Lecture #18

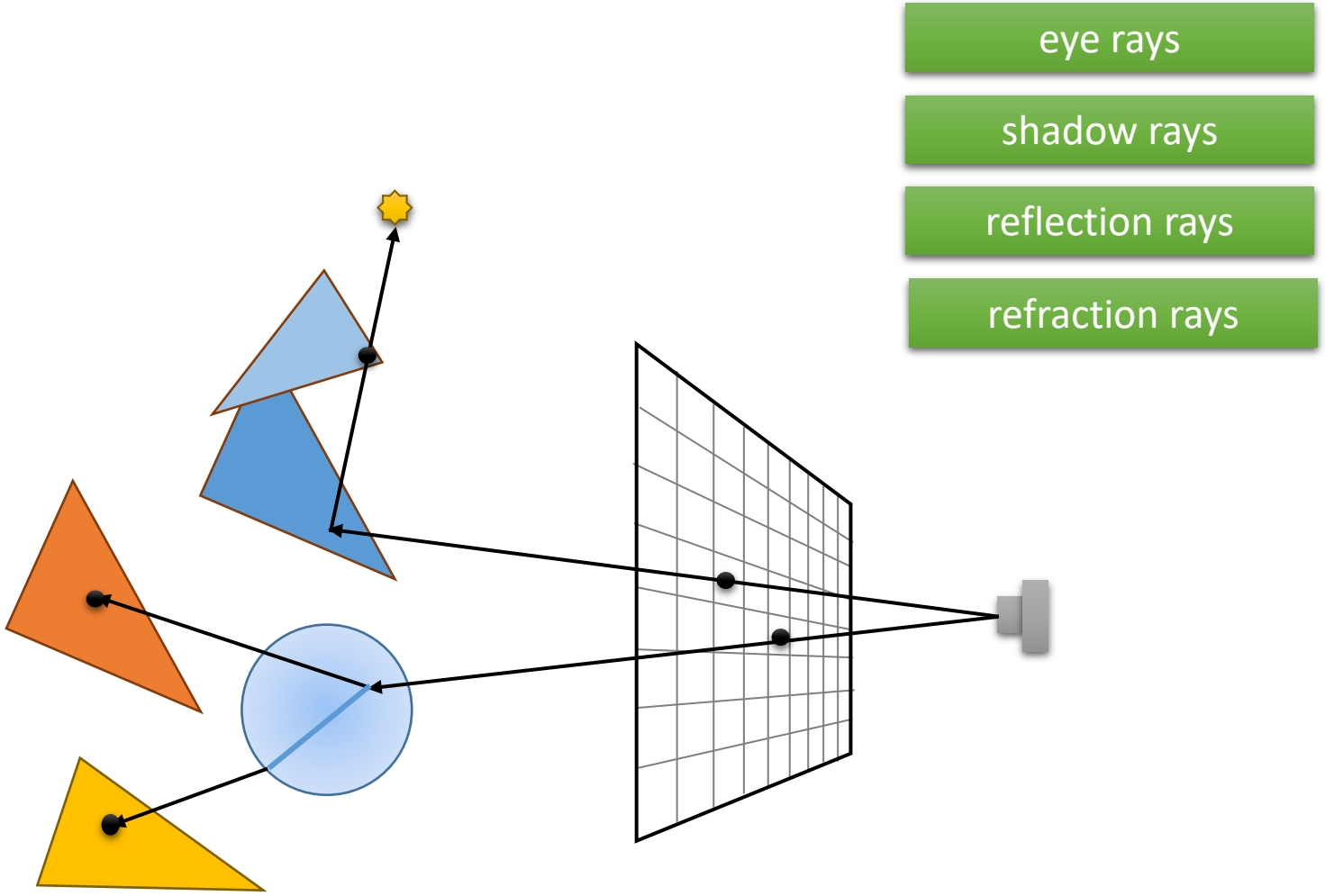
Distribution Ray Tracing

Computer Graphics

Winter Term 2020/21

Marc Stamminger / Roberto Grosso

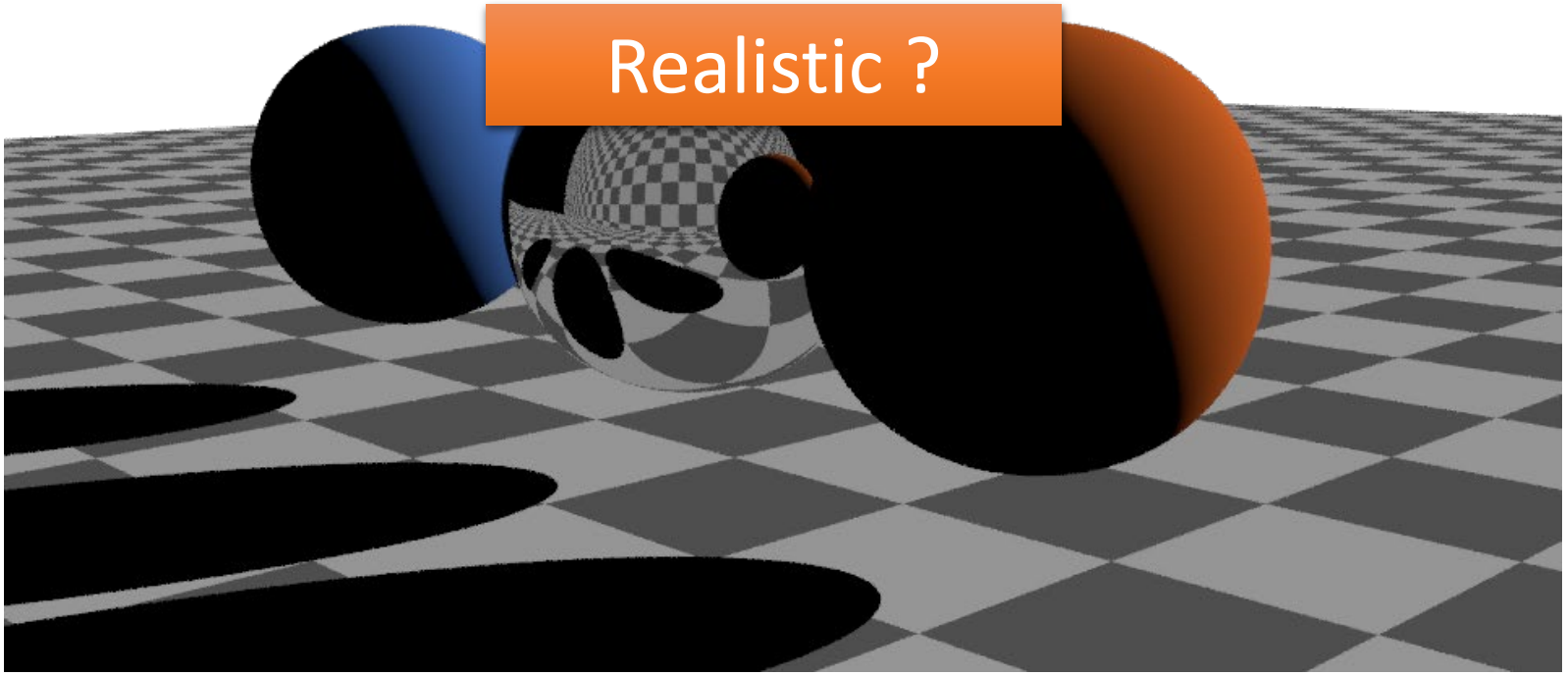
Remember: Ray Tracing



- **Recursive Process !**

Ray Tracing

- Simple result



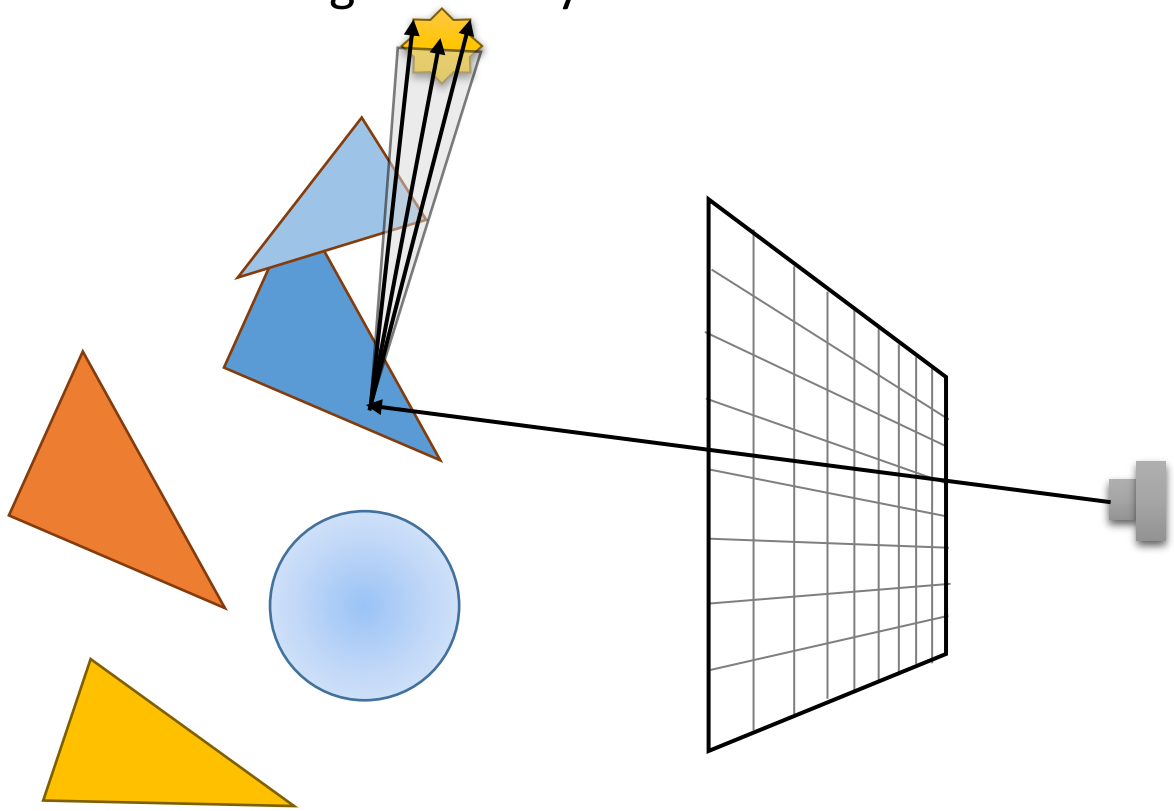
Ray Tracing

- Unrealistic:
  - hard shadow boundaries → real light sources have some extent, so shadow is somewhat blurred
  - indirect light is missing, shadow regions are never completely black
