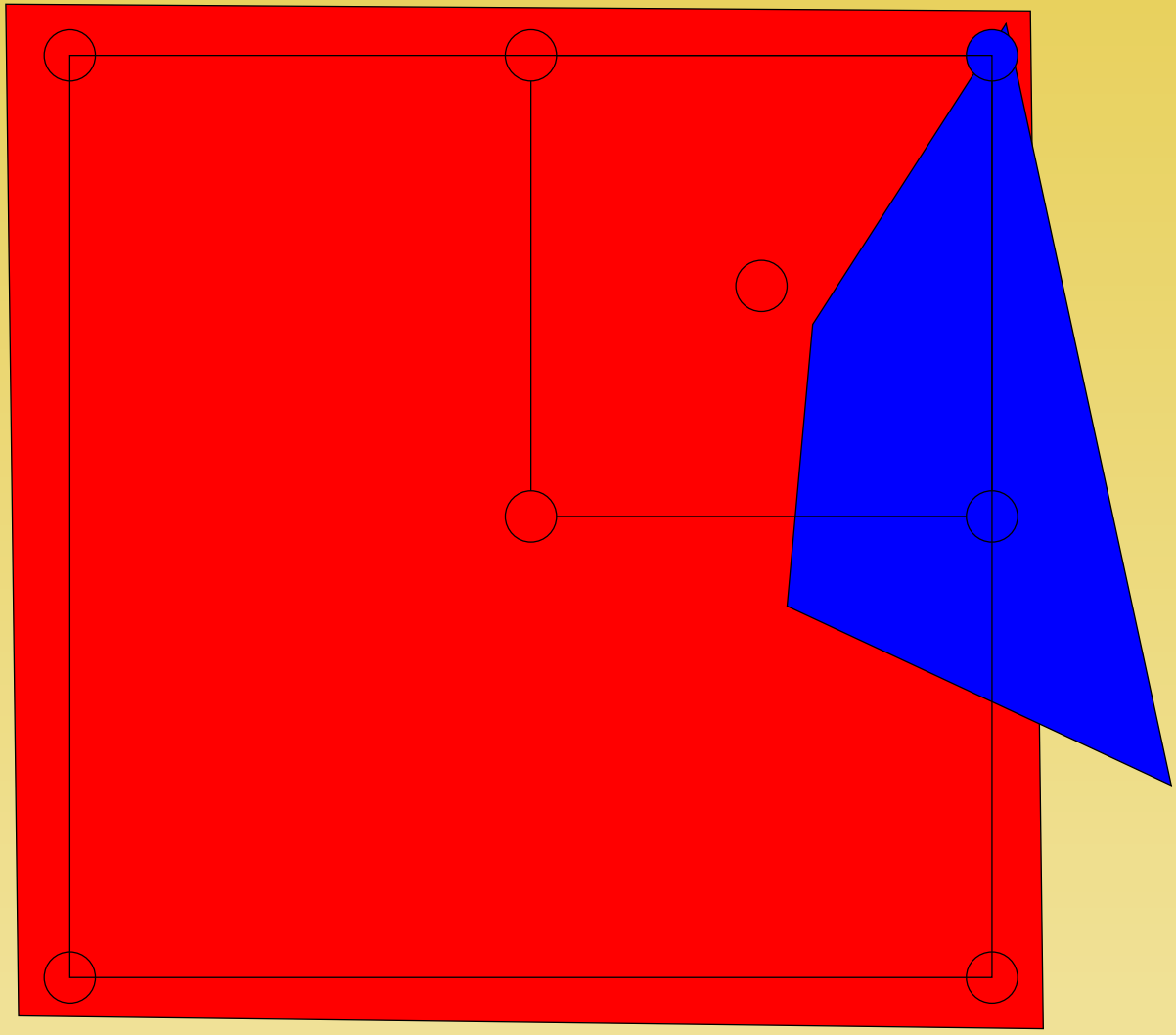

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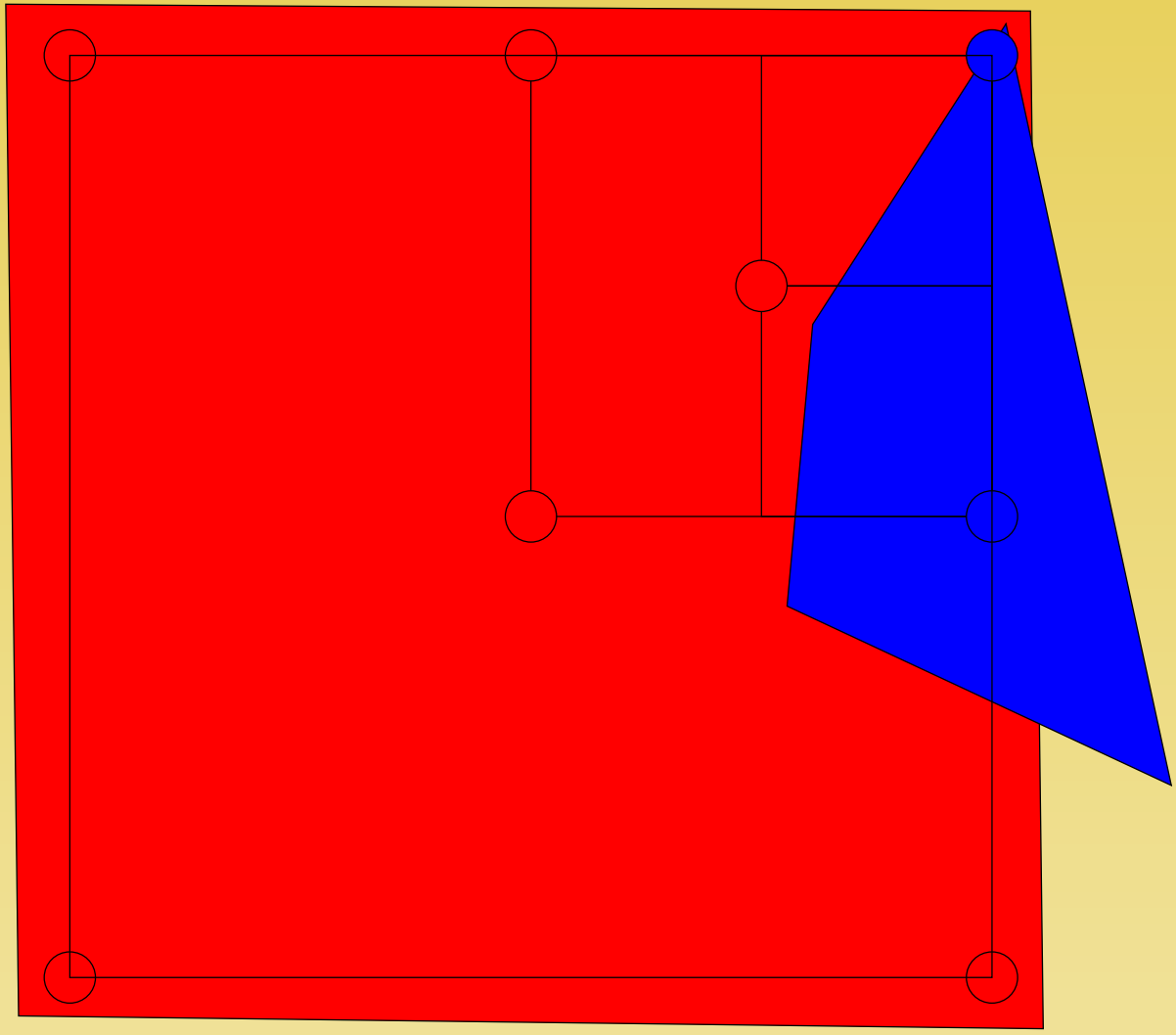

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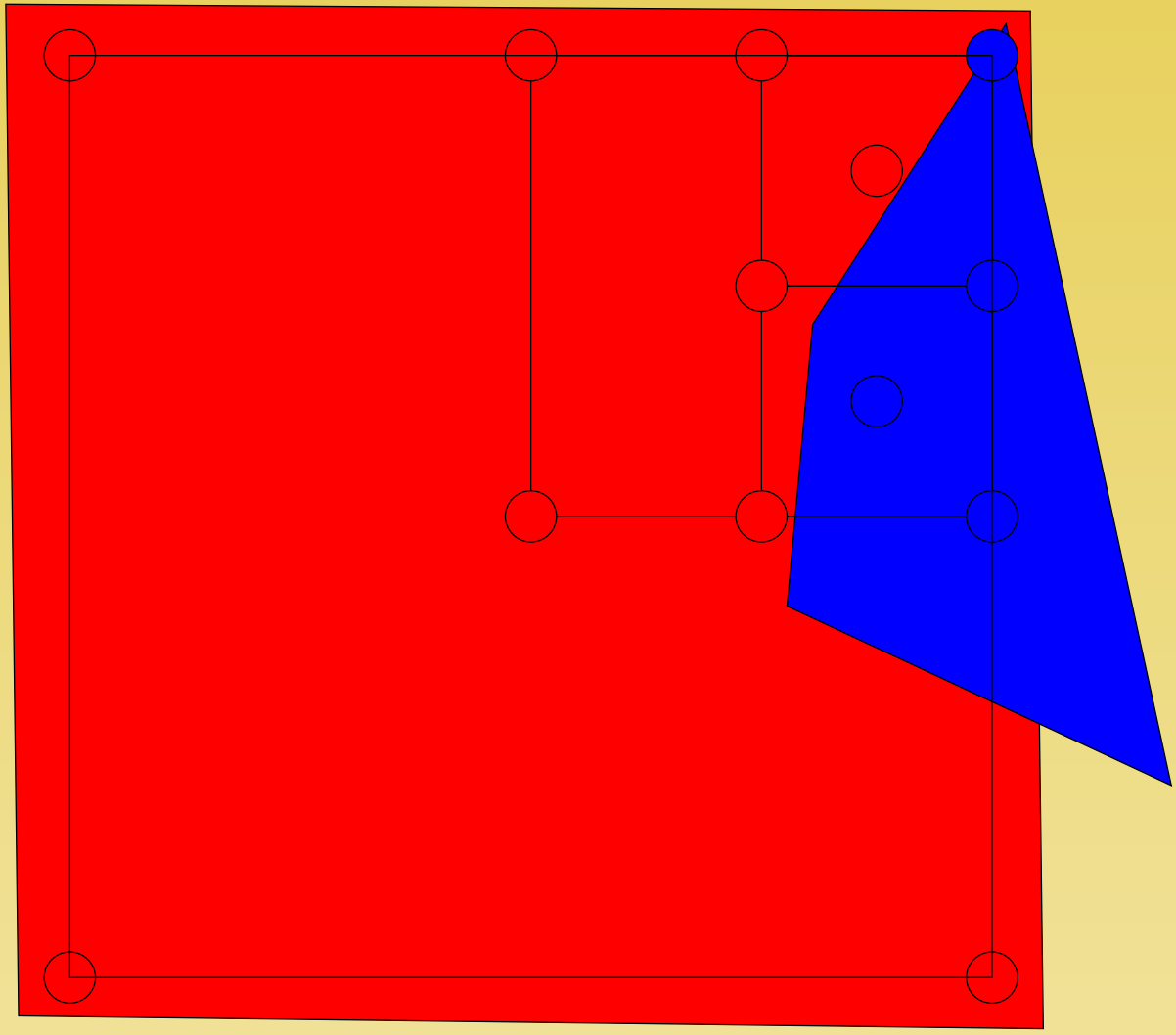

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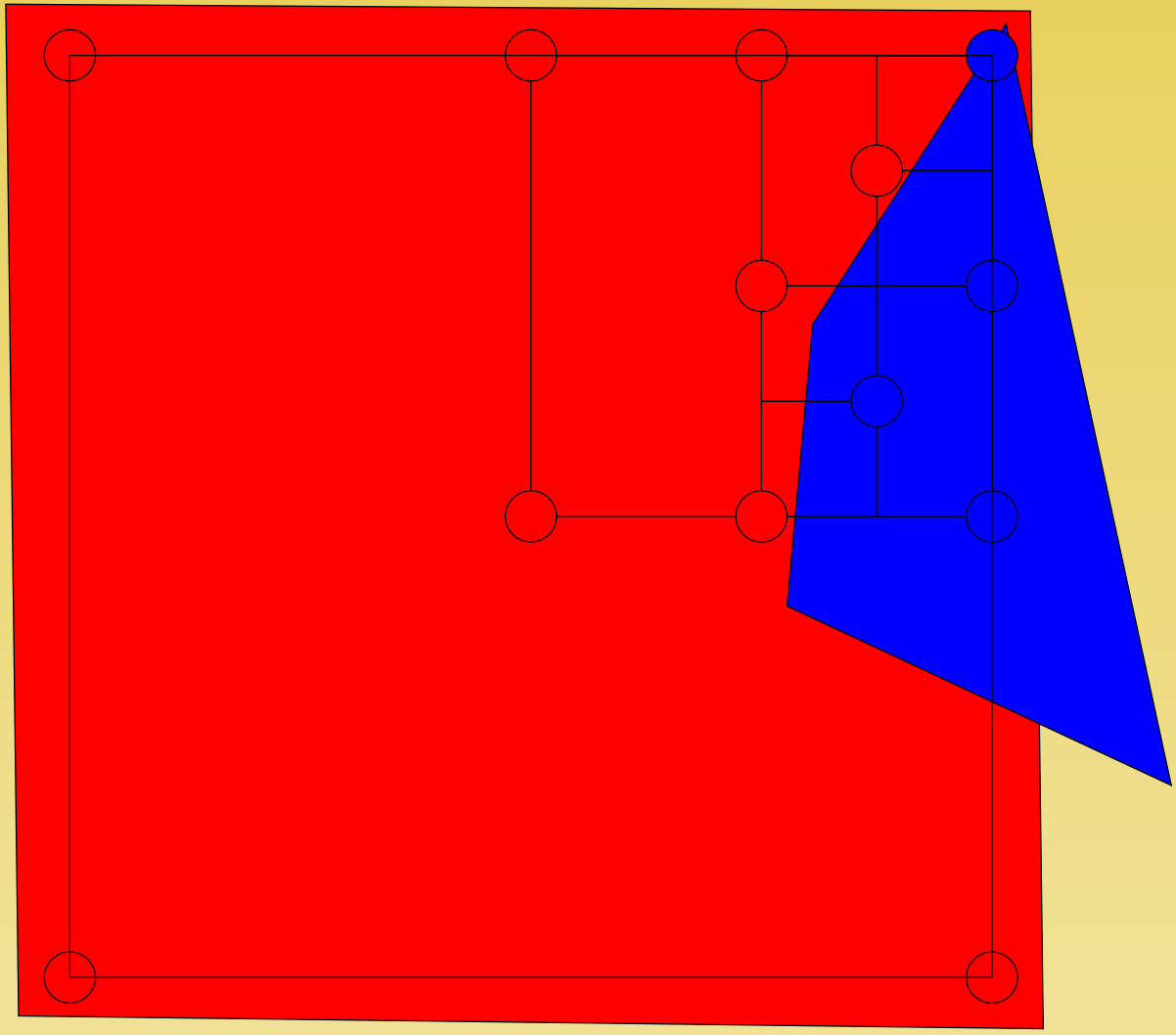

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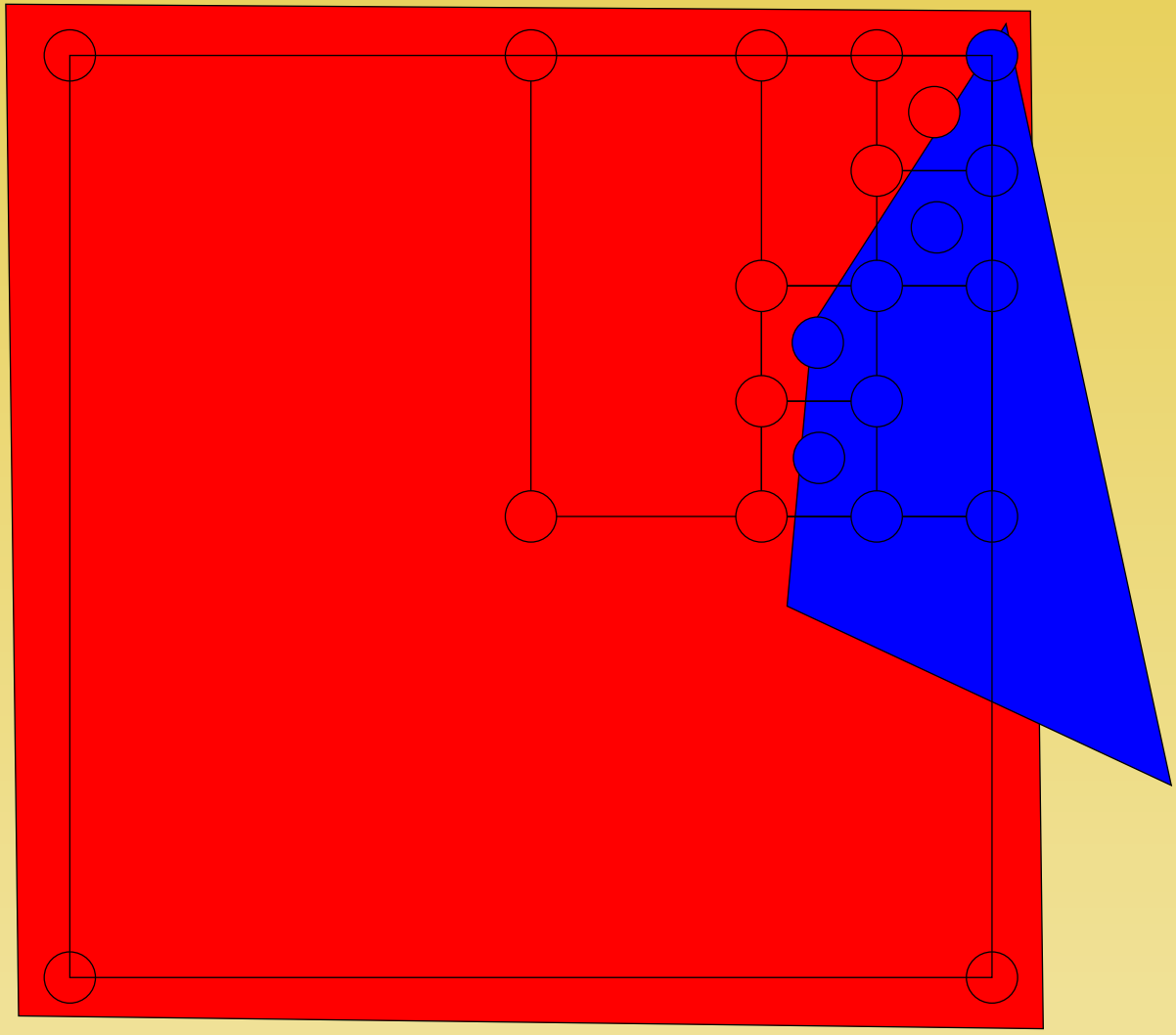

