Ray Tracing I: Switching gears…

Btw…You can now do Vulkan ray tracing in the advanced course LP4.

NVIDIA's RTX real-time ray tracing demo, 2019.

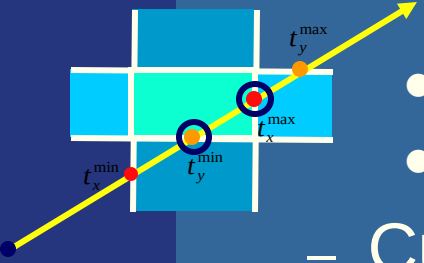
For your convenience

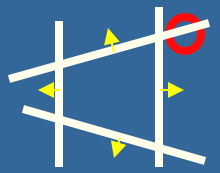
- Half-Time Summary Slides

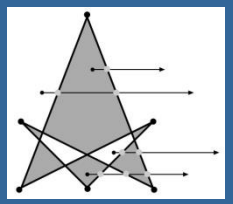
Date	Lecture	Readings/Läsanvisningar	Notes
Week 1			
Tue	Lecture 1 - Introduction + Pipeline and OpenGL	pipeline.pdf, RTR chapter 2 + 3, ch: 18.2, (freeSync/G-sync p:1011), double buffering ch: 23.6.2. Start working on lab 1-7 Bonus: VC++ for dummies.pdf. Also, see A Quick Introduction to C++ with example code.	Deadlines: Lab 1+2+3, Thurs. week 2. Lab 4+5, Thurs. week 3. Lab 6, Thurs. week 4. Lab 3D-World, Thurs. week 7.
Fri	Lecture 2 - Vectors and Transforms	vectors and transforms.pdf, RTR ch 4: 4.1, 4.2.1, 4.2.4, 4.3 (briefly), 4.7, (Repetition for your convenience: Immersive Linear Algebra, RTR online Appendix A+B). Bonus: The OpenGL projection matrix, Quick repetition of vector algebra: vectors.zip (lösenordsskyddad - se ovan) . Matrix exercise: matrixexercise.zip	
Week 2			
Mon	Lecture 3 - Shading and Antialiasing	shading.pdf , aliasing.pdf , RTR ch:5.1-5.3 (briefly), 5.4, 5.5.1, 5.6. Bonus: Physically-Based Shading.pdf, Cook-Torrance Shading.pdf (lösenordsskyddad - se ovan)	Deadline Thurs. w2: lab 1+2+3
Tue	Lecture 4 - Texturing	texturing, RTR ch. 6: 6.1, 6.2 - 6.2.4, 6.5 - 6.7, (RTR ch. 12: briefly - at your likings), 10.4, 13.5 - 13.8.	
Fri	Lecture 5 - OpenGL	OpenGL.pdf, RTR ch 16.4 (briefly).	Deadline Thurs. w3: lab 4+5
Week 3			
Tue	Lecture 6 - Intersections	isect.pdf, RTR ch 22: 22.2, 22.3-22.3.2, 22.5 - 22.7.1, 22.8 (skip 22.8.2), 22.9, 22.10 (skip 22.10.2), 22.13.1, 22.13.3, 22.13.5 (or see Sep Axis Theorem in slides), 22.14, (skip: 22.14.1, 22,14.3).	
Fri	Lecture 7 - Spatial data structures and Collision Detection	spatial.pdf, colldet.pdf, RTR ch: 19: 19.1 (skip 19.1.4), 19.2, 19.3, 19.4 - 19.7 (briefly: 19.7.1, 19.7.2, 19.8, 19.9). RTR online ch:25.1-15.2.2.	Deadline Thurs. w4: lab 6
Week 4			
Half-Time Wrap-Up:	Halftime-wrapup slides. These slides correspond to the most important issues of each lecture so far in the course.		

Typical Exam Questions

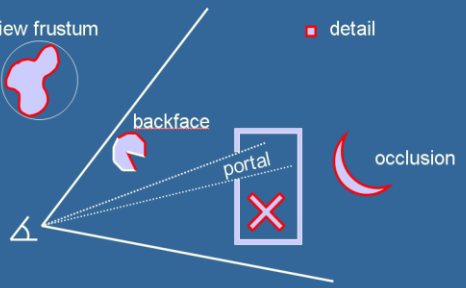
- Prev Lecture:
  - Describe **one** intersection test for
    - ray/triangle – (e.g. analytically, Jordans Cross theorem or summing angles)
    - Ray/box (slabs)
    - View Frustum Culling using spheres





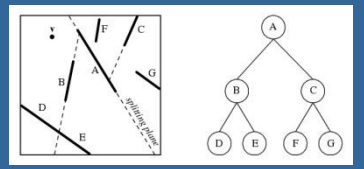


  - Culling – VFC, Portal, Detail, Backface, Occlusion

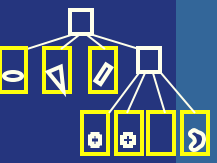


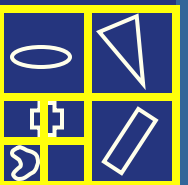
  - What is LODs

  - Describe how to build and use BVHs, AABSP-tree, Polygon aligned BSP-tree.



  - Describe the octree/quadtree.





What is ray tracing?

- Another rendering algorithm
  - Fundamentally different from polygon rendering (using e.g., OpenGL)
  - OpenGL
    - renders one triangle at a time
    - Z-buffer sees to it that triangles appear ”sorted” from viewpoint
    - Local lighting --- per vertex
  - Ray tracing
    - Gives correct reflections!
    - Renders one pixel at a time
    - Sorts per pixel
    - Global lighting equation (reflections, shadows)

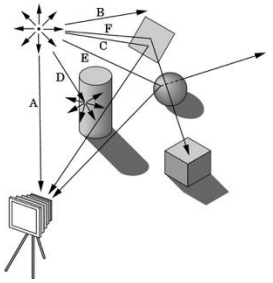
History and terminology

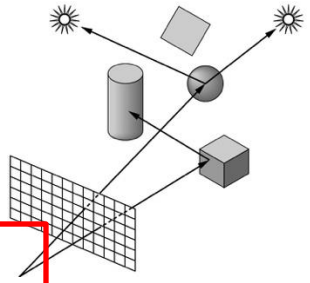
- *Ray casting*
  - Means “shooting a ray”. (Arthur Appel, 1968, for shadow rays.)
- *Ray Tracing*: recursive process of shooting rays
  - *Whitted Ray Tracing (or Whitted-style ray tracing):*
    - Turner Whitted, *“An improved illumination model for shaded display”*, ACM, Volume 23, Issue 6, June 1980 pp 343–349.
    - Shadow rays + pure reflection/refraction rays.
- In general, *ray tracing*, means following rays, even when part of more complicated methods, e.g., *path tracing* (next lecture).

Computer Graphics: – two main principles…

…for computer-generating the appearance of a virtual 3D scene:

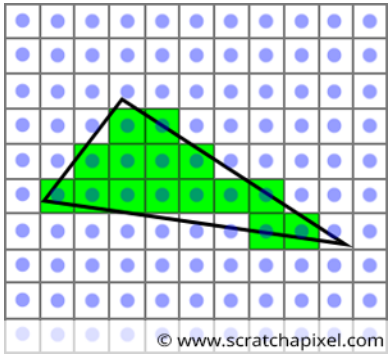
- Ray Tracing:
  - **Forward** ray tracing: Tracing light beams from light sources and how they reach the virtual camera.
  - **Backward** ray tracing: Tracing the light beams backwards, i.e., from the camera and all the way back to the light sources.





    - Whitted-style ray tracing:
      - recursively shoot pure reflection and refraction rays.
      - No semi-glossy surfaces. No indirect illumination (color bleeding) for diffuse surfaces.

- Rasterization:
  - Draw the scene triangles one by one onto the pixels of the screen and, for each pixel, compute the color (by regarding light sources and perhaps also surrounding objects).

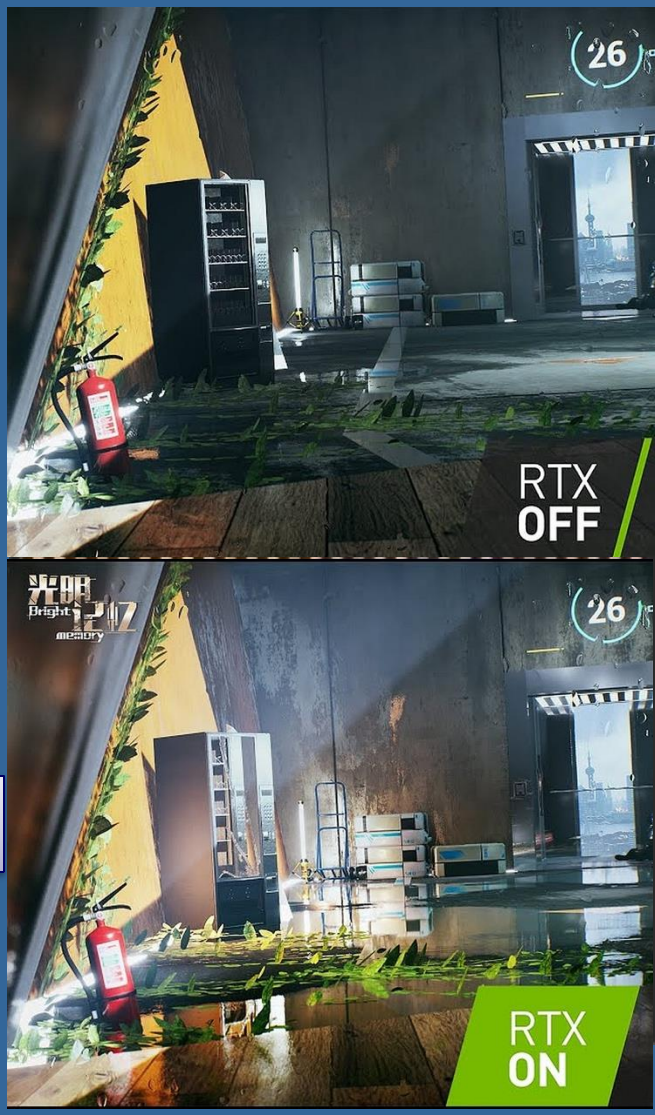


What is ray tracing?

- Another rendering algorithm
  - Fundamentally different from polygon rendering (using e.g., OpenGL)
  - OpenGL
    - renders one triangle at a time
    - Z-buffer sees to it that triangles appear ”sorted” from viewpoint
    - Fast. Often just *local lighting*
  - Ray tracing
    - Gives correct reflections!
    - Renders one pixel at a time
      - i.e., finds first visible triangle per pixel
    - Slow. More of *Global lighting* (reflections, shadows)

O(n)

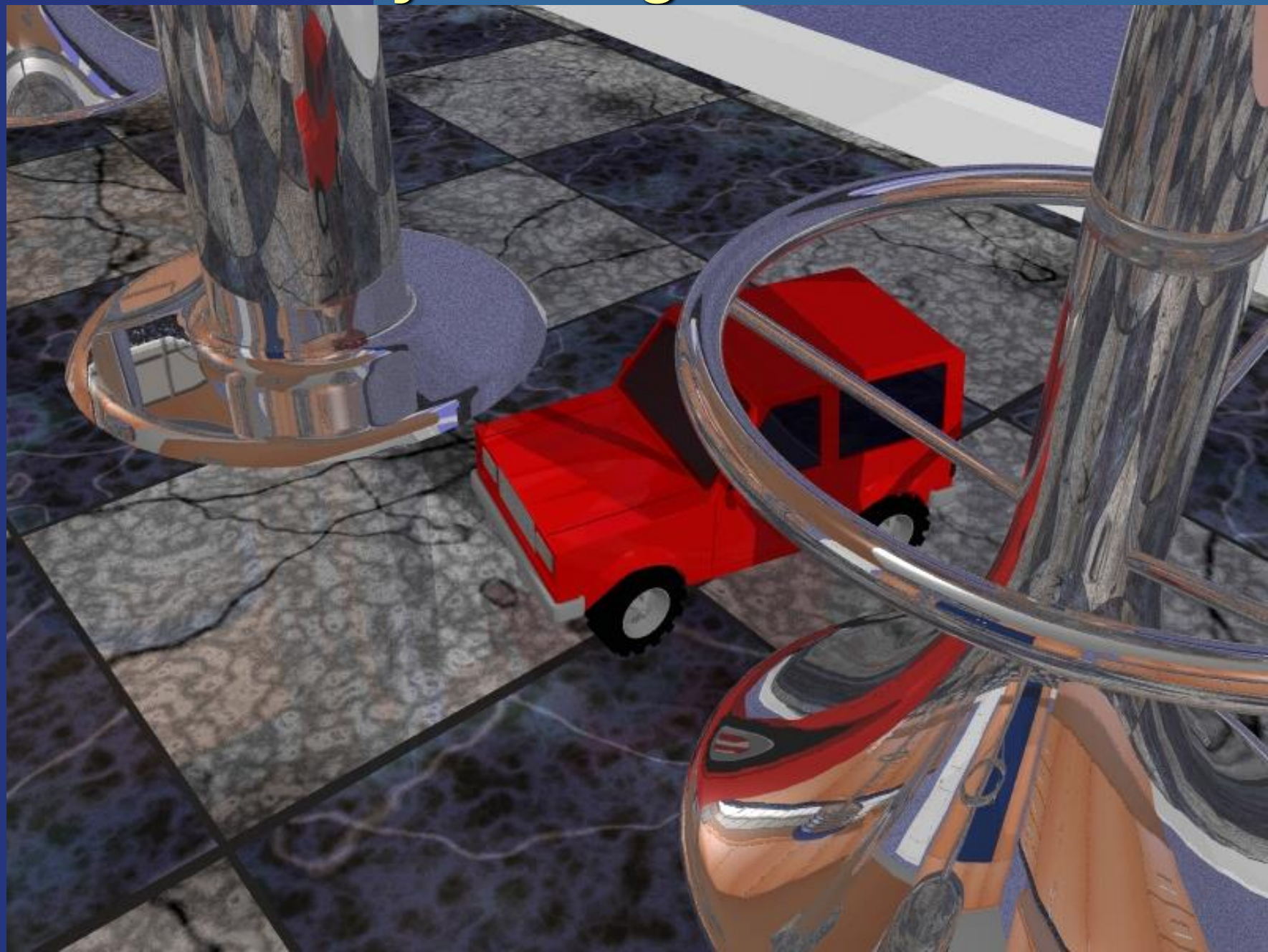
r O(log n)

