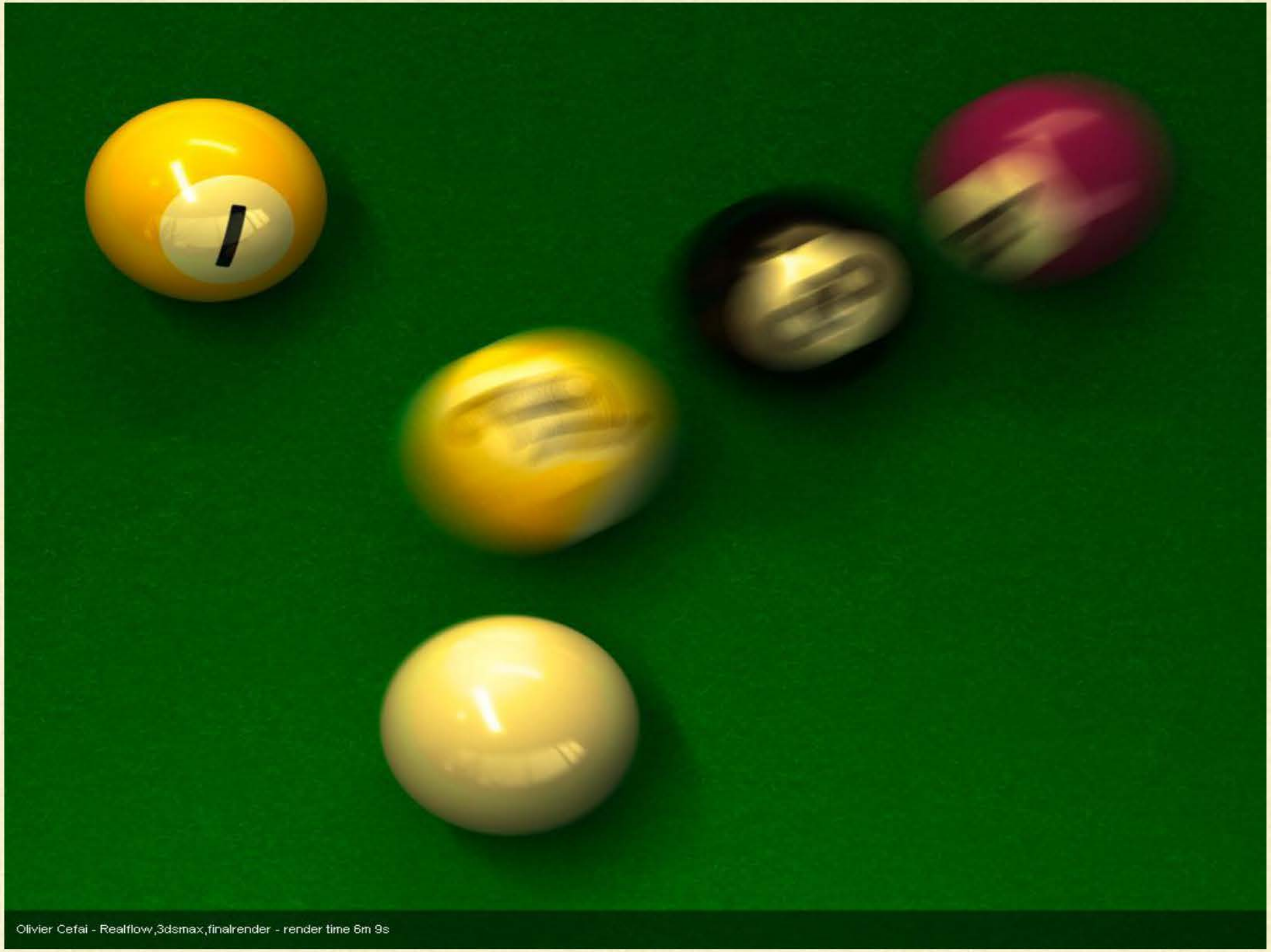
Advanced Rendering

Motion Blur


Olivier Cefai - Realflow,3dsmax,finalrender - render time 6m 9s

Shutter Speed

- The <u>shutter</u> allows light to hit the sensor for a finite duration of time
- While the shutter is open, moving objects create streaks on the sensor resulting in <u>motion blur</u>
- A faster shutter prevents motion blur, but limits the amount of entering light (often) making the image too dark (especially when the aperture is small)

