

Lecture 12: Ray-tracing based rendering

DHBW, Computer Graphics

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Syllabus

- 3D scene
 - Object
 - Camera
 - Light
 - Rendering
 - Ray-tracing based rendering
 - Rasterization-based rendering
 - Image and display
- Ray-tracing based rendering
 - Overview
 - Camera rays
 - Intersections
 - Shading
 - Light transport
-
- The diagram consists of two main parts. On the left, there is a vertical list of topics under 'Syllabus'. On the right, there is a detailed list under 'Ray-tracing based rendering'. A blue rounded rectangle encloses the 'Ray-tracing based rendering' section. Two blue arrows point from the 'Rendering' and 'Image and display' items on the left towards the enclosed section on the right, indicating they are sub-topics of it.

Inter-reflections

Glossy reflections

Soft shadows

Specular
transmission



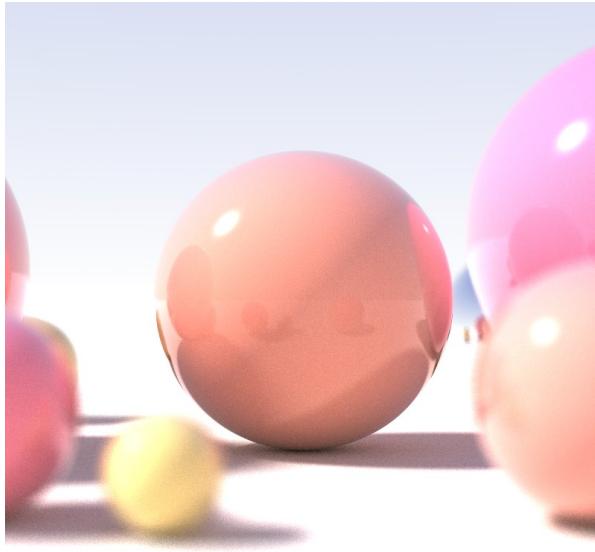
Ray-tracing-based rendering:

https://www.realtimerendering.com/Real-Time_Rendering_4th-Real-Time_Ray_Tracing.pdf

Raytracing-based rendering overview

Introduction

- Ray-tracing is a method **inspired by physics of light** → realistic image synthesis
- Ray-tracing is considered one of the **most elegant techniques** in computer graphics.
- Many phenomena such as **shadows, reflections and refracted light** are **intuitive and straightforward** to implement.



Robert L. Cook Thomas Porter Loren Carpenter. "Distributed Ray-Tracing" (1984).



[https://en.wikipedia.org/wiki/Ray_tracing_\(graphics\)](https://en.wikipedia.org/wiki/Ray_tracing_(graphics))

Rendering recap

- Rendering: calculate a color of each pixel of the virtual image plane
- Rendering process: visibility and shading
 - **Visibility**: find objects that are visible from camera
 - Find which surfaces are visible, ignore participating media
 - **Shading**: what is the color of visible objects
 - Use light, view, shape and material information

Ray-tracing-based rendering

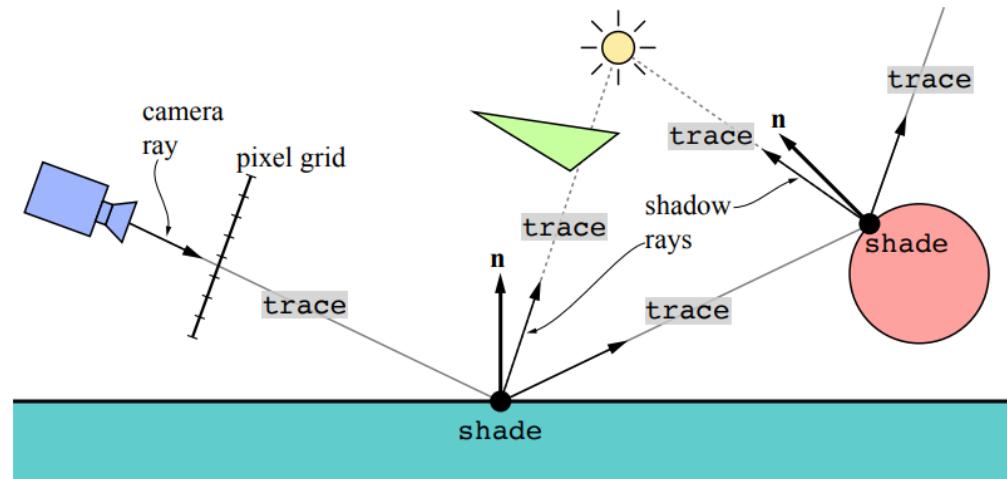
- **Visibility problem:** two points are visible to each other if line segment that joins them does not intersect any obstacle.
- Ray-tracing fundamentally **solves visibility problem using ray-casting**
 - **Finding objects visible from camera:** generate ray from camera and test intersections with objects
 - **Shading** requires finding from where light might be incident to surface by generating rays from shading point into 3D scene - **light transport**

Ray-tracing-based rendering

- **Generate ray** for each pixel of virtual image plane → **camera ray**
 - **Perspective camera**: generate rays from aperture to each pixel
 - **Orthographic camera**: generate parallel rays for each pixel
- **Ray-object intersection**: testing intersection of generated ray and 3D scene objects to obtain what is visible from camera
- **Shading**: calculating the color and intensity of intersected points
 - Light-matter calculation
 - Light transport for incoming light

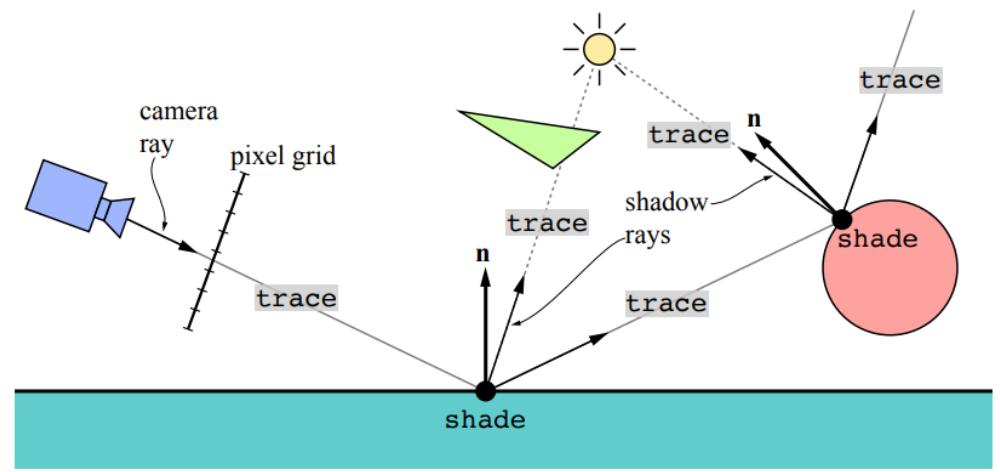
Ray-tracing-based rendering: trace & shade

- Raytracing can be described with two functions **trace()** and **shade()**
- **trace()** is geometrical part of algorithm responsible for finding closest intersection between ray and the objects in 3D scene
- **Shade()** returns color of the ray intersecting object found by **trace()**



trace() for camera rays

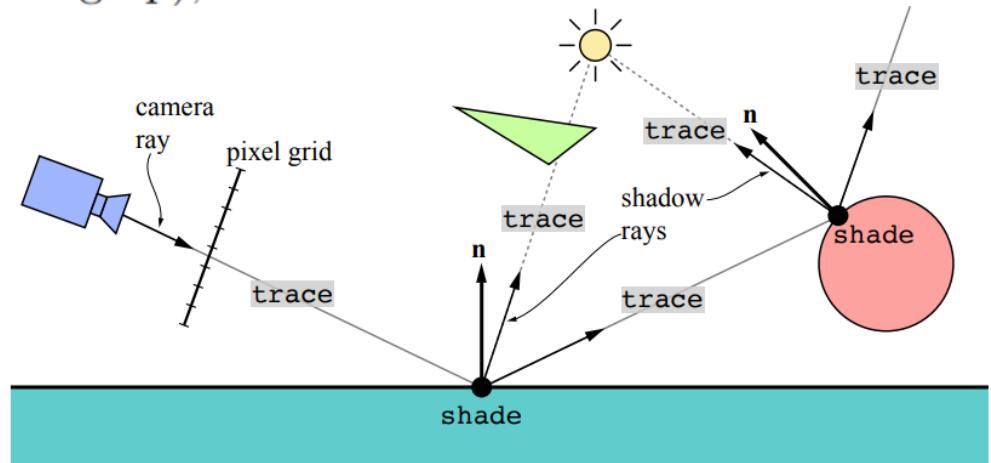
- Rendering starts by generating camera rays for each pixel in the image
- trace() function is used on generated camera rays
 - Find closest intersection of camera ray with 3D scene objects
 - Naive trace() function: loop through all n objects in the scene and returns closest intersection
 - $O(n)$ performance. Spatial acceleration structure (BVH or k-d tree) $\rightarrow O(\log(n))$ performance



trace() for camera rays

```
function RAYTRACEIMAGE
    for p do in pixels
        color of p = TRACE(camera ray through p);
    end for
end function
```

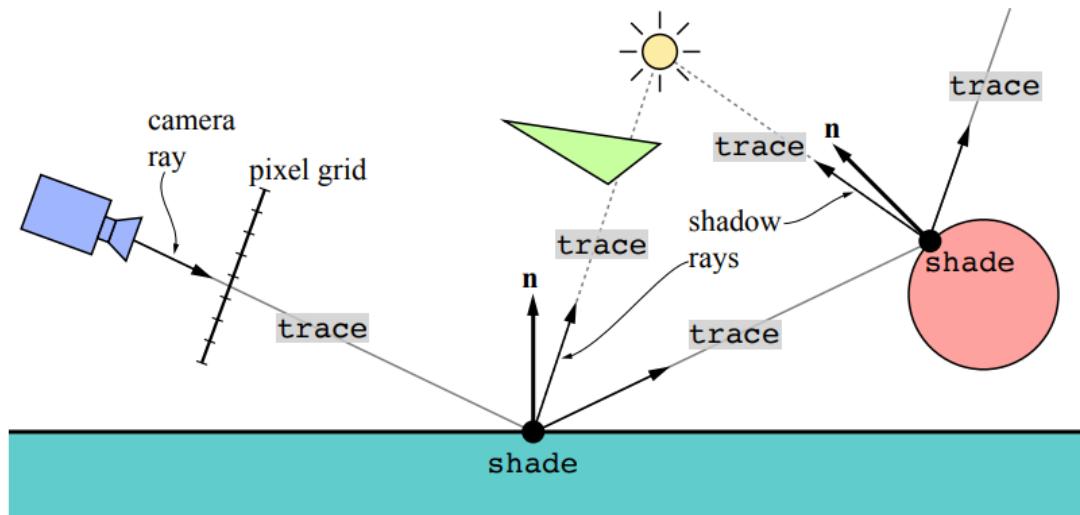
```
function TRACE(ray)
    pt = find closest intersection;
    return SHADE(pt);
end function
```



Ray-casting is often used in trace() function for determining visibility between two points.

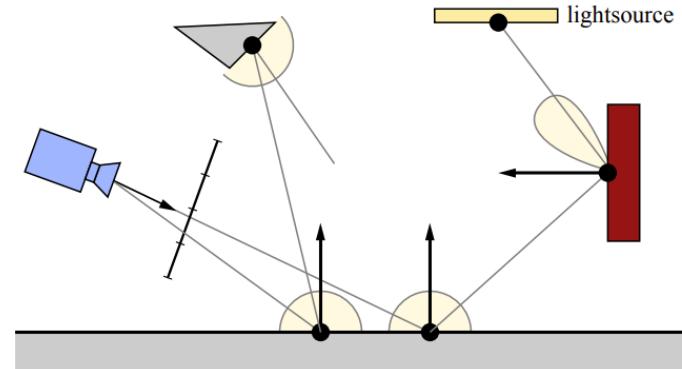
shade () for intersections

- shade () calculates color in intersection.
- shade () can be arbitrarily complex:
 - It can just return the color of object
 - It can use material information in intersected point with incoming light information
 - Use trace () for closest light sources
 - Use trace () to gather incoming light from all directions (e.g., other surfaces)



trace() for light transport

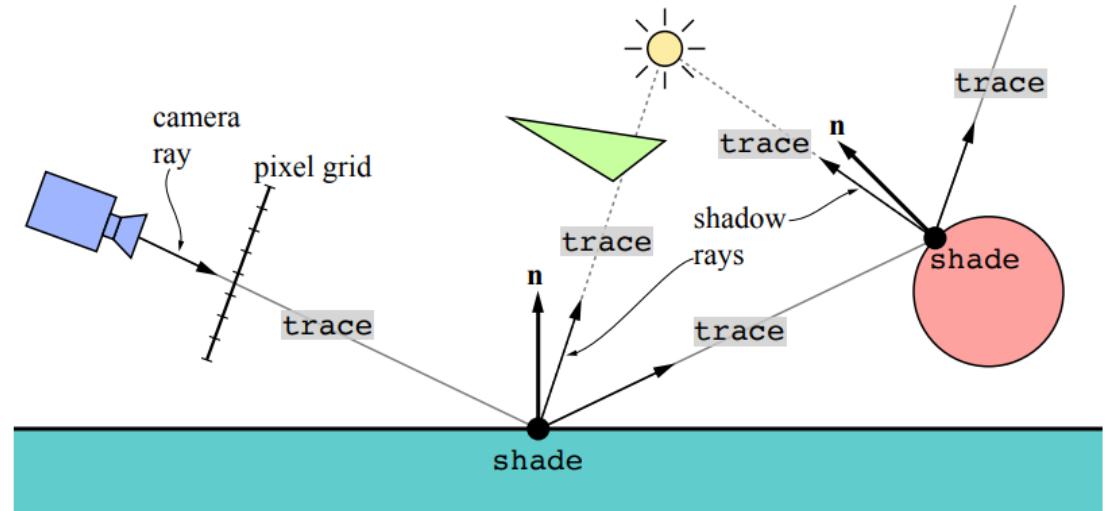
- Light transport: obtaining incident light on shading point
- trace() can calculate visibility between shaded point and light source – shadow ray
- trace() can compute reflection or refraction ray



shade () for intersections

```
function SHADE(point)
    color = 0;
    for L do in light sources
        TRACE(shadow ray to L);
        color += evaluate material;
    end for
    color += TRACE(reflection ray);
    color += TRACE(refraction ray);
    return color;
end function
```

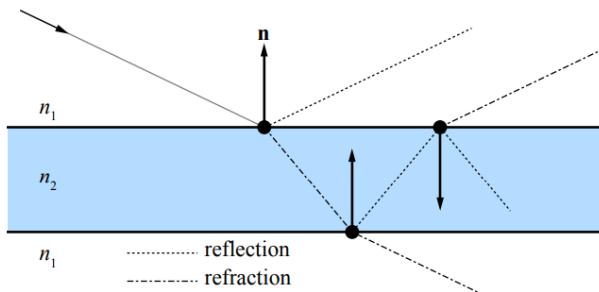
```
function TRACE(ray)
    pt = find closest intersection;
    return SHADE(pt);
end function
```



- Each shade () can call trace () and each trace () can call shade ()
- **Ray depth** is term with indicates number of rays that have been shot recursively along a ray path.

Shade() and trace()

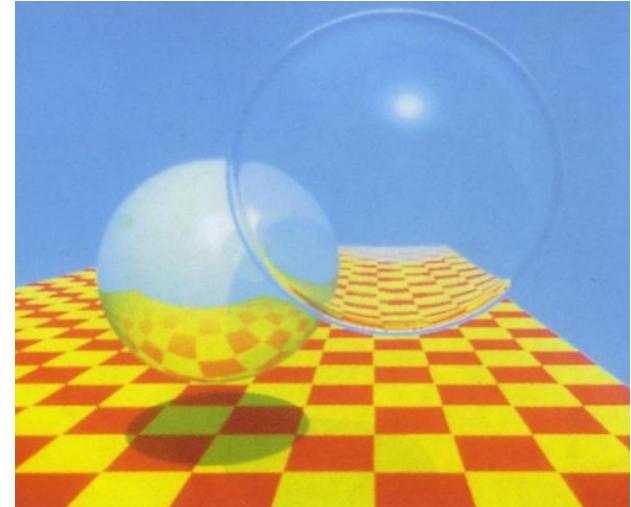
- shade() function is implemented by user as a **shader** program
 - Material (scattering functions and textures) is used to light-surface interaction, that is, color
- Traversal and intersection testing which takes place in trace() function is often implemented on CPU
 - GPU rendering uses compute or ray-tracing shaders in Vulkan or DXR



shade() defines interaction of light with surface, its color.

Ray-tracing structure

- Ray-tracing structure consisting of `shade()` and `trace()` is basis for **Whitted ray-tracer**
 - Whitted ray-tracing consists of perfectly sharp (specular) reflections and refractions
- Whitted ray-tracing is foundation of many other rendering variants such as path-tracing which are solving rendering equation and global illumination.