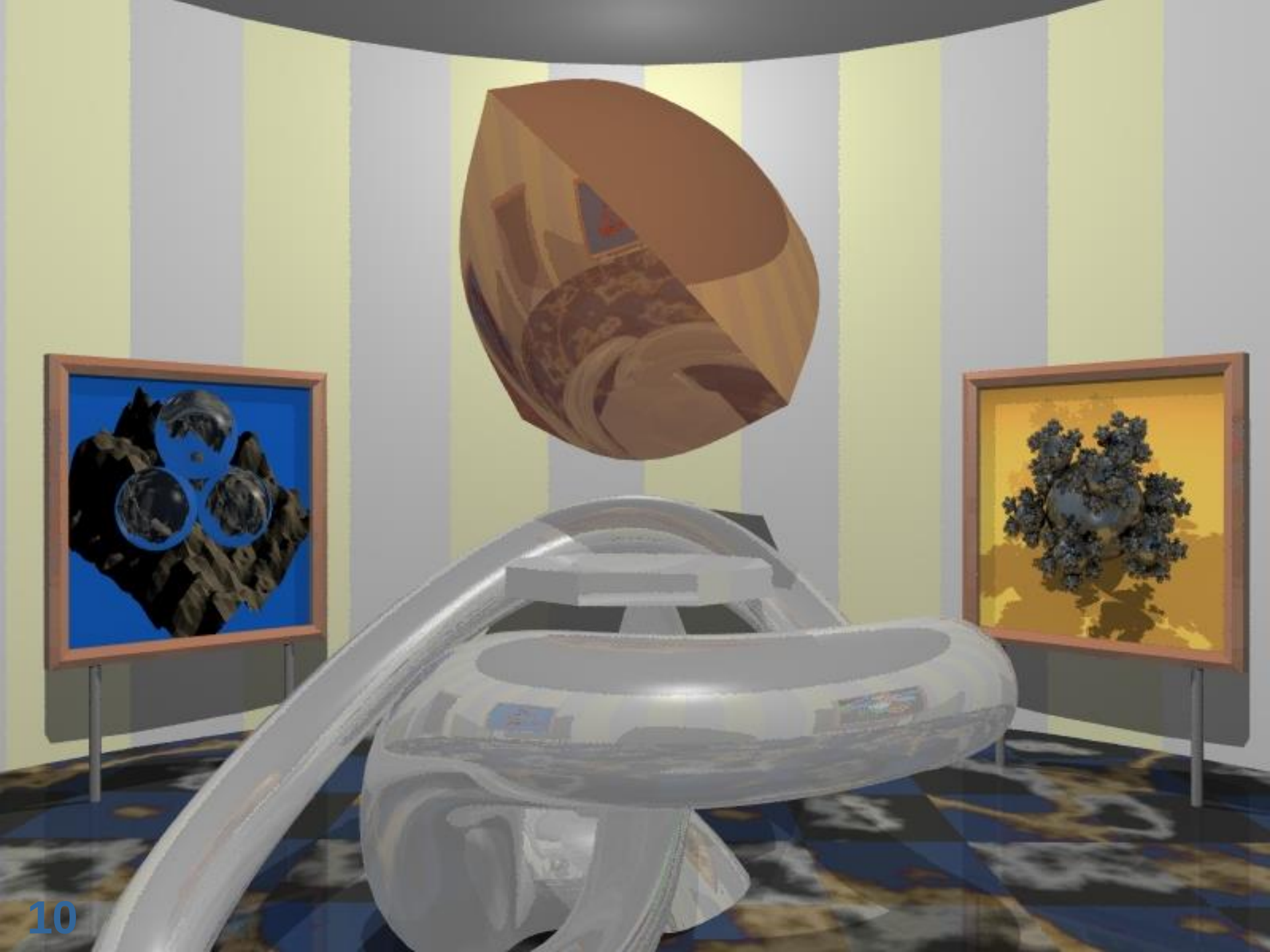


What is the point of ray tracing?

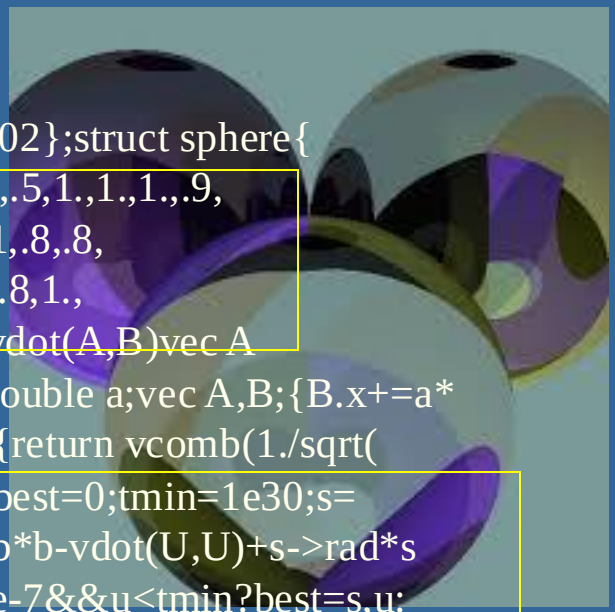
- Higher quality rendering
  - Global lighting equation (more accurate shadows, reflections, refraction)
- Is the base for more advanced algorithms
  - Global illumination, e.g., path tracing, photon mapping
- It is extremely simple to write a (naive) ray tracer
- A disadvantage: it is inherently slow!

Whitted ray tracing





Again: it is simple to write a ray tracer! – A la Paul Heckbert:

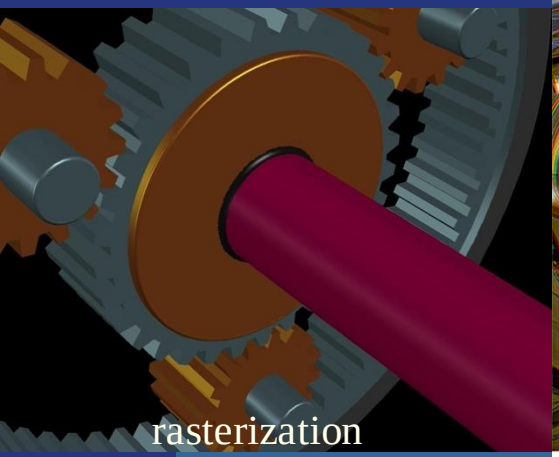


```
typedef struct{double x,y,z}vec;vec U,black,amb={.02,.02,.02};struct sphere{
vec cen,color;double rad,kd,ks,kt,kl,ir}*s,*best,sph[]={0.,6.,.5,1.,1.,1.,.9,
.05,.2,.85,0.,1.7,-1.,8.,-.5,1.,.5,.2,1.,.7,.3,0.,.05,1.2,1.,8.,-.5,.1,.8,.8,
1.,.3,.7,0.,0.,1.2,3.,-6.,15.,1.,.8,1.,7.,0.,0.,0.,.6,1.5,-3.,-3.,12.,.8,1.,
1.,5.,0.,0.,0.,.5,1.5,};yx;double u,b,tmin,sqrt(),tan();double vdot(A,B)vec A
,B;{return A.x*B.x+A.y*B.y+A.z*B.z;}vec vcomb(a,A,B)double a;vec A,B;{B.x+=a*
A.x;B.y+=a*A.y;B.z+=a*A.z;return B;}vec vunit(A)vec A;{return vcomb(1./sqrt(
vdot(A,A)),A,black);}struct sphere*intersect(P,D)vec P,D;{best=0;tmin=1e30;s=
sph+5;while(s-->sph)b=vdot(D,U=vcomb(-1.,P,s->cen)),u=b*b-vdot(U,U)+s->rad*s
->rad,u=u>0?sqrt(u):1e31,u=b-u>1e-7?b-u:b+u,tmin=u>=1e-7&&u<tmin?best=s,u:
tmin;return best;}vec trace(level,P,D)vec P,D;{double d,eta,e;vec N,color;
struct sphere*s,*l;if(!level--)return black;if(s=intersect(P,D));else return
amb;color=amb;eta=s->ir;d= -vdot(D,N=vunit(vcomb(-1.,P=vcomb(tmin,D,P),s->cen
)));if(d<0)N=vcomb(-1.,N,black),eta=1/eta,d= -d;l=sph+5;while(l-->sph)if((e=l
->kl*vdot(N,U=vunit(vcomb(-1.,P,l->cen))))>0&&intersect(P,U)==l)color=vcomb(e
,l->color,color);U=s->color;color.x*=U.x;color.y*=U.y;color.z*=U.z;e=1-eta*
eta*(1-d*d);return vcomb(s->kt,e>0?trace(level,P,vcomb(eta,D,vcomb(eta*d-sqrt
(e),N,black))):black,vcomb(s->ks,trace(level,P,vcomb(2*d,N,D)),vcomb(s->kd,
color,vcomb(s->kl,U,black))));}main(){printf("%d %d\n",32,32);while(yx<32*32)
U.x=yx%32-32/2,U.z=32/2-yx++/32,U.y=32/2/tan(25/114.5915590261),U=vcomb(255.,
trace(3,black,vunit(U)),black),printf("%.0f %.0f %.0f\n",U);}/*minray!*/
```

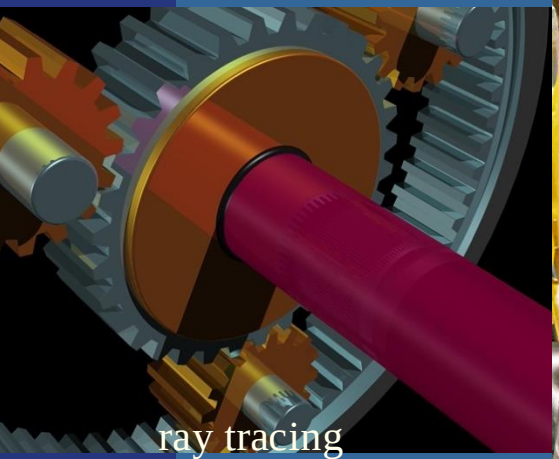
Which rendering algorithm will win at the end of the day?

- Ray tracing or polygon rendering?
- Ray tracing is:
  - Slow
  - Easier to code to get realistic results.
  - Therefore, focus is on creating faster algorithms, and various hardware acceleration NVIDIA RTX / Microsoft DXR, GPU, (RPU)
- Polygon rendering (OpenGL) is:
  - Fast (simpler to hardware accelerate)
  - Less realistic (harder to code to get realistic results)
  - Therefore, focus is on creating more realism.
- Answer: right now, it depends on what you want, but for the future, no one really knows
  - Maybe ray tracing will eventually win due to simplicity vs the high cost of developing good-looking render engines?

