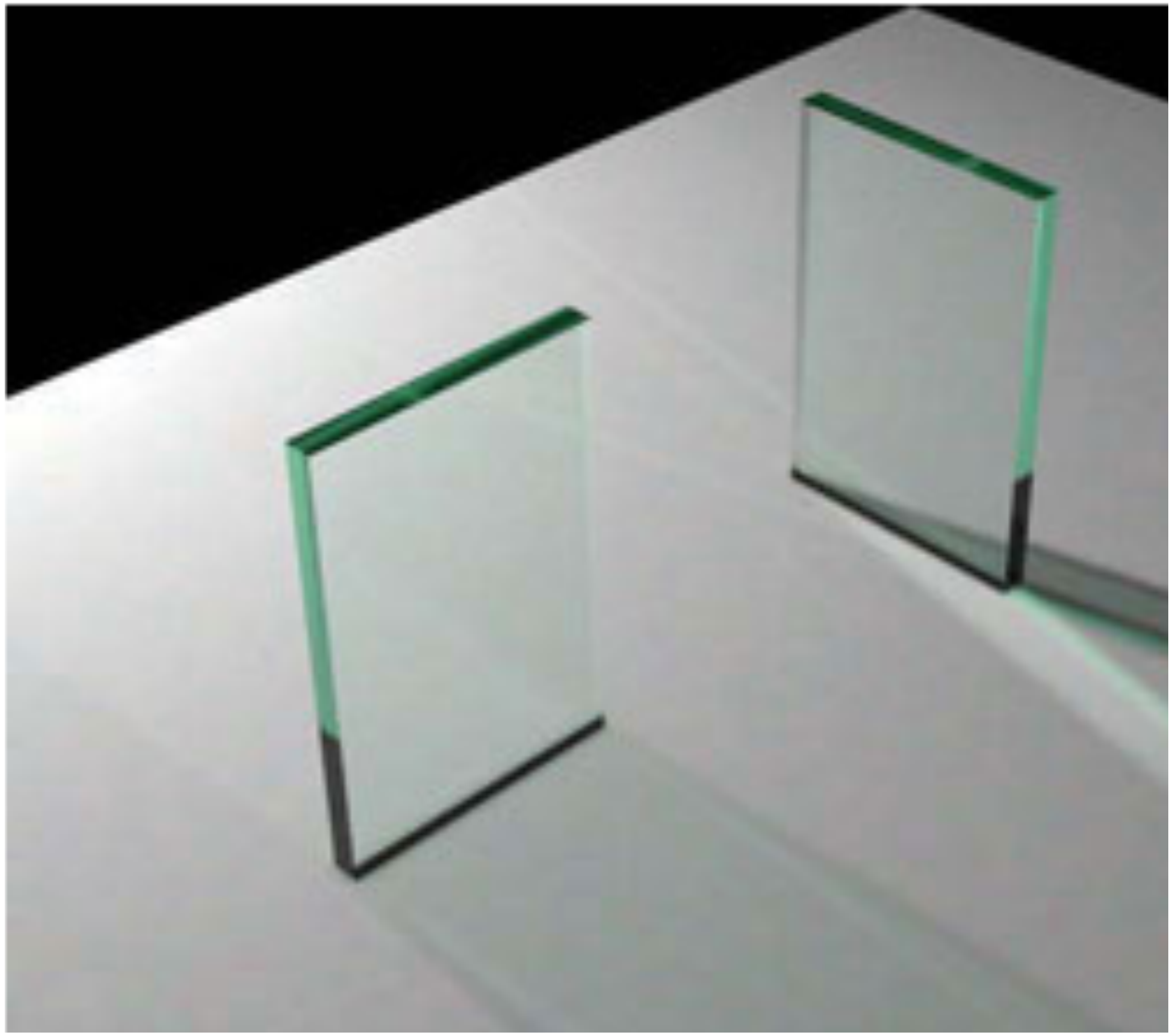

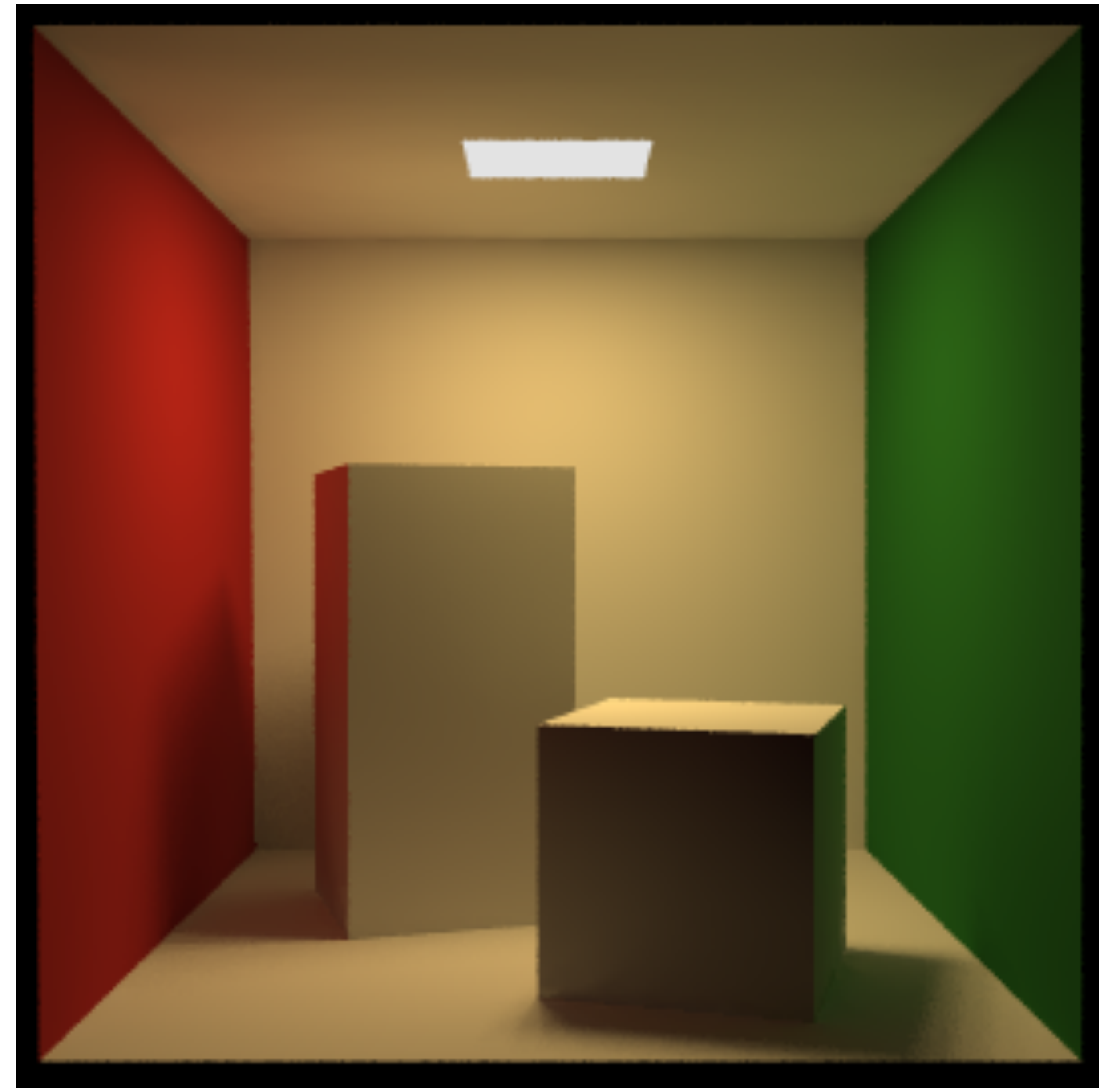

Computer Graphics

Lecture 11

Acceleration Structures

Advanced Ray Tracing

Announcements

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- Feedback survey out this afternoon - please respond by Monday night (10pm)

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- Feedback survey out this afternoon - please respond by Monday night (10pm)
- A1 grading should be done by Monday.
- Final projects - proposals will be due in ~2 weeks; start thinking about topics now. More on this later.

Today

- A high-level overview of what comes next in ray tracing.
- Useful for A2 extensions and/or final project ideas.
- Not getting into gory detail -
  see the book references on the slides.

Barycentric ray-triangle intersection

- Every point on the plane can be written in the form:

  $$\mathbf{a} + \beta(\mathbf{b} - \mathbf{a}) + \gamma(\mathbf{c} - \mathbf{a})$$

  for some numbers β and γ.
- If the point is also on the ray then it is

  $$\mathbf{p} + t\mathbf{d}$$

  for some number t.
- Set them equal: 3 linear equations in 3 variables

  $$\mathbf{p} + t\mathbf{d} = \mathbf{a} + \beta(\mathbf{b} - \mathbf{a}) + \gamma(\mathbf{c} - \mathbf{a})$$

  …solve them to get t, β, and γ all at once!

Barycentric ray-triangle intersection

$$\mathbf{p} + t\mathbf{d} = \mathbf{a} + \beta(\mathbf{b} - \mathbf{a}) + \gamma(\mathbf{c} - \mathbf{a})$$

$$\beta(\mathbf{a} - \mathbf{b}) + \gamma(\mathbf{a} - \mathbf{c}) + t\mathbf{d} = \mathbf{a} - \mathbf{p}$$

$$\begin{bmatrix} \mathbf{a} - \mathbf{b} & \mathbf{a} - \mathbf{c} & \mathbf{d} \end{bmatrix} \begin{bmatrix} \beta \\ \gamma \\ t \end{bmatrix} = \begin{bmatrix} \mathbf{a} - \mathbf{p} \end{bmatrix}$$

$$\begin{bmatrix} x_a - x_b & x_a - x_c & x_d \\ y_a - y_b & y_a - y_c & y_d \\ z_a - z_b & z_a - z_c & z_d \end{bmatrix} \begin{bmatrix} \beta \\ \gamma \\ t \end{bmatrix} = \begin{bmatrix} x_a - x_p \\ y_a - y_p \\ z_a - z_p \end{bmatrix}$$

- This is a linear system: Ax = b
- Various ways to solve, but a fast one uses *Cramer's rule*.
- See 4.4.2 for the TL;DR formula
- See 5.3.2 for an explanation of Cramer's rule

Ray tracing is expensive.

```
for each pixel:
  for each triangle:
    compute barycentric intersection
```

How expensive? Let's (informally) count some FLOPs.

floating-point operations

Last time: barycentric ray-triangle intersection

$$\mathbf{p} + t\mathbf{d} = \mathbf{a} + \beta(\mathbf{b} - \mathbf{a}) + \gamma(\mathbf{c} - \mathbf{a})$$

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9 subtractions

Pre-calculate entries and rename:

$$\begin{bmatrix} a & d & g \\ b & e & h \\ c & f & i \end{bmatrix} \begin{bmatrix} \beta \\ \gamma \\ t \end{bmatrix} = \begin{bmatrix} j \\ k \\ l \end{bmatrix}$$

Barycentric Ray-Triangle Intersection

Cramer's rule gives us

5 add/sub
10 mult/div

$$\beta = \frac{j(ei - hf) + k(gf - di) + l(dh - eg)}{M},$$

$$\gamma = \frac{i(ak - jb) + h(jc - al) + g(bl - kc)}{M},$$

$$t = -\frac{f(ak - jb) + e(jc - al) + d(bl - kc)}{M},$$

where

Reusing from above:
3 mult

$$M = a(ei - hf) + b(gf - di) + c(dh - eg).$$

Barycentric Ray-Triangle Intersection

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Total: 27 FLOPs

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Reusing from above:
3 mult

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Assume, conservatively that on average, we calculate β and determine that it doesn't intersect (because $\beta < 0$ or $\beta > 1$)

Ray tracing is expensive.

```
for each pixel:
  for each triangle:
    compute barycentric intersection
```

720p = 1280×720 = 921600 pixels

bunny: 114 triangles

27 flops

= 2,836,684,800

= 2.8 GFLOPs

A typical laptop can currently can do about 100-200 GFLOPS

gigaflops per second

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so what's the problem?

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computer game model: 40k triangles

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~= 1 TFLOP

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Want to render this for an interactive game?

Simply do this 30+ times per second.

What can we do?

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- Optimize the inner-inner loop: more efficient intersection routines

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these only go so far...

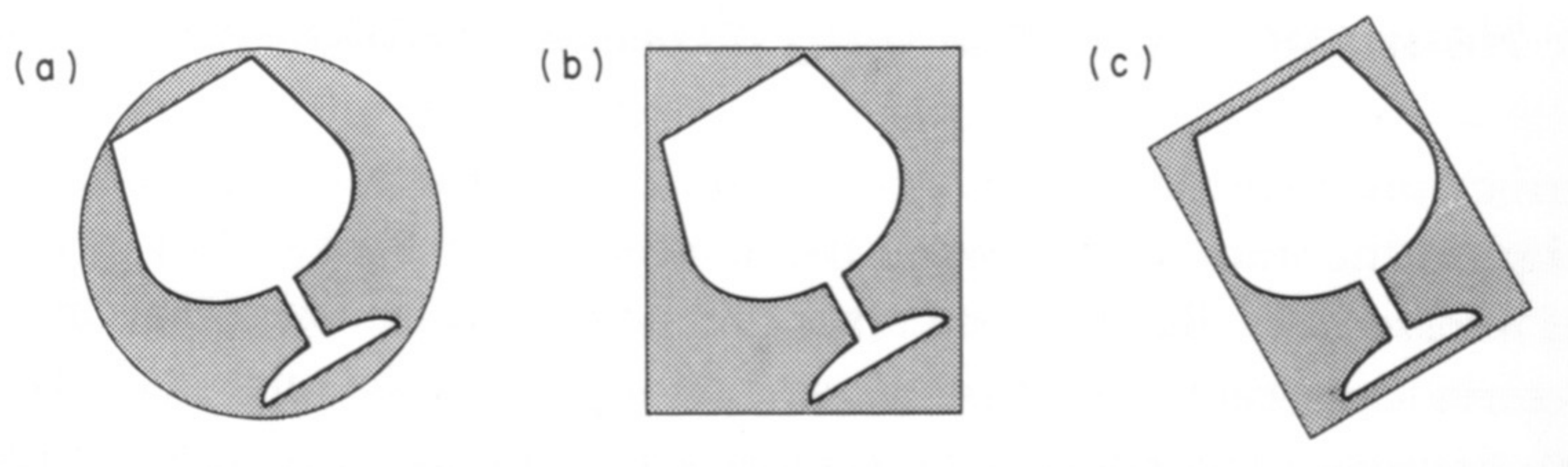
- Intersect fewer things

  - Most ray intersections don't hit the object!

  - Basic strategy: efficiently find big chunks of the scene that definitely **don't** intersect your ray

Bounding Volumes

- Quick way to avoid intersections: bound object with a simple volume
  - Object is fully contained in the volume
  - If it doesn't hit the volume, it doesn't hit the object
  - So test bvol first, then test object if it hits



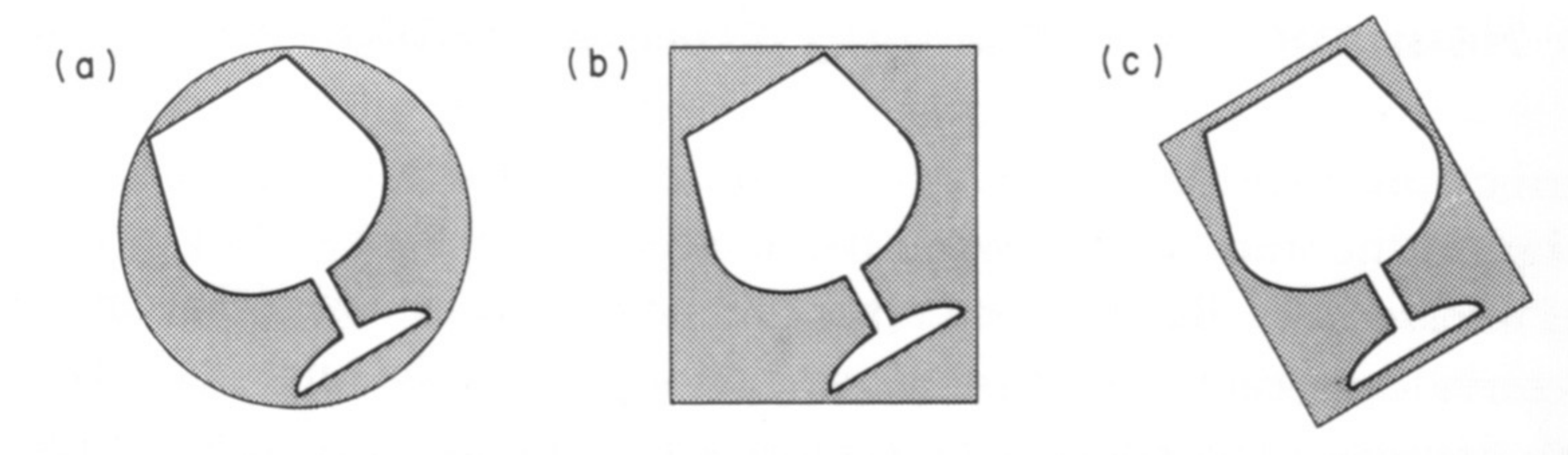
sphere axis-aligned box oriented box

[Glassner 89, Fig 4.5]

Bounding Volumes

Algorithm:

```
if ray intersects bounding volume:
    if ray intersects object:
        do stuff
```



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[Glassner 89, Fig 4.5]

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```

Cost: more for hits and near misses, but less for far misses

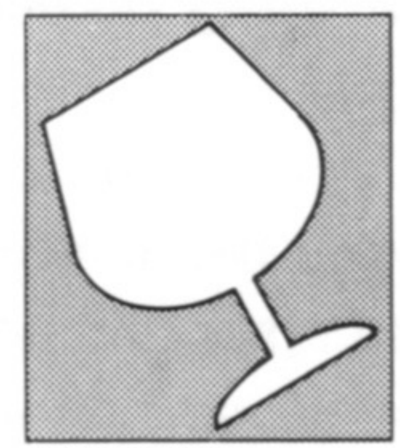
Is this worth it?

- bvol intersection should be much cheaper than object intersection
  - works best for simple bvols, complicated objects
- bvol should bound object as tightly as possible

Tradeoff: efficient intersection vs tightness

Bounding Volume Intersection

Exercise: In 2D, devise an algorithm to intersect a ray with an **axis-aligned bounding box**.