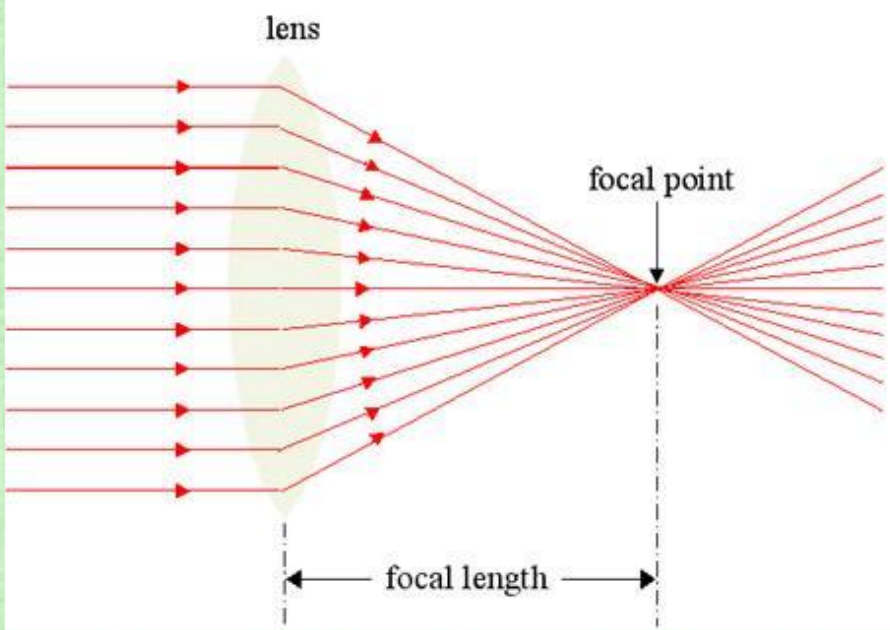
Ray Tracing Animated Geometry

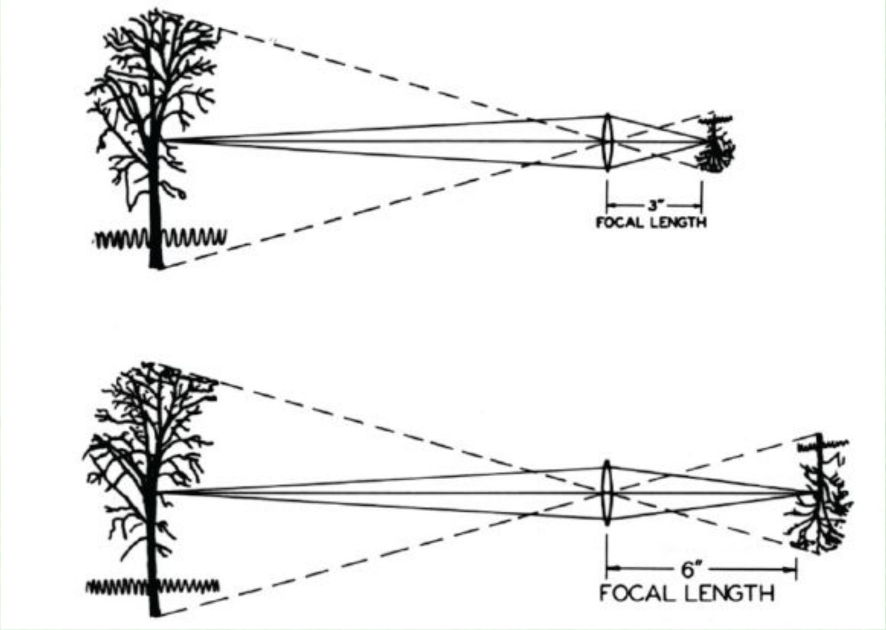
- Create an animation for a moving object during the time interval $[T_0, T_1]$, when the shutter is open
    - E.g. specify the object's transform as a function $F(t)$ for time $t \in [T_0, T_1]$
- Then, for each ray:
    - Assign a random time: $t_{ray} = (1 - \alpha)T_0 + \alpha T_1$ with α randomly selected from [0,1]
    - Place the object into its time t_{ray} location, given by the transform $F(t_{ray})$
    - Trace the ray (recursively, if applicable) through the whole scene to get a color for that ray
- Works significantly better when many rays per pixel are used to combat temporal aliasing