Ray-tracing based rendering

Ray

- Ray is fundamental element of ray-tracing used for solving visibility

- Ray is defined as:

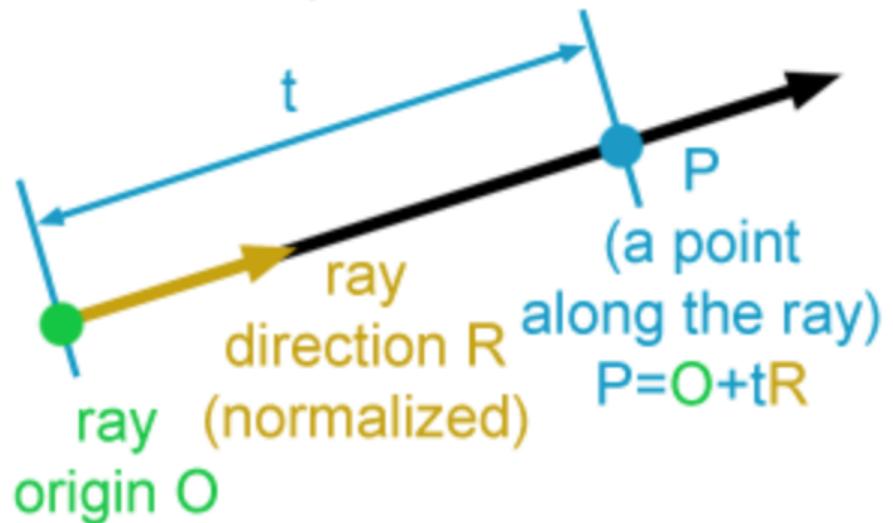
- `vector3f origin;`
 - `vector3f direction;`

- Any point on ray is defined with parametric equation:

$$P(t) = \text{origin} + t * \text{direction};$$

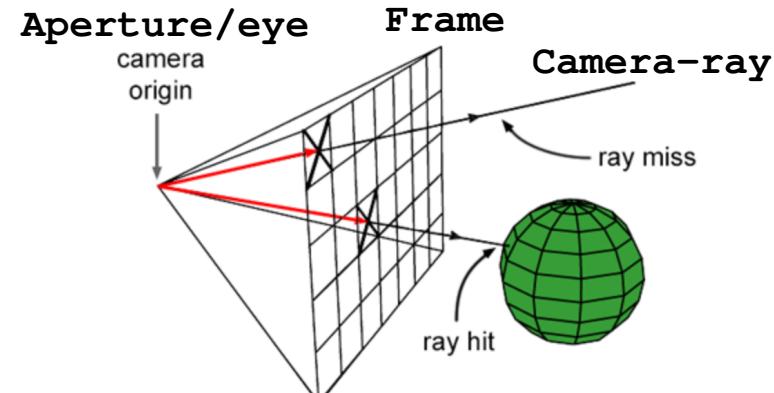
- t – distance from origin to $P(t)$
 - $t > 0 \rightarrow P(t)$ is in front of ray's origin
 - $t < 0 \rightarrow P(t)$ is behind the ray's origin

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Generating camera rays

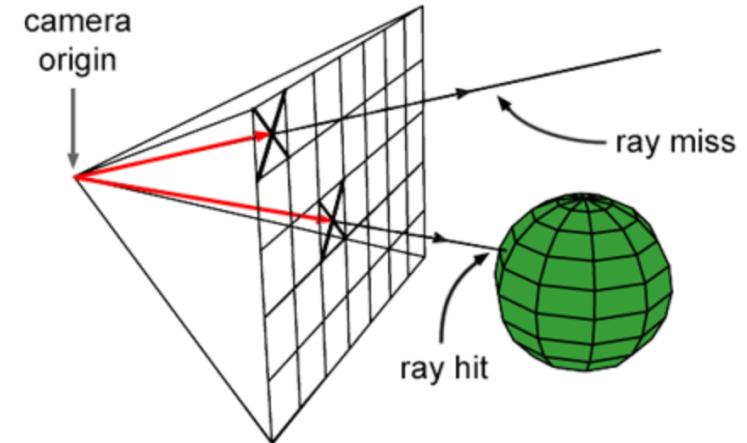
- Camera:
 - **Aperture** (eye) position and orientation of camera line of sight
 - **Field of view**: how much of the scene we see
 - **Frame**: array of pixels where image is formed
- **Camera rays** are generated starting from camera aperture and passing through each pixel in the film plane into 3D scene → **backward/eye-tracing**
 - Used to compute the visible objects → **ray-casting**



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Generating camera rays

```
Vector3f ImageBuffer[imageWidth, imageHeight];  
  
For (int j = 0; j < imageHeight; ++j)  
{  
    For (int i = 0; i < imageWidth; ++i)  
    {  
        For (int k = 0; k < nObjectsInScene; ++k)  
        {  
            Ray ray = buildCameraRay(i, j);  
            if (intersect(ray, object[k], intersectionContext))  
            {  
                // Object hit. Compute shading using intersectionContext.  
                ImageBuffer[j * imageWidth + i] = shadingResult;  
            }  
            else  
            {  
                // Background hit. Compute background color...  
                ImageBuffer[j * imageWidth + i] = backgroundColor;  
            }  
        }  
    }  
}
```

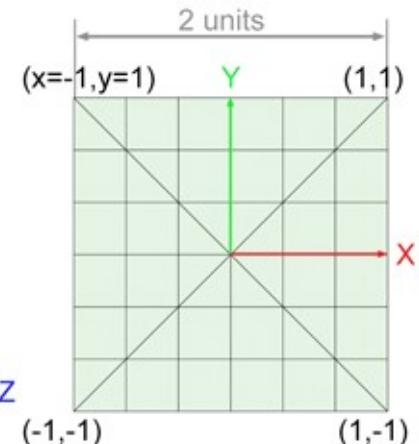
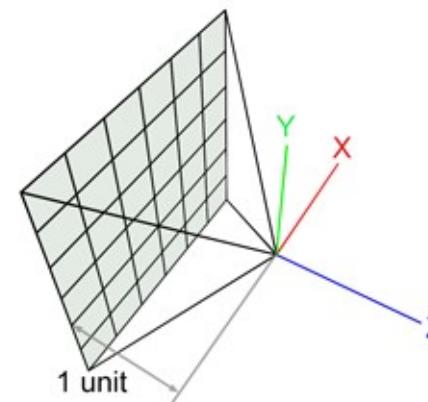


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Generating camera rays: basic setup

- Assume:
 - Camera origin (aperture, eye) is in $(0, 0, 0)$
 - Camera is looking in negative Z axis
 - Film (image) plane is placed 1 unit from camera's origin
 - Film dimensions are 2×2 units
 - Film is centered around Z axis
 - Image is square (`image_width == image_height`)
- Ray is created by connecting world-space points:
 - Camera origin – aligned with world coordinate origin
 - Pixel center – requires transformation from raster space to world space

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Pixel center coordinates

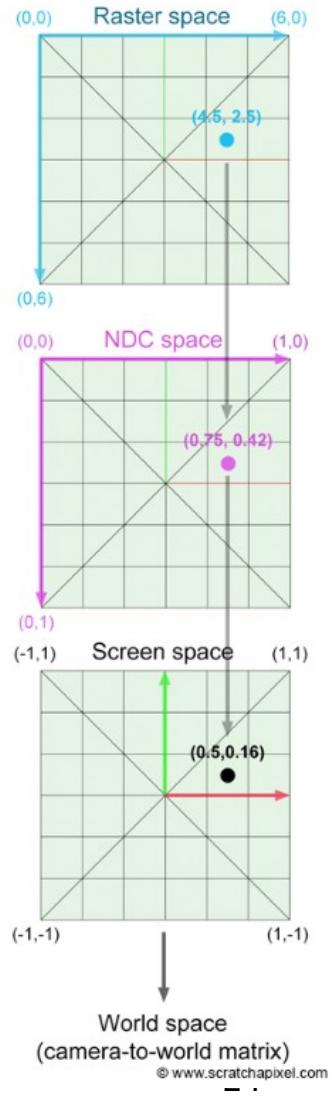
- Pixel coordinates are originally defined in **raster space** [`image_height`, `image_width`]
 - Integer coordinates (Pixel_x , Pixel_y) where left-top corner of frame is $(0, 0)$
- Pixel position must be first normalized using frame dimensions giving **normalized device coordinates (NDC)** $[0, 1]$

$$\text{PixelNDC}_x = \frac{(\text{Pixel}_x + 0.5)}{\text{ImageWidth}},$$
$$\text{PixelNDC}_y = \frac{(\text{Pixel}_y + 0.5)}{\text{ImageHeight}}.$$

- Finally, pixels are transformed from NDC to **screen space**

$$\text{PixelScreen}_x = 2 * \text{PixelNDC}_x - 1,$$

$$\text{PixelScreen}_y = 1 - 2 * \text{PixelNDC}_y.$$

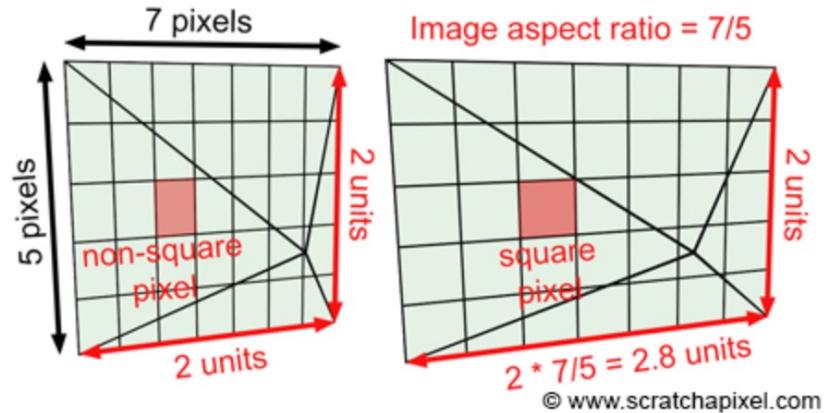


Pixel center coordinates (frame with arbitrary aspect ratio)

- To ensure square pixels for image arbitrary aspect ratio, use image aspect ratio to scale frame size

$$\text{ImageAspectRatio} = \frac{\text{ImageWidth}}{\text{ImageHeight}},$$

$$\text{PixelCamera}_x = (\text{PixelScreen}_x) * \text{ImageAspectRatio},$$
$$\text{PixelCamera}_y = (\text{PixelScreen}_y).$$

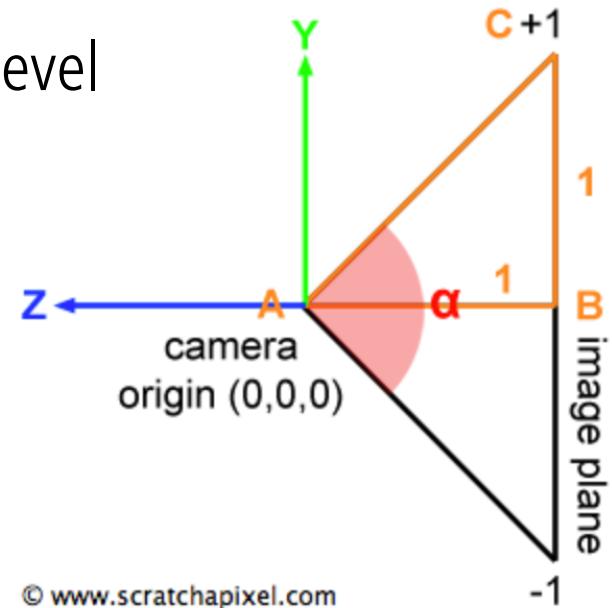


Pixel center coordinates (arbitrary field of view)

- Field of view defines how much we see or zoom level
- To incorporate arbitrary field of view:

$$PixelCamera_x = (PixelScreen_x) * ImageAspectRatio * \tan\left(\frac{\alpha}{2}\right),$$

$$PixelCamera_y = (PixelScreen_y) * \tan\left(\frac{\alpha}{2}\right).$$



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$$\|BC\| = \tan\left(\frac{\alpha}{2}\right).$$

Pixel center coordinates: camera space

- Now, pixel coordinates are expressed in camera coordinate space
 - Pixel coordinates are defined with regards to camera's image plane
- Currently, **camera is in default position** (camera coordinate system is aligned with world coordinate system)
 - Camera origin O (aperture): $(0, 0, 0)$
 - Orientation: negative Z axis
 - Image plane: 1 unit away from camera's origin
- Pixel coordinate position on the image plane

$$P_{cameraSpace} = (PixelCamera_x, PixelCamera_y, -1)$$

Generating camera rays: world space

- Camera space ray can be constructed using camera origin and pixel position in camera space

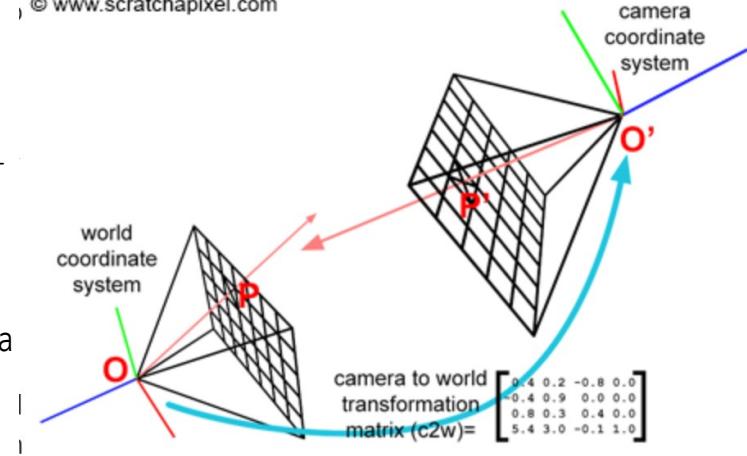
```
vector3 RayOrigin = cameraOrigin;  
vector3 rayDirection = normalize(pixelCameraPosition -  
cameraOrigin);
```

- World space ray can be constructed:

- Camera-to-world matrix is first applied on pixel position and camera origin
- vector3 RayOrigin = cameraOriginWorld;
- vector3 rayDirection = normalize(pixelPositionWorld - cameraOrigin);

- Camera-to-world can be constructed using look-at matrix.

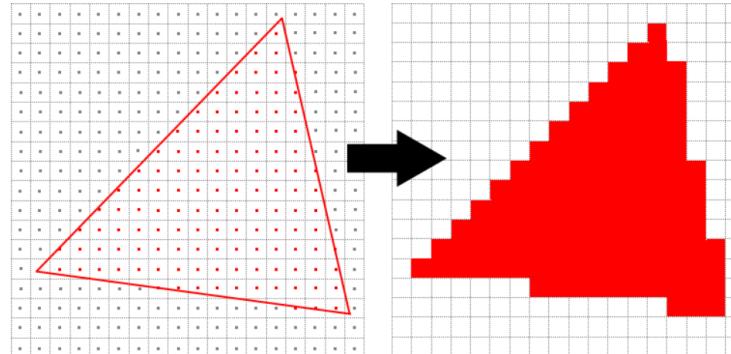
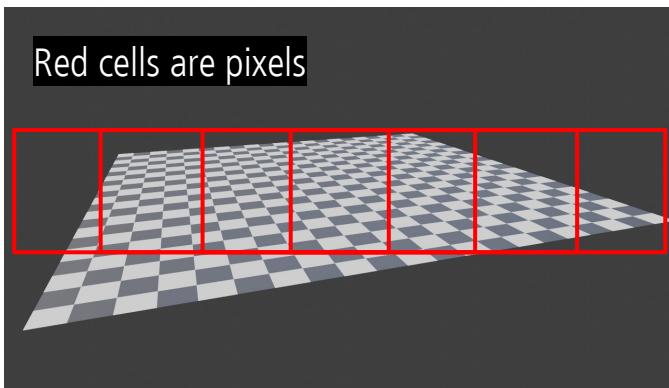
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Camera is originally set in its default position.
Camera-to-world matrix is used to move camera origin and pixel position for generating world space rays.