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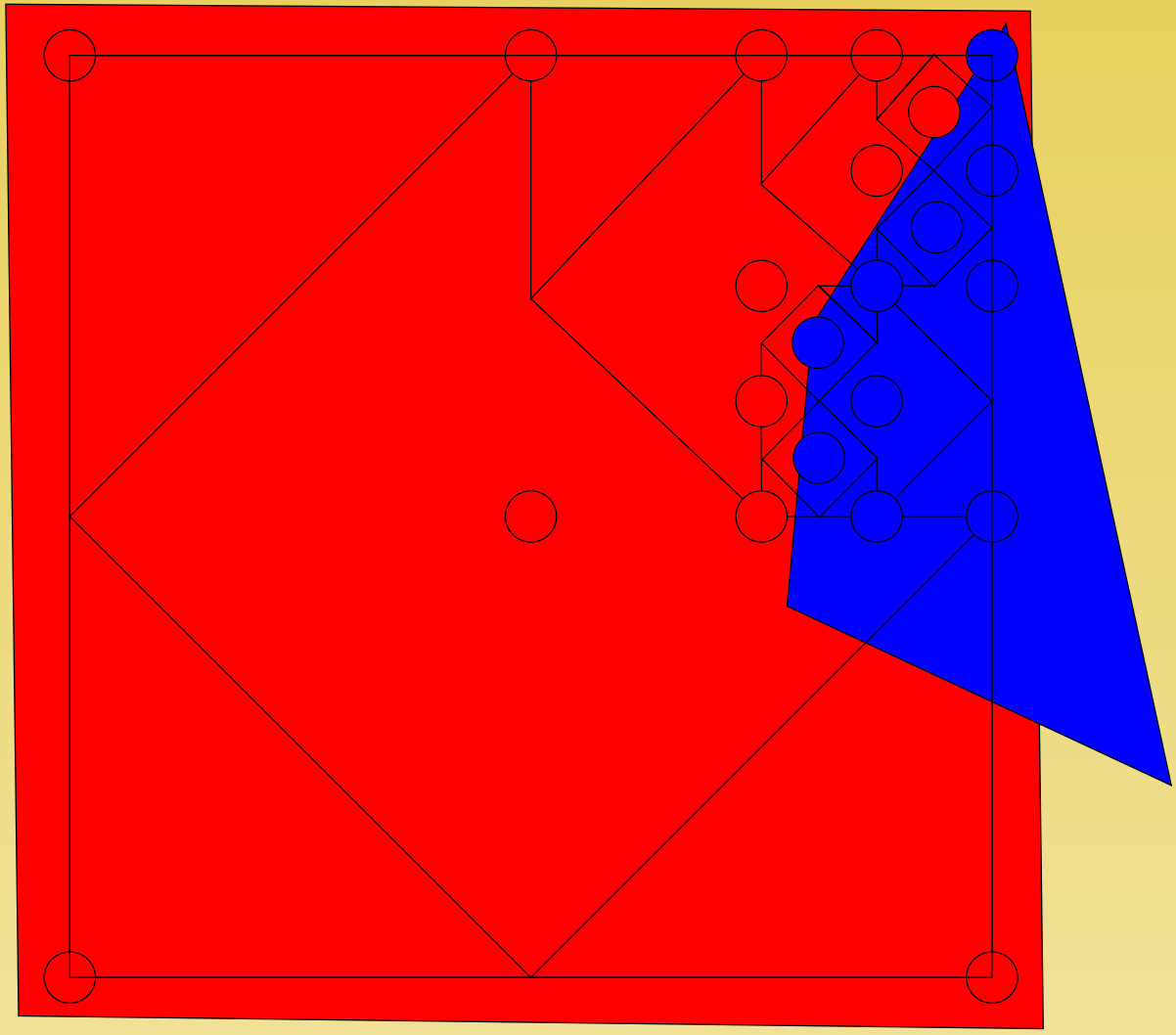
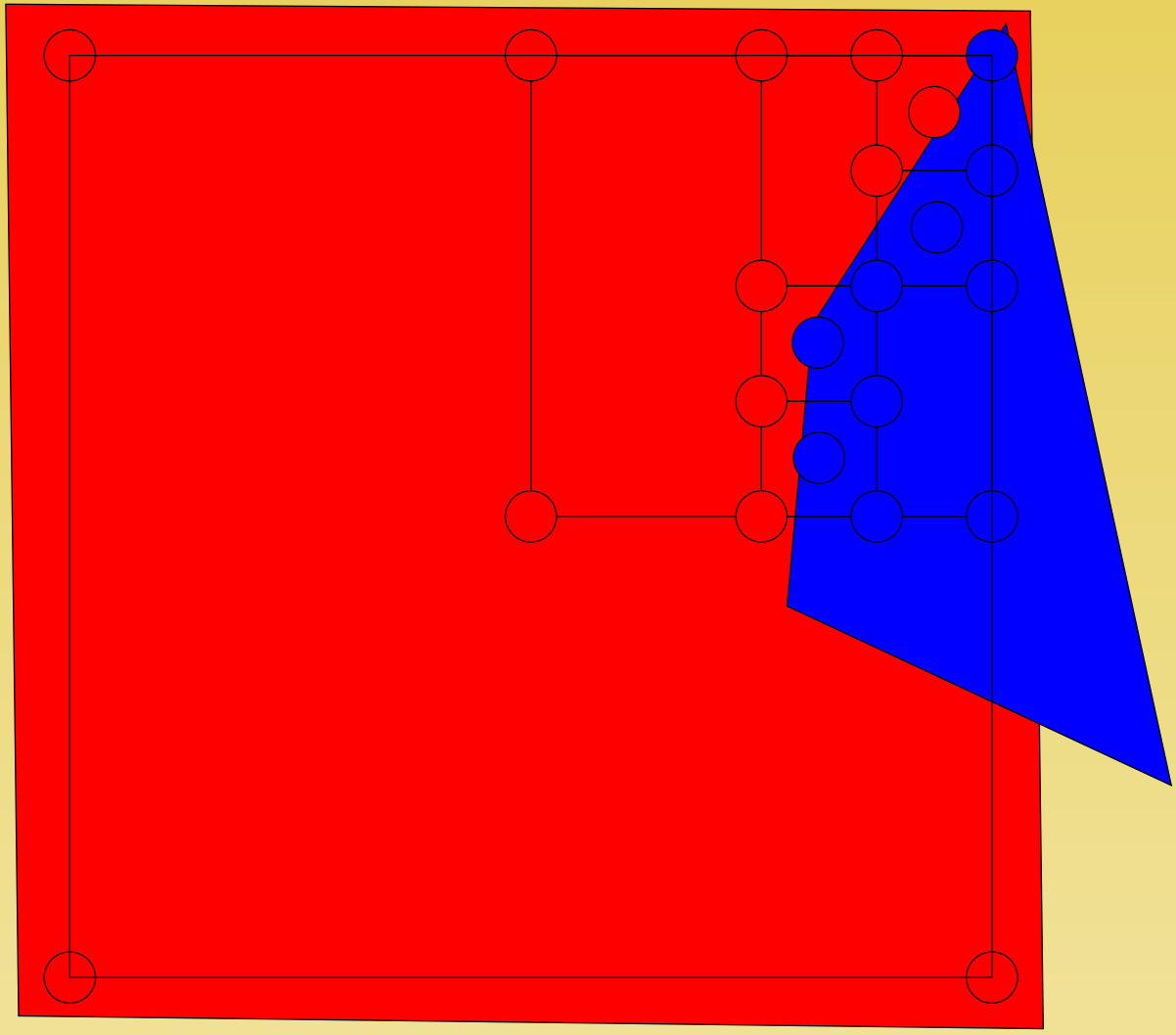


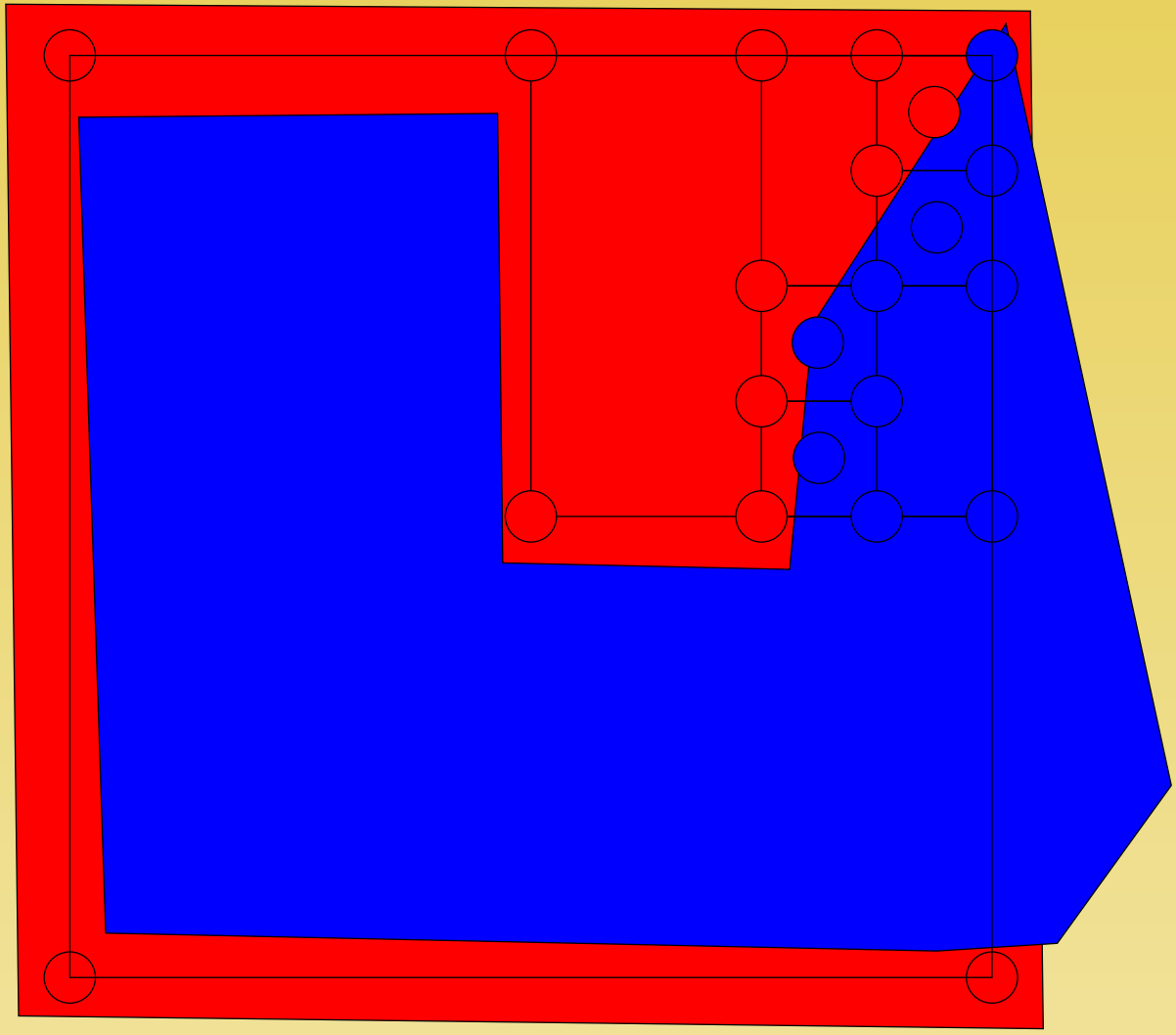
Adaptive Super-sampling

- Tries to only fire rays that are needed.
- But the assumption that if the rays are the same that the correct pixel value has been determined is wrong.

Adaptive Super-sampling



Adaptive Super-sampling



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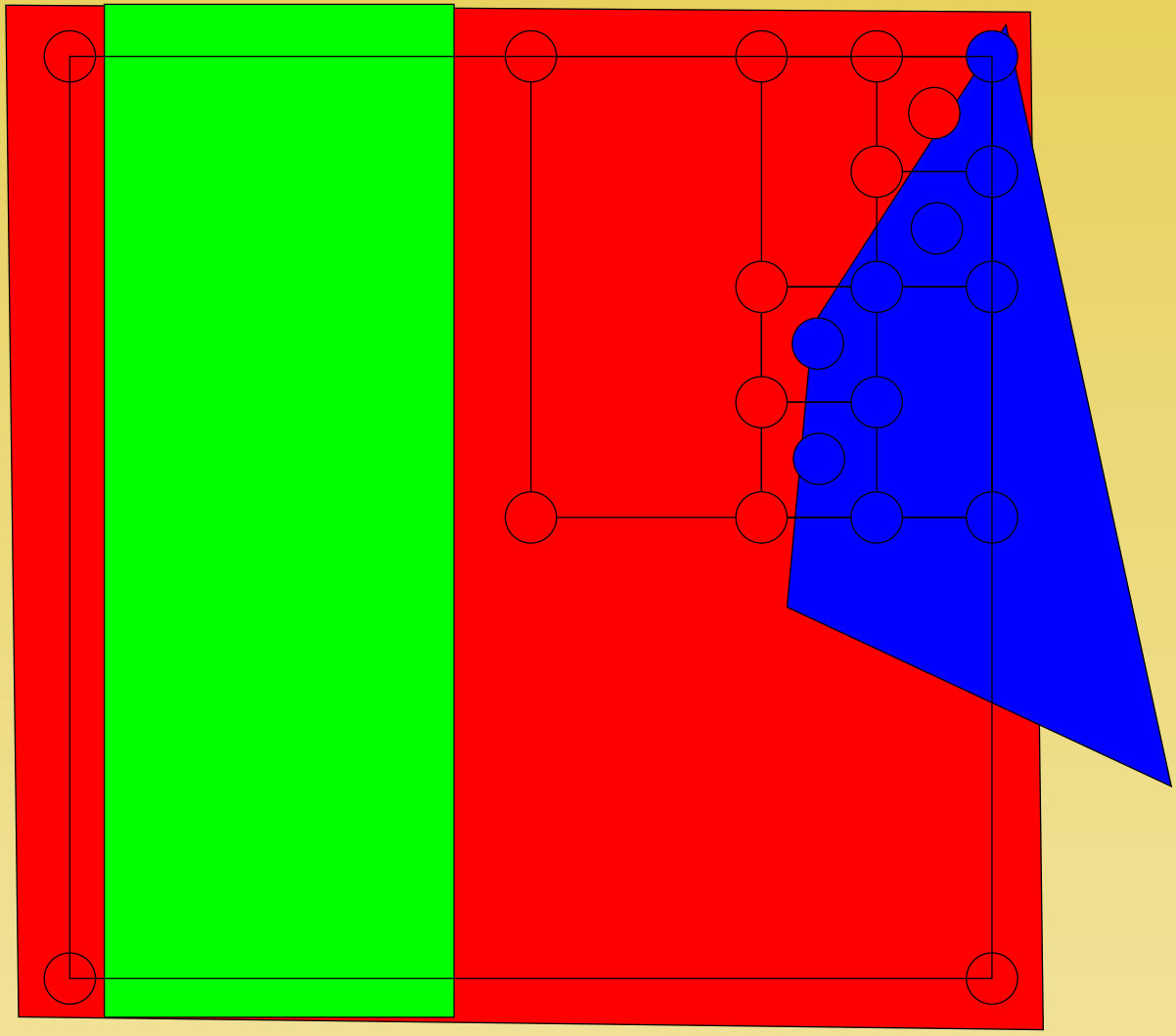
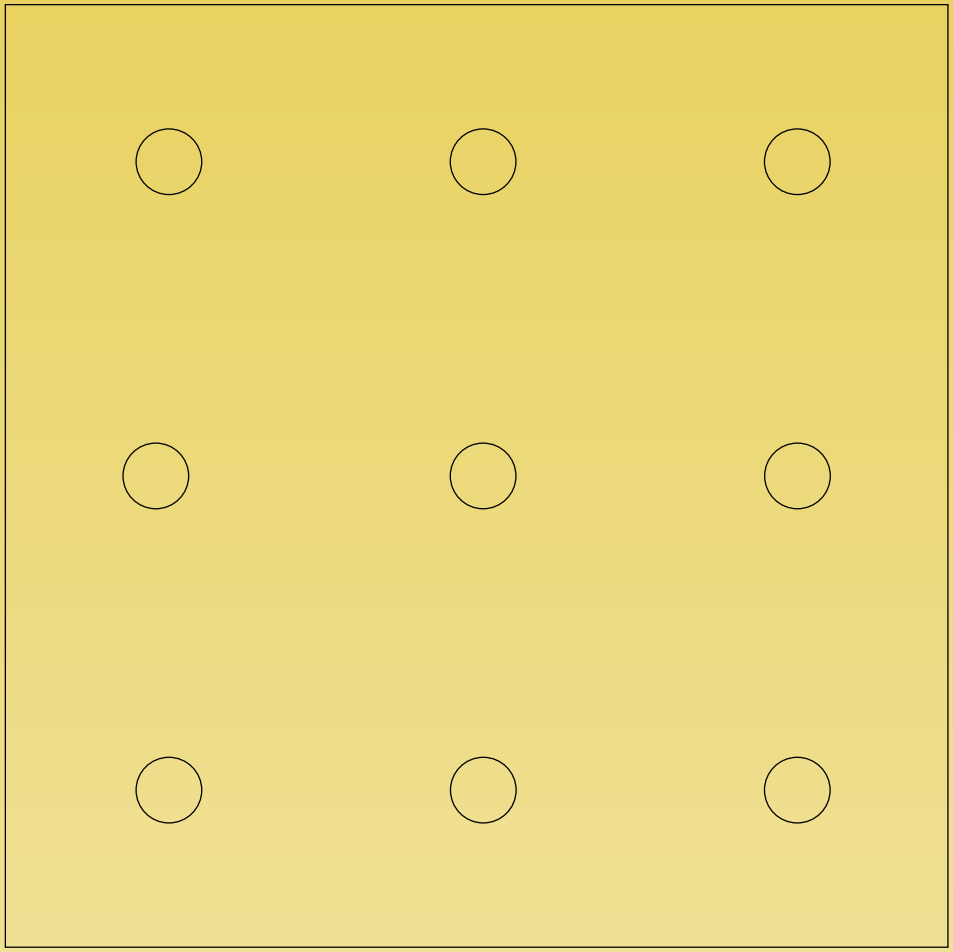


Distributed/Stochastic Ray Tracing



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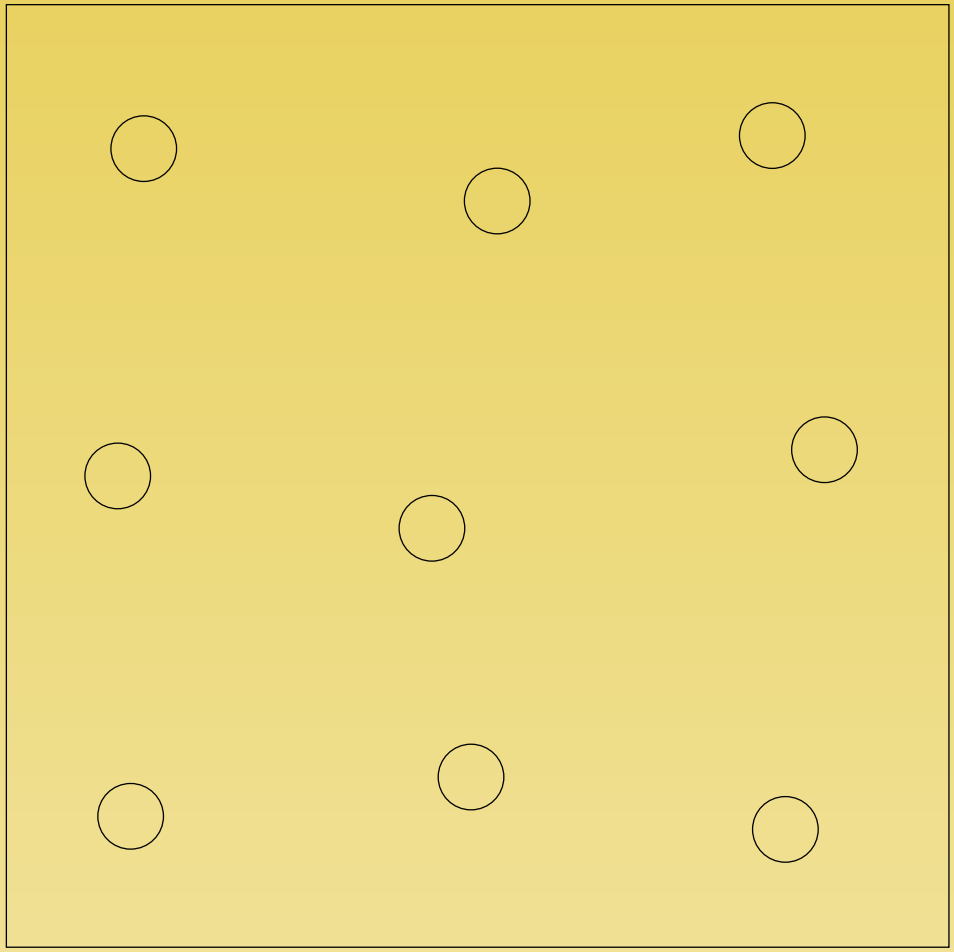


Motion blur

Cook, Porter, Carpenter 1984

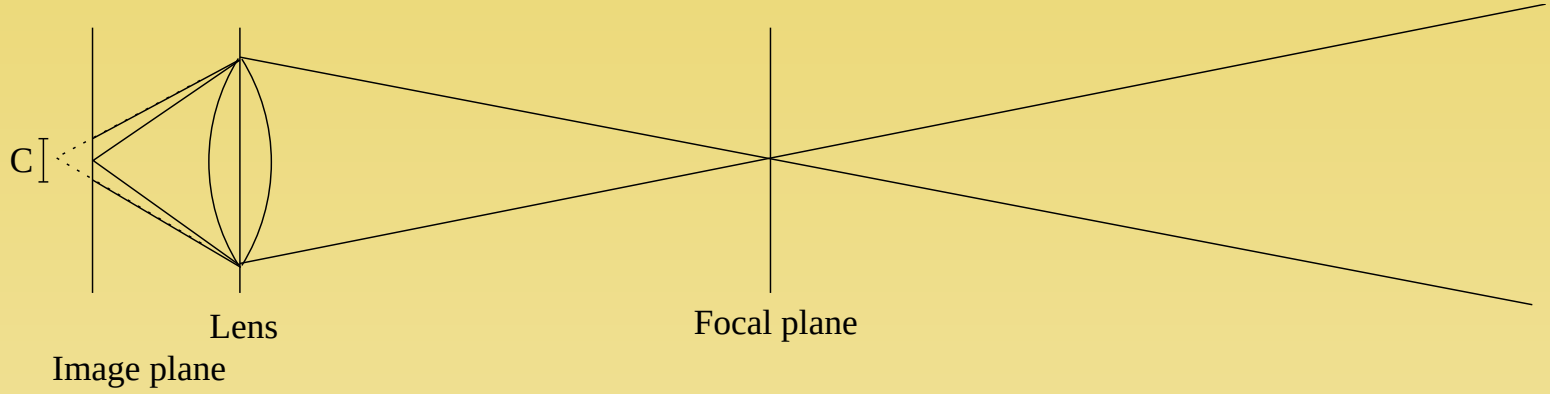
motion blur

- Sample the image temporally; temporal anti-aliasing.
- Can perform with other rendering techniques.
- Modeling the shutter of a camera.
- In ray tracing, can combine with spatial anti-aliasing by giving each ray a jittered time.

