Topics Covered

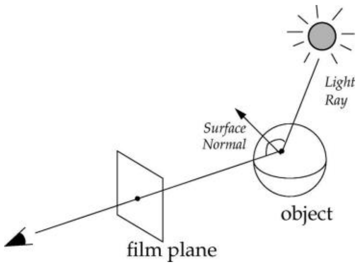
- Ray Tracing
  - Ray Types
  - Recursion in Ray Tracing
  - Ray-Object Intersection

- Discussion on Ray Tracing
  - As Hidden Surface Removal
  - As Global Illumination
  - Acceleration Techniques
  - Path Tracing

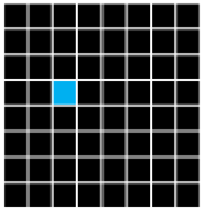
- Recent Trend in Ray Tracing

Recall: Two Approaches to Rendering - 2

```
for each pixel in image(film plane)
    determine which object should be shown at the pixel
    set color of the pixel based on texture and lighting model
```

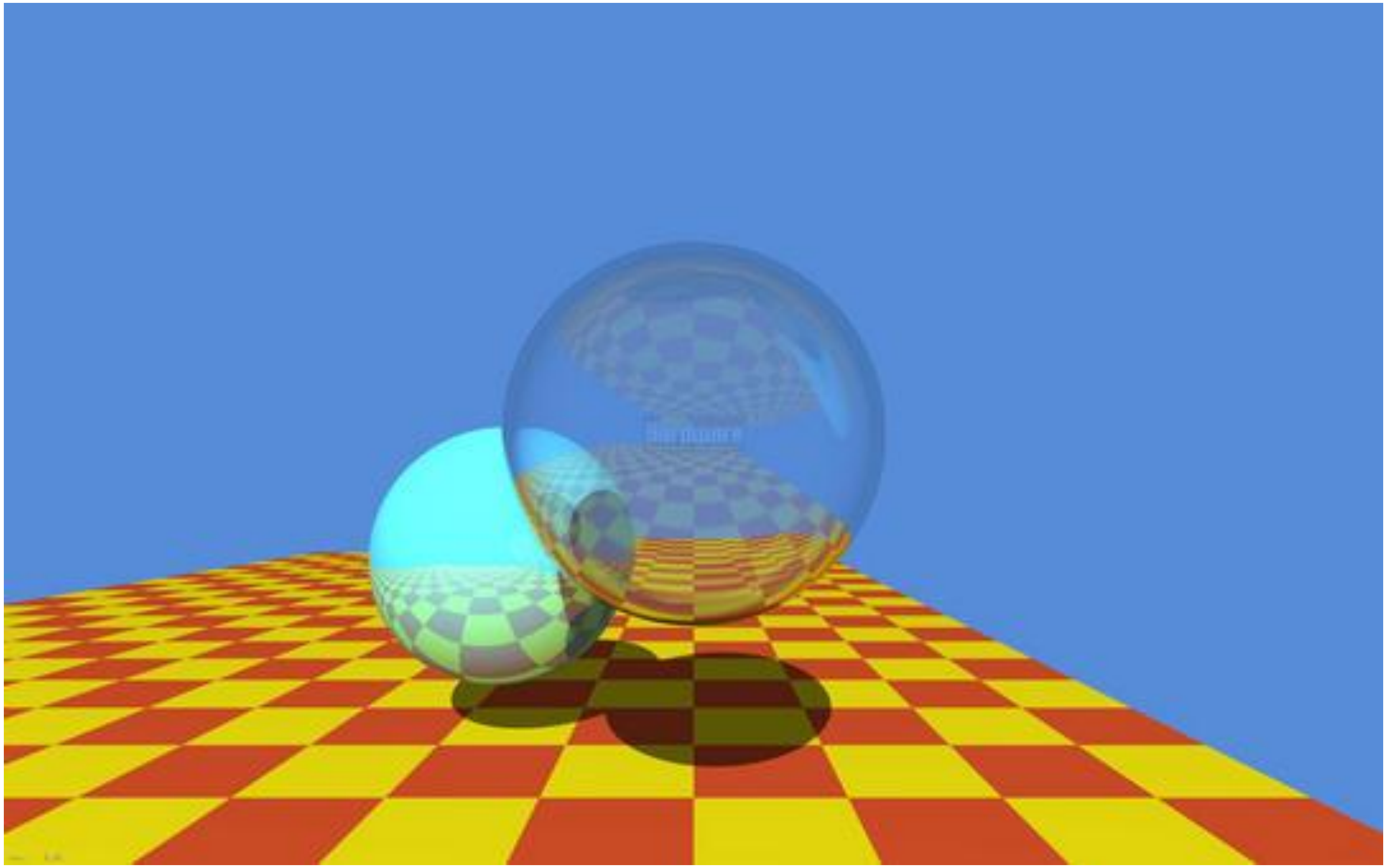


(ray intersection is rendered to screen)



- Called **image-oriented rendering** or **ray tracing**

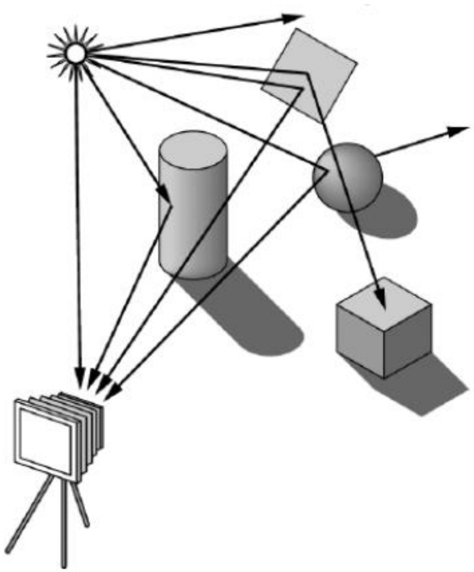
Ray Tracing



Turner Whitted, 1980

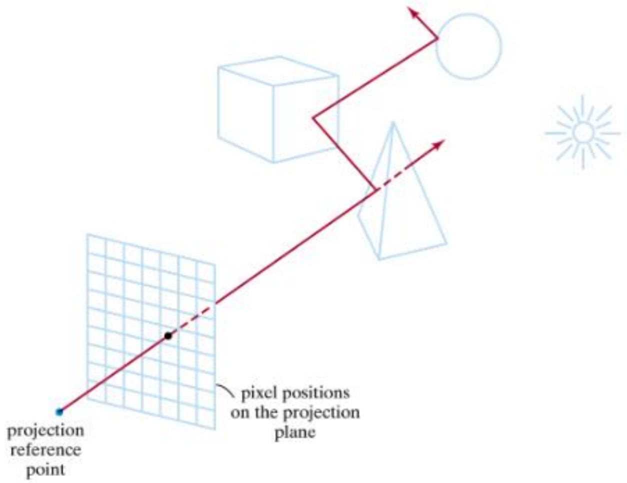
Forward Ray Tracing

- Simulate lights in nature
- A light source emits *photons*
- Follow photons using rays – as paths of photons
- Problem: Many rays will not contribute to image
- Highly inefficient!