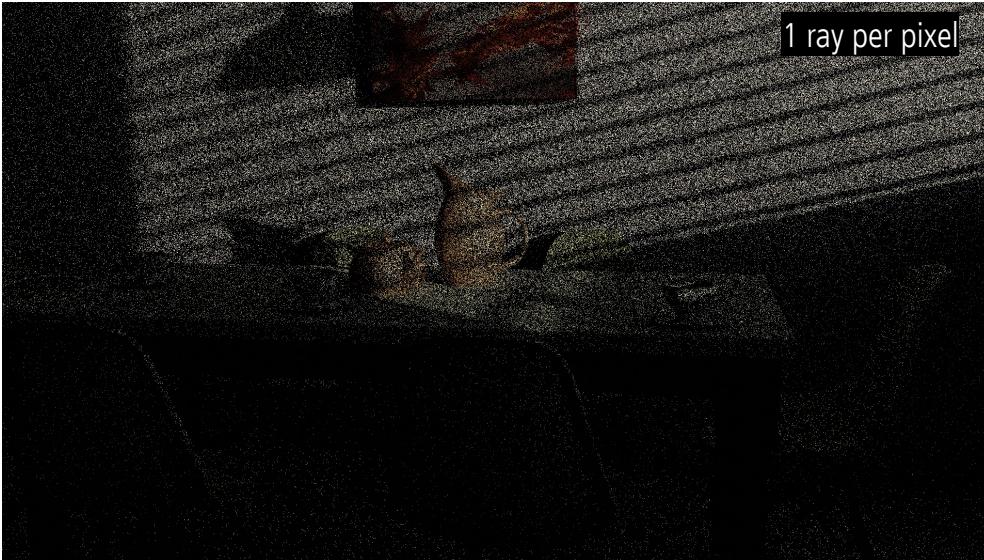
Generating multiple camera rays per pixel

- Pixel footprint in 3D scene can cover large area with different textures and objects
- Since pixel can represent only one color, it is important to use multiple rays to obtain the color which is the most representative for the part of the scene covered by that pixel
 - Instead of pixel center, random points on pixel area are taken for building rays
 - Multiple rays per pixel are also called multiple samples per pixel (SPP)



Generating multiple camera rays per pixel

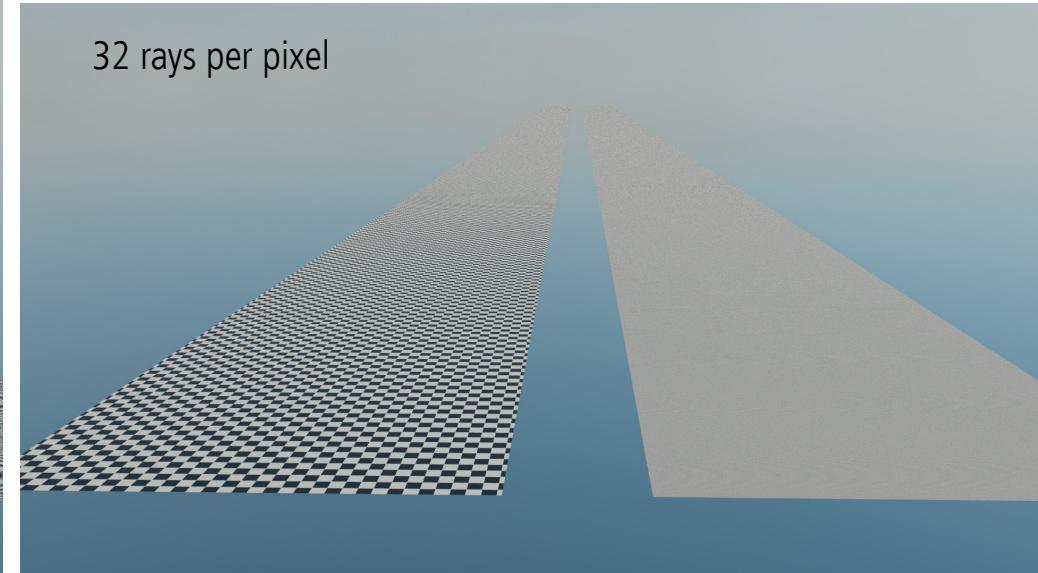
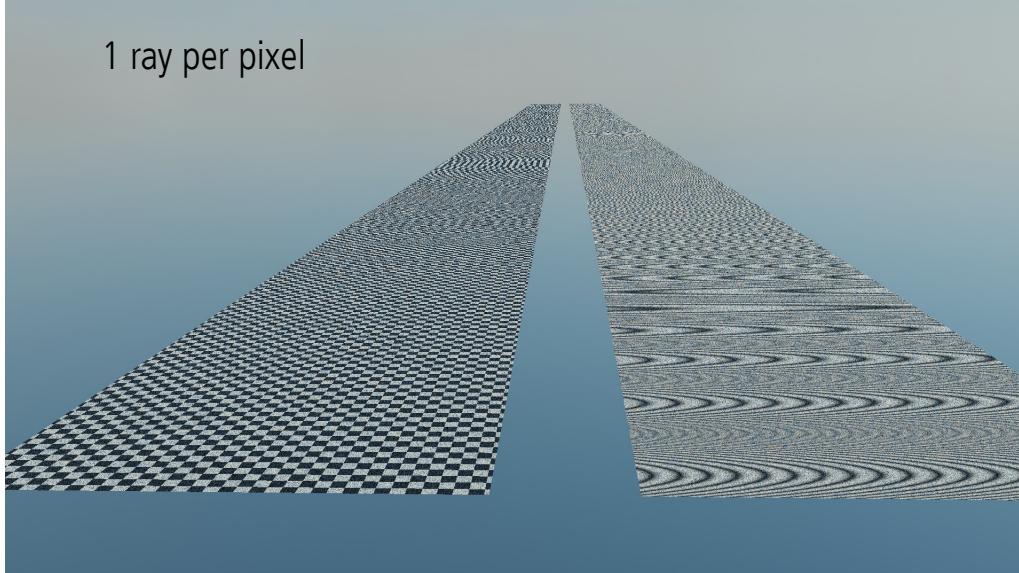
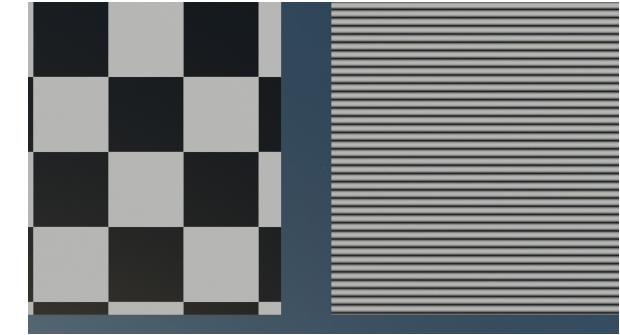
- Using multiple rays per pixels, **reduces noise**



- Using multiple rays per pixel is especially important for methods building on raytracing and using stochastic sampling (e.g., Monte Carlo) such as path tracing.

Generating multiple camera rays per pixel

- Using multiple rays per pixels, **reduces aliasing**



Ray-tracing: image centric method

- Since rendering starts from virtual image plane, ray-tracing is called **image centric approach**
- Once camera rays are generated, they are traced into scene and tested for intersections with objects
 - Looping over all objects in 3D scene is performed and each is tested for intersection with current ray → **visibility test**
 - Testing intersections with objects depends on object shape, i.e., triangulated mesh

```
for P do in pixels
    for T do in triangles
        determine if ray through P hits T
    end for
end for
```

Camera ray-objects intersection testing

```
...
for (int k = 0; k < nObjectsInScene; ++k)
{
    Ray ray = buildCameraRay(i, j);
    if (intersect(ray, objects[k], intersectionContext))
    {
        // Object hit. Compute shading using intersectionContext.
        framebuffer[j * imageWidth + i] = shadingResult;
    }
    else
    {
        // Background hit. Compute background color...
        framebuffer[j * imageWidth + i] = backgroundColor;
    }
}
...
```

- `intersect()` method depends on object shape
- `ShadingResult` depends on object material.
- That is why decoupling material and shape of 3D object is useful.

Testing ray-object intersections

- Objects in 3D scene can be represented with different **shape (geometry) representations**
 - Parametric representations
 - Spheres, disks, planes, etc.
 - Surfaces and curves (e.g., Bezier curves, NURBS, etc.)
 - Implicit surfaces SDFs: spheres, cubes, etc.
 - Polygonal meshes (e.g., triangles, quads) and subdivision surfaces
 - Voxels
 - Etc.
- We will discuss:
 - Ray-sphere intersection
 - Ray-triangle intersection and its extension to triangulated meshes

Ray-sphere intersection

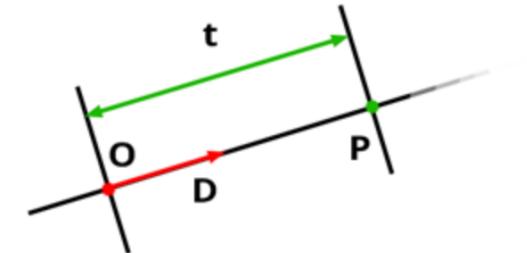
- Ray-sphere intersection is simplest ray-geometry intersection
- Parametric ray description: $P(t) = O + t * D$
- Implicit (algebraic) sphere form at world origin and radius R:

$$x^2 + y^2 + z^2 = R^2$$

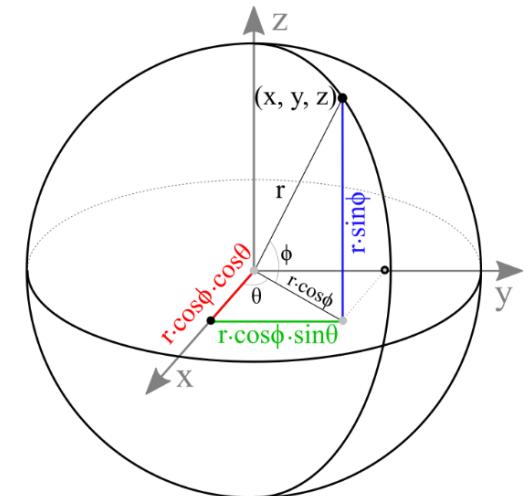
- x, y, z are coordinates of a point on a sphere:

$$P^2 - R^2 = 0$$

- Implicit function which defines implicit sphere shape



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http://www.songho.ca/opengl/gl_sphere.html

Ray-sphere intersection

- Start with $P^2 - R^2 = 0$ and $P(t) = O + t * D$
- Substitute P with ray equation: $|O + t * D|^2 - R^2 = 0$
 - Develop: $O^2 + (Dt)^2 + 2ODt - R^2 = O^2 + D^2t^2 + 2ODt - R^2 = 0$
- Quadratic equation: $f(x) = ax^2 + bx + c$:
 - $a = D^2$, $b = 2OD$, $c = O^2 - R^2$. Solution:

$$t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$
$$\Delta = b^2 - 4ac$$

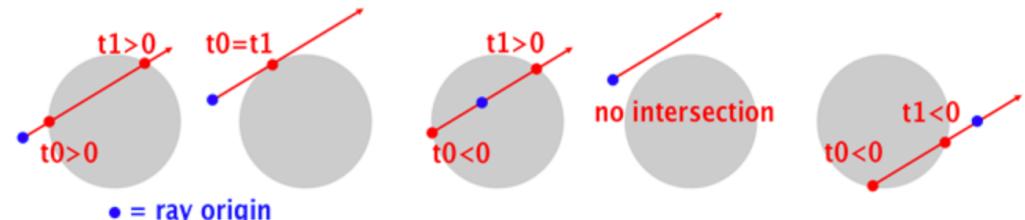
- $\Delta > 0$: ray intersects sphere in two points (t_0 and t_1):

$$\frac{-b + \sqrt{\Delta}}{2a} \quad \text{and} \quad \frac{-b - \sqrt{\Delta}}{2a}$$

- $\Delta = 0$: ray intersects sphere in one point ($t_0 = t_1$):

$$-\frac{b}{2a}$$

- $\Delta < 0$: ray doesn't intersect the sphere



Ray-sphere intersection: arbitrary sphere position

- If sphere is translated from origin to point C, then:

$$- |P - C|^2 - R^2 = 0$$

- Substituting the ray equation:

$$- |O + t * D - C|^2 - R^2 = 0$$

- Solving quadratic equation gives t_0 and t_1 :

$$t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$a = D^2 = 1 \quad (\text{ray direction } D \text{ is normalized})$$

$$b = 2D(O - C)$$

$$c = |O - C|^2 - R^2$$

Ray-sphere intersection: intersection point and context

- t_0 , when inserted into ray equation $P(t) = O + t * D$ gives closest **intersection point** of ray with a sphere

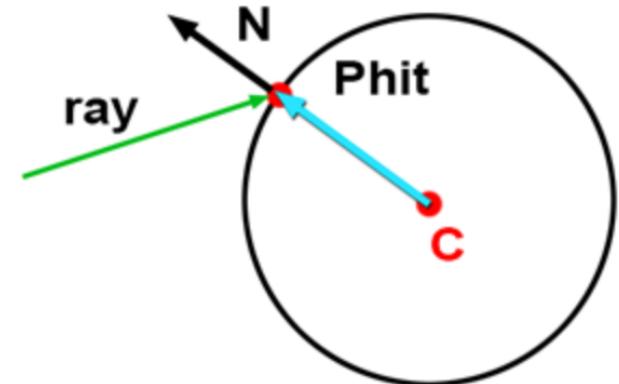
```
vector3 Phit = O + D * t0
```

- Next to intersection point $Phit$, renderer often computes additional intersection information – **intersection context**:
 - **Normal** in intersection point
 - **Texture coordinate** in intersection point
 - Etc.
- Intersection context information calculation depends on object shape:
 - For parametric surfaces (u,v) parameters can be used as texture coordinates
 - For polygonal (e.g., triangle) mesh, texture coordinates must be precomputed and stored per vertex. Intersection point is used to interpolate texture coordinates per triangle face (e.g., barycentric interpolation)
- **Intersection context contains information which is used for shading of intersection point**

Ray-sphere intersection: normal

- Normal calculation in intersection point depends on shape representation
- For implicit sphere with center $C(x, y, z)$

```
vector3 N = normalize(Phit - C)
```



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Ray-sphere intersection: texture coordinates

- Sphere can be written in parametric form:

$$P.x = \cos(\theta) \sin(\phi),$$

$$P.y = \cos(\theta),$$

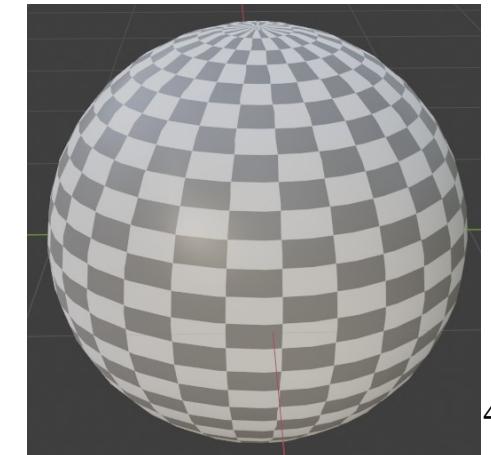
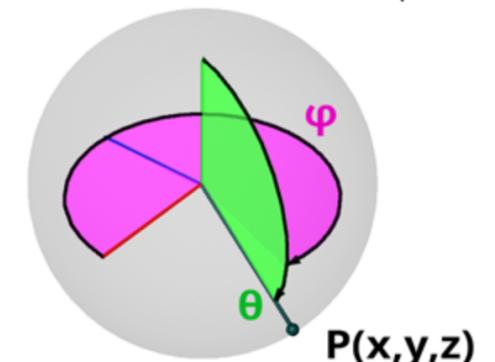
$$P.z = \sin(\theta) \sin(\phi).$$

- Texture coordinates for sphere are simply spherical coordinates:

$$\phi = \text{atan}(z, x),$$

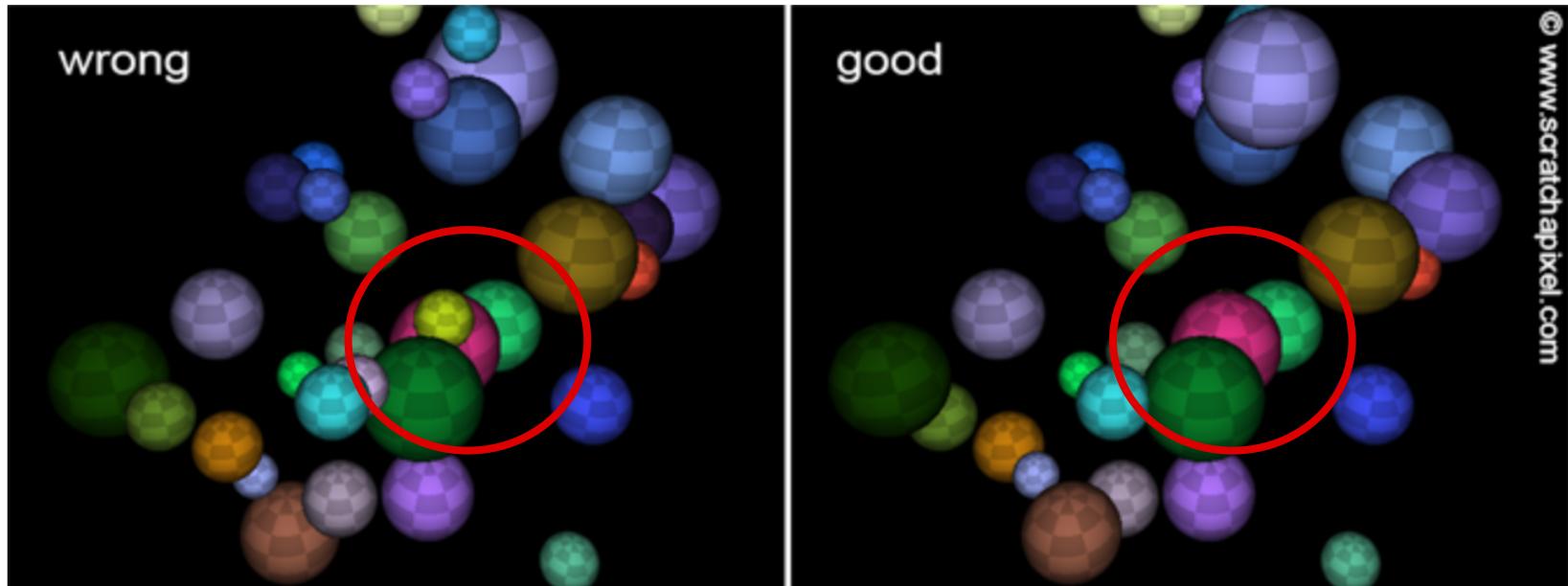
$$\theta = \text{acos}\left(\frac{P.y}{R}\right).$$