Cook, Porter, Carpenter 1984

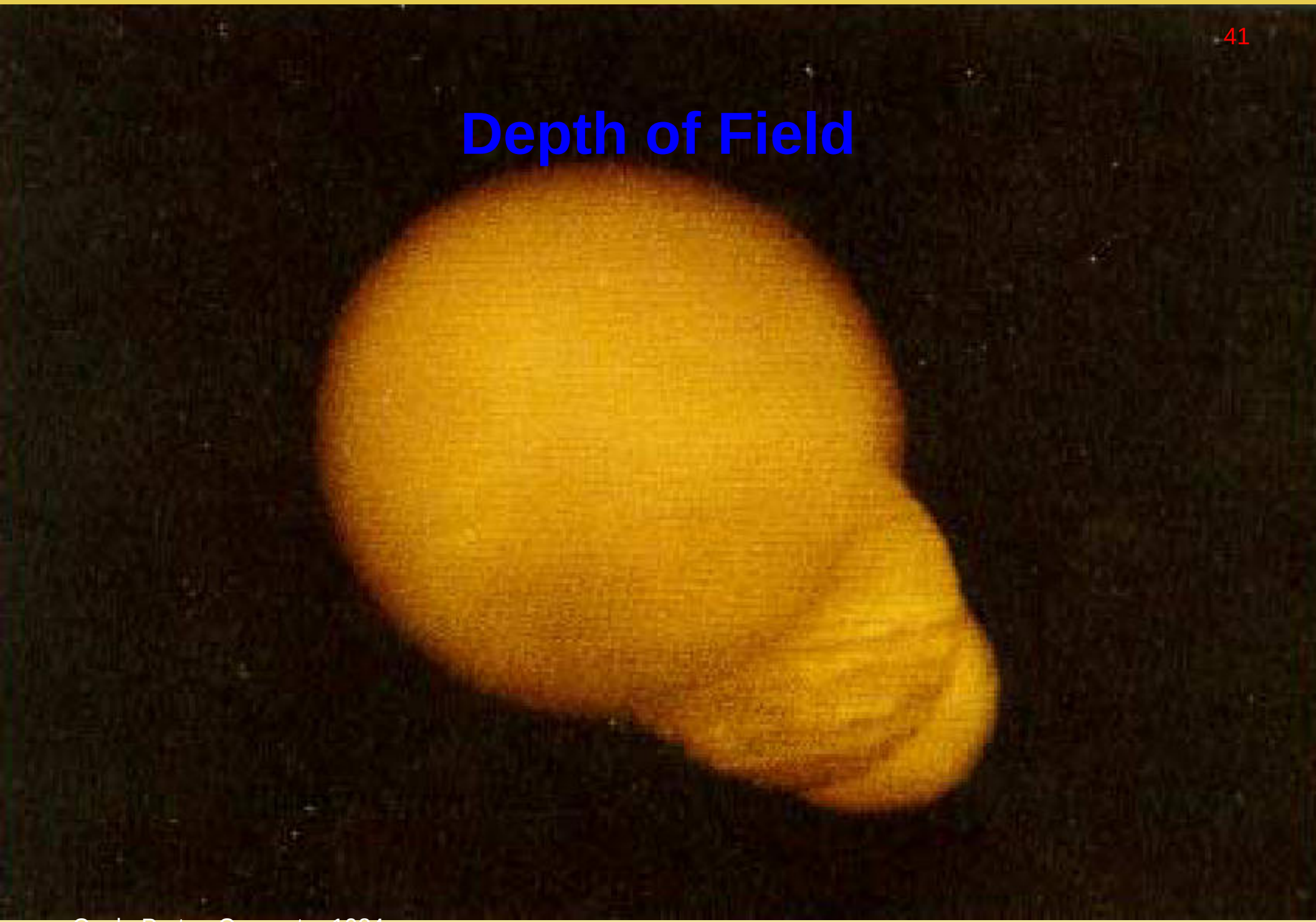
Depth of field

- Model the lens of a camera.
- All points in the scene project as a circle on the image plane, called the *circle of confusion*. Objects at the focal distance are sharp, others are blurred.



Cook, Porter, Carpenter 1984

Depth of Field



Cook, Porter, Carpenter 1984

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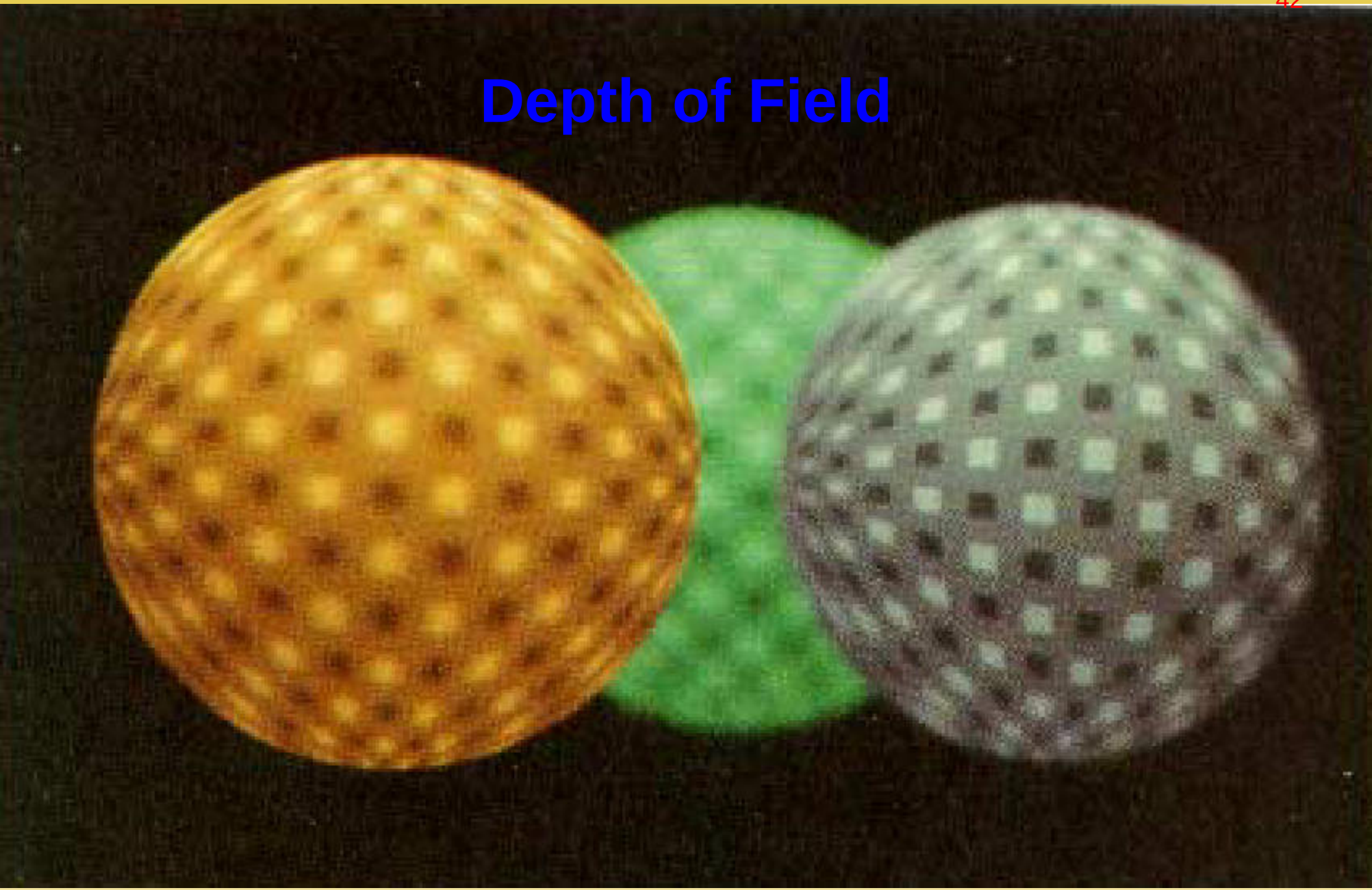

Cook, Porter, Carpenter 1984

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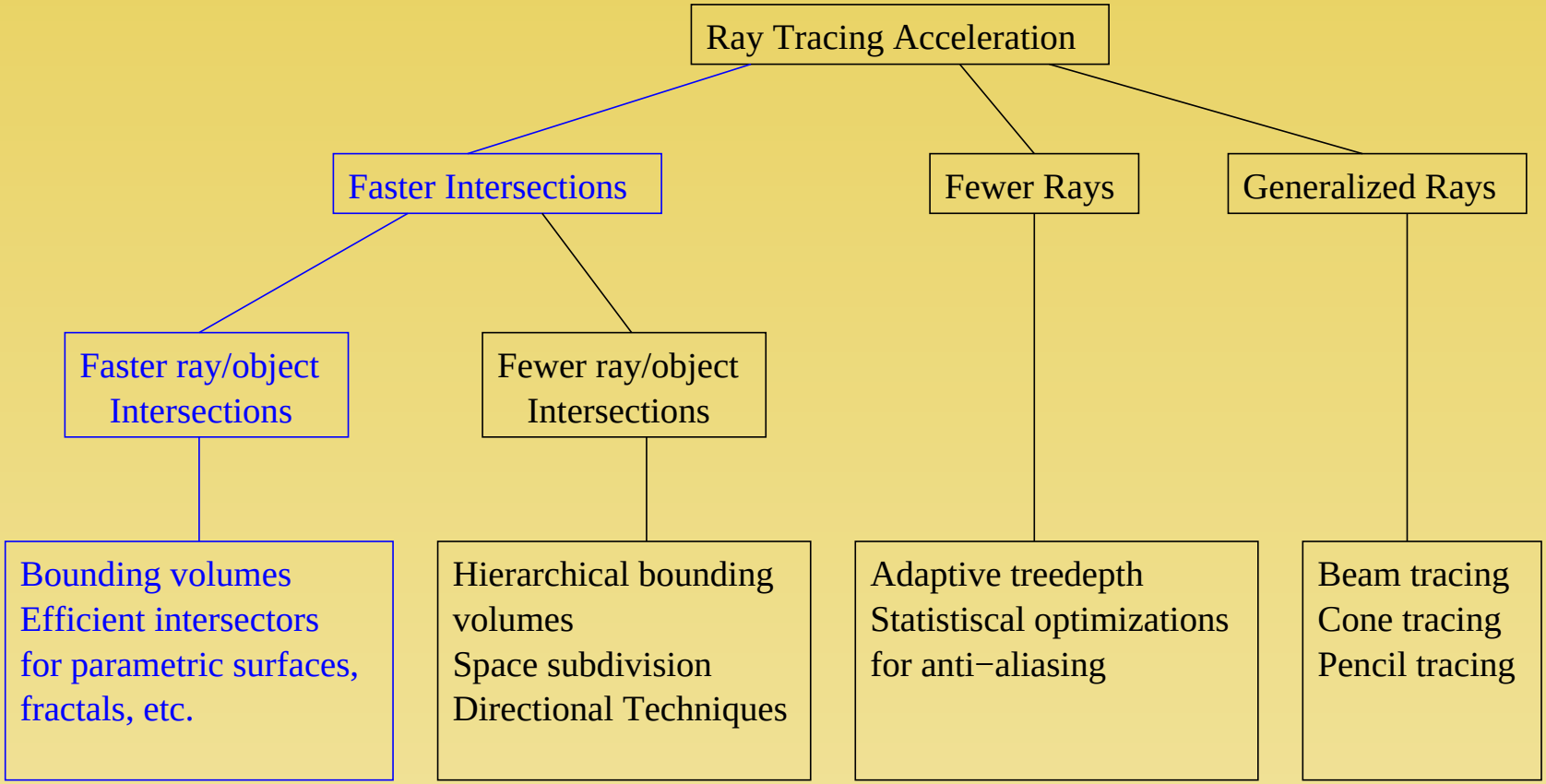

Bounding Volumes

- How does the number of intersection tests compare to the number of primitives?

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- How many times will a ray hit a sphere made of 40 triangles?
- How many times will a ray hit a sphere made of 4000 triangles?

Bounding Volumes

- Enclose objects/primitives inside volume with simpler intersection test.
- For objects that are intersected do we have an increase or decrease in computation?

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Bounding Volumes

- Enclose objects/primitives inside volume with simpler intersection test.
- For objects that are intersected do we have an increase or decrease in computation?
- For objects away from ray do we have an increase or decrease in calculations?
- Which case happens more often?

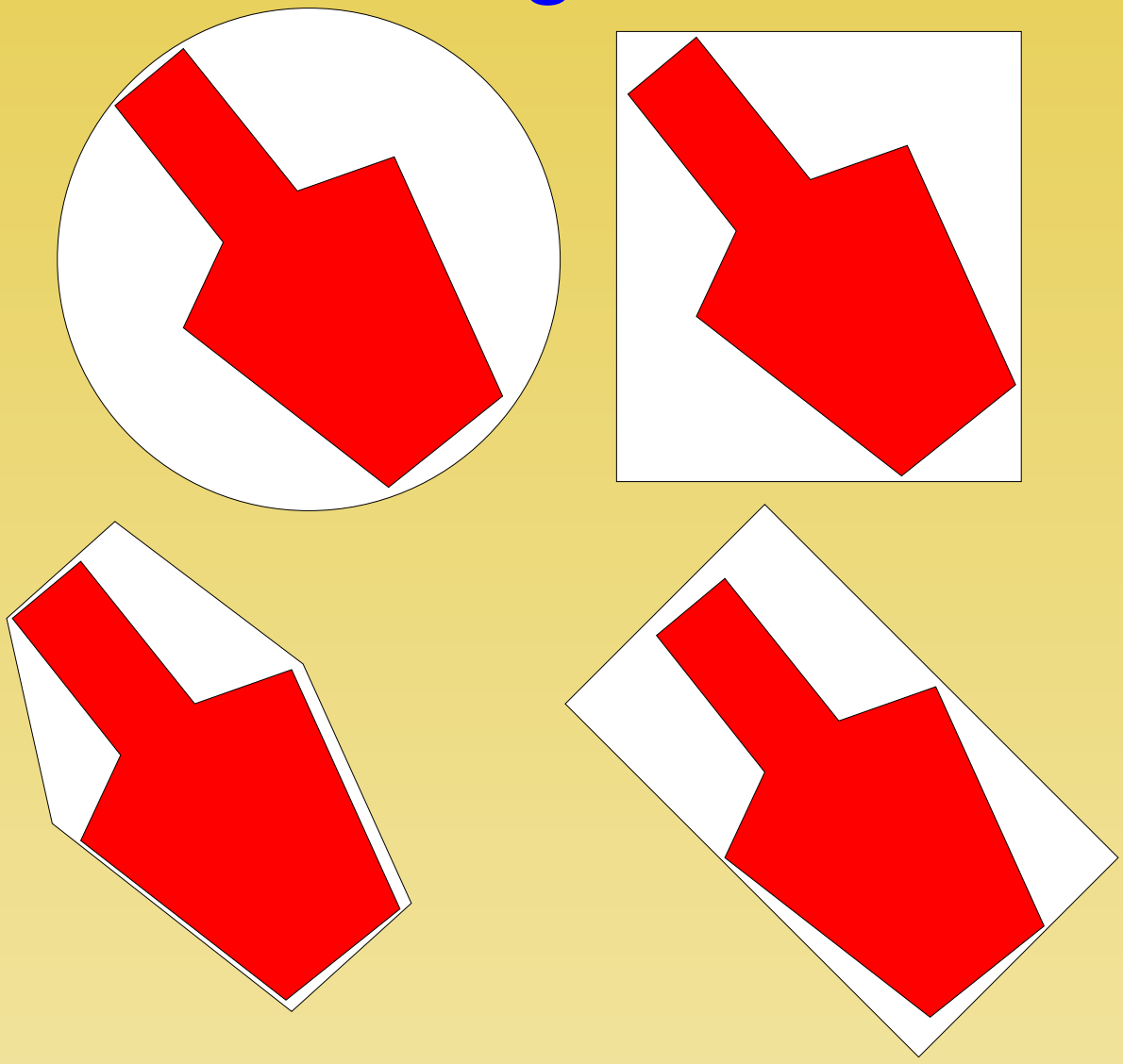
Bounding Volumes

- Spheres
- Axes aligned boxes
- Boxes (parallelepipeds)
- Slabs (pairs of parallel planes)

$$Cost = n * B + m * I$$

where n - number of rays,
m - number of rays that intersect bounding volume,
I cost of intersecting object within,
B cost of intersecting bounding volume.