  - often objects are not a perfect mirror, reflections are more or less blurred
  - …

- With **Distribution Ray Tracing**, we extend ray tracing by sampling additional domains with multiple rays to achieve different effects.

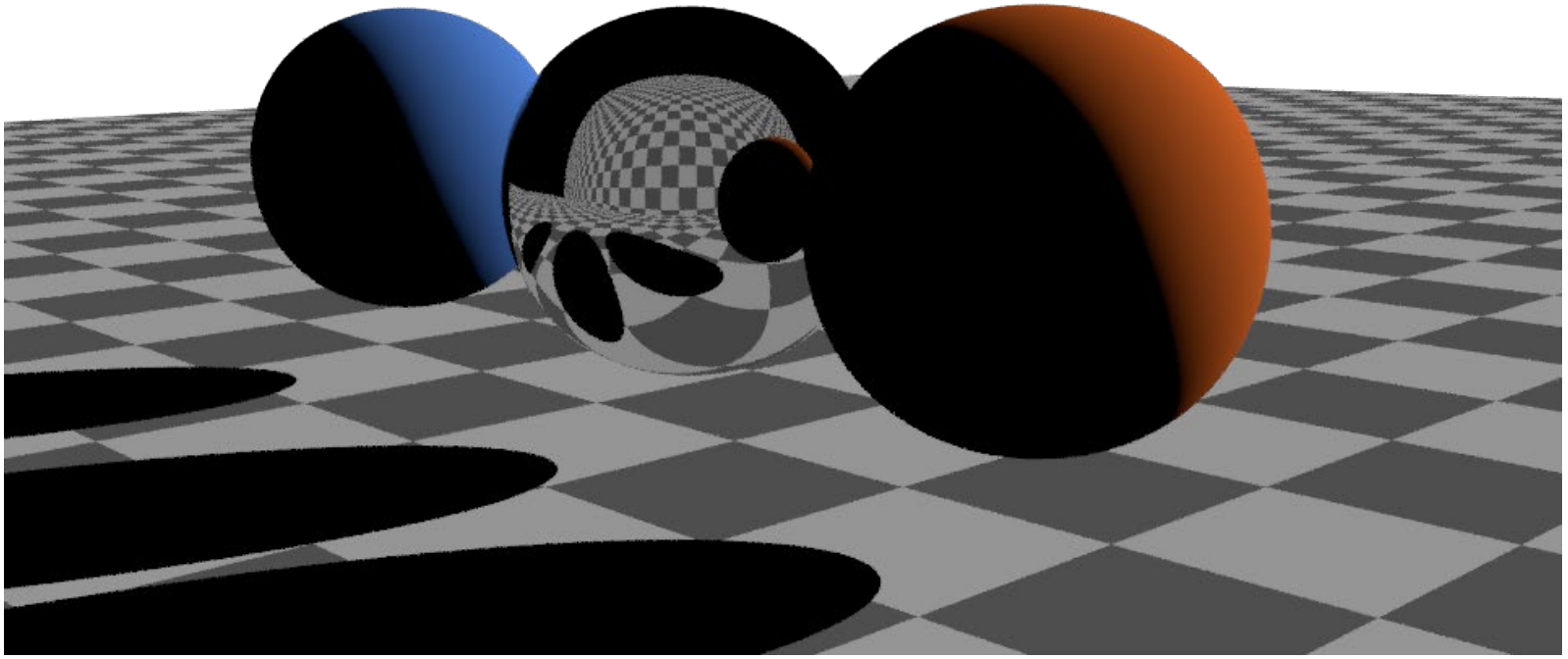
Sampling the light source

- Real light sources are not points, but have some extent
  → shadow rays should be distributed over light source
  → jitter light source by some radius, use multiple shadow rays
  → shadow value is average visibility