Depth of Field

Focal Length

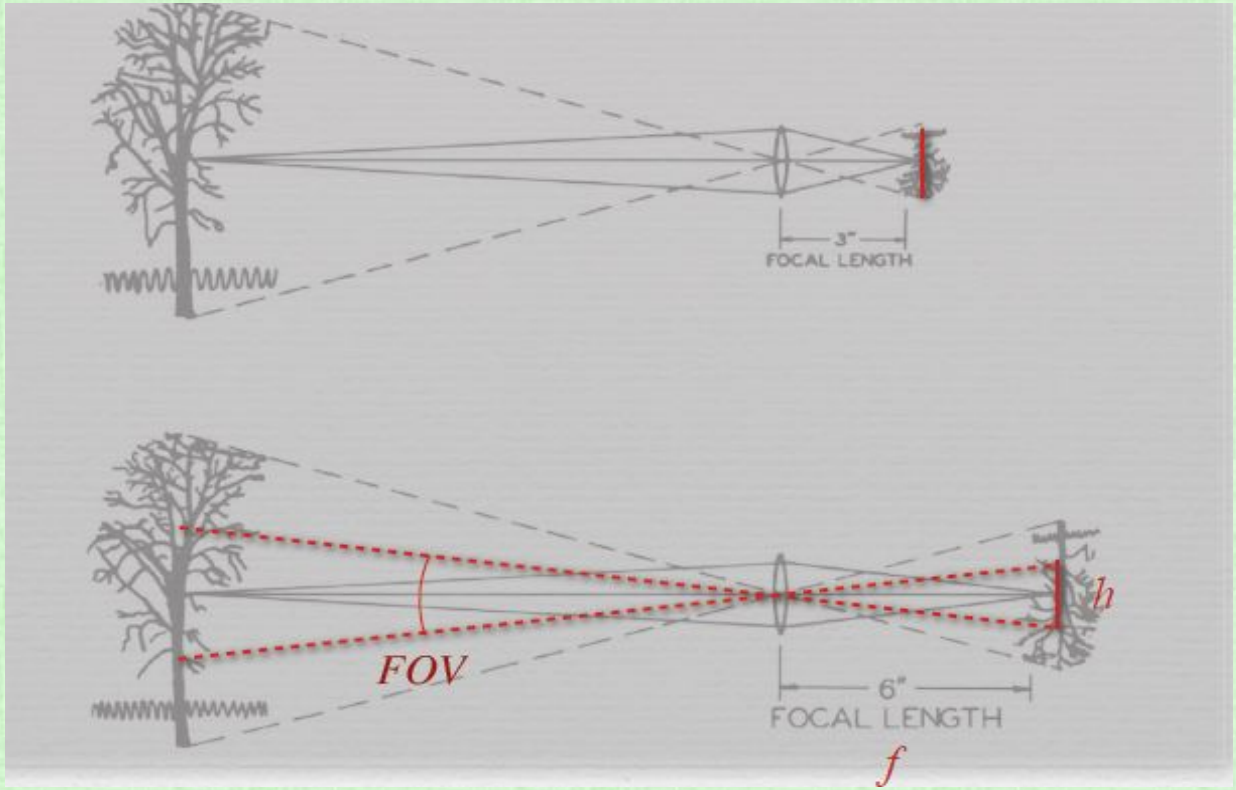
- The focal length is the distance over which initially parallel rays are brought into focus (onto a focal point) by a lens (or lens system)
  - A stronger lens (or lens system) has a shorter focal length (bending rays more easily)
  - Individual elements of a lens system can be adjusted to change the overall focal length (but each individual lens has a fixed focal length)
  - The farther away an object is, the closer the image plane (or sensor) should be placed to the focal point (for it to be in focus)