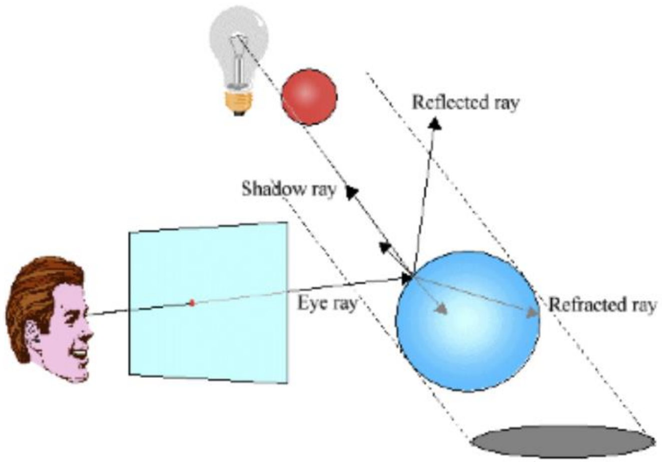
Backward Ray Tracing

- Trace rays backward from viewer to light sources
- Each ray goes through each pixel in image plane from eye position
- Color of each pixel is determined based on which object the ray intersects with
- Much more efficient than forward approach - we can only consider rays that contribute image!
- Actually, this approach is what we call “Ray Tracing”



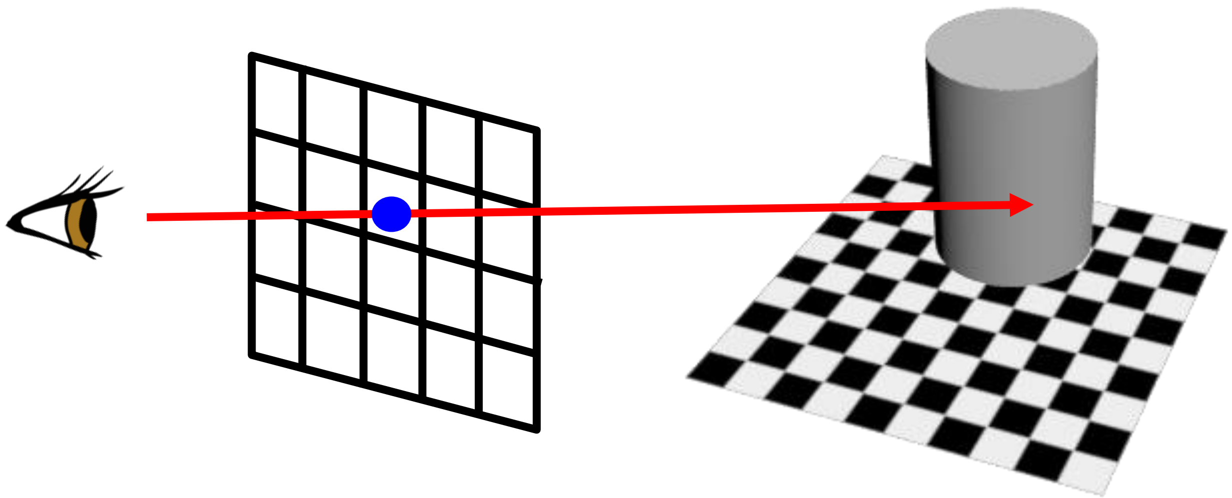
Types of Rays

- Eye rays
  – from eye to surface, passing through each pixel
- Shadow (Illumination) rays
  – from surface point to light source
- Reflection rays
  – from surface point in mirror direction
- Refraction rays
  – from surface point in refracted direction