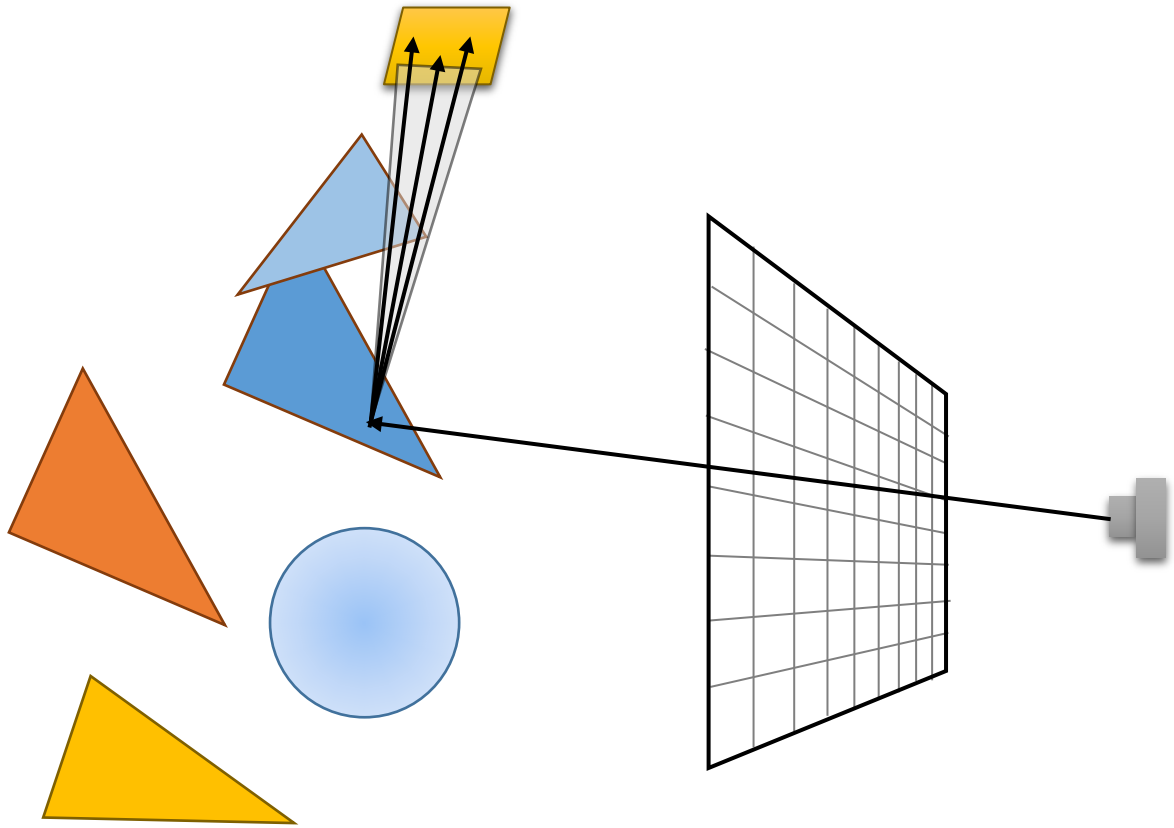
Sampling the light source

- Result



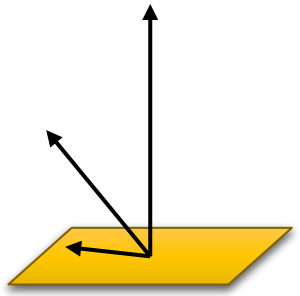
Sampling the light source

- better: define **Area Light Source** and sample this area with shadow rays

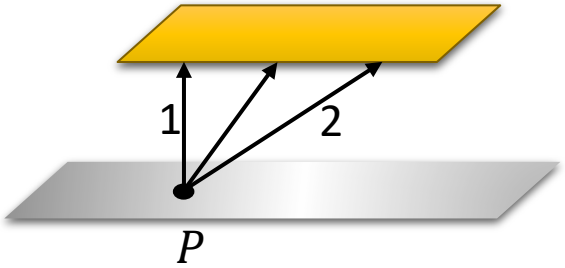


Sampling the light source

- **Problem (i):**
  Area Light Sources emit more light in perpendicular direction than under a grazing angle



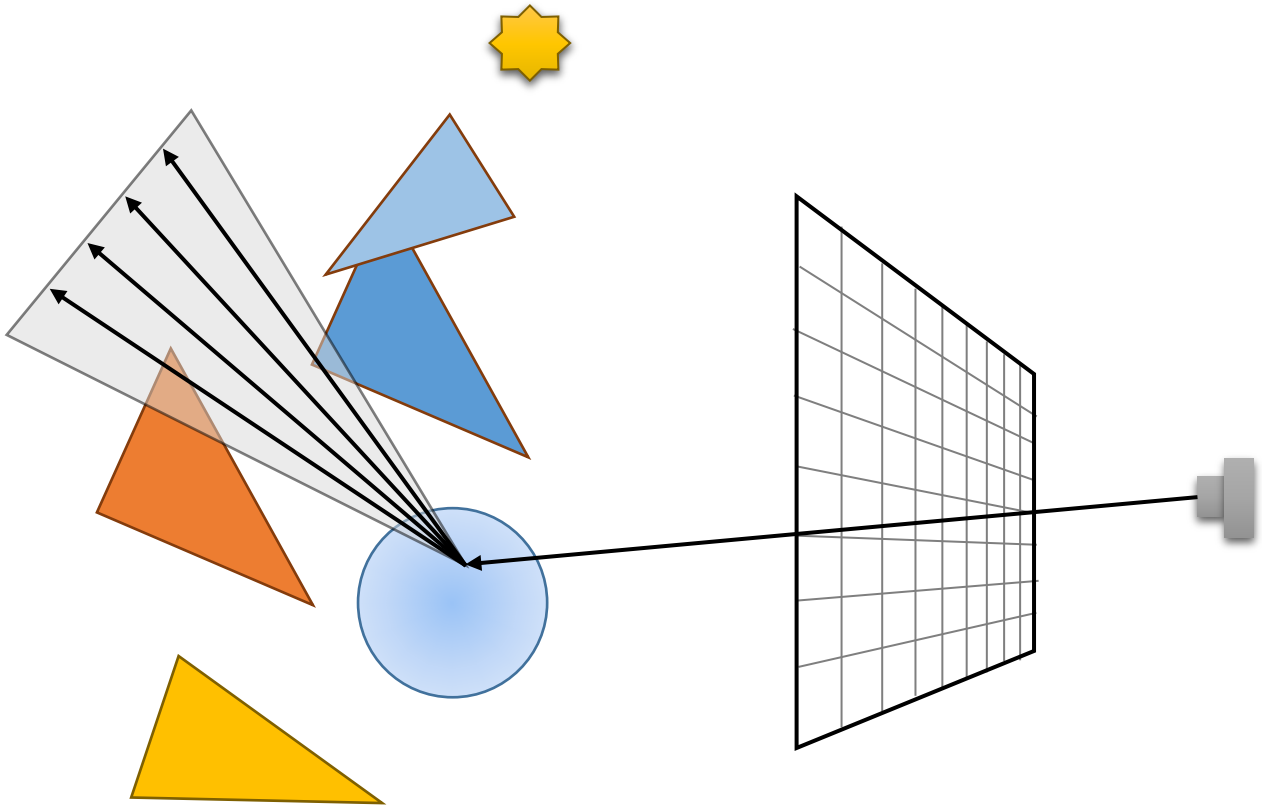
- **Problem (ii)**
  For P, ray #1 is more important than #2
  → occlusion should be weighted accordingly



- **How to do this weighting ?**
  → we have to understand the physics of light transport
  → see lecture “Global Illumination”