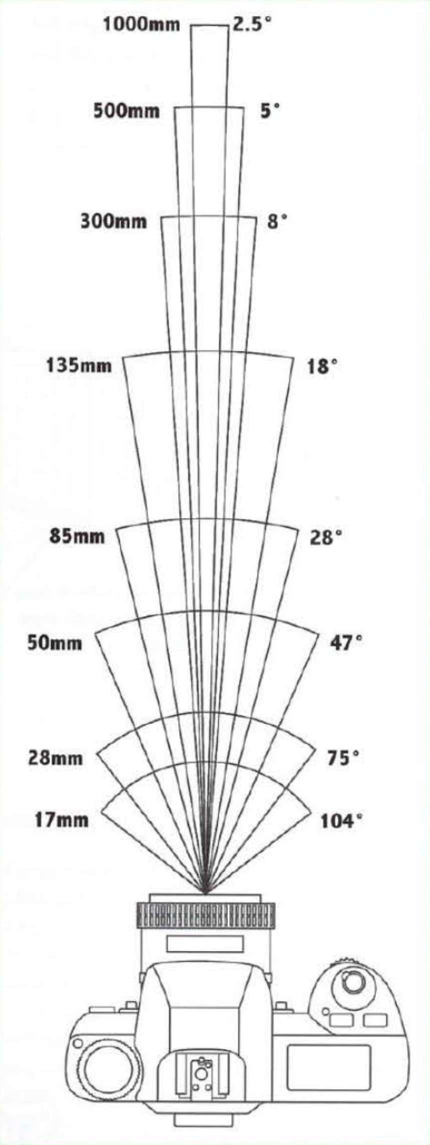


Field of View

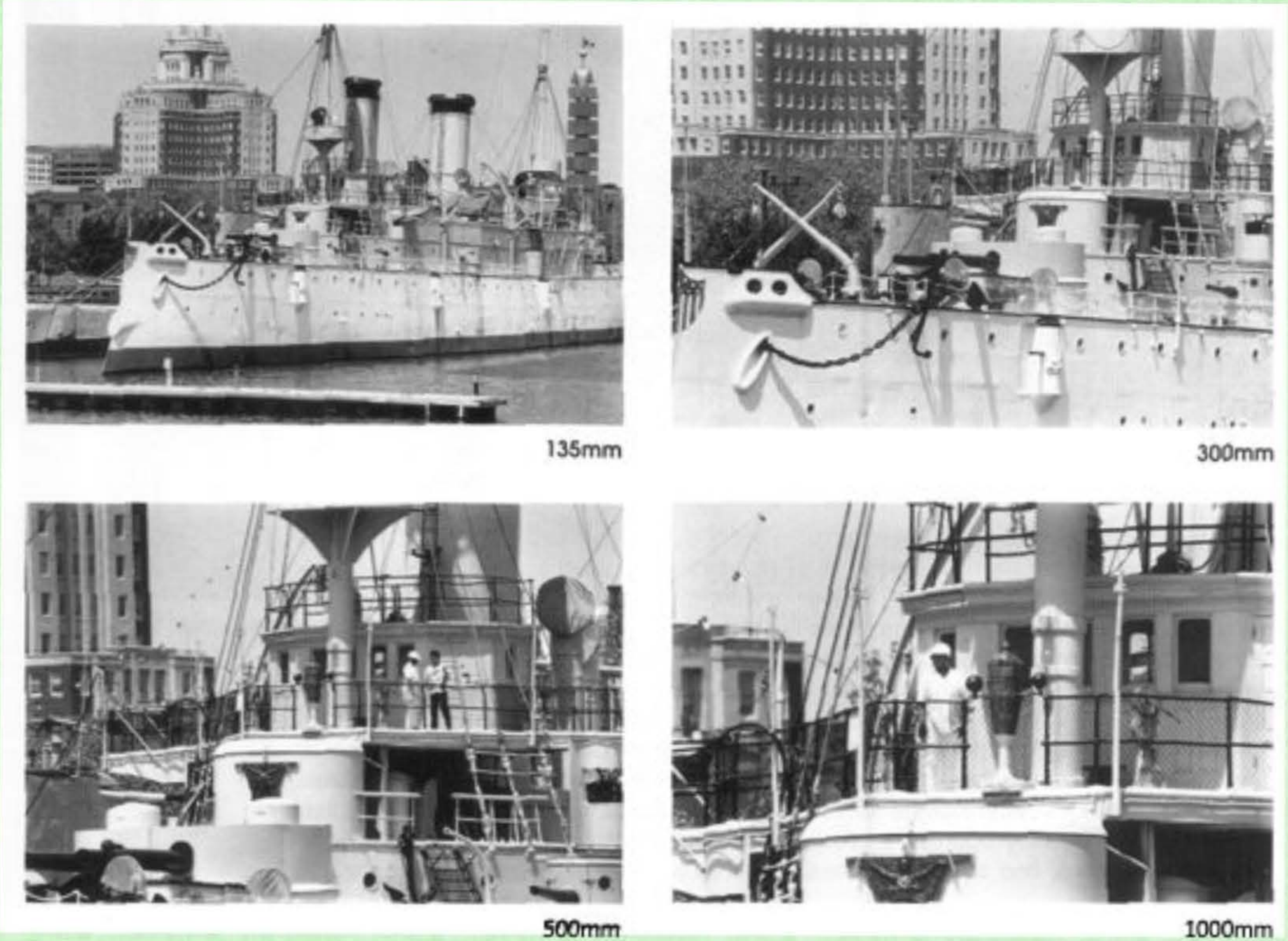
- Portion of the world visible to the sensor
- Zoom in/out by increasing/decreasing the focal length of the lens system
- Move the sensor out/in to adjust for the new focal length
- Since the sensor size doesn't change, the field of view shrinks/expands
- Get more/less pixels per feature (more/less detail)