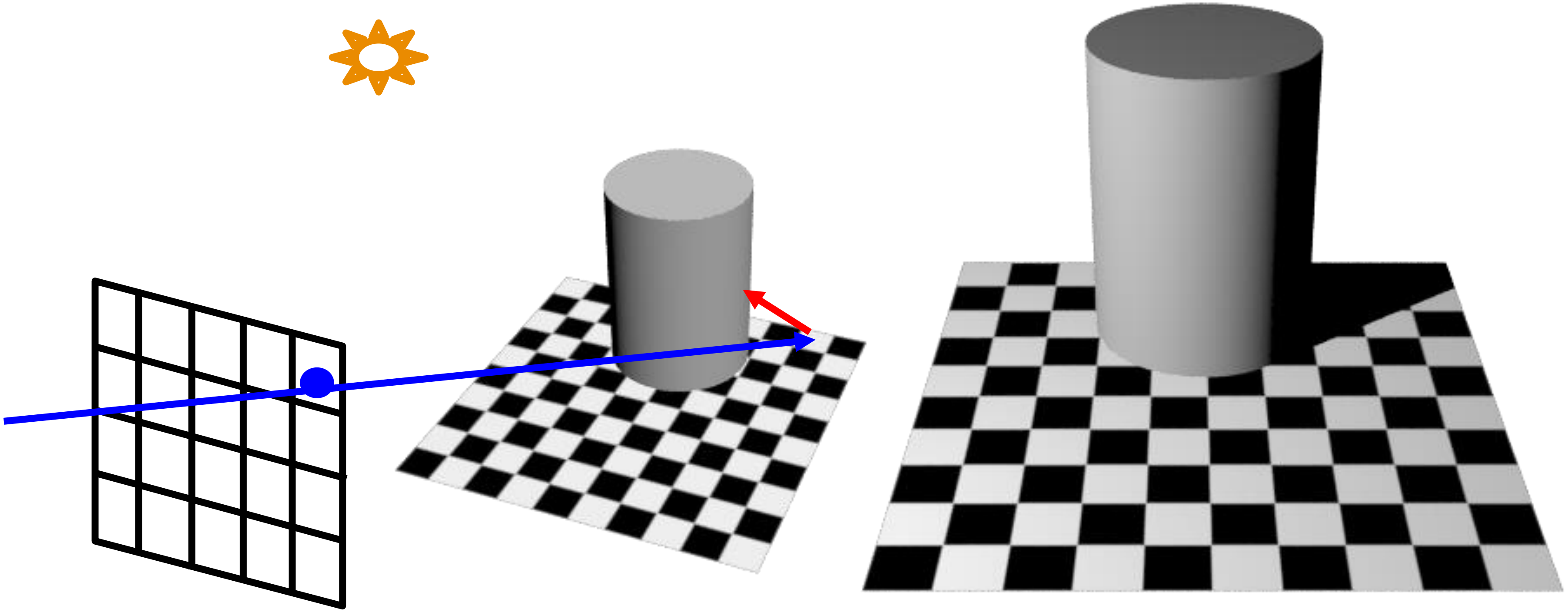
Eye Rays

- Casted from eye (or camera) to surface, passing through a pixel
- Find closest surface point hit by the ray



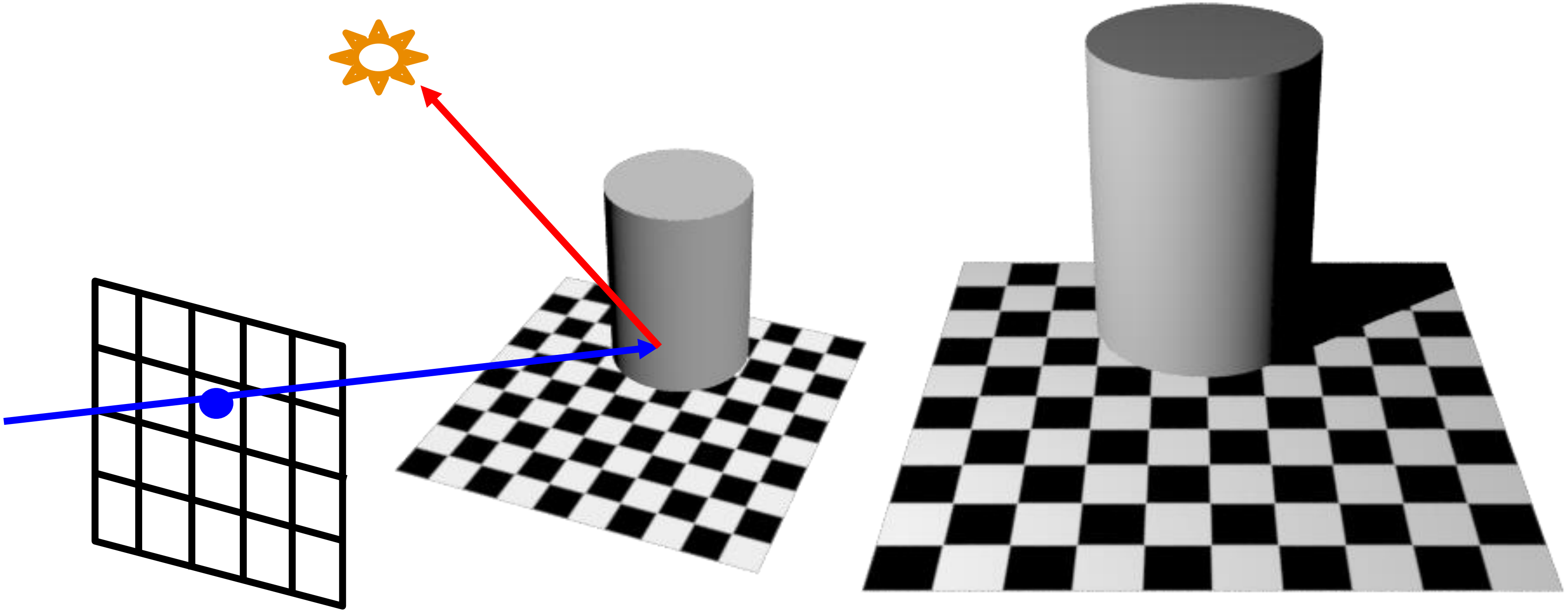
Shadow (Illumination) Rays

- Casted from surface point to *each* light source
  - If the ray is **blocked** by an opaque object, no contribution of the light for the pixel color (shadow)