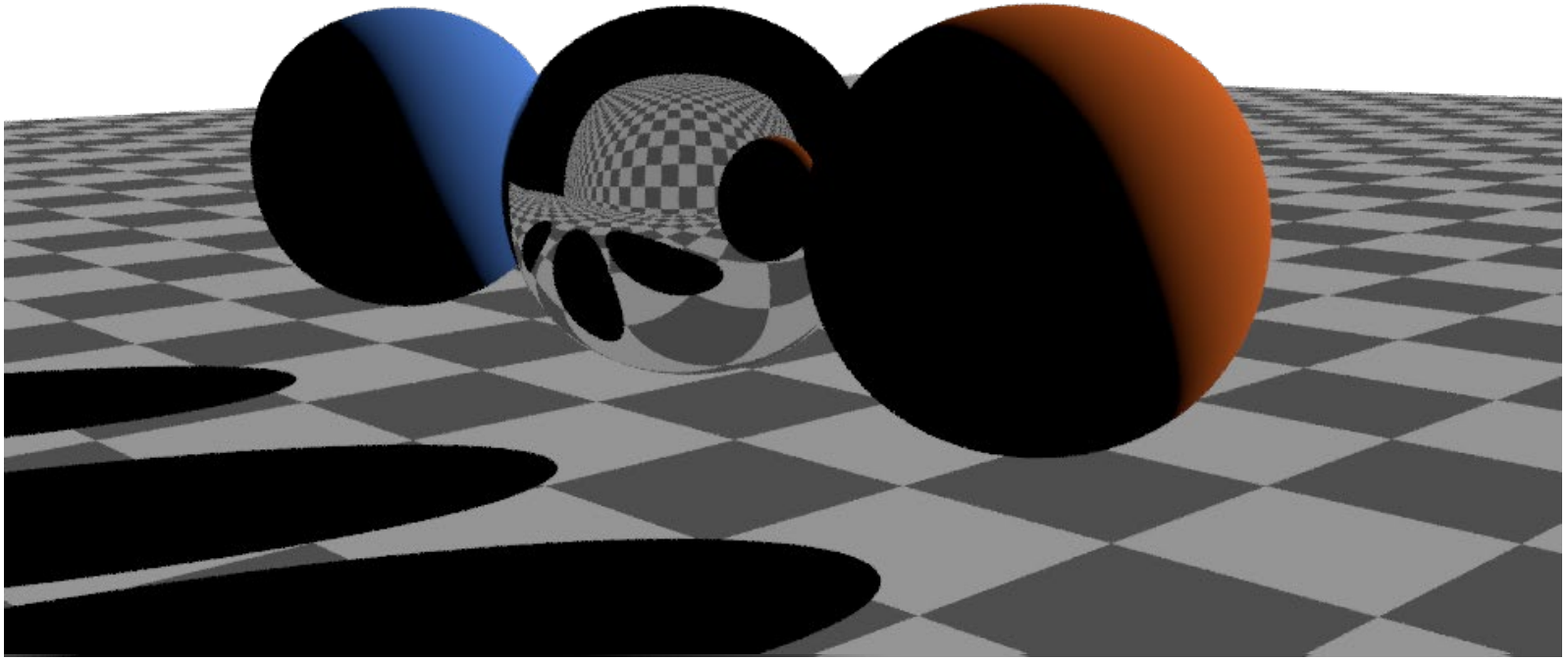
Sampling reflection directions

- For rough surfaces, we can consider a cone of reflection directions
  → reflection rays should be distributed around reflection direction
- corresponds to specular reflection of Phong lighting model



Sampling reflection directions

- Result



Sampling reflection directions

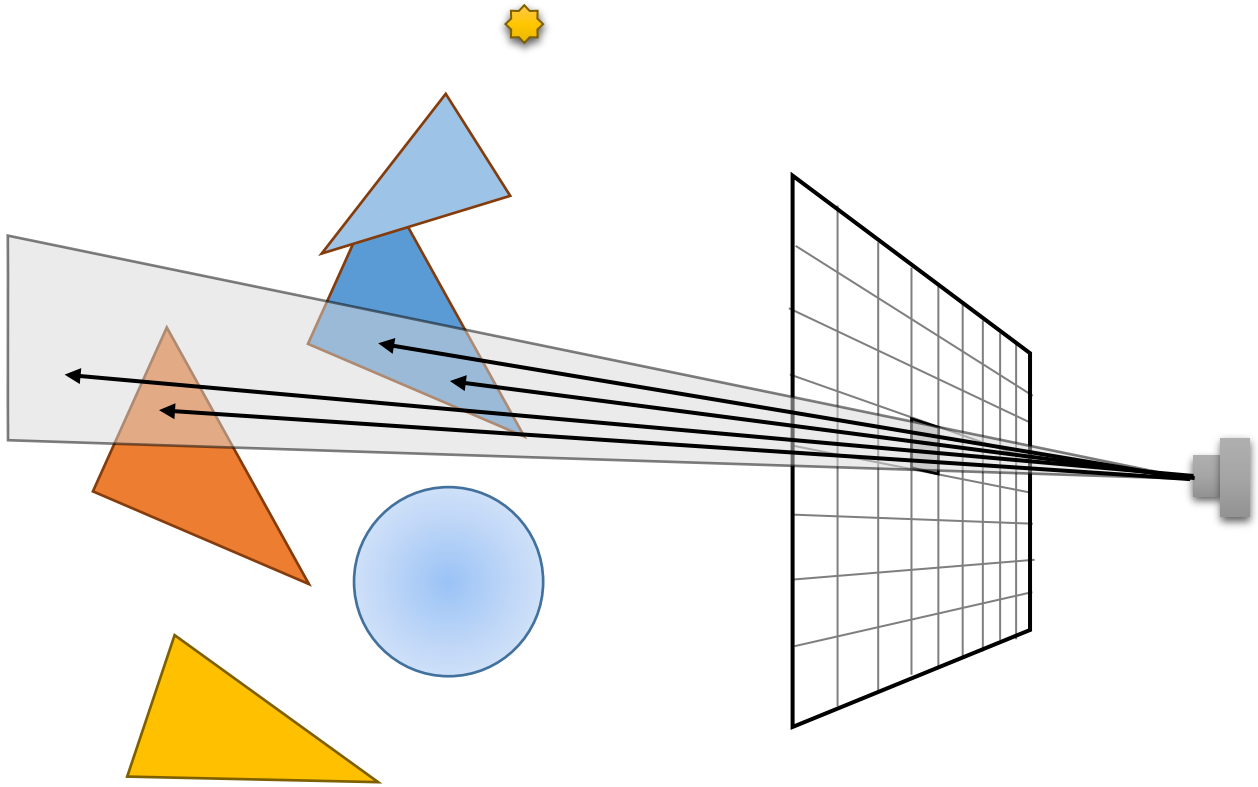
- The jittering radius and the distribution of the rays within this radius define the material:
  → large jitter radius: rough material (corresponds to small Phong-exponent)
  → small radius: glossy material (large Phong exponent)

- **Problem:**
  Given a reflection model for a surface (e.g. Phong or Torrance-Sparrow), how should we distribute the reflection rays ?

  → Consider reflection function as probability distribution and generate rays according to this distribution
  → see lecture “Global Illumination”

