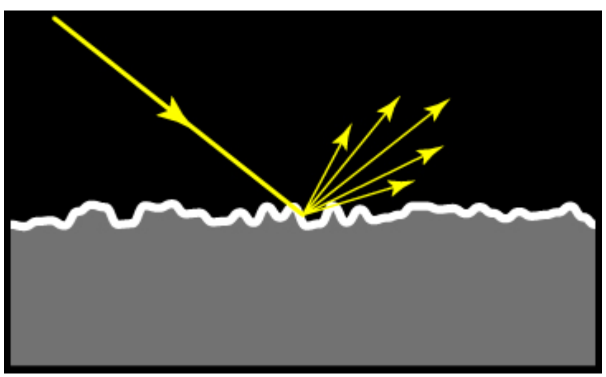
Ray Tracing

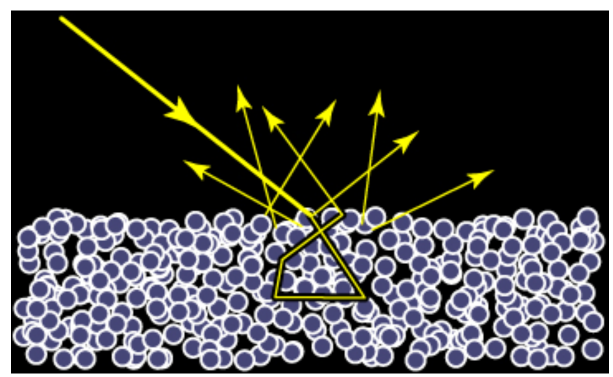
Light Reflection, Illumination

Hierarchies, Transforms, Advanced Rendering

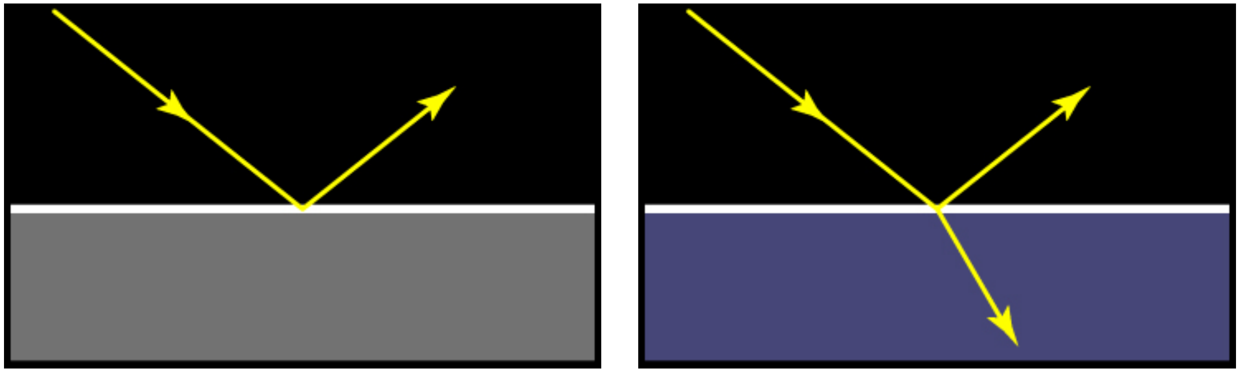
CS 4620 Lecture 36

Adding microgeometry

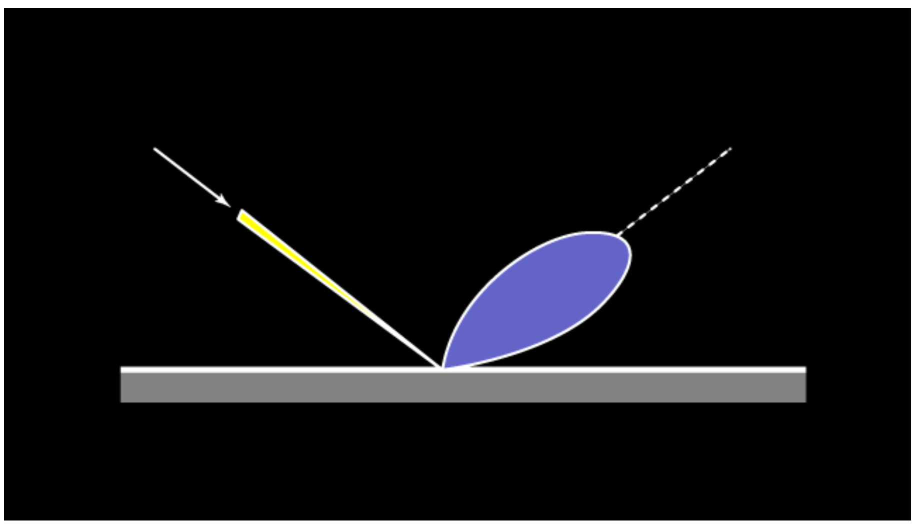




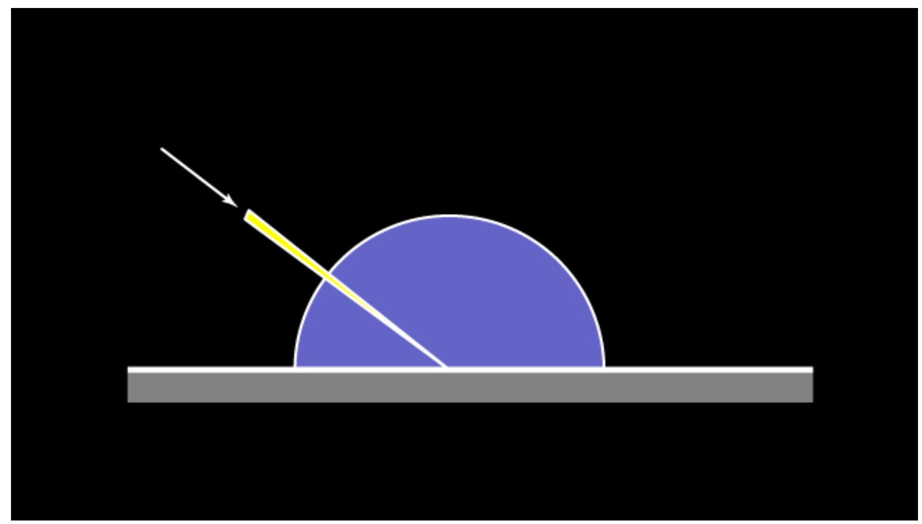
Classic reflection behavior



ideal specular (mirror)



glossy specular



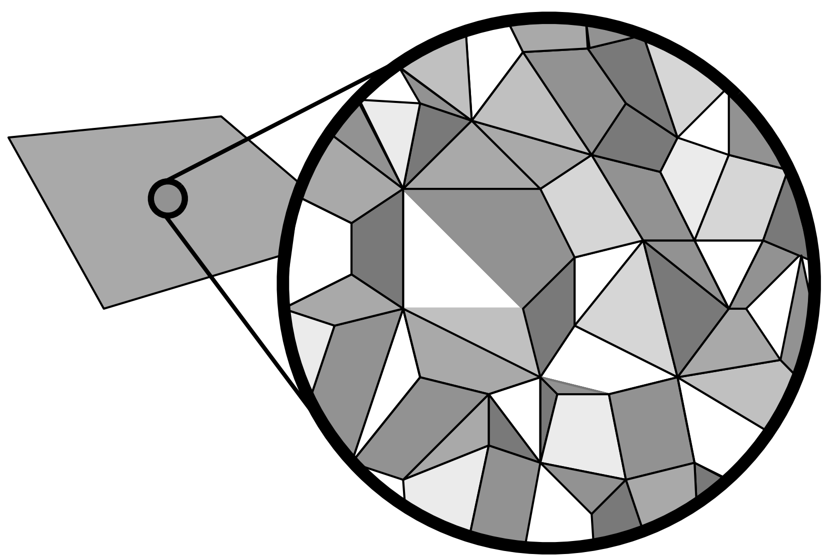
Lambertian

Broad modeling approaches

- Empirical expressions
  - a long and glorious history…
  - you know these: Phong, Ward, Kajiya, etc.
- Microfacet models
  - a geometric optics approach for surface reflection
  - based on statistical averaging over microgeometry
- Other geometric-optics surface models
  - including Oren-Nayar and other diffuse models
  - also several grooved-surface models
- Subsurface scattering models
  - Hanrahan-Kreuger; diffusion models

Cook-Torrance BRDF Model

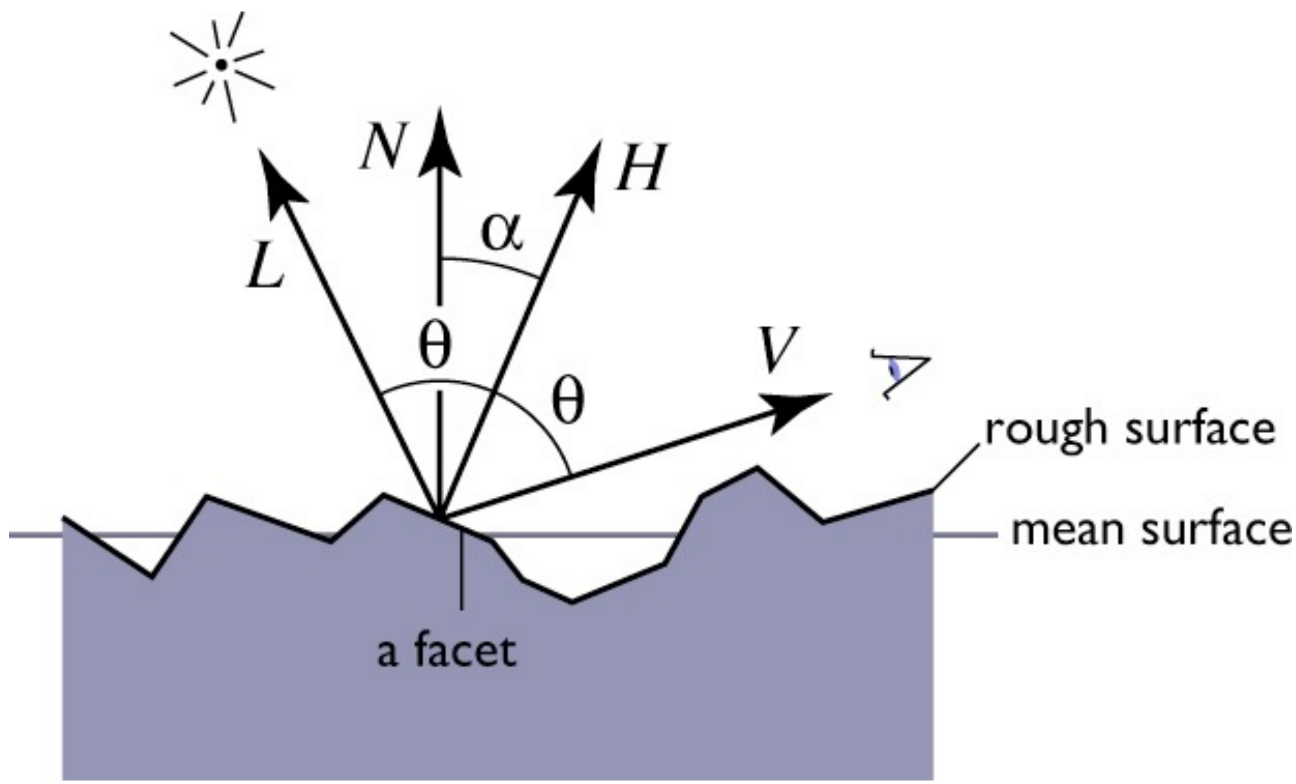
- A *microfacet* model
  - – surface modeled as random collection of planar facets
  - – an incoming ray hits exactly one facet, at random
- Key input: probability distribution of facet angle