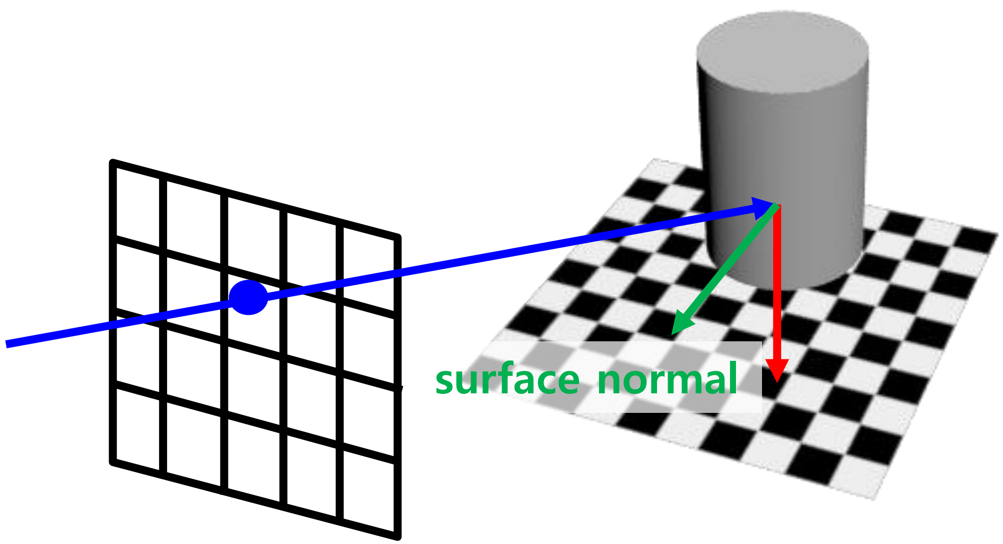
Shadow (or Illumination) Rays

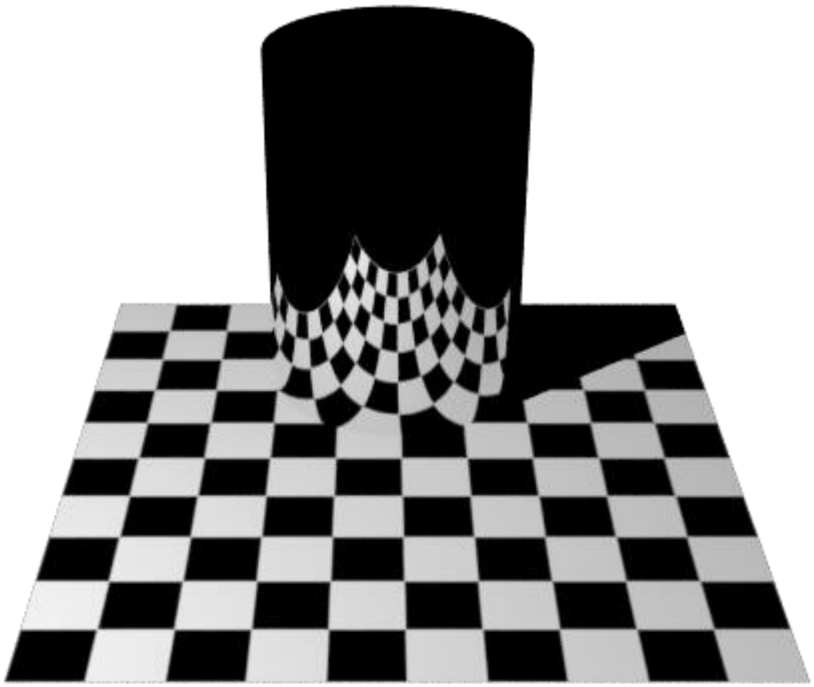
- Casted from surface point to *each* light source
  - If the ray is **blocked** by an opaque object, no contribution of the light for the pixel color (shadow)
  - If the ray **reaches the light**, compute the contribution of the light for the pixel color using local illumination model (such as Phong model)



Reflection Rays

- Casted from surface point in mirror direction if the surface is specular (following the laws of reflection)
- If this ray reaches other surfaces, cast shadow / reflection / refraction rays from that surface point again (recursive)

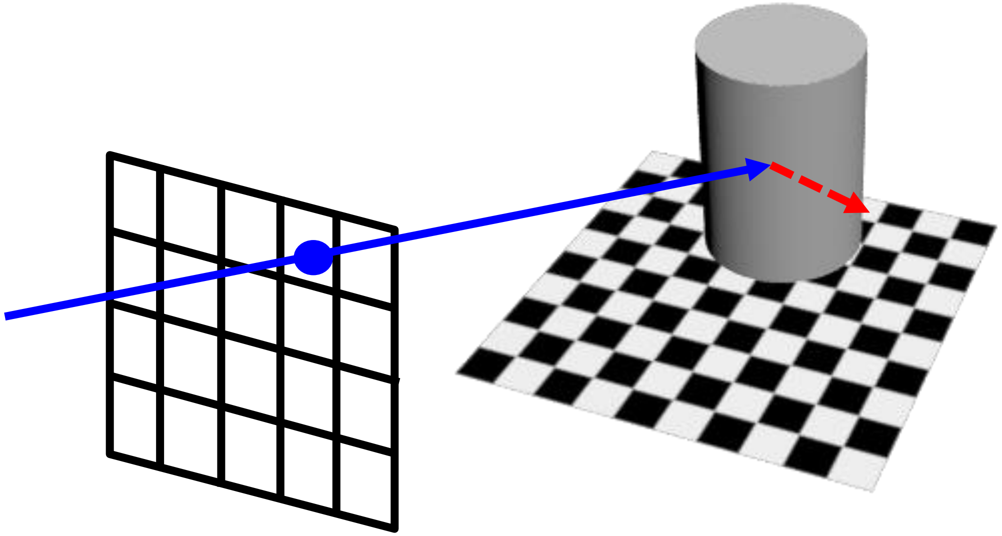


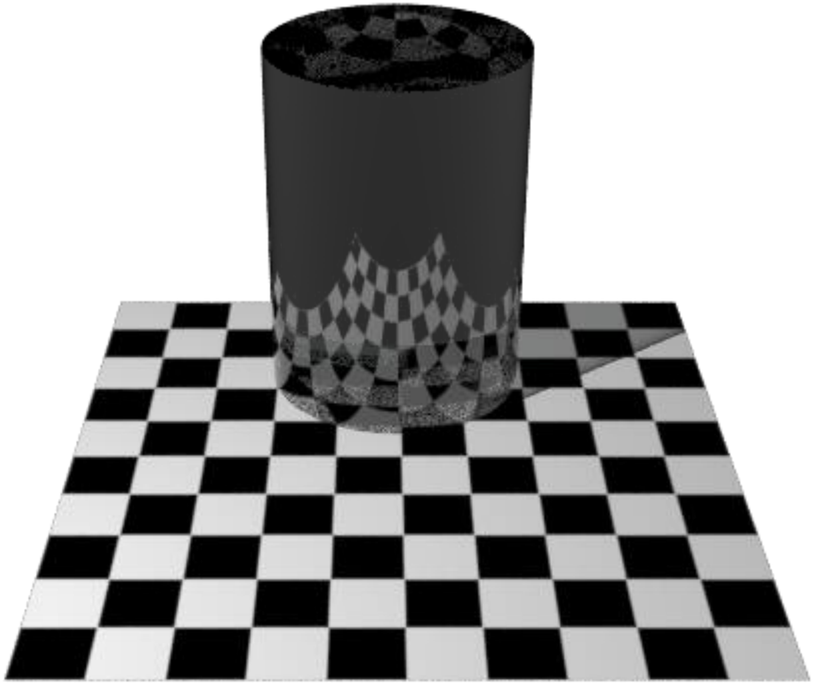


Refraction Rays

- Casted from surface point in refracted direction if the surface is transparent (following Snell’s law)

- If this ray reaches other surfaces, cast shadow / reflection / refraction rays from that surface point again (recursive)