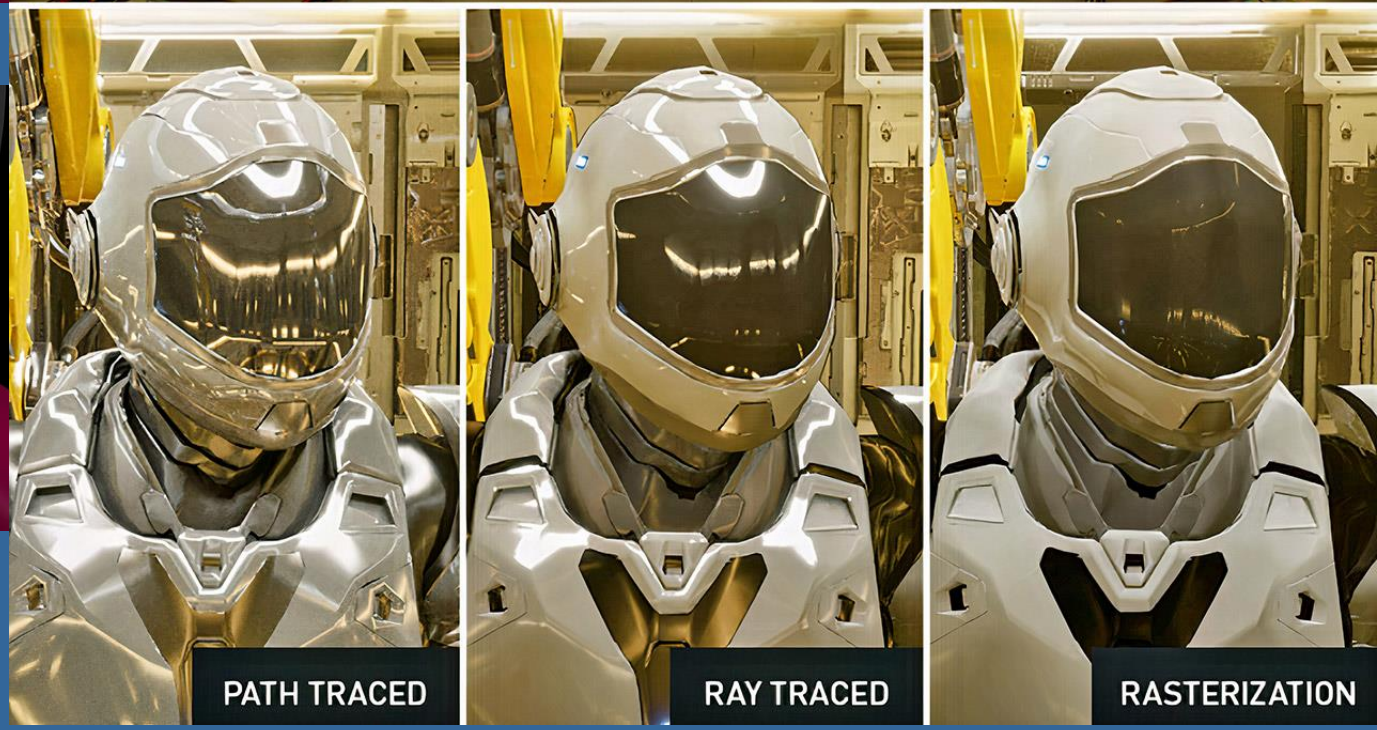
Side by side comparison



rasterization

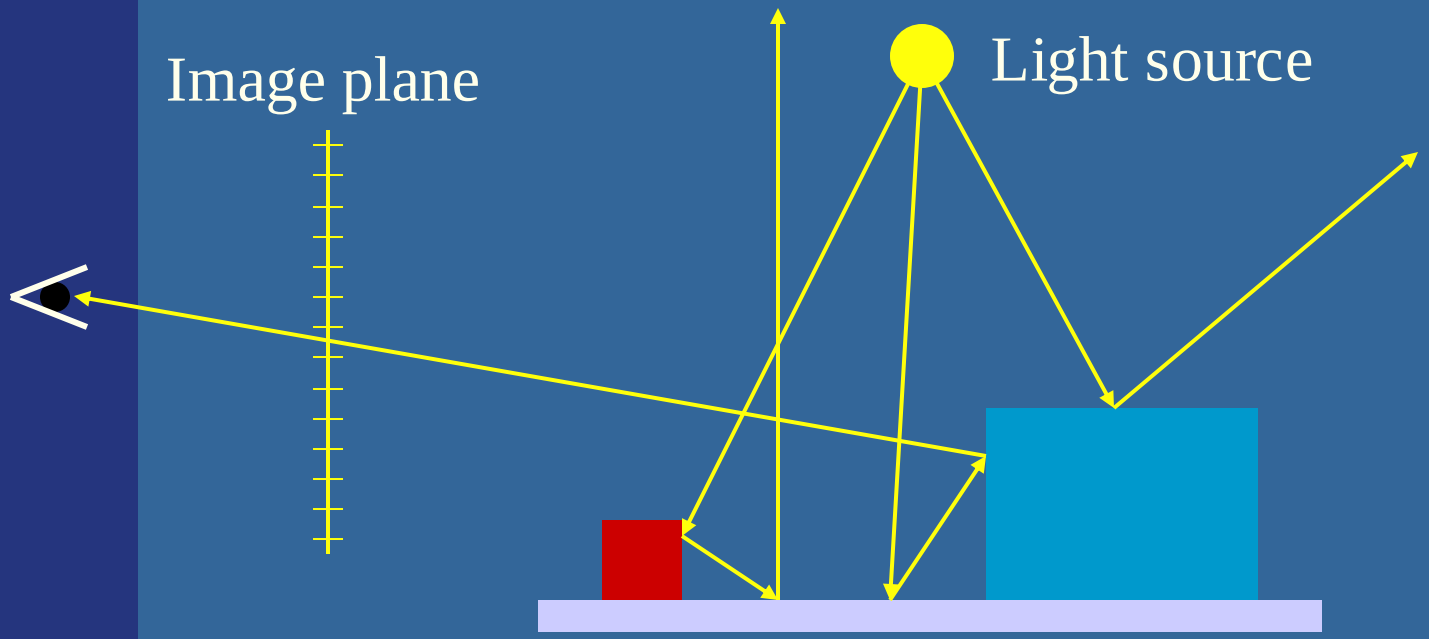


ray tracing



To be physically correct, follow photons from light sources…

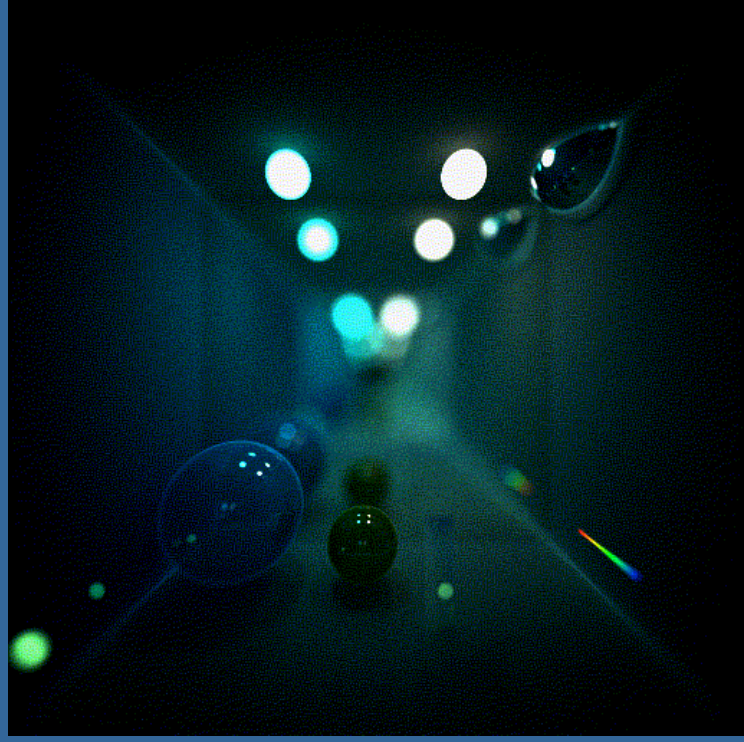
- Not what we do for a simple ray tracer
  - Though this is almost what we do for more advanced techniques (photon mapping)



- Not effective, not many rays will arrive at the eye

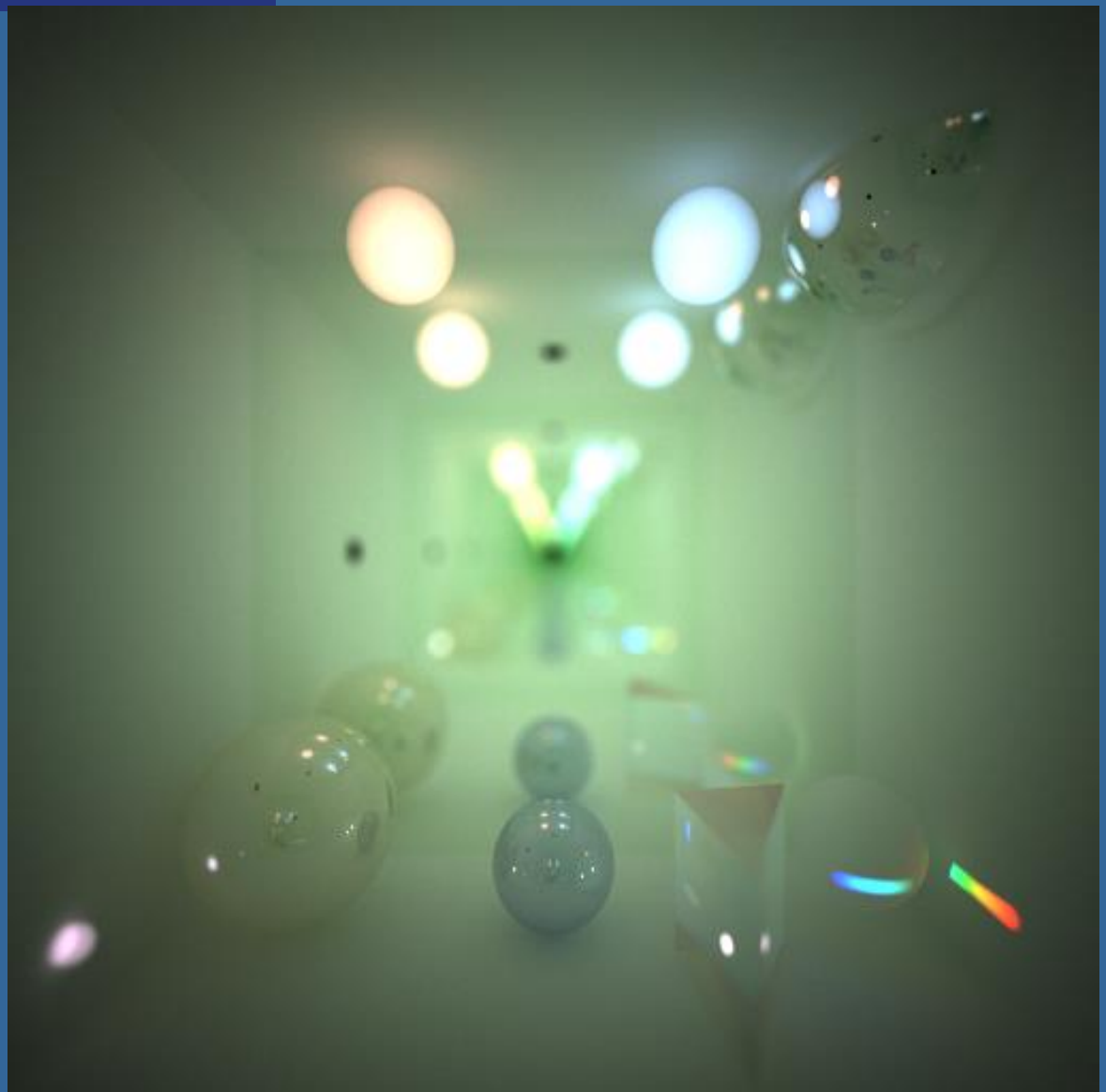
This image was generated in 1991 by simulating the motion of 29.8 Billion photons in a room. The room is 2 meters cubed with a 30 cm aperture in one wall. The opposite and adjacent walls are mirrors, so this is a 'tunnel of mirrors'. The depth of field is very shallow. In the foreground is a prism, resting on the floor. A beam of light emerges from the left wall, goes through the prism and makes a spectrum on the right wall. About 1 in 177 photons made it through the aperture.

The image took 100 Sun SparcStation1s 1 month to generate using background processing time. This represents 10 CPU years of processing time. If the lights are 25 watt bulbs this represents a few picoseconds of time.



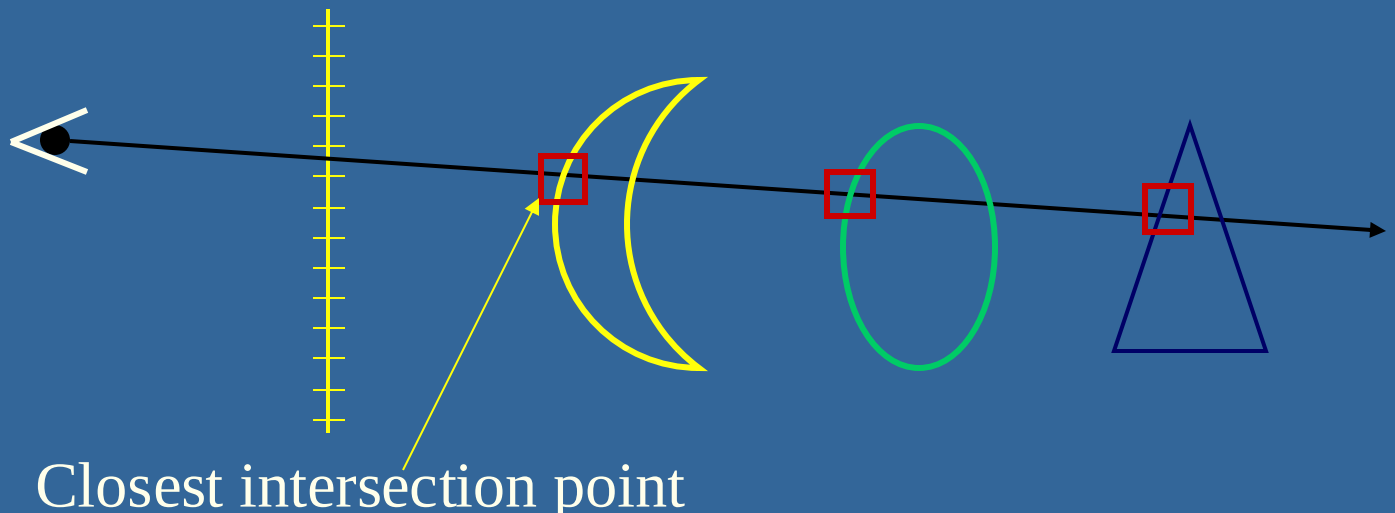
29.8 Billion photons

Same image but with 382 Billion Photons



Follow photons backwards from the eye: treat one pixel at a time

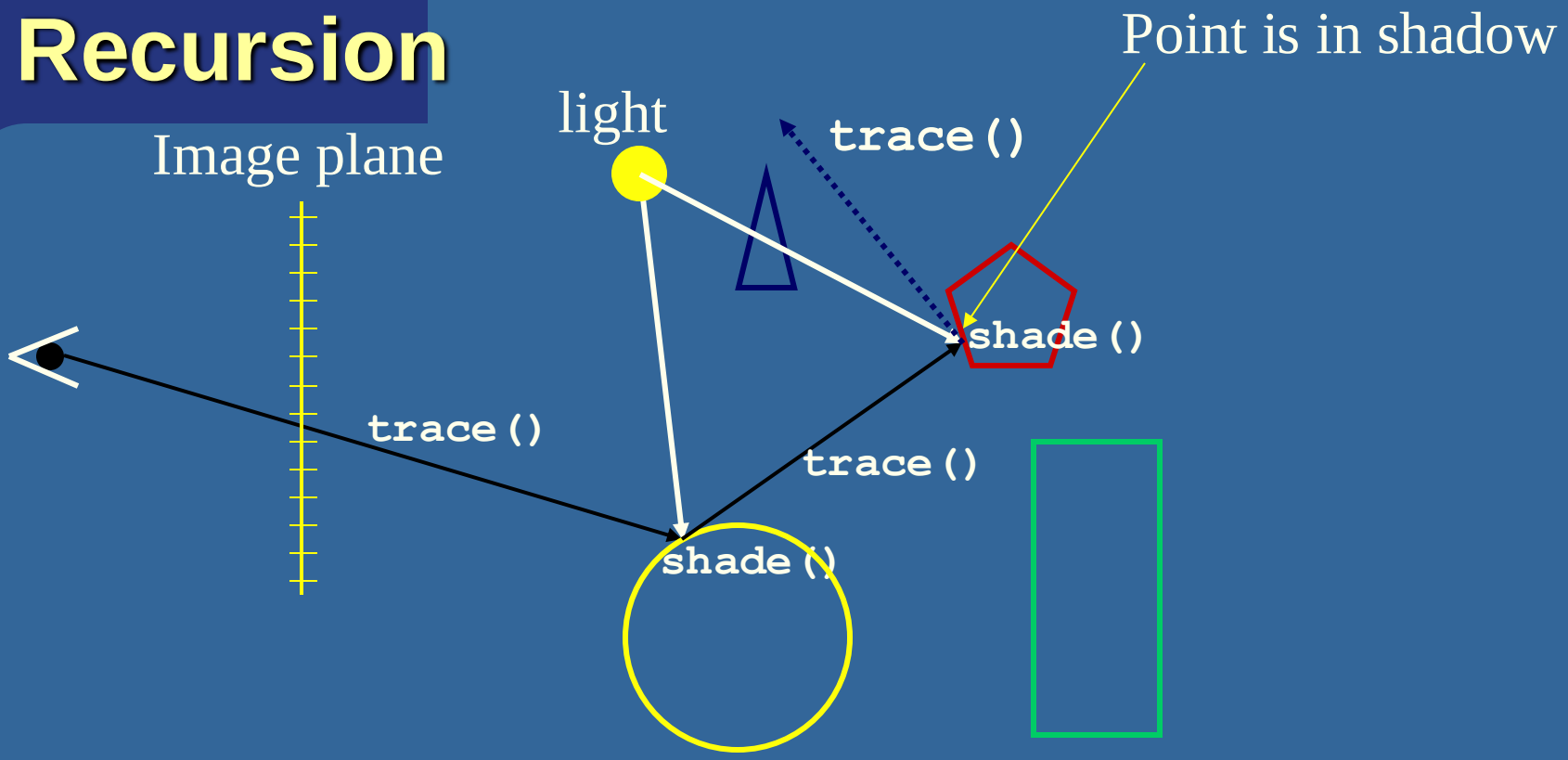
- Rationale: find photons that arrive at each pixel
- How do one find the visible object at a pixel?
- With intersection testing
  - Ray, $\mathbf{r}(t)=\mathbf{o}+t\mathbf{d}$, against geometrical objects
  - Use object that is closest to camera!
  - Valid intersections have $t > 0$
  - t is a signed distance