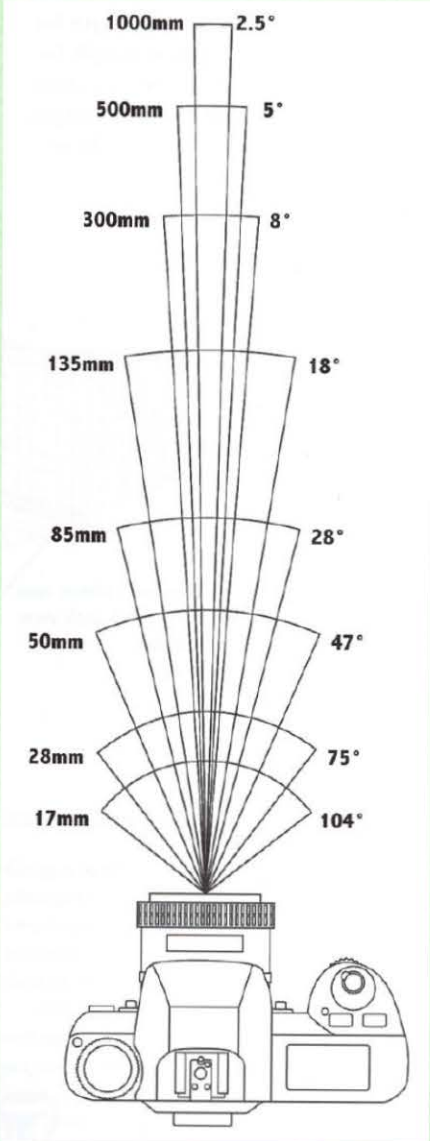


Zooming In Shrinks the Field of View



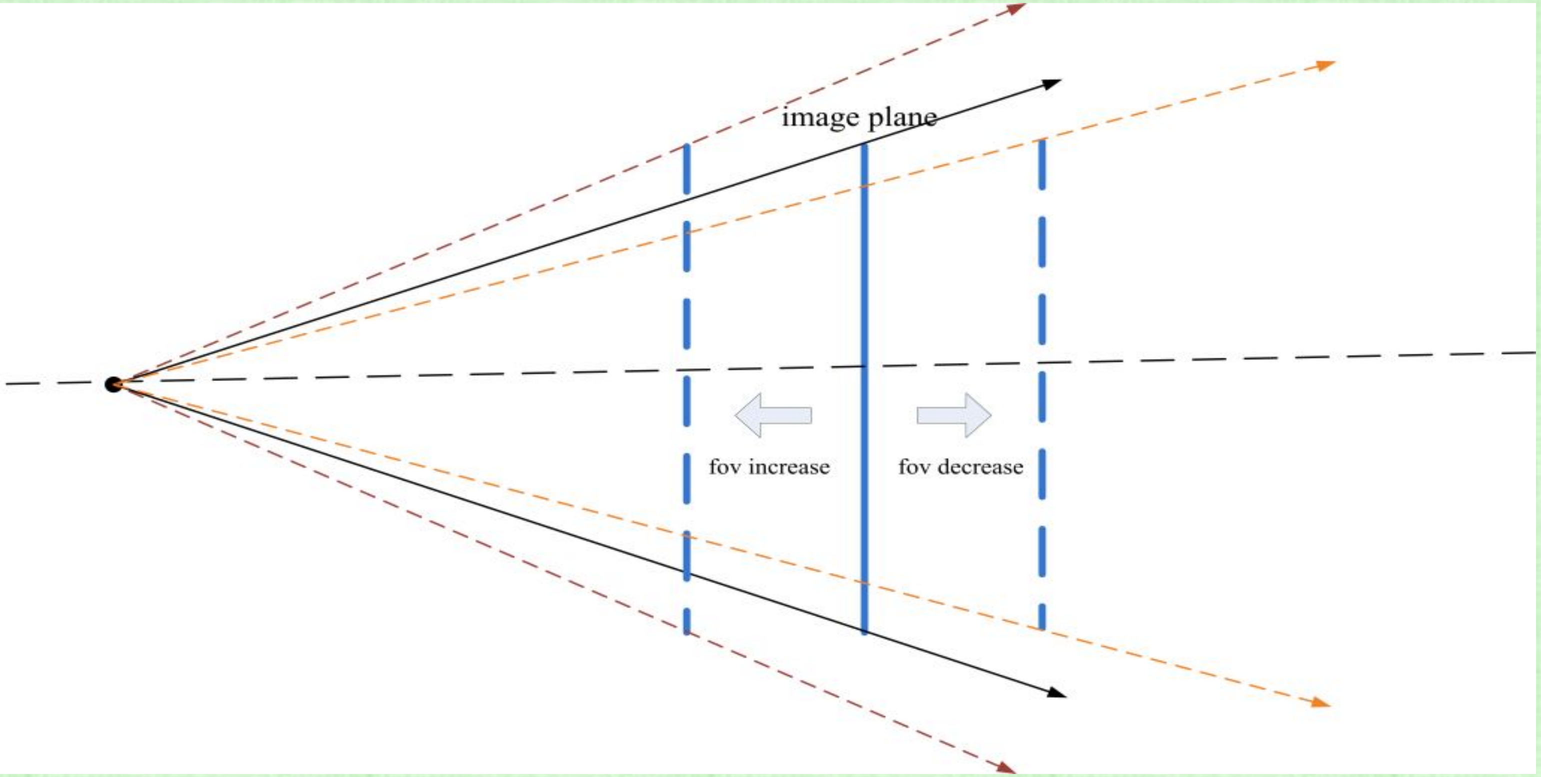
Zooming In Shrinks the Field of View





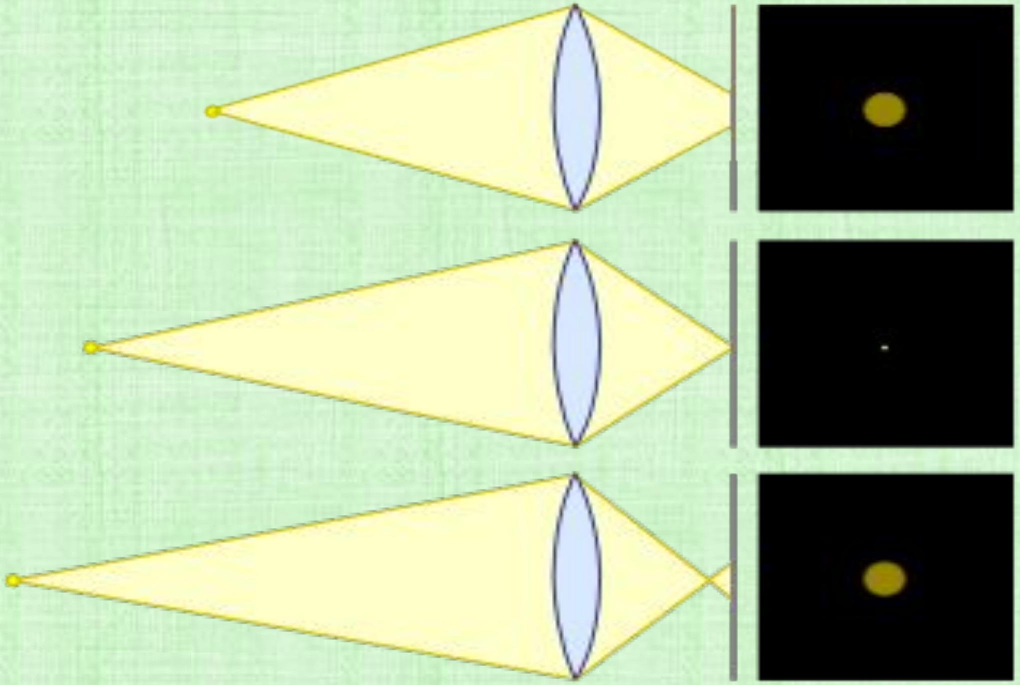
Ray Tracer Field of View (FOV)

- Ray tracer FOV is adjusted by changing the distance between the aperture and the image plane
- Alternatively, can change the sensor/film size (unlike in a real camera)
- Common mistake is to place the film plane too close to objects
    - Then, the desired FOV is (incorrectly) obtained by placing the aperture very close to the film plane, or by making a very large film plane (un-natural fish-eye lens effect)



Circle of Confusion

- An optical “spot”, caused by a cone of light rays not entirely re-focusing when imaging a point
- When the spot is about the size of a pixel (on the sensor), the object is “in focus”
- Objects at varying distances require varying sensor placement to keep the object “in focus”
  - <u>Depth of Field</u> - distance between the nearest and farthest objects in a scene that appear to be “in focus” (i.e., the range of distances where the circle of confusion is not too big)