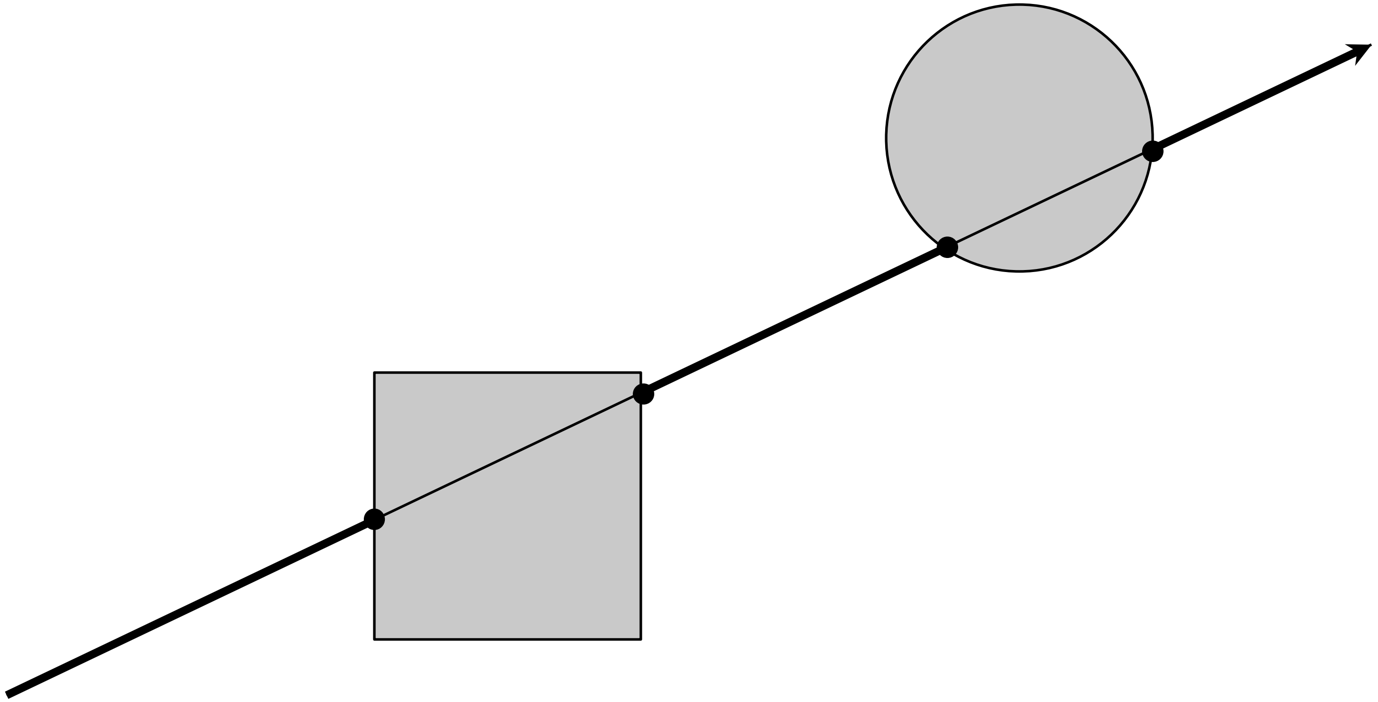


Recursion in Ray Tracing

- Reflection & refraction rays recursively spawn new shadow, reflection, refraction rays at each intersection with object surface until
  - contribution is negligible
  - or some max recursion depth is reached

- Rays are attenuated with
  - Specular reflectivity of object surface
  - Opacity of transparent material
  - Distance traveled through transparent material

Ray intersection

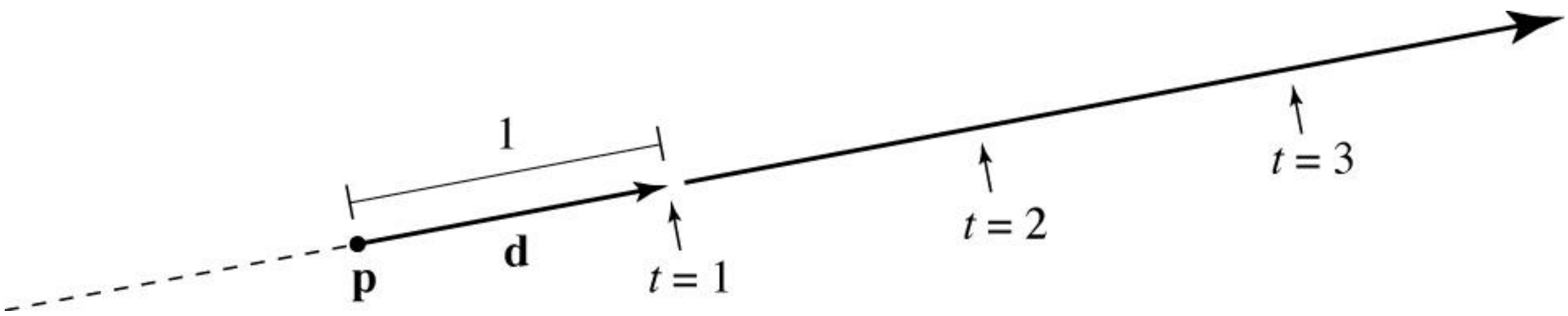


Ray: a half line

- Standard representation: point **p** and direction **d**

  $$\mathbf{r}(t) = \mathbf{p} + t\mathbf{d}$$

  - this is a *parametric equation* for the line



Simple Strategy

- **Parametric ray equation**
  - **Gives all points along the ray as a function of the parameter**

$$\dot{p}(t) = \dot{o} + t\vec{d}$$

- **Implicit surface equation**
  - **Describes all points on the surface as the zero set of a function**

$$f(\dot{p}) = 0$$

- **Substitute ray equation into surface function and solve for t**

$$f(\dot{o} + t\vec{d}) = 0$$

Ray-sphere intersection: algebraic

- Condition 1: intersection point r is on ray

$$\mathbf{r}(t) = \mathbf{p} + t\mathbf{d}$$

- Condition 2: point is on sphere
  - assume unit sphere;

$$\|\mathbf{x}\| = 1 \Leftrightarrow \|\mathbf{x}\|^2 = 1$$

$$f(\mathbf{x}) = \mathbf{x} \cdot \mathbf{x} - 1 = 0$$

- Substitute:

$$(\mathbf{p} + t\mathbf{d}) \cdot (\mathbf{p} + t\mathbf{d}) - 1 = 0$$

  - this is a quadratic equation in *t*

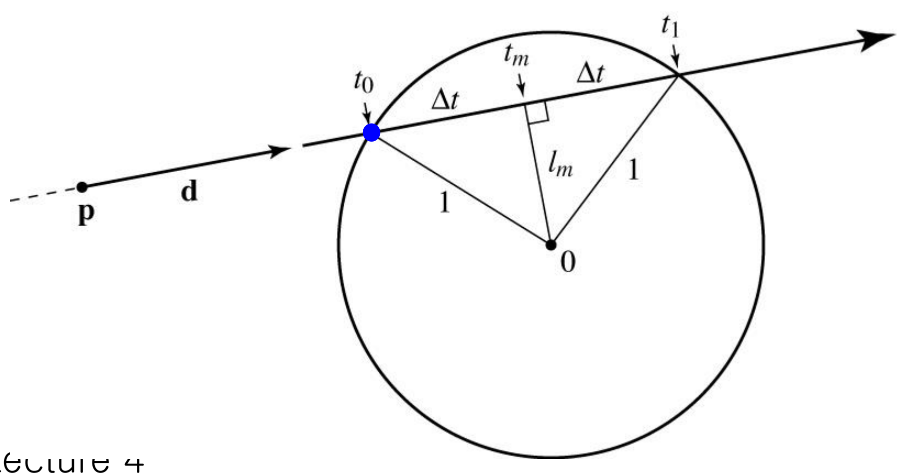
Ray–sphere intersection: algebraic

- Solution for *t* by quadratic formula:

$$t = \frac{-\mathbf{d}\cdot\mathbf{p} \pm \sqrt{(\mathbf{d}\cdot\mathbf{p})^2 - (\mathbf{d}\cdot\mathbf{d})(\mathbf{p}\cdot\mathbf{p} - 1)}}{\mathbf{d}\cdot\mathbf{d}}$$

$$t = -\mathbf{d}\cdot\mathbf{p} \pm \sqrt{(\mathbf{d}\cdot\mathbf{p})^2 - \mathbf{p}\cdot\mathbf{p} + 1}$$

- Choose the smallest positive t

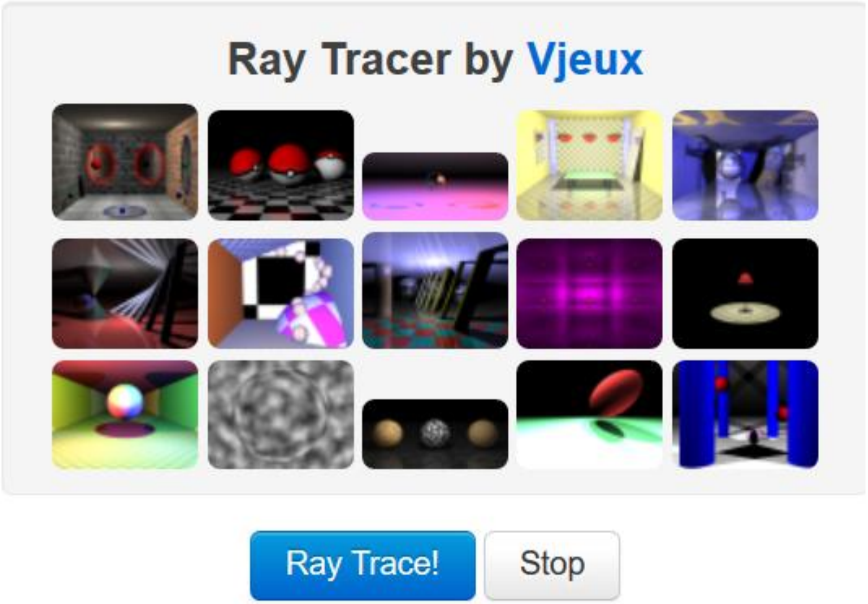


Ray-Object Intersection

- Similarly, we can find ray intersection with
  - Box
  - Plane
  - Triangle (which means we can use not only implicit surfaces but also polygon meshes in ray tracing)

- I'll just skip more details of ray-object intersection

[Practice] Ray Tracing Online Demo

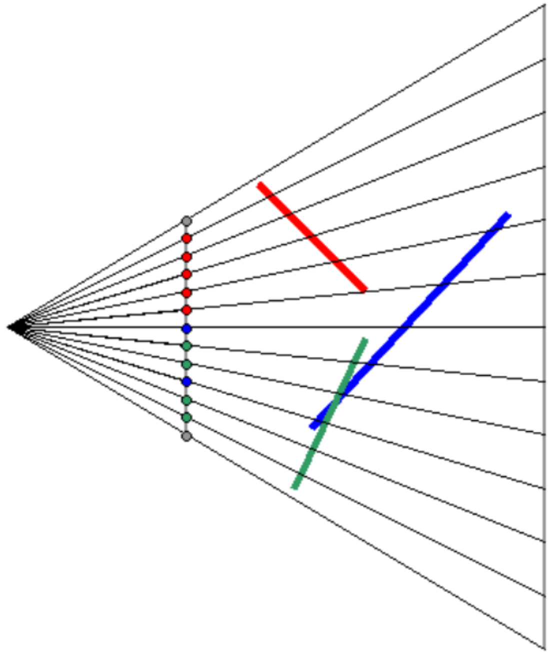


http://fooo.fr/~vjeux/epita/raytracer/raytracer.html#portal

- Change the scene and click “Ray Trace!” button

Discussion: Ray Tracing as Hidden Surface Removal

- Ray-object intersection solves "Hidden Surface Removal" problem
  - Finding closest surface point hit by the ray



Discussion: Ray Tracing as Global Illumination

- Computing each pixel color (lighting) in ray tracing
  - Use local illumination model to calculate **direct** contribution from light sources (with shadow rays)
  - Recursively compute **indirect** contribution from reflection / refraction (with reflection / refraction rays)

- Final pixel color is the sum of these contributions
  - So ray tracing can be considered as global (indirect) illumination model