[Stephen Westin]

Facet Reflection

- *H* vector used to define facets that contribute
  - L and V determine H; only facets with that normal matter
  - reflected light is proportional to number of facets



Cook-Torrance BRDF Model

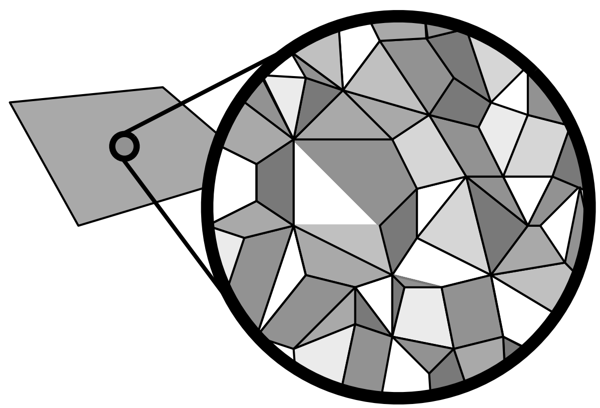
- "Specular" term (really glossy, or directional diffuse)

$$f_r(\mathbf{n}, \mathbf{l}, \mathbf{v}) = \frac{F(\mathbf{l}, \mathbf{h}) D(\mathbf{h}) G(\mathbf{l}, \mathbf{v}, \mathbf{h})}{4|\mathbf{n} \cdot \mathbf{l}||\mathbf{n} \cdot \mathbf{v}|}$$

Cook-Torrance BRDF Model

Facet distribution

$$f_r(\mathbf{n}, \mathbf{l}, \mathbf{v}) = \frac{F(\mathbf{l}, \mathbf{h}) D(\mathbf{h}) G(\mathbf{l}, \mathbf{v}, \mathbf{h})}{4 |\mathbf{n} \cdot \mathbf{l}| |\mathbf{n} \cdot \mathbf{v}|}$$



[Stephen Westin]

Facet Distribution

- D function describes distribution of H
- Popular choice is due to Beckmann
  - – derivation based on Gaussian random surface
  - – for the purposes of this model we take it as given

$$D(\mathbf{h}) = \frac{e^{-\frac{\tan^2(\mathbf{h},\mathbf{n})}{m^2}}}{\pi m^2 \cos^4(\mathbf{h}, \mathbf{n})}$$

Cook-Torrance BRDF Model

Fresnel Reflectance

$$f_r(\mathbf{n}, \mathbf{l}, \mathbf{v}) = \frac{F(\mathbf{l}, \mathbf{h})D(\mathbf{h})G(\mathbf{l}, \mathbf{v}, \mathbf{h})}{4|\mathbf{n} \cdot \mathbf{l}||\mathbf{n} \cdot \mathbf{v}|}$$

- Fresnel reflectance for smooth facet
  - – more light reflected at grazing angles

Cook-Torrance BRDF Model

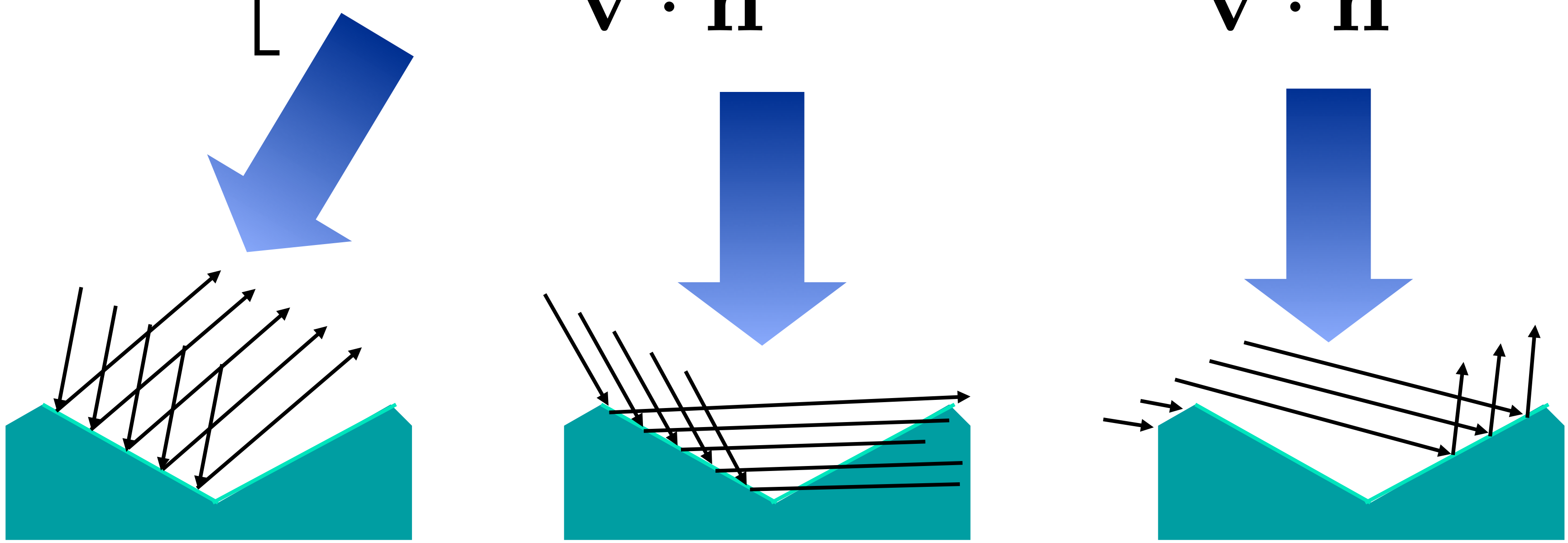
Masking/shadowing

$$f_r(\mathbf{n}, \mathbf{l}, \mathbf{v}) = \frac{F(\mathbf{l}, \mathbf{h}) D(\mathbf{h}) G(\mathbf{l}, \mathbf{v}, \mathbf{h})}{4|\mathbf{n} \cdot \mathbf{l}||\mathbf{n} \cdot \mathbf{v}|}$$

Masking and Shadowing

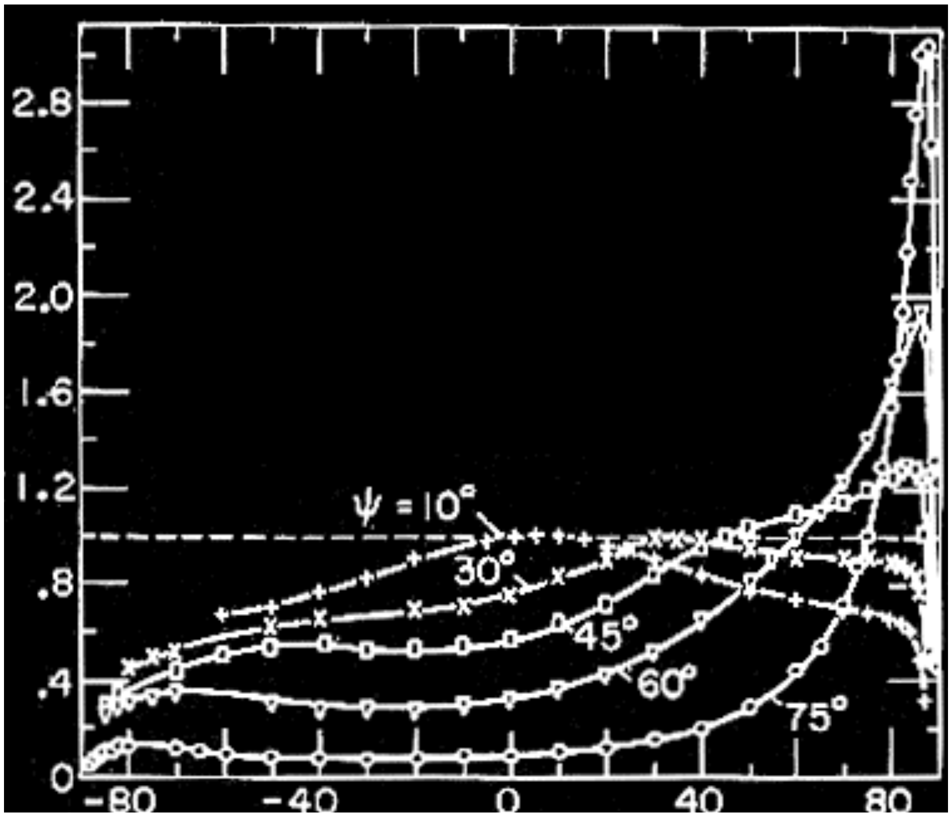
- Many options; C-T chooses simple 2D analysis:

$$G(\mathbf{l},\mathbf{v},\mathbf{h}) = \min\left[1, \frac{2(\mathbf{n}\cdot\mathbf{h})(\mathbf{n}\cdot\mathbf{v})}{\mathbf{v}\cdot\mathbf{h}}, \frac{2(\mathbf{n}\cdot\mathbf{h})(\mathbf{n}\cdot\mathbf{l})}{\mathbf{v}\cdot\mathbf{h}}\right]$$

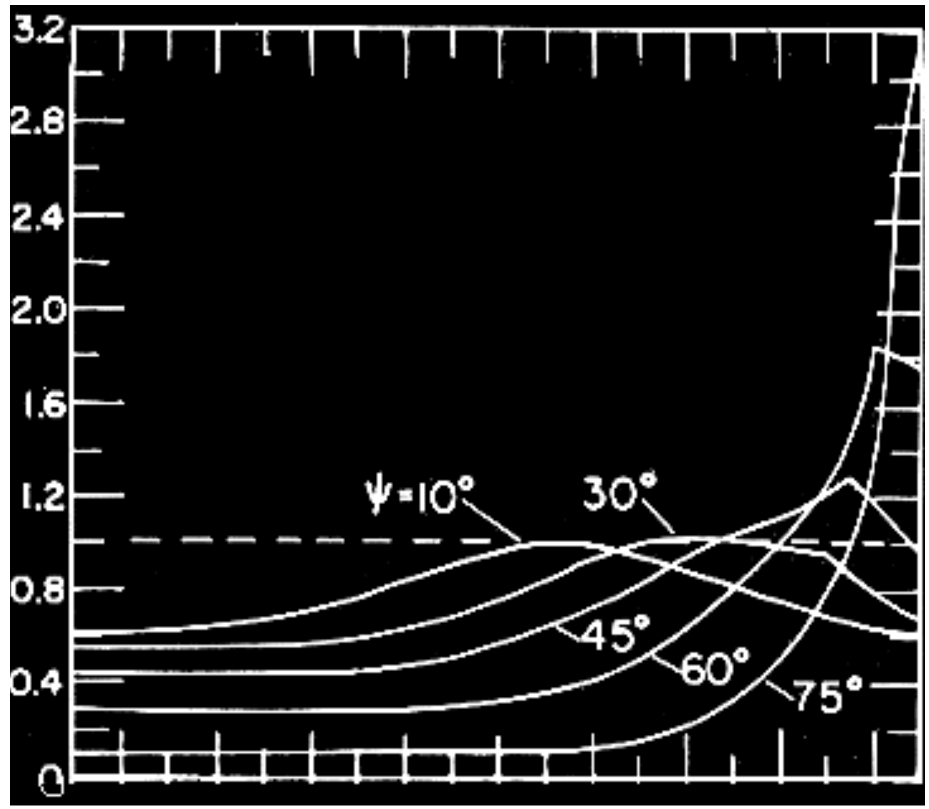


[Stephen Westin]

Model vs. measurement: aluminum



Measured



Model

[Torrance & Sparrow 1967]