[Glassner 89, Fig 4.5]

axis-aligned box

Inputs:

- `ray (p and d)`
- `left_x`
- `right_x`
- `left_y`
- `right_y`

Output: boolean, whether ray hits box

Bounding Volumes

Algorithm:

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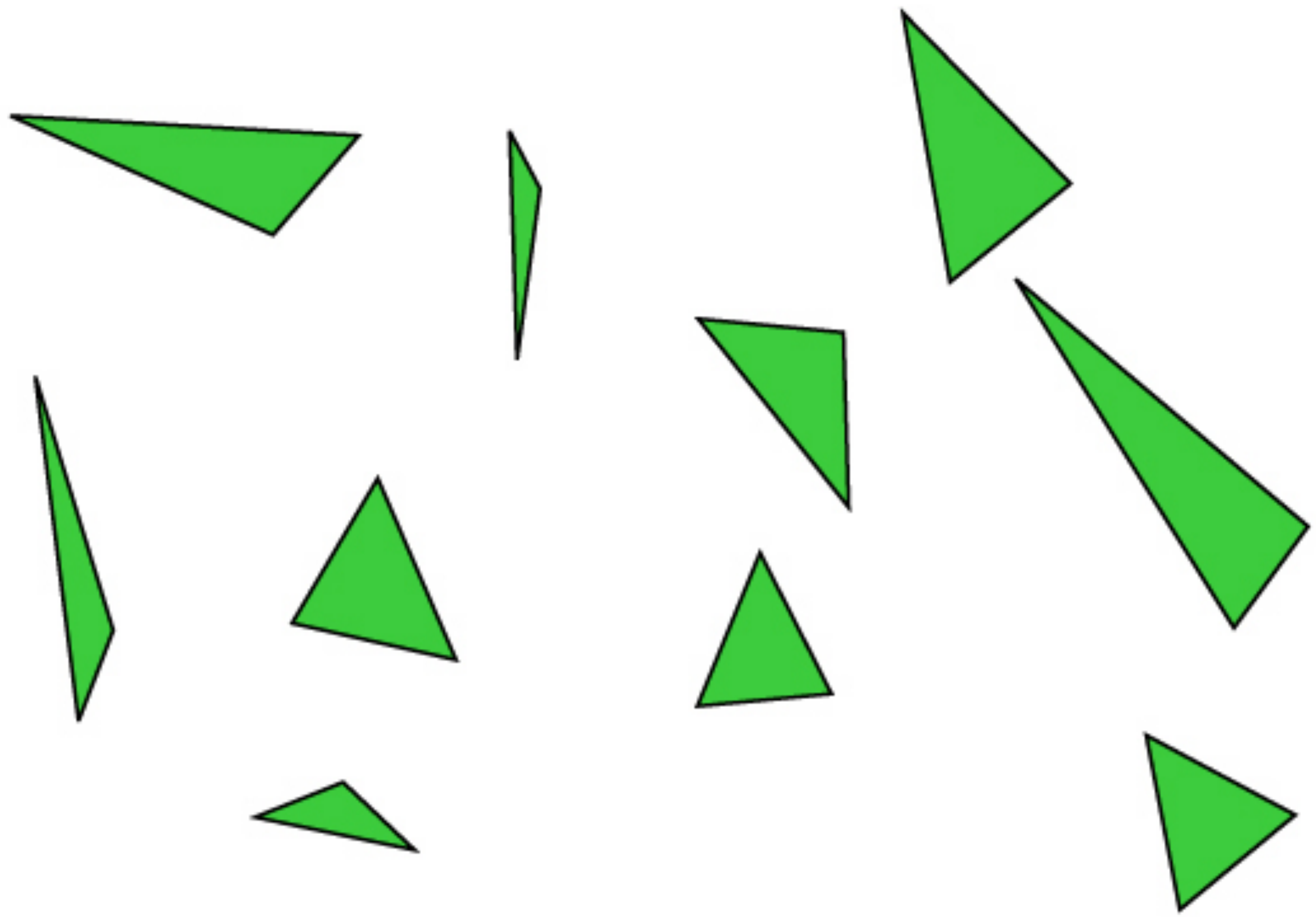
Bounding Volume Hierarchy

- Bvols around objects *might* help
- Bvols around groups of objects **will** help
- Bvols around parts of complex objects will help
- Idea: use bounding volumes all the way from the whole scene down to groups of a few objects

Building the Hierarchy

- Ideally: bound nearby clusters of objects
- Practical solution: partition along axis

BVH construction example



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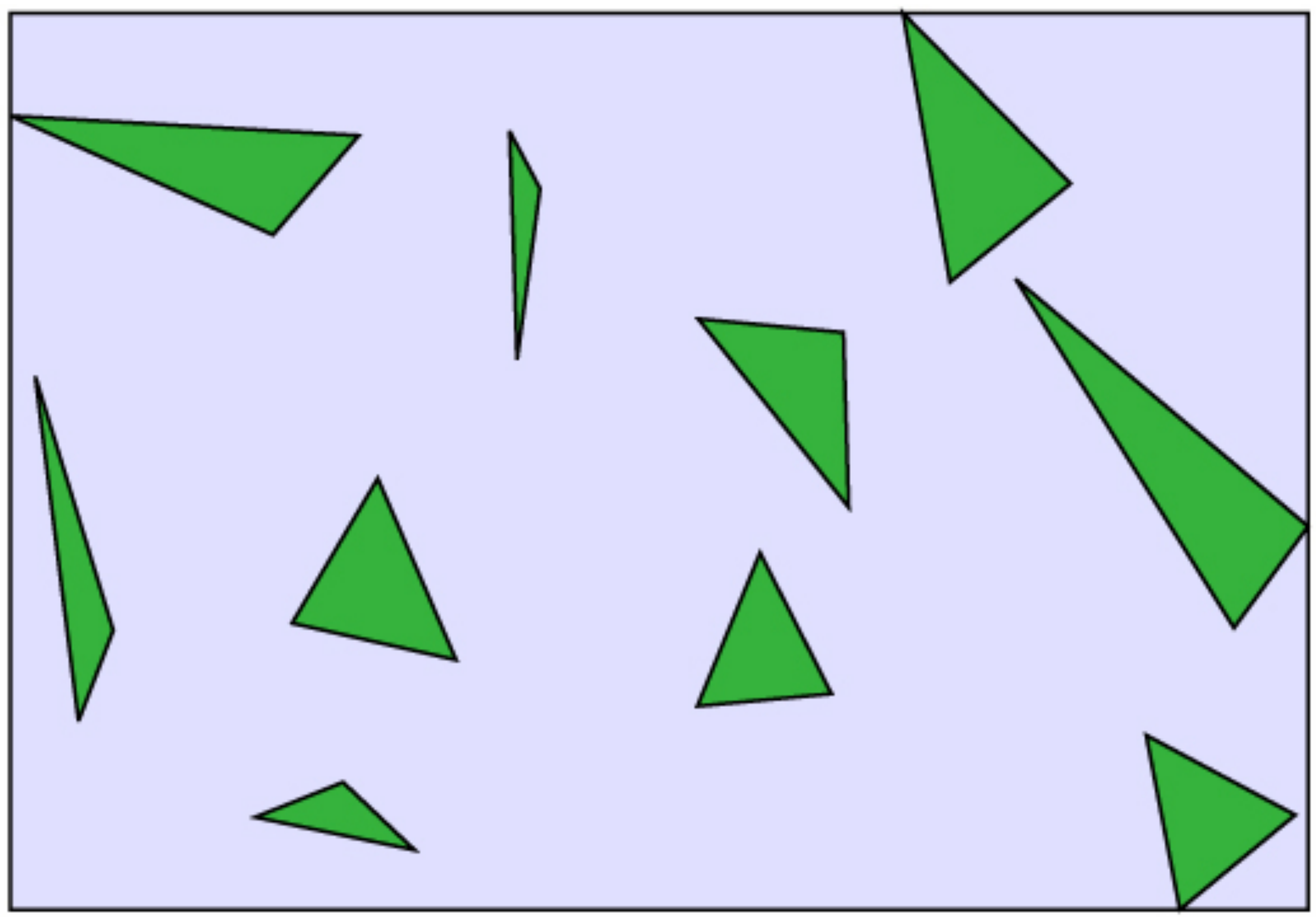

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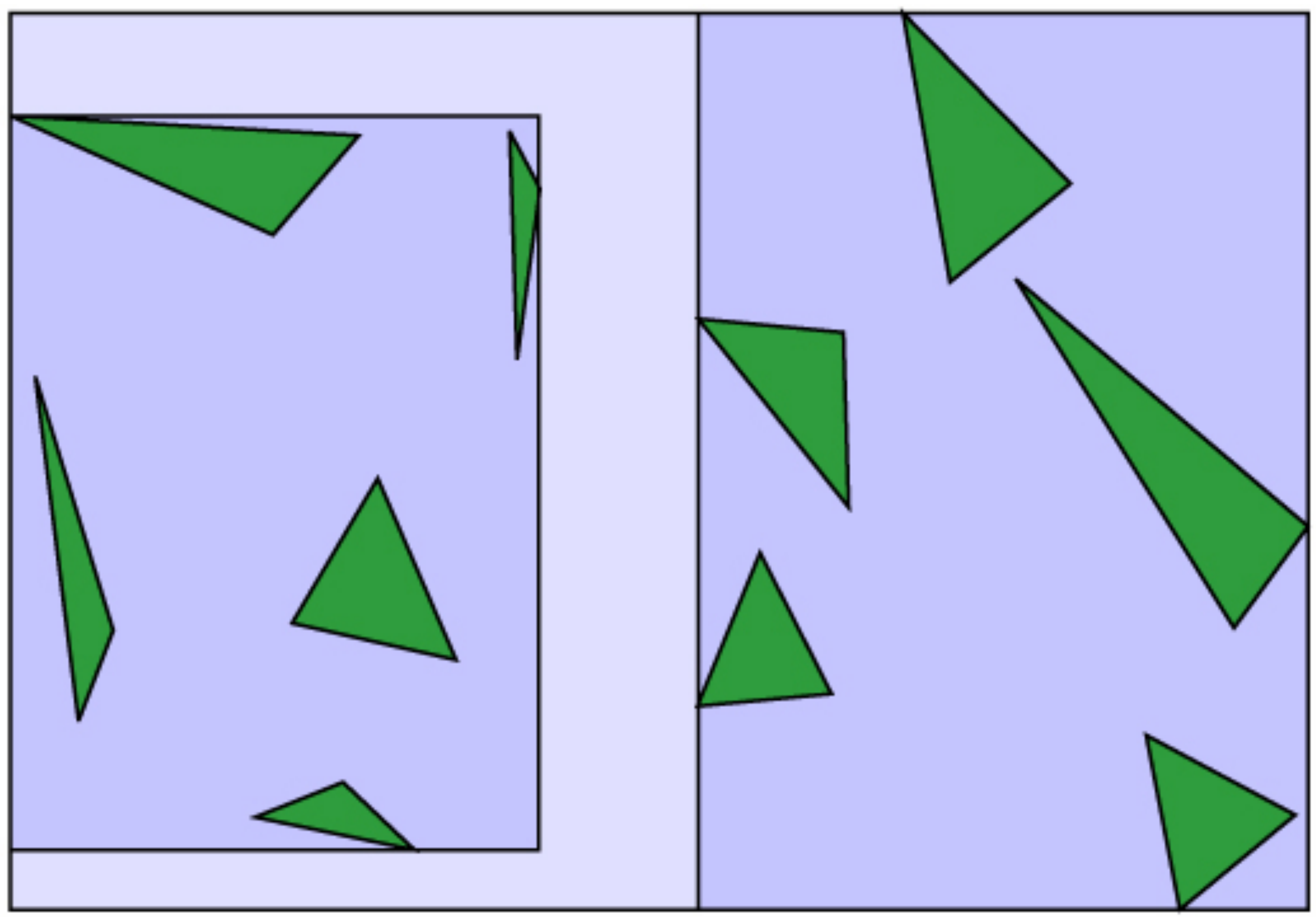

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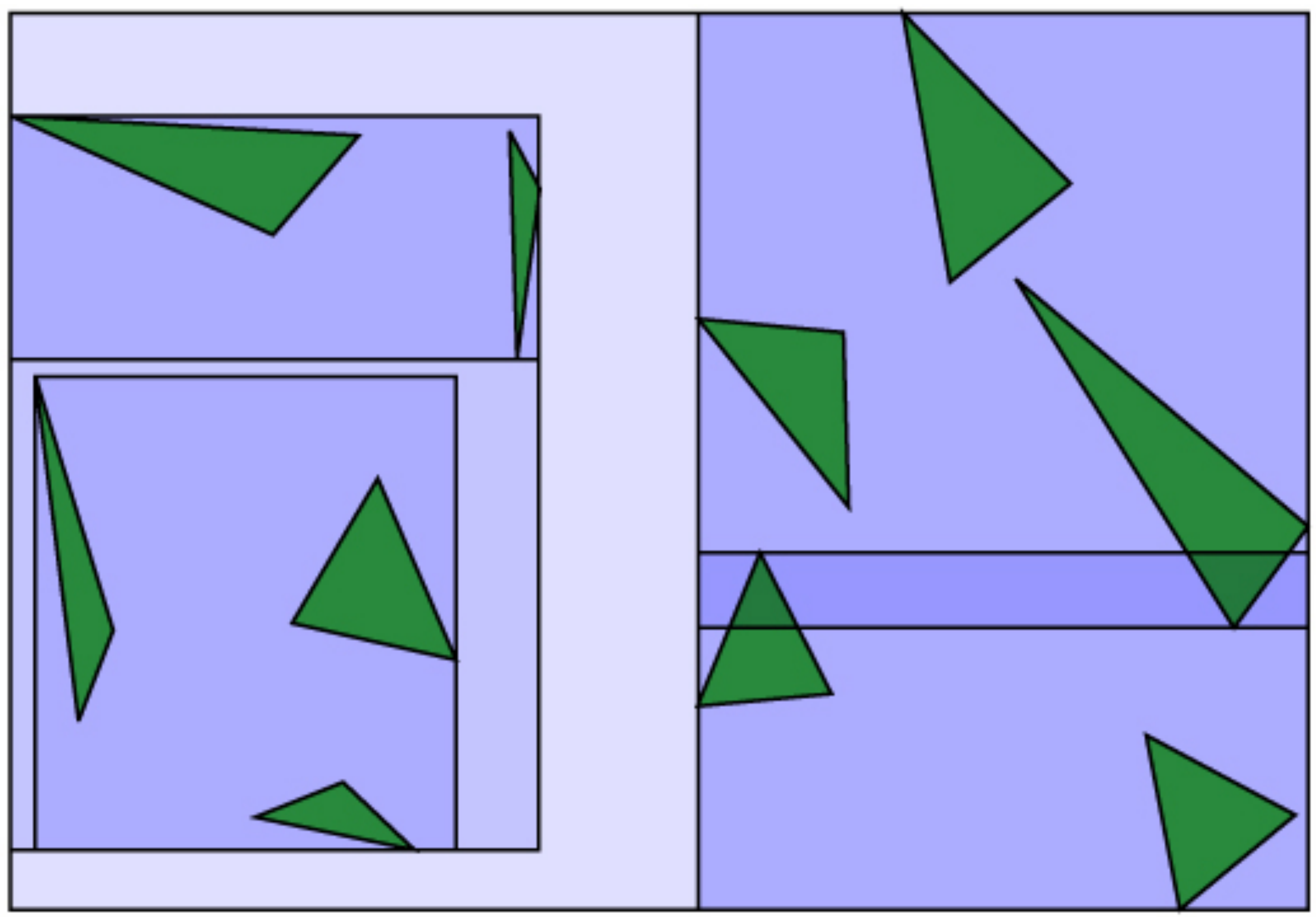
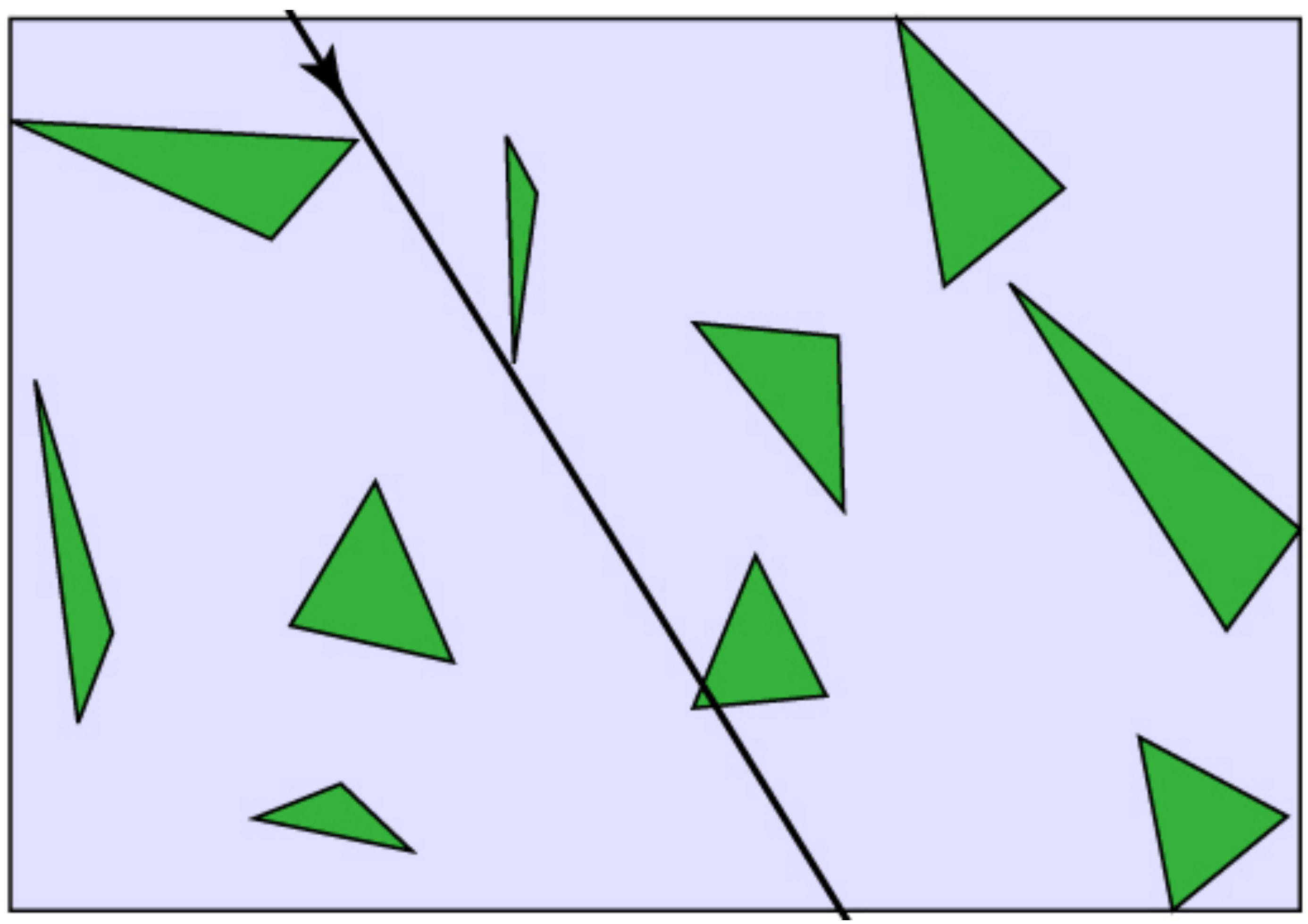