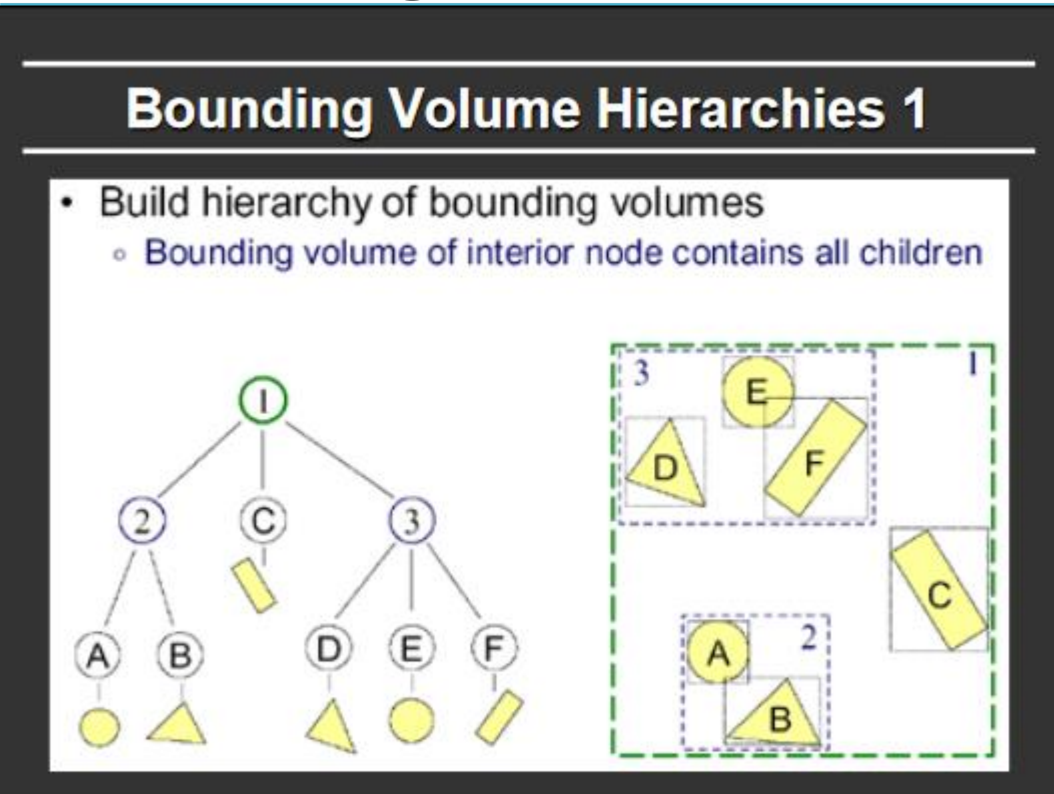
- No diffuse reflection rays → Ray tracing is *limited approximation* to global illumination

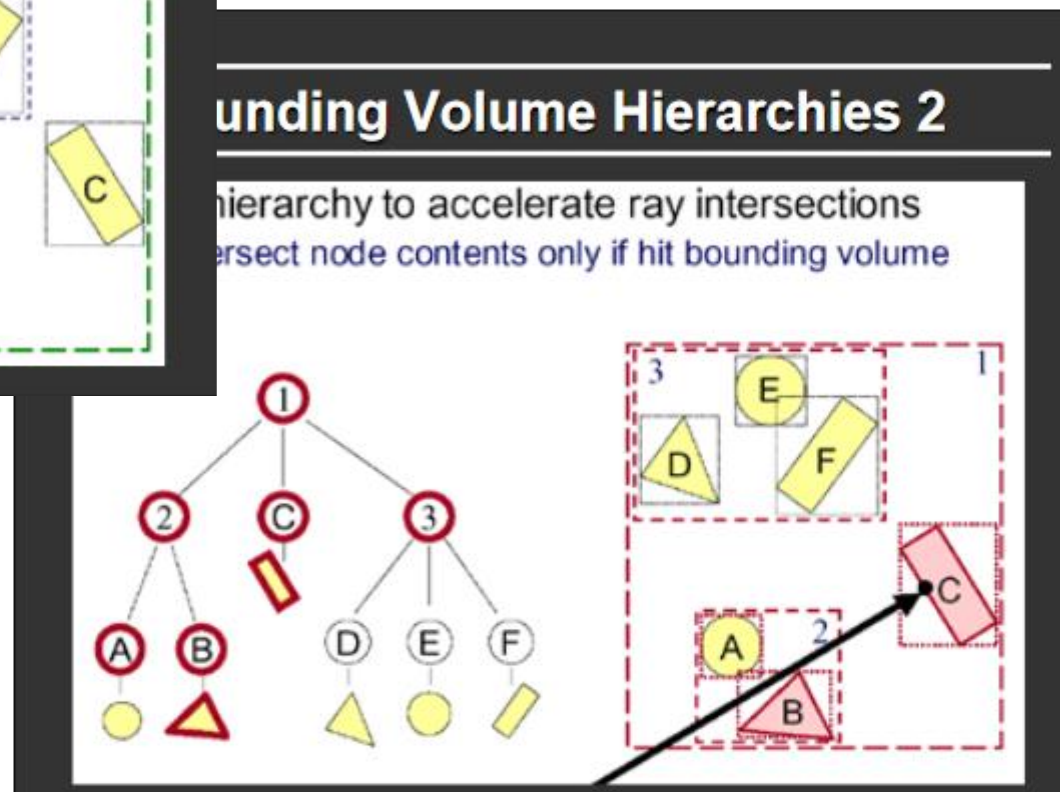
Discussion: Acceleration Techniques for Ray Tracing

- Ray tracing is slow!
  - Spend most of time in ray-object intersection
  - Proportional to (the number of pixels) × (the number of primitives in the scene)

- To reduce the number of ray-object test,
  - Bounding volume hierarchies
  - Spatial subdivision

Discussion: Acceleration Techniques for Ray Tracing





Traditional Use of Rasterization

- Generally, ray-tracing is slower than rasterization, but generates better quality results

- Thus, rasterization have been dominant for real-time application
  - A single frame should be rendered in a few tens of milliseconds
  - e.g. OpenGL or Direct3D for computer games

Traditional Use of Ray Tracing

- But moviemakers can take as long as they like to render a single frame

- So ray-tracing-based rendering is dominant for non-realtime applications
  - e.g. movies, animations
  - Generally rendered in offline using large CPU cluster, called *render farm*
  - Pixar, ILM, Weta Digital, ...

- Similar but much more improved technique, *path tracing*, captures diffuse scattering (with hundreds of thousands rays in a pixel), so it can generates photo-realistic images
  - Used not only by film makers, but also by architects


GENESIS
PINK
FLOYD

Recent Trend in Ray Tracing

- Modern ray tracers have started to use GPUs to speed up the computation
  - Arnold(Autodesk), V-Ray(Chaos Group), Renderman(Pixar), ...

- Even real-time ray tracing engines have been announced

- Perhaps, ray tracing based games will become popular..?