Rob Cook's vases

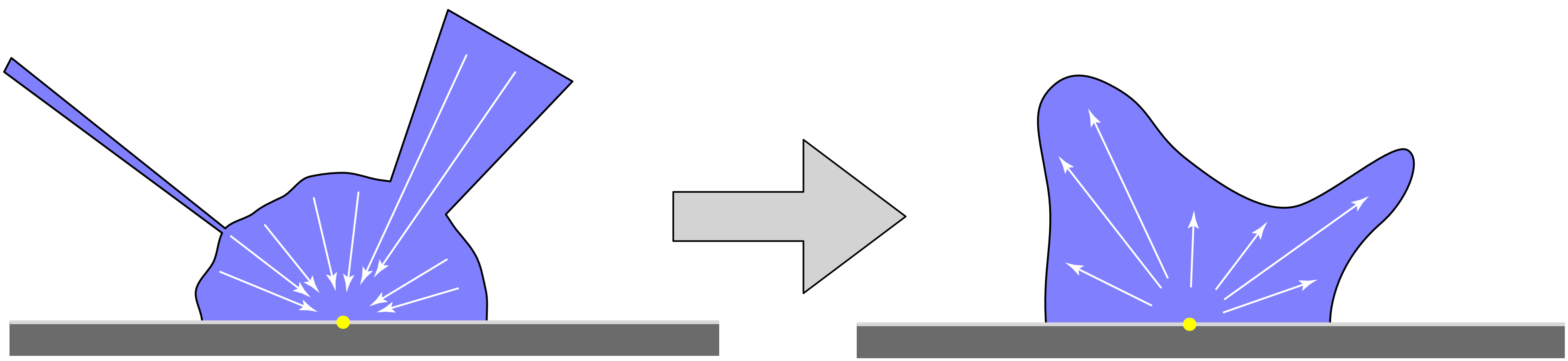
[Cook & Torrance 1981]

Sources of illumination

- Point sources
  - energy emanating from a single point
- Directional sources
  - aka. point sources at infinity
- Area sources
  - energy emanating from an area of surface
- Environment illumination
  - energy coming from far away
- Light reflected from other objects
  - leads to *global illumination*

Light reflection: full picture

- all types of reflection reflect all types of illumination
  – diffuse, glossy, mirror reflection
  – environment, area, point illumination

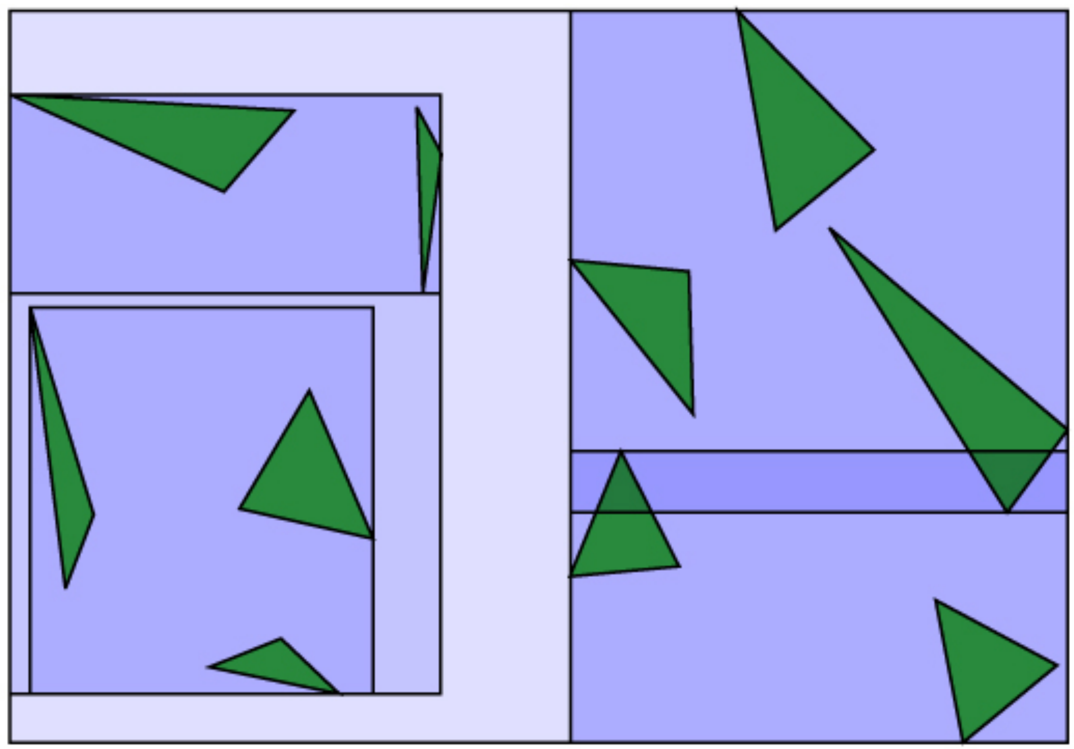


incident distribution (function of direction) | reflected distribution (function of direction)

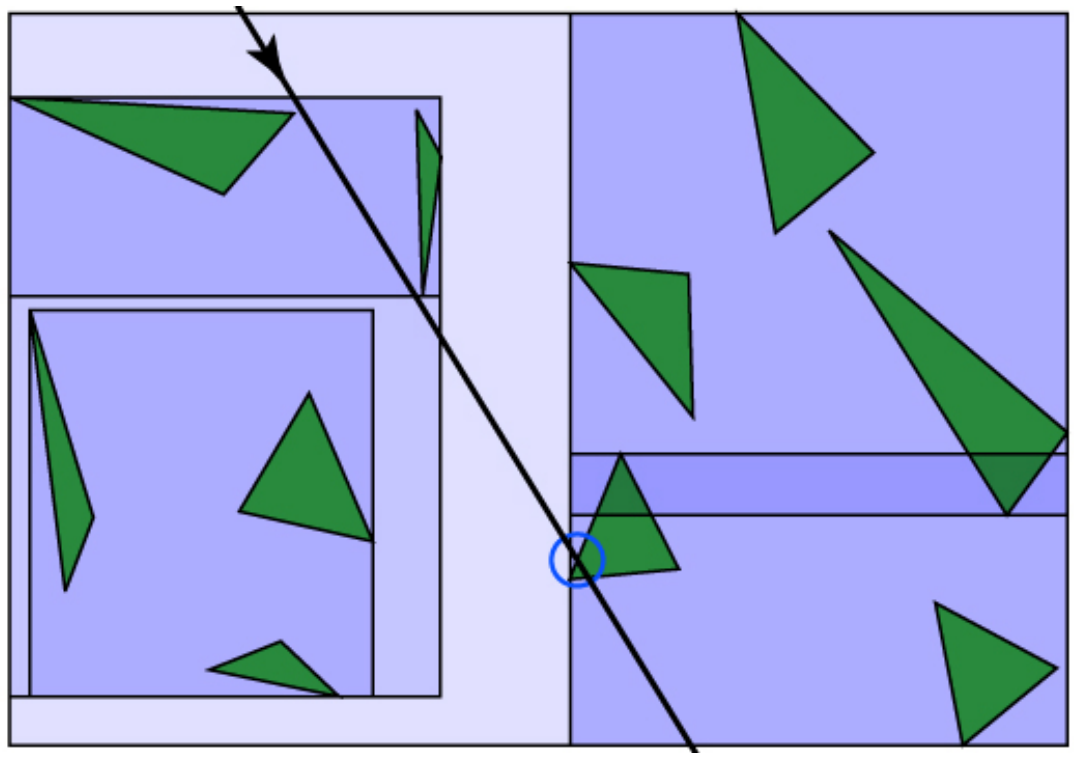
Implementing a bvol hierarchy

- A BoundedSurface can contain a list of Surfaces
- Some of those Surfaces might be more BoundedSurfaces
- Voilà! A bounding volume hierarchy
  – And it's all still transparent to the renderer