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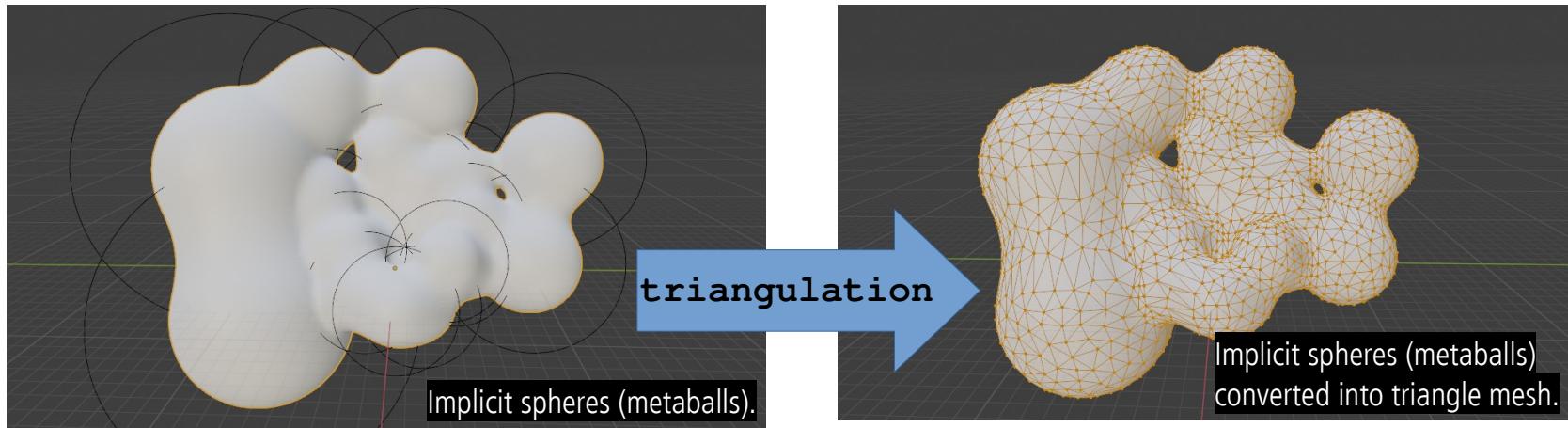
Ray-sphere intersection: intersection order

- If scene contains multiple objects then certain **depth sorting** is needed
 - Keep track of closest intersection distance, closest t , and use this value for comparison when testing intersection with new object



Intersecting other shape representations

- Define ray-shape intersection for each representation separately (e.g., triangulated mesh and parametric curves)
- Alternative solution: **convert each shape representation to same internal representation which is used for rendering**
 - Professional rendering software often work on **triangulated mesh** which is obtained using **triangulation**



Tessellation and triangulated mesh

- Two sides of the computer graphics/image generation: authoring of 3D scene and rendering
 - Some representations are much more easier and efficient to handle on authoring level
 - Some are much more efficient to handle for rendering purposes
 - Therefore, efficient mapping of those representations quite important and researched.
- Renderer working with single primitive is much more efficient than supporting various primitives
- Why triangles?
 - Can approximate any surface and shape well
 - Conversion of almost any type of surface to a triangulated mesh (tessellation) is well researched and feasible
 - Triangulated mesh is also basic rendering primitive for rasterization-based renderers
 - Graphics hardware is adapted and optimized to efficiently process triangles
 - Triangles are necessary co-planar which makes various computations, such as ray-triangle, much easier
 - Lot of research was devoted to efficient computation of ray-triangle intersection: <https://www.realtimerendering.com/intersections.html>
 - For triangles we can easily compute barycentric coordinates which are essential to shading
- Tessellation process can be done after modeling of shape is done and when exporting takes place or it can be done during rendering (render time)

Ray-triangle intersection test

- Basic ray-triangle intersection is straight forward, complexity comes due to multitude of different cases which must be accounted for
 - Thus, there are several algorithms that have been developed and are being developed:
<https://www.realtimerendering.com/intersections.html>
- Ray-triangle intersection testing steps:
 - Does ray intersect a plane defined by a triangle?
 - Does ray intersect point inside the triangle?

Ray-triangle intersection tools

- **Triangles are coplanar:** vertices are lying on a plane and plane can be defined with those vertices
- **Using triangle vertices, normal can be computed**

- Plane on which triangle lies has the same normal

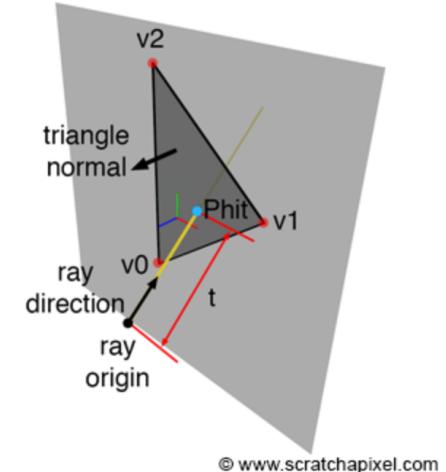
```
vector3 a = v1 - v0
```

```
vector3 b = v2 - v0
```

```
vector3 c = cross(a, b)
```

```
vector3 normal = normalize(c)
```

- Winding order of vertices defines normal and thus surface orientation – important for shading!



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$$\mathbf{a} = a_1 \mathbf{i} + a_2 \mathbf{j} + a_3 \mathbf{k}$$

$$\mathbf{b} = b_1 \mathbf{i} + b_2 \mathbf{j} + b_3 \mathbf{k}$$

$$\mathbf{a} \times \mathbf{b} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \end{vmatrix}$$

$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} a_2 b_3 - a_3 b_2 \\ a_3 b_1 - a_1 b_3 \\ a_1 b_2 - a_2 b_1 \end{bmatrix}$$

Ray-triangle intersection test: intersecting plane

- Intersected point is somewhere on ray:

$$P_{hit} = P(t) = O + t * R$$

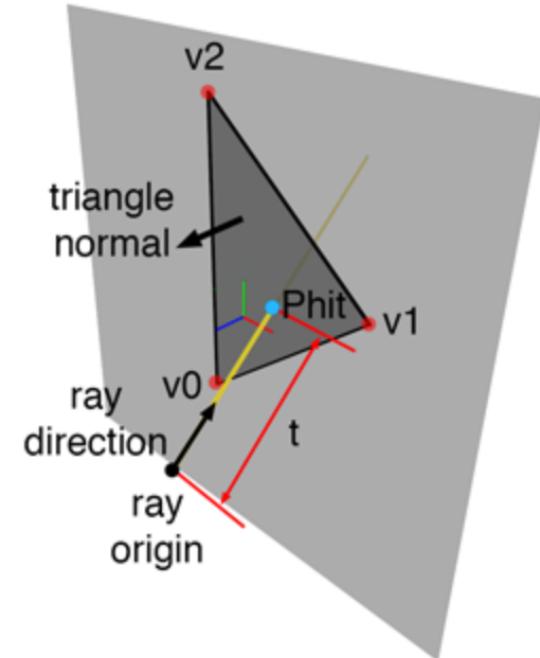
- Plane equation :

$$Ax + By + Cz + D = 0$$

$$D = -(Ax + By + Cz)$$

- A, B, C are coordinates of plane normal $N = (A, B, C)$
 - D is distance from origin $(0, 0, 0)$ to the plane
 - x, y, z are coordinates of point on a plane
- Normal N can be calculated using triangle vertices
 - D can be calculated using any triangle vertex v and normal N :

$$D = \text{dotProduct}(N, v0) = -(N.x * v0.x + N.y * v0.y + N.z * v0.z);$$



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Ray-triangle intersection: intersecting plane

- Substitute ray equation $P(t) = O + t * R$ into plane equation $Ax + By + Cz + D = 0$:

$$A * P.x + B * P.y + C * P.z + D = 0$$

$$A * (O.x + t * R.x) + B * (O.y + t * R.y) + C * (O.z + t * R.z) + D = 0$$

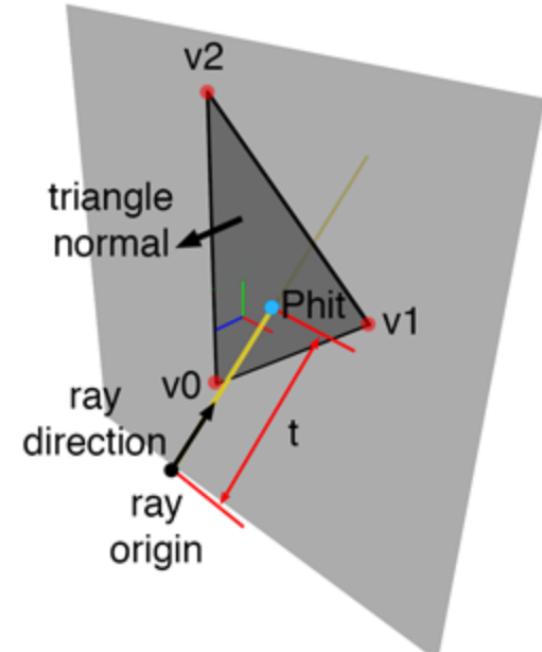
- Solving by t :

$$t = -\frac{N(A, B, C) \cdot O + D}{N(A, B, C) \cdot R}$$

- Finally, intersection point of ray and plane:

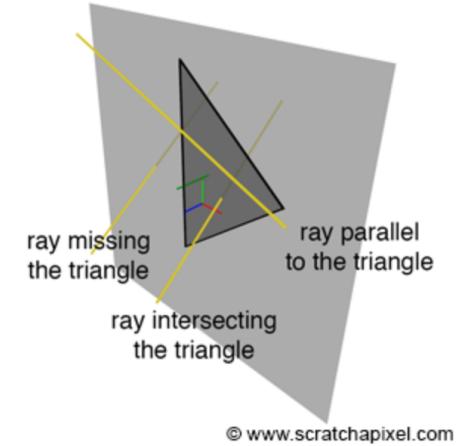
```
float t = - (dot(N, O) + D) / dot(N, R)
```

```
Vector3 Phit = O + t * R
```

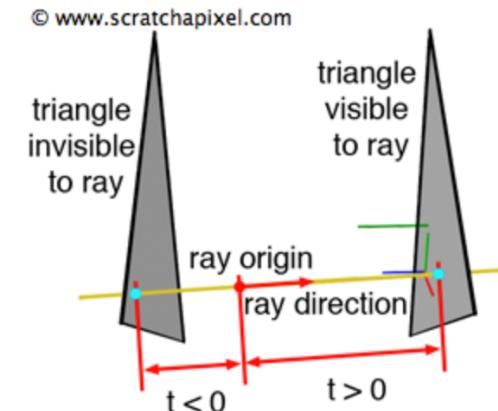


Ray-triangle intersection: intersecting plane

- Special cases of non-intersection:
 - Ray and triangle (plane) are parallel
 - Triangle's normal and ray direction are perpendicular
 $\text{dot}(N, R) = 0$
 - Triangle is behind ray origin
 - If $t < 0 \rightarrow$ triangle behind ray origin. Else, triangle is visible



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Ray-triangle intersection: point inside triangle?

- We have found intersection point P on plane. Is it inside triangle?

- **Inside-out test**

```
vector3 edge0 = v1 - v0;  
vector3 edge1 = v2 - v1;  
vector3 edge2 = v0 - v2;  
  
vector3 C0 = P - v0;  
vector3 C1 = P - v1;  
vector3 C2 = P - v2;  
  
bool q1 = dotProduct(N, crossProduct(edge0, C0)) > 0;  
bool q2 = dotProduct(N, crossProduct(edge1, C1)) > 0;  
bool q3 = dotProduct(N, crossProduct(edge2, C2)) > 0;  
  
If (q1 and q2 and q3) then inside;
```

Inside-outside test:

- Test if dot product of vector along edge and vector defined with first vertex of the test edge and P is positive \rightarrow if P is on left side of the edge.
- If P is on the left side of all three edges, then P is inside triangle

Ray intersection with triangle mesh

- We have a routine to compute ray-triangle intersection
- To test ray intersection with object which is represented as triangulated mesh:
 - Loop over all triangles of triangulated mesh
 - Test if ray intersects triangles of triangulated mesh
 - Respect depth sorting by keeping track of nearest object
- For generated camera ray, we can write `intersect()` function which:
 - Takes triangulated mesh and ray
 - Returns information on intersection
 - Return information on intersection context

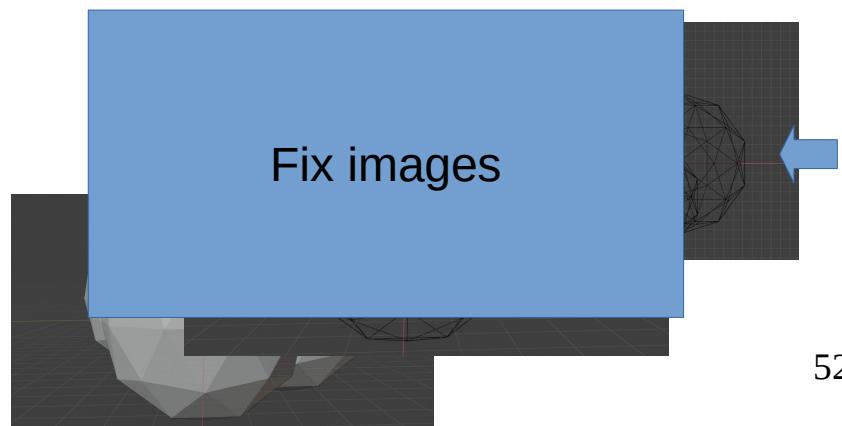
Testing ray intersections: intersect() function

```
bool intersect (Ray ray, Object objects, &intersectionContext)
{
    bool intersected = true;
    for (int k = 0; k < objects.nObjects; ++k)
    {
        for (int n = 0; n < objects[k].nTriangles; ++n)
        {
            if(rayTriangleIntersect(ray, objects[k].triangle[n]))
            {
                intersected = true;
                IntersectionContext.objIdx = k;
                IntersectionContext.triIdx = n;
            }
        }
    }
    return intersected;
}
```

intersect () : depth

```
bool intersect (Ray ray, Object objects, &intersectionContext, &tNearest)
{
    bool intersected = true;
    tnearest = INFINITY;
    for (int k = 0; k < objects.nObjects; ++k)
    {
        for (int n = 0; n < objects[k].nTriangles; ++n)
        {
            if(rayTriangleIntersect(ray, objects[k].triangle[n], t) and t < tNearest)
            {
                intersected = true;
                IntersectionContext.objIdx = k;
                IntersectionContext.triIdx = n;
                tNearest = t;
            }
        }
    }
    Return intersected;
}
```

- Ray may intersect several triangles.
- Keep track of closest intersection and update it with each intersection

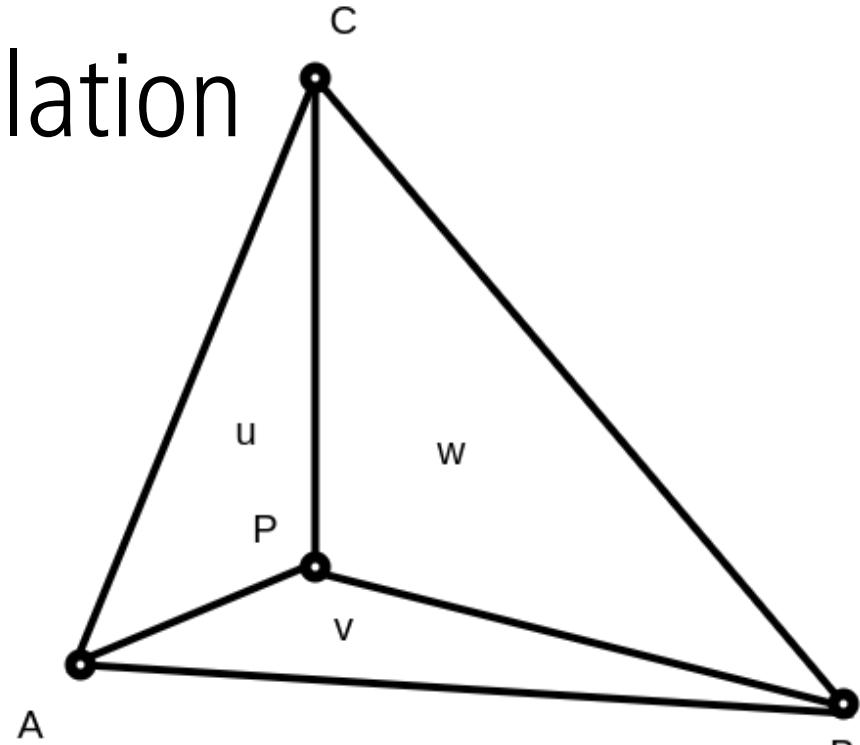


intersect () function: intersection context

- `intersect ()` function must return information **if ray intersects object** (triangle) as well as **intersection context**:
 - Object index: `objIdx`
 - Triangle index: `triIdx`
 - Ray parameter `t` for nearest intersection: `tNearest`
 - Intersection point coordinates
 - Intersection point normal
 - Intersection point texture coordinates
 - etc.
 - Information of `objIdx`, `triIdx` and `tNearest` can be used to compute the rest of intersection context information
- Often, triangulated meshes contain information stored per vertices, barycentric interpolation is used to obtain value for specific intersection point
- Intersection context information will be used for shading the intersected point

Recap: barycentric interpolation

- Any point P on triangle is described as:
 - $P = uA + vB + wC$, where A, B, C are triangle vertices
 - u, v, w are **barycentric (areal) coordinates**
 - $u + v + w = 1$
 - When $0 \leq u, v, w \leq 1$ P inside or on triangle edge. Otherwise P is outside of triangle.
- Barycentric coordinates: u, v, w are proportional to area of sub-triangles defined by P
- Interpolating vertex data
 - We know P and A, B, C . Calculate u, v, w and use these factors for interpolating



$$\text{Area}(\text{Triangle}(ABC)) = \| (B-A) \times (C-A) \| / 2$$

$$u = \text{Area}(\text{Triangle}(CAP)) / \text{Area}(\text{Triangle}(ABC))$$

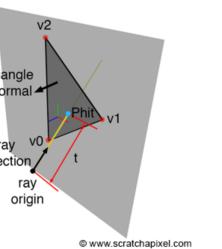
$$v = \text{Area}(\text{Triangle}(ABP)) / \text{Area}(\text{Triangle}(ABC))$$

$$w = \text{Area}(\text{Triangle}(BCP)) / \text{Area}(\text{Triangle}(ABC))$$

Intersection context: normal

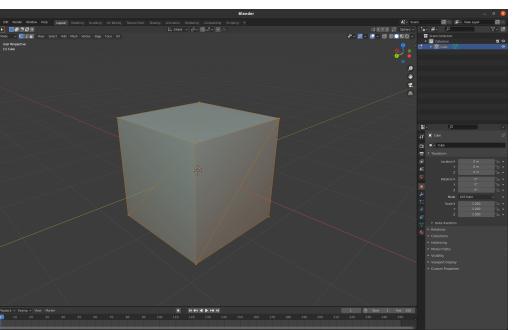
- Triangle normal, thus intersection point normal, can be calculated from triangle vertices:

```
vector3 a = v1 - v0  
vector3 b = v2 - v0  
vector3 c = cross(a, b)  
vector3 normal = normalize(c)
```