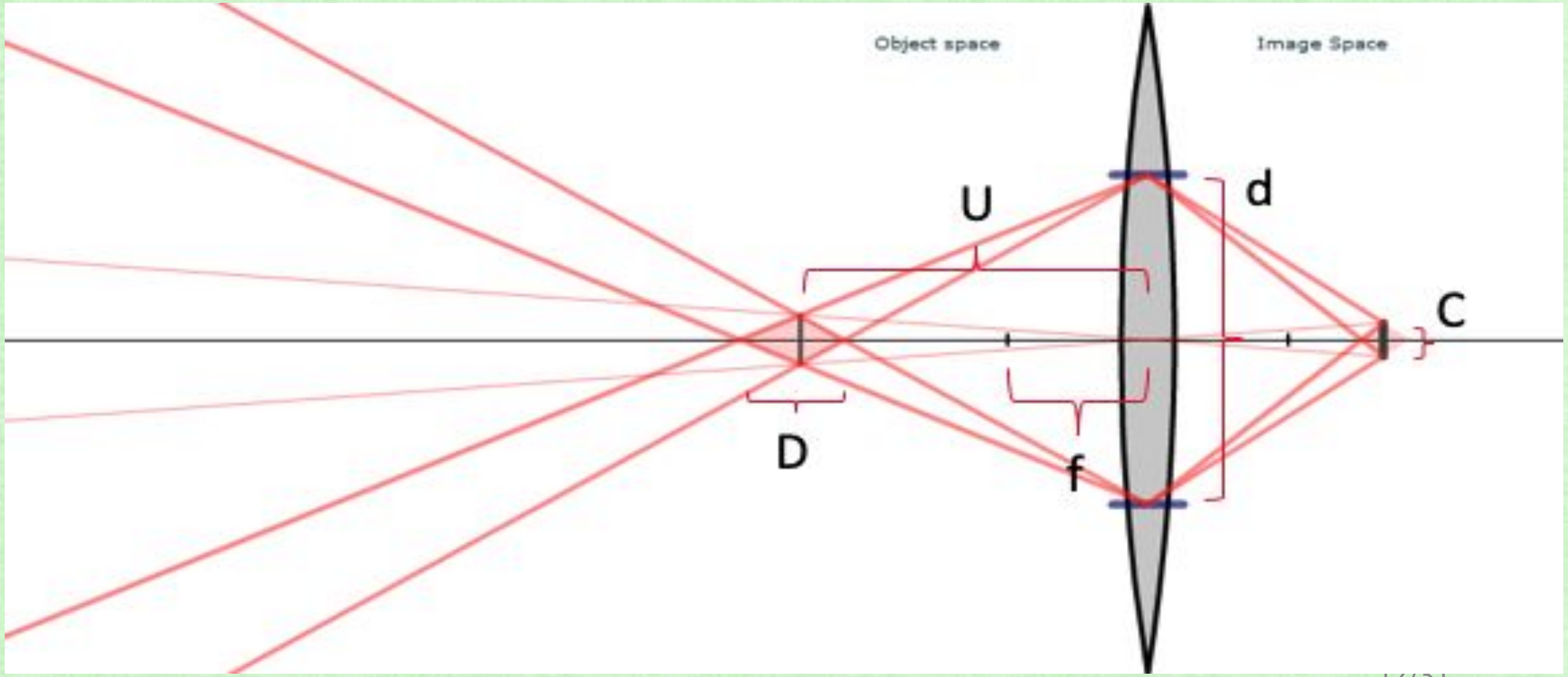


Depth of Field

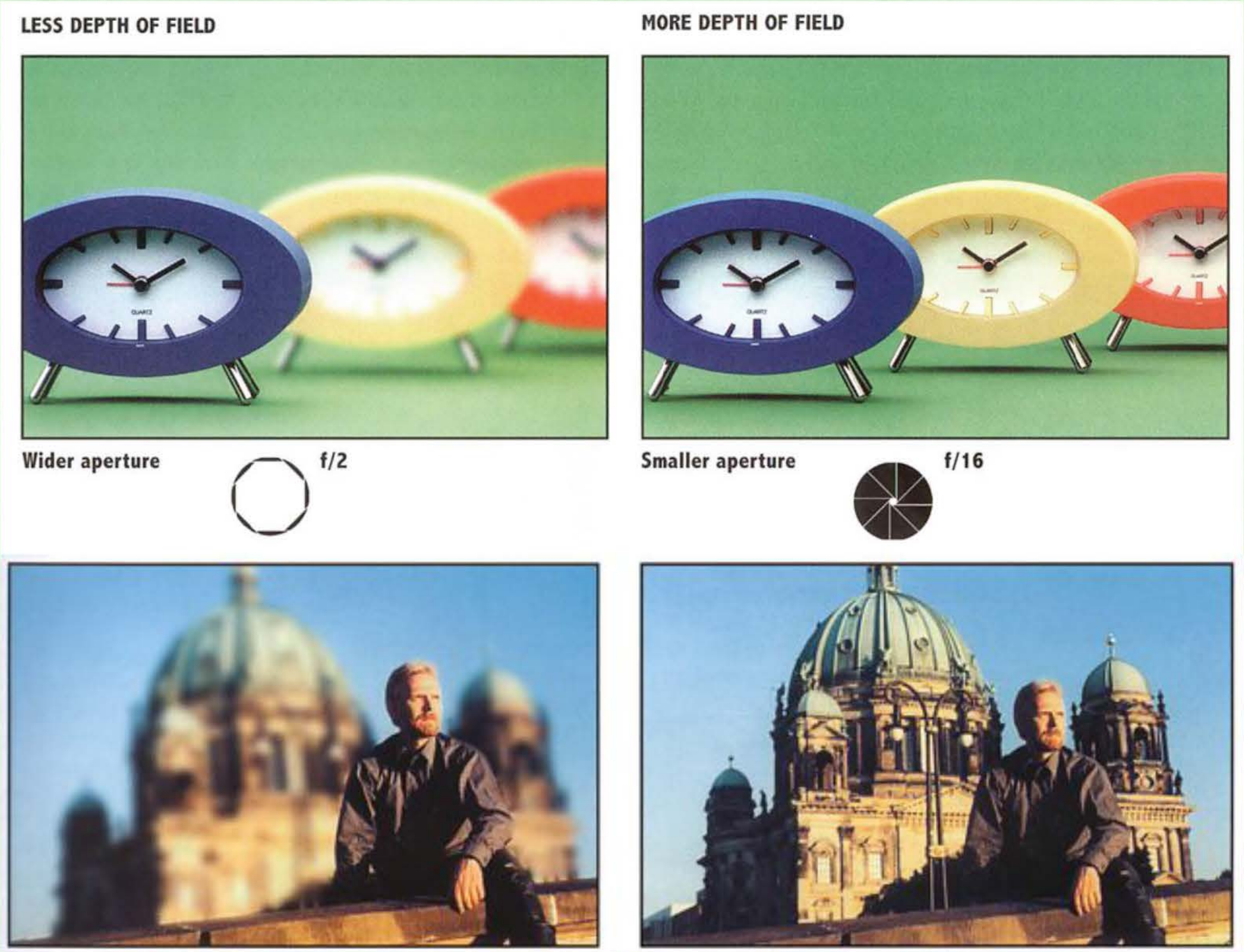
- A pinhole camera has infinite depth of field
- Making the aperture smaller increases the depth of field
  - However, that limits amount of light entering the camera (and the image is too dark/noisy)
  - Decreasing shutter speed lets in more light (but creates motion blur)
  - Also, a small aperture causes undesirable light diffraction