BVH construction example



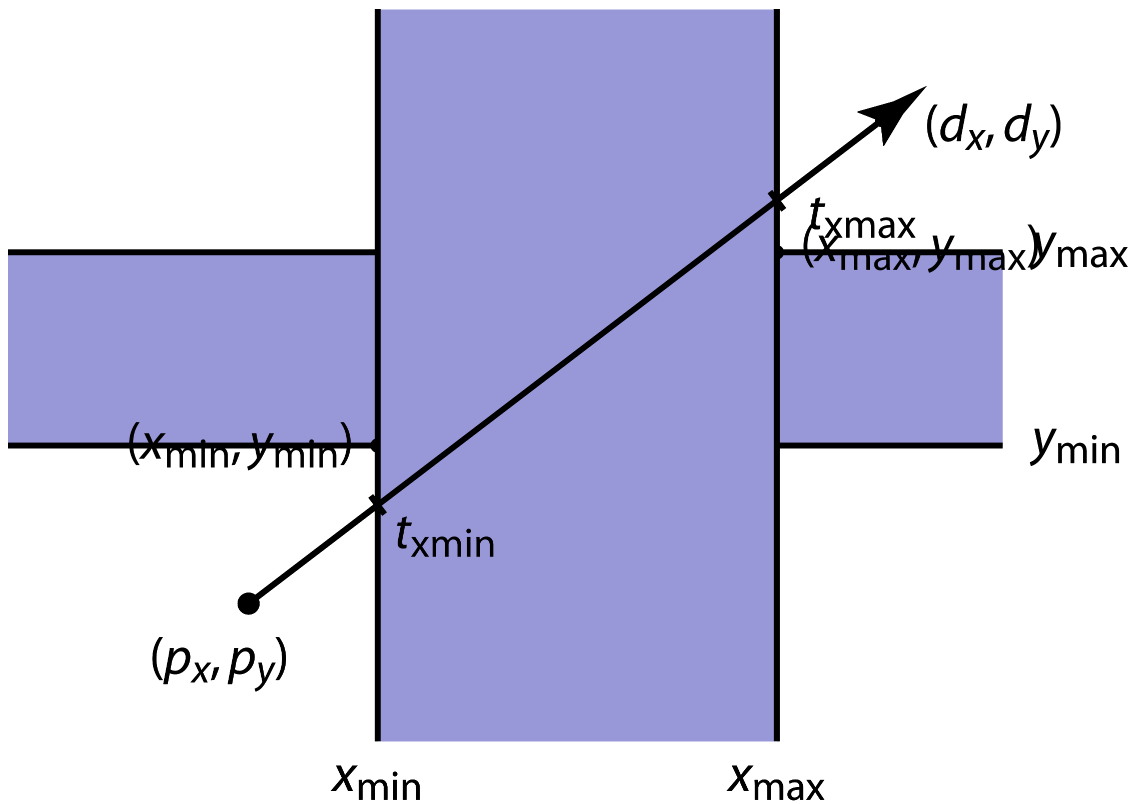
BVH ray-tracing example



Ray-slab intersection

$$p_x + t_{x\min}\, d_x = x_{\min}$$
$$t_{x\min} = (x_{\min} - p_x)/d_x$$

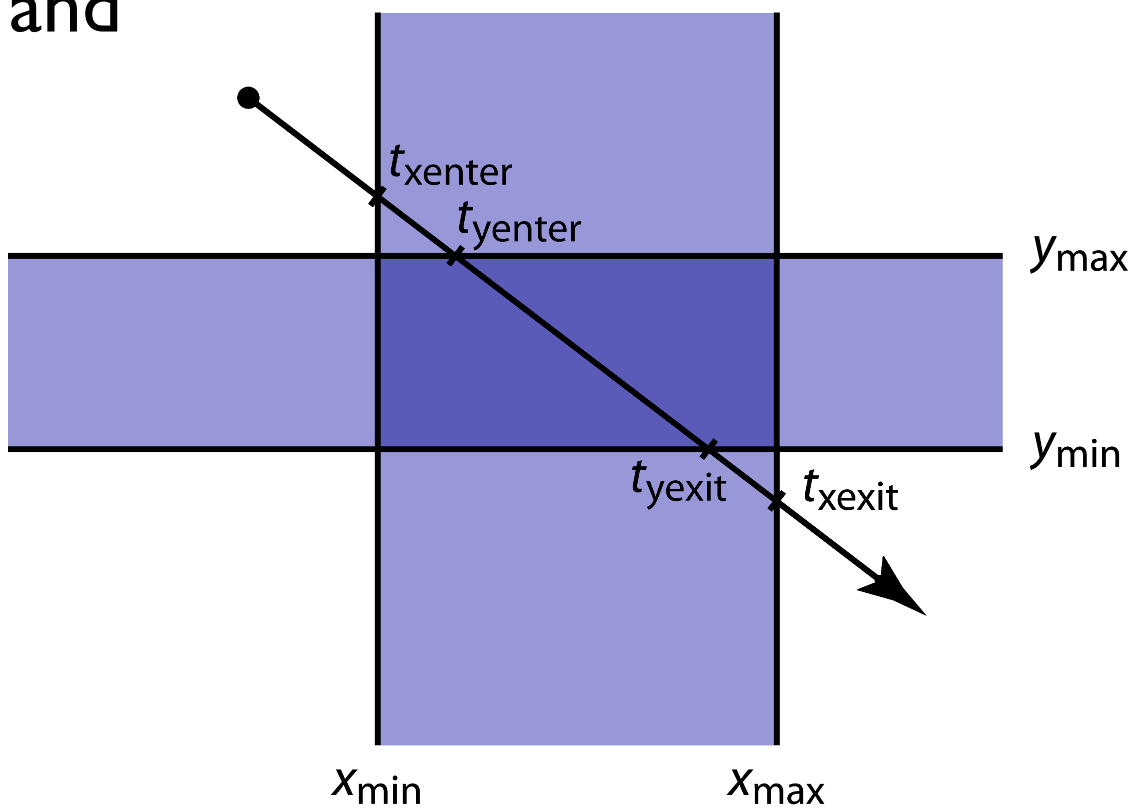
$$p_y + t_{y\min}\, d_y = y_{\min}$$
$$t_{y\min} = (y_{\min} - p_y)/d_y$$



Intersecting intersections

- Each intersection is an interval
- Want last entry point and first exit point

$$t_{x\text{enter}} = \min(t_{x\min}, t_{x\max})$$
$$t_{x\text{exit}} = \max(t_{x\min}, t_{x\max})$$
$$t_{y\text{enter}} = \min(t_{y\min}, t_{y\max})$$
$$t_{y\text{exit}} = \max(t_{y\min}, t_{y\max})$$
$$t_{\text{enter}} = \max(t_{x\text{enter}}, t_{y\text{enter}})$$
$$t_{\text{exit}} = \min(t_{x\text{exit}}, t_{y\text{exit}})$$



Building a hierarchy

- Top Down vs Bottom Up
- Top down
  - Make bbox for whole scene, then split into (maybe 2) parts
    - Recurse on parts
    - Stop when there are just a few objects in your box
- Bottom Up
  - Expensive, but optimal
  - Good for static (maybe)

Building a hierarchy

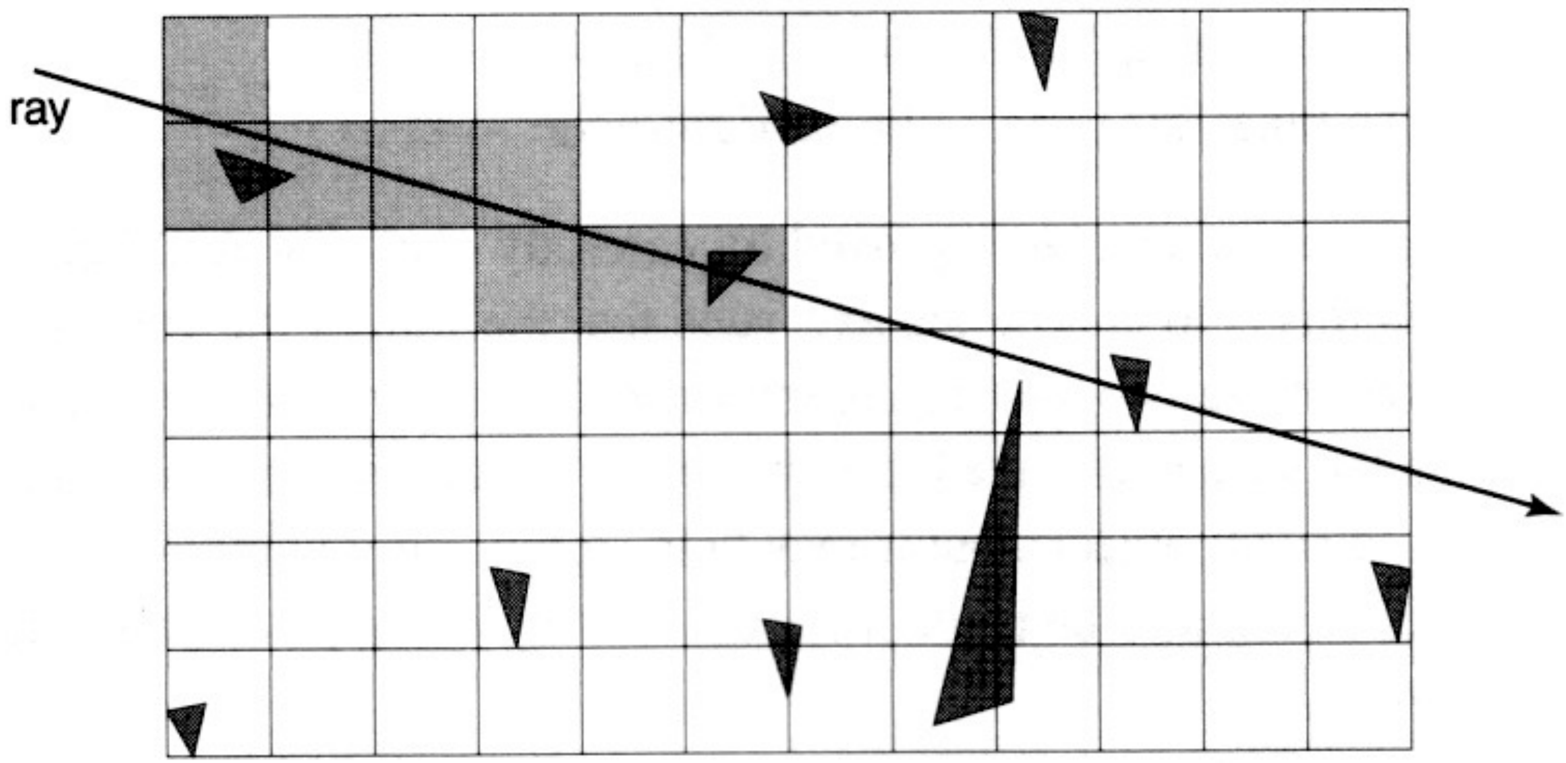
- How to partition?
  - Ideal: clusters
  - Practical: partition along axis
    - Center partition
      - Less expensive, simpler
      - Unbalanced tree
    - Median partition
      - More expensive
      - More balanced tree
    - Surface area heuristic
      - Model: expected cost of ray intersection
      - Generally produces best-performing trees

BVH Intersection

- Trace ray with root node
- If intersection, trace rays with ALL children
  - If no intersection, eliminate tests with all children