- Smooth normals can be created when modeling triangulated mesh

- Those are stored per vertex
 - To obtain smooth normal in intersection point, barycentric interpolation can be performed using intersection point and triangle vertices



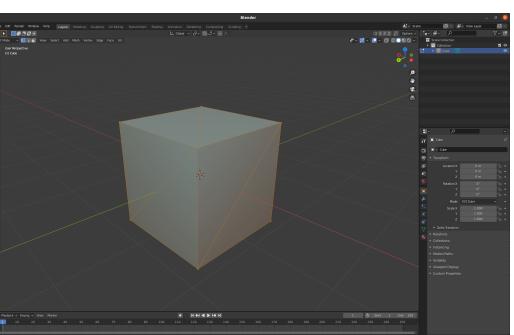
```
1 # Blender v2.92.0 OBJ File: ''  
2 # www.blender.org  
3 o Cube_Cube.002  
4 v -1.000000 -1.000000 1.000000  
5 v -1.000000 1.000000 1.000000  
6 v -1.000000 -1.000000 -1.000000  
7 v -1.000000 1.000000 -1.000000  
8 v 1.000000 -1.000000 1.000000  
9 v 1.000000 1.000000 1.000000  
10 v 1.000000 -1.000000 -1.000000  
11 v 1.000000 1.000000 -1.000000  
12 vt 0.625000 0.000000  
13 vt 0.375000 0.250000  
14 vt 0.375000 0.000000  
15 vt 0.625000 0.250000  
16 vt 0.375000 0.500000  
17 vt 0.625000 0.500000  
18 vt 0.375000 0.750000  
19 vt 0.625000 0.750000  
20 vt 0.375000 1.000000  
21 vt 0.125000 0.750000  
22 vt 0.125000 0.500000  
23 vt 0.875000 0.500000  
24 vt 0.625000 1.000000  
25 vt 0.875000 0.750000  
26 vn -1.0000 0.0000 0.0000  
27 vn 0.0000 0.0000 -1.0000  
28 vn 1.0000 0.0000 0.0000  
29 vn 0.0000 0.0000 1.0000  
30 vn 0.0000 -1.0000 0.0000  
31 vn 0.0000 1.0000 0.0000  
32 s OFF  
33 f 2/1/1 3/2/1 1/3/1  
34 f 4/4/2 7/5/2 3/2/2  
35 f 8/6/3 5/7/3 7/5/3  
36 f 6/8/4 1/9/4 5/7/4  
37 f 7/5/5 1/10/5 3/11/5  
38 f 4/12/6 6/8/6 8/6/6  
39 f 2/1/1 4/4/1 3/2/1  
40 f 4/4/2 8/6/2 7/5/2  
41 f 8/6/3 6/8/3 5/7/3  
42 f 6/8/4 2/13/4 1/9/4  
43 f 7/5/5 5/7/5 1/10/5  
44 f 4/12/6 2/14/6 6/8/6
```

Intersection context: texture coordinates

- Texture coordinates for each vertex of triangulated meshes are created during mesh modeling using:
 - Mesh unwrapping
 - Texture projections, e.g., spherical, cylindrical, triplanar, etc.
- To compute texture coordinate in intersection point, barycentric interpolation is used
- Note: texture projections can be also used to create texture coordinates on the fly



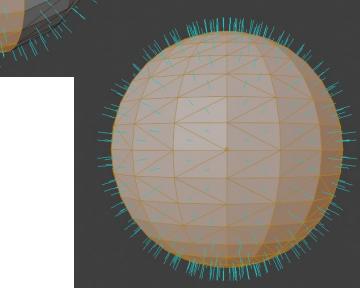
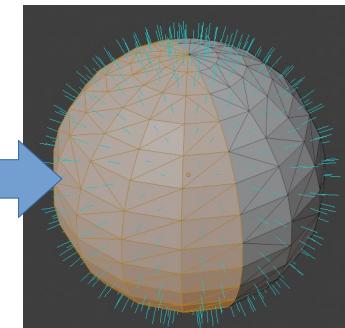
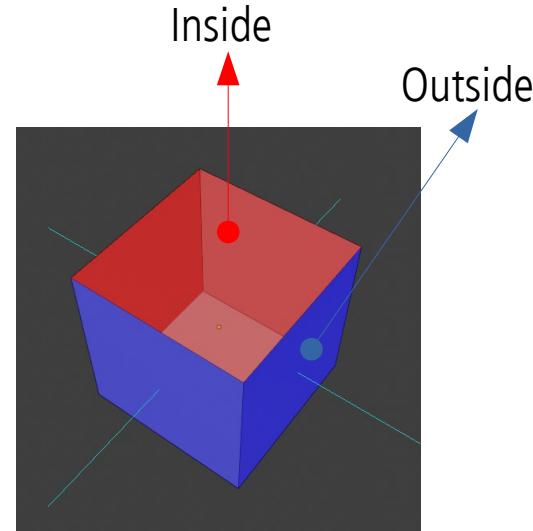
```
1 # Blender v2.92.0 OBJ File: ''
2 # www.blender.org
3 o Cube_Cube.002
4 v -1.000000 -1.000000 1.000000
5 v -1.000000 1.000000 1.000000
6 v -1.000000 -1.000000 -1.000000
7 v -1.000000 1.000000 -1.000000
8 v 1.000000 -1.000000 1.000000
9 v 1.000000 1.000000 1.000000
10 v 1.000000 -1.000000 -1.000000
11 v 1.000000 1.000000 -1.000000
12 vt 0.625000 0.000000
13 vt 0.375000 0.250000
14 vt 0.375000 0.000000
15 vt 0.625000 0.250000
16 vt 0.375000 0.500000
17 vt 0.625000 0.500000
18 vt 0.375000 0.750000
19 vt 0.625000 0.750000
20 vt 0.375000 1.000000
21 vt 0.125000 0.750000
22 vt 0.125000 0.500000
23 vt 0.875000 0.500000
24 vt 0.625000 1.000000
25 vt 0.875000 0.750000
26 vn -1.0000 0.0000 0.0000
27 vn 0.0000 0.0000 -1.0000
28 vn 1.0000 0.0000 0.0000
29 vn 0.0000 0.0000 1.0000
30 vn 0.0000 -1.0000 0.0000
31 vn 0.0000 1.0000 0.0000
32 s off
33 f 2/1/1 3/2/1 1/3/1
34 f 4/4/2 7/5/2 3/2/2
35 f 8/6/3 5/7/3 7/5/3
36 f 6/8/4 1/9/4 5/7/4
37 f 7/5/5 1/10/5 3/11/5
38 f 4/12/6 6/8/6 8/6/6
39 f 2/1/1 4/4/1 3/2/1
40 f 4/4/2 8/6/2 7/5/2
41 f 8/6/3 6/8/3 5/7/3
42 f 6/8/4 2/13/4 1/9/4
43 f 7/5/5 5/7/5 1/10/5
44 f 4/12/6 2/14/6 6/8/6
```



Single and double sided triangle

- Winding order of triangle vertices defines normal orientation → surface orientation
 - Surface normal pointing inwards
 - Surface normal pointing outwards
- Surface or triangle is front-facing or back-facing
- **Single-sided** primitives: only front-facing triangles will be rendered
- **Double sided** primitives: both front- and back-facing
- **Back-face culling**: back-facing triangles will not be rendered (drawn)
 - For casting shadows, back-face culling can not be used.
 - Test: `dotProduct (ray.direction, N) > 0`

<https://www.scratchapixel.com/lessons/3d-basic-rendering/ray-tracing-rendering-a-triangle/single-vs-double-sided-triangle-backface-culling.html>

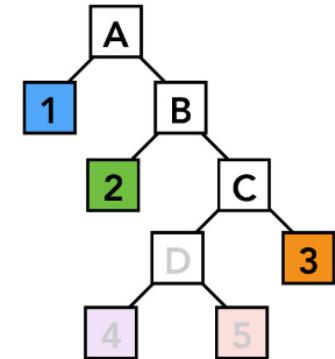
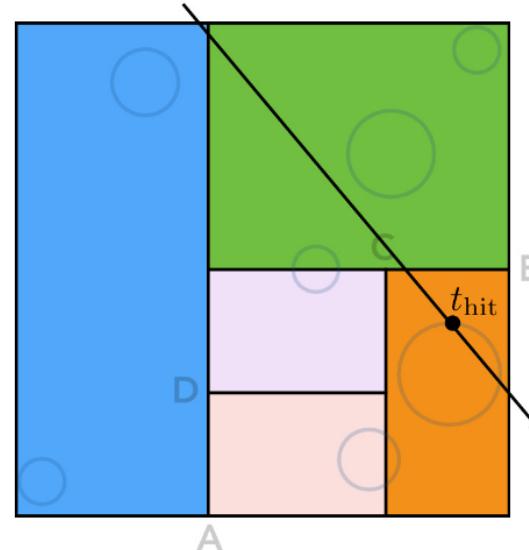


Testing intersections

- Time to render a scene is (directly) proportional to the number of triangles in the scene
- For shading purposes, all triangles must be stored into memory and each must be tested for intersection for ray
 - Rasterization-based rendering discards triangle not visible from camera (e.g., back faces of object – back face culling) thus faster, but therefore has lower shading capabilities
- Therefore, efficient ray-object intersections are needed!
 - <https://www.realtimerendering.com/intersections.html>

Testing intersections

- If certain parts of the scene are not relevant for current ray, they can be skipped
 - **Spatial acceleration data structures**
 - object shape information is “sorted” in 3D scene and scene is spatially subdivided.
 - Rays first test larger volumes of the scene and if that volume is not relevant, all objects inside do not have to be tested for intersections!
 - Such acceleration structures require **pre-computation overhead**
 - Static scenes: only once before rendering.
 - Animated scenes, these datastructures must be pre-computed each time objects move (each frame) before rendering.



Intersection found

<https://cs184.eecs.berkeley.edu/sp22/lecture/10/ray-tracing-acceleration>

Spatial acceleration data structures

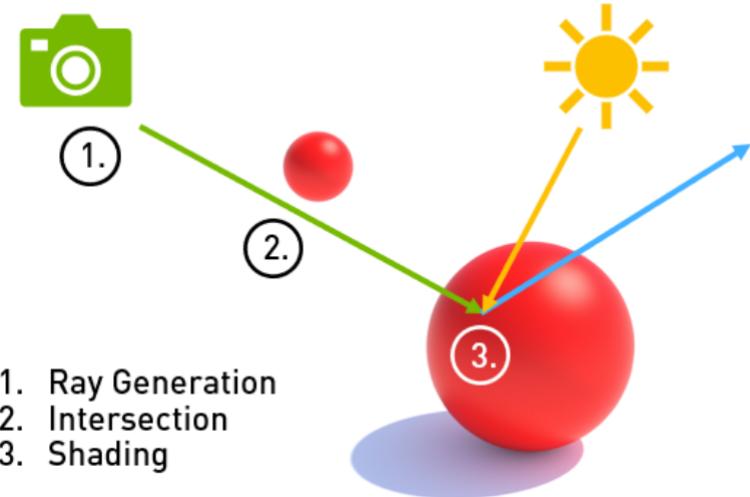
- TODO
RTR BOOK



TODO

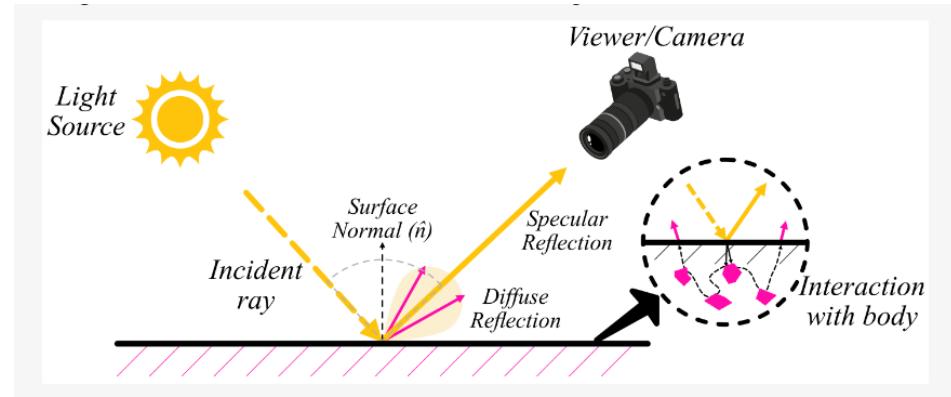
Shading

- Once intersection of camera ray with object is found (visibility is solved), we need to calculate color and intensity of that point → **shading**.
 - Intersection point → **shading point**.
- Shading and thus appearance of object depends on:
 - Material of the object surface (scattering model, texture)
 - Shape of the object surface (normal)
 - Incoming light on surface (direction, color, intensity)
 - Camera viewpoint (position and orientation)
- Color of an object at any point is the result of the way object reflects light falling on that point to camera.



1. Ray Generation
2. Intersection
3. Shading

<https://developer.nvidia.com/blog/rtx-best-practices/>



<https://www.mdpi.com/1424-8220/22/17/6552>

Shading: participating media

- Ray traveling from camera to surface can pass through participating media

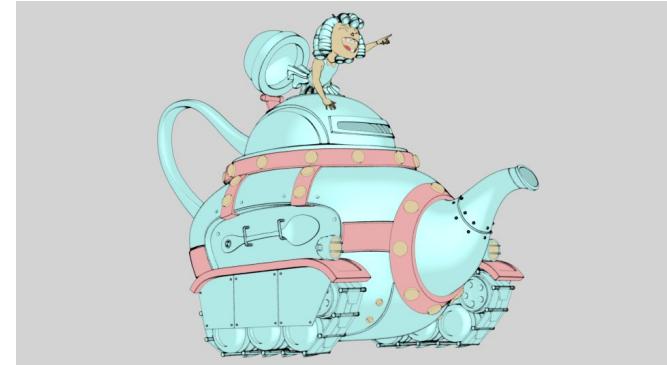


(Non-)Photo-realistic rendering

- Level of photo-realism depends on reproducing the color and intensity of objects (appearance)
- Shading plays crucial role for photo-realistic rendering
- Shading, can be also utilized to render expressive or artistic images → non-photo-realistic rendering.
- Photo-realistic rendering is useful for understanding physically-based shading from which non-photo realistic rendering can be derived with means of exaggeration



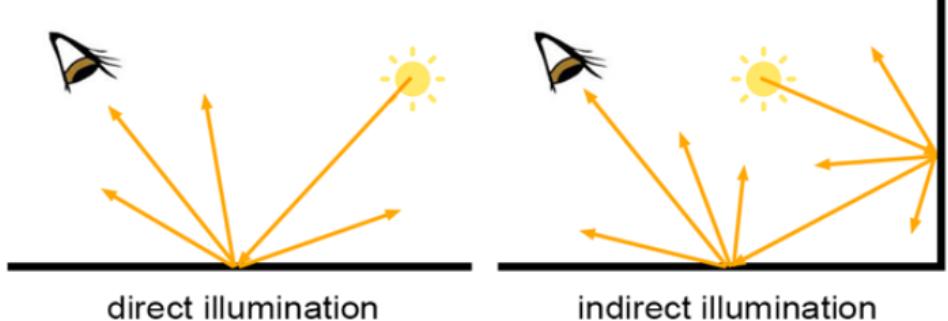
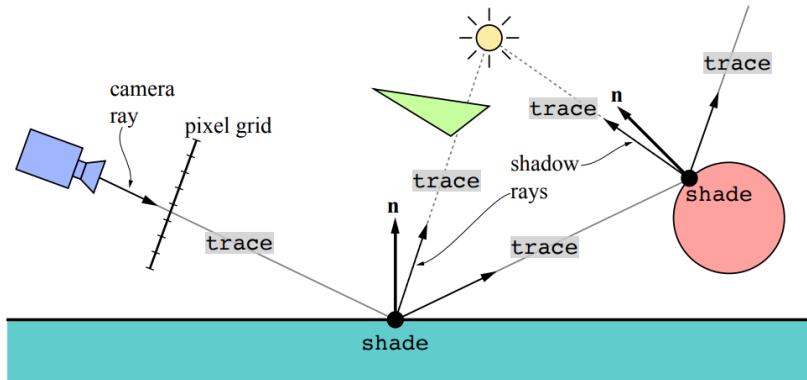
<https://www.artstation.com/artwork/rANDoE>



"Rolling Teapot" - Model by Brice Laville, concept by Tom Robinson, render by Esteban Tovagliari - RenderMan 'Rolling Teapot' Art Challenge:
<https://appleseedhq.net/gallery.html#https%3A%2F%2Fappleseedhq.net%2Fimg%2Frender%2Frolling-teapot.jpg>