BVH ray-tracing example



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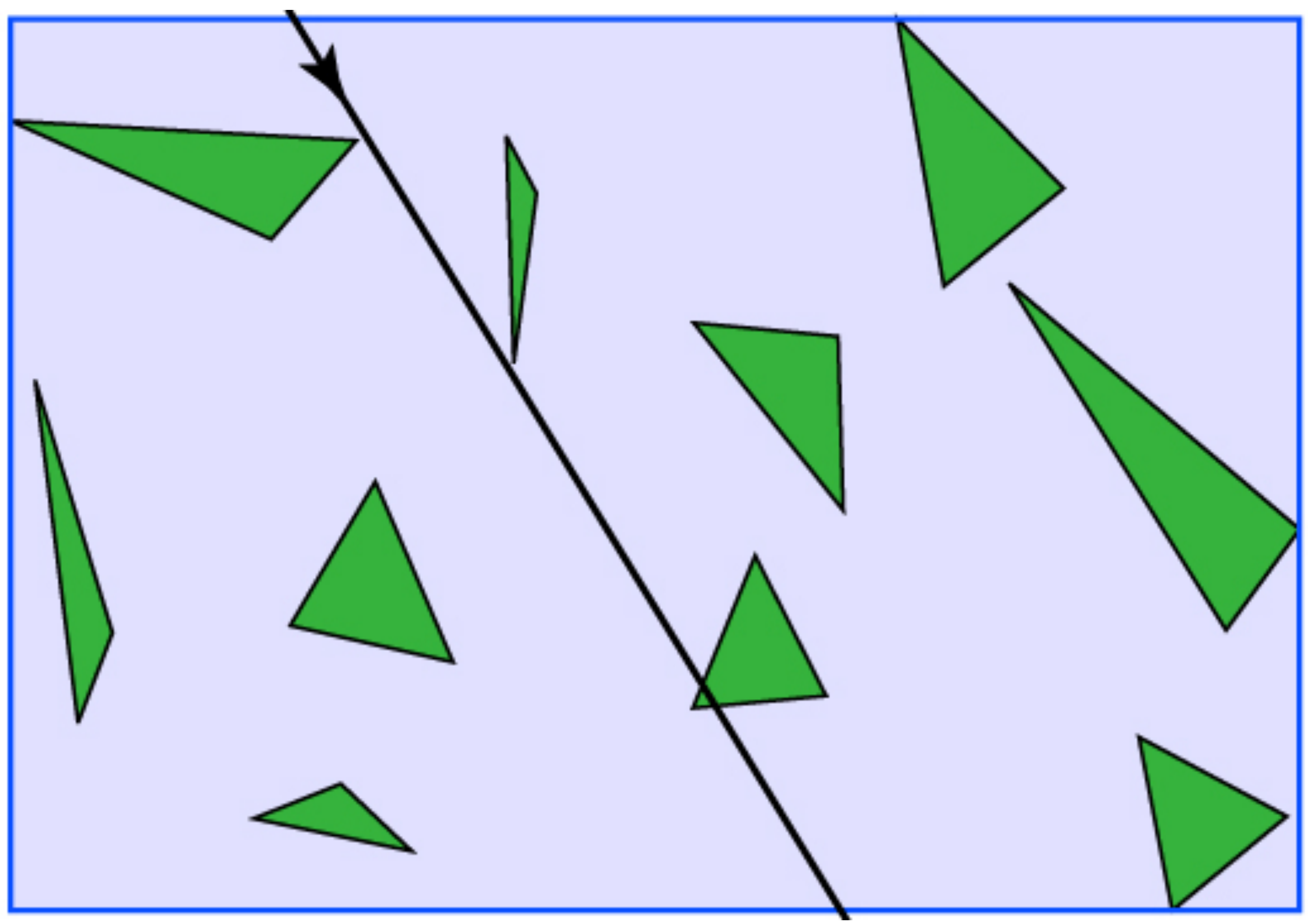

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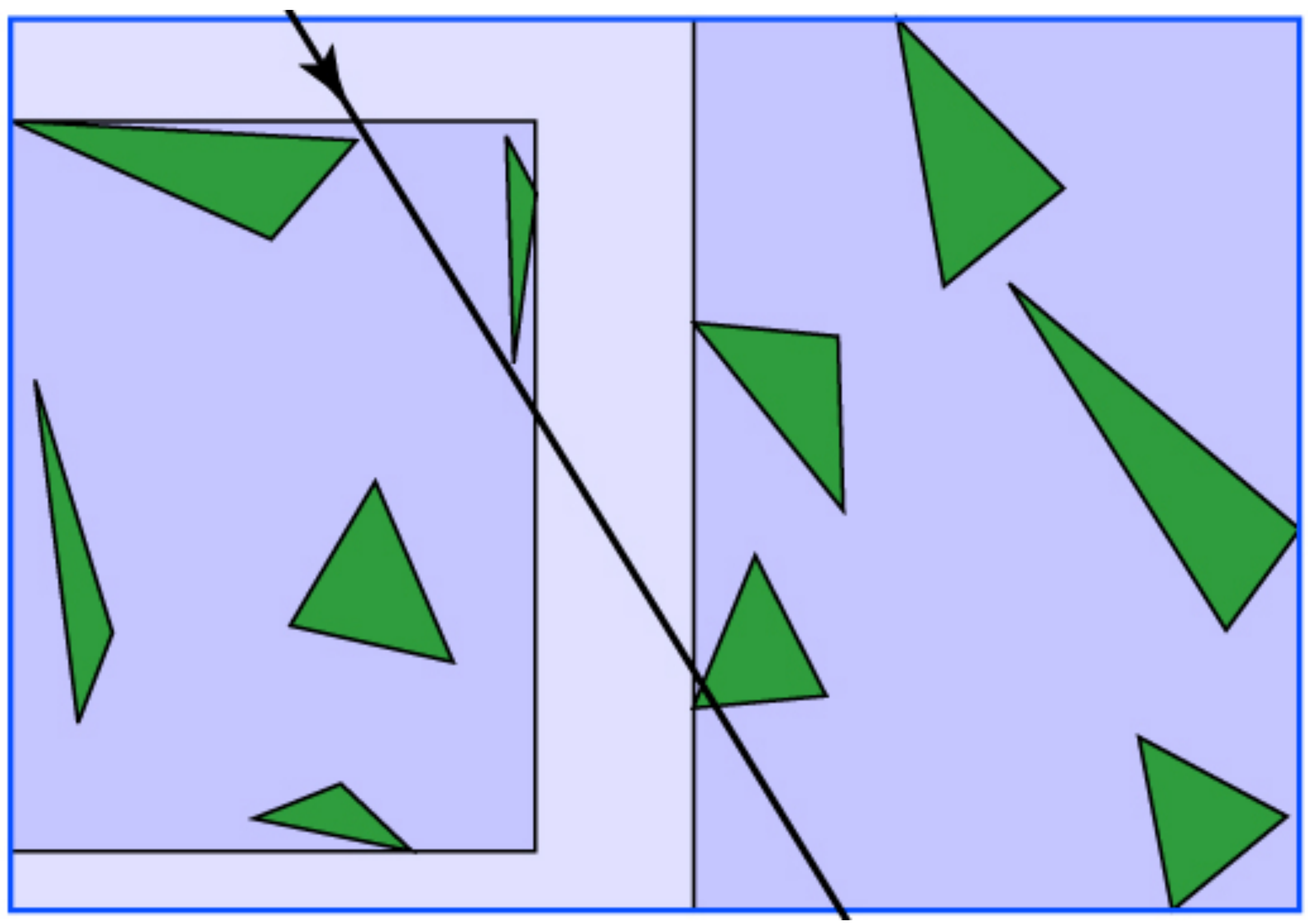

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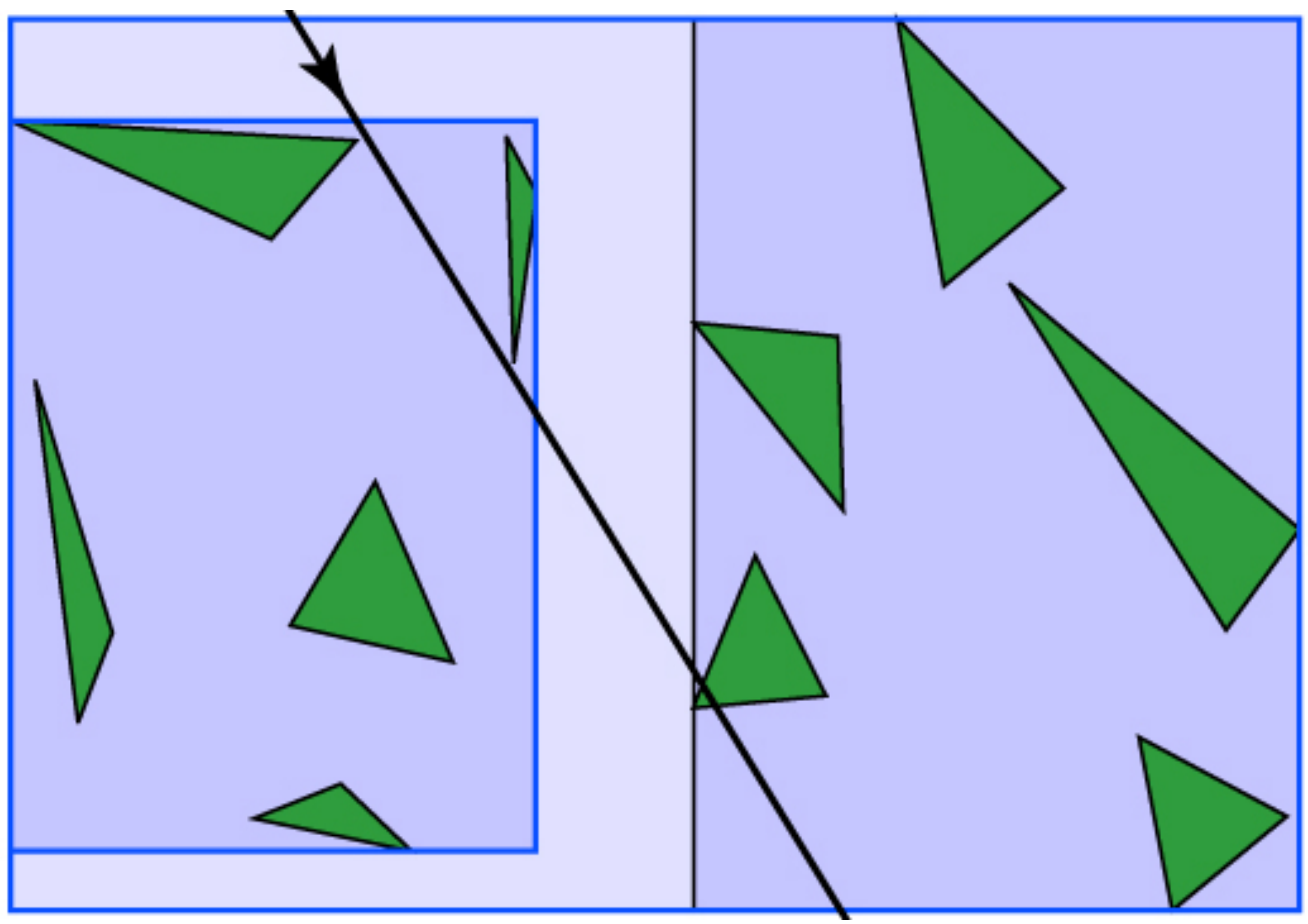

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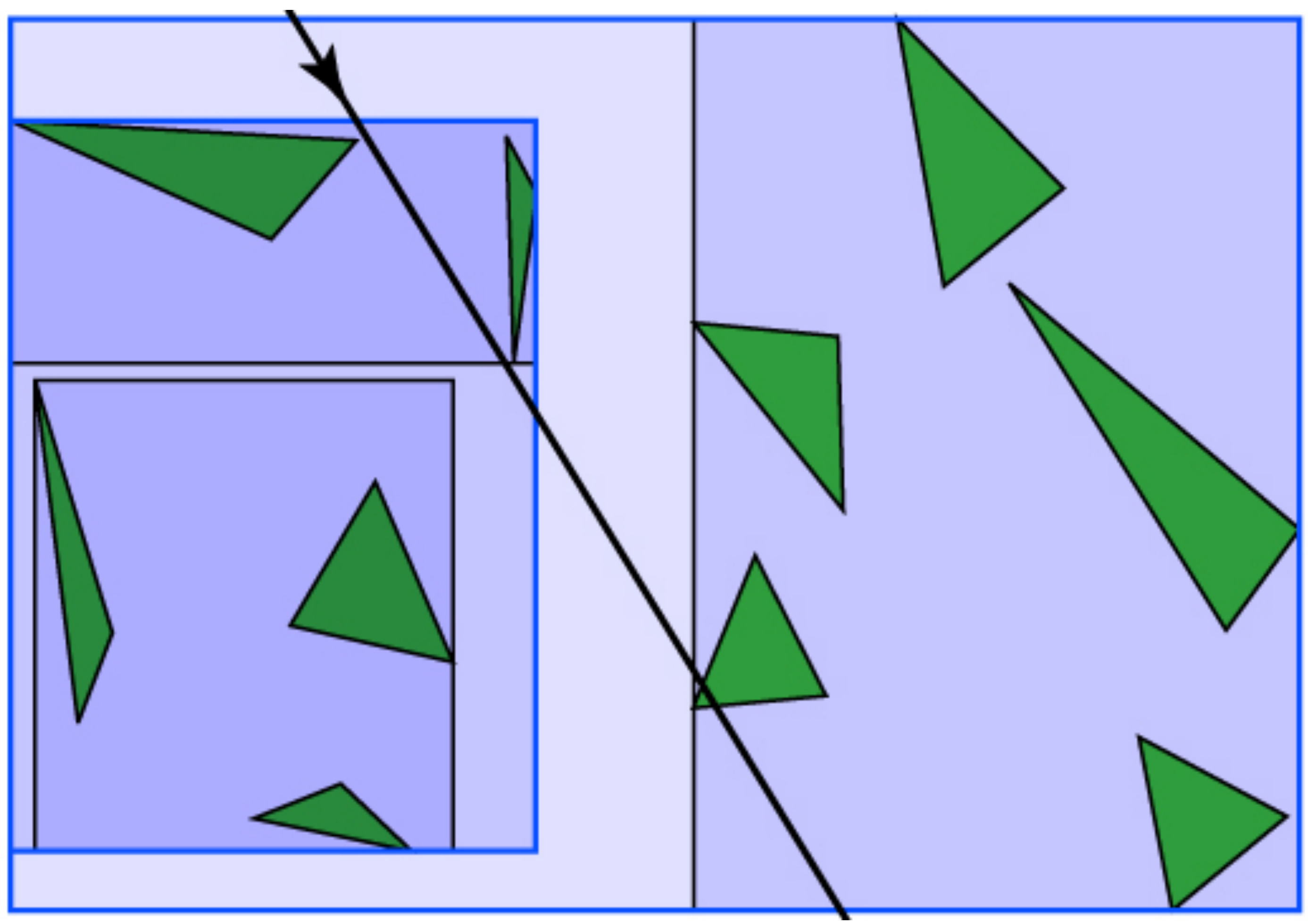

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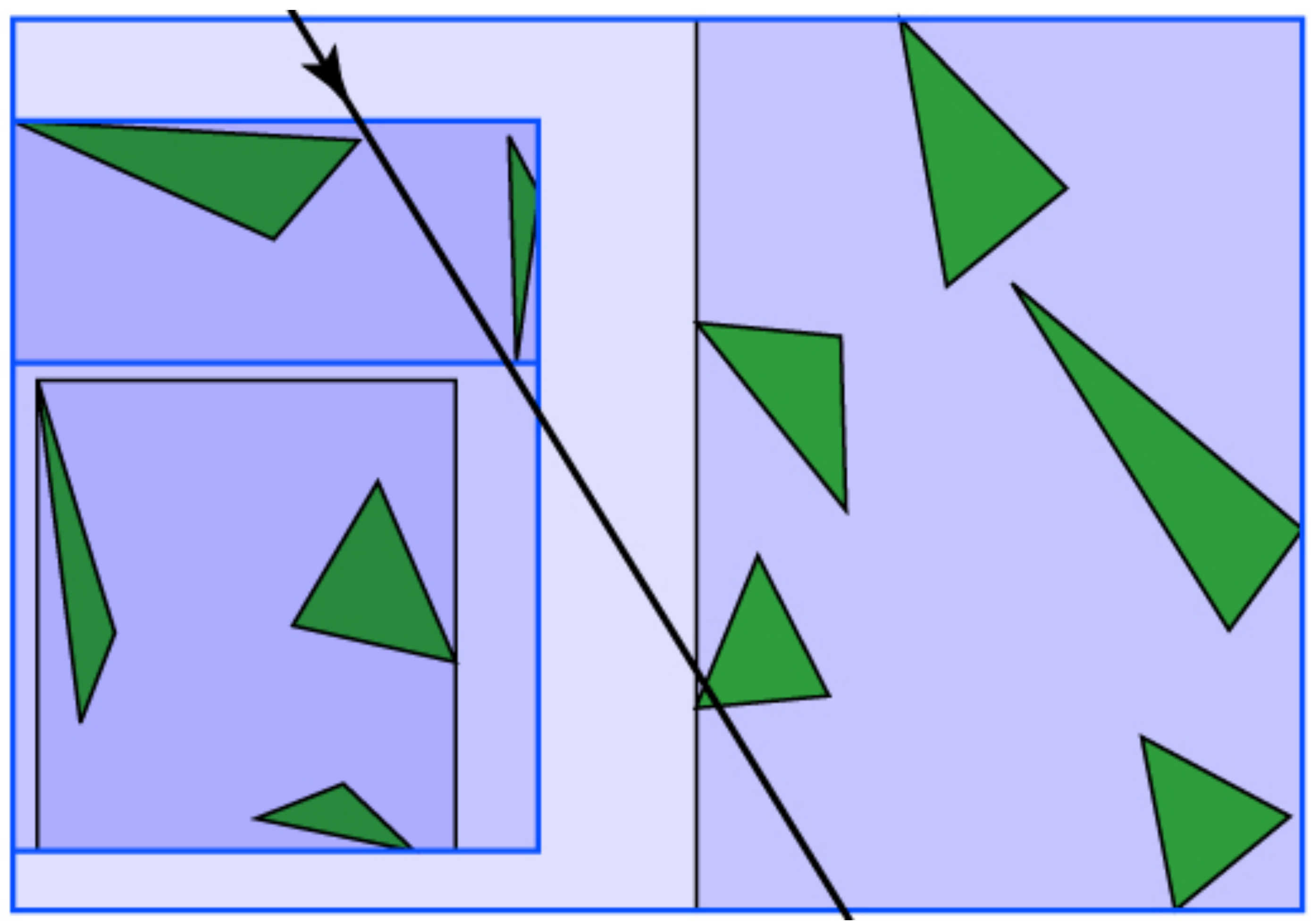