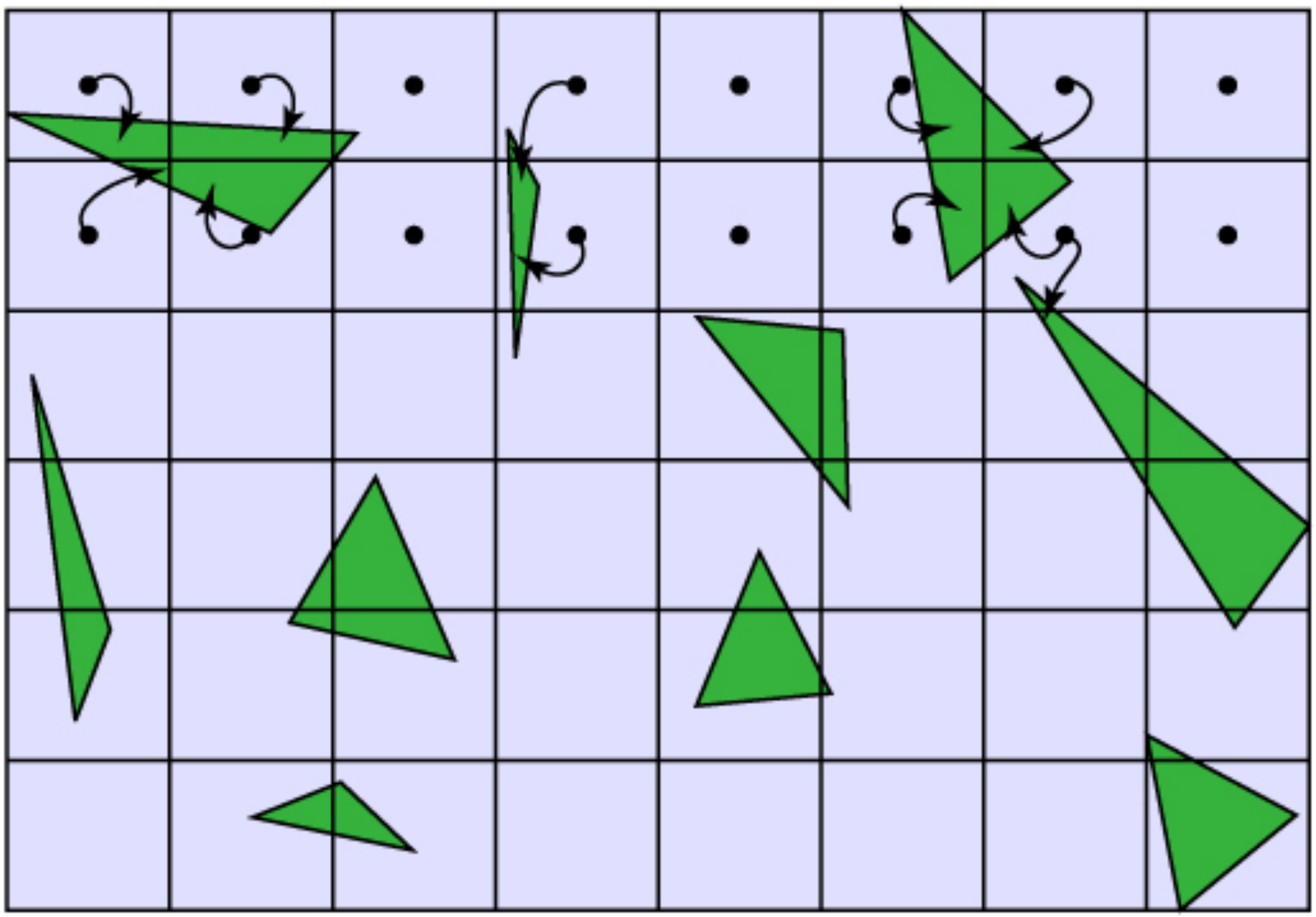
Regular space subdivision

- An entirely different approach: uniform grid of cells

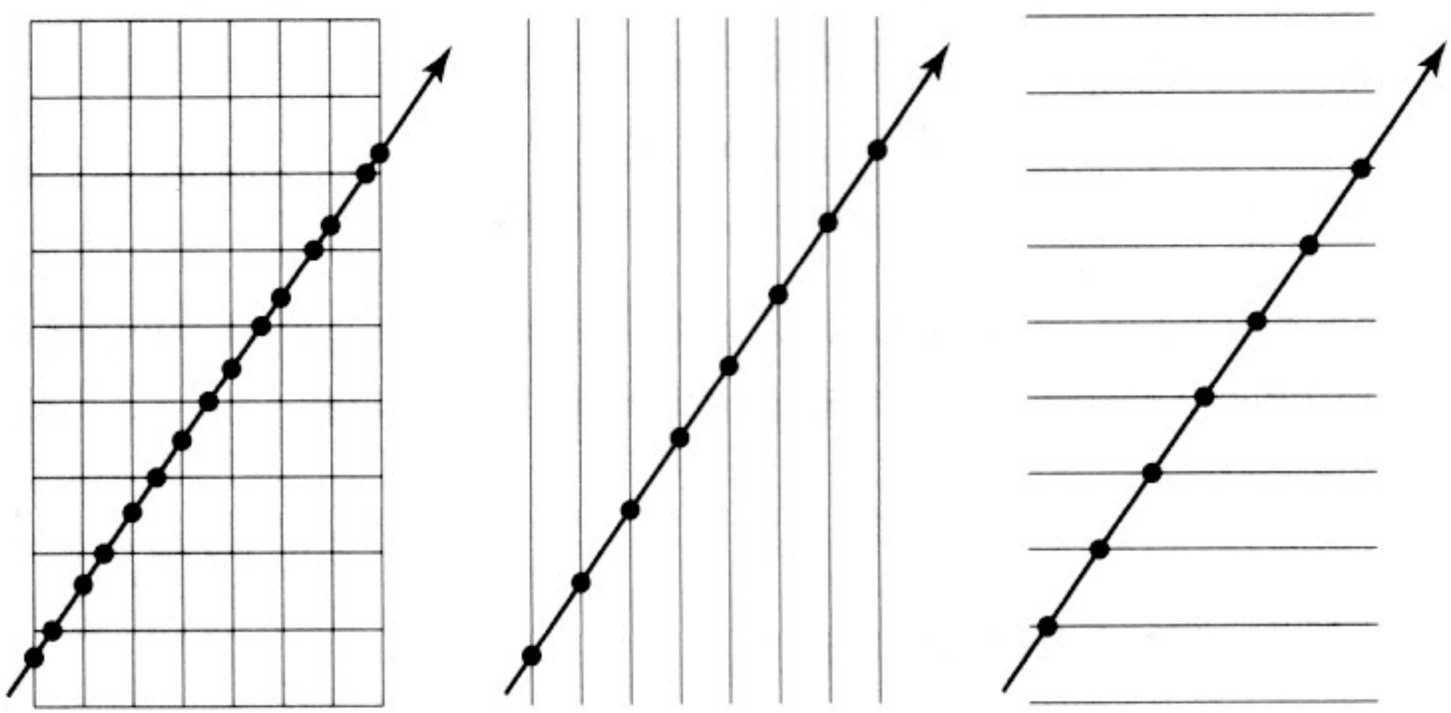


Regular grid example

- Grid divides space, not objects

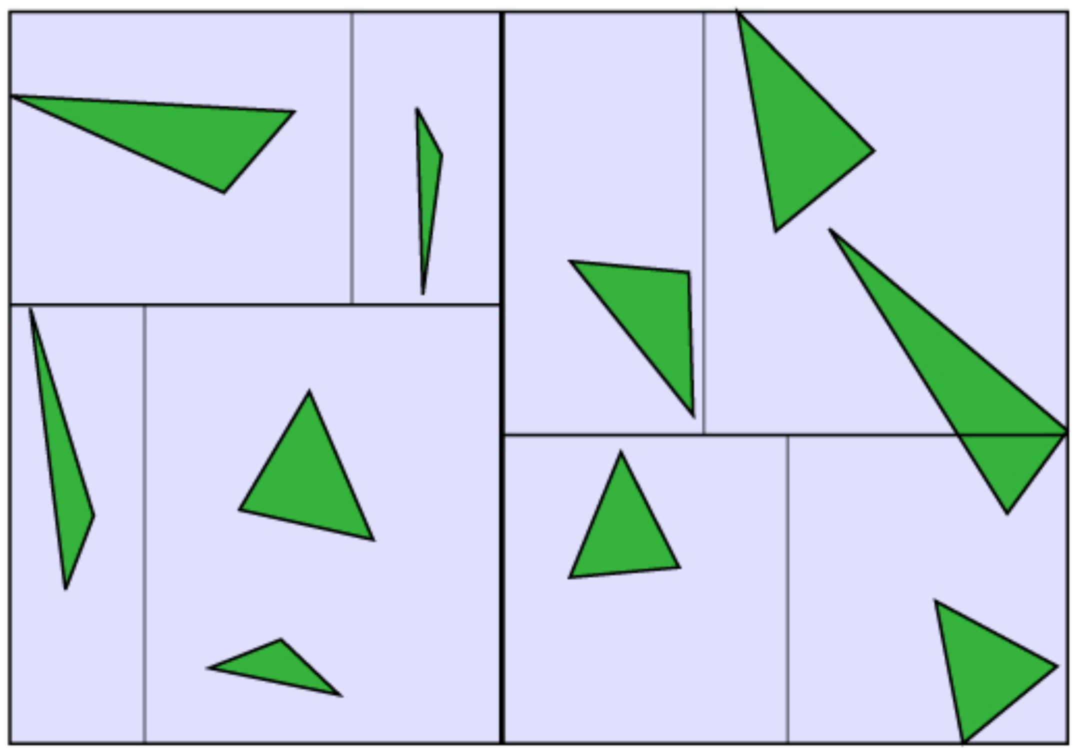


Traversing a regular grid



Non-regular space subdivision

- *k*-d Tree
  - subdivides space, like grid
  - adaptive, like BVH



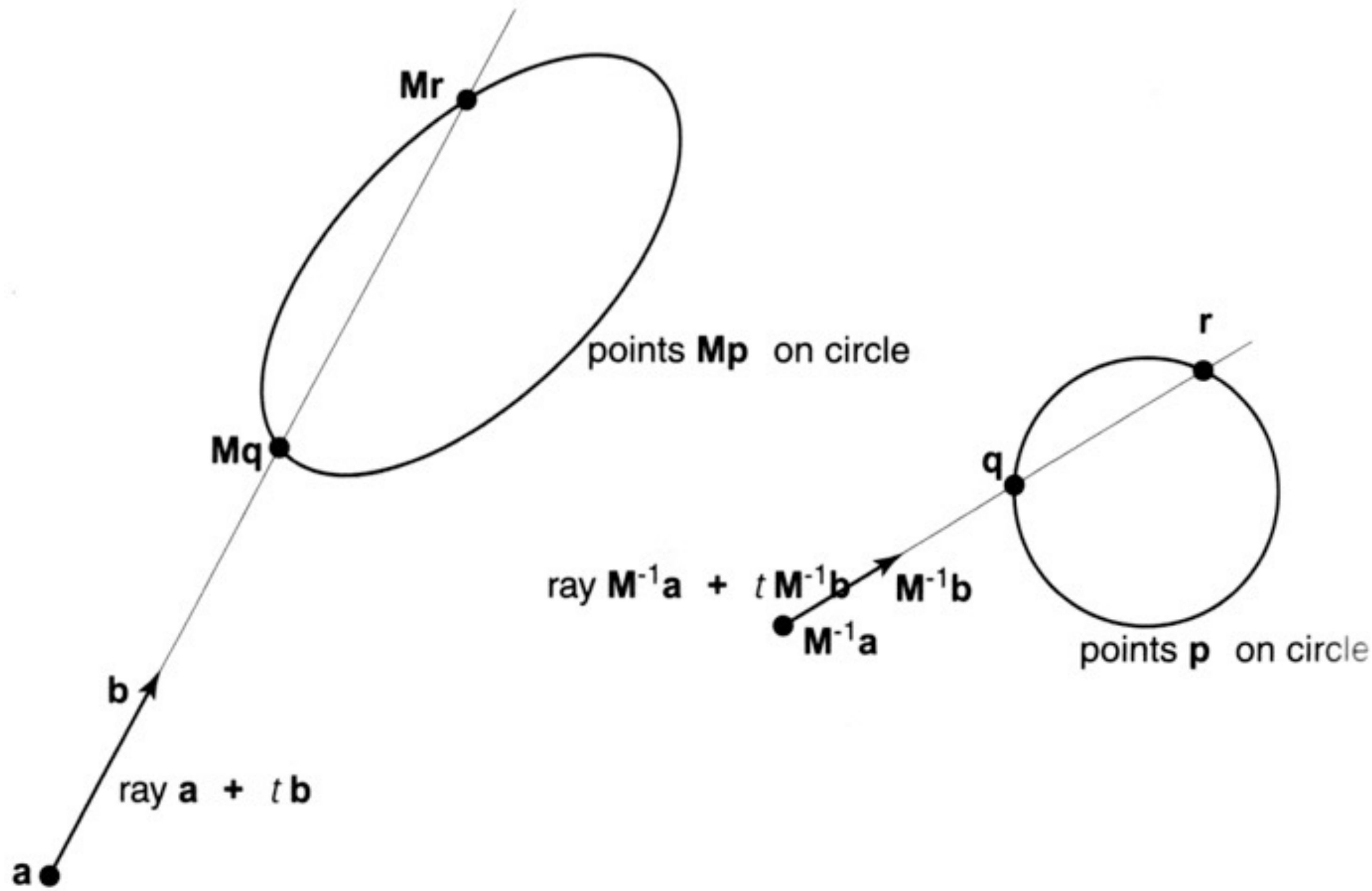
Implementing acceleration structures

- Conceptually simple to build acceleration structure into scene structure
- Better engineering decision to separate them

Transforming objects

- In modeling, we've seen the usefulness of transformations
  - How to do the same in RT?
- Take spheres as an example: want to support transformed spheres
  - Need a new Surface subclass
- Option 1: transform sphere into world coordinates
  - Write code to intersect arbitrary ellipsoids
- Option 2: transform ray into sphere's coordinates
  - Then just use existing sphere intersection routine

Intersecting transformed objects



[S]