Finding closest point of intersection

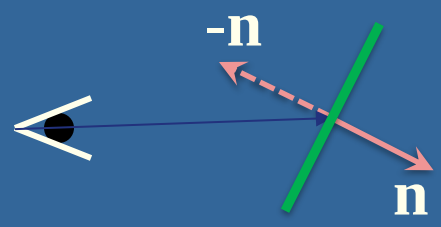
- Naively: test all geometrical objects in the scene against each ray and select closest point
  - Very very slow!
- Be smarter:
  - Use spatial data structures, e.g.:
    - **Bounding volume hierarchies (BVH): AABBH**
    - **Sparse Voxel Octrees** – octrees storing colors, not triangles
    - (Octrees),
    - kd trees - i.e., AABSP-trees.
    - Grids
    - Neural BHV:s.
    - Or a combination (hierarchies) of those
- We will return to this topic a little later

`trace()` and `shade()`: Recursion



- First call `trace()` to find first intersection
- `trace()` then calls `shade()` to compute lighting
- `shade()` then calls `trace()` for reflection and refraction directions

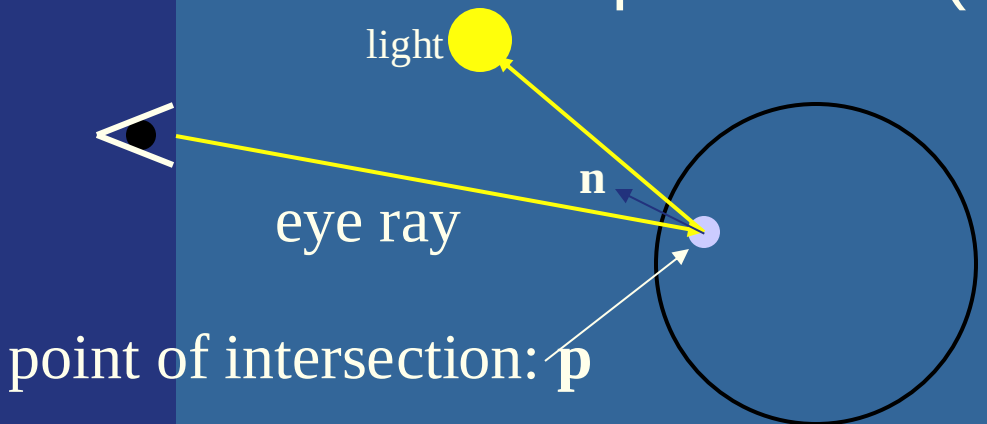
trace() in detail




```
Color trace(Ray R)
{
        float t;
        Object O; // typically a triangle
        Color col;
        bool hit=findClosestIntersection(R,&t,&O);
        if(hit)
        {
                // Compute intersection point P
                Vec3f P = R.origin() + t*R.direction();
                // Compute normal at intersection point
                Vec3f N = computeNormal(P,O);
                // flip normal if pointing in wrong dir.
                if(dot(N,R.direction()) > 0.0) N=-N;
                col=shade(R,O,P,N);
        }
        else col=background_color;
        return col;
}
```

In `trace()`, we need a function `findClosestIntersection()`

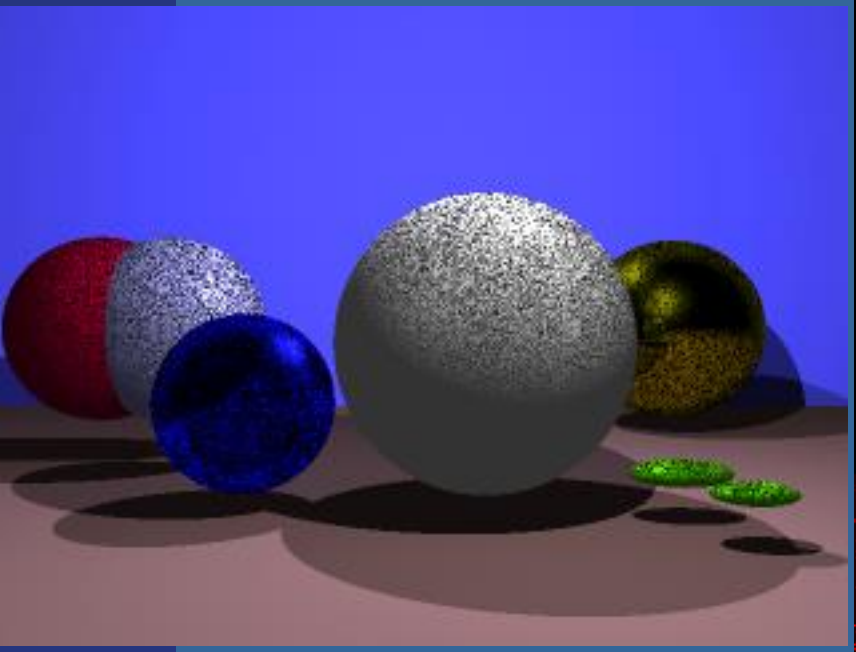
- Use intersection testing (from a previous lecture) for rays against objects
- Intersection testing returns signed distance(s), t, to the object
- Use the t that is smallest, but >0
- Naive: test all objects against each ray
  - Better: use spatial data structures (more later)
- Precision problems (exaggerated):

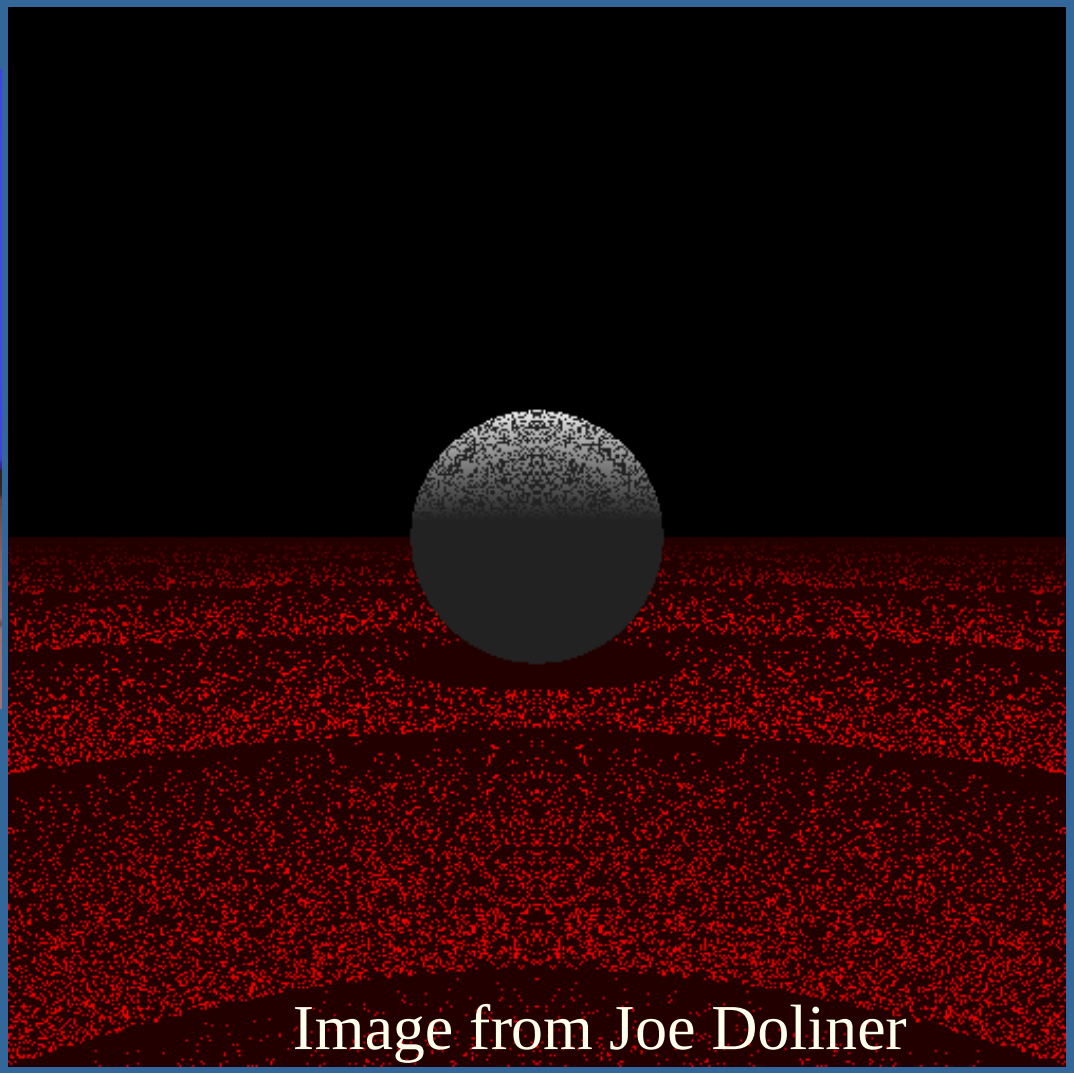


The point, **p**, can be incorrectly self-shadowed, due to imprecision

Solution: after **p** has been computed, update as: $\mathbf{p'}=\mathbf{p}+\varepsilon\mathbf{n}$
($\mathbf{n}$ is normal at p, ε is small number >0)

Example of Surface Acne





shade() in detail

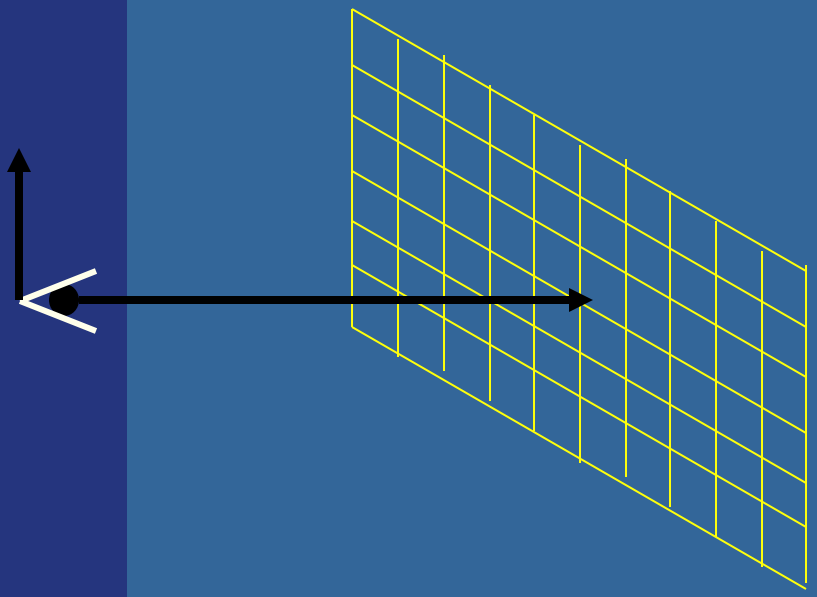
```
Color shade(Ray R, Mtrl &m, Vector P,N)
{
        Color col(0,0,0); // black
        Vector refl,refr;
        for each light L
        {
                if(not inShadow(L,P))
                        col+=DiffuseAndSpecular();

        }
        col+=AmbientTerm();
        if(recursed_too_many_times()) return col;
        refl=reflectionVector(R,N);
        col+=m.specular_color()*trace(refl);
        refr=computeRefractionVector(R,N,m);
        col+=m.transmission_color()*trace(refr);
        return col;
}
```

For more accurate shading, see https://pbr-book.org/3ed-2018/Reflection_Models/Specular_Reflection_and_Transmission

Who calls `trace()` or `shade()`?

- Someone need to spawn rays
  - One or more per pixel
  - A simple routine, **`raytraceImage()`**, computes rays, and calls **`trace()`** for each pixel.



- Use camera parameters to compute rays
  - Resolution, fov, camera direction & position & up

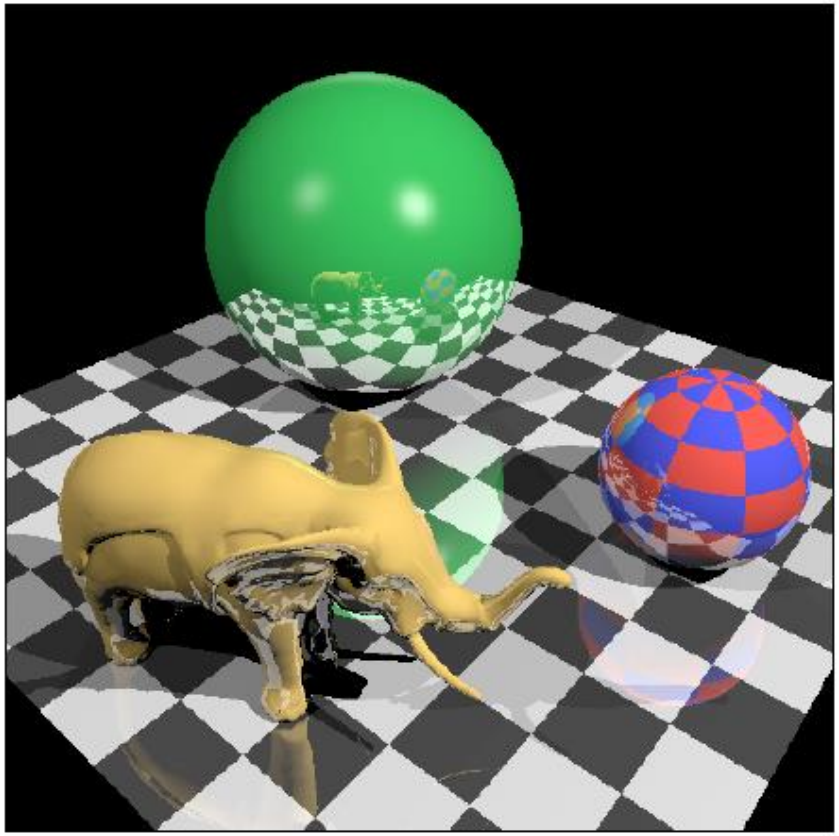
When does recursion stop?

- Recurse until ray does not hit something?
  - Does not work for closed scenes.
- One solution is to allow for max N levels of recursion
  - N=3 is often sufficient (sometimes 10 is sufficient)
- Another is to look at material parameters.
  - E.g., if specular material color is (0,0,0), then the object is not reflective, and we don't need to spawn a reflection ray.
  - More systematic: **for each bounce, light is attenuated** (physically by material's brdf that depends on color, Fresnel, angles, …)
    - **So, send a weight, w, with recursion**
    - Initially w=1, and after each bounce, w is attenuated by shading model:
      - E.g.: w = w * (brdf) $(\boldsymbol{n} \cdot \boldsymbol{\omega}_i)$;
    - Terminate recursion when weight is too small (say <0.05).
      - Or use a weight per rgb, **w**=(1,1,1) and stop when max($\mathbf{w}_r$, $\mathbf{w}_g$, $\mathbf{w}_b$) < 0.05 or when ||**w**|| < 0.05.