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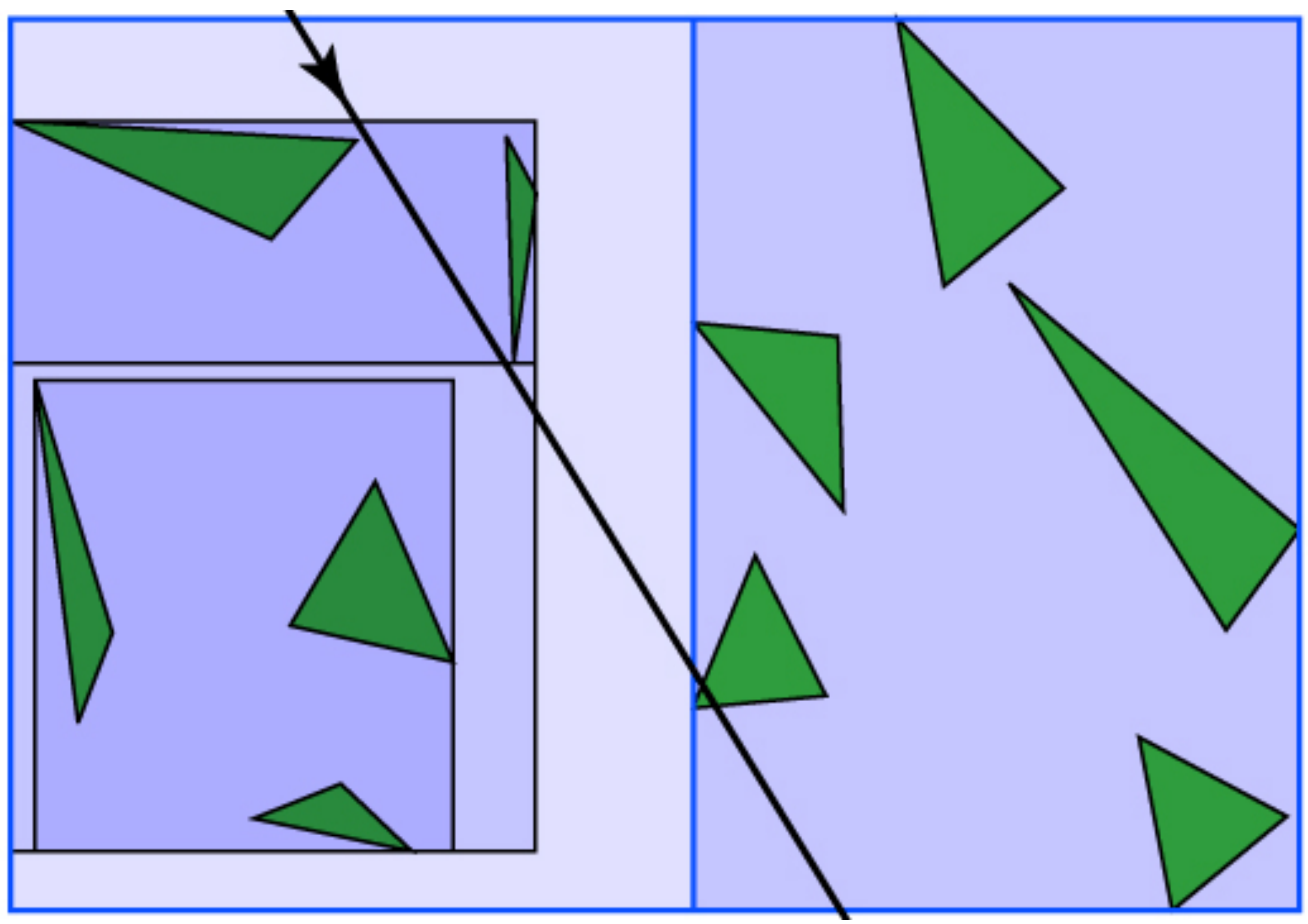

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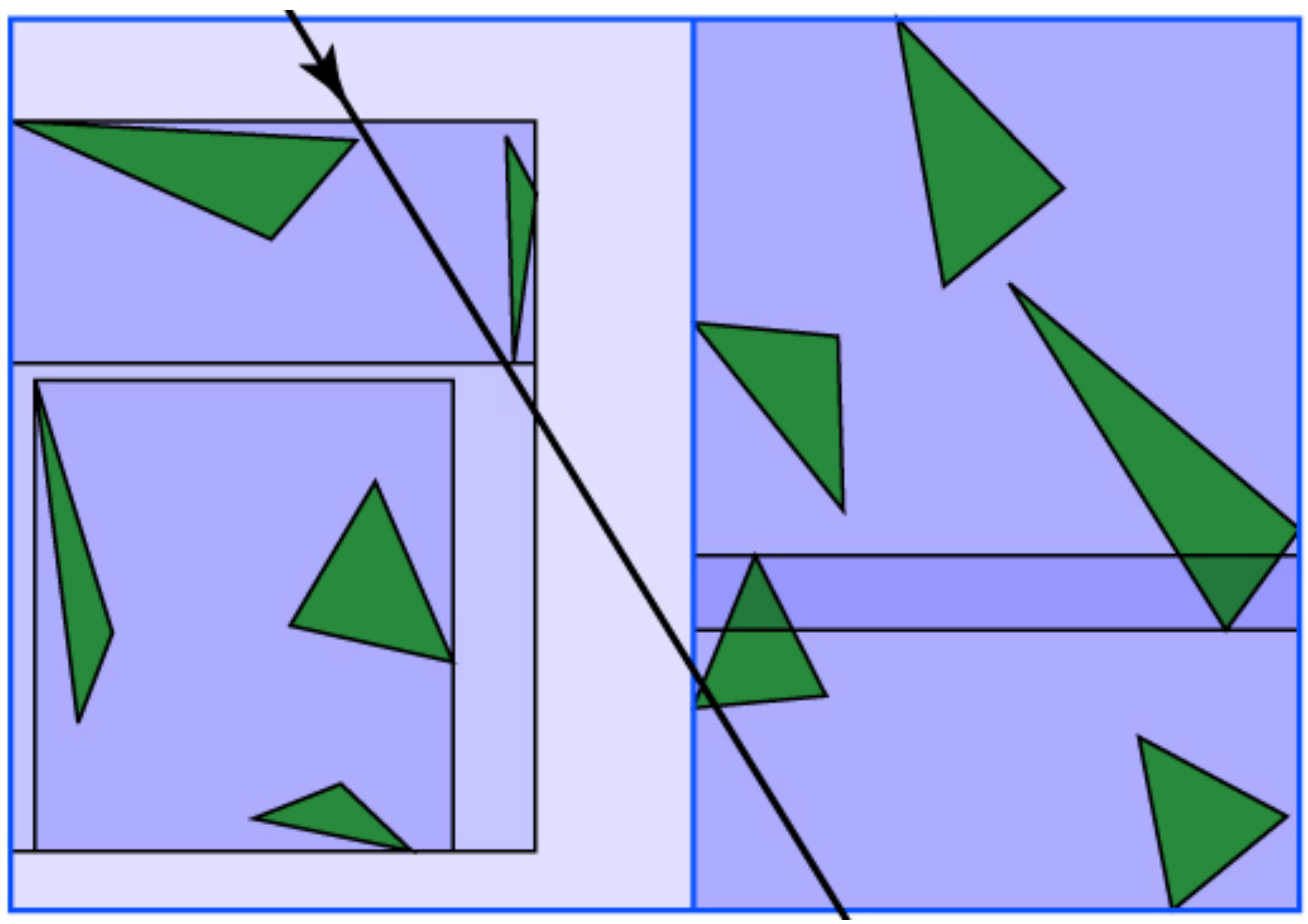

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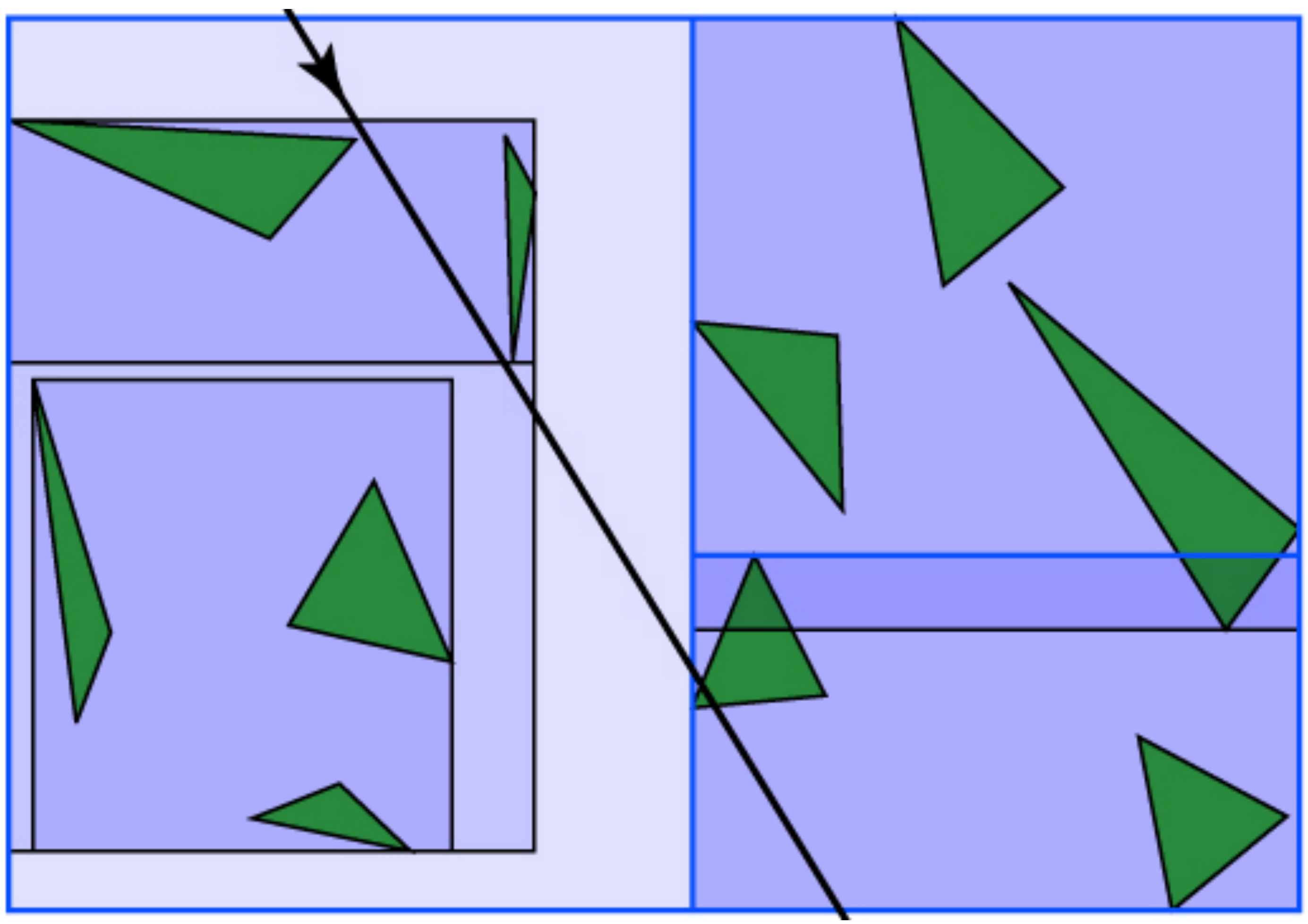

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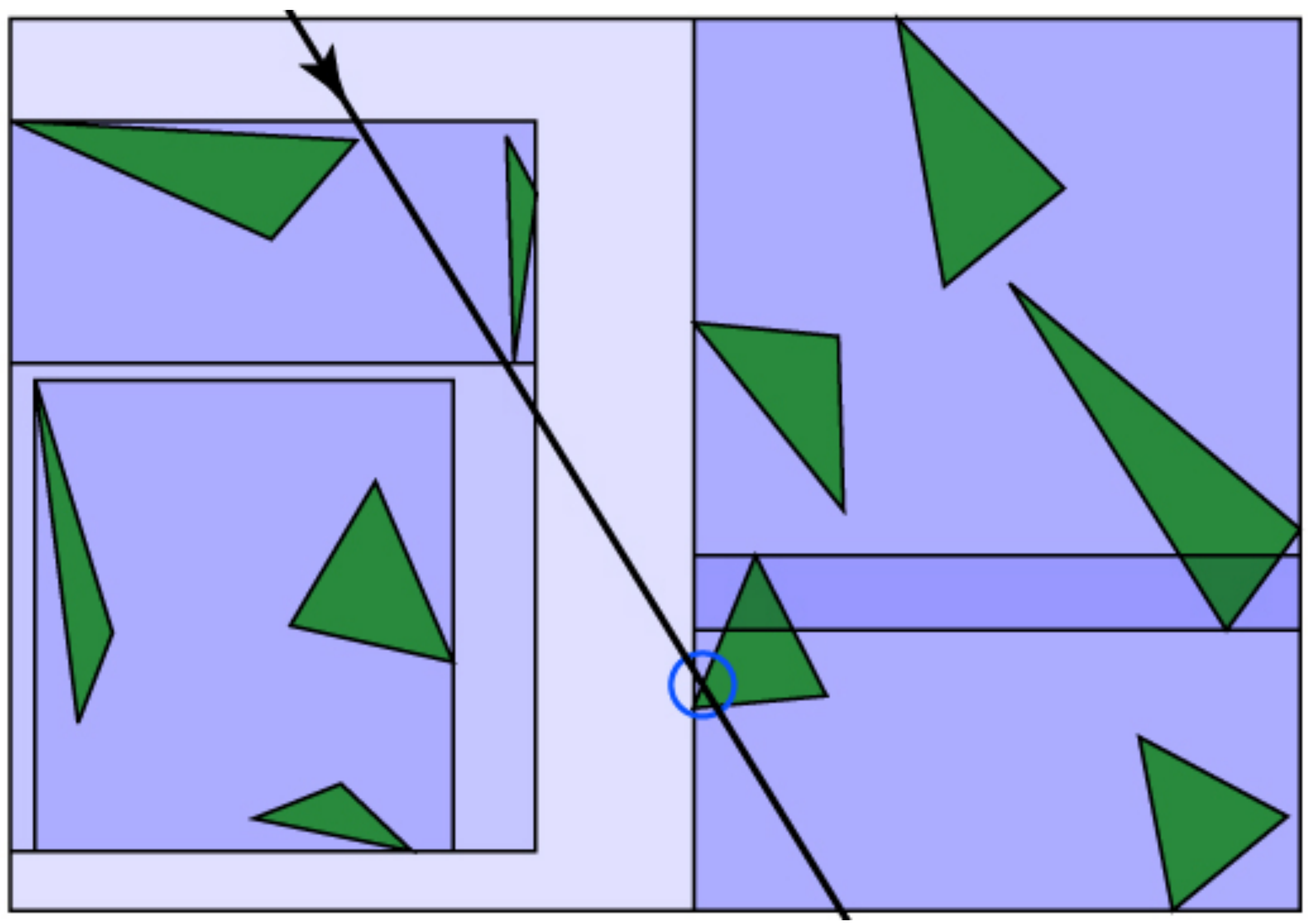
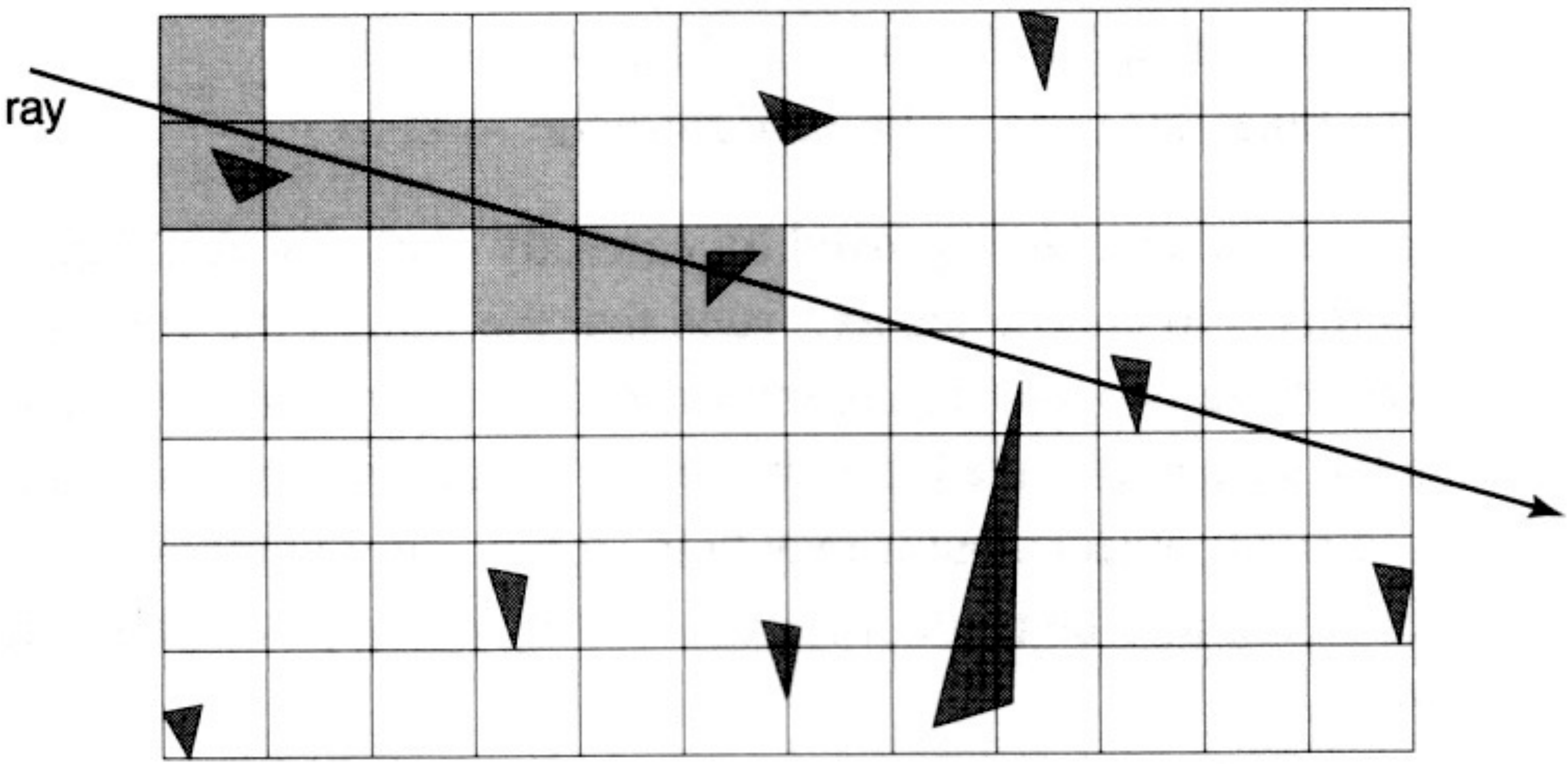