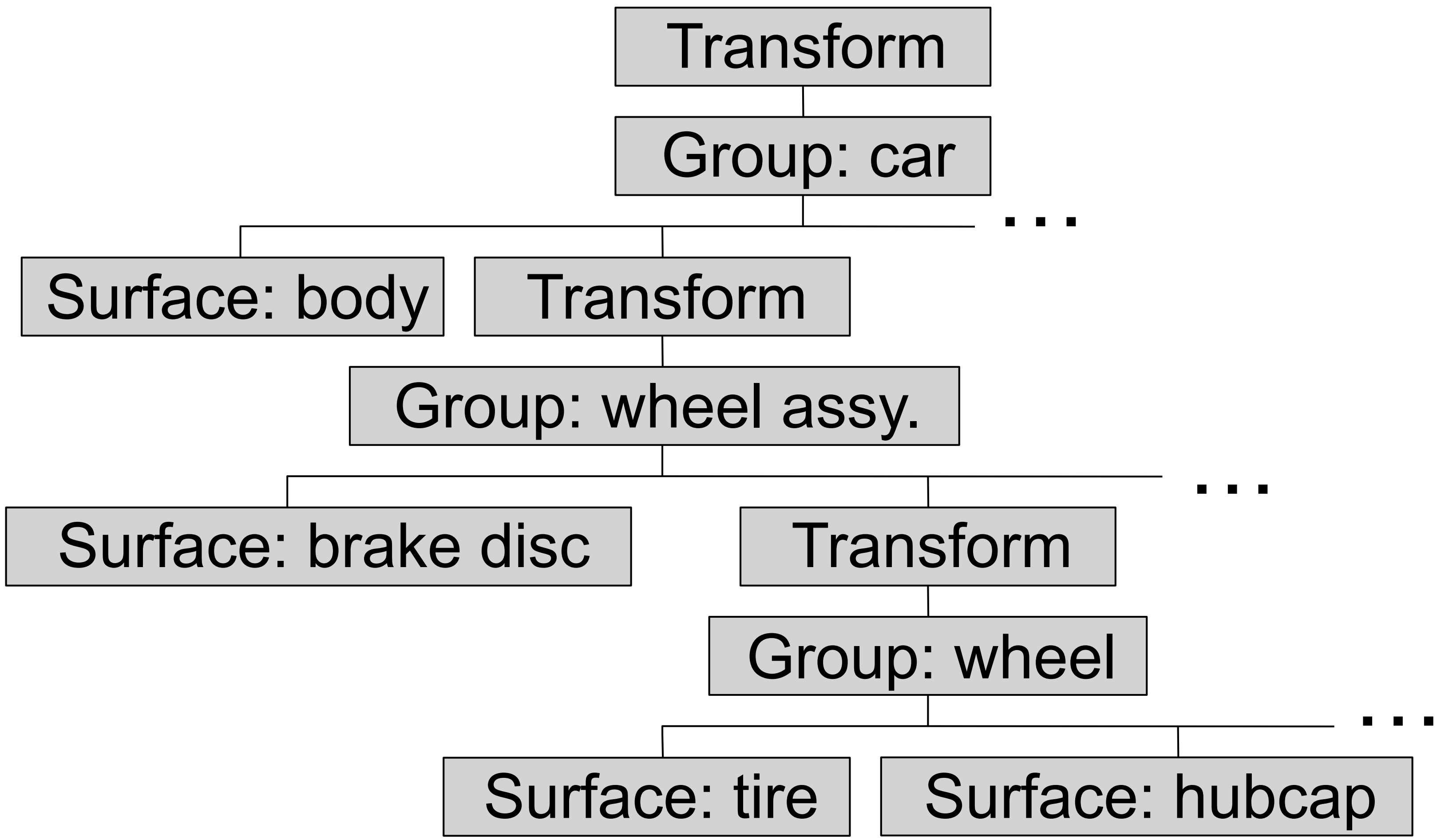
Implementing RT transforms

- Create wrapper object "TransformedSurface"
  - Has a transform T and a reference to a surface S
  - To intersect:
    - Transform ray to local coords (by inverse of T)
    - Call surface.intersect
    - Transform hit data back to global coords (by T)
      - Intersection point
      - Surface normal
      - Any other relevant data (maybe none)

Groups, transforms, hierarchies

- Often it's useful to transform several objects at once
  – Add "SurfaceGroup" as a subclass of Surface
    - Has a list of surfaces
    - Returns closest intersection
      – Opportunity to move ray intersection code here to avoid duplication
- With TransformedSurface and SurfaceGroup you can put transforms below transforms
  – Voilà! A transformation hierarchy.

A transformation hierarchy

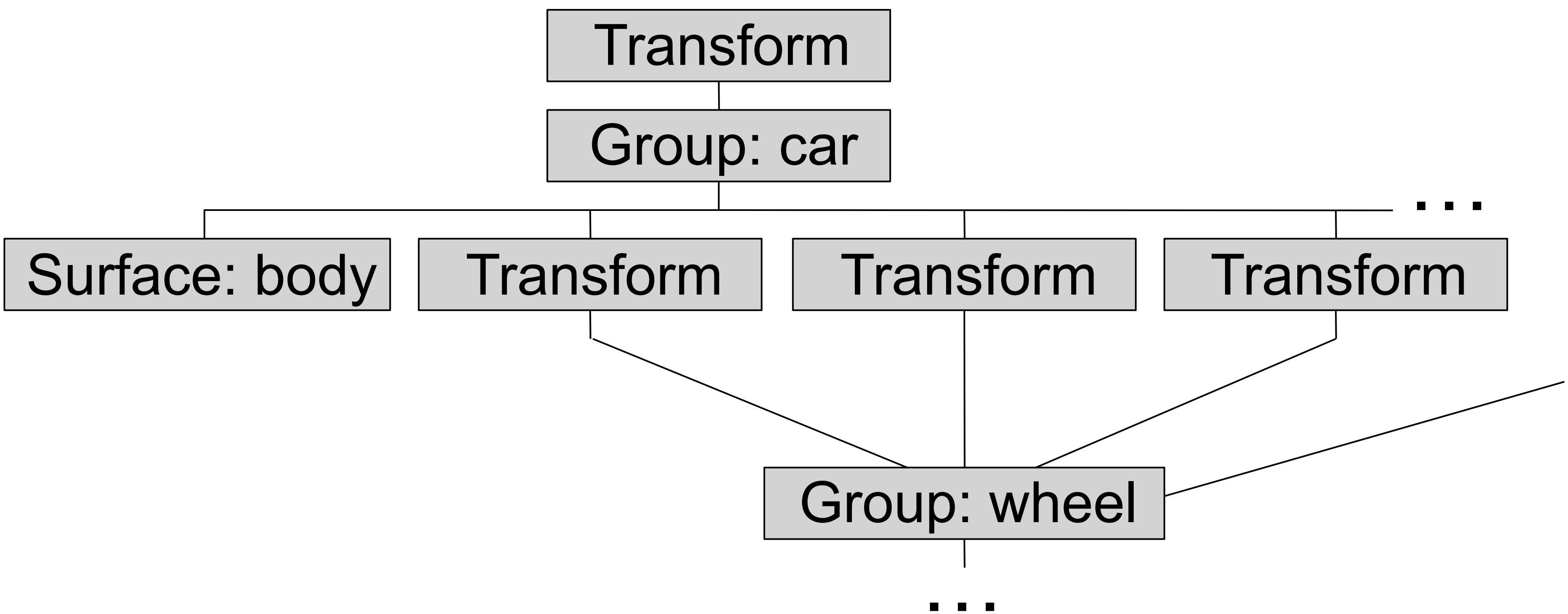


– Common optimization: merge transforms with groups

Instancing

- Transform objects several ways
  - Many models have repeated subassemblies
    - Mechanical parts (wheels of car)
    - Multiple objects (chairs in classroom, …)
  - Nothing stops you from creating two TransformedSurface objects that reference the same Surface
    - Allowing this makes the transformation tree into a DAG
      - (directed acyclic graph)
    - Mostly this is transparent to the renderer

With instancing



Advanced Ray Tracing

Basic ray tracing

- Many advanced methods build on the basic ray tracing paradigm
- Basic ray tracer: one sample for everything
  - –one ray per pixel
  - –one shadow ray for every point light
  - –one reflection ray, possibly one refraction ray, per intersection

[Glassner 89]

Discontinuities in basic RT

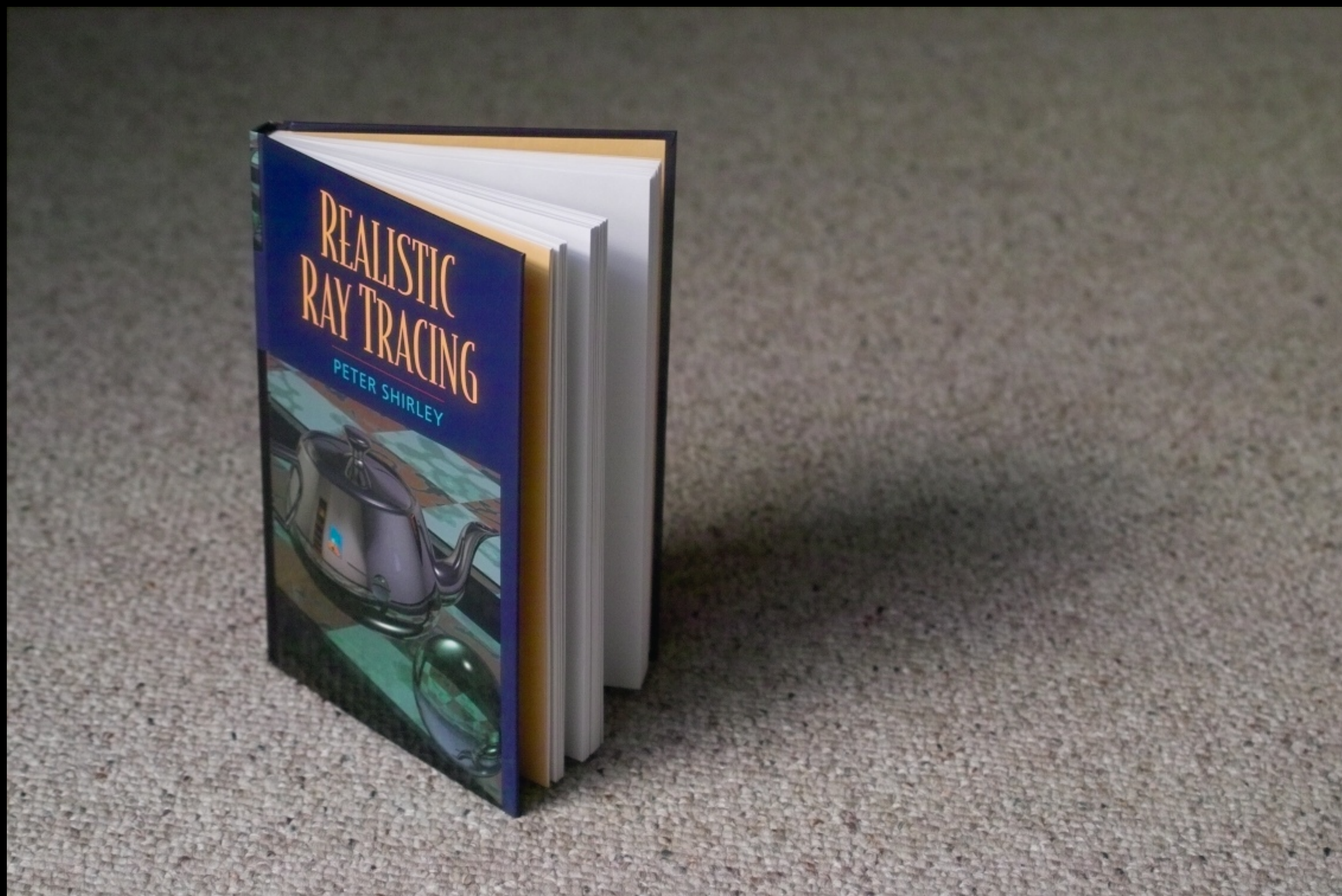
- Perfectly sharp object silhouettes in image
  –leads to aliasing problems (stair steps)
- Perfectly sharp shadow edges
  –everything looks like it's in direct sun
- Perfectly clear mirror reflections
  –reflective surfaces are all highly polished
- Perfect focus at all distances
  –camera always has an infinitely tiny aperture
- Perfectly frozen instant in time (in animation)
  –motion is frozen as if by strobe light