When to stop recursion

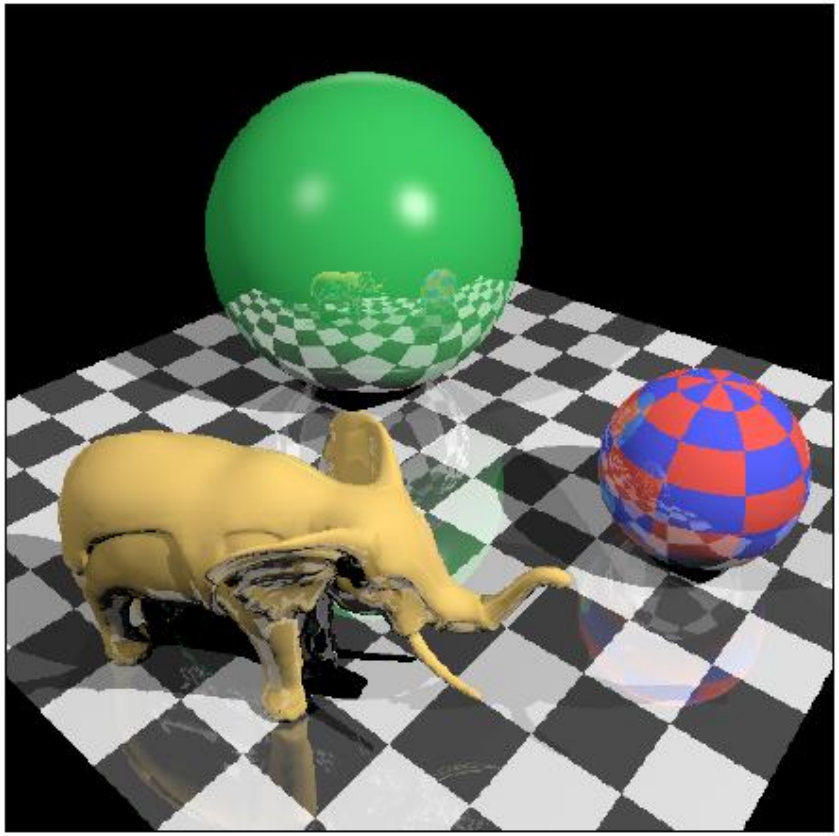
Reflections - Result

- Direct illumination with shadows + reflections
- Depth cutoff = 1



Reflections - Result

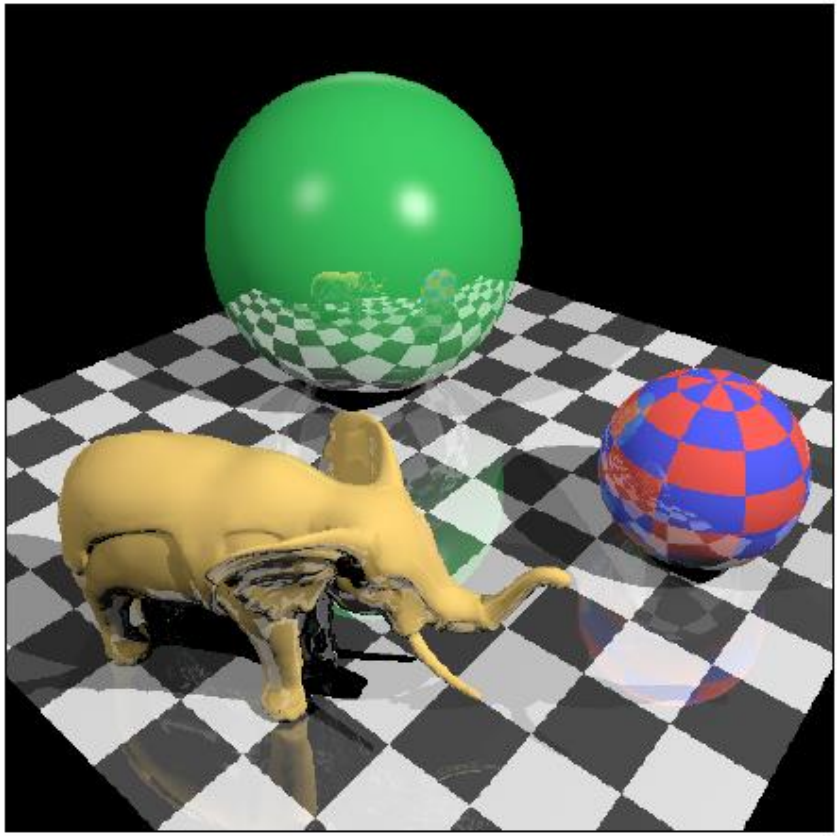
- Direct illumination with shadows + reflections
- Depth cutoff = 2



30

Reflections - Result

- Direct illumination with shadows + reflections
- Depth cutoff = 3



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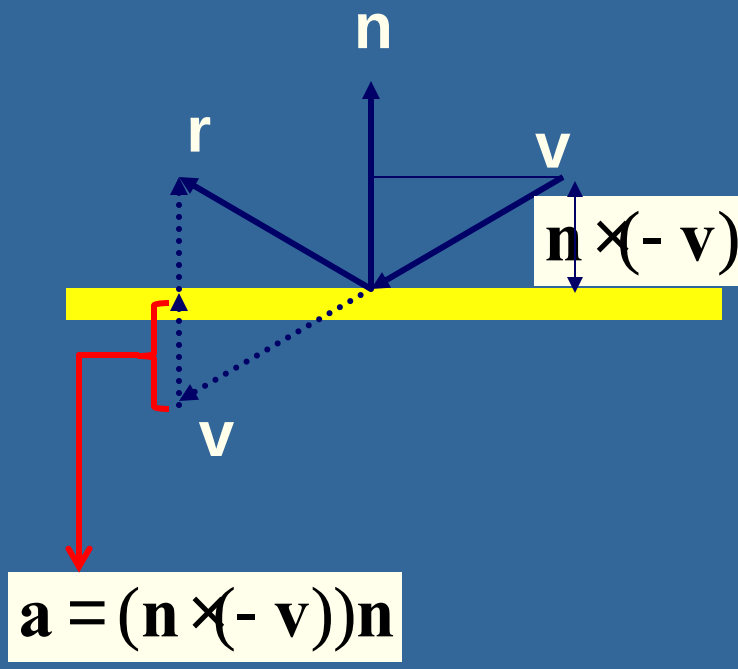
Reflection vector (recap)

- Reflecting the incoming ray **v** around **n:**
- **N**ote that the incoming ray is sometimes called **–v** depending on the direction of the vector.
- **r** can be computed as **v**+(2**a**). I.e.,

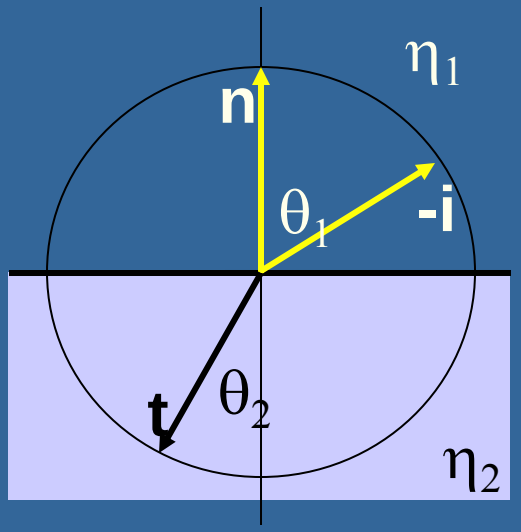
$$\mathbf{r} = \mathbf{v} - 2(\mathbf{n} \times \mathbf{v})\hat{\mathbf{n}}$$



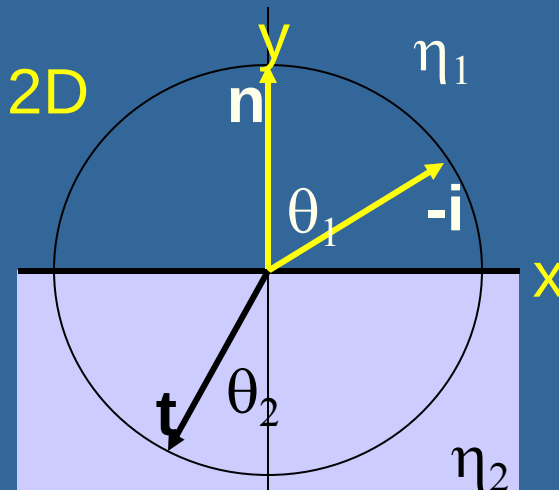
Refraction:
Need a transmission direction vector, t

Known as Heckbert's method

- **n**, **i**, **t** are unit vectors
- η_1 & η_2 are refraction indices
- Snell's law says that:
  - $\sin(\theta_2)/\sin(\theta_1) = \eta_1/\eta_2 = \eta$, where η is relative refraction index.
- How can we compute the refraction vector **t** ?



- This would be easy in 2D:
  - $t_x = -\sin(\theta_2)$
  - $t_y = -\cos(\theta_2)$
  - I.e., $\mathbf{t} = -\sin(\theta_2)\hat{\mathbf{x}} - \cos(\theta_2)\hat{\mathbf{y}}$

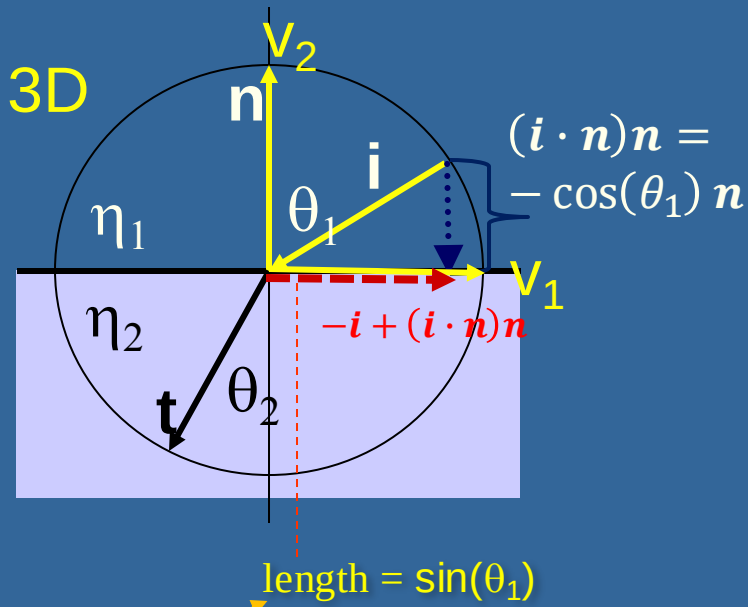


Refraction:

$$\mathbf{t} = -\sin(\theta_2)\hat{\mathbf{x}} - \cos(\theta_2)\hat{\mathbf{y}}$$

- **But we are in 3D, not in 2D!**
- So, the solution will look like:

$$\mathbf{t} = -\sin(\theta_2)\hat{\mathbf{v}}_1 - \cos(\theta_2)\hat{\mathbf{v}}_2$$



v_2=n

v_1 = normalize$(-i + (i \cdot n)n)$

So we could concider us done. But let's continue simplifying to avoid expensive trigonometric functions (sin, cos, arcsin). Only use cheap $\cos(\theta_1) = (-i \cdot n)$.

1. We know v_1's length before normalization is $\sin(\theta_1)$:
   - $\mathbf{v}_1 = (-i + (i \cdot n)n) / \sin(\theta_1)$ This also allows trick using Snell's law in step 3 below
2. Plugin v_1 into t
   ⇒ $\mathbf{t} = \sin(\theta_2)\ (i - (i \cdot n)n) / \sin(\theta_1) - \cos(\theta_2)\mathbf{n}$
3. Use Snell: $\sin(\theta_2)/\sin(\theta_1) = \eta$
   ⇒ $\mathbf{t} = \eta(i - (i \cdot n)n) - \cos(\theta_2)\mathbf{n}$
4. Simplify $\cos(\theta_2)$ using Trig1: $\cos(\theta_2)^2 = 1 - \sin(\theta_2)^2$ and Snell: $\sin(\theta_2) = \eta \sin(\theta_1)$:

⇒ $\cos(\theta_2)$=[Trig1] $= \sqrt{1 - \sin(\theta_2)^2}$ =[Snell]$=\sqrt{1 - \eta^2 \sin(\theta_1)^2}$ =[Trig1]$= \sqrt{1 - \eta^2\ (1 - \cos(\theta_1)^2}$

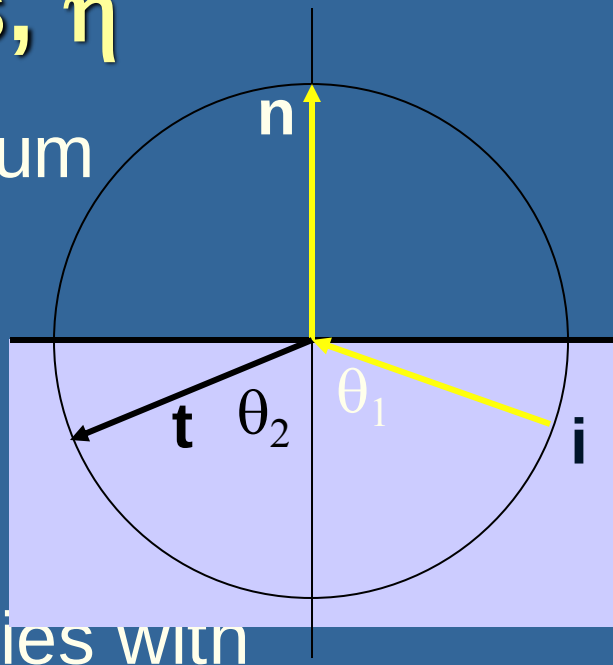
⇒ $\mathbf{t} = \eta(i - (i \cdot n)n) - \sqrt{1 - \eta^2\ (1 - \cos(\theta_1)^2}\ \mathbf{n}$ // replacing $\cos(\theta_2)$ with an expression of $\cos(\theta_1)$

⇒ $\mathbf{t} = \eta(i - (i \cdot n)n) - \sqrt{1 - \eta^2\ (1 - (-i \cdot n))^2}\ \mathbf{n}$ // which is fast to compute since $\cos(\theta_1) = (-i \cdot n)$