Implementation

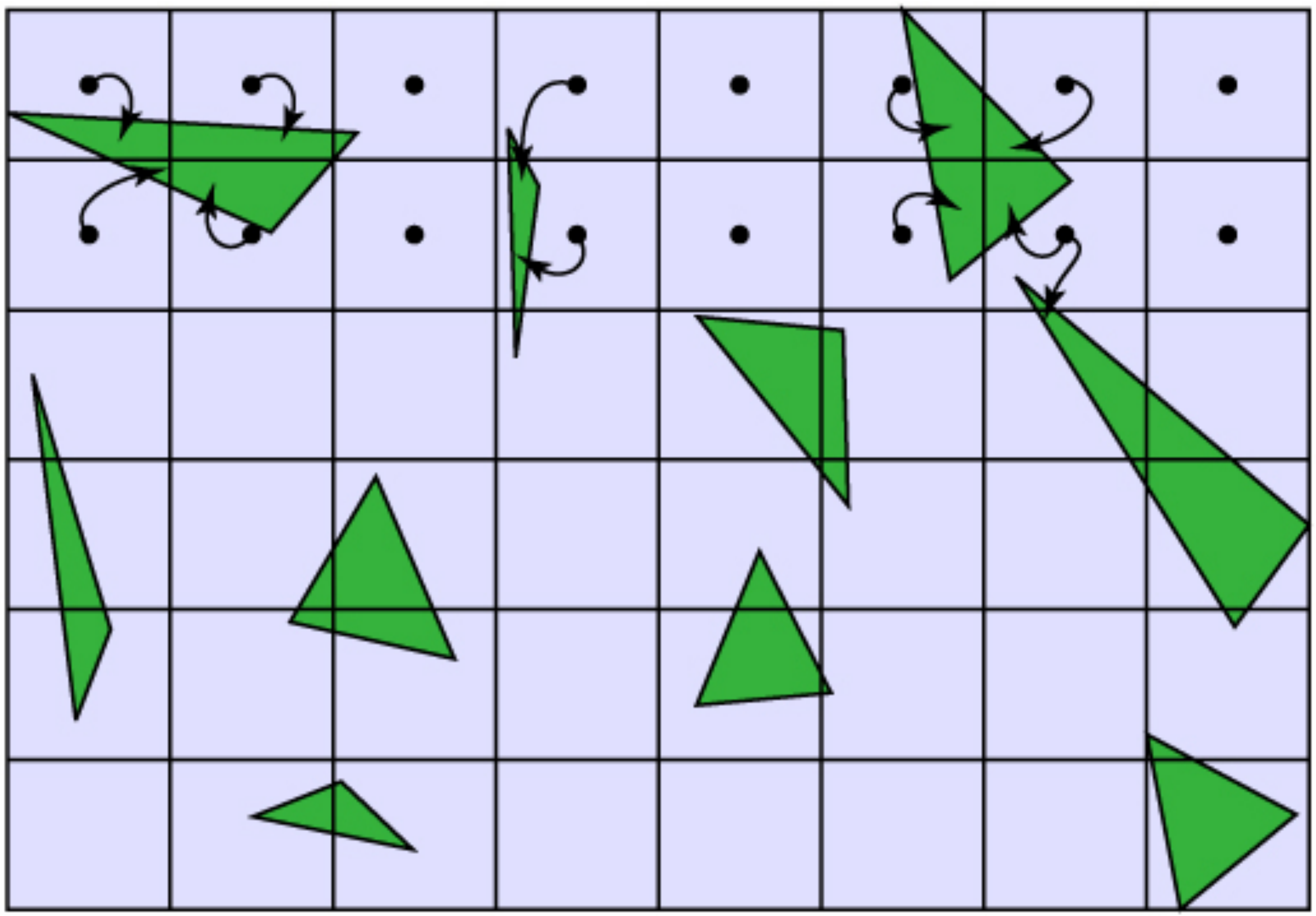
- New kind of object: BoundedObject
  - stores references to contained objects
    (can be BoundedObjects themselves!)
- New `ray_intersect` routine:
  - Intersect with each child; if any, return closest.

Other Approaches:

- Uniform Space Subdivision



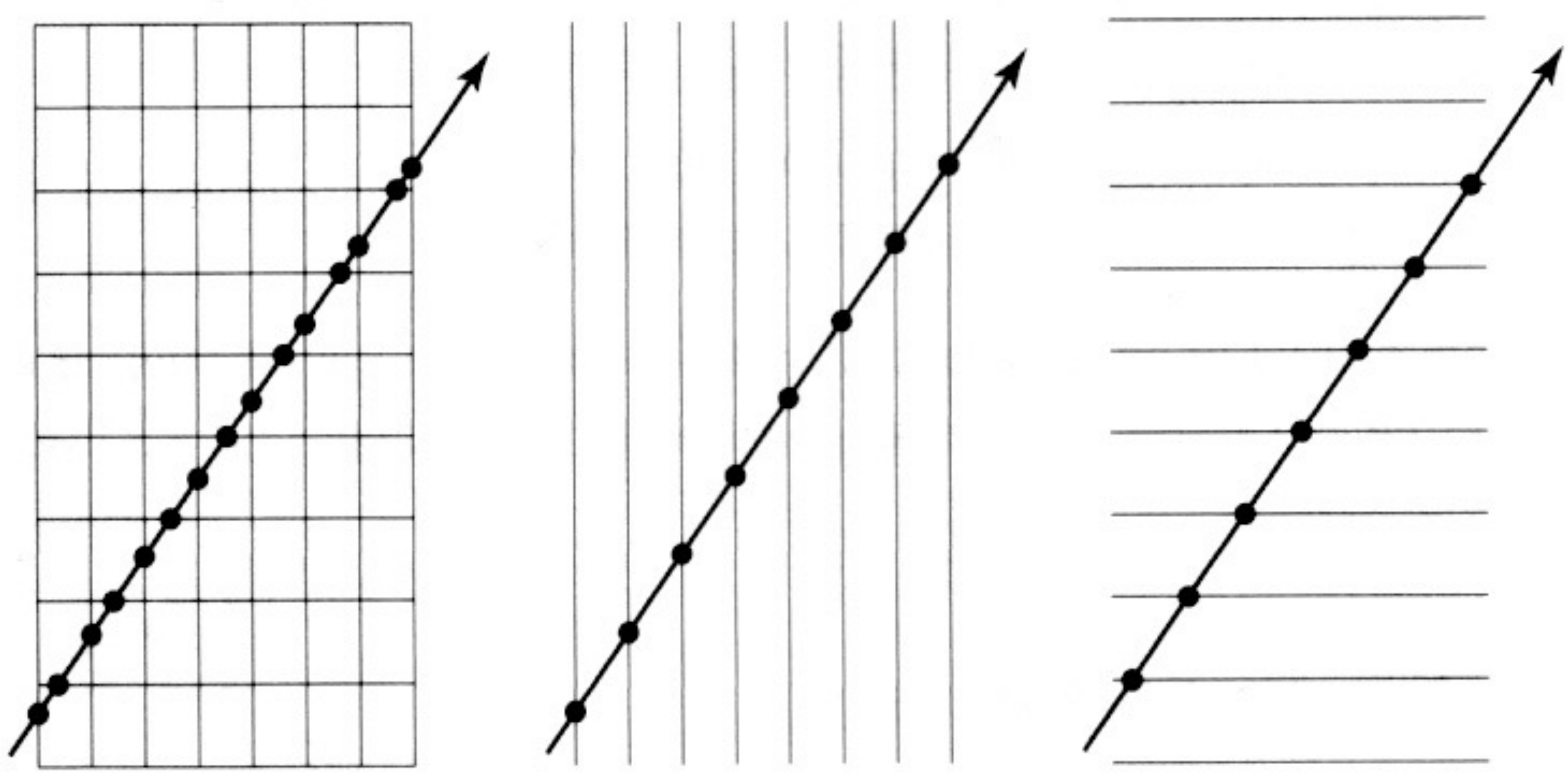
Uniform Space Subdivision



- Grid cells store references to overlapping objects

Compute the grid cells intersected by a ray

Constant offset between cell edge intersections in each dimension:

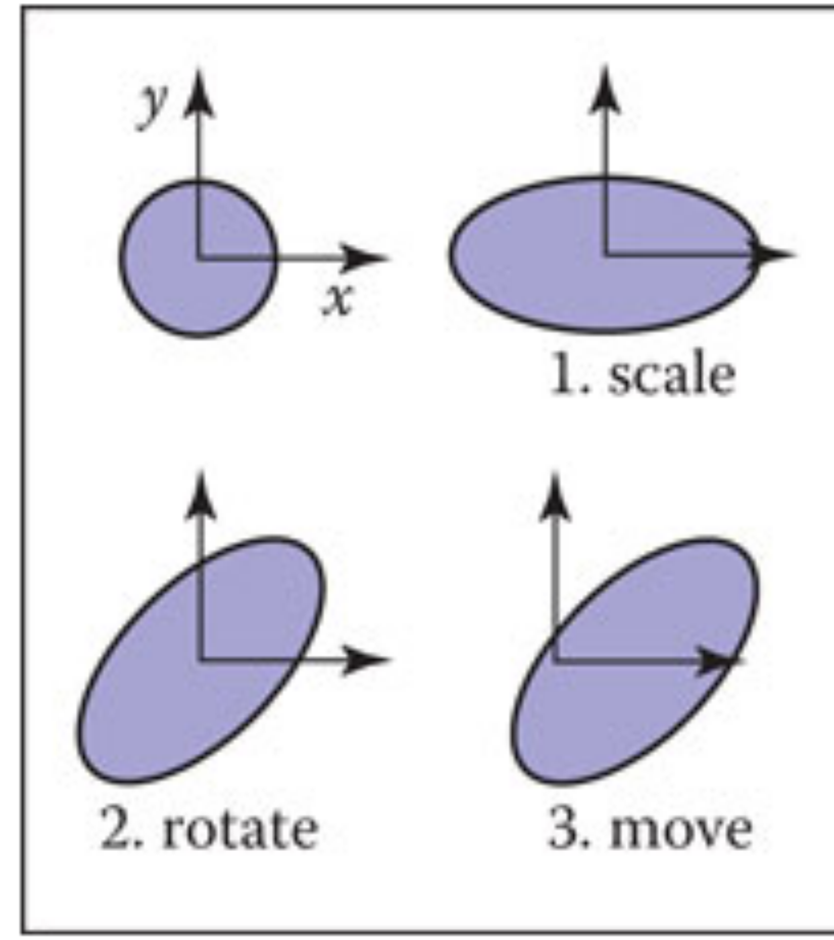


Ok, what else can't we do?

- Rotate, scale, shear objects - *transformations* (more on this next week, and in 13.2)
- Render transparent things - *transmission and refraction* (Ch 13.1)
- Intersect more kinds of objects - *Constructive Solid Geometry* (Ch
- Area light sources, soft shadows, depth of field - *distribution ray tracing* (Ch 13.4)

Transformations and Instancing

- Next week we'll talk about how to transform objects:



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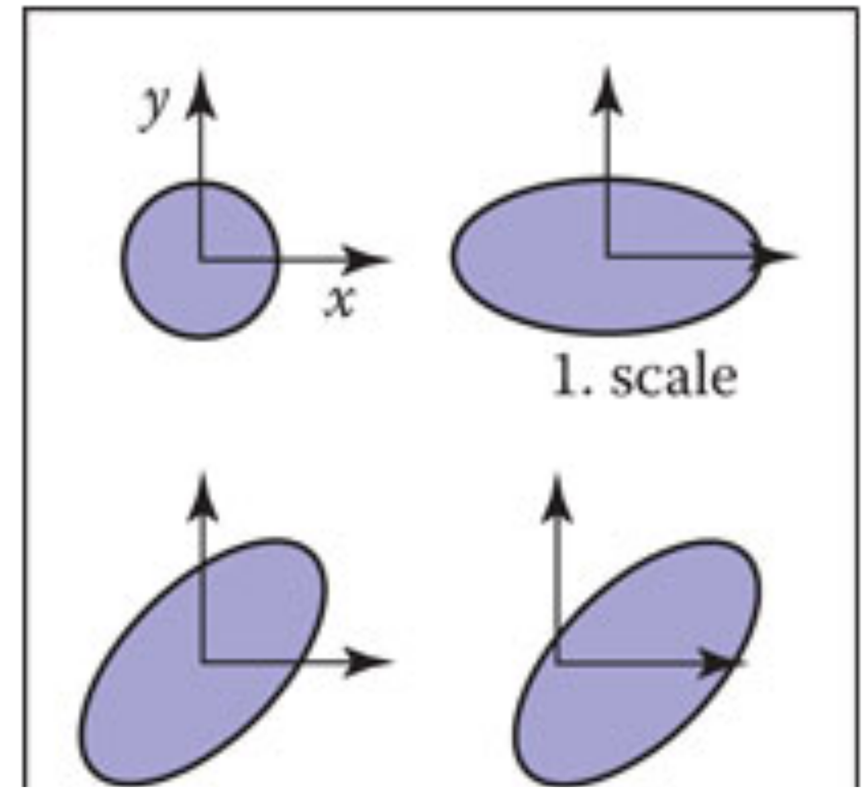

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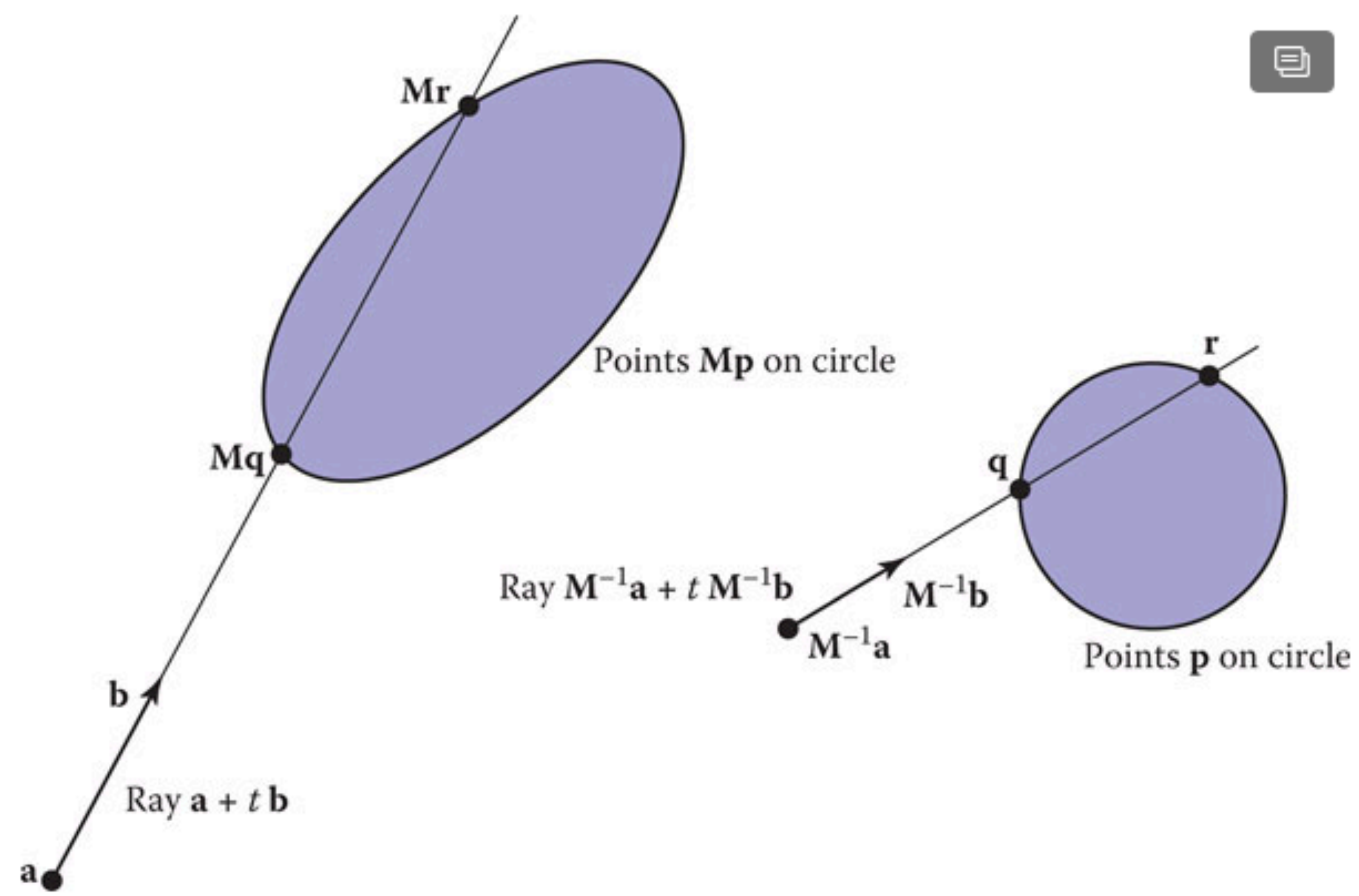
When ray tracing, we can alternatively transform the *rays:*