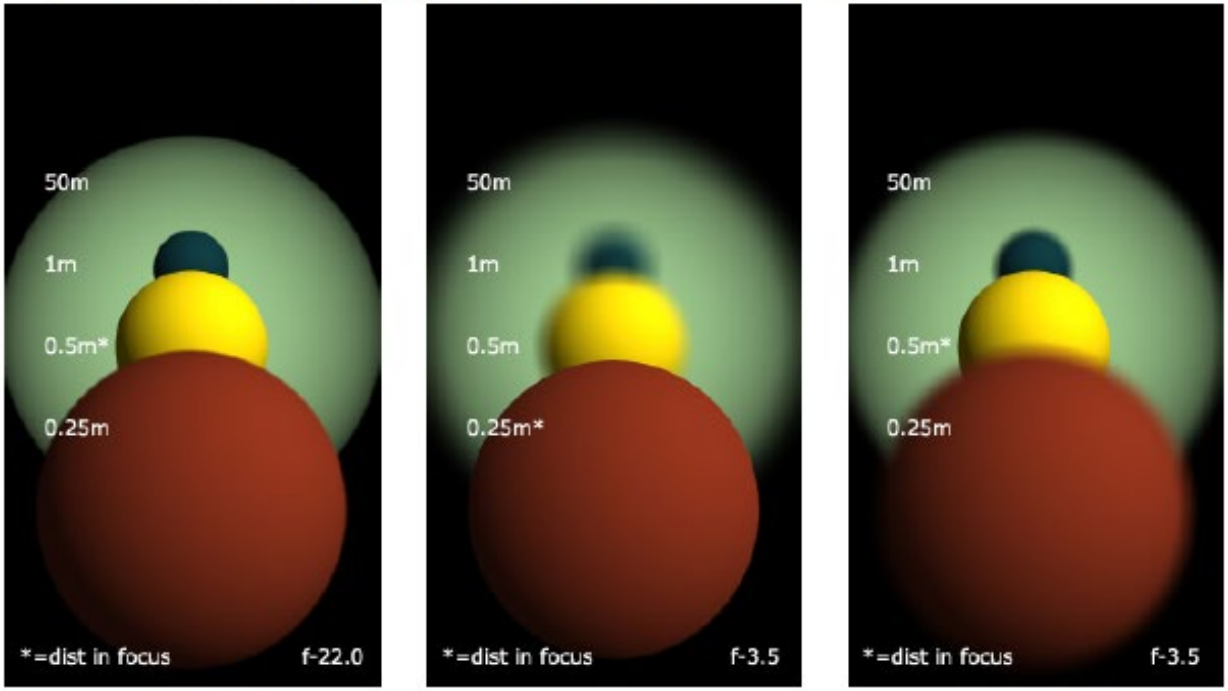
Sampling the pixel

- The color of a pixel is the average over the entire pixel
  → eye rays should be distributed over pixel
  → see Lectures **#4 “Polygon Rasterization” and #11 “Texture Aliasing”**



Sampling the Lens

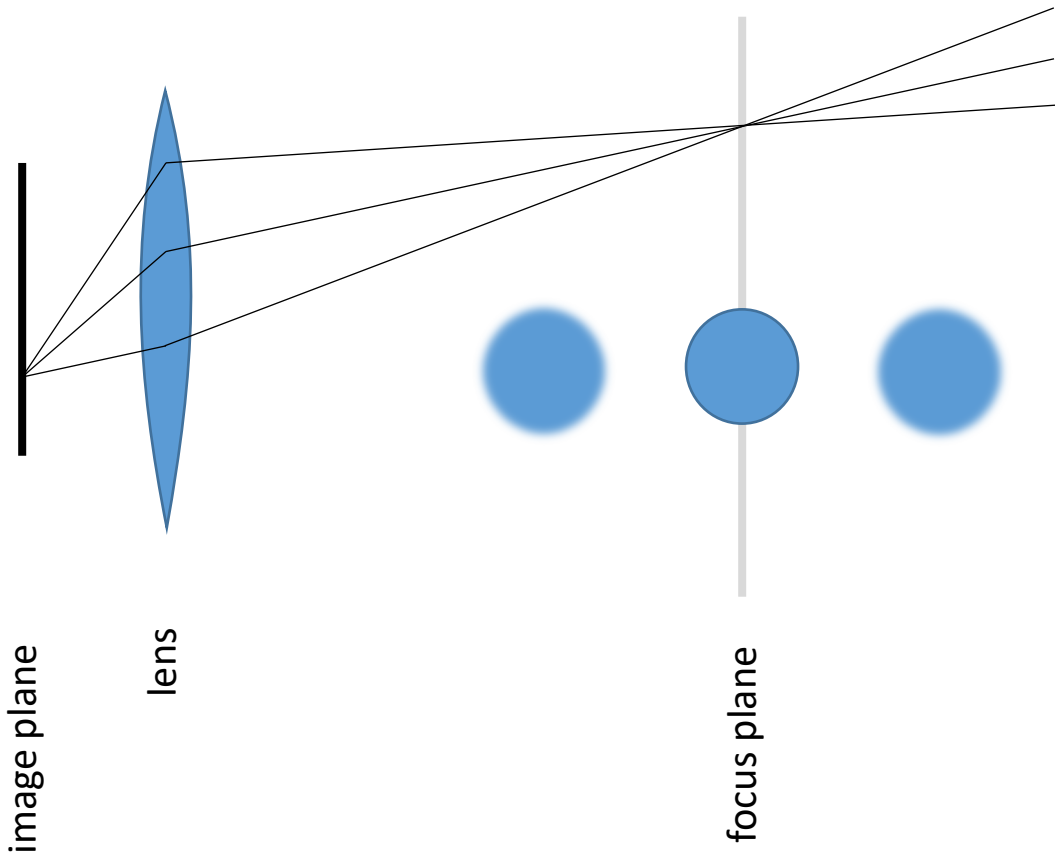
- Depth-of-Field
  - Pinhole model not realistic
  - Real lens has focus plane, only objects on this plane are sharp



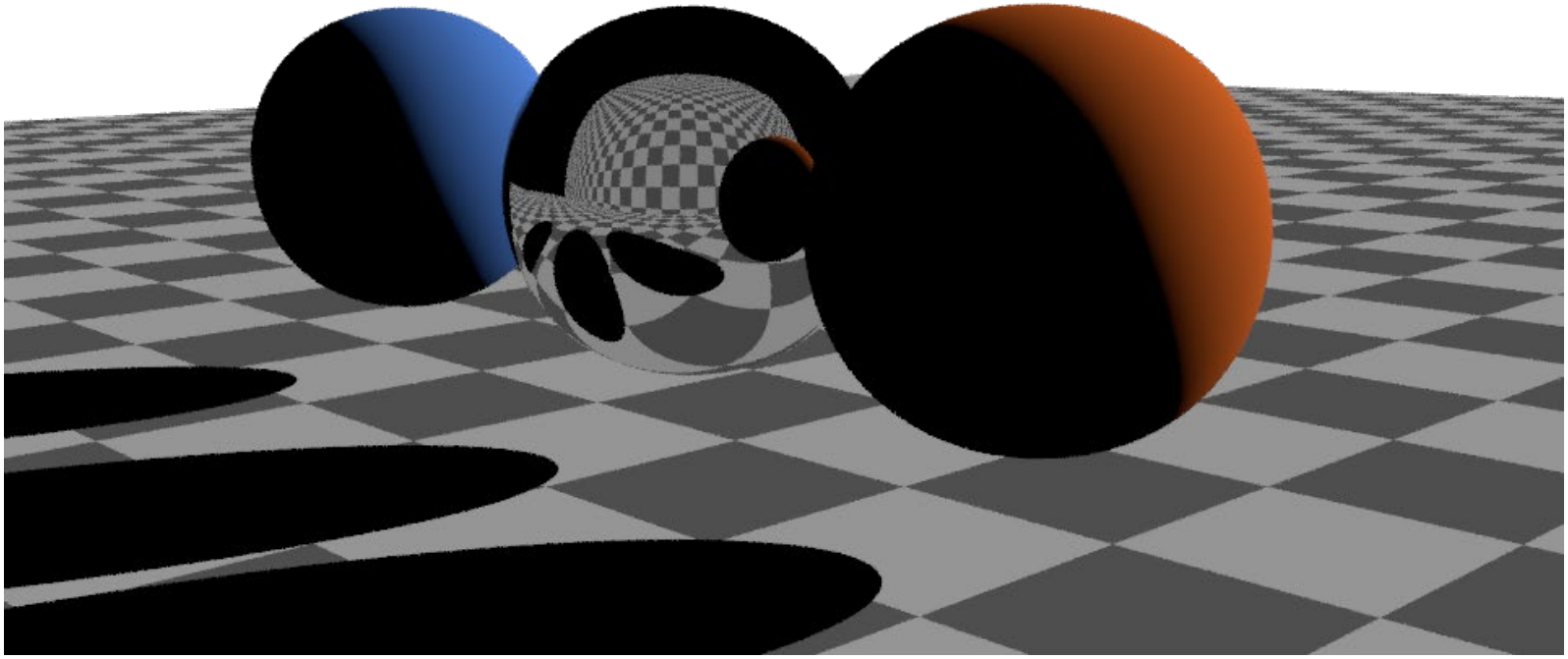
[Jason Waltman / jasonwaltman.com]