Known as Heckbert's method

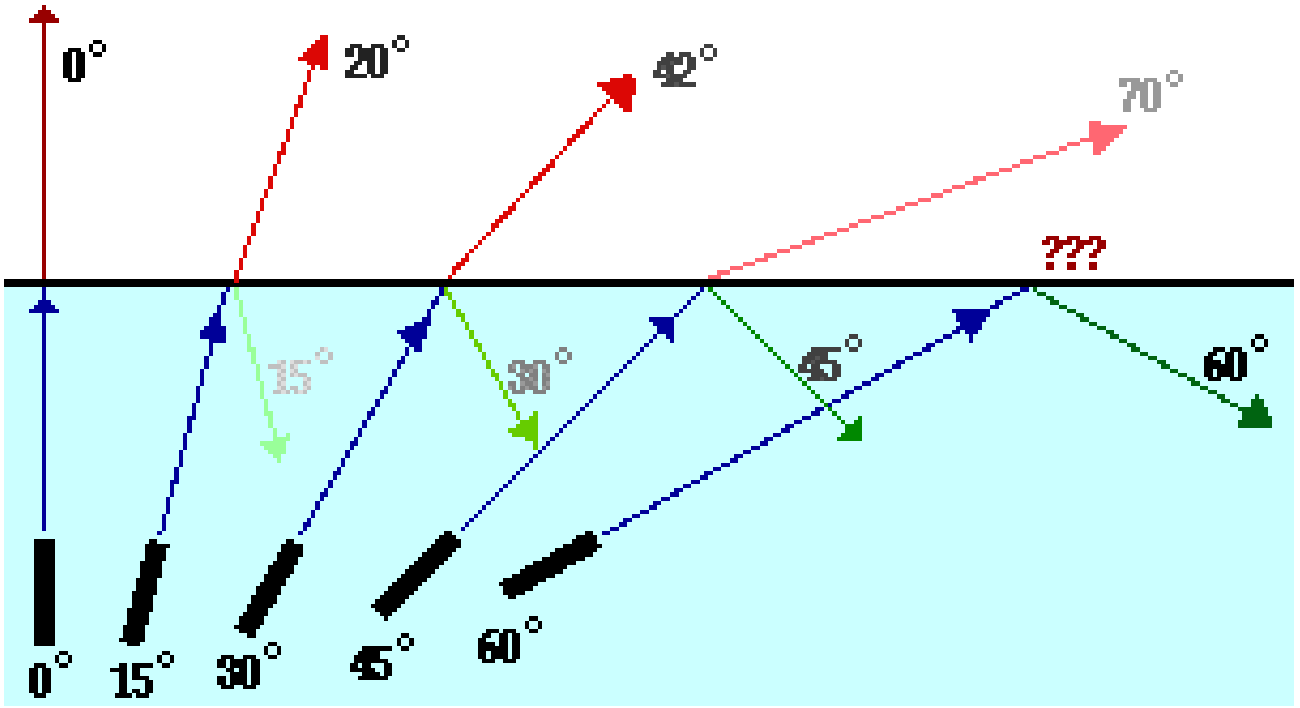
Image with a refractive object

Some refraction indices, η



- Measured with respect to vacuum
  - Air: 1.0003
  - Water: 1.33
  - Glass: around 1.45 – 1.65
  - Diamond: 2.42
  - Salt: 1.54
- Note 1: the refraction index varies with wavelength for metals, i.e., one index per color channel, RGB.
- Note 2: can get Total Internal Reflection (TIR)
  - Means no transmission, only reflection
  - TIR occurs when the square root has an imaginary solution.
    - Or put differently:
      - $\theta_2 = \arcsin(\eta \sin(\theta_1))$
      - TIR occurs when $|\eta \sin(\theta_1)| > 1$, i.e., arcsin() undefined

As the angle of incidence increases from 0 to greater angles ...

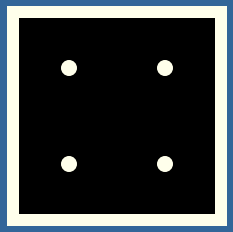


...the refracted ray becomes dimmer (there is less refraction)

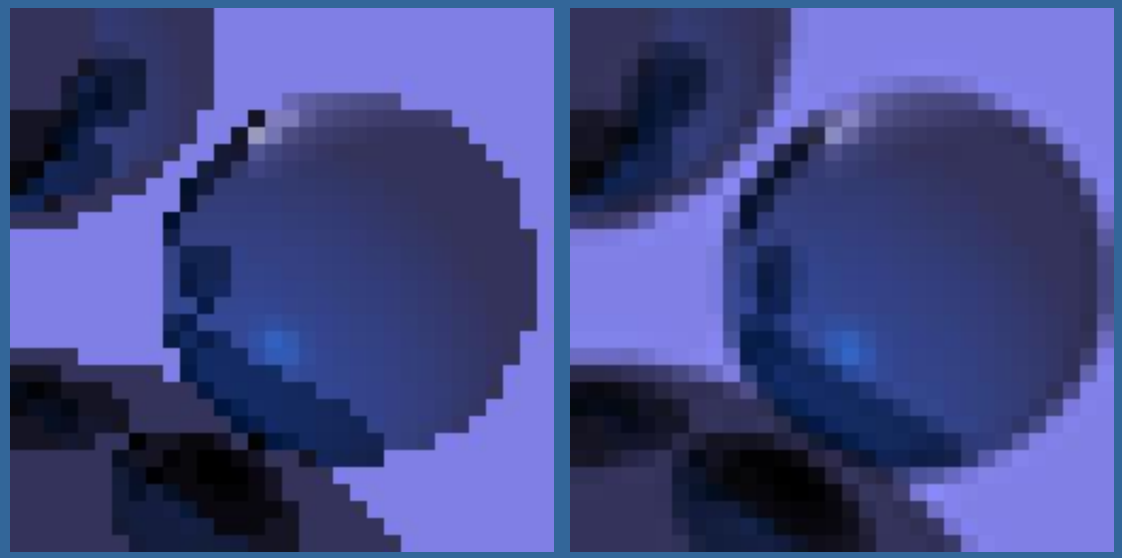
...the reflected ray becomes brighter (there is more reflection)

...the angle of refraction approaches 90 degrees until finally a refracted ray can no longer be seen.

Supersampling

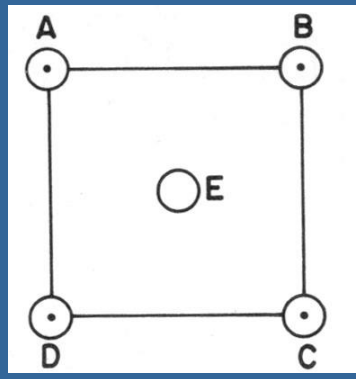


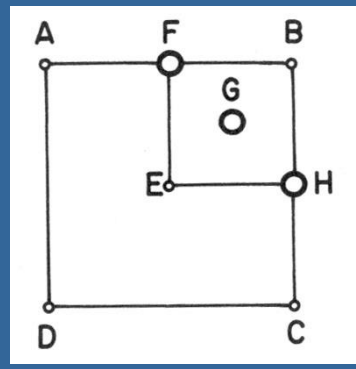
- Evenly distribute ray samples over pixel
- Use box (or tent filter) to find pixel color
- More samples gives better quality
  - Costs more time to render
- Example of 4x4 samples against 1 sample:

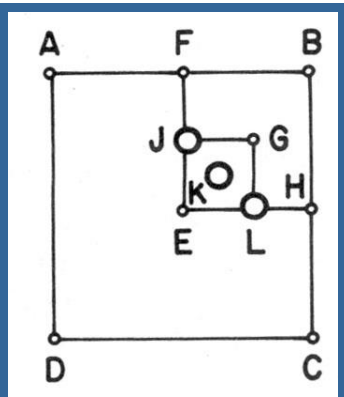


Be a bit smarter, make it cheaper: Adaptive supersampling (1)

- Quincunx sampling pattern to start with
  - 2 samples per pixel, 1 in center, 1 in upper-left
  - Note: adaptive sampling is not feasible in graphics hardware, but simple in a ray tracer
- Colors of AE, DE are quite similar, so don't waste more time on those.
- The colors of B & E are different, so add more samples there with the same sampling pattern
- Same thing again, check FG, BG, HG, EG: only EG needs more sampling
- So, add rays for J, K, and L

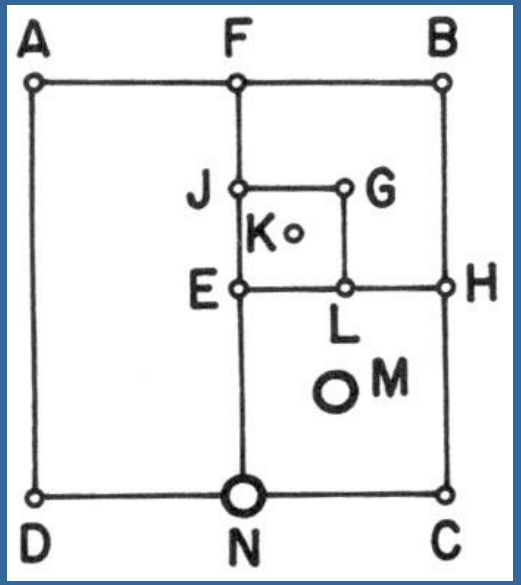




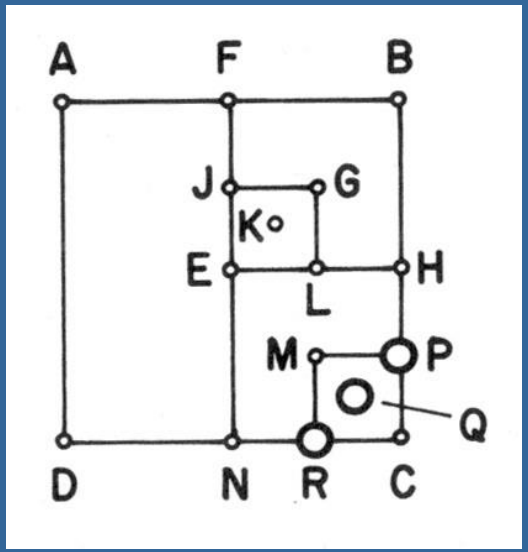


Adaptive supersampling (2)

- C & E were different too
- Add N & M
- Compare EM, HM, CM, NM



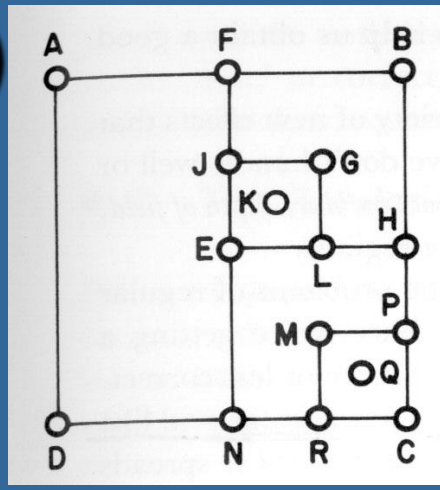
- C & M are too different
- So add rays at P, Q, and R

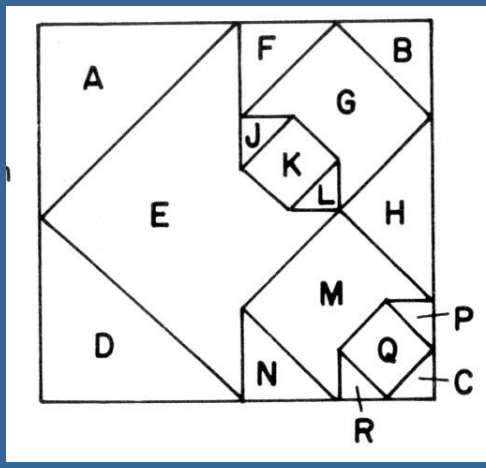


- At this point, we consider the entire pixel to be sufficiently sampled
- Time to weigh (filter) the colors of all rays

Adaptive supersampling (3)

- Final sample pattern for pixel:
- How filter the colors of the rays?
- Think of the pattern differently:
- And use the area of each ray sample as its weight:





$$\frac{1}{4}\left(\frac{A+E}{2}+\frac{D+E}{2}+\frac{1}{4}\left[\frac{F+G}{2}+\frac{B+G}{2}+\frac{H+G}{2}+\frac{1}{4}\left\{\frac{J+K}{2}+\frac{G+K}{2}+\frac{L+K}{2}+\frac{E+K}{2}\right\}\right]\right.$$

$$\left.+\frac{1}{4}\left[\frac{E+M}{2}+\frac{H+M}{2}+\frac{N+M}{2}+\frac{1}{4}\left\{\frac{M+Q}{2}+\frac{P+Q}{2}+\frac{C+Q}{2}+\frac{R+Q}{2}\right\}\right]\right)$$

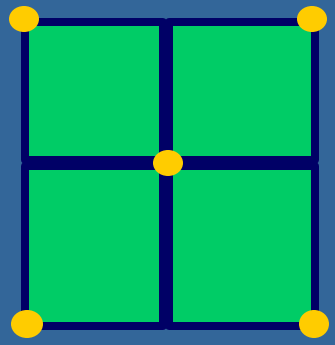
Adaptive Supersampling

Pseudo code:

Color AdaptiveSuperSampling() {

- Make sure all 5 samples exist
  - (Shoot new rays along diagonal if necessary)
- Color col = black;
- For each quad i
  - If the colors of the 2 samples are fairly similar
    - col += (1/4)*(average of the two colors)
  - Else
    - col +=(1/4)* adaptiveSuperSampling(quad[i])
- return col;