$$D \sim \frac{U^2 C}{df}$$

- d is aperture diameter
- U is object distance
- f is focal length
- C is allowable circle of confusion

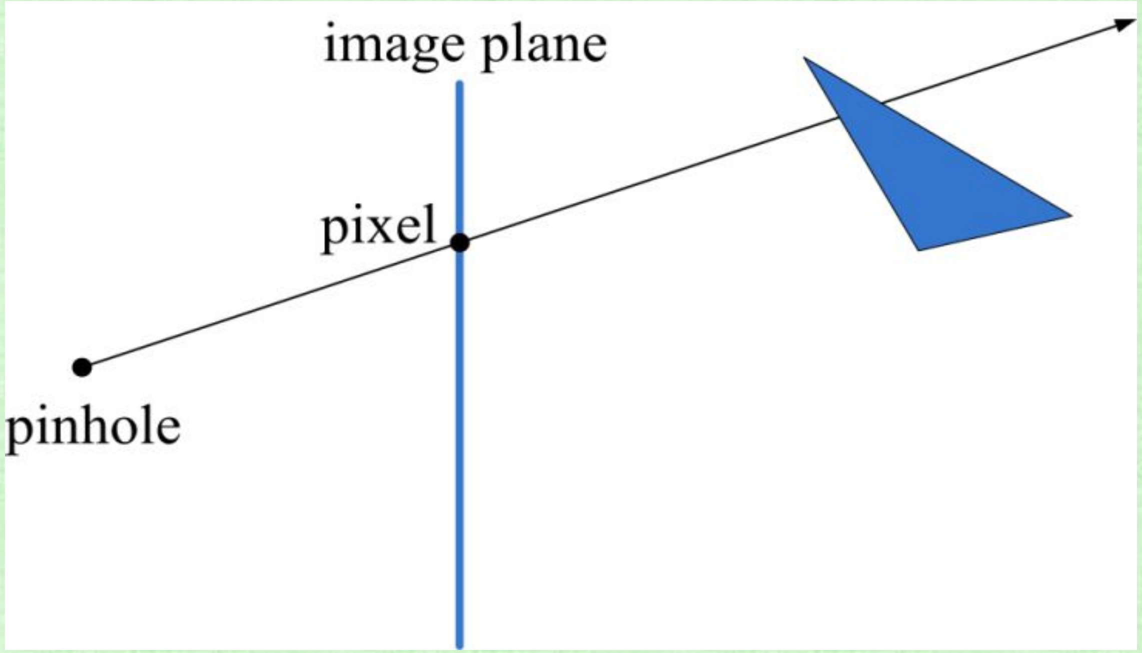


Aperture vs. Depth of Field