Distribution Ray Tracing

- Depth-of-Field
  - No pinhole, but lens (size varies with aperture)
  - Eye rays from a point on the image plane converge at focus plane
  - Objects on focus plane appear sharp, those before and behind get unsharp
- Can be simulated by casting multiple rays from lens to point on focus plane



Depth of Field



Distribution Raytracing

Combine all these effects:

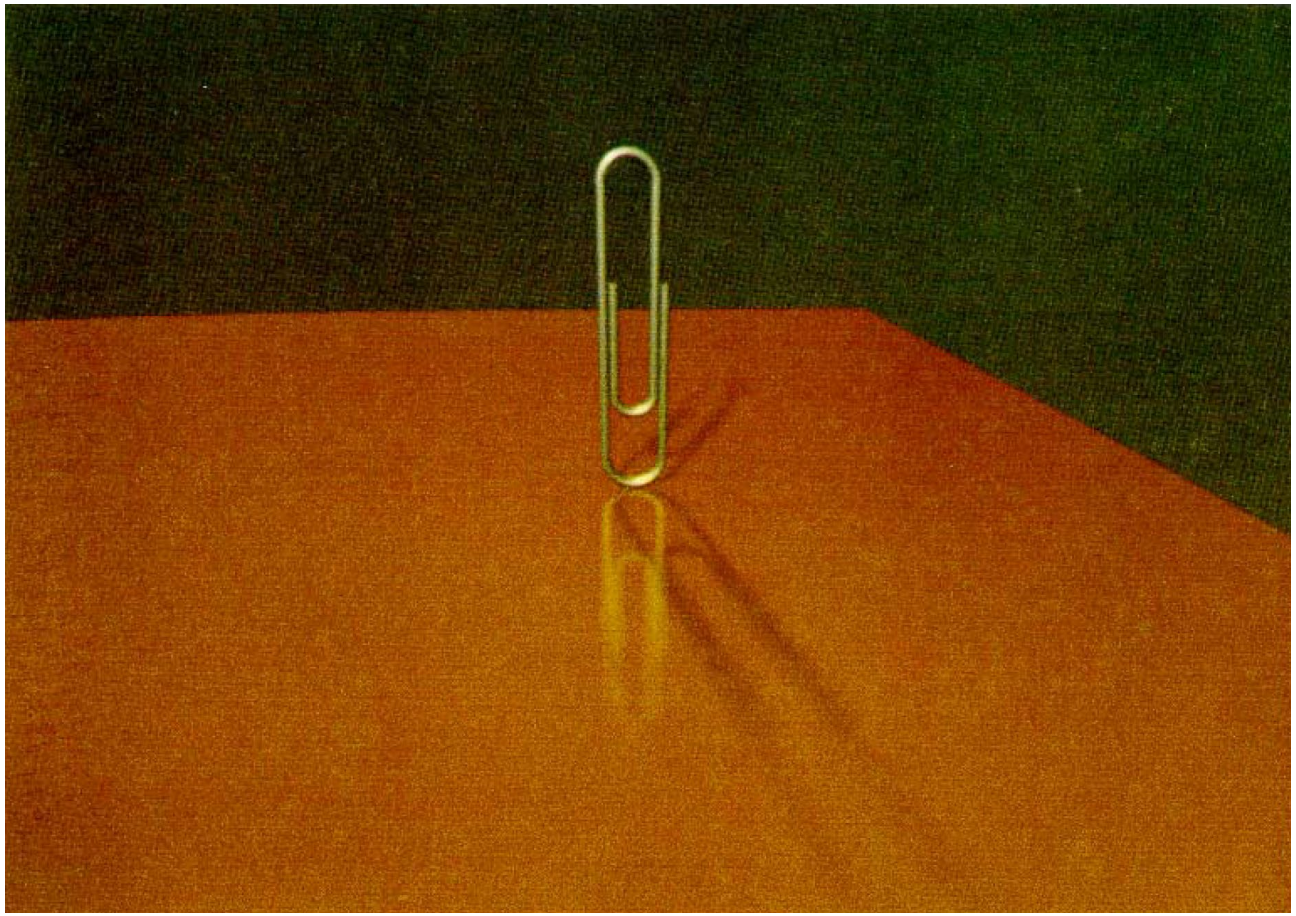
- Eye rays distributed over pixel and over lens
- Shadow rays distributed over light source
- Reflection rays distributed over reflection cone
- other effects: motion blur, frequency sampling, …

→ **Distribution Raytracing**

- Simple to integrate:
  - instead of one eye ray, we cast n_{AA} eye rays (n_{AA}: nr. of antialiasing samples)
  - we also jitter eye rays over the lens with n_{dof} samples (depth of field samples)
  - for each eye ray, we compute n_{sh} shadow rays (n_{sh}: nr. of shadow samples)
  - for each eye ray, we cast n_{refl} reflection rays (n_{refl}: nr. of reflection samples)

Distribution Raytracing

- Original paper: Cook, Porter, Carpenter (Lucasfilm): “Distributed Ray Tracing”, Siggraph 1984



rough glossy reflection

Distribution Raytracing

- Original pap
  Tracing", Sig

Distributed Ray

Distributed Ray Tracing

Robert L. Cook
Thomas Porter
Loren Carpenter

Computer Division
Lucasfilm Ltd.

Abstract

Ray tracing is one of the most elegant techniques in computer graphics. Many phenomena that are difficult or impossible with other techniques are simple with ray tracing, including shadows, reflections, and refracted light. Ray directions, however, have been determined precisely, and this has limited the capabilities of ray tracing. By distributing the directions of the rays according to the analytic function they sample, ray tracing can incorporate fuzzy phenomena. This provides correct and easy solutions to some previously unsolved or partially solved problems, including motion blur, depth of field, penumbras, translucency, and fuzzy reflections. Motion blur and depth of field calculations can be integrated with the visible surface calculations, avoiding the problems found in previous methods.

CR CATEGORIES AND SUBJECT DESCRIPTORS: I.3.7 [**Computer Graphics**]: Three-Dimensional Graphics and Realism;

ADDITIONAL KEY WORDS AND PHRASES: camera, constructive solid geometry, depth of field, focus, gloss, motion blur, penumbras, ray tracing, shadows, translucency, transparency

1. Introduction

Ray tracing algorithms are elegant, simple, and powerful. They can render shadows, reflections, and refracted light, phenomena that are difficult or impossible with other techniques[11]. But ray tracing is currently limited to sharp shadows, sharp reflections, and sharp refraction.

Ray traced images are sharp because ray directions are determined precisely from geometry. Fuzzy phenomenon would seem to require large numbers of additional samples per ray. By distributing the rays rather than adding more of them, however, fuzzy phenomena can be rendered with no additional rays beyond those required for spatially oversampled ray tracing. This approach provides correct and easy solutions to some previously unsolved problems.