Bounding Volumes



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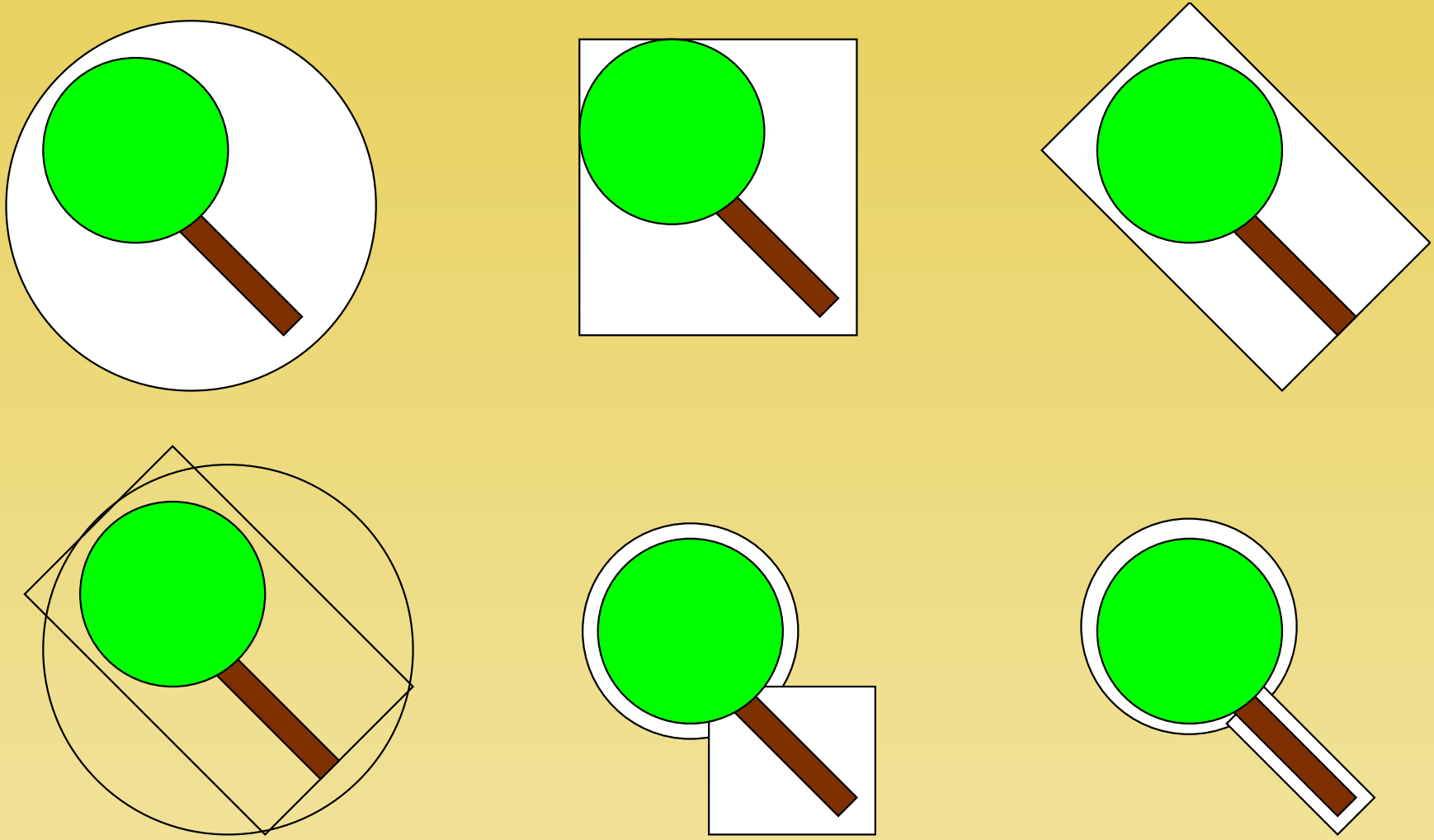

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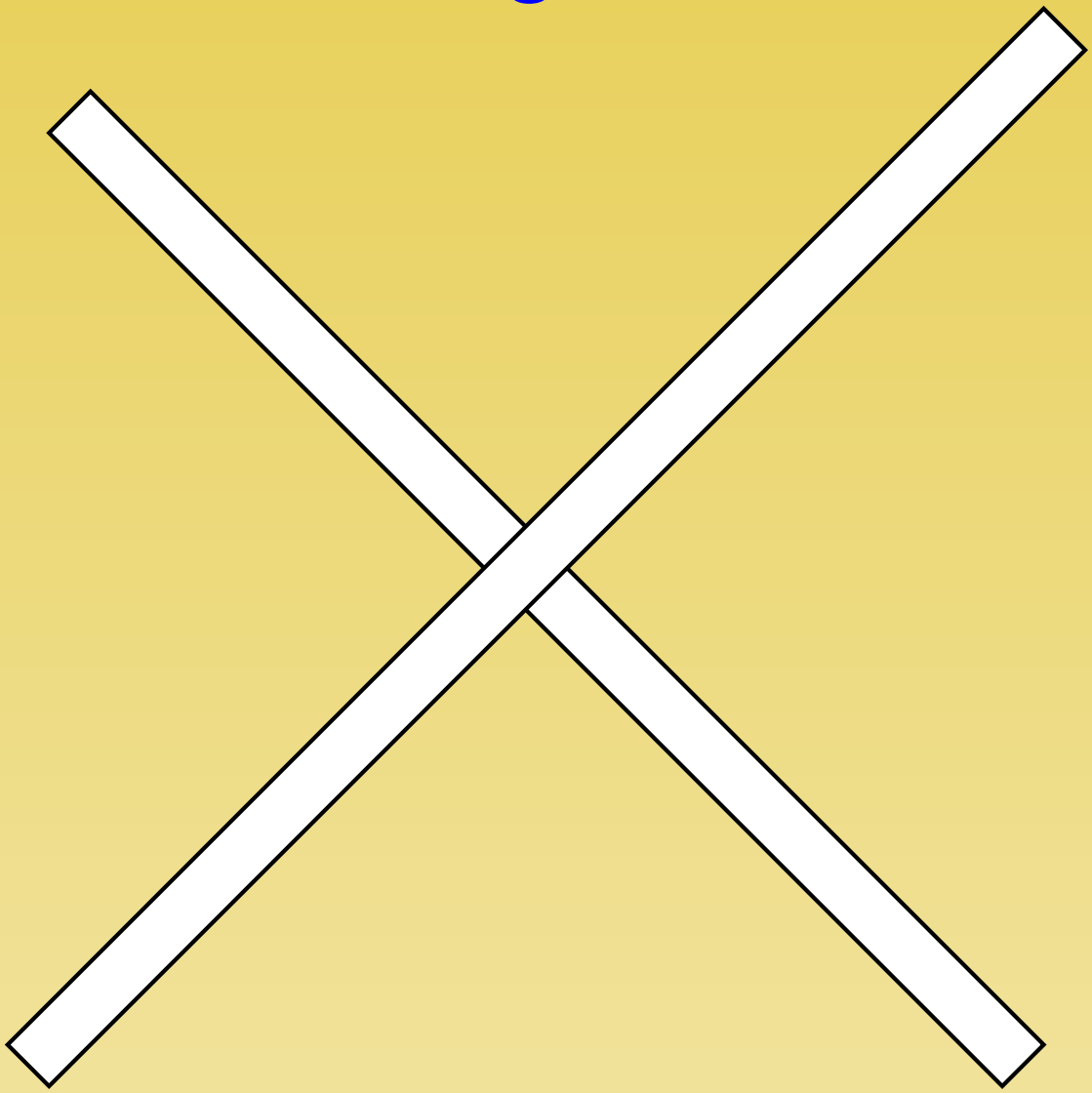


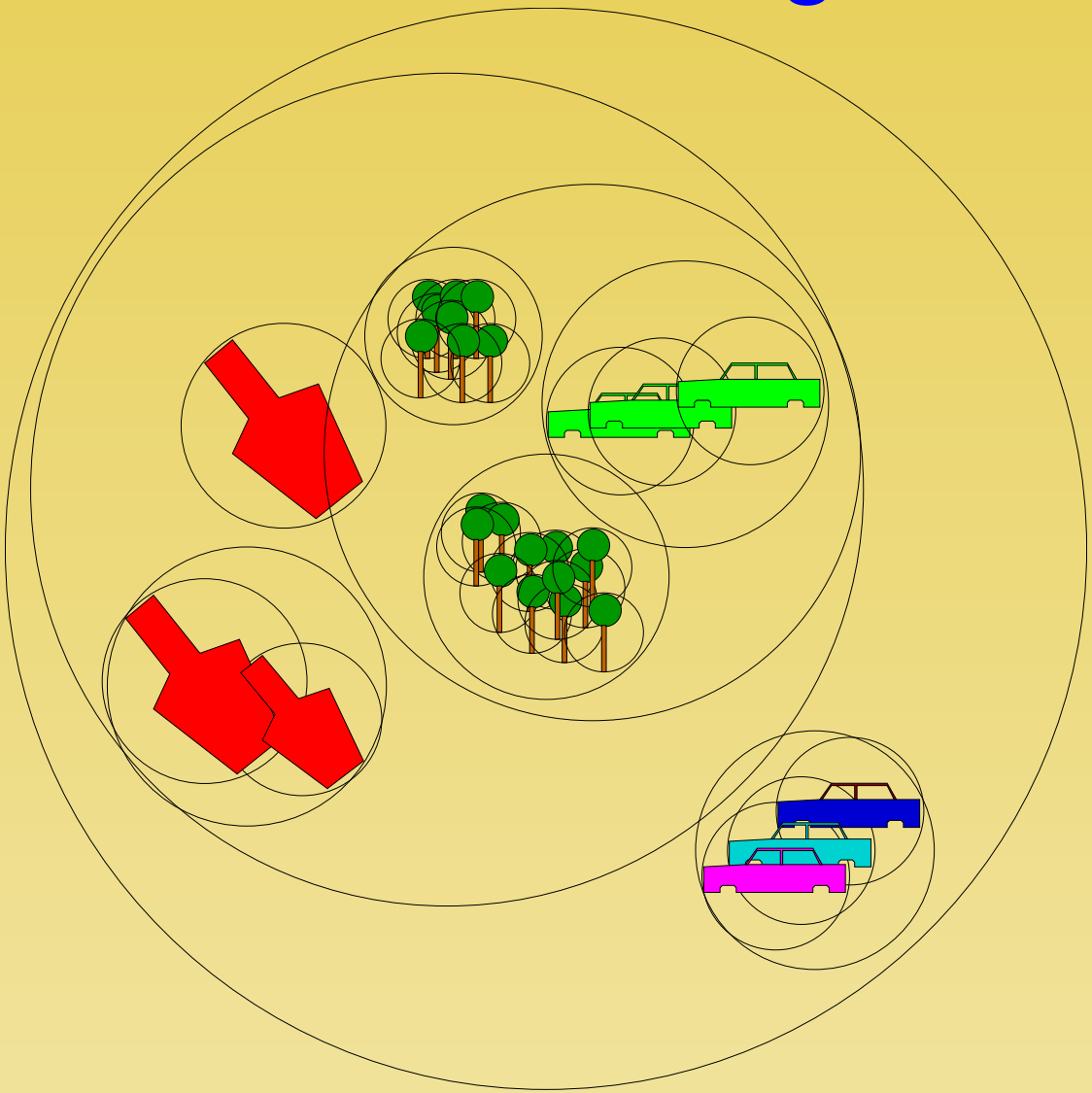
Bounding Volumes

- Trade off complexity versus closeness of fit.
- Transformed bounding volumes.
- Intersection of bounding volumes.
- Union of bounding volumes.

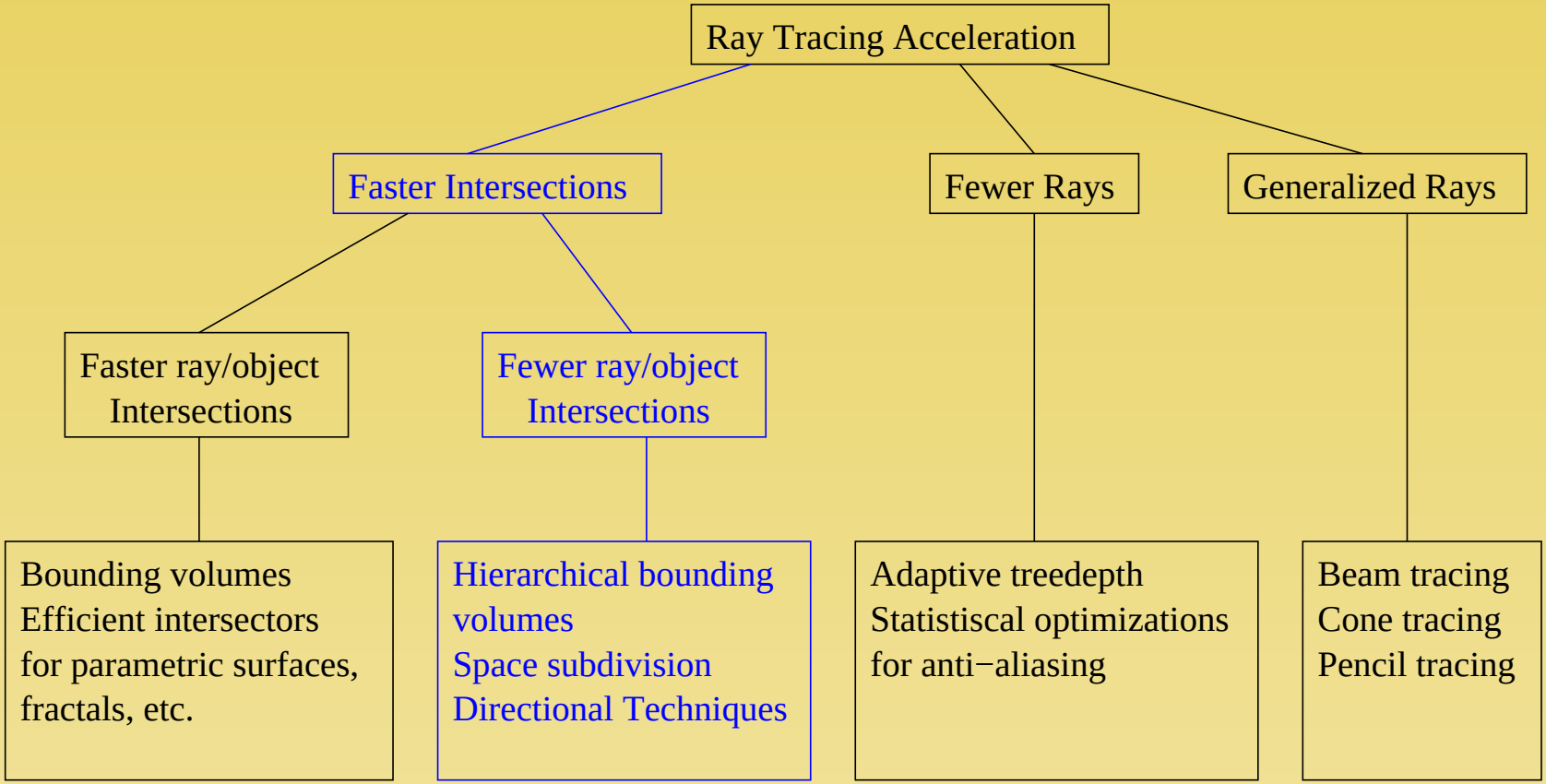
Bounding Volumes

- Trade off complexity versus closeness of fit.
- Transformed bounding volumes.
- Intersection of bounding volumes.
- Union of bounding volumes.
- What about hierarchies?

Hierarchical Bounding Volumes



Ray Tracing Acceleration Classification



Bounding Volumes: Why Hierarchies

- What is the complexity of the intersection tests?

Bounding Volumes: Why Hierarchies

- What is the complexity of the intersection tests?
- What if you create a tree-like bounding volumes?

Bounding Volumes: Why Hierarchies

- What is the complexity of the intersection tests?
- What if you create a tree-like bounding volumes?
- Using hierarchies are theoretically $\mathcal{O}(\log(n))$.
- When enclosing several volumes with a new volume, the cost of doing the extra check must pay off.
- Top-down or bottom-up approach.
- Minimize volume/surface area.
- Hierarchies are not always simple to construct.

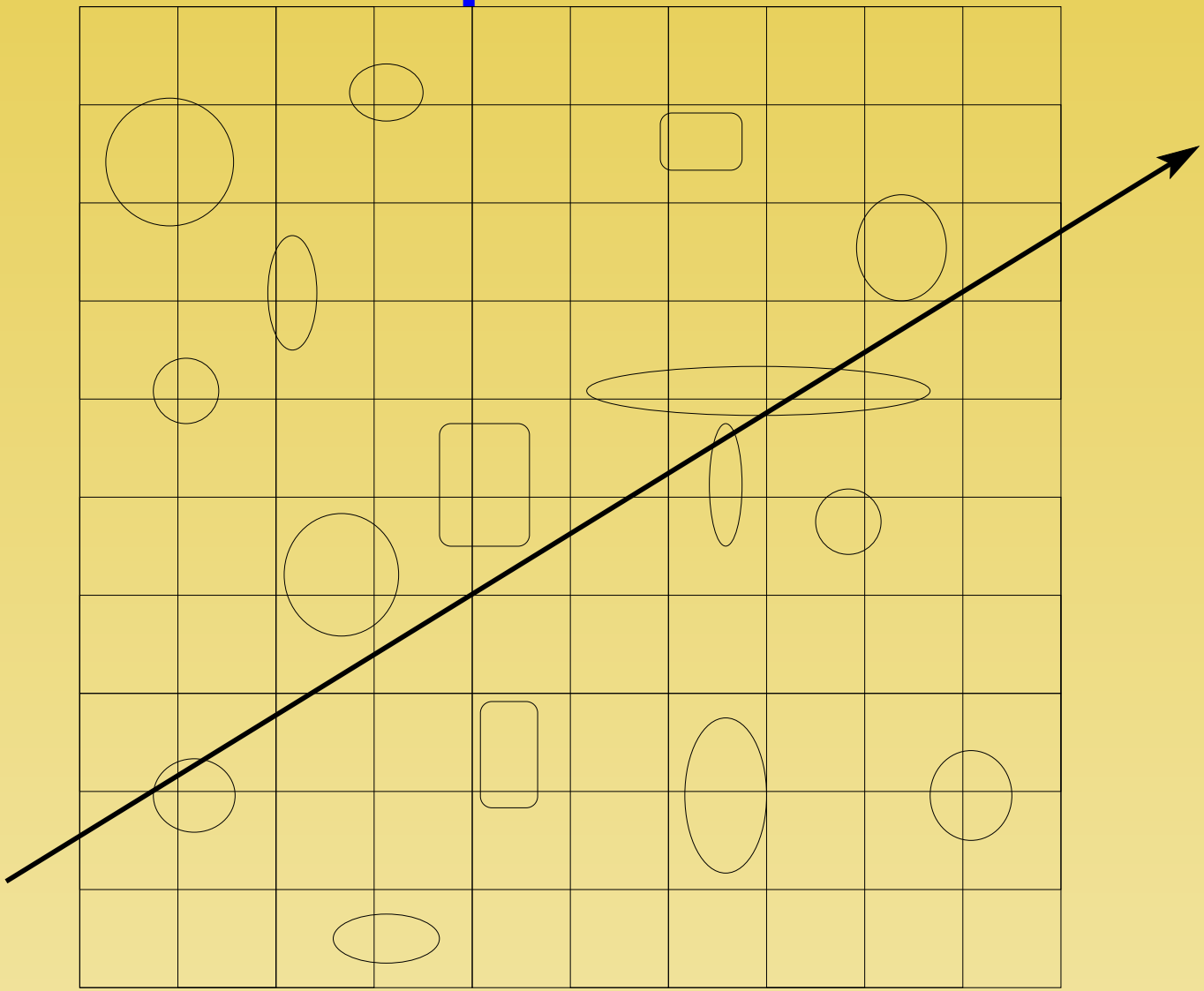
Bounding Volumes

- No correct volume for all cases. Often a combination is best.
- No automatic way to determine the best volumes, can do a good job though.
- Placement of volumes usually requires help for really good results.

Spatial Subdivision

- Bounding volumes divide the space based on the objects.
- Instead lets just divide the space.
- Divide the space into *voxels*.