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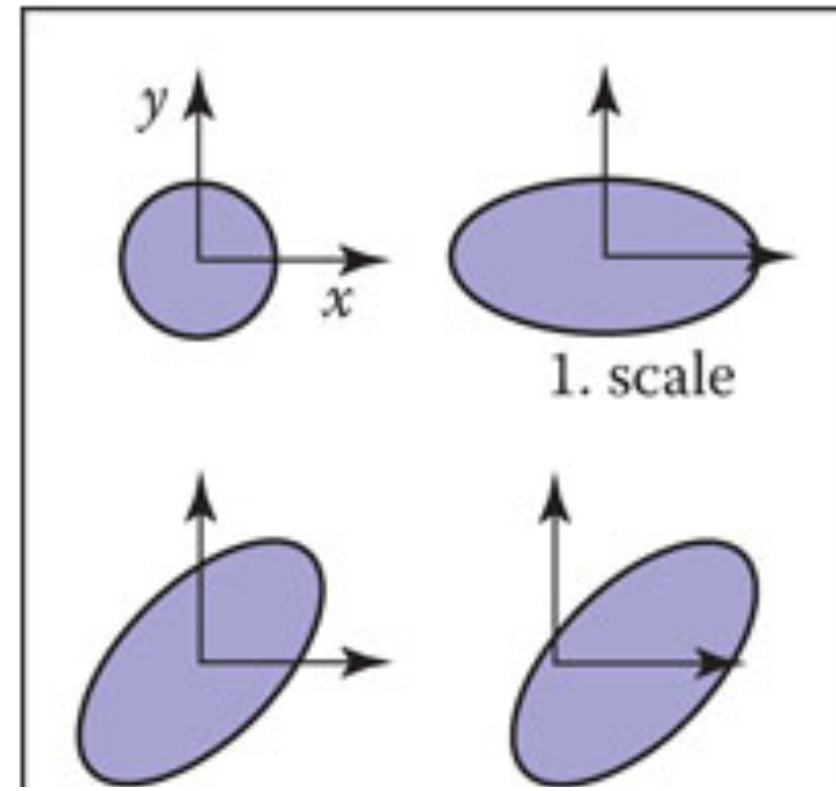

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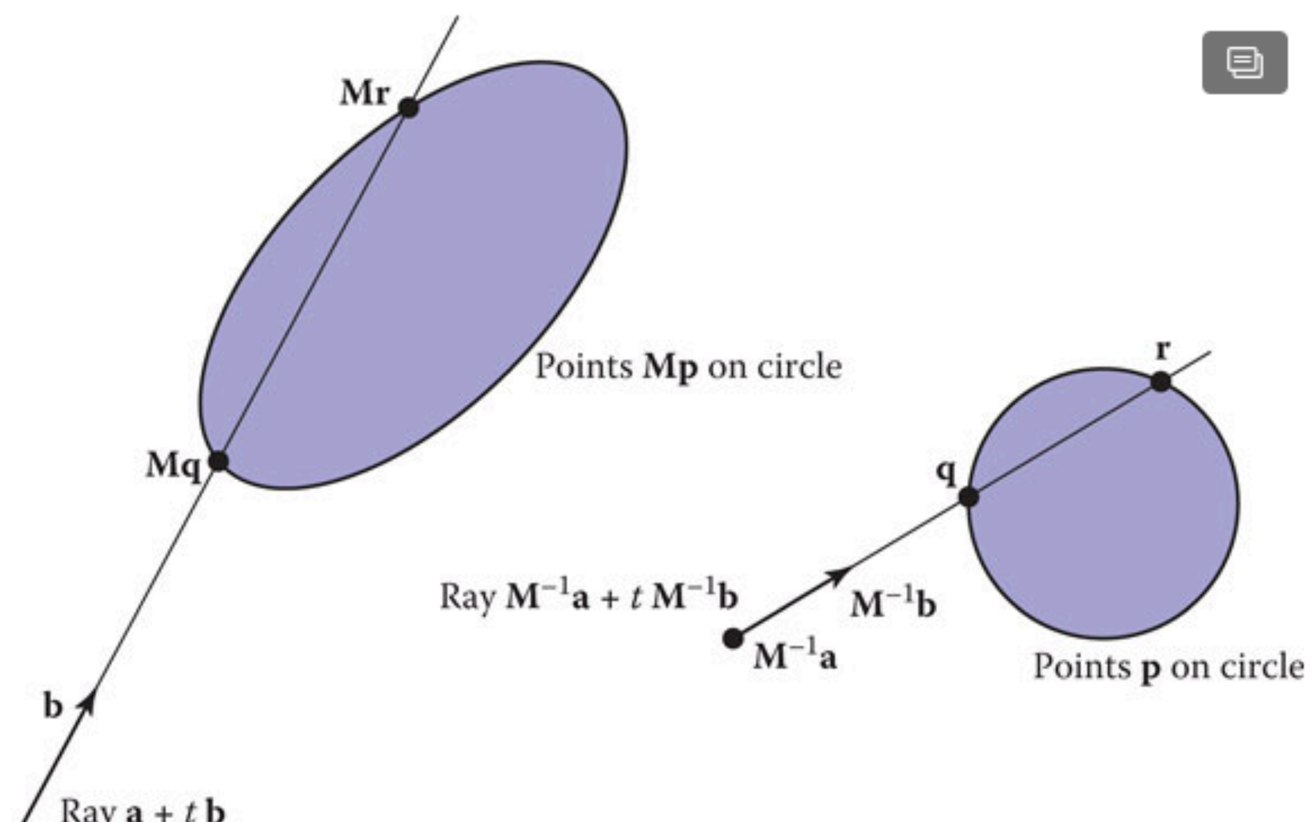
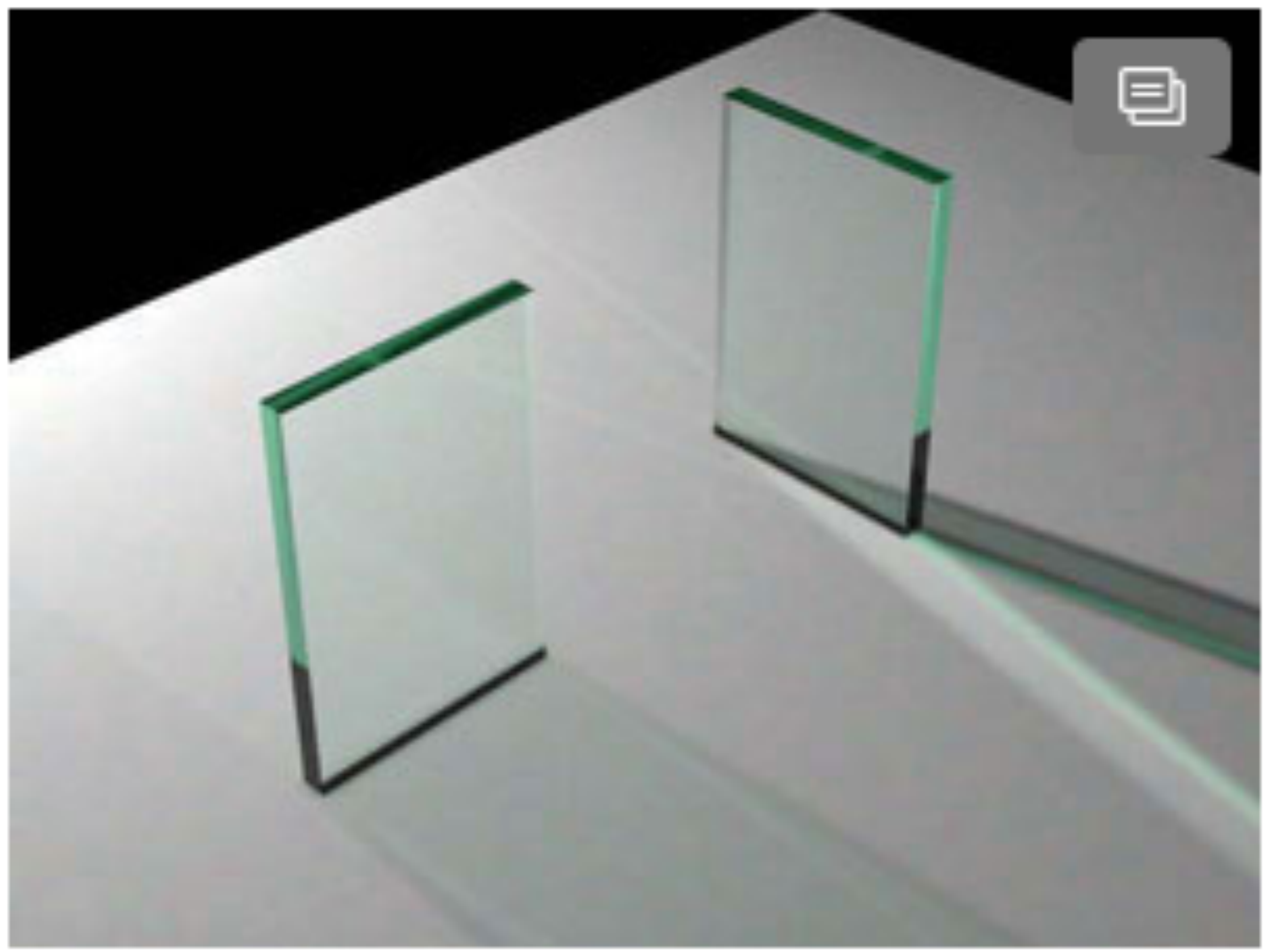


Same idea allows us to include multiple *instances* of the same object in a scene.

Transparency and Refraction

Our framework assumes surfaces reflect light.

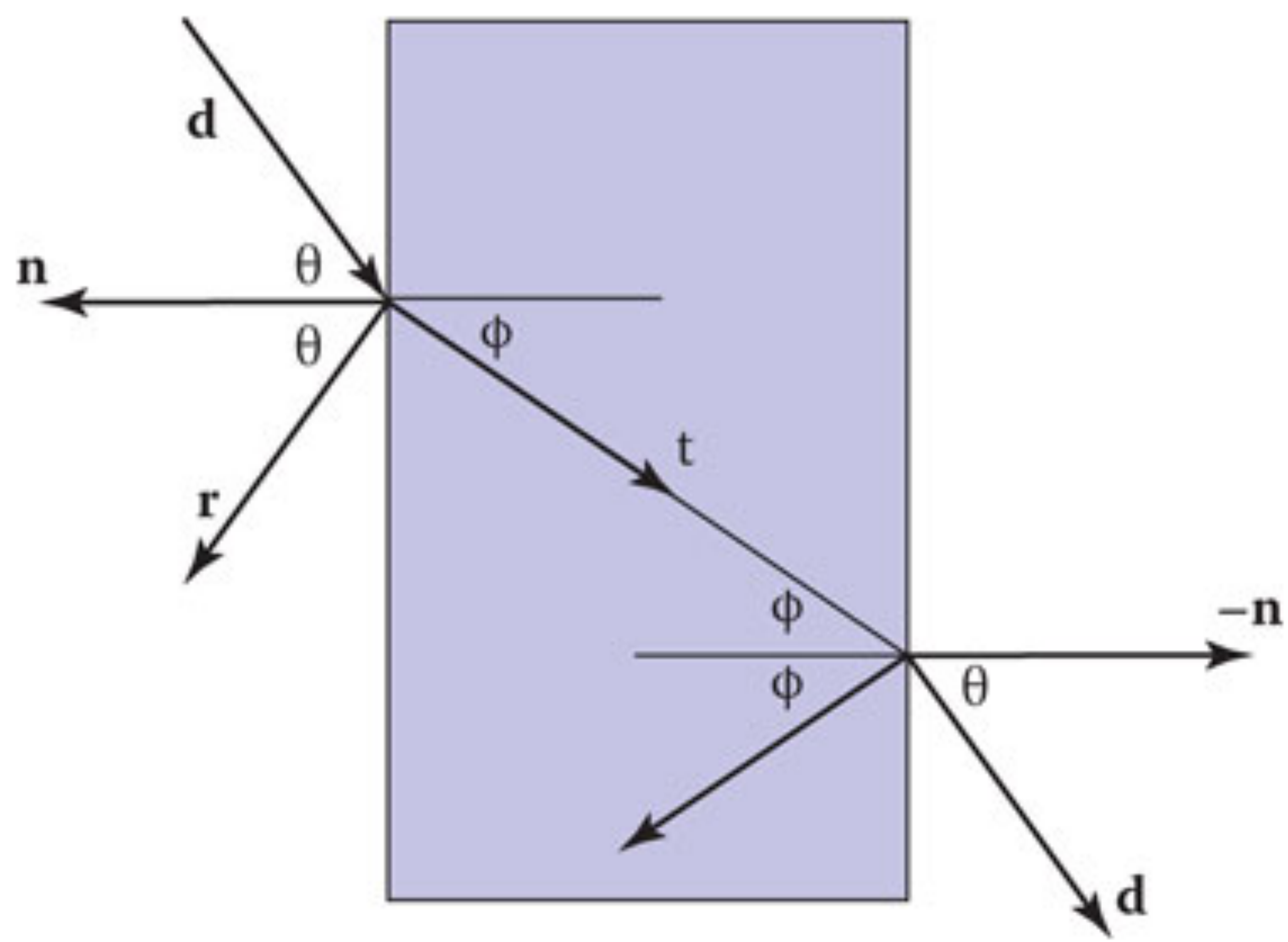


What if they don't?

Basically, physics

- Laws of physics govern how light transmits through *dielectric* surfaces. Snell's law:

$$n \sin\theta = n_t \sin\phi.$$



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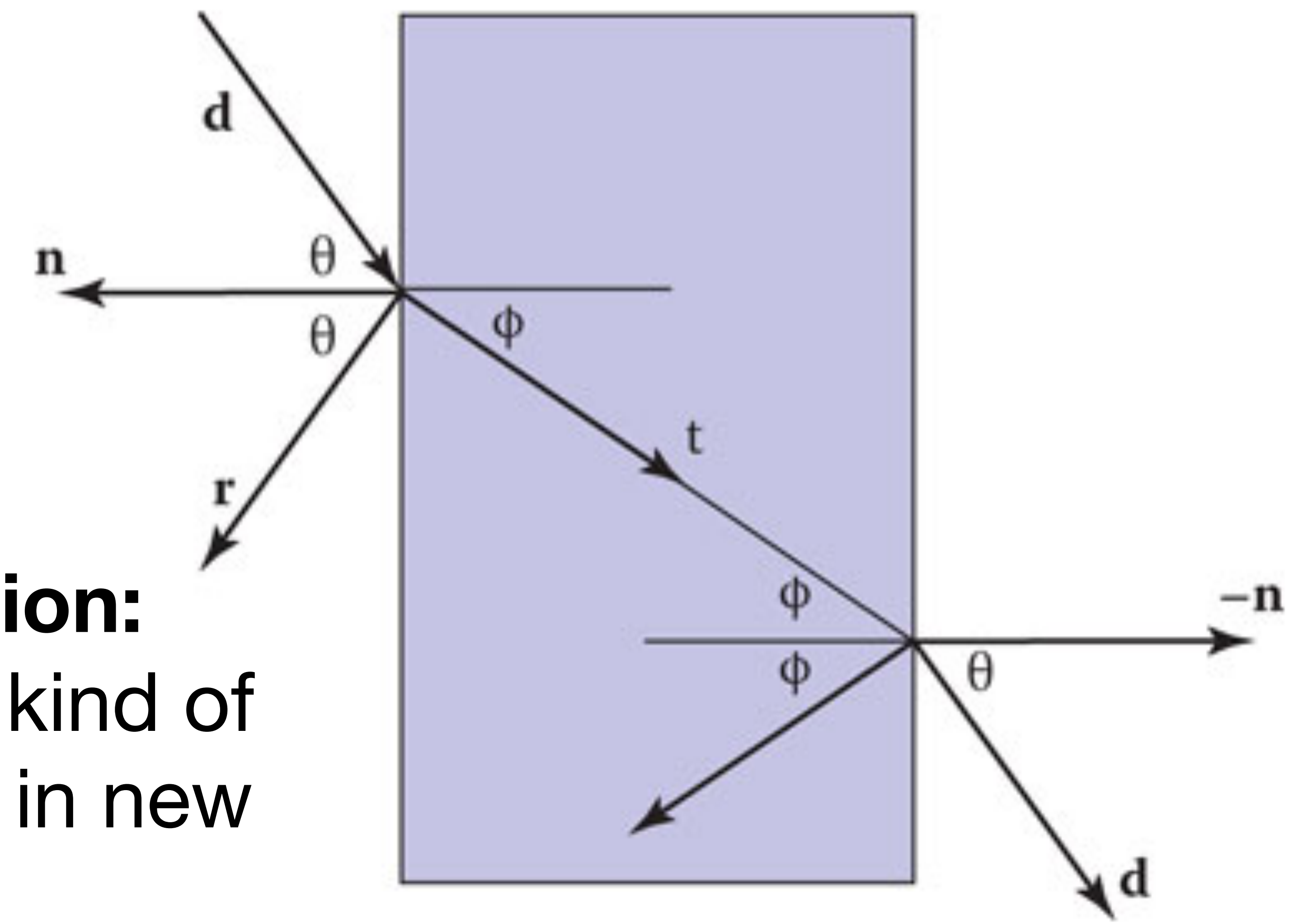
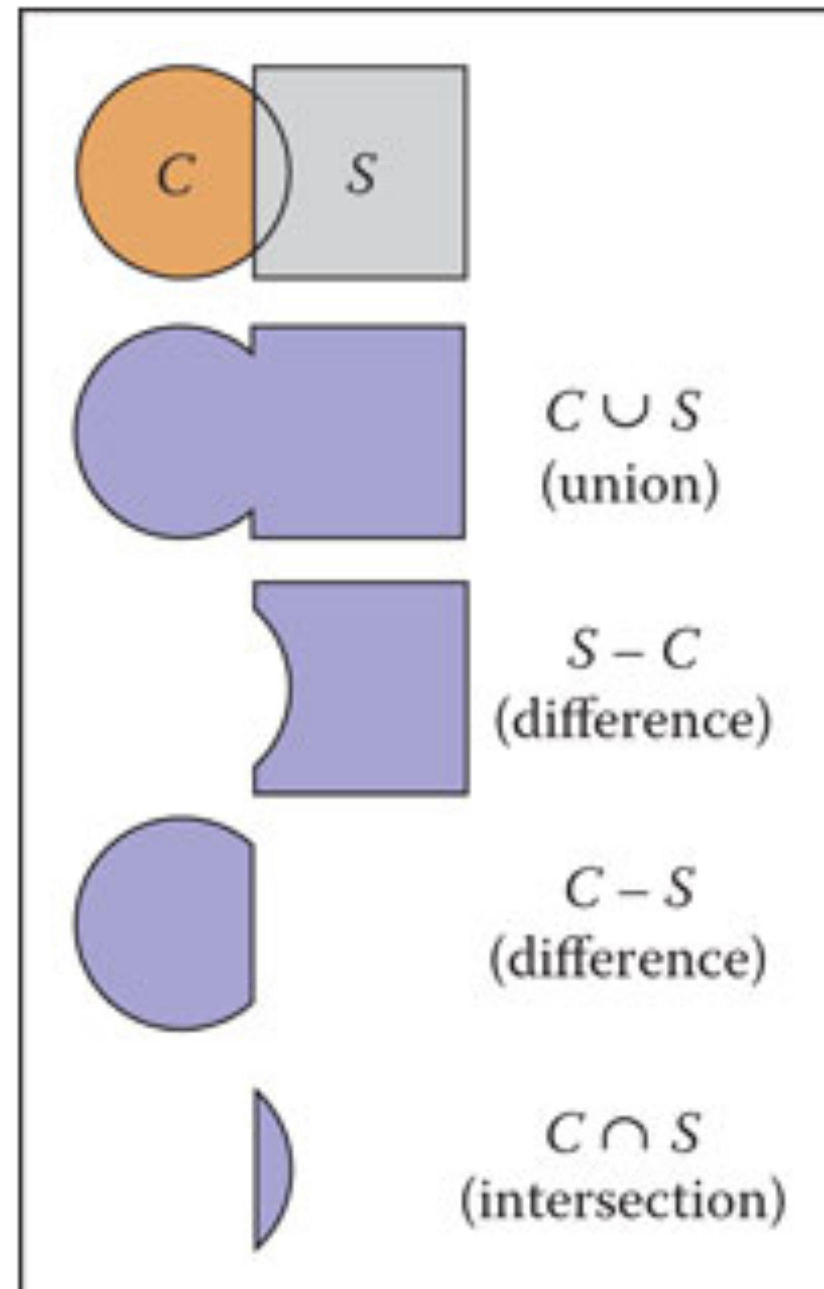


Similar to mirror reflection: When light hits a special kind of surface, shoot a new ray in new direction.