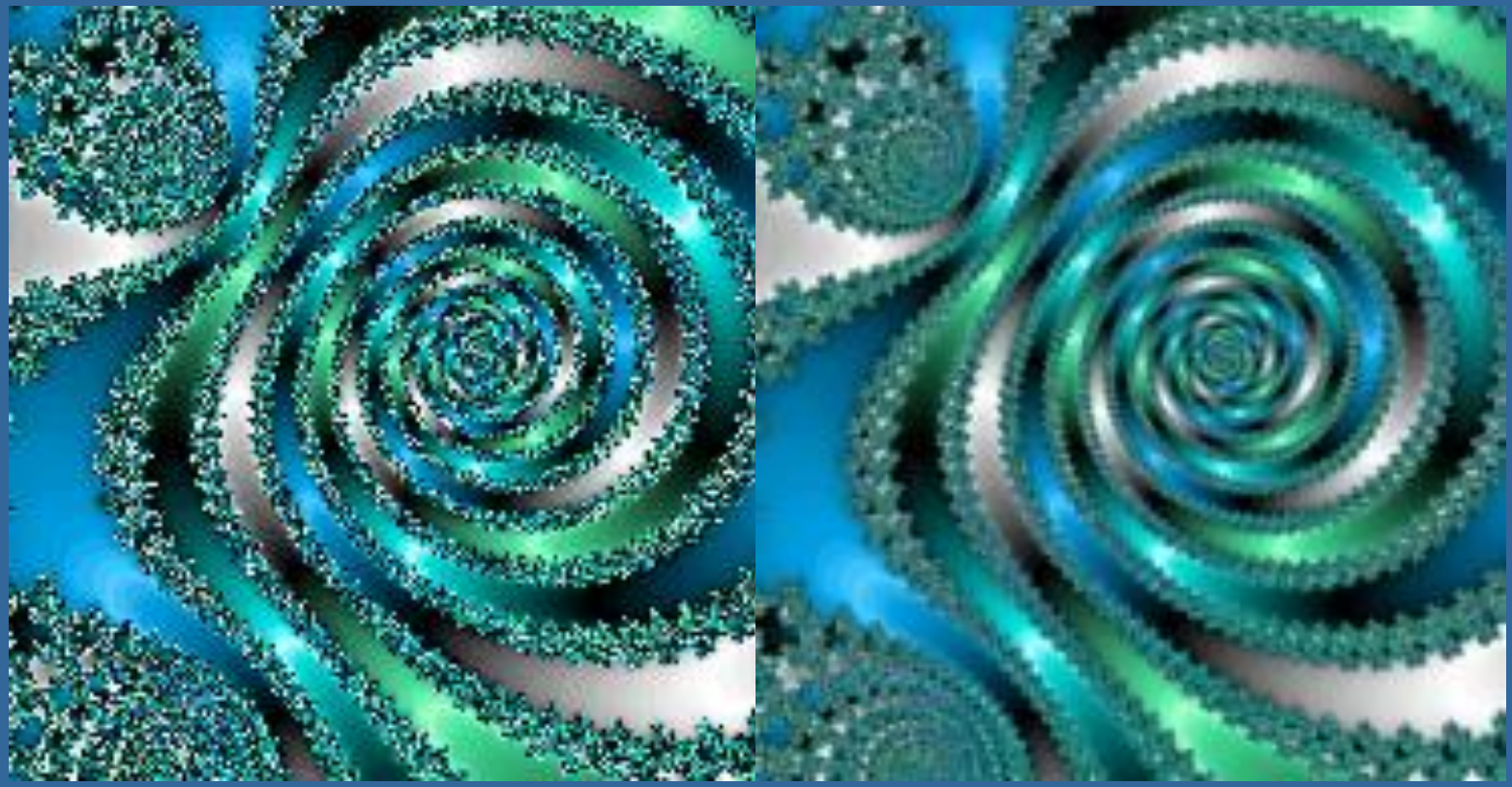
}



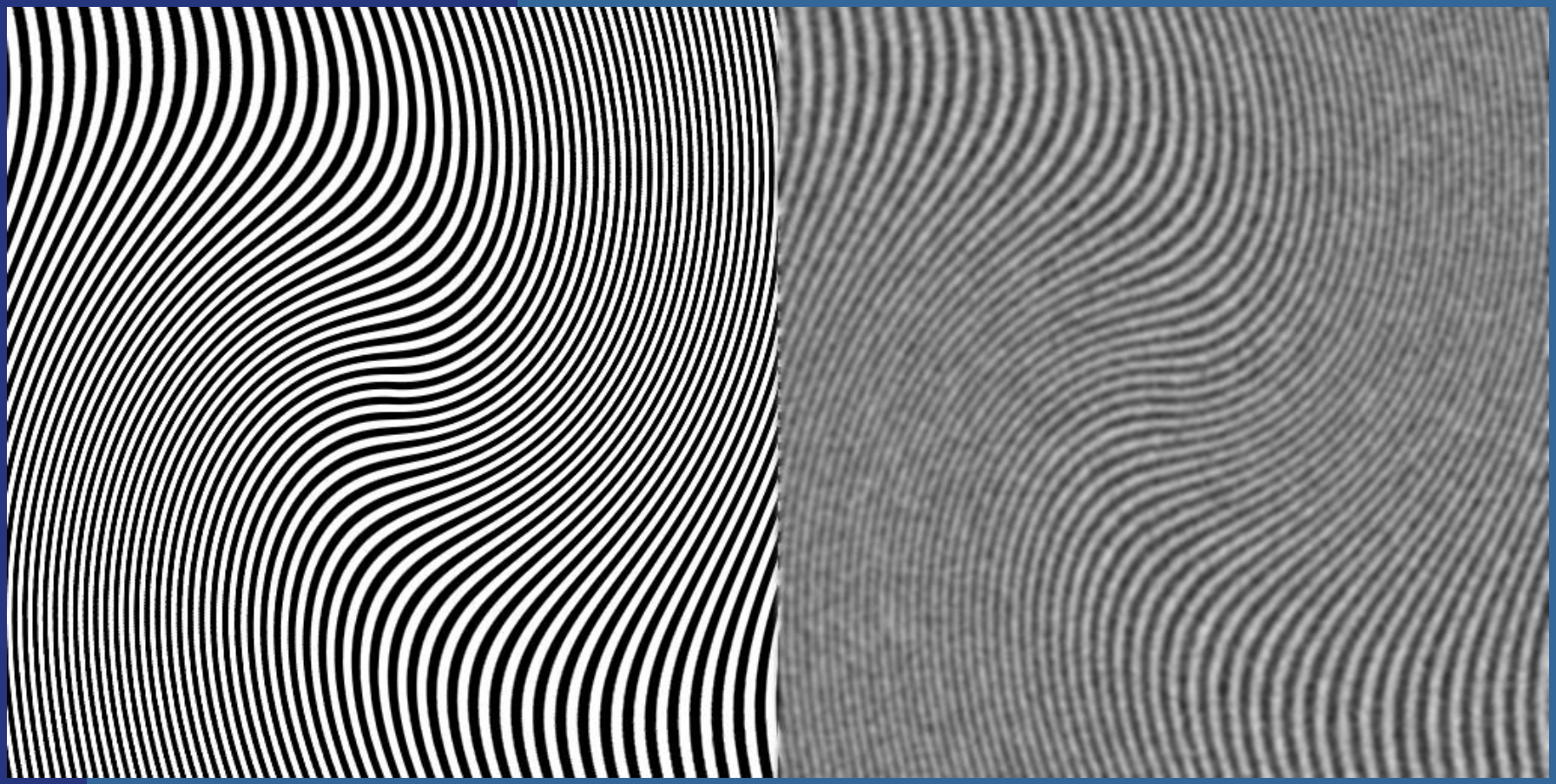
Caveats with adaptive supersampling (4)

- May miss really small objects anyway
- It's still supersampling, but smart supersampling
  - Cannot fool Nyquist!
  - Only reduce aliasing – does not eliminate it

Antialiasing - example



Moire example

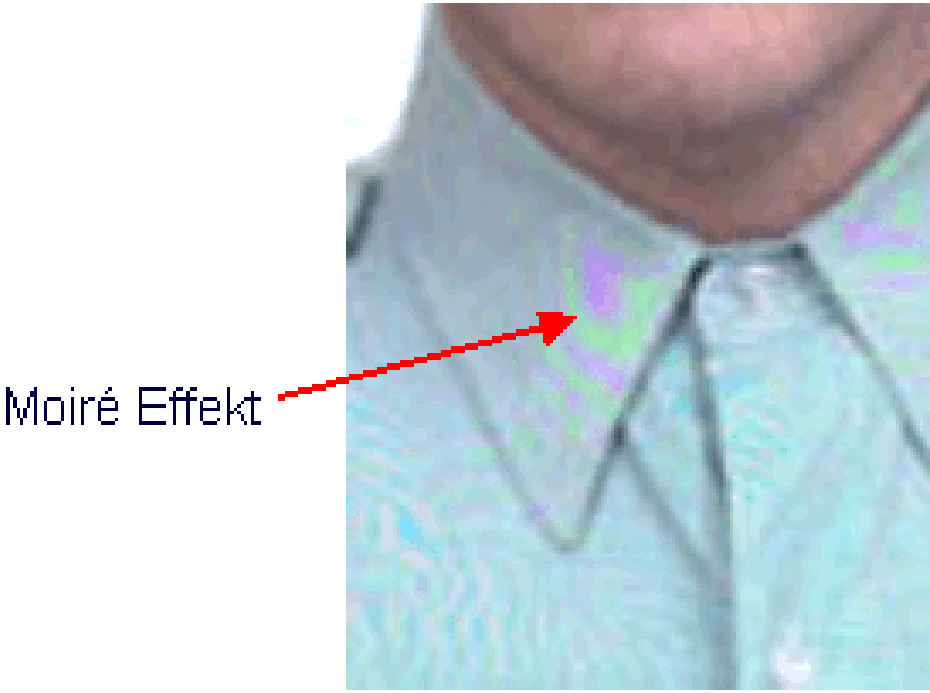


Moire patterns

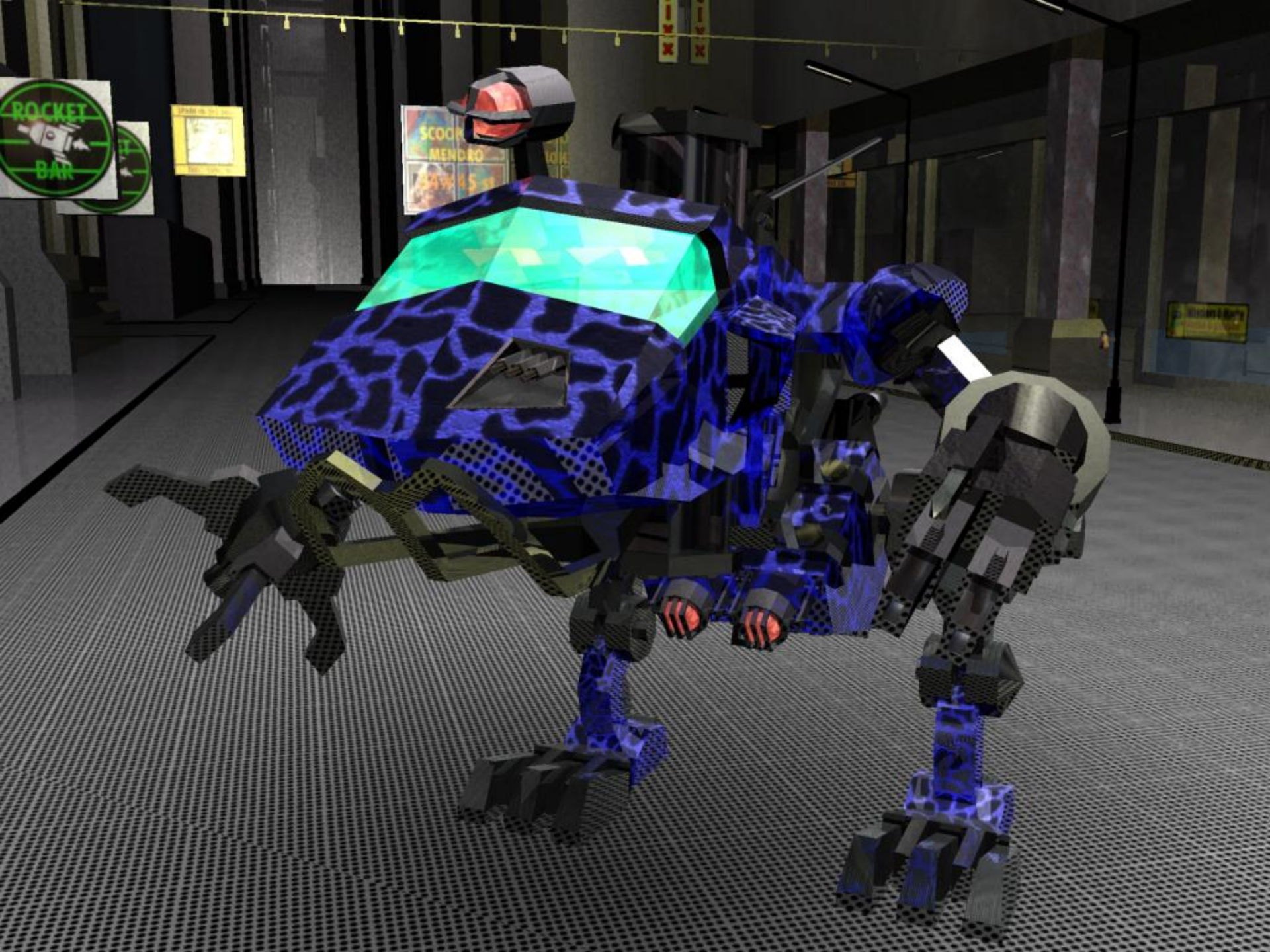
Noise + gaussian blur

(no moire patterns)

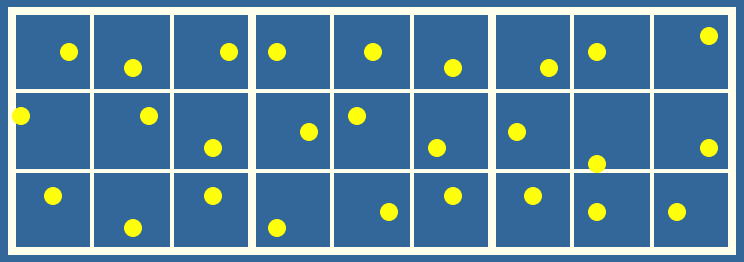
Why



“Moiré effects occur whenever tiny image structures (like the pattern on a shirt) can not be resolved sufficiently by the resolution of the image sensor. According to the Nyquist theorem, each period of an image structure must be covered with at least two pixels. When this is not the case, Moiré effects are the consequence. To avoid Moiré Effects the manufacturers of CCD camera systems use a filter that diffuses the light hitting the sensor area in such a way that it corresponds to the resolution of the ccd. “


ROCKET
BAR

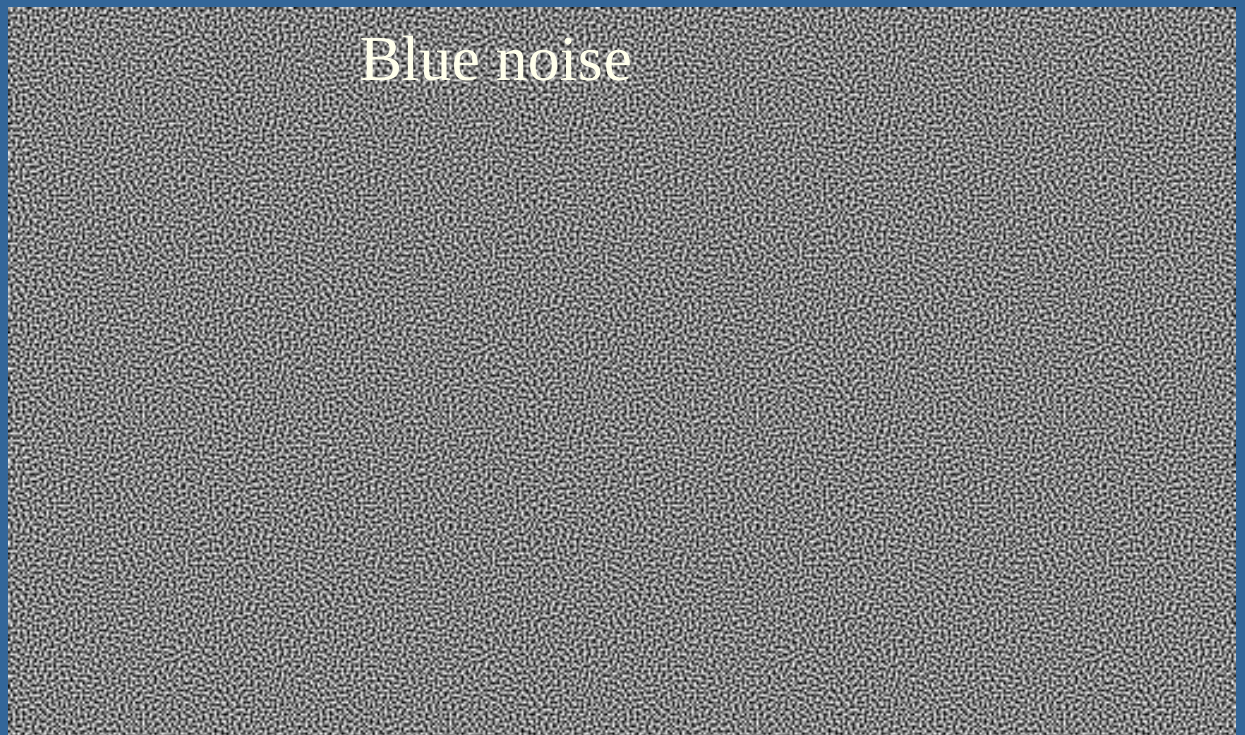
Jittered sampling



- Works as before
  - Replaces aliasing with noise
  - Our visual system likes that better
- This is often a preferred solution
- Can use adaptive strategies as well

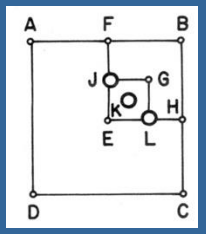
Better use even more randomness

- More professionally – use noise patterns or quasi-random sequences
  - E.g., (spatio-temporal) blue noise to position the supersamples.
  - Halton, Sobol, and Hammersley sequences…



Typical Exam Questions

- Describe the basic ray tracing algorithm (see next slide)
- Compute the reflection + refraction vector
  - You do not need to use Heckbert's method
- Describe an adaptive super sampling scheme
  - Including recursively computing weights
- What is jittering?