Uniform Space Subdivision



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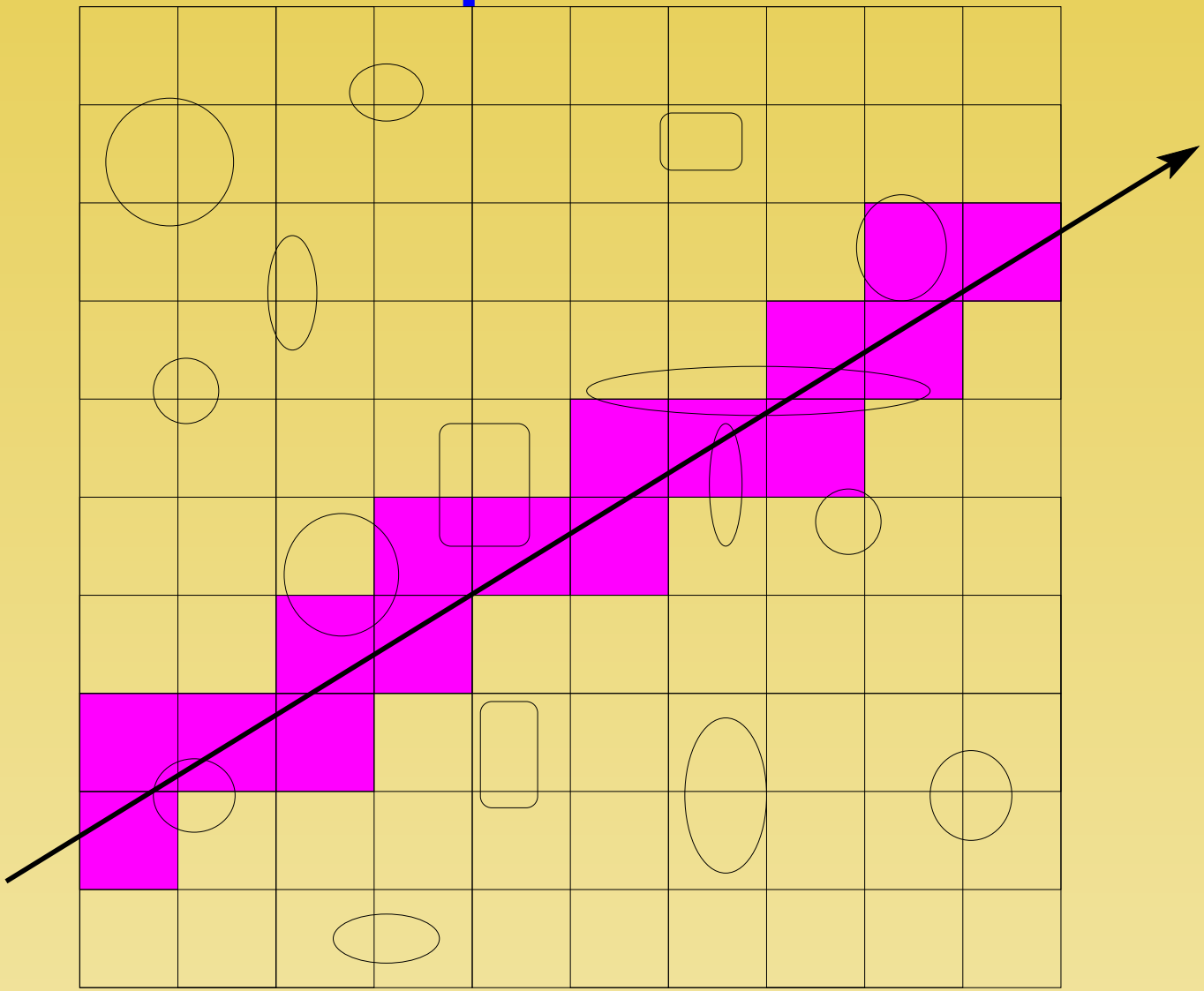
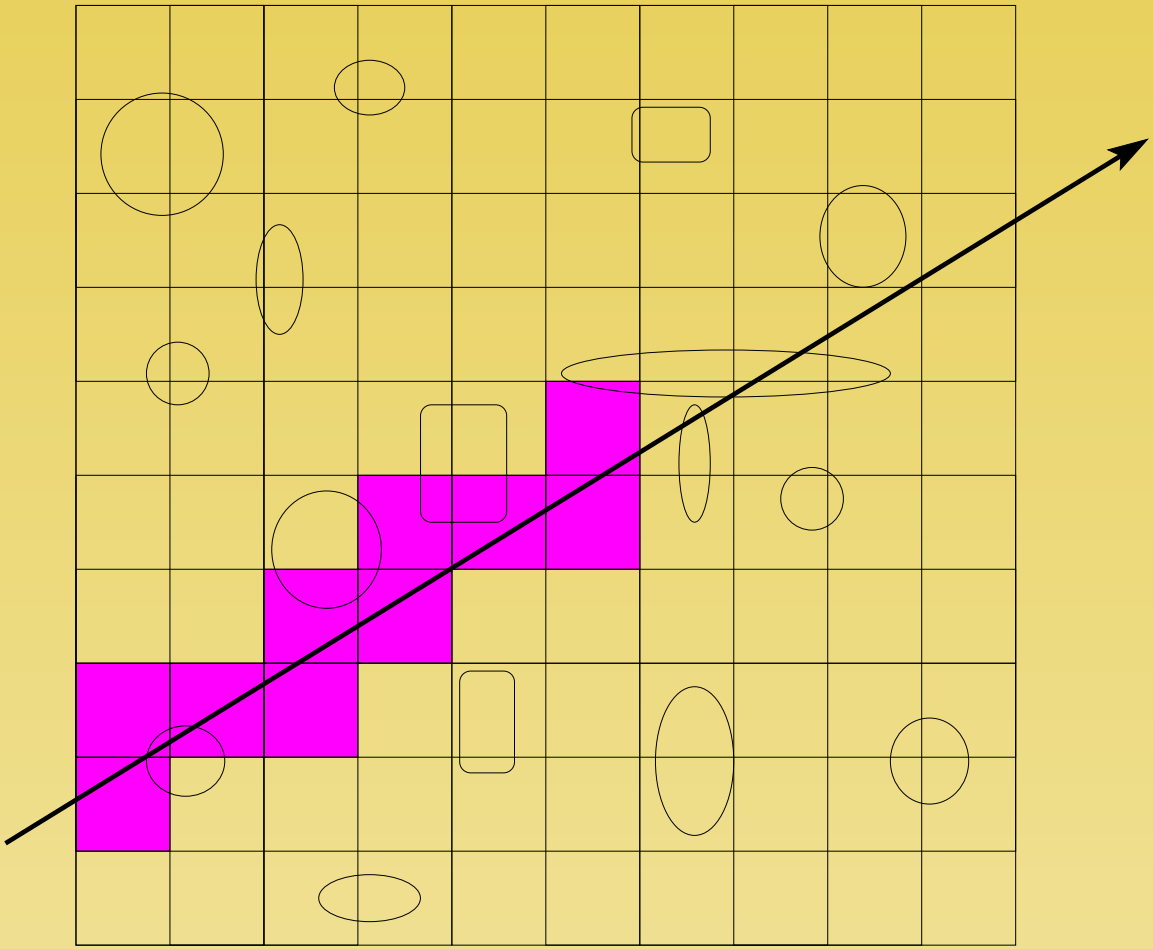
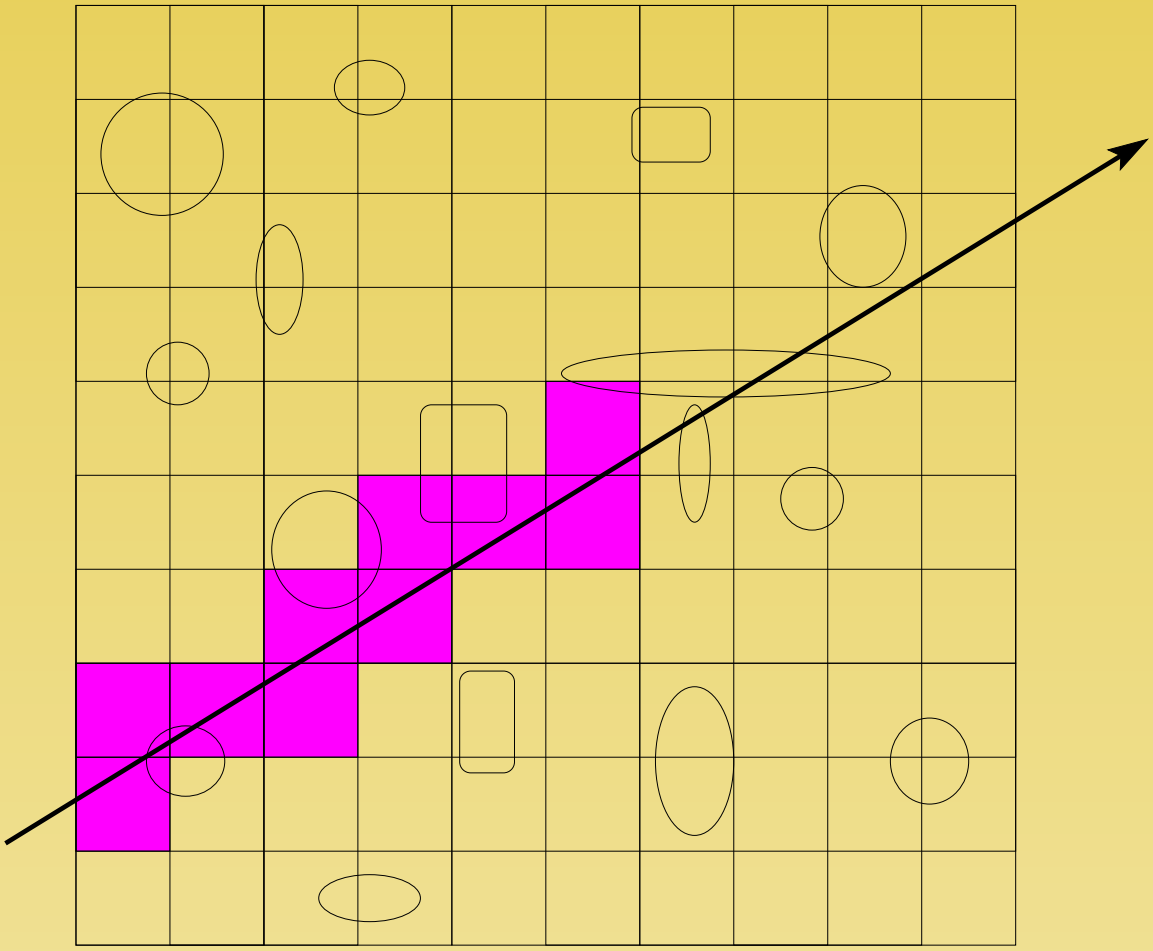


Uniform Space Subdivision



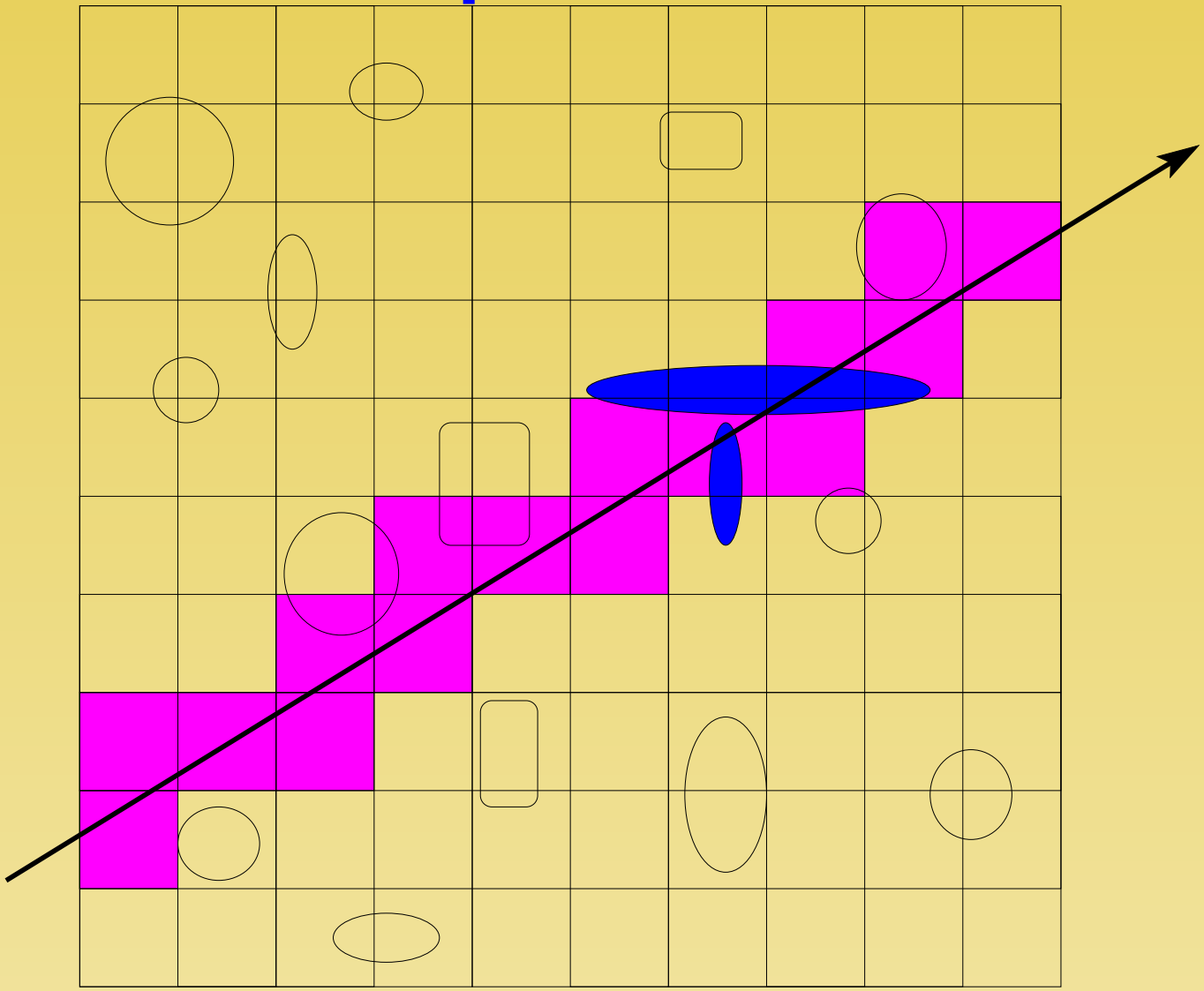
How do we determine the next voxel to test?

Uniform Space Subdivision

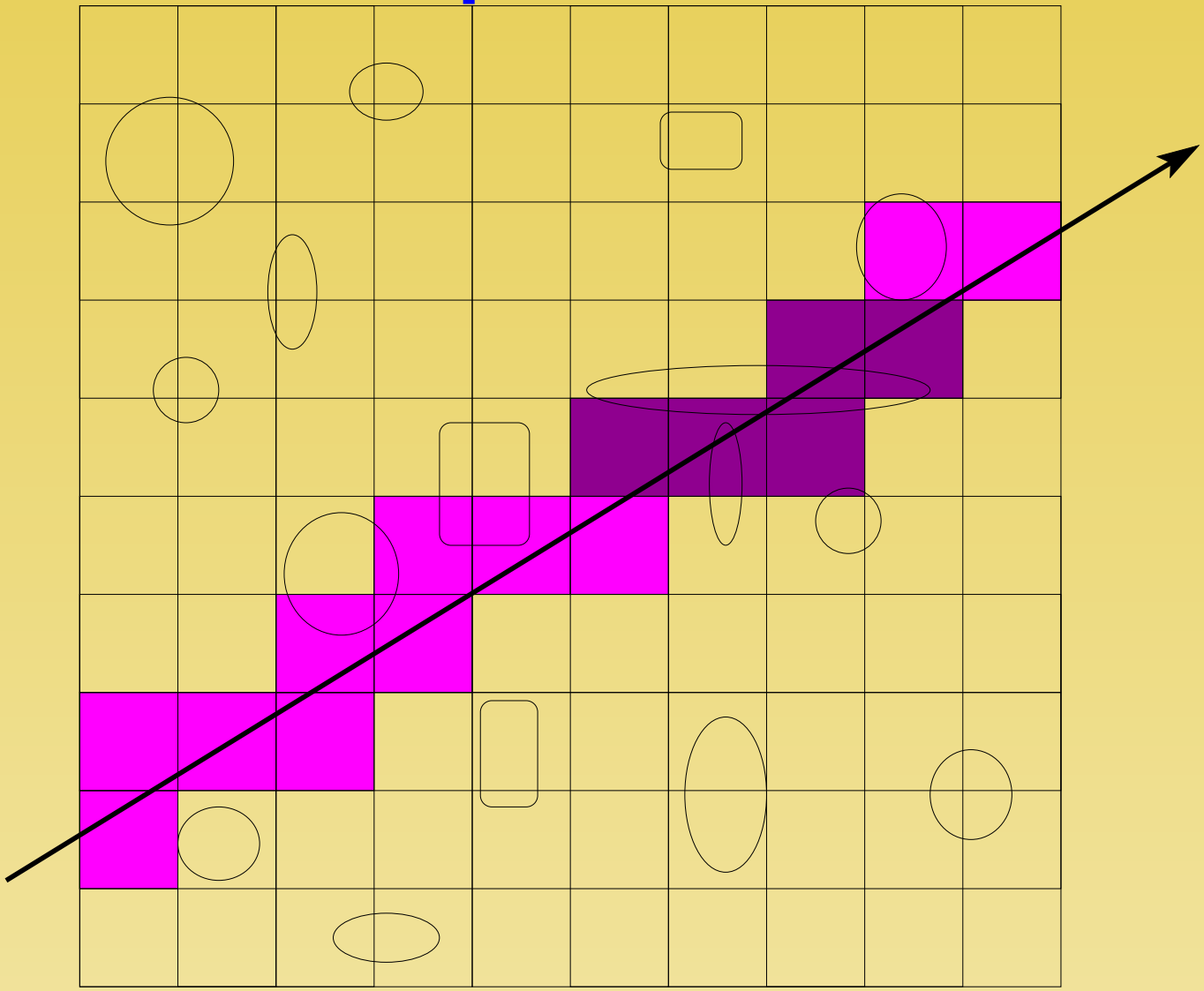


How do we determine the next voxel to test?3D-DDA 3D Digital Differential Analyzer

Uniform Space Subdivision



Uniform Space Subdivision



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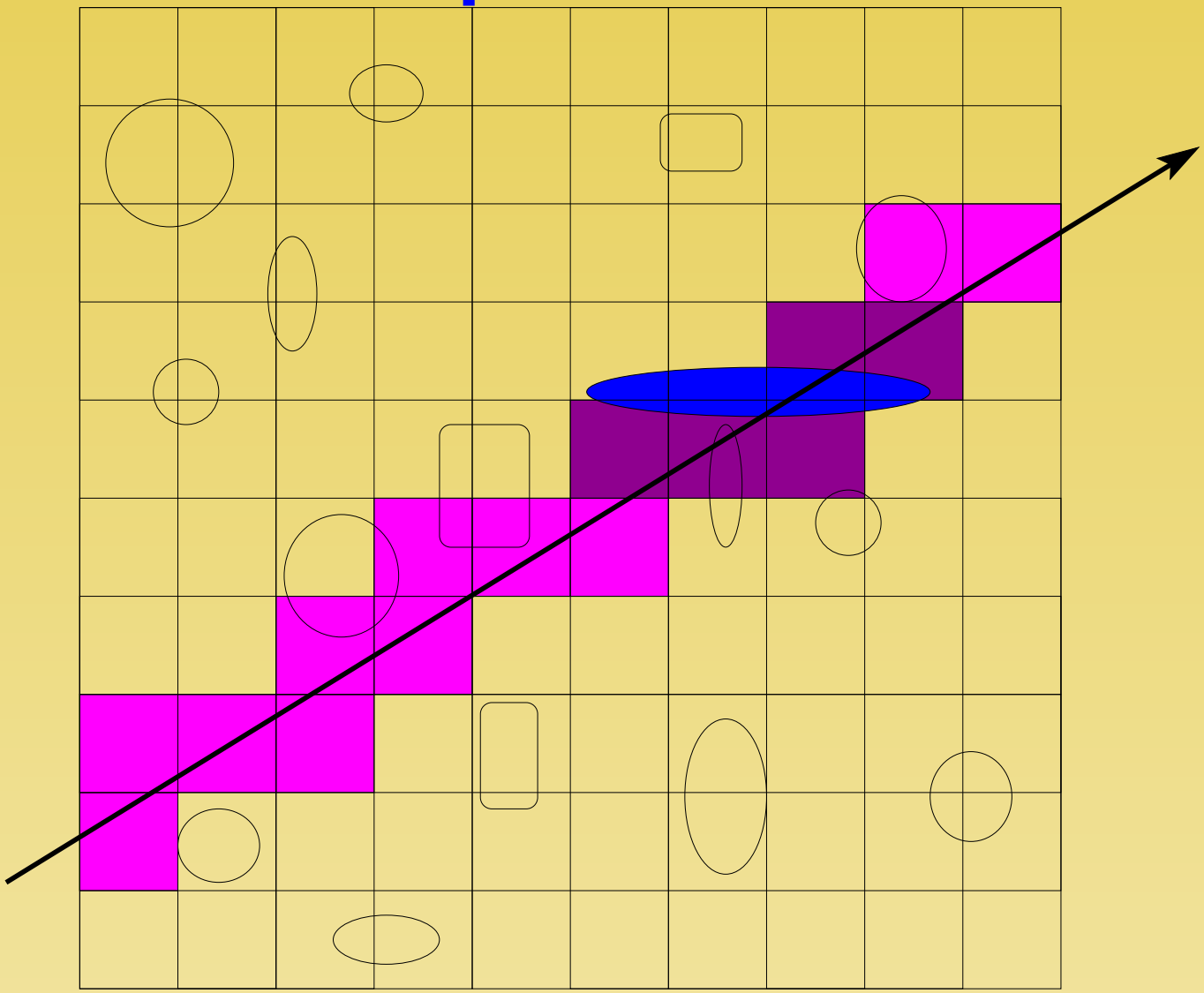