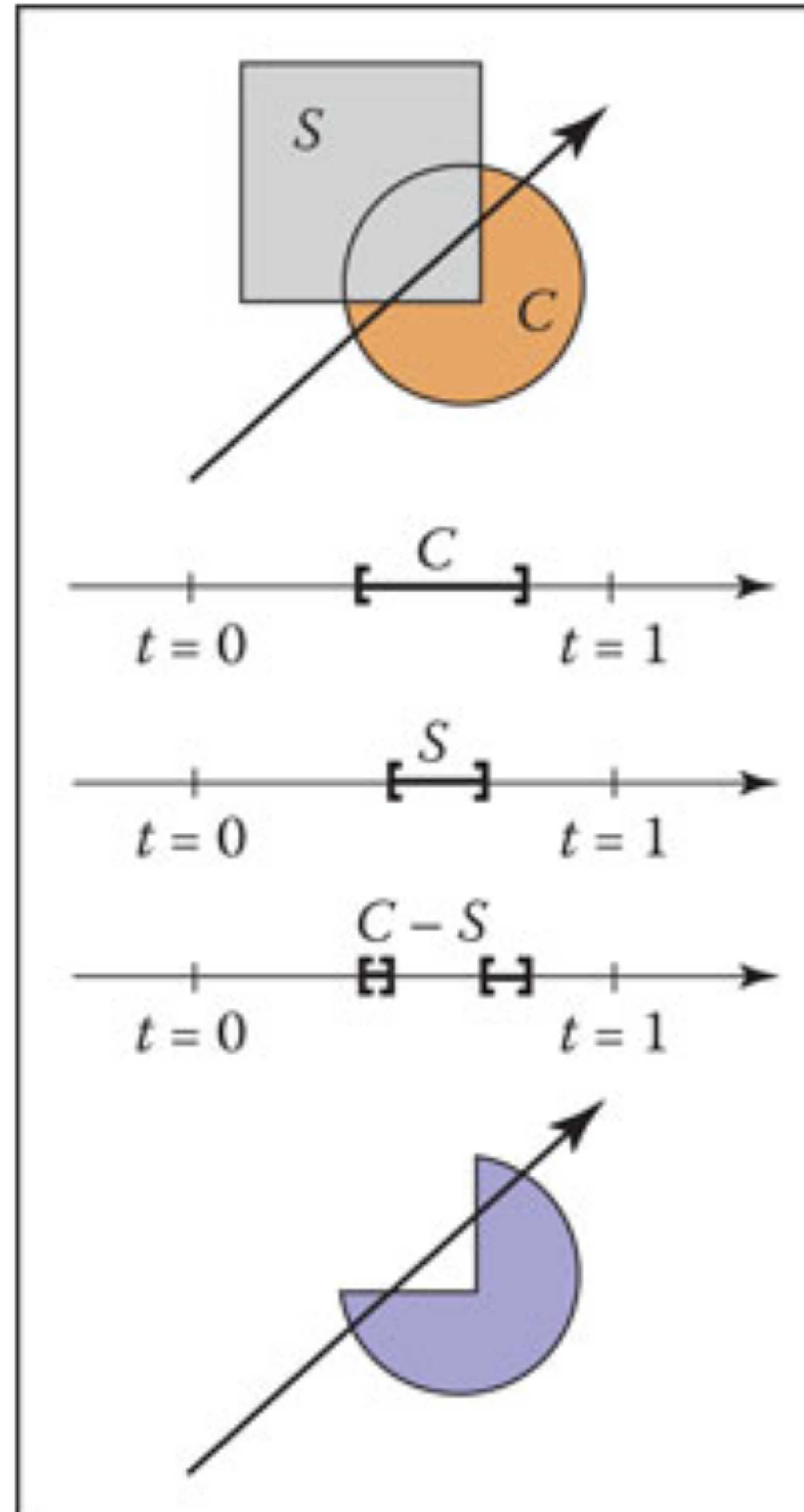
Constructive Solid Geometry

- Compose objects from other objects using set operations:



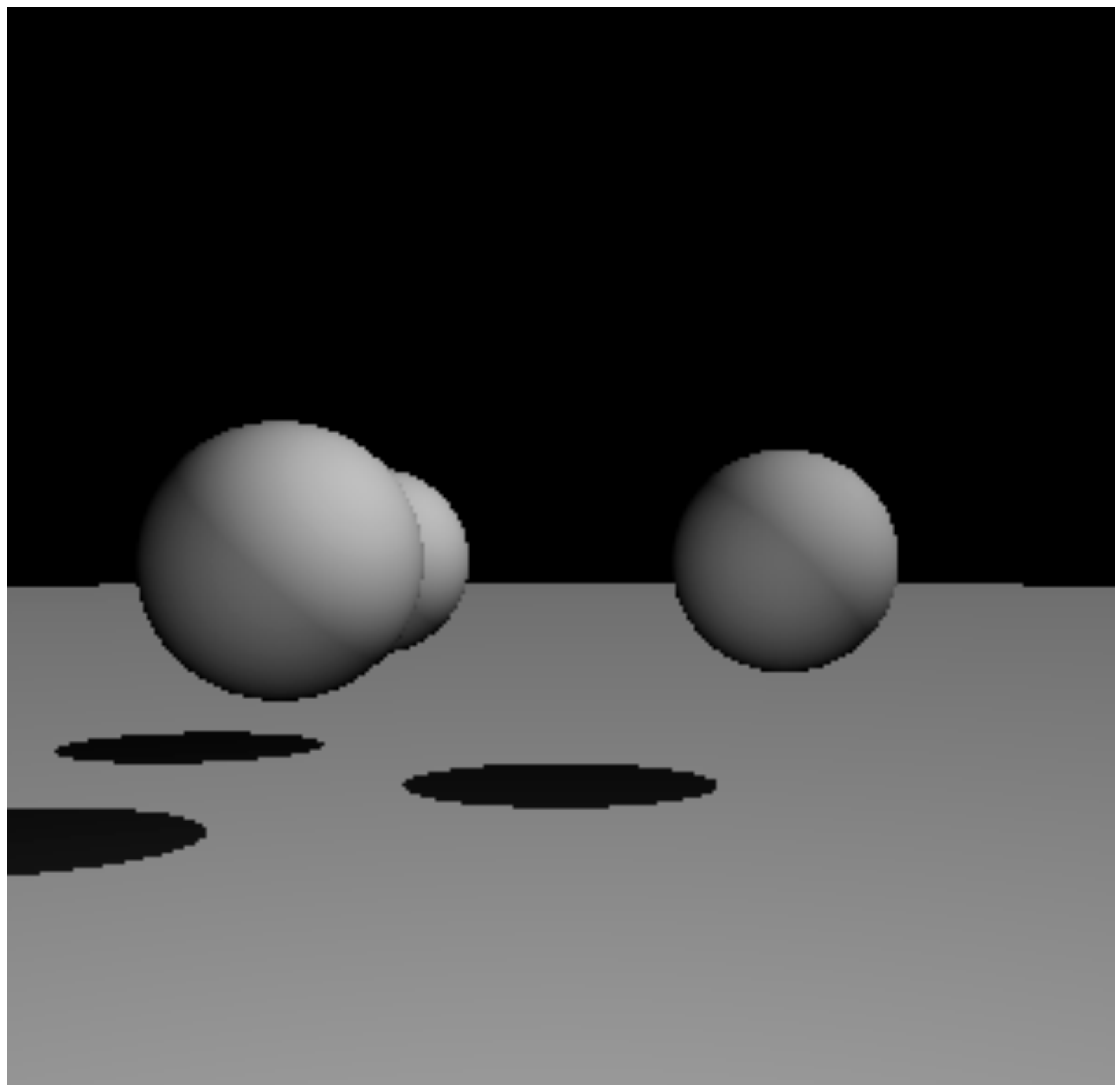
Constructive Solid Geometry

- Intersections yield intervals of *t*
- Perform the set operations on those intervals to determine intersection point.



Distribution Ray Tracing

- Problem: jagged object and shadow edges



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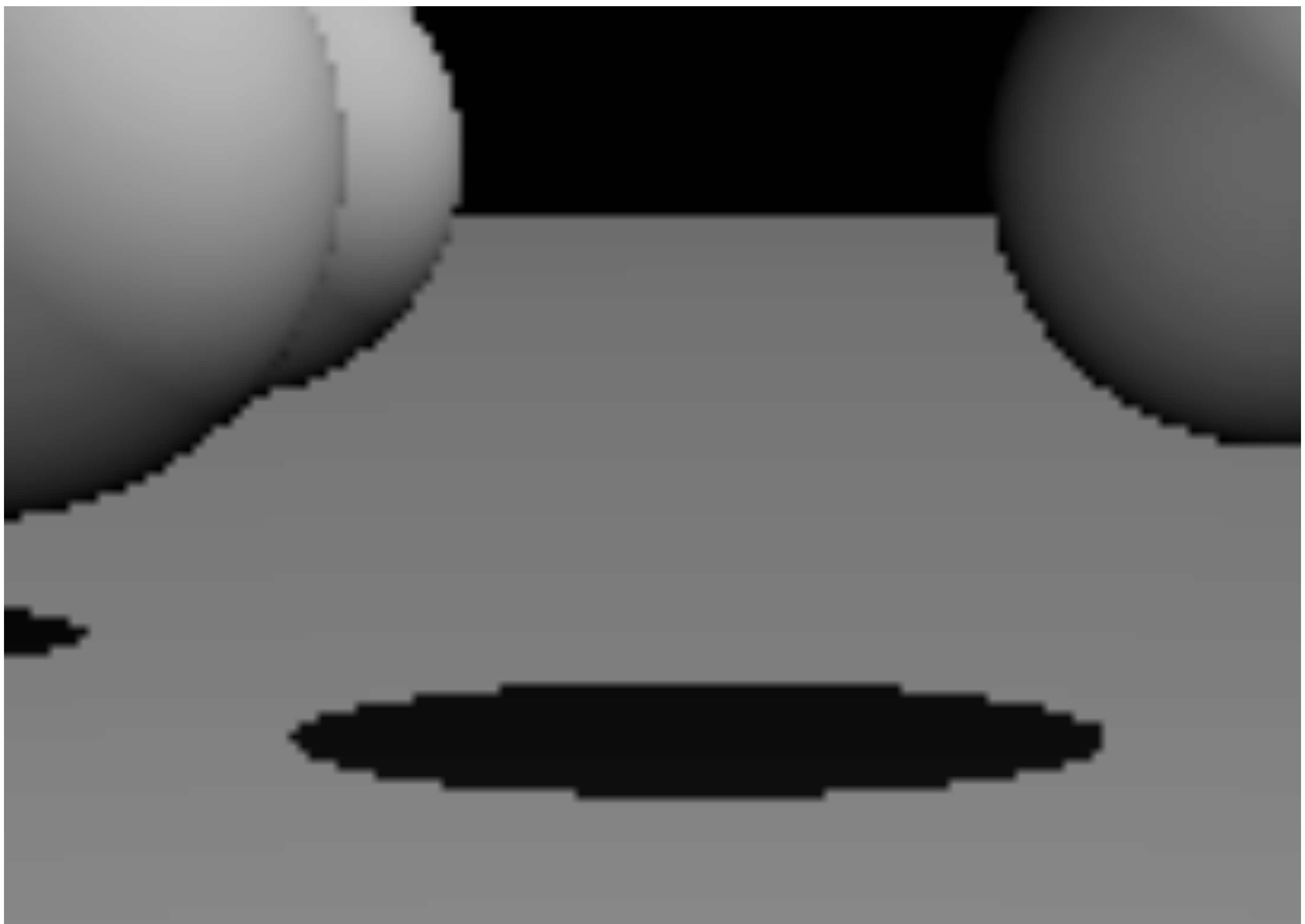
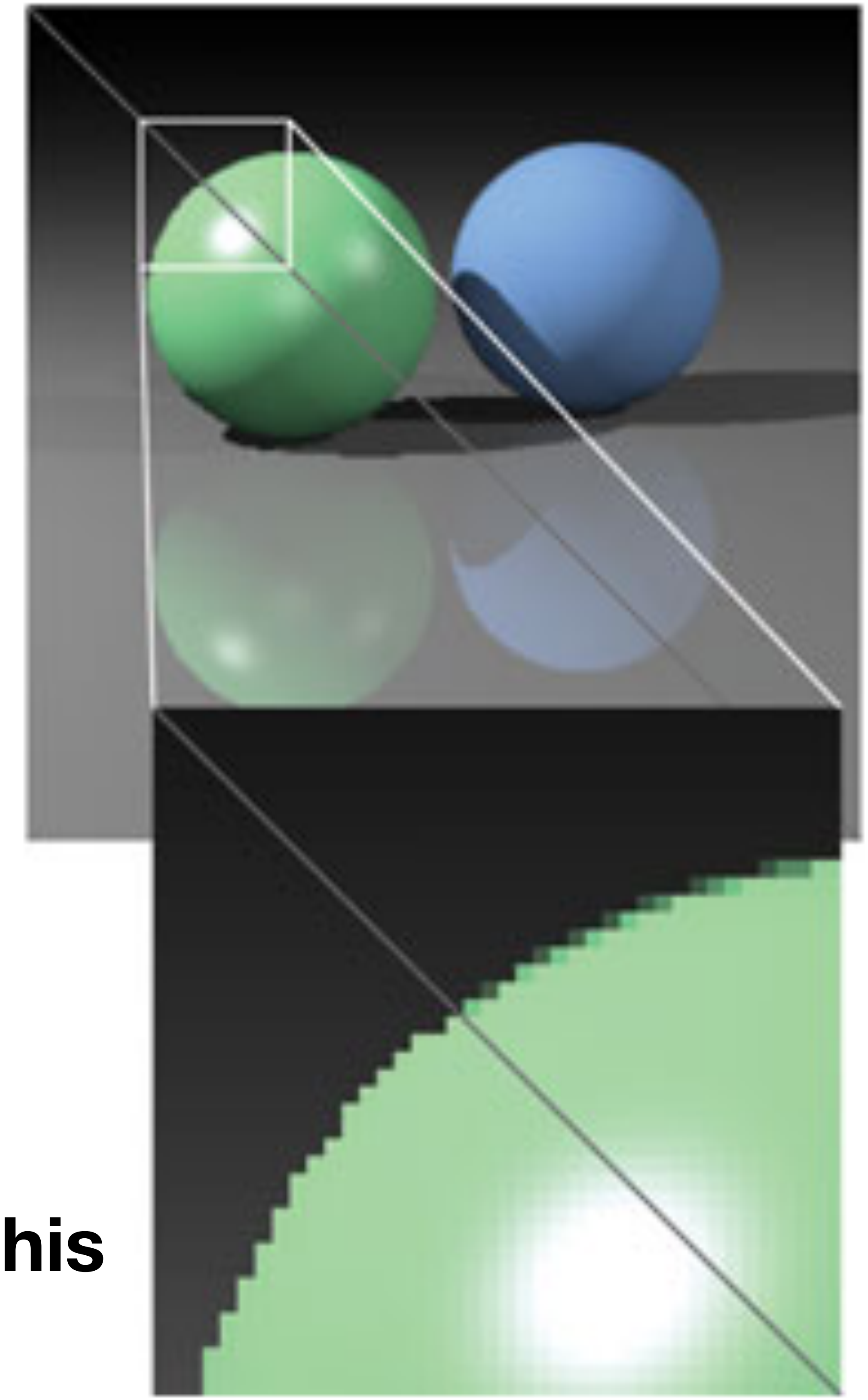
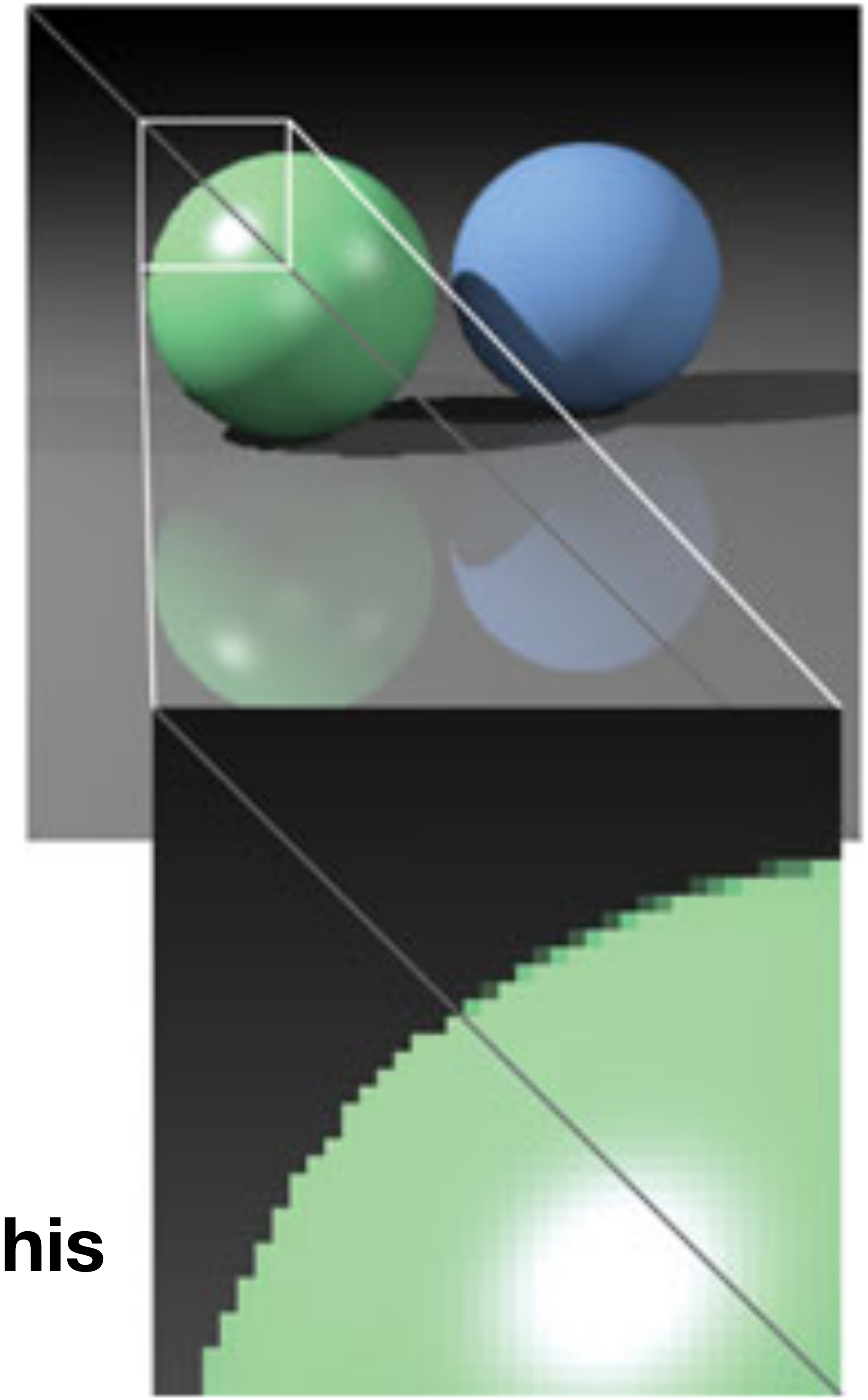