This approach has not been possible before because of aliasing. Ray tracing is a form of point sampling and, as such, has been subject to aliasing artifacts. This aliasing is not inherent, however, and ray tracing can be filtered as effectively as any analytic method[4]. The filtering does incur the expense of additional rays, but it is not merely oversampling or adaptive oversampling, which in themselves cannot solve the aliasing problem. This antialiasing is based on an approach proposed by Rodney Stock. It is the subject of a forthcoming paper.

Antialiasing opens up new possibilities for ray tracing. Ray tracing need not be restricted to spatial sampling. If done with proper antialiasing, the rays can sample motion, the camera lens, and the entire shading function. This is called *distributed ray tracing.*

Distributed ray tracing is a new approach to image synthesis. The key is that no extra rays are needed beyond those used for oversampling in space. For example, rather than taking multiple time samples at every spatial location, the rays are distributed in time so that rays at different spatial locations are traced at different instants of time. Once we accept the expense of oversampling in space, distributing the rays offers substantial benefits at little additional cost.

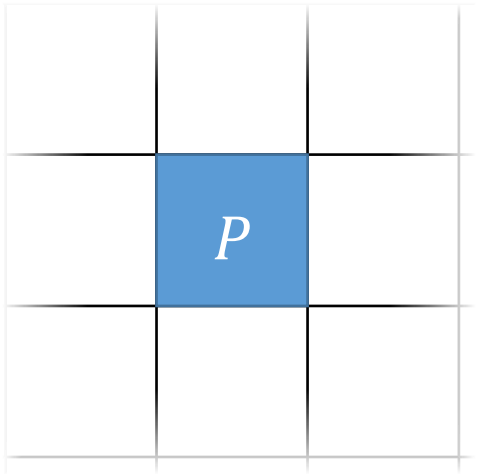
- Sampling the reflected ray according to the specular distribution function produces gloss (blurred reflection).
- Sampling the transmitted ray produces translucency (blurred transparency).
- Sampling the solid angle of the light sources produces penumbras.

Distribution Raytracing = Numeric Integration

- Mathematically:

  color of pixel P is integral over pixel:

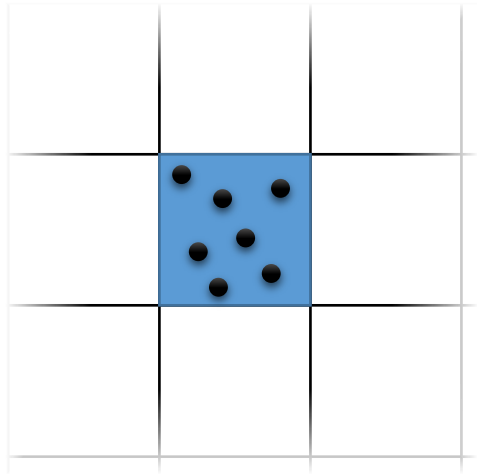
$$C_p = \frac{1}{|P|} \iint_P C(x,y)dx\,dy$$



- Numerically:

  approximate integral by averaging samples:

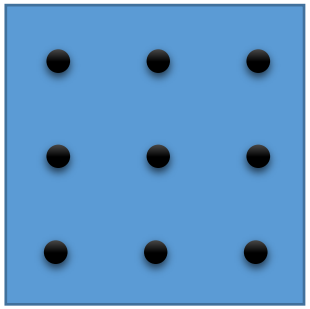
$$C_P \approx \frac{1}{n} \sum_{i=1\ldots n} C(x_i, y_i)$$



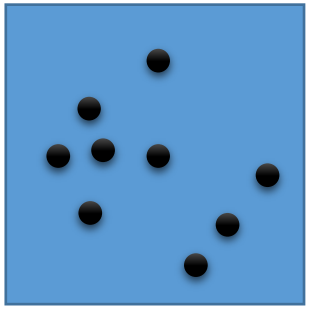
integration is essentially the same as averaging !

Low-Dimensional Numerical Integration

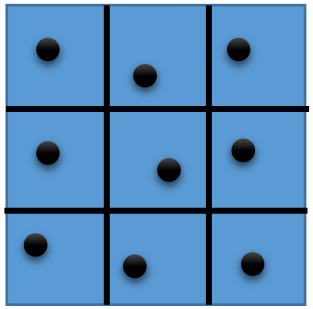
- Pixel example: how to distribute samples over pixel



uniform:
- very uniform distribution
- good numerical properties
- only square numbers as sample numbers



random:
- non-uniform distribution
- worse numerical properties
- arbitrary sample numbers, incrementable



random stratified:
- uniform distribution
- good numerical properties
- only square numbers as sample numbers

High-Dimensional Numerical Integration

- Same is true for other effects
  → Pixel Color is **high dimensional integral**

$$C_p = \underset{pixel}{\iint} \underset{lens}{\iint} \underset{reflection}{\iint} \underset{area\ light}{\iint} \ldots \; d \ldots$$

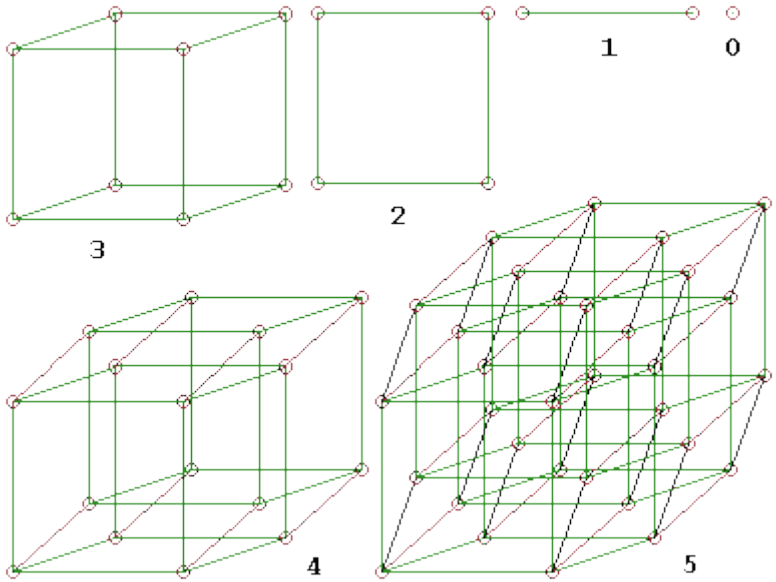
- **how does this integral look like ?**
  → “The Rendering Equation”

High-Dimensional Numerical Integration

- Let's say 10 dimensions
  →We have to sample a 10D cube

- **Uniform / Stratified**
  - n samples in one dimension
  - n^{10} samples overall
  - not practical
  - **→ curse of dimensionality**

- **Random Samples**
  - works, but can generate uneven distributions
  - numerically not very good, slow convergence
  - but practically often the best one can do…



hypercubes up to 5D
(wikipedia.de)

Random Sampling for Distribution Raytracing

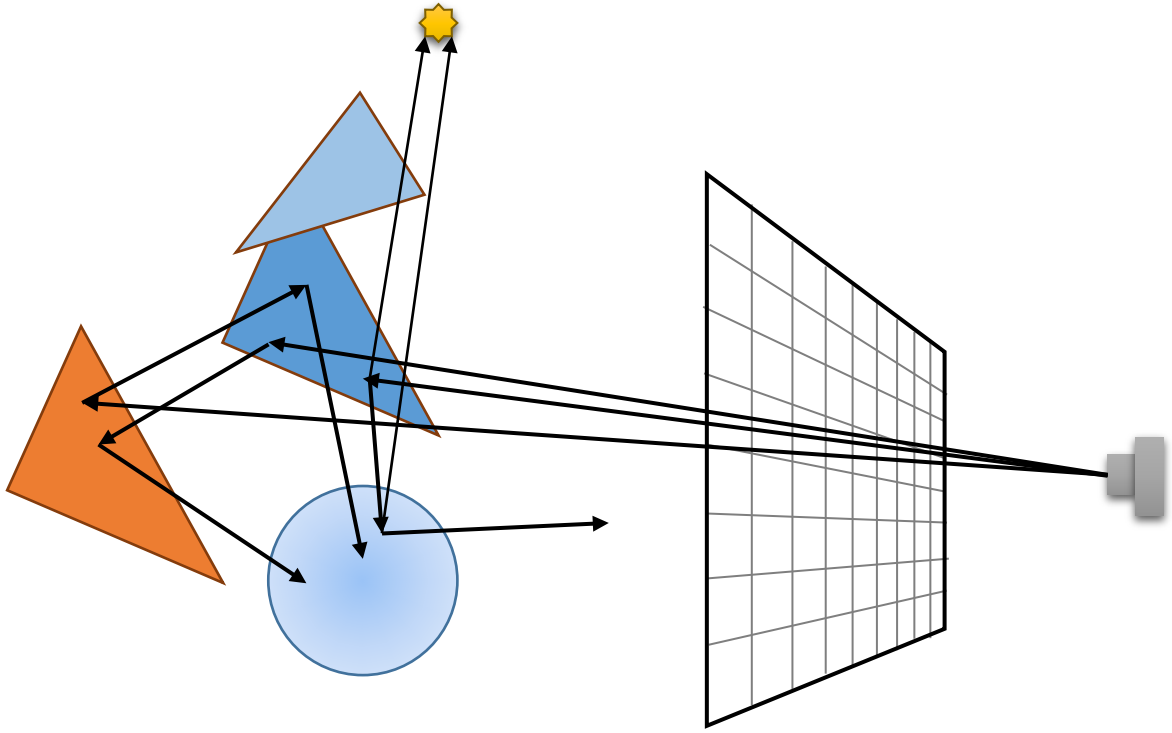
- Practical solution: random sampling → **“Monte-Carlo-Raytracing”**
- What is a random sample?

$$C_p = \iint_{pixel} \iint_{lens} \iint_{reflection} \iint_{area\ light} \dots\ d\ \dots$$

choose random pixel position	choose random lens position	choose random reflection direction	choose random position on area light

Random Sampling for Distribution Raytracing

- Each sample is a random path through the pixel



Path Tracing

Path Tracing

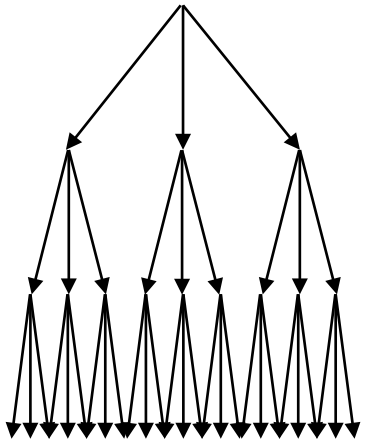
- Uniform Sampling

```
computePixelColor()
```

pixel position

lens position

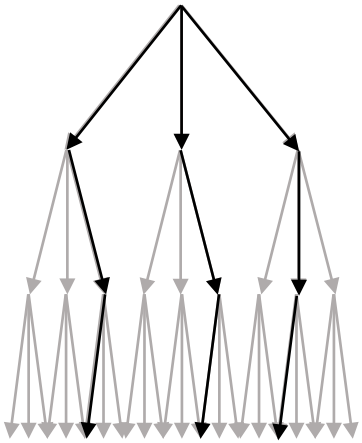
reflection direction



.....

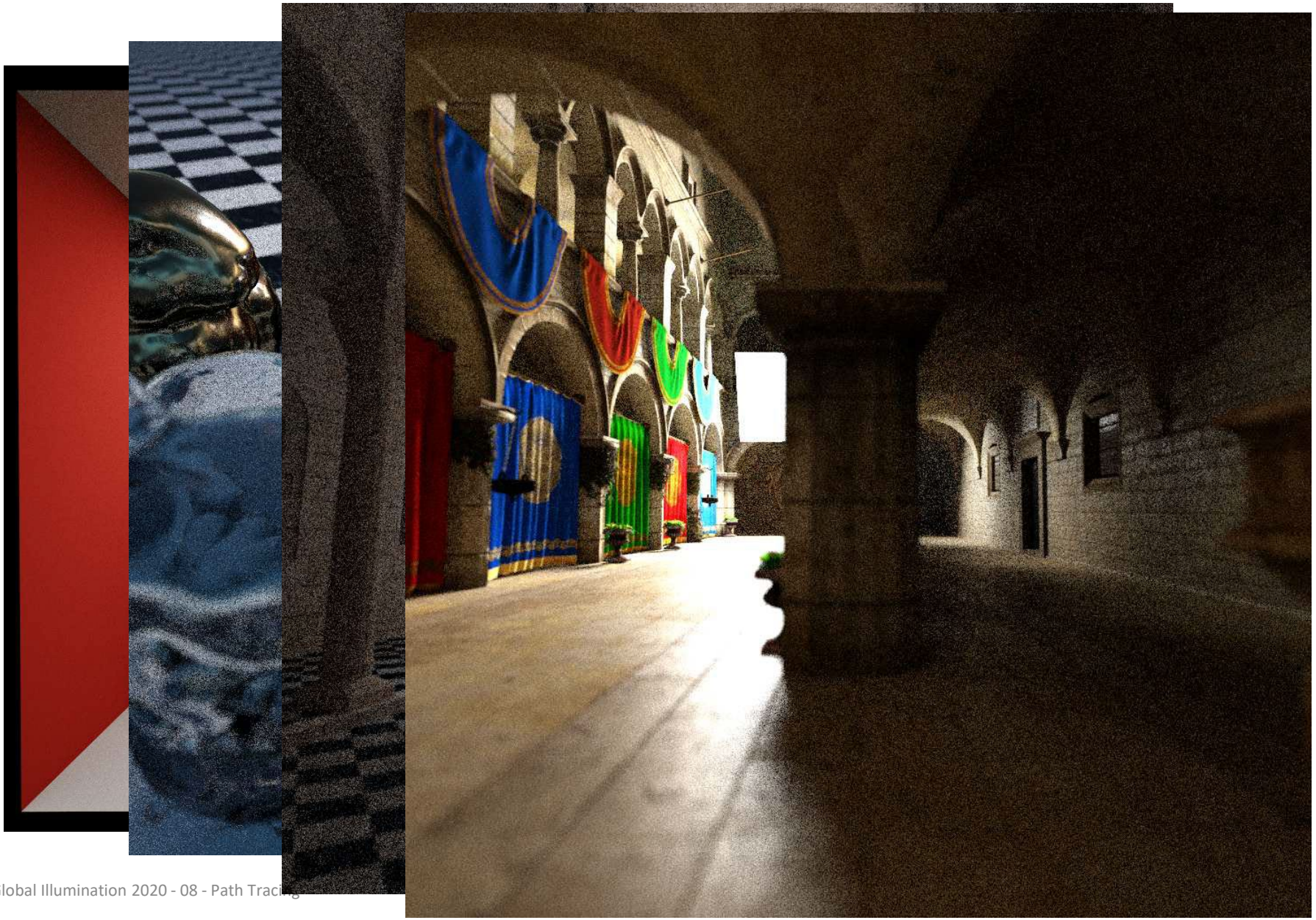
- Random Sampling = Path Tracing

```
computePixelColor()
```



.....

Examples from exercises of “Global Illumination”



Path Tracing

- Randomness results in **image noise**
- Many samples per pixel needed to reduce noise to acceptable level
- Nevertheless, path tracing is still state-of-the art, even in production rendering!

Thanks for your attention