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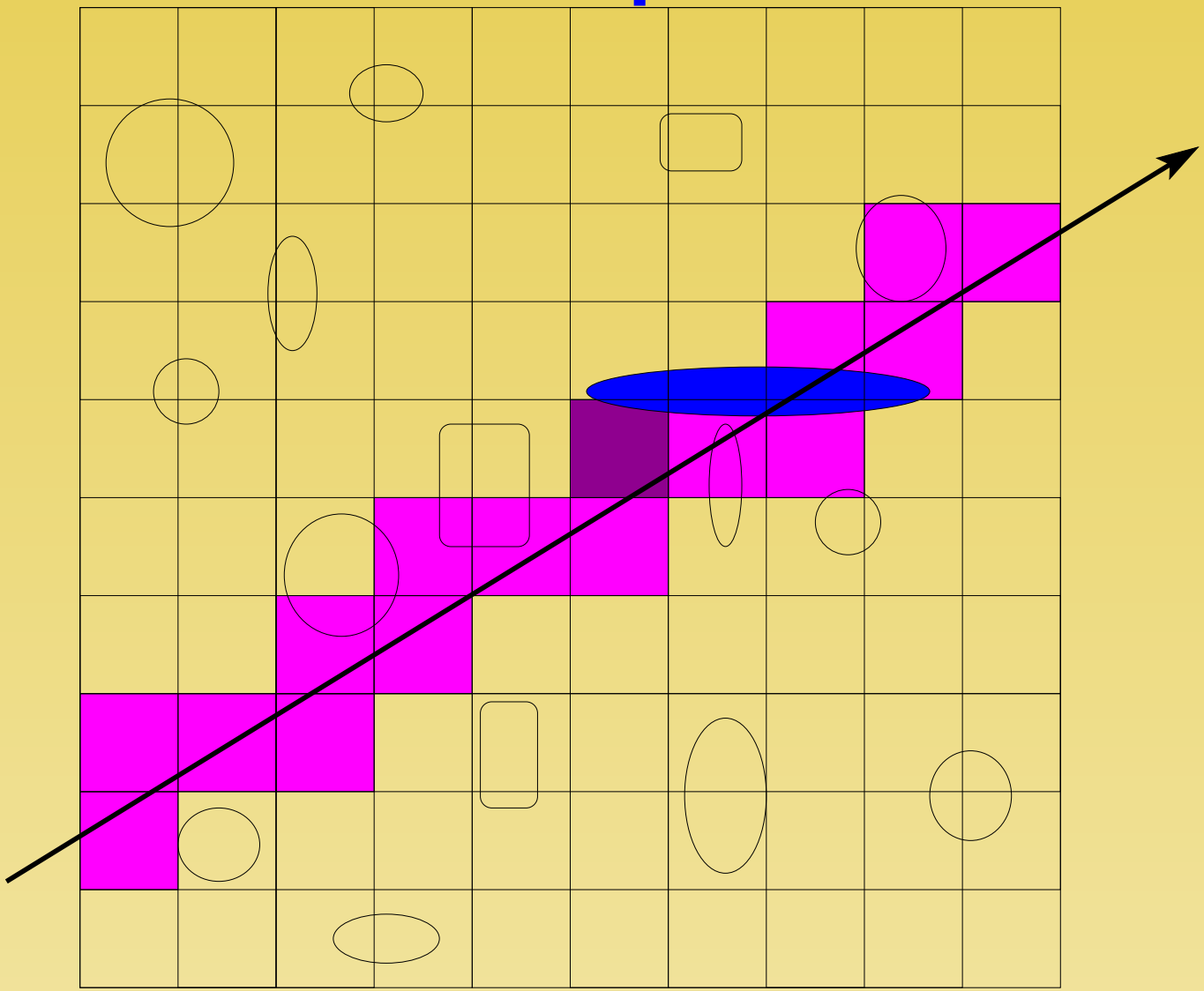

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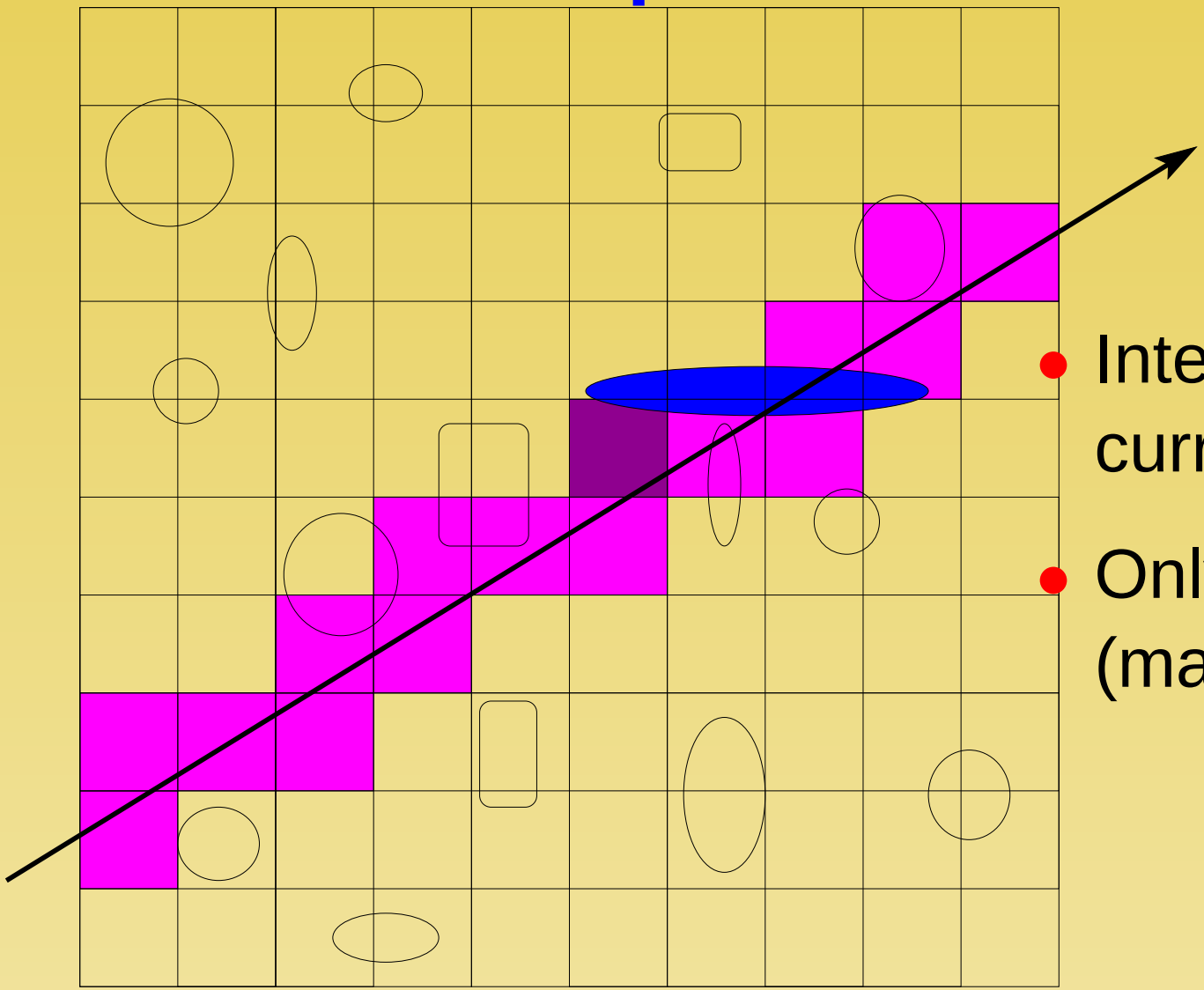
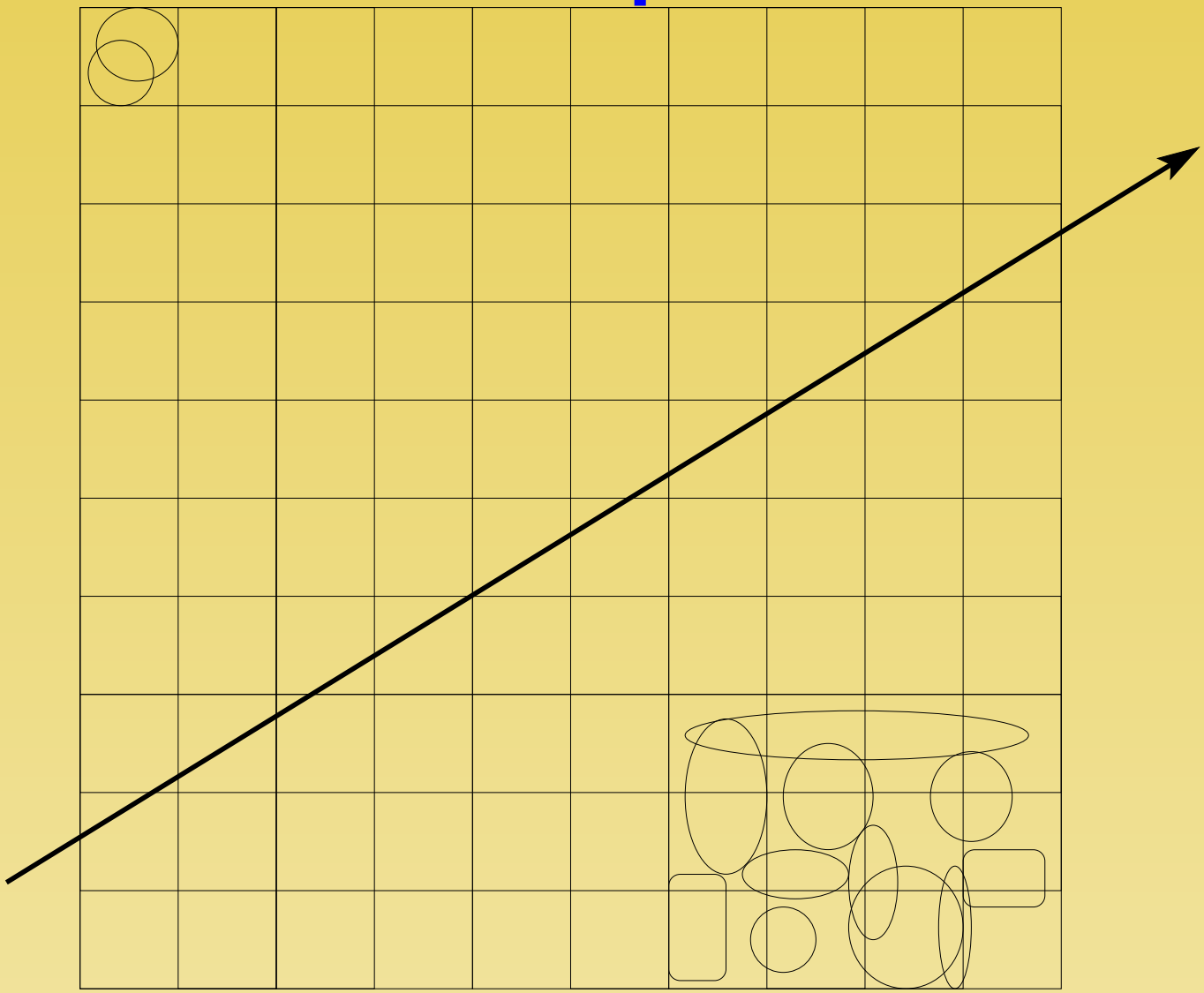


- Intersection in current voxel.
- Only test once (mailboxes).

Uniform Space Subdivision

- To construct, start with scene bounding box then sub-divide.
- What affect does the size of the voxels have.

Uniform Space Subdivision

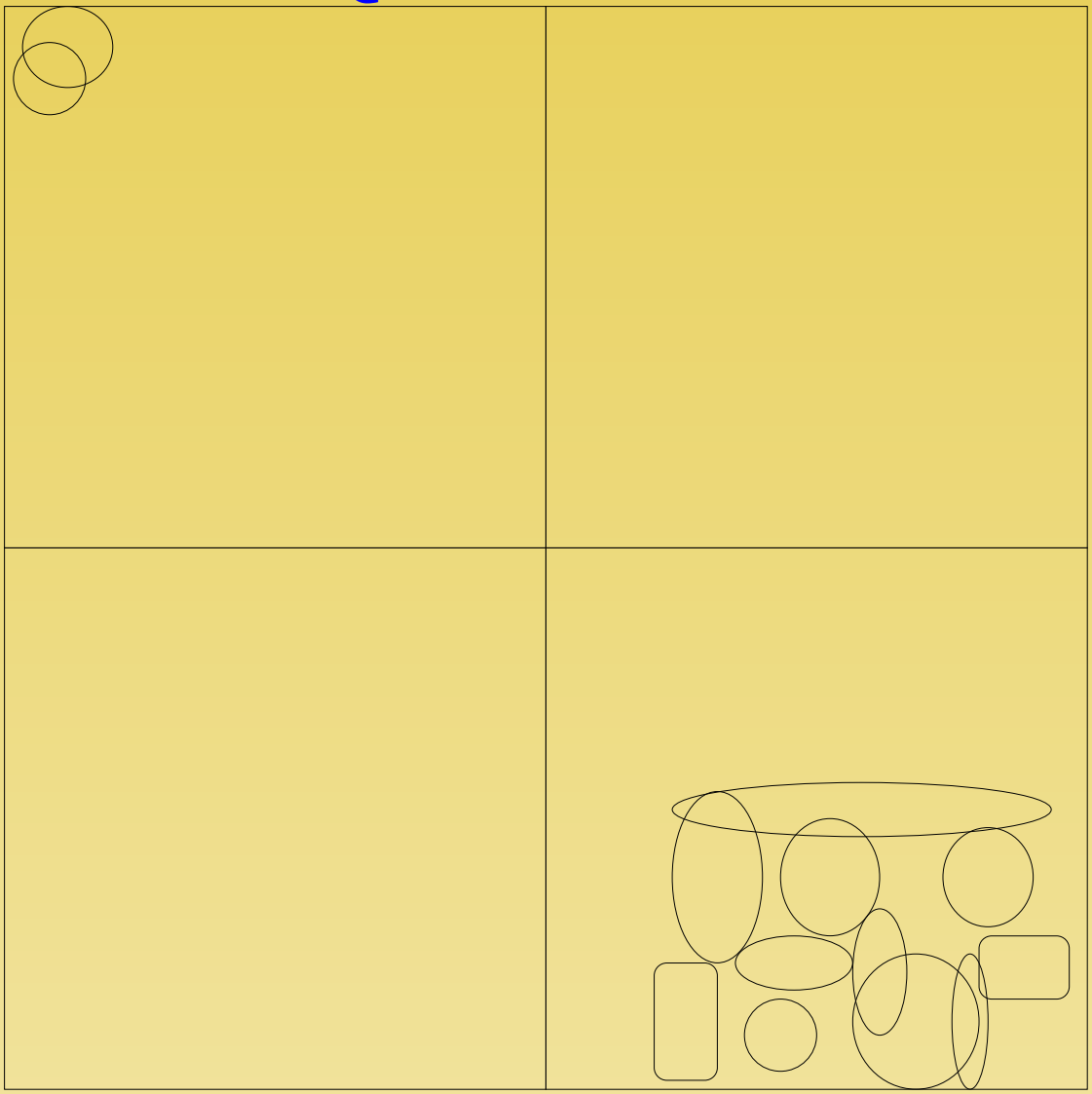


Why is this bad?

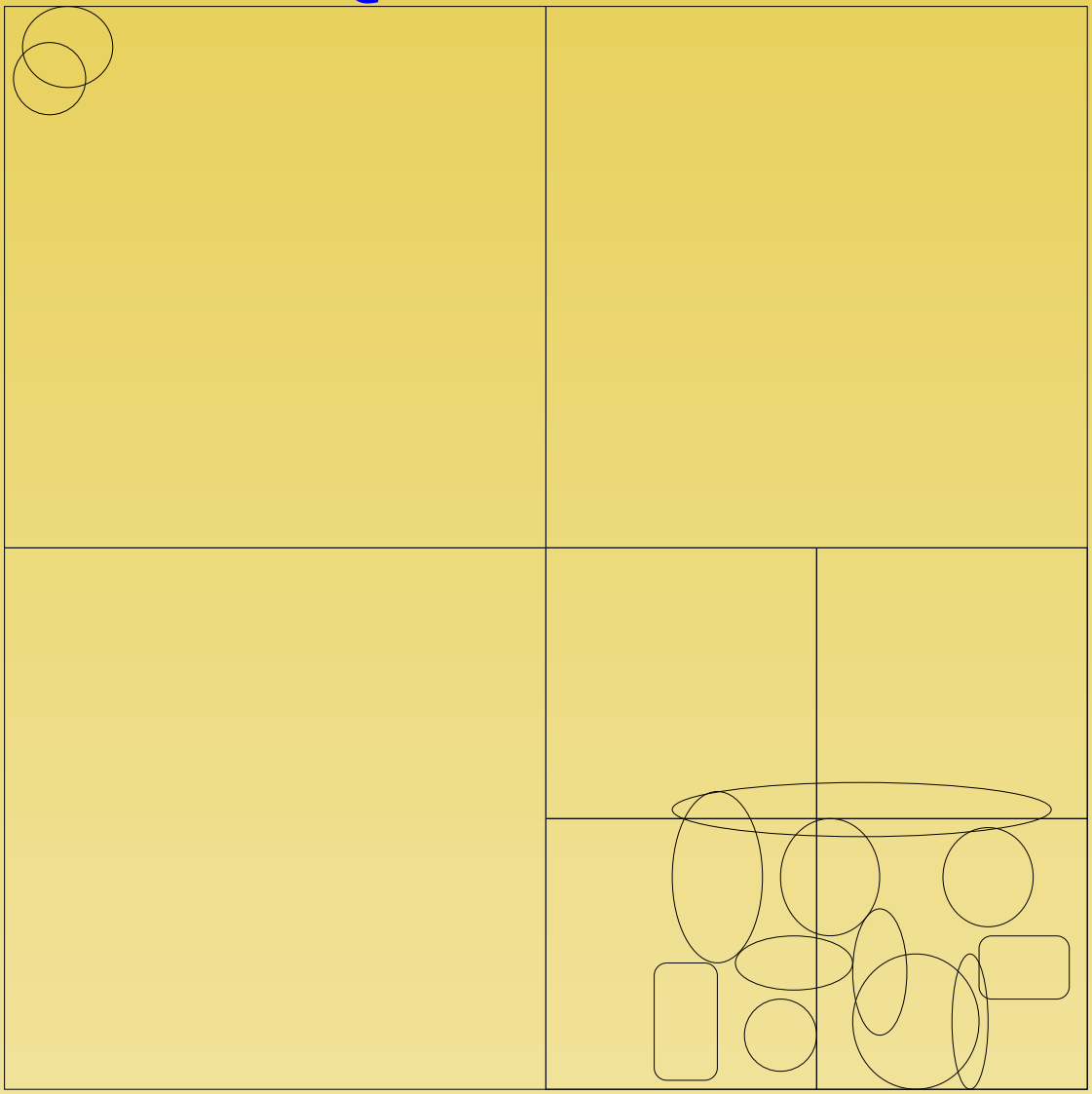
Nonuniform Subdivision (Hierarchical)

- Instead of having lots of empty little cells, lets have just a few empty big cells.
- This gives us a tree structure (hierarchy again!)
- Less voxels.
- But at what cost?
- Octrees.
- KD trees.
- BSP trees.