Pseudo code:

Color AdaptiveSuperSampling() {

- Make sure all 5 samples exist
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  - Else
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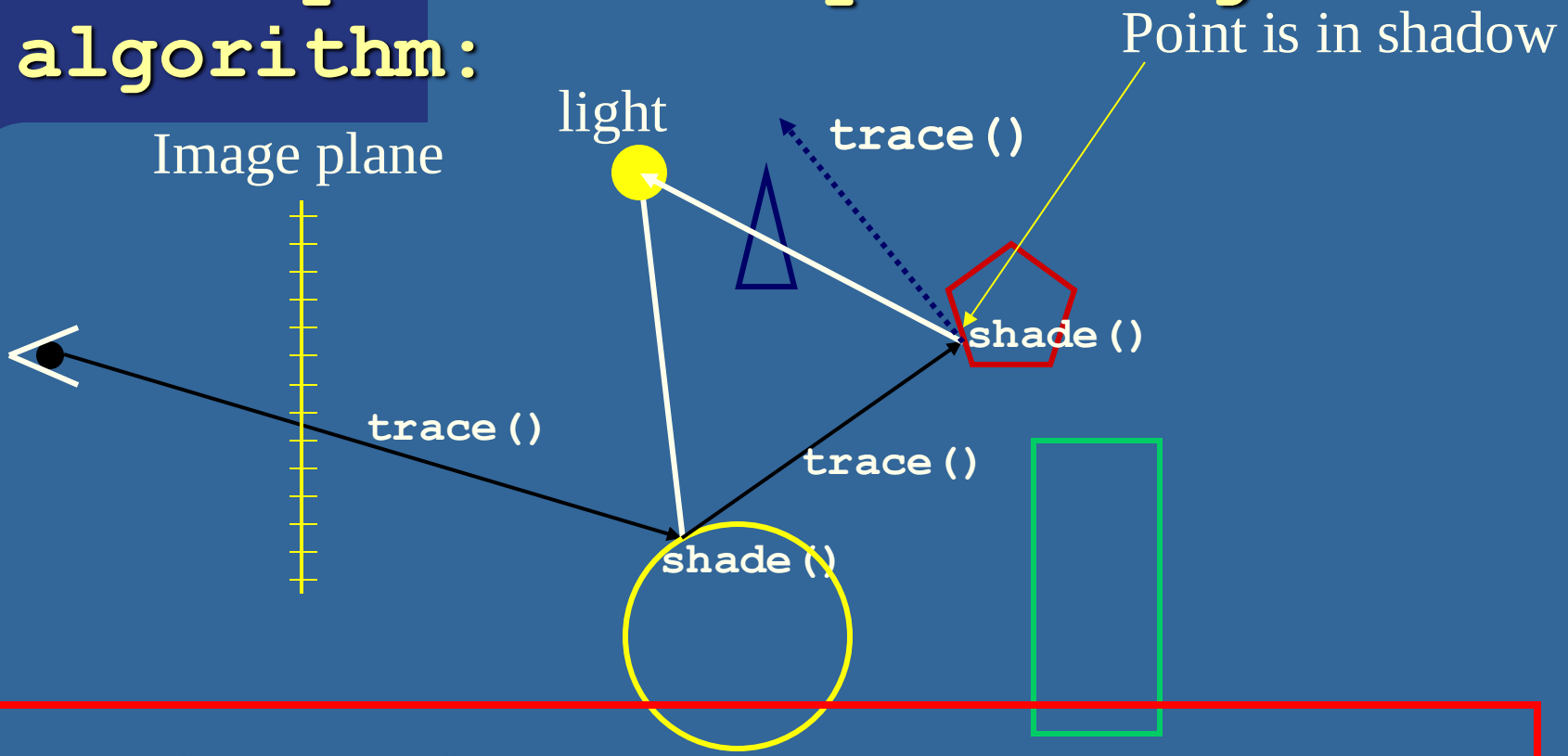
- return col;

}

Summary of the Ray tracing-algorithm:



- main()-calls trace() for each pixel
- trace(): should return color of closest hit point along ray.
  1. calls findClosestIntersection()
  2. If any object intersected → call shade().
- Shade(): should compute color at hit point
  1. For each light source, shoot shadow ray to determine if light source is visible
     If not in shadow, compute diffuse + specular contribution.
  2. Compute ambient contribution
  3. Call trace() recursively for the reflection- and refraction ray.

Real-Time Ray Tracing

$a_n = b_n + c_n \times d_n$

- Hardware:
  - CPU: SIMD/SSE/AVX/APX – 4/8/16/32 registers doing same instruction.
  - GPU – has thousands of cores. Each group of typically 32 cores do same instruction.
  - NVIDIA RTX - GPU accelerated ray tracing:
    - Ray vs AABBH, ray/triangle intersections
    - Use perhaps 1 ray/pixel for shadows + reflections for 2 ray bounces. And then denoise with AI.
    - AABB-hierarchy construction:
      - *Ploctree: A fast, high-quality hardware BVH builder*. Viitanen et al. 2018.
      - *Ploc++ parallel locally-ordered clustering for bounding volume hierarchy construction revisited*. Benthin et al. 2022.
- Low level optimizations
  - Precomputation of constants per frame, e.q., ray-AABB test.
- Rasterize primary rays – in particular for RTX
  - Else often not worth it, since primary rays are few compared to all secondary rays.
- Adaptive sub sampling
- Frameless rendering (motion blur)
- Temporal Reprojection – can be used for rasterization and ray tracing.

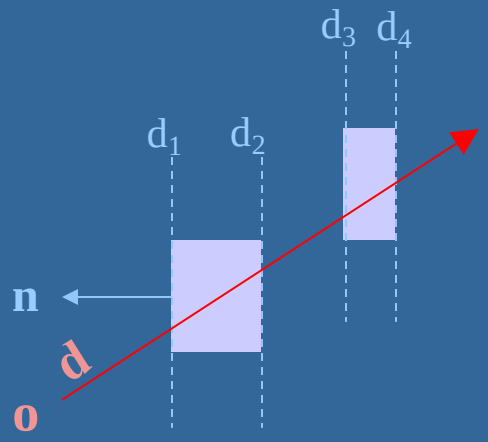
Ray-AABB hierarchy test, optimized

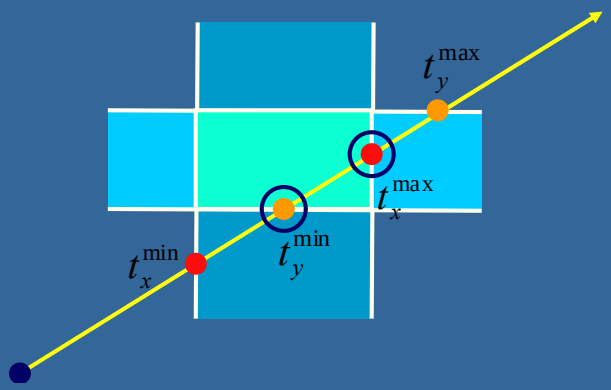
t= (-($\boldsymbol{n} \cdot \boldsymbol{o}$) -d) / ($\boldsymbol{n} \cdot \boldsymbol{d}$)
Compute constants per ray and slab axis (x,y, or z). With **o**, **d** and **n** constant, we can precompute:

a = -($\boldsymbol{n} \cdot \boldsymbol{o}$) / ($\boldsymbol{n} \cdot \boldsymbol{d}$)
b = -1/ ($\boldsymbol{n} \cdot \boldsymbol{d}$)
$\Rightarrow$ t = a + d*b // just 1 madd instr. per plane

Per AABB:
- 6 ray/plane computations à 1 *madd*.
- ~5 *max* instr.

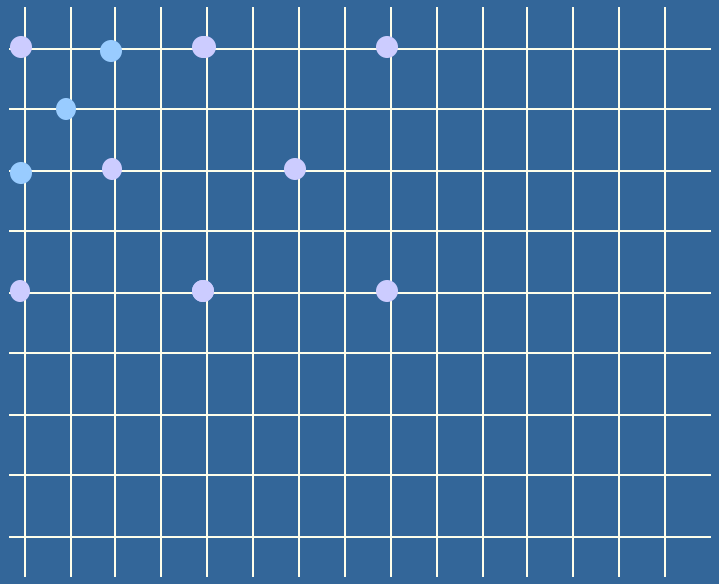
+ a few comparison instructions.
VERY FAST





- Keep max of $t^{min:s}$ and min of $t^{max:s}$
- If $t^{min} < t^{max}$ then intersection
- Special case when ray parallell to slab

Adaptive Sub Sampling



Many versions exist. E.g., quincunx again:

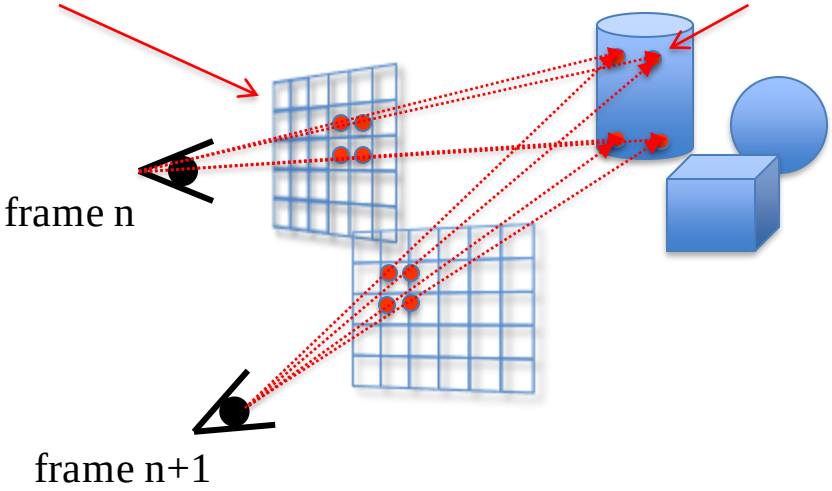
- Start by sampling every 4x4 pixel corners and in the middle. Gives on average 2 samples per 16 pixels.
- If a quadrant's 2 samples are fairly similar,
  - fill in pixel colors by interpolation.
- Else, supersample recursively.

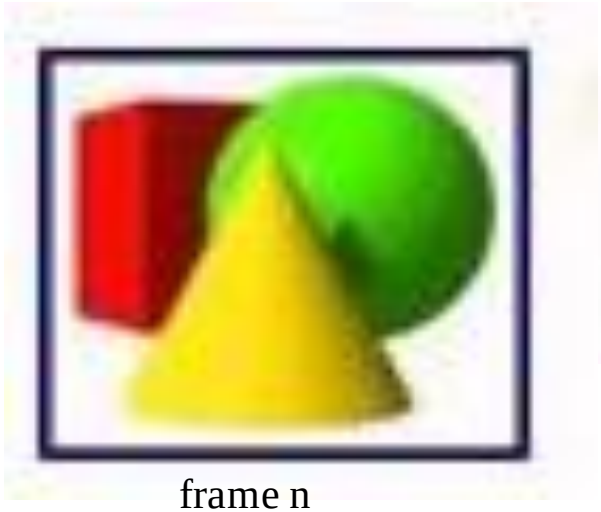
Frameless rendering

Frameless Rendering – updating e.g. only10% of all pixels each frame

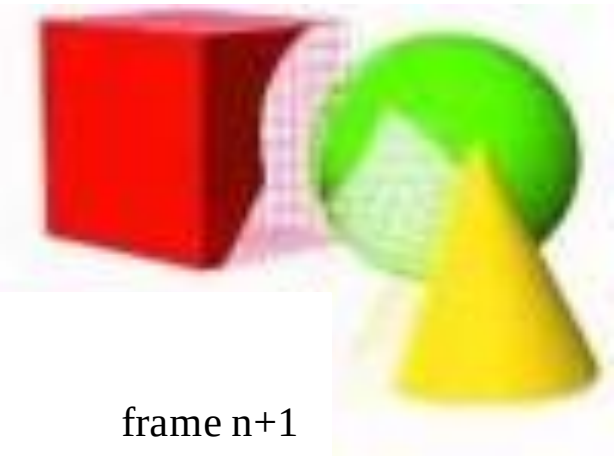
Temporal Reprojection

Store (r,g,b) color and world space (x,y,z) per pixel





frame n



frame n+1

Reproject samples from frame *n* to frame *n+1*. Then:

- For pixel with <1 sample
  - trace new ray
- For pixel with >=1 sample
  - use closest (smallest z)
- Does not work as well for spec. mtrl.