- Latest Pixar short
- Made partly to showcase new more photorealistic rendering

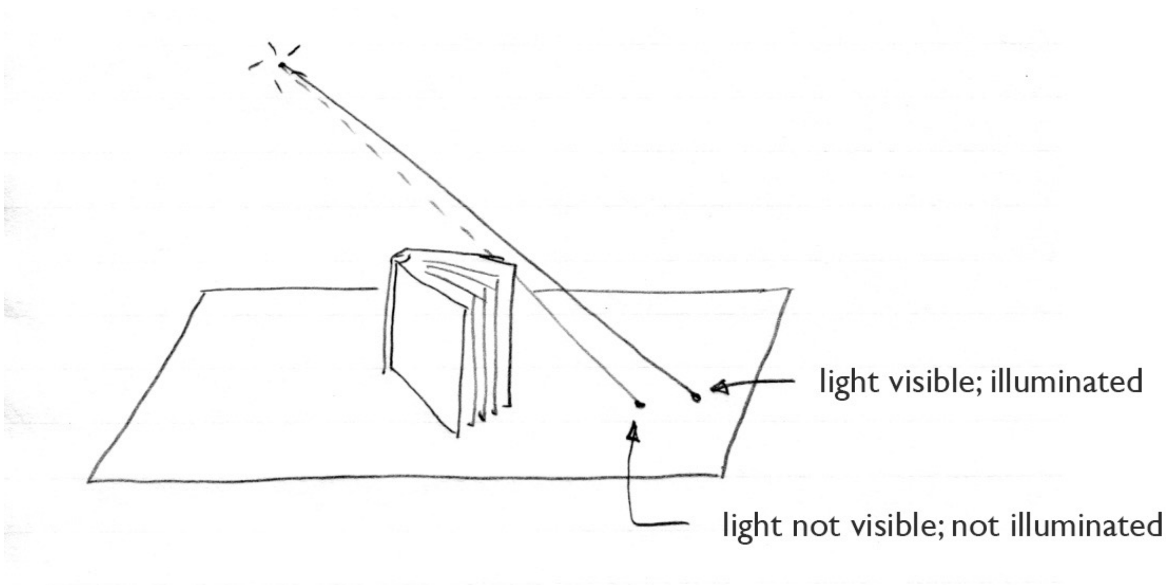
–much of it based on the ideas in this lecture

worth a look:
http://rainycitytales332.tumblr.com

Soft shadows

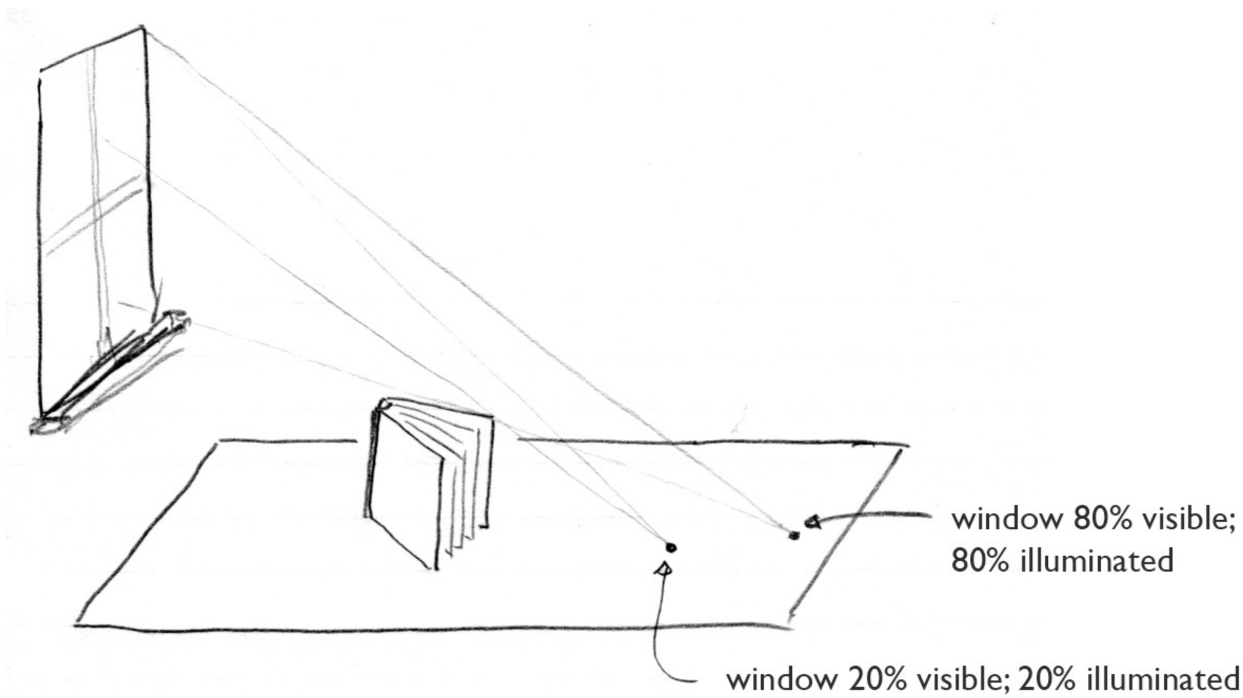


Cause of soft shadows



point lights cast hard shadows

Cause of soft shadows

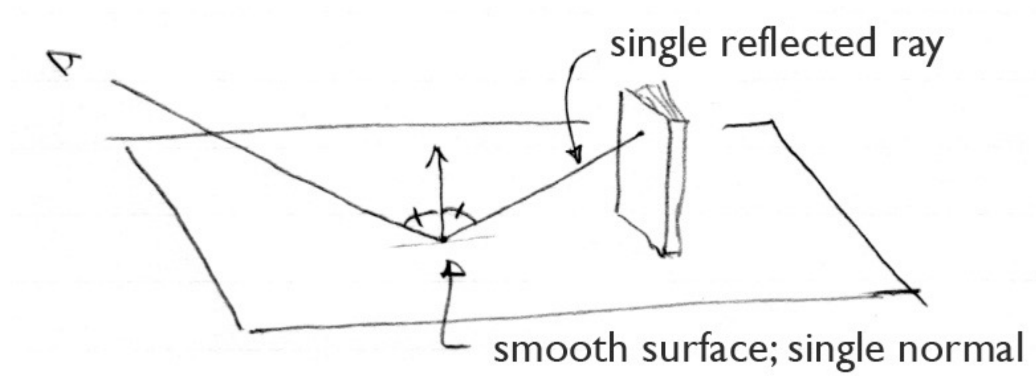


area lights cast soft shadows

Glossy reflection

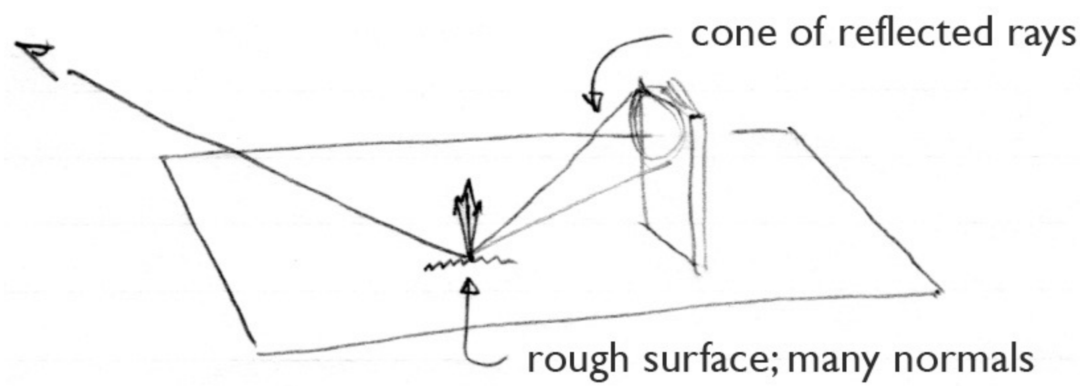
[Lafortune et al. 97]

Cause of glossy reflection



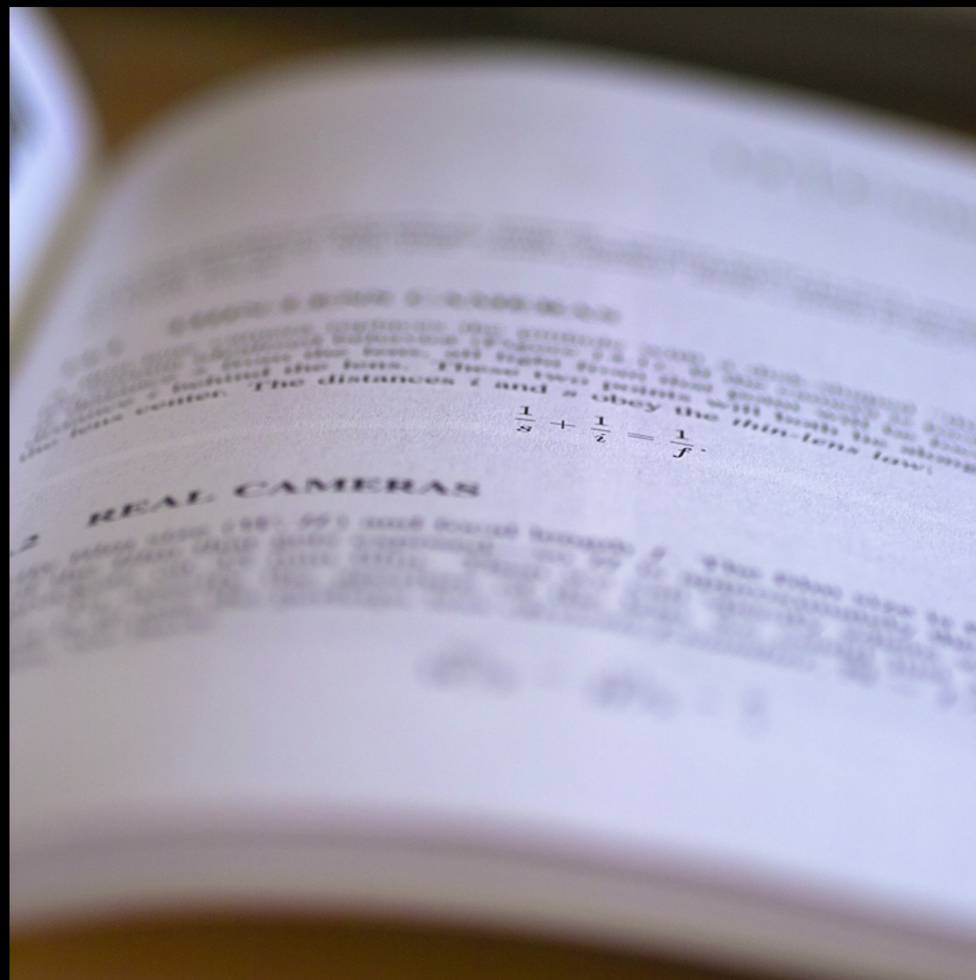
smooth surfaces produce sharp reflections