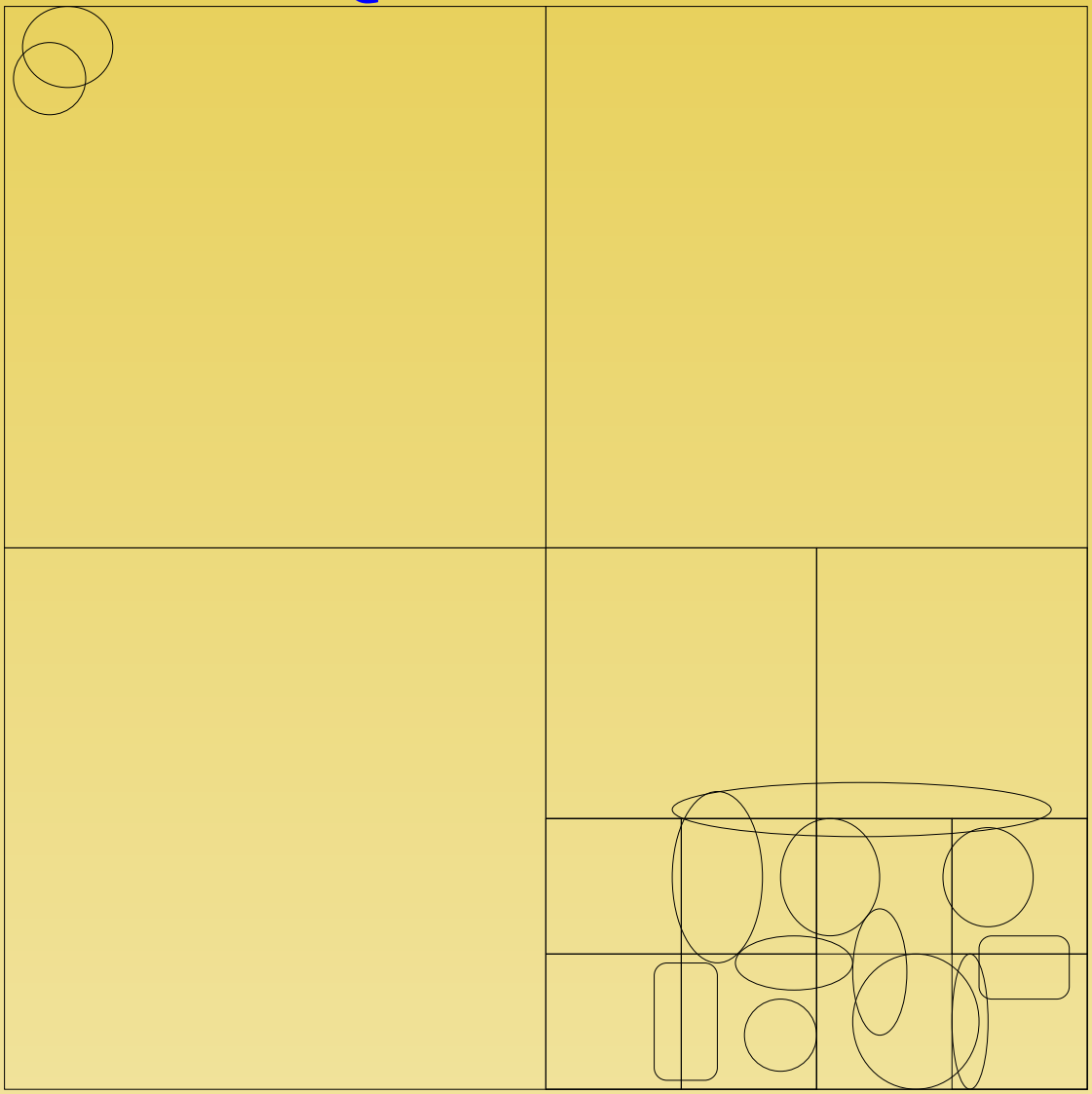
Quadtrees



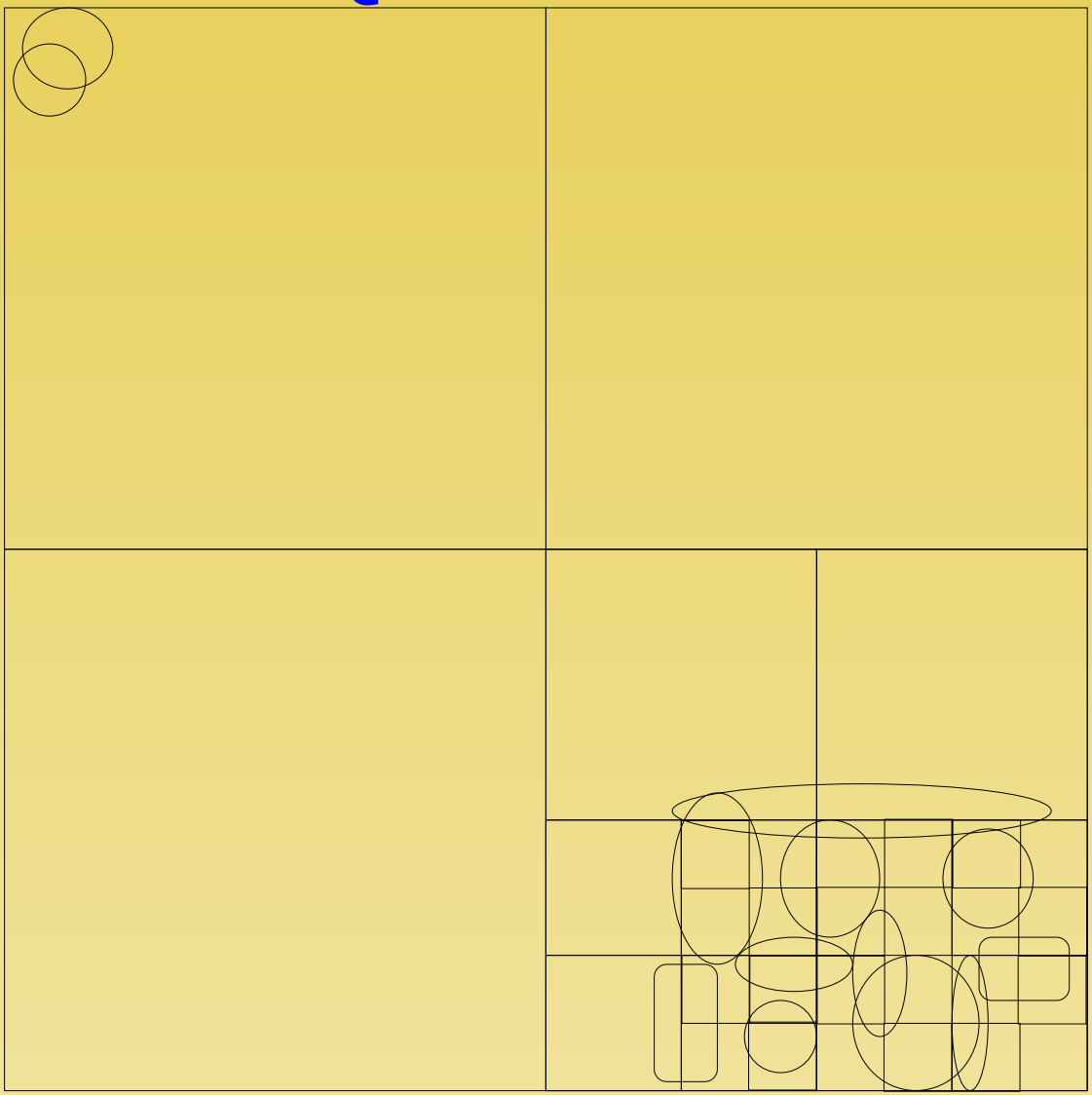
Quadtrees



Quadtrees



Quadtrees



Octrees

- Divide until a cell (voxel) has less than some number of objects (often 1) or until a minimum size is reached.
- Can subdivide on the fly to help improve efficiency of quadtree

Octrees: Dynamic Subdivision

- Don't divide it voxel too small or fewer than x objects.
- Don't divide if less than N rays (4 is good) and none of them have hit an object.
- Don't divide if $MK \geq N$, (M - num rays through voxel that hit something, k (2 or higher) user defined weight. (If a voxel is working why subdivide?)

Octrees: Ray Traversal Algorithms

- Point location from root (Glassner)
- Neighbor finding (Samet)
- Recursive inorder traversal (Kaplan, Arvo, Jansen)

Hiearchical Grids

- Instead of just one type of grid, why not do a combination?
- Recursive grids - Jevans and Wyvill (1989).
- Hierarchy of uniform grids - Cazals *et al. (1995)*
- *Adaptive grid - Klimaszewski (Ph.D. 1997)*

Recursive grids - Jevans and Wyvill (1989)

- Construct a uniform grid.
- Place objects within the grid.
- Recursively descend into voxels with too many objects creating a new uniform grid.
- Continue until maximum depth or minimum number of objects per voxel.

Hierarchy of uniform grids - Cazals *et al.* *(1995)*

- Make a global grid.
- Compute histogram based on object size.
- Split object into groups using histogram.
- Cluster objects within groups according to distance.
- For clusters with too many objects insert a new sub grid .

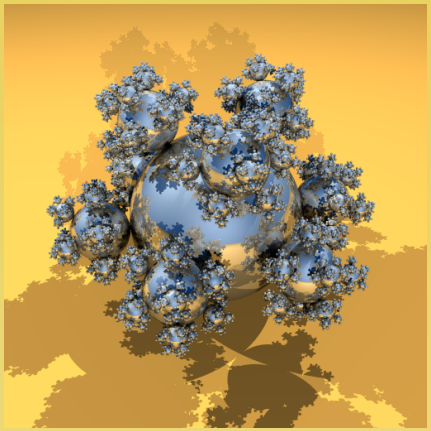
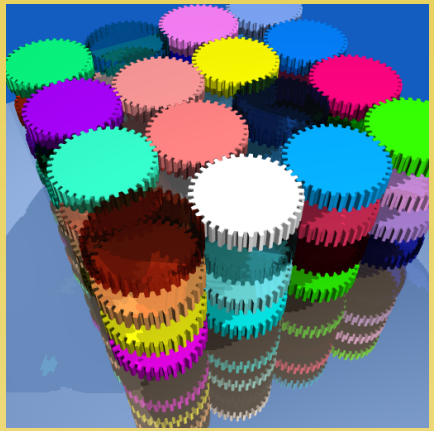
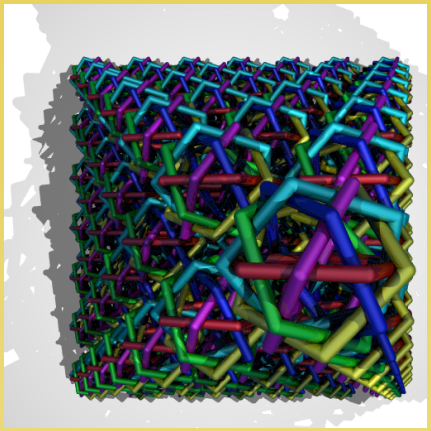
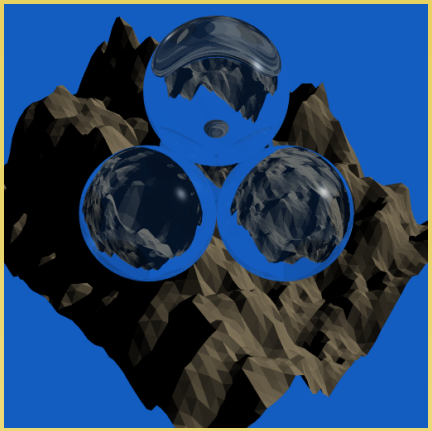
Adaptive grid - Klimaszewski (Ph.D. 1997)

- Cluster two things at a time (objects, clusters)
- Cluster based on distance, surface area of new cluster, and overall size.
- Build a bounding volume hierarchy over clusters.
- Build a grid for leaves of hierarchy.
- Subdivide these grids if too many objects.

Hierarchical Grid Differences

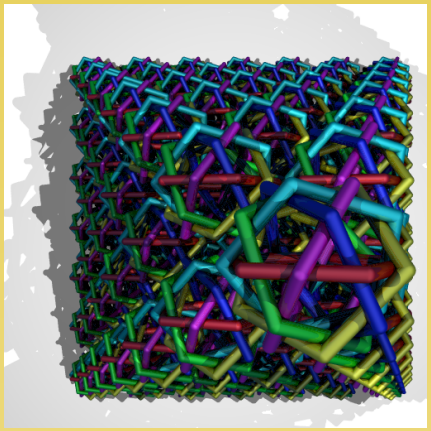
- Recursive grids cannot overlap, others can, so each nested grid tested only once.
- HUG requires mail boxes for traversal using grids as objects.
- Ray traversal very similar but the BVH must be traversed for adaptive grids.
- data from http://www.acm.org/tog/resources/ RT-News/html/rtnv12n1.html#art3

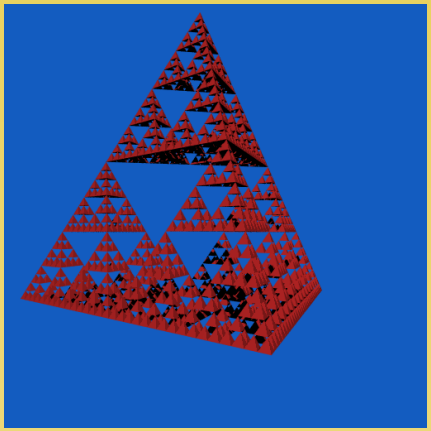
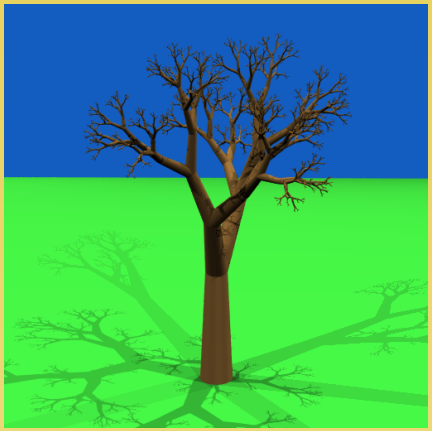
Hierarchical Grid Comparison (startup)

	balls	gears	lattice	mount
Uniform - D = 1.0	0.19	0.38	0.38	0.26
Uniform - D = 20.0	0.39	1.13	1.27	0.4
Recursive	0.39	5.06	0.16	1.98
HUG	0.4	1.04	0.3	0.16
Adaptive	2.79	5.88	0.6	2.54

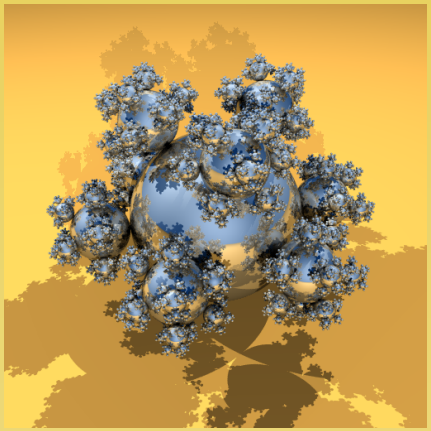
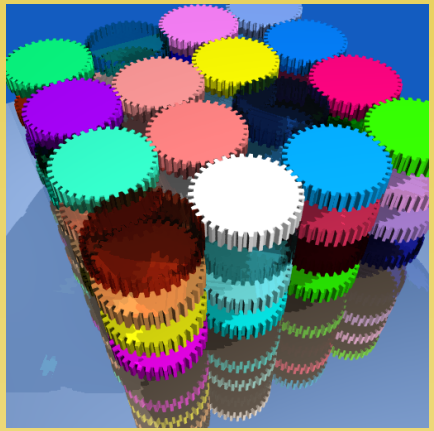
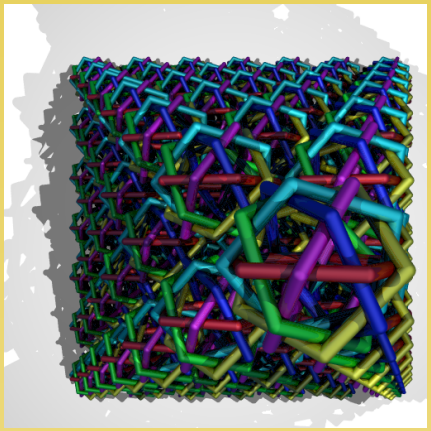
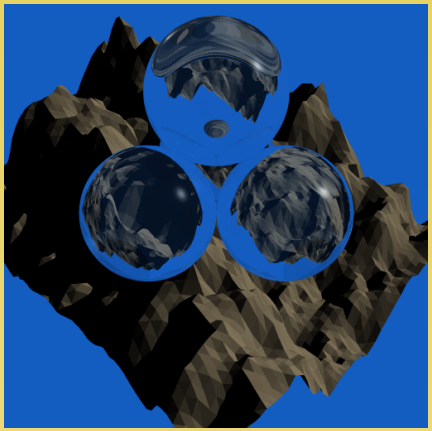
Hierarchical Grid Comparison (startup)



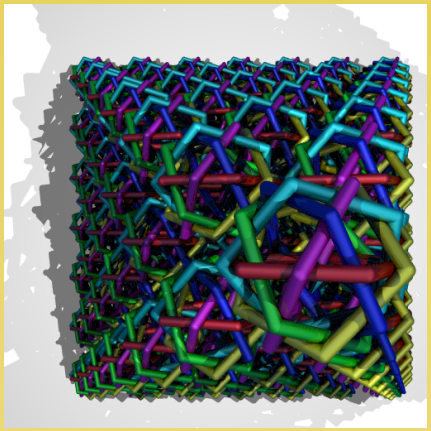
	rings	teapot	tetra	tree
Uniform - D = 1.0	0.35	0.3	0.13	0.22
Uniform - D = 20.0	0.98	0.65	0.34	0.33
Recursive	0.39	1.55	0.47	0.28
HUG	0.45	0.53	0.24	0.48
Adaptive	1.82	3.16	1.19	1.46

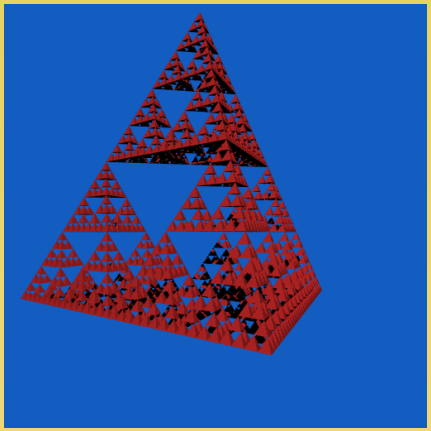
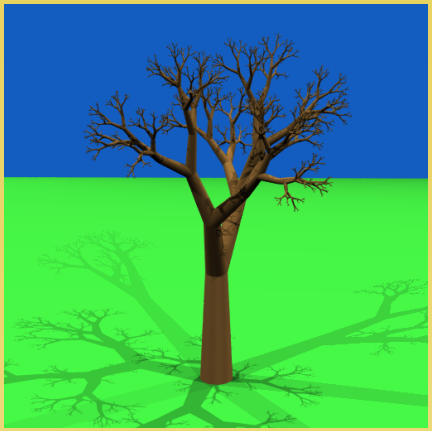
Hierarchical Grid Comparison

	balls	gears	lattice	mount
Uniform - D = 1.0	244.7	201.0	54.68	28.99
Uniform - D = 20.0	38.52	**192.3**	**34.21**	**25.15**
Recursive	36.73	214.9	82.05	30.28
HUG	34.0	242.1	71.62	62.31
Adaptive	**30.51**	330.0	129.6	59.05

Hierarchical Grid Comparison



	rings	teapot	tetra	tree
Uniform - D = 1.0	129.8	28.68	5.54	1517.0
Uniform - D = 20.0	**83.7**	**18.6**	**3.86**	781.3
Recursive	113.9	22.67	7.23	33.91
HUG	116.3	25.61	7.22	33.48
Adaptive	167.7	43.04	8.71	**18.38**

KD Trees

Java Demo Snagged from

http://www.rolemaker.dk/nonRoleMaker/uni/algogem/kdtree.htm

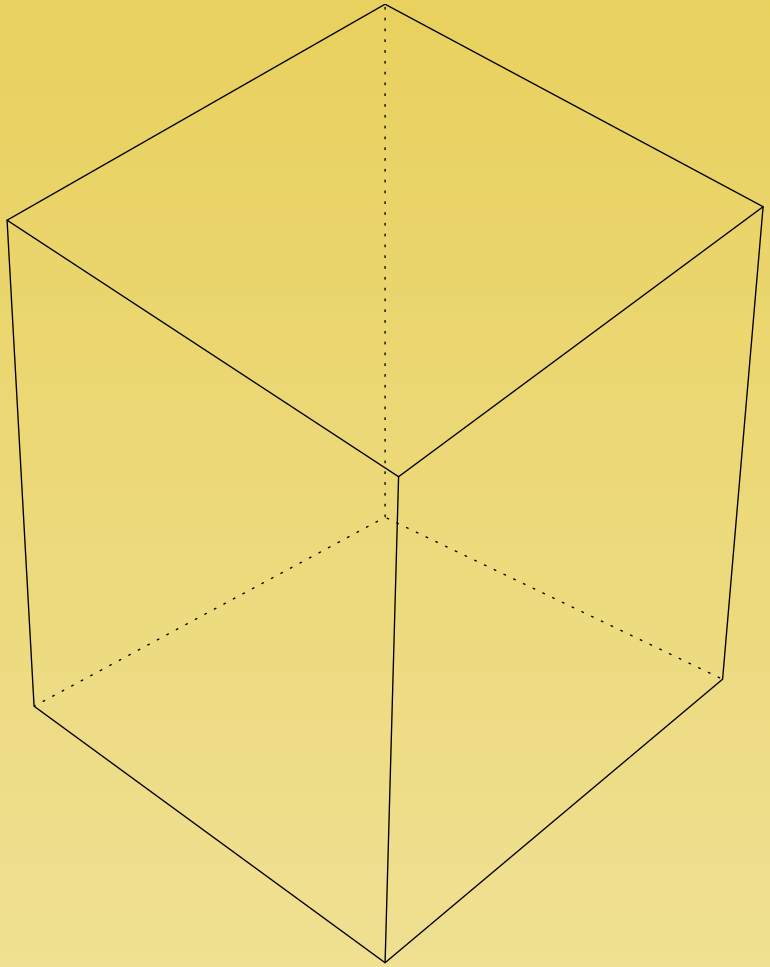
BSP Trees

Java Demo Snagged from
http://symbolcraft.com/graphics/bsp/index.html
http://graphics.lcs.mit.edu/ jcyang/6.838/pset2/

Nonuniform vs Uniform Subdivision

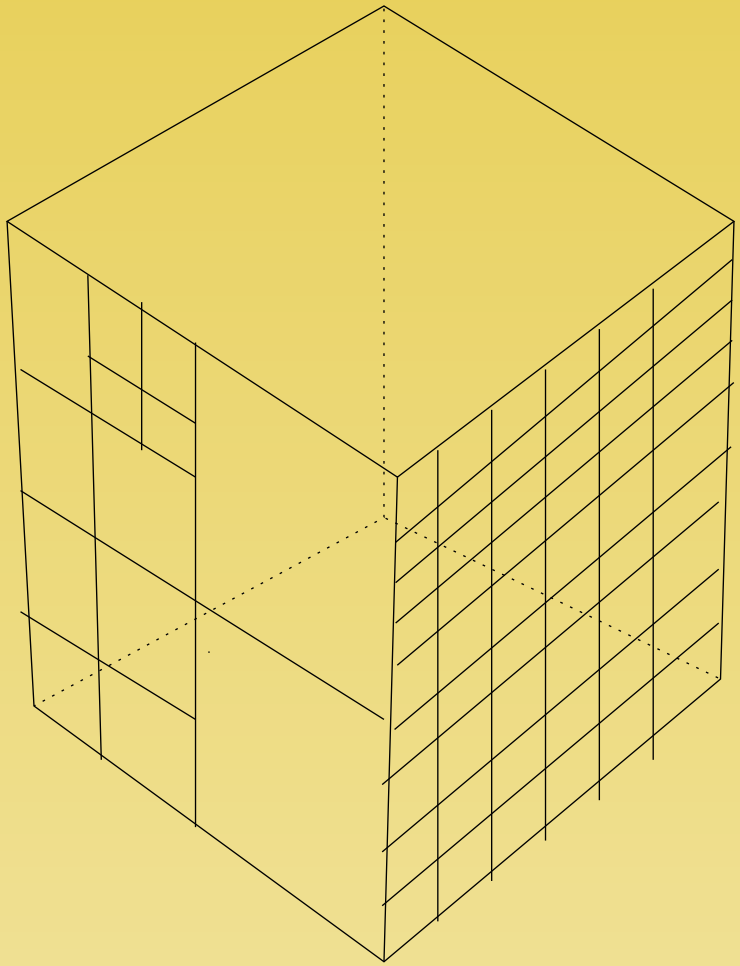
- How does finding next voxel compare?
- Which has more empty voxels?
- Are empty voxels bad?
- Teapot in a stadium.