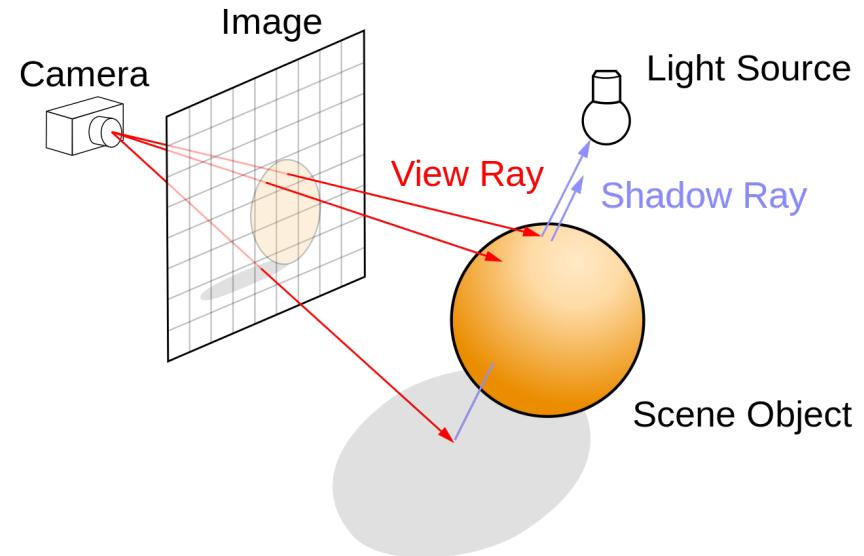
Shading and light

- Light is essential to shading
- Incoming light to shaded surface point can be:
 - Direct illumination: light emitted directly by light sources
 - Indirect illumination: light reflected from another object surface



Direct illumination

- **Directional lights**
 - Light direction is given as vector L
 - Light color and intensity
- **Point lights or spot lights**
 - **Shadow rays** are generated from shading point P to light source S (visibility solving via raytracing):
 - Light direction: $L = \text{normalize}(S - P)$;
 - Light color and intensity
 - Inverse square law: intensity falls with squared distance to light source



[https://en.wikipedia.org/wiki/Ray_tracing_\(graphics\)](https://en.wikipedia.org/wiki/Ray_tracing_(graphics))

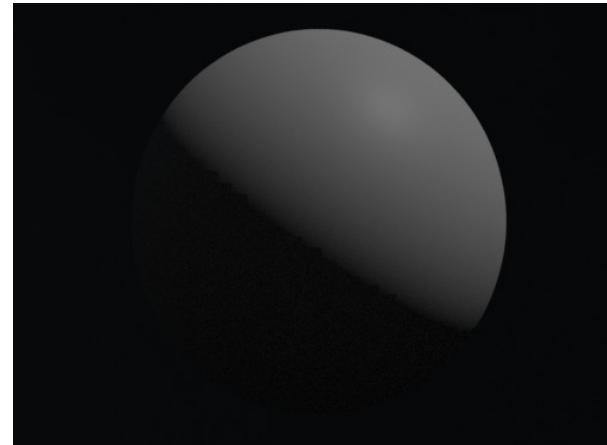
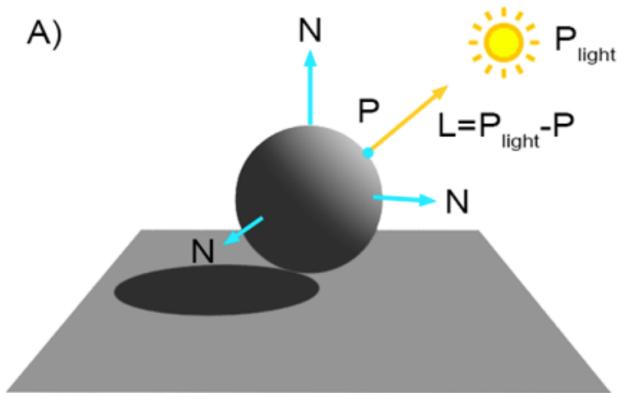
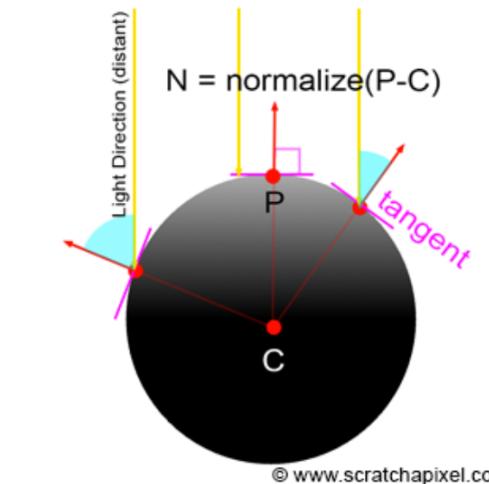
Direct illumination

- Area lights



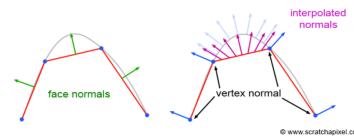
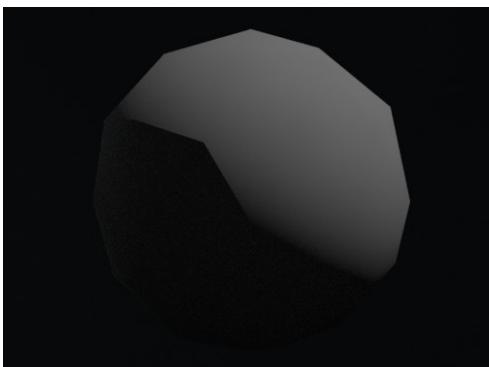
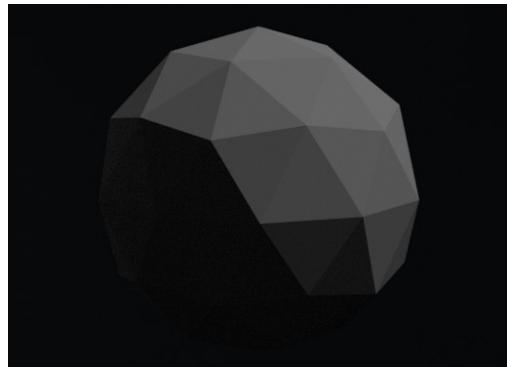
Shading: normals

- Surface normal is essential to shading
- Surface normal \mathbf{N} in shading point defines surface orientation
 - Surface normal and light direction determine surface brightness
 - Simple shading:

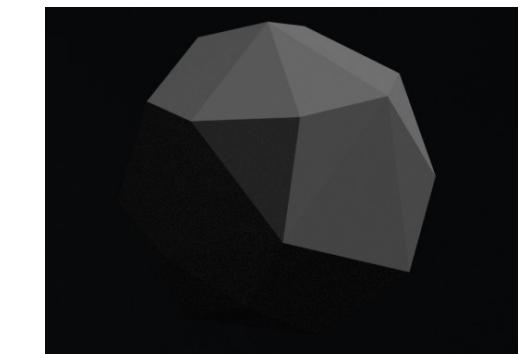


Shading: normals

- Triangulated mesh can't represent perfectly smooth surface
- Shading depends on surface normal and triangulated mesh gives faceted look
 - Flat shading
- Solution: Gourad shading
 - Produce smooth shading over surface by using **linearly interpolated vertex normals**
 - Linear interpolation of vertex normals is done using barycentric coordinates
- Vertex normals are:
 - Computed on the fly
 - Given from smooth surface from which triangulated mesh was created

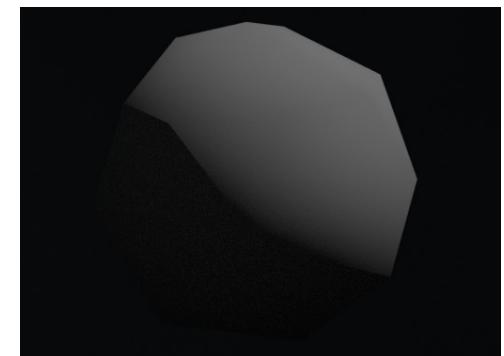


Implicit sphere



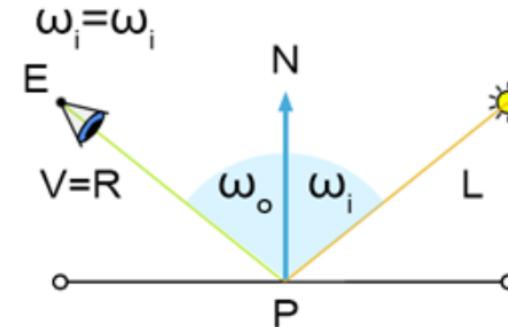
Triangulated mesh
from implicit
sphere

Triangulated mesh
from implicit
sphere with
smooth shading



Shading: material

- Appearance of object surface is further defined by reflectance model –
BRDF $f(L, N, V)$
 - Mathematical model approximating interaction of light and microscopic structure of object material
 - Besides parameters, it depends on incident light direction L and view direction V
 - Diffuse/Lambertian, specular, Phong, Blinn-Phong, Lafortune, Torrance-Sparrow, Cook-Torrance, Ward, Oren-Nayar, etc.
- BRDF contains number of parameters which are varied over surface using **texture**
- General shading; one point light:
 - `shaded_color = f(L, V, N) * light_color * light_intensity * max(0, dotProduct(N, L))`



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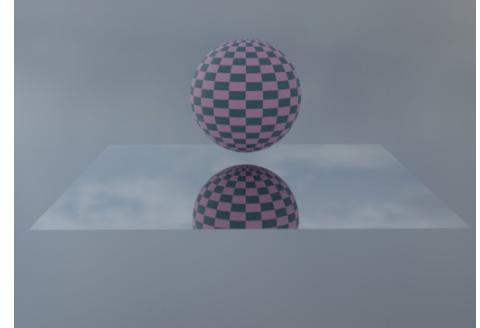
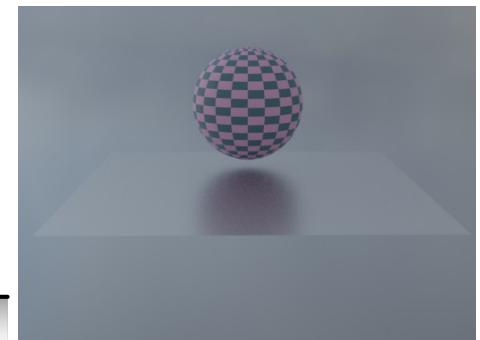
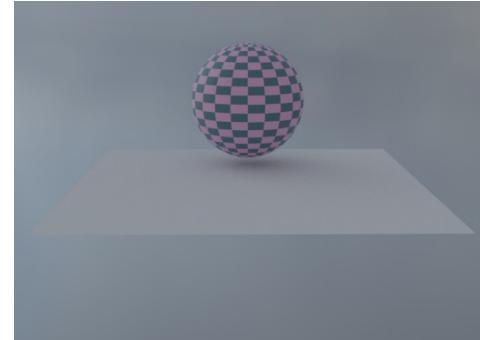
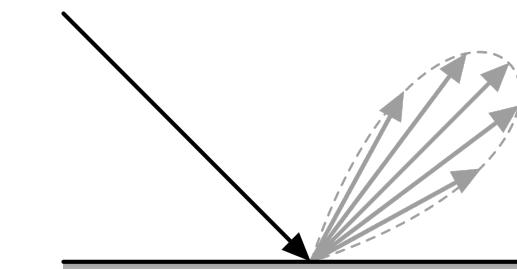
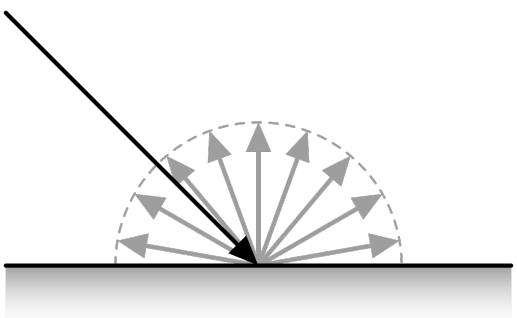
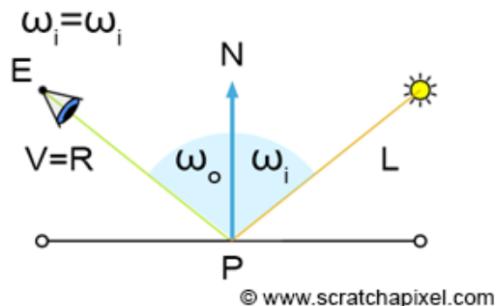
Shading and BRDF

- Amount reflected light in view direction \mathbf{v} given incident direction \mathbf{l} - BRDF: $f(\mathbf{v}, \mathbf{n}, \mathbf{l})$

- \mathbf{l} – incoming/incident direction
 - Angle of incidence: ω_i (between \mathbf{l} and \mathbf{n})
- \mathbf{v} – view direction
 - Line joining eye/camera E and shaded point
- \mathbf{r} – outgoing/reflected light direction
 - Angle of reflection: ω_o (between \mathbf{n} and \mathbf{r})

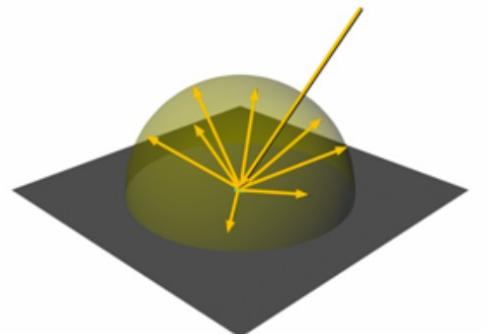
- Most materials can be described with following BRDFs:

- Mirror
- Diffuse/Lamberian
- Glossy

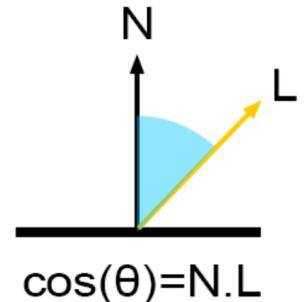


Shading: diffuse/Lambert surface

- Light falling on surface is attenuated based on surface normal and incoming light direction
 - Lambert's cosine law: $\text{dotProduct}(N, L)$
- Diffuse BRDF: albedo / PI
 - albedo RGB in [0,1]
 - Albedo = $(\text{reflected_light} / \text{incident_light})$
- Diffuse surfaces are reflecting light in all directions equally – over whole hemisphere at shading point P around normal N. Final color:
 - $\text{diffuse_surface} = (\text{albedo} / \text{PI}) * \text{light_color} * \text{light_intensity} * \max(0, \text{dotProduct}(N, L))$
- Surface is **view independent**



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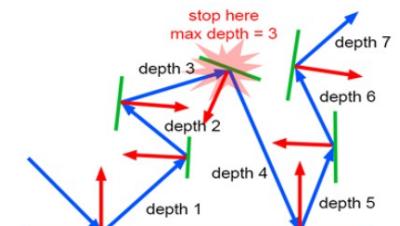


Shading: perfect specular surface

- Light bounces in direction symmetrical to incident direction around normal at shading point → **law of reflection**
 - $\text{incident_angle} = \text{reflected_angle}$
- Reflected direction:
 - $R = L - 2(N * L) * N$
- Surface is **view dependent**
- Reflection of mirror surface:
 - Reflection direction is calculated using view direction (primary ray direction) and normal in intersected point
 - Primary ray color (shading result) is equal to color of reflected ray
 - This process is **recursive** until it hits background or non-specular surface → terminate with **ray depth** – trade off between render time and quality
 - Ray-tracing here is solving visibility!



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Shading: perfect specular surface

- Perfectly specular surfaces only reflect other surfaces in the 3D scene

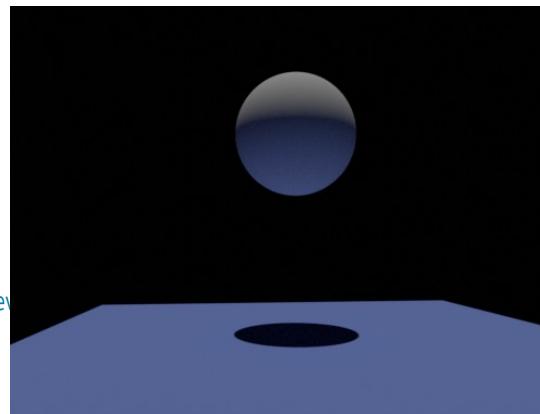
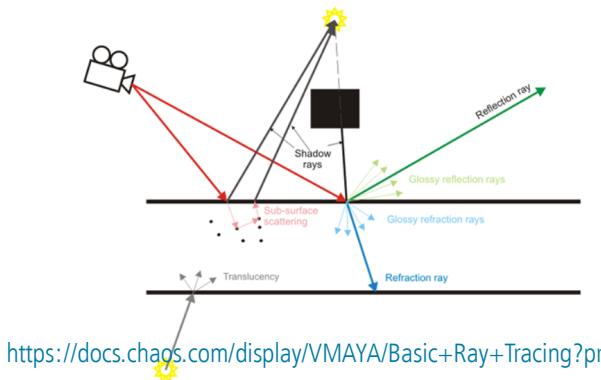


Without objects in 3D scene, specular sphere is not visible since it reflects only black color.