Cause of glossy reflection

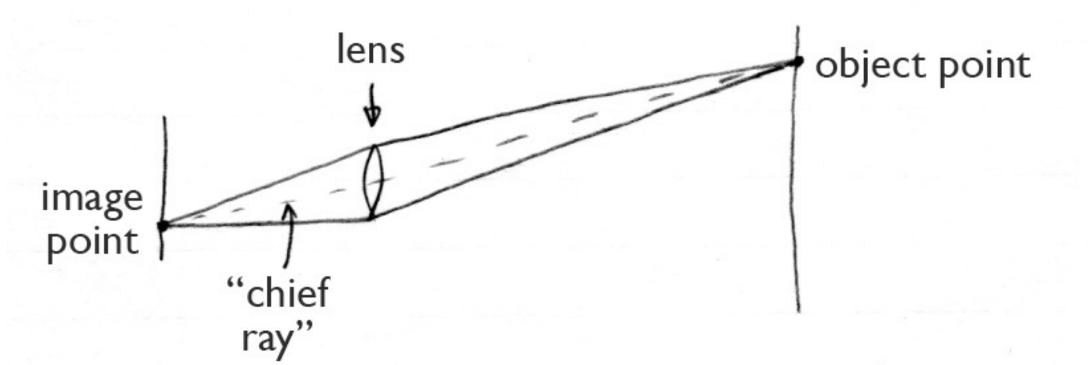


rough surfaces produce soft (glossy) reflections

Depth of field

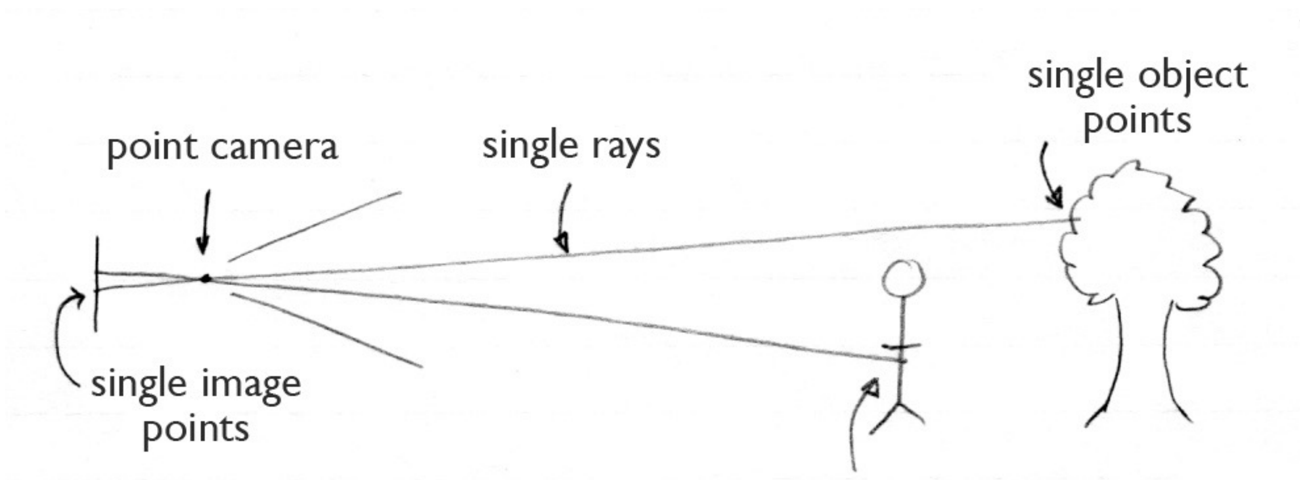


Cause of focusing effects



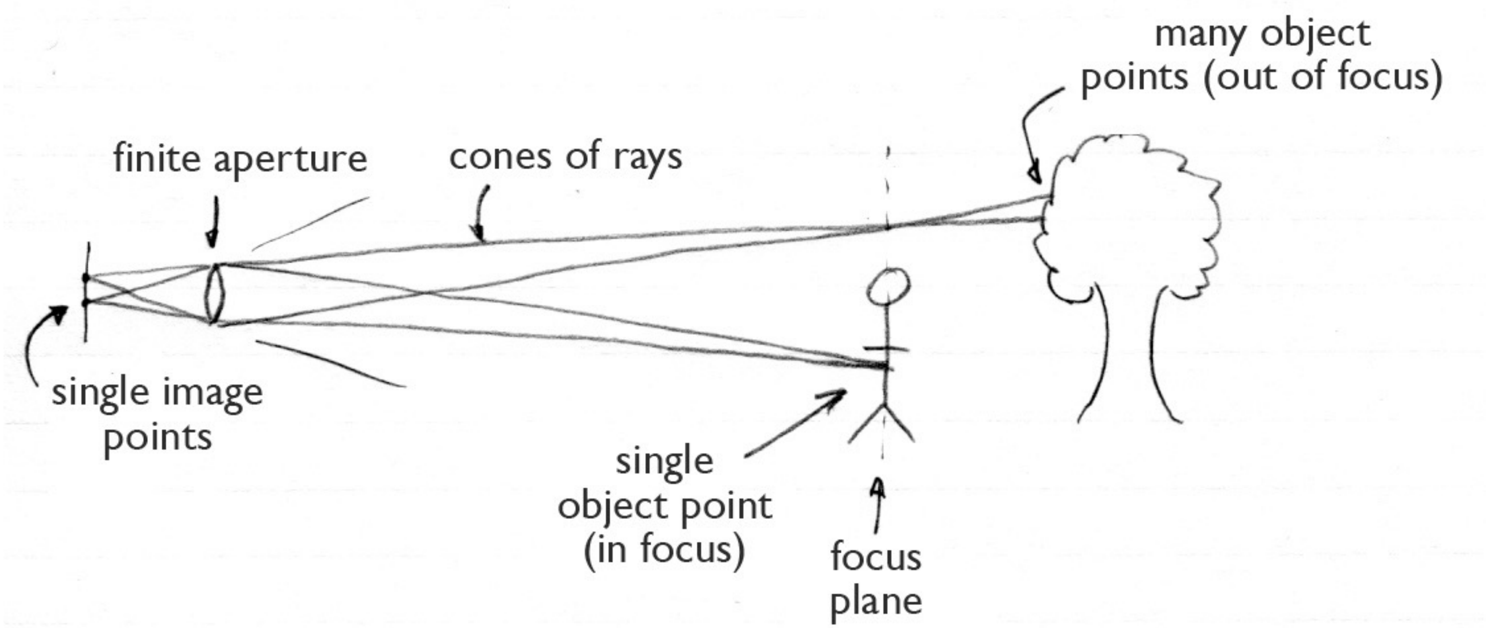
what lenses do (roughly)

Cause of focusing effects



point aperture produces always-sharp focus

Cause of focusing effects

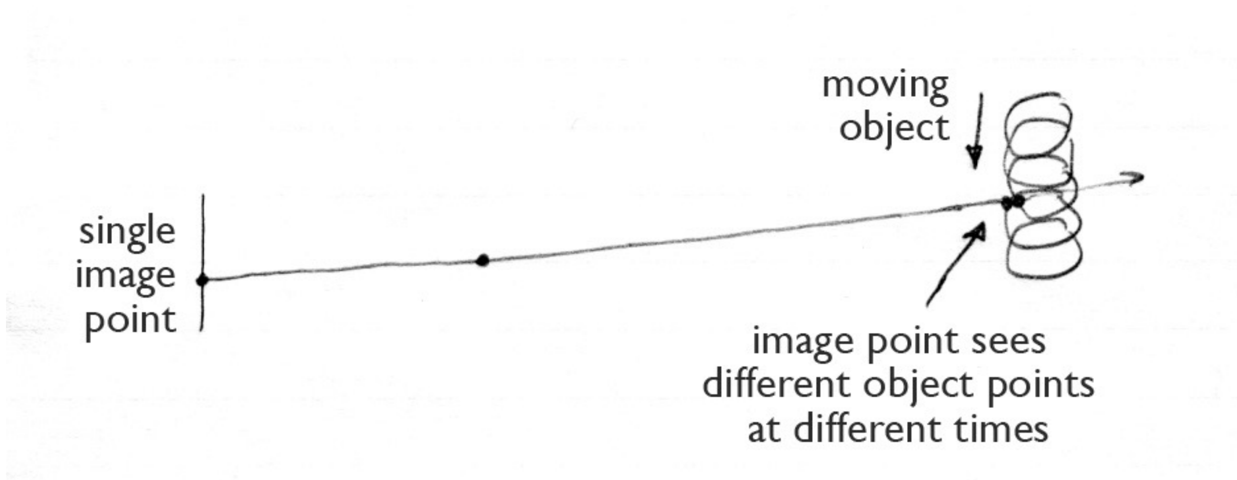


finite aperture produces limited depth of field

Motion blur

[Cook, Porter, Carpenter 1984]

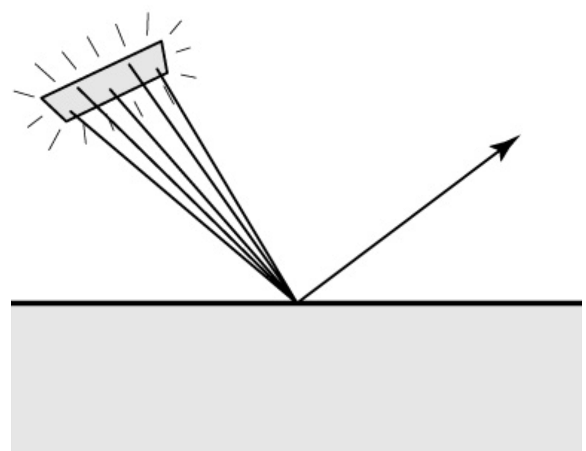
Cause of motion blur



Pixar—*Monsters University* (2013)

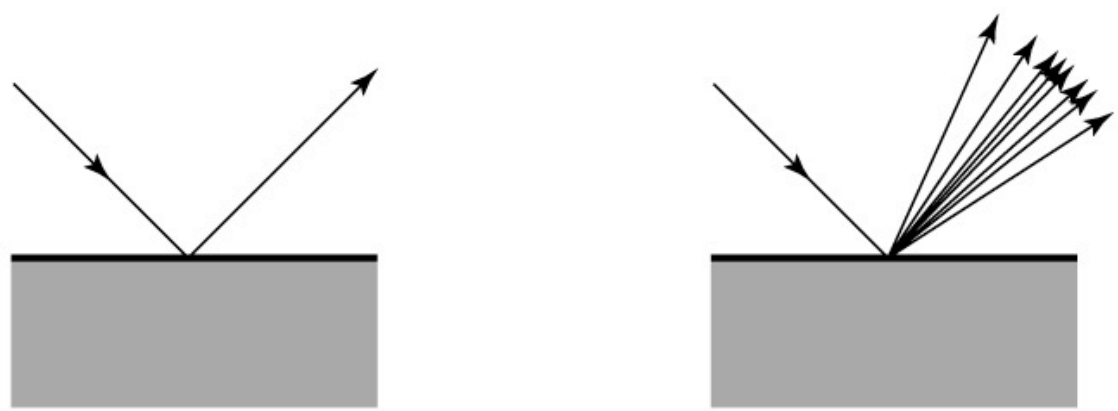
Creating soft shadows

- For area lights: use many shadow rays
  - and each shadow ray gets a different point on the light
- Choosing samples
  - general principle: start with uniform in square



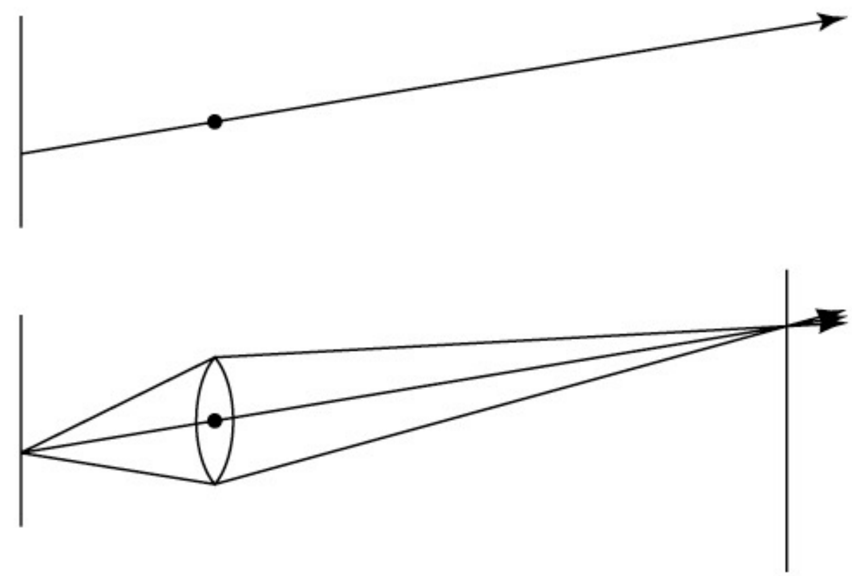
Creating glossy reflections

- Jitter the reflected rays
  - –Not exactly in mirror direction; add a random offset
  - –Can work out math to match Phong exactly
  - –Can do this by jittering the normal if you want



Depth of field

- Make eye rays start at random points on aperture
  - –always going toward a point on the focus plane



Motion blur

- Caused by finite shutter times
  - –strobing without blur
- Introduce time as a variable throughout the system
  - –object are hit by rays according to their position at a given time
- Then generate rays with times distributed over shutter interval