Directional Technigues



A Ray eminating from the center will pierce one face!

Directional Technigues



- Light Buffer - Haines and Greenburg (1986).
- Ray Coherence - Ohta and Maekawa (1987).
- Ray Classification - Arvo and Kirk (1987).

Light Buffer

- Do we care which object occludes a light ray?

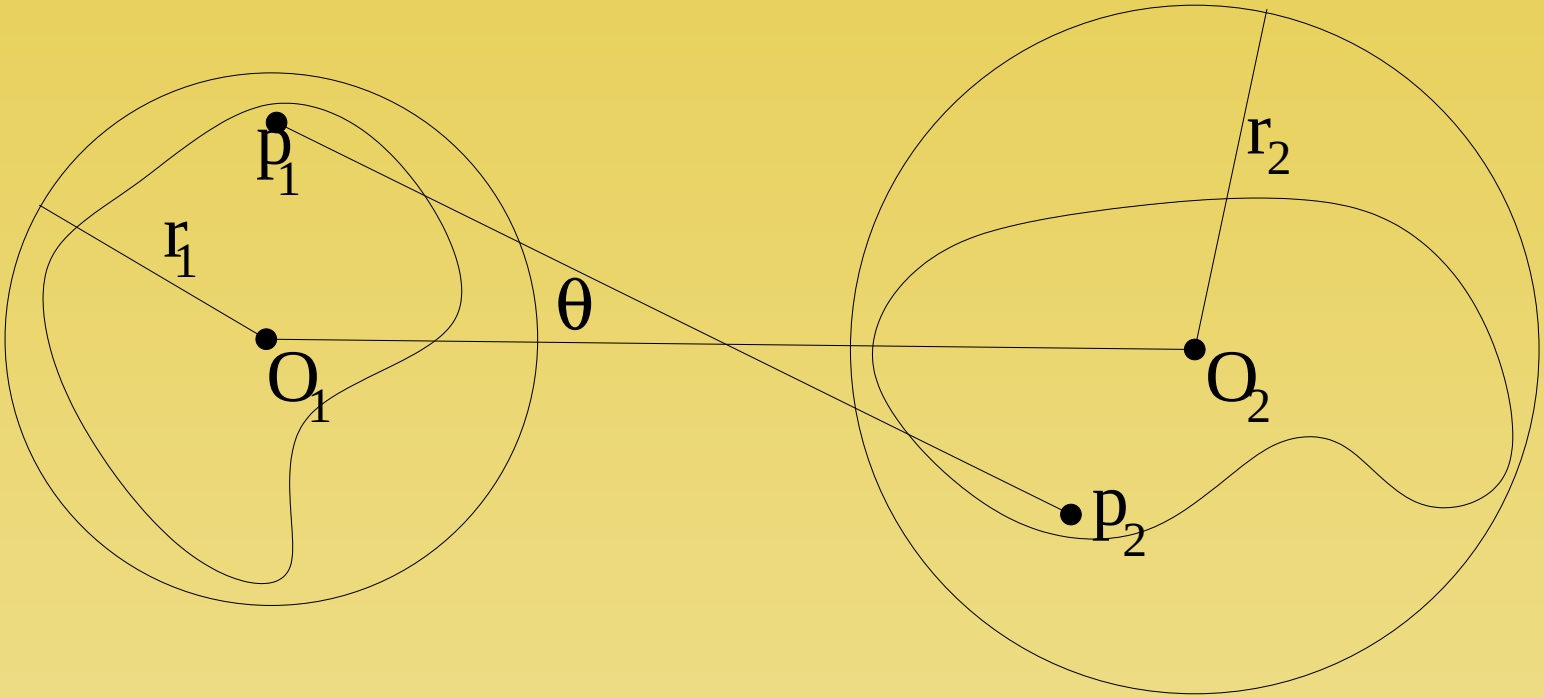
Light Buffer

- Do we care which object occludes a light ray?
- How did you do the test in your ray tracer?

Light Buffer

- Do we care which object occludes a light ray?
- How did you do the test in your ray tracer?
- How could we use the direction information?

Ray Coherence



$$cos\theta > \sqrt{\left(1 - \frac{r_1 + r_2}{||O_1 - O_2||}\right)}$$

Ray Coherence

- Make a direction cube for all ray origins (lights, eye, reflective surface, refractive surface).

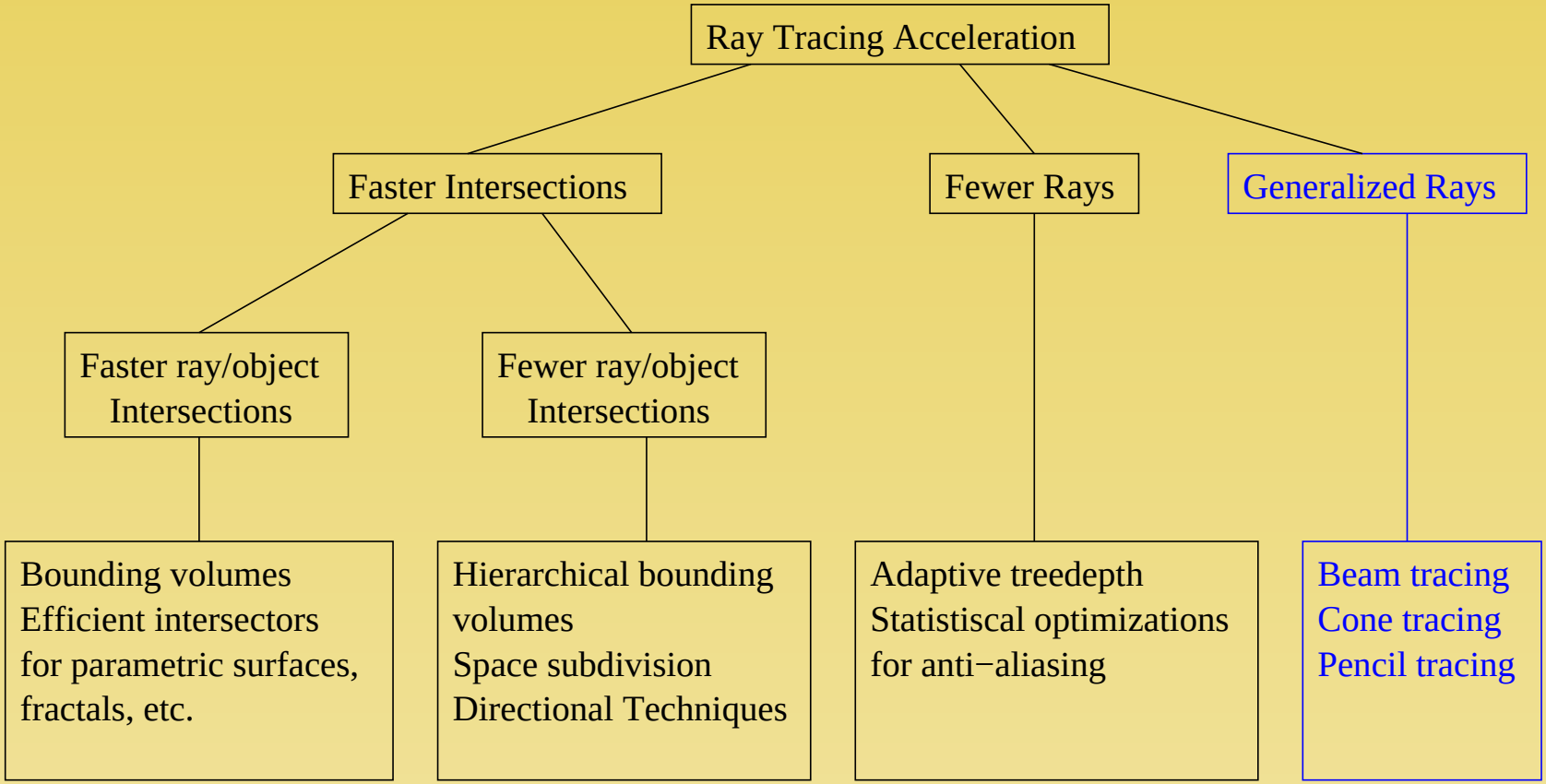
Ray Classification

- Subdivide *Ray space instead of object space.*
- *Gives 5D hypercubes*
- *Given a ray, only objects in its hypercube can possibly be intersected.*
- *No traversal of object space required.*

Coherence

- Object
- Image (viewing dependent object)
- ray coherence similar rays intersect similar objects.
- frame coherence (image + temporal)
- spatial, temporal.

Ray Tracing Acceleration Classification



Generalized Rays

- Better anti-aliasing.
- Exploiting coherency.
- Gains: speed, anti-aliasing, effects
- Lose: flexibility (primitive types), approximation to intersection.

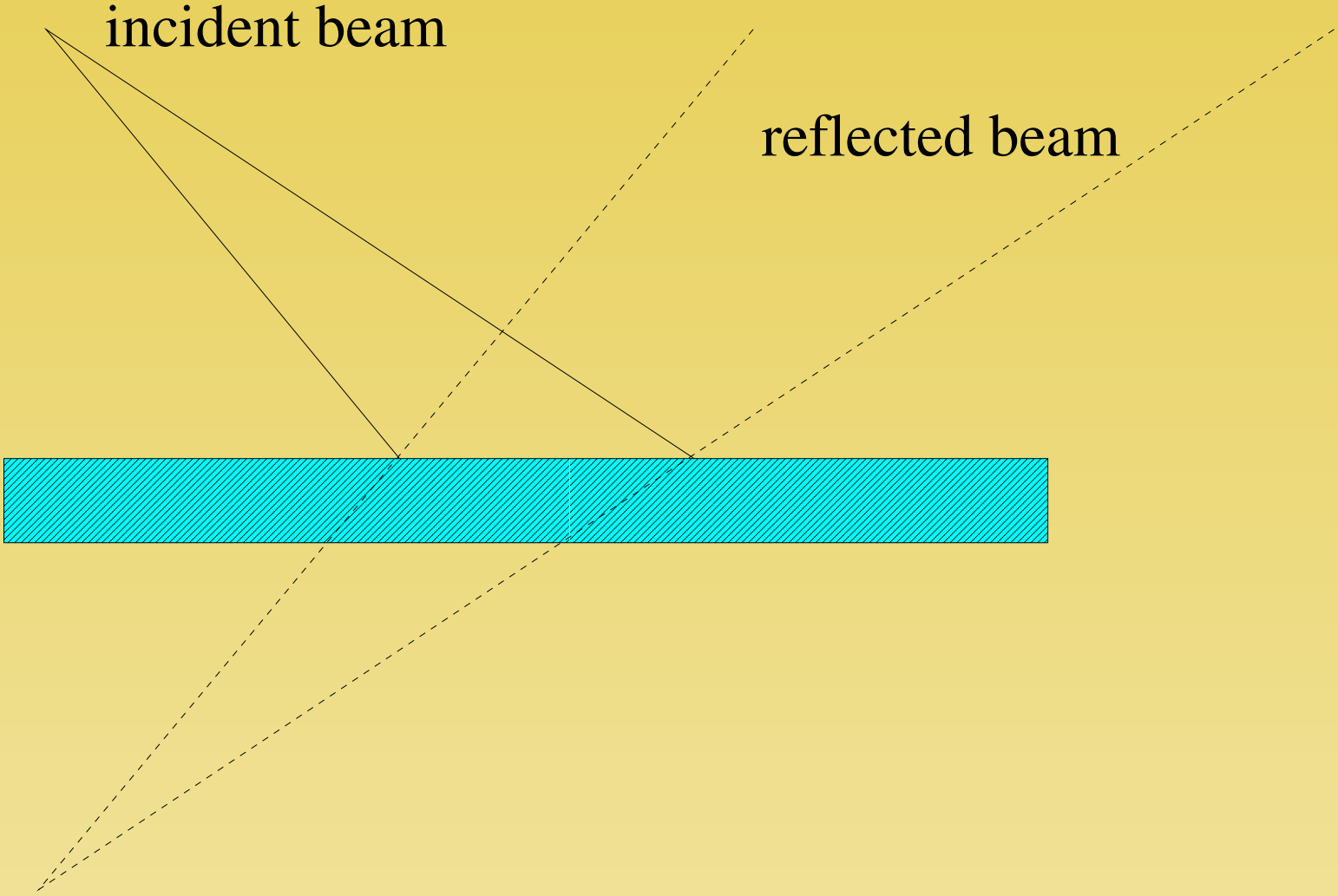
Cone Tracing - Amanatides (1984)

- Ray are generalized as right circular cones, apex, center line, and spread angle.
- Detect intersections and % of cone blocked.
- Maintain list of closest intersections to combine partial intersections.
- New center line for reflections/refractions uses normal, but apex and angle uses curvature.
- Only allows spheres, planes, and polygons.
- Will do penumbrae.

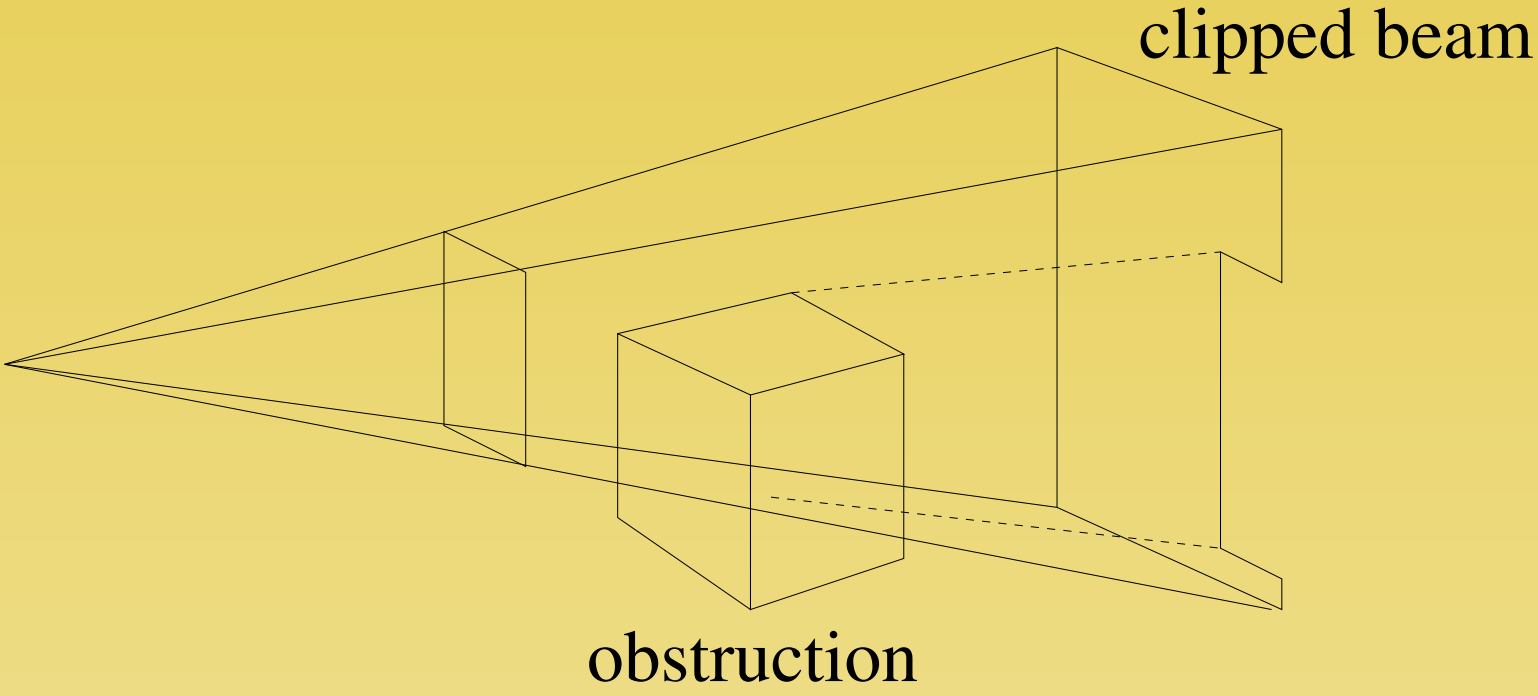
Beam Tracing

- Heckbert and Hanrahan (1984)
- Why trace an infinitesimally thin ray?
- Why not take advantage of ray coherence (almost parallel rays close together will most likely hit the same objects)?
- Based on the Weiler-Atherton hidden surface removal algorithm.

Beam Tracing



Beam Tracing



Beam Tracing

- Only works for polygonal objects.
- Beams that only partially intersect objects become complex.
- Refraction is nonlinear so beam geometry not preserved, must be approximated.
- It is more efficient.
- Produces better quality.
- Can combine with volume hierarchies and spatial subdivision.

Pencil Tracing - Shinya *et al. (1987)*

- Reference rays (axial ray)
- Nearby rays (paraxial rays) form the pencil - 4D vectors in a coordinate system of the axial ray.
- Uses paraxial approximation theory (from optical design) to trace ray.
- Pencil transformations are linear (4x4 matrices)
- Erorr analysis gives max spread angle of pencil.
- Requires smooth surfaces.

Rasterization-based Approximations

- Use rasterization to compute frames.
- Add special effects with ray tracing.
- Approximation so shows artifacts.
- Assumes ray tracing slower.

Image-based Approximation

- Approximate new frames from old frame.
- Add new information with ray tracing as time allows.
- Great for static scenes.
- Artifacts for dynamic scenes.

Ray Tracing-based Approximation

- Try to reduce the cost per pixel with approximations.
- Adaptive sampling (pixel-selected ray tracing: color interpolation in image space for regions with smooth changes in color. Only image regions with high contrast are sample at high rates.
- Interpolate in ray space with error bounds.

Accelerating ray tracing.

- BSP-trees, octrees, hierarchical grids, bounding volume hierarchies, hybrids.
- New methods deal with running on newer hardware, which doesn't deal well with recursion.
- Parallel techniques (load balancing, latency hiding, reduced comm.)
- Hardware implementation.

Frustum Culling

- remove bounding volumes that are outside the viewing frustum.
- Good for space partitioning?

First hit speedup

Use some form of visibility algorithm such as Z-buffer. Assumes it is faster than ray casting.

Selective ray tracing of certain objects.

Parallel Rendering

- Raytracing is a ridiculously parallel algorithm.
- Through each pixel at a different processor.
- Scales nicely, limited by load balancing and synchro-nization
- Can employ frameless rendering.

Interactive Ray Tracing

- Logarithmic on number of primitives.
- Flexible
- More realism
- Shading done only after visibility.
- Parallel scalability.

Questions

- Which is faster? Ray-tracing or rasterization?

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