we want this

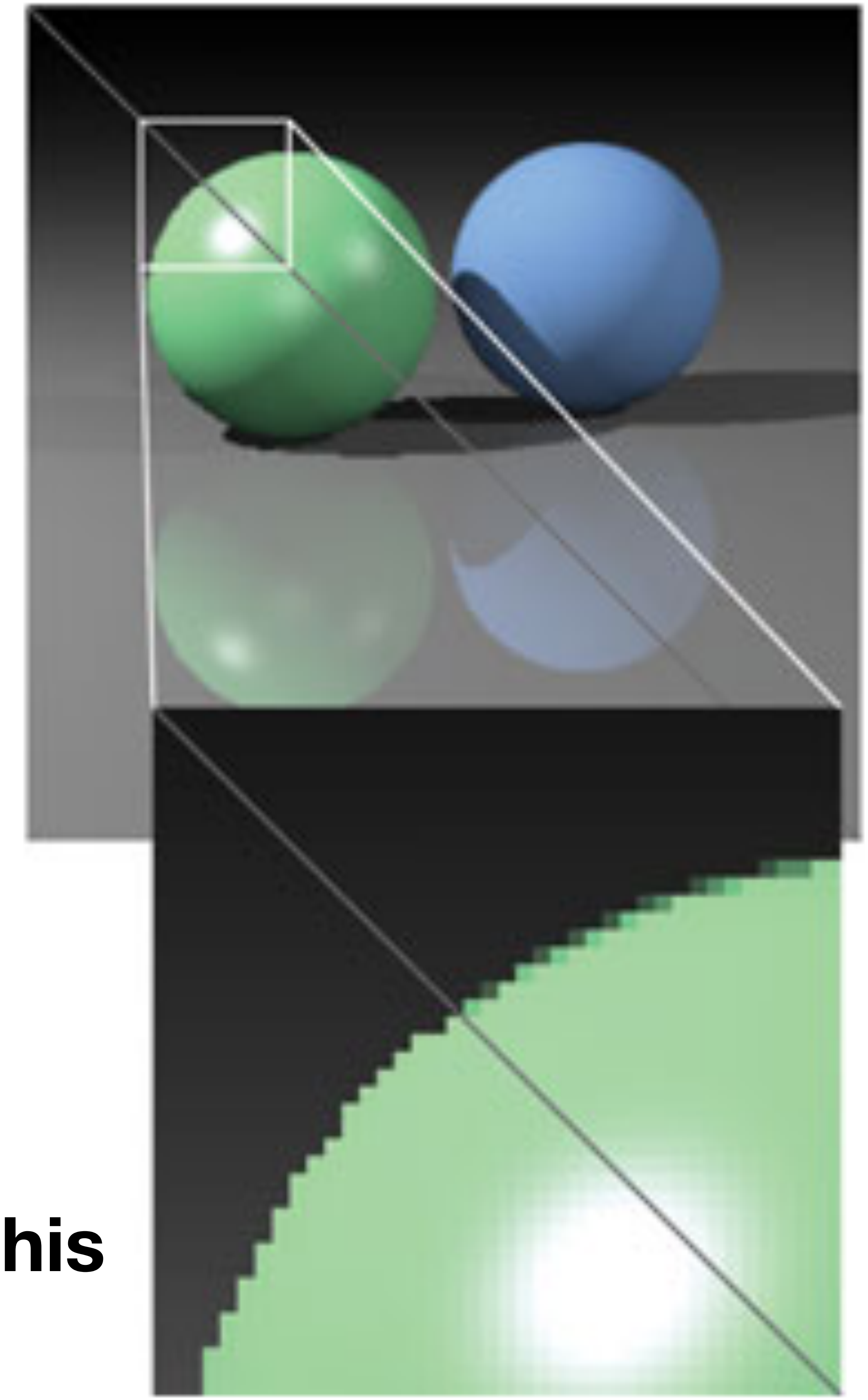
we have this



we want this

we have this

Idea: **supersample** rays within each pixel.



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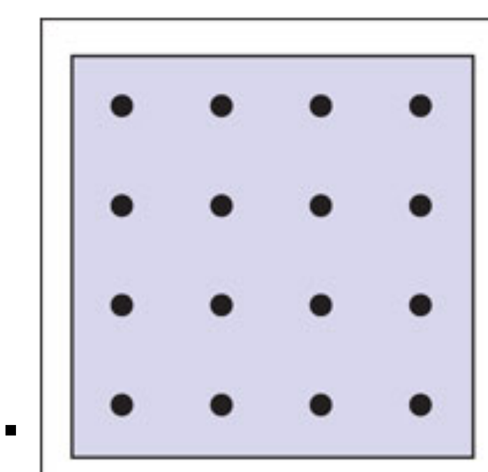
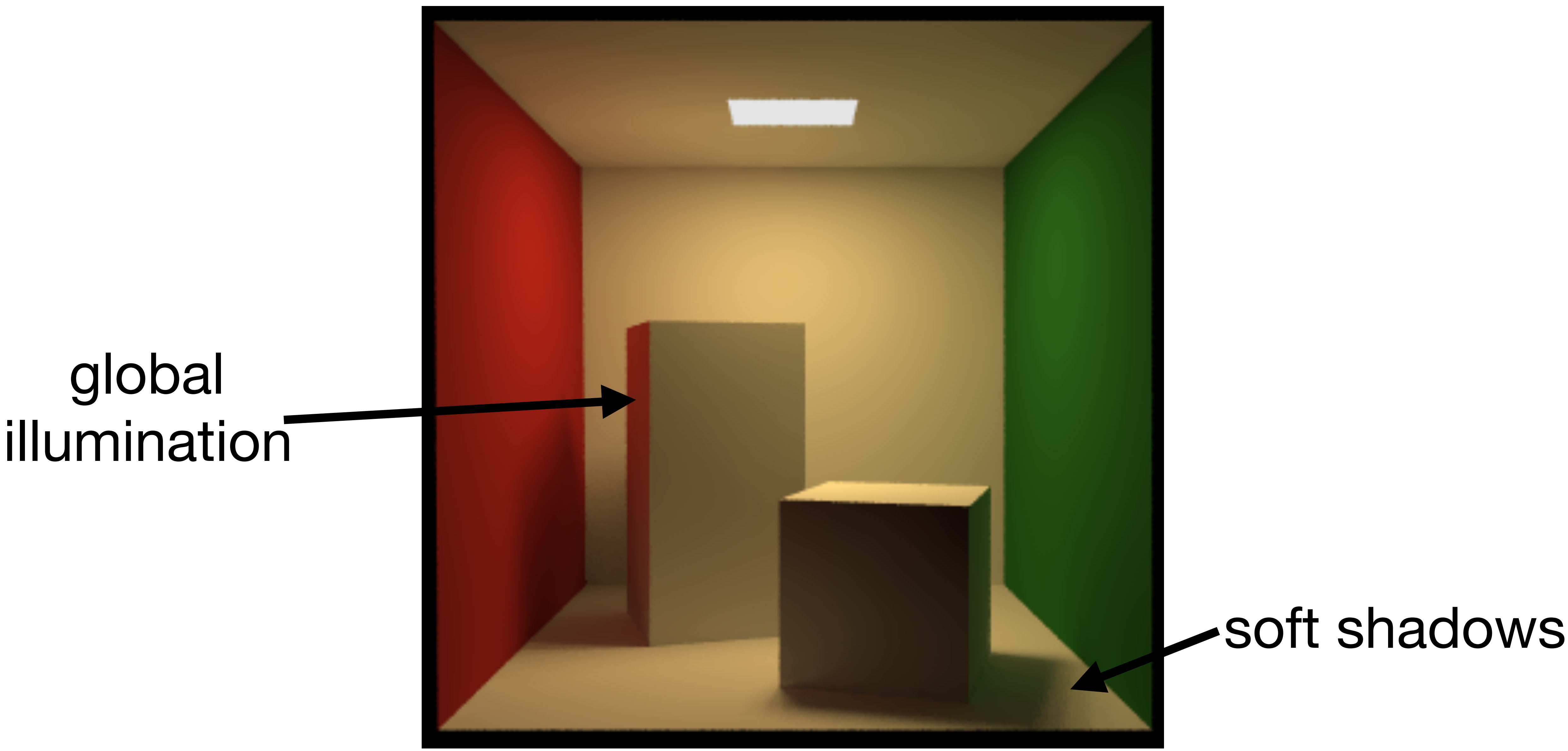


Distribution Ray Tracing

- Problem: area light sources



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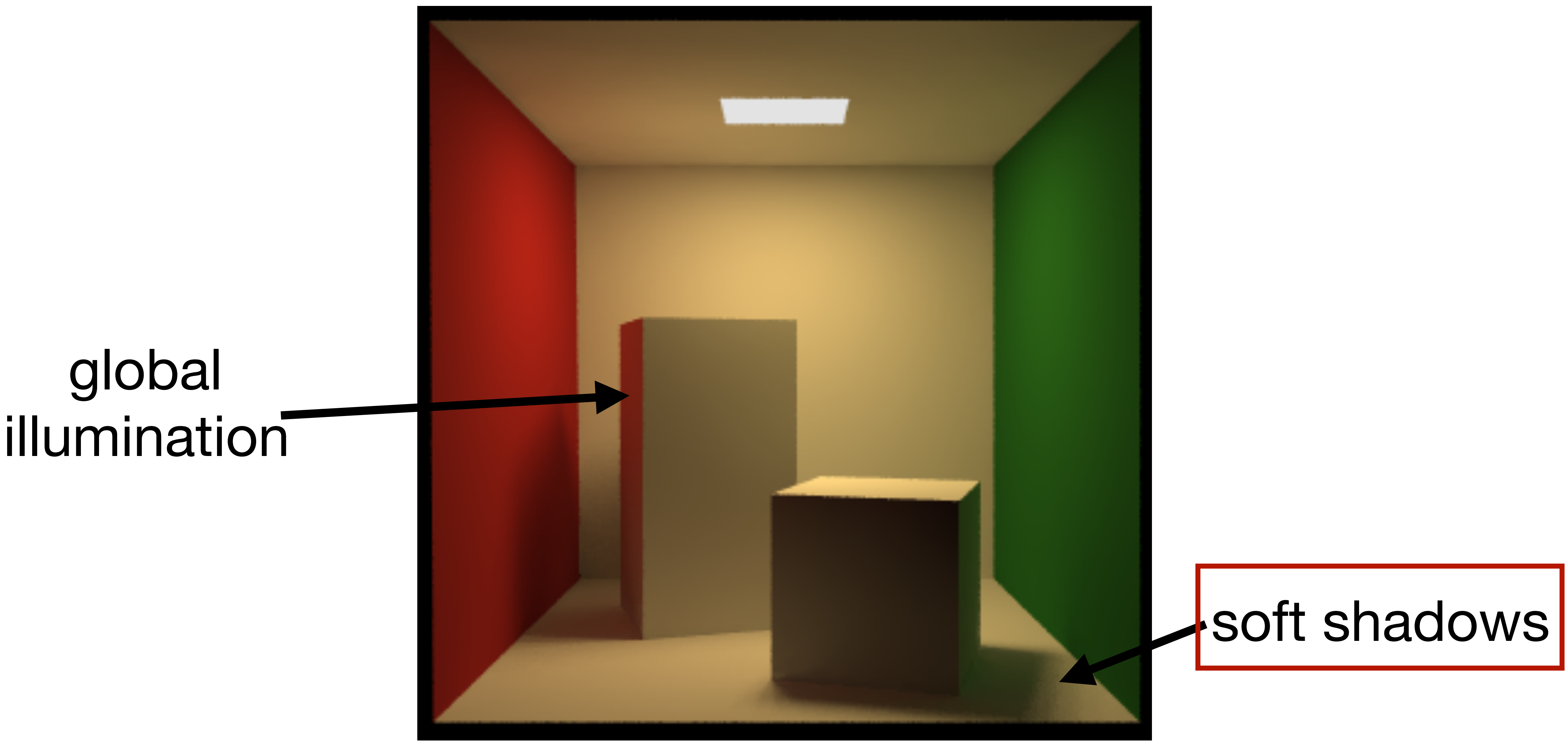

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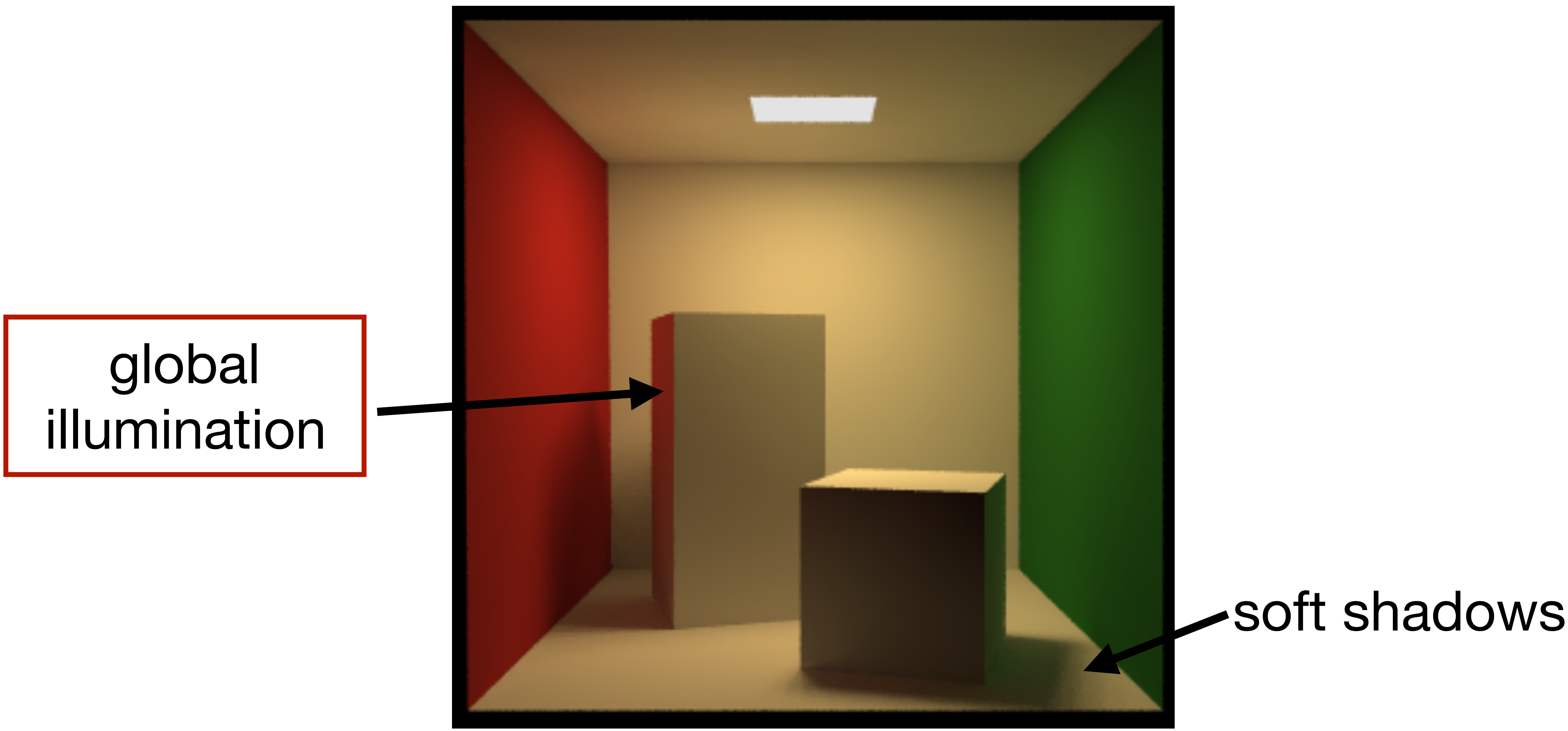
- Problem: area light sources



Next week:

- Transformations - positioning, scaling, rotating, shearing, etc. of objects and cameras in the scene.
- Intro to object-order rendering.