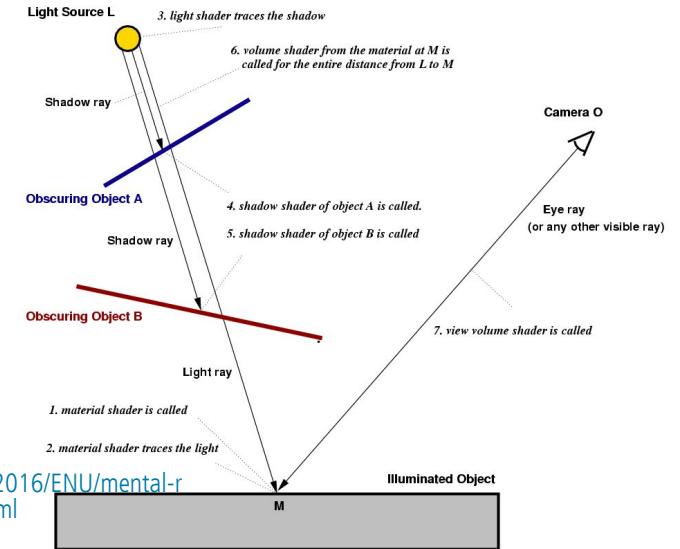


Shading: shadows

- After primary ray intersection has been found, shadow ray is sent from shading point to light source.
- Beside information of light direction, intensity and color, the purpose of shadow ray is to determine if some objects are intersected on the path
- If shading point is shadowed, it has zero light contribution → black color



https://help.autodesk.com/cloudhelp/2016/ENU/mental-ray-docs/mr_docs/manual/node102.html



Shading: Multiple lights

- 3D scene often contain multiple light sources
- Contribution of each light source adds up linearly:

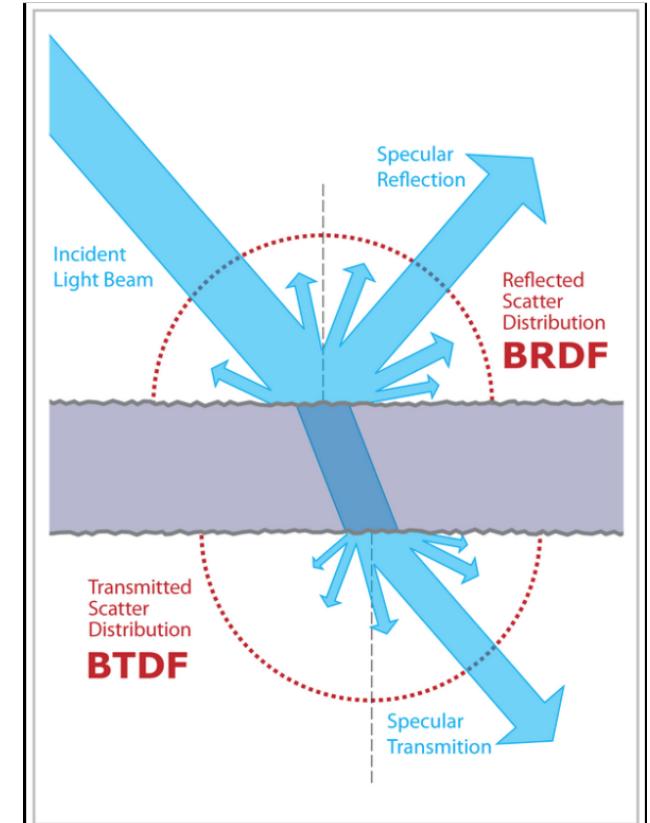
$$shading_result = \sum_{i=1}^n f(l_i, n, v) c_{light_i} (n \cdot l_i)$$

$$c_{light_i} = light_color_i * light_intensity_i$$



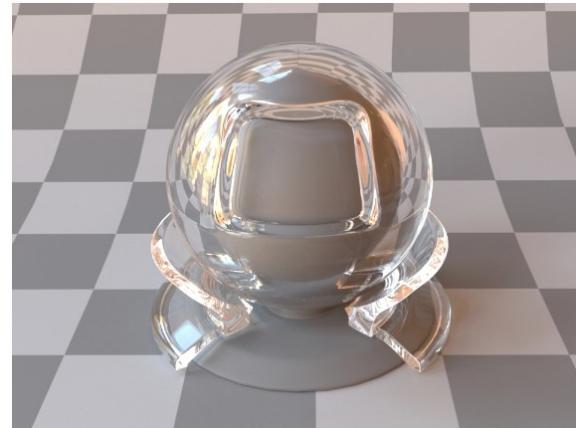
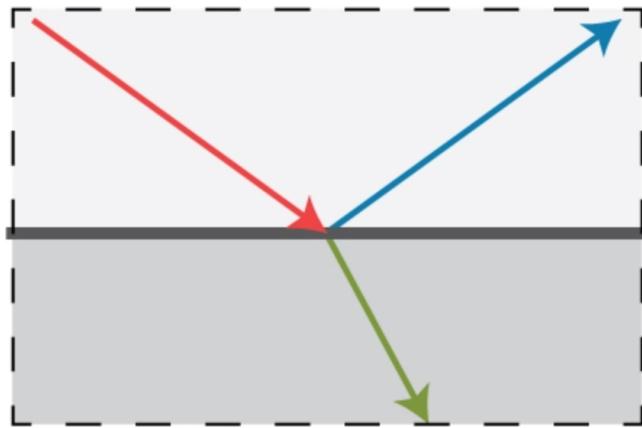
Shading and BTDF

- For transparent objects (e.g., glass), light is reflected and **refracted**
 - Reflection: light changes direction traveling outside of the surface
 - Refraction: light changes direction traveling inside of the surface
 - Transmission: light that enters object on one side and leaves object on other side



Shading and perfect specular transmission

- Refraction direction is determined by **Snell's law**
- Amount of reflection and refraction is determined by **Fresnel's law**
- Similarly as for specular reflection, specular transmission is recursive tracing since its color depends on objects it reflects



Shading and perfect specular transmission

- Perfectly specular surfaces only reflect and transmit other surfaces in the 3D scene

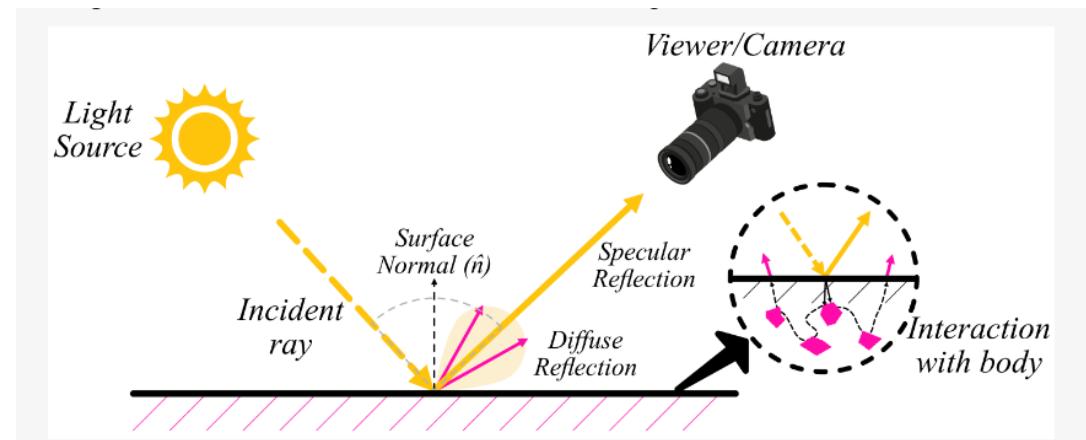
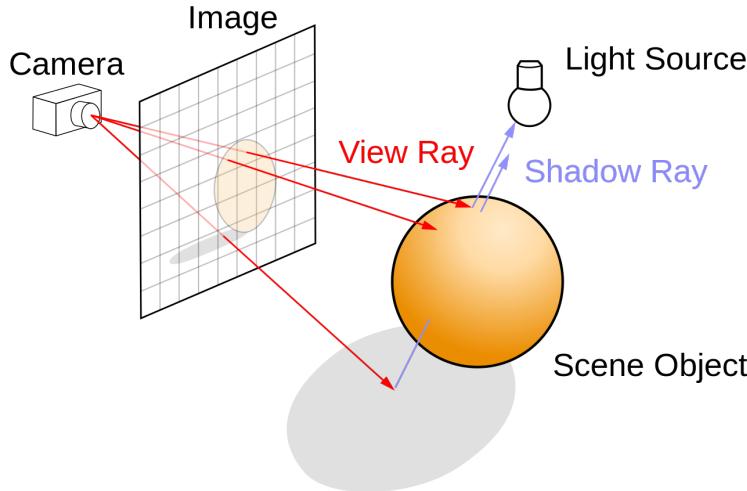


Without objects in 3D scene, specular sphere is not visible since it reflects only black color.



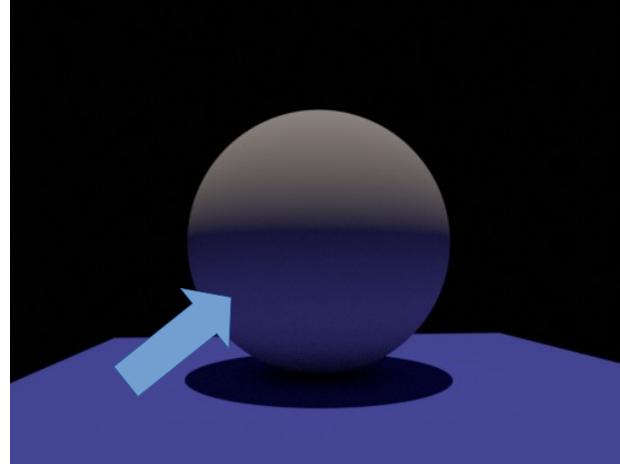
Direct illumination recap

- For now we have:
 - Created primary ray
 - Traced primary ray for intersection
 - Traced shadow ray from shading point to light source
 - Calculate shading based on surface shape (normal), material, primary ray and shadow ray information

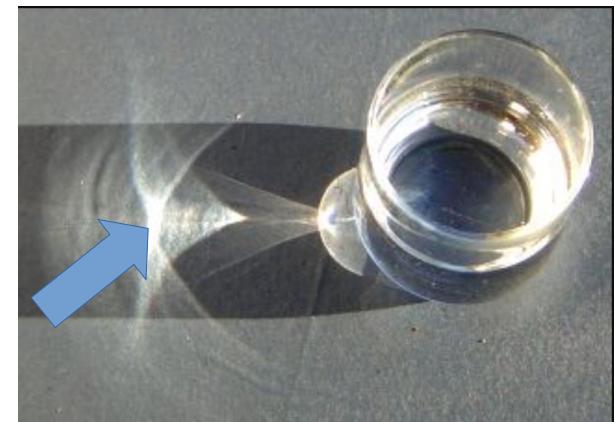


Indirect illumination

- Shading very much depends on incoming light
 - Light coming directly from light source
 - Light can travel from light source, reflecting from objects and finally fall on shaded surface
→ **indirect illumination**
- Gathering indirect light on shading point is called **light transport**



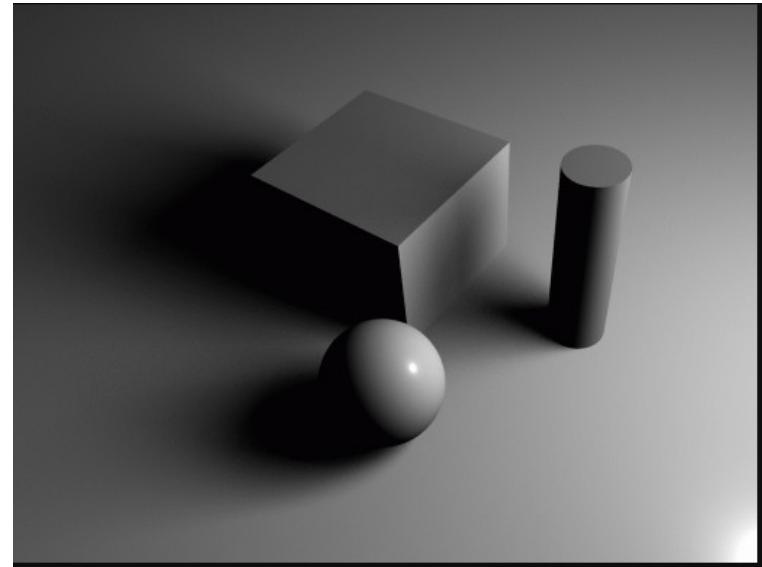
Indirect diffuse – diffuse objects reflect light which illuminates other objects in the scene



Indirect specular - specular objects reflect light which illuminates other objects in the scene
https://upload.wikimedia.org/wikipedia/commons/2/2f/Kettle_billiard.jpg

Indirect illumination

- Besides material properties, geometrical shape also contributes to appearance of the scene:
 - Soft shadows



Shading and light transport

- Appearance of object and can be divided into:
 - **Shading:** how object appears.
 - How light interacts with matter: what happens to light which reaches the surface and how light leaves the surface
 - Uses scattering model (e.g., BRDF) to compute color
 - Effects: reflection, transparency, specular reflection, diffuse reflection, sub-surface scattering.
 - **Light transport:** how much light object receives
 - How light bounces from surface to surface
 - Which paths light take and how does it depends on material
 - Is light blocked by another surface?
 - Uses scattering model (e.g., BRDF) for computing light reflection
 - Effects: Indirect diffuse, indirect specular, soft shadows
- Distinction between shading and light transport is very thin

Global illumination

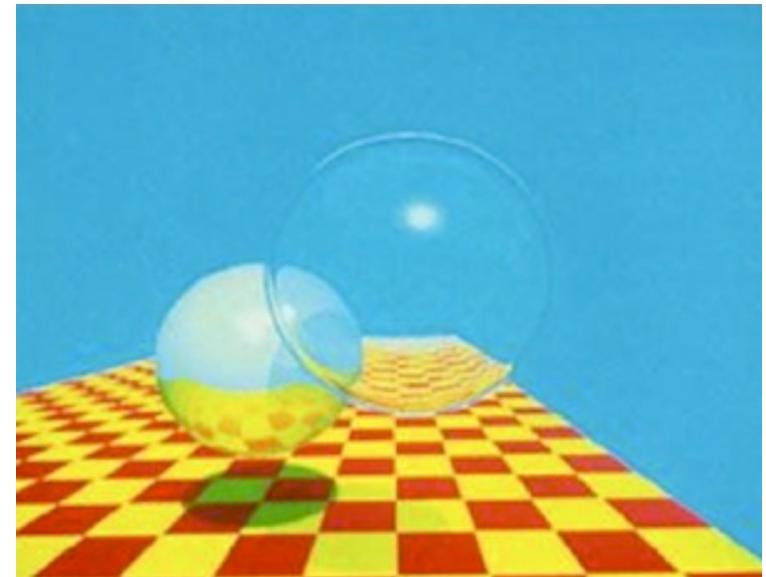
- **Global illumination:** simulating both direct and indirect illumination
- This problem is described by **reflectance equation:**
 - Color in intersected point L_o is results of summing all incoming light from hemisphere of directions ω , multiplying it with BRDF $f(l, n, v)$ and with $\max(0, \text{dotProduct}(n, l))$

$$L_o(p, v) = \int_{l \in \omega} f(l, n, v) L_i(p, l) (n \cdot l)^+ dl$$

- Which is a special case of **rendering equation**
- Solving rendering equation requires advanced light transport strategies

Global illumination and light transport

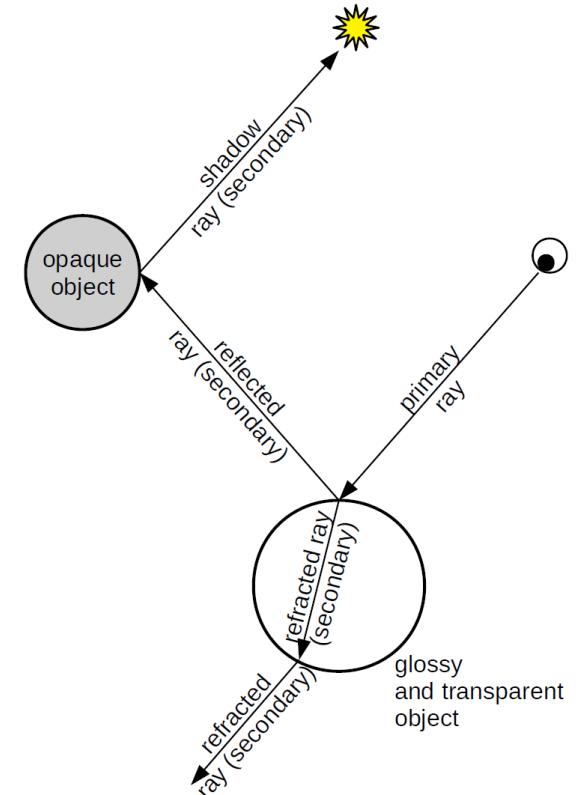
- Various light transport strategies based on ray-tracing for solving global illumination exist. Most popular:
 - Path tracing and bidirectional path tracing
- Classical example of light transport is **Whitted ray-tracing**
 - This strategy is not solving global illumination
 - This strategy is utilizing ray-tracing for introducing indirect illumination
 - Advanced light transport strategies build on this method



An Improved Illumination Model for Shaded Display. Turner Whitted, 1980

Whitted ray-tracing

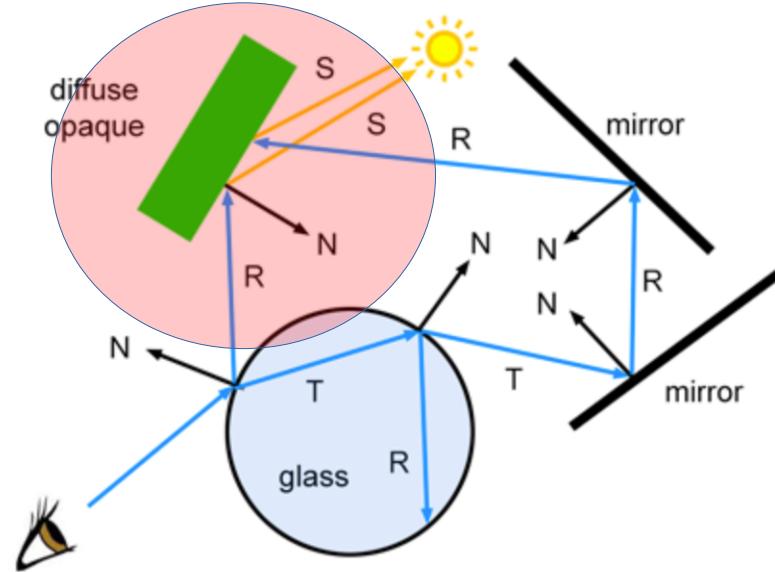
- Simulating complex reflections and refractions
- Use scattering models (BSDF) to compute light paths
 - Laws of reflection and refraction are used to compute direction of light rays intersecting reflective or transparent surfaces → **secondary rays**
 - Follow light rays bouncing around the scene and find out color of objects they intersect
- 3 main cases for light paths



https://www.researchgate.net/publication/336285790_Heuristic_based_real-time_hybrid_rendering_with_the_use_of_rasterization_and_ray_tracing_method

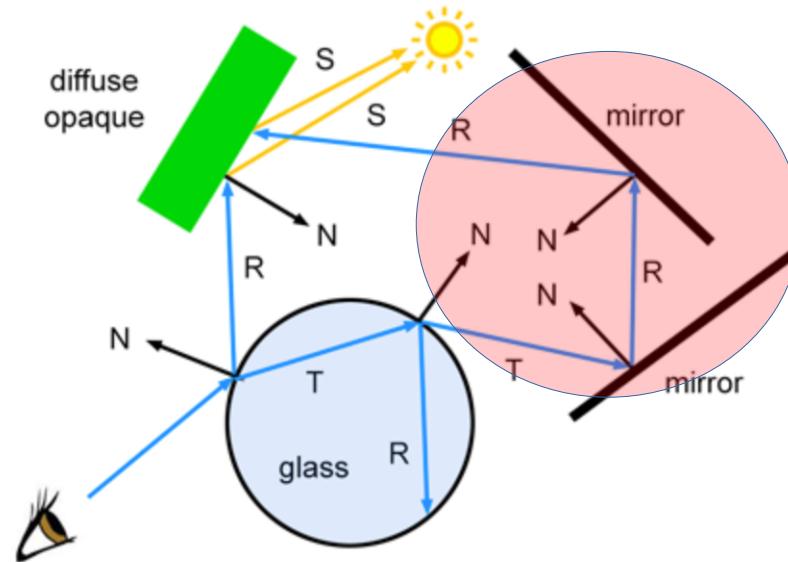
Whitted ray-tracing: case 1

- Surface at intersection is point is **diffuse**:
 - Cast a **shadow ray** in direction of light to find light direction, intensity, color and if it is shadowed
 - Use **scattering model (BRDF)** to compute **color** of the object: e.g., Lamberitan BRDF.



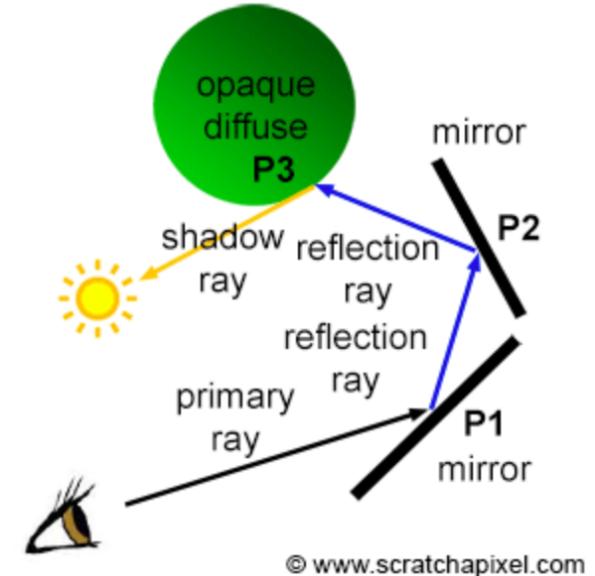
Whitted ray-tracing: case 2

- Surface at intersection is point is **mirror (specular reflection)**:
 - Trace secondary ray – **reflection ray** from intersection point in direction of specular reflection



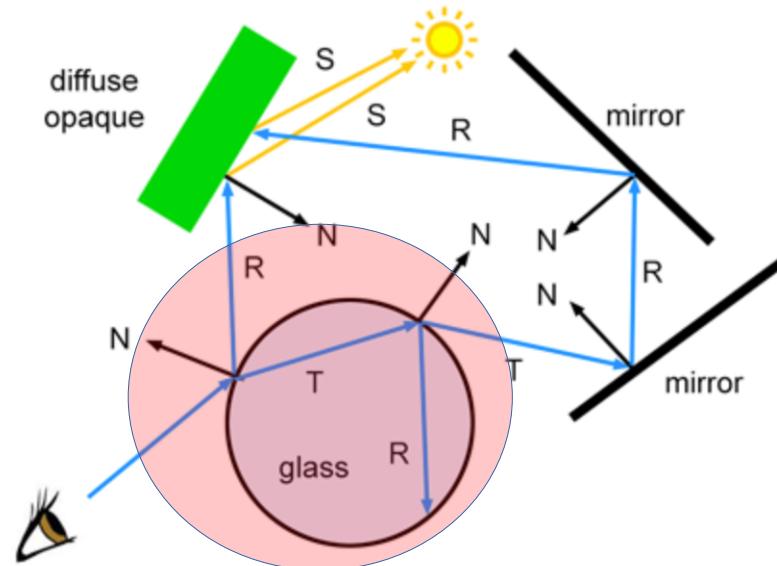
Whitted ray-tracing: reflection ray

- Backward ray-tracing:
 - Primary ray is generated and intersects mirror surface at P1
 - At intersected point P1 reflection ray is generated and intersects mirror surface at P2
 - At intersected point P2 reflection ray is generated and intersects diffuse surface at P3
 - At P3 color of the surface is calculated
- Return color on created path
 - Color at P3 becomes color at P2
 - Color at P2 becomes color at P1
 - Color at P1 is color of primary ray
 - Color of primary ray is color of pixel from which primary ray was generated



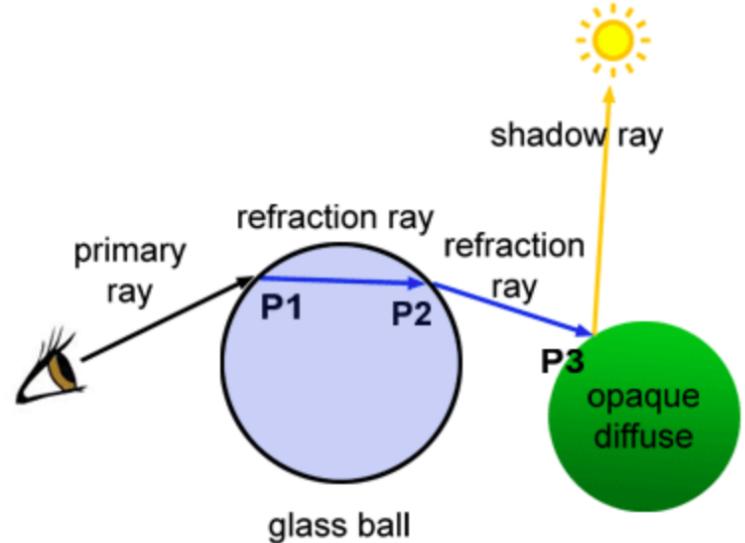
Whitted ray-tracing: case 3

- Surface at intersection is point is **transparent (specular transmission)**:
 - Trace secondary ray – **refraction ray** from intersection point in direction of specular refraction



Whitted ray-tracing: refraction ray

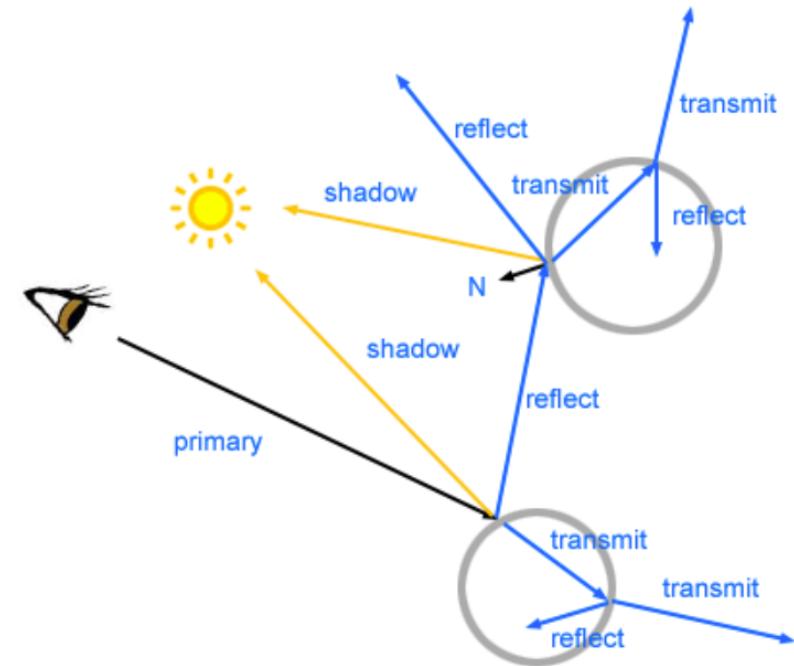
- Backward ray-tracing:
 - Primary ray is generated and intersects transparent surface at P1
 - At intersected point P1 refraction ray is generated and intersects
 - At intersected point P2 refraction ray is generated and intersects
 - At P3 color of the surface is calculated
- Return color on created path
 - Color at P3 becomes color at P2
 - Color at P2 becomes color at P1
 - Color at P1 is color of primary ray
 - Color of primary ray is color of pixel from which primary ray was generated



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Whitted light-transport properties: recursive nature

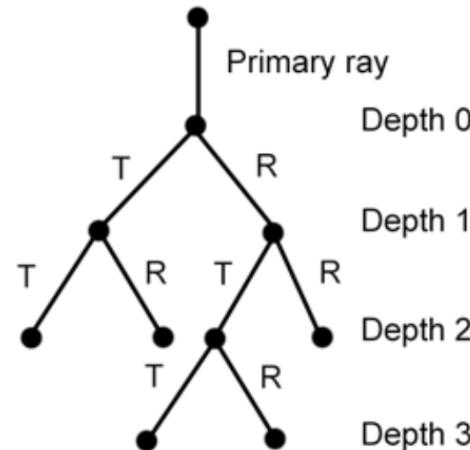
- Intersecting reflective surface causes generation of reflection ray
- Intersection of transparent surface causes generation of two new rays: reflected and refracted
- These rays can further intersect reflective or transparent surfaces → **recursion**
 - To evade explosion, max recursion depth is exposed as parameter



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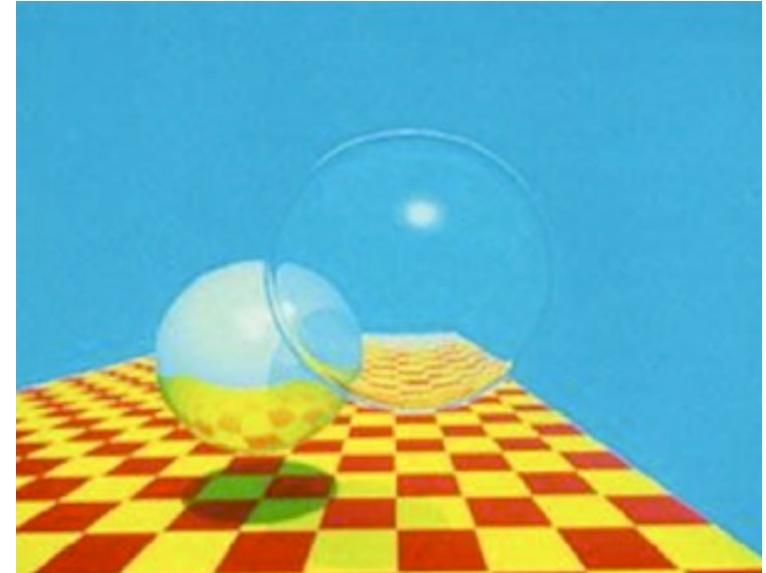
Whitted light-transport properties: tree of rays

- All secondary rays (reflection or refraction) spawned by primary or other secondary rays can be represented tree-like structure
- Each intersection marks new depth/level of the tree and thus one level of recursion



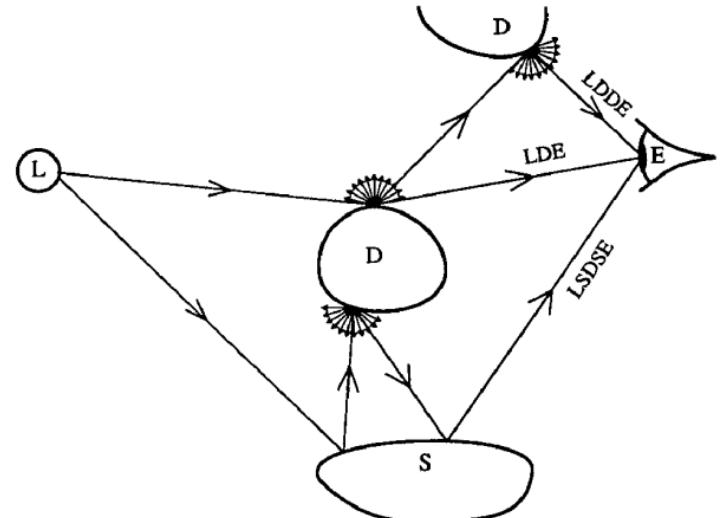
Whitted ray-tracing and light transport

- Whitted ray-tracing - classic light transport algorithm with which rendered image exhibit appearance of:
 - Diffuse objects
 - Mirror-like objects
 - Transparent objects
- Different light transport strategies simulate different effects which is the basis for their categorization



Categorization of light transport strategies

- Light transport strategies vary by light paths (effects) they simulate
- Each intersection of light ray from light source (L) to eye (E) can be:
 - Diffuse (D)
 - Specular (S)
 - Glossy (G)
- Advanced light transport strategies based on ray-tracing:
 - Path-tracing
 - Bidirectional path-tracing
 - Metropolis light transport



Whitted ray-tracing and beyond

- Whitted ray-tracing is not full solution to global illumination
 - Light reflected from any direction than mirror reflection or refraction is ignored
 - Direct lights are only represented with point lights
- Fully evaluation of global illumination is proposed by Kajiya as path-tracing method
 - Correct solution which generates global illumination
 - After camera ray intersection is found and during shading evaluation, many rays are generated in different directions
 - For diffuse surface, rays over hemisphere at intersection are shot
 - For glossy surface, rays in lobe at intersection are shot
 - Etc.
 - Problem with this approach is explosion of rays, thus Monte Carlo sampling methods are employed for generating paths through environment.
 - Several of such paths are averaged for each pixel
 - General problem with path-tracing is noise and amount of rays that have to be shot

Practical raytracing-based rendering

Code

Code

- <https://www.scratchapixel.com/code.php?page=lessons/3d-basic-rendering/ray-tracing-overview>
- <https://raytracing.github.io/books/RayTracingInOneWeekend.html#overview>
- <https://www.scratchapixel.com/lessons/3d-basic-rendering/ray-tracing-overview/light-transport-ray-tracing-whitted>

TODO

gin=/e

Ray-tracing based rendering: verdict

- Good:
 - Ray-tracing based rendering is clear and straightforward method to implement*
 - It represent unified framework for computing what is visible from camera (primary ray intersections), with inherent perspective/orthographics projection and computing light transport – visibility between surfaces in 3D scene (secondary ray intersections) required for the shading process.
 - Powerful shading capabilities when it comes to light transport

* Implementing production ray-tracing based rendering requires a lot of additional features than ones that we have discussed: support for render-time displacement mapping (shape vertices offsetting given height map), motion blur, programmable shading stage (a program which is evaluated for primary ray intersections).

Ray-tracing based rendering: verdict

- Bad:
 - It requires efficient methods for testing ray-shape intersections: sometimes hard to develop (good understanding of mathematics, particularly geometry and linear algebra for geometrical or analytical solutions)
 - Ray-shape intersections test are core element during rendering and they are often very expensive
 - For advanced light transport needed in shading stage, ray-tracing-based renderer must store all scene objects must be readily available for intersection testing and material evaluation*. An example where this is needed is to compute indirect light or shadows casted by different objects.
 - Additional acceleration datastructures are often desired to accelerate ray-scene intersections. These datastructures require efficient development, cause additional precomputations (with tremendous acceleration times, though) and require a lot of memory – even more for animated scenes.

Practical-raytracing based rendering

Production

Back to motivation scene

- Show cycles rendering in Blender
- TODO



Note: real-time ray-tracing

- Due to nature of ray-tracing-based visibility and shading calculations, porting ray-tracers to GPU was done in 90s
- Ray-tracing ideas are often used on GPU and rasterizer renderers, but hybrid approaches exist: rasterization might be used to determine objects/surfaces visible from camera. Raytracing may be employed for reflection and refraction calculations.
- Newer graphics hardware (currently led by Nvidia with RTX family of graphics cards) and new graphics APIs (DirectX 12, Vulkan) are supporting hardware-accelerated ray-tracing – a new hardware and software element called raytracing kernel can be now used in combination with rasterizer-based renderer to compute complex scene effects such as reflections, soft shadows, indirect illumination, etc.

TODO

open for CPUs

we discussed

Acknowledgments

- <https://www.scratchapixel.com>