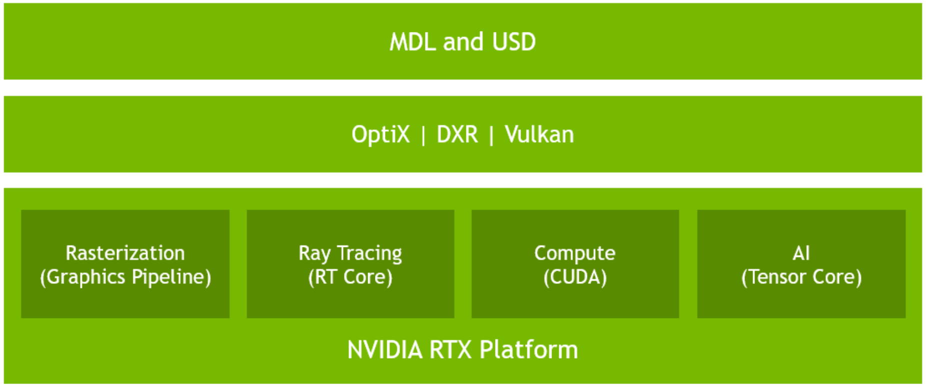
Recent Trend in Ray Tracing

- NVIDIA OptiX
  - A software development kit for achieving high performance ray tracing on the GPU
  - Announced at SIGGRAPH 2009
  - https://developer.nvidia.com/optix

- Microsoft DirectX® Raytracing (DXR)
  - Fully integrates ray tracing into DirectX, and makes it a companion to rasterization
  - Announced on March 19, 2018
  - https://blogs.msdn.microsoft.com/directx/2018/03/19/announcing-microsoft-directx-raytracing/

Recent Trend in Ray Tracing

- NVIDIA RTX™ Platform
  - Ray Tracing (OptiX, Microsoft DXR, Vulkan)
  - AI-Accelerated Features (NGX)
  - Rasterization (Advanced Shaders)
  - Simulation (CUDA 10, PhysX, Flex)
  - Asset Interchange Formats (USD, MDL)
  - https://developer.nvidia.com/rtx
  - https://youtu.be/tjf-1BxpR9c

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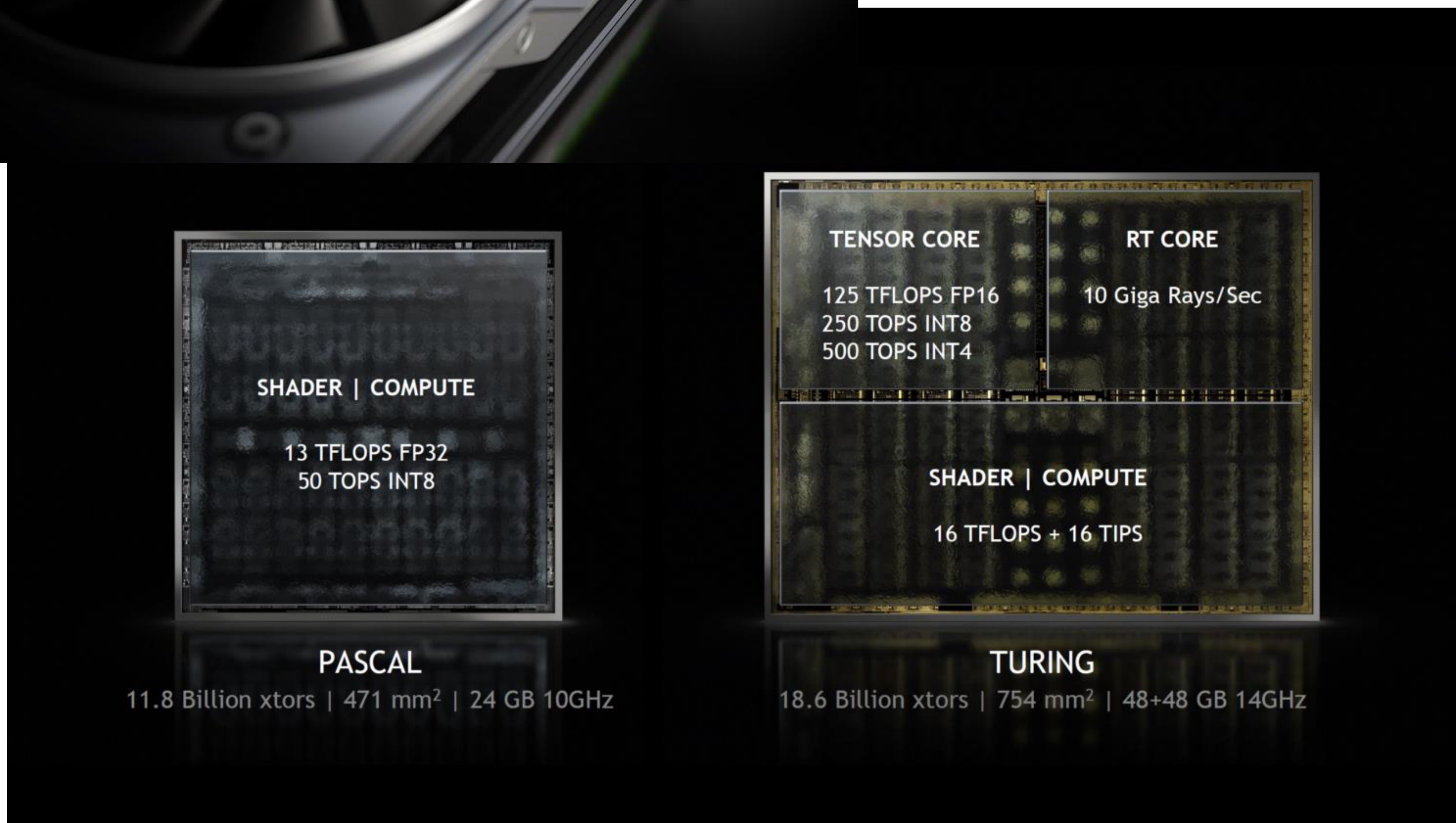
SHADER | COMPUTE
13 TFLOPS FP32
50 TOPS INT8
PASCAL
11.8 Billion xtors | 471 mm² | 24 GB 10GHz
TENSOR CORE
125 TFLOPS FP16
250 TOPS INT8
500 TOPS INT4
RT CORE
10 Giga Rays/Sec
SHADER | COMPUTE
16 TFLOPS + 16 TIPS
TURING
18.6 Billion xtors | 754 mm² | 48+48 GB 14GHz

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  - Prof. Sung-eui Yoon, KAIST, https://sglab.kaist.ac.kr/~sungeui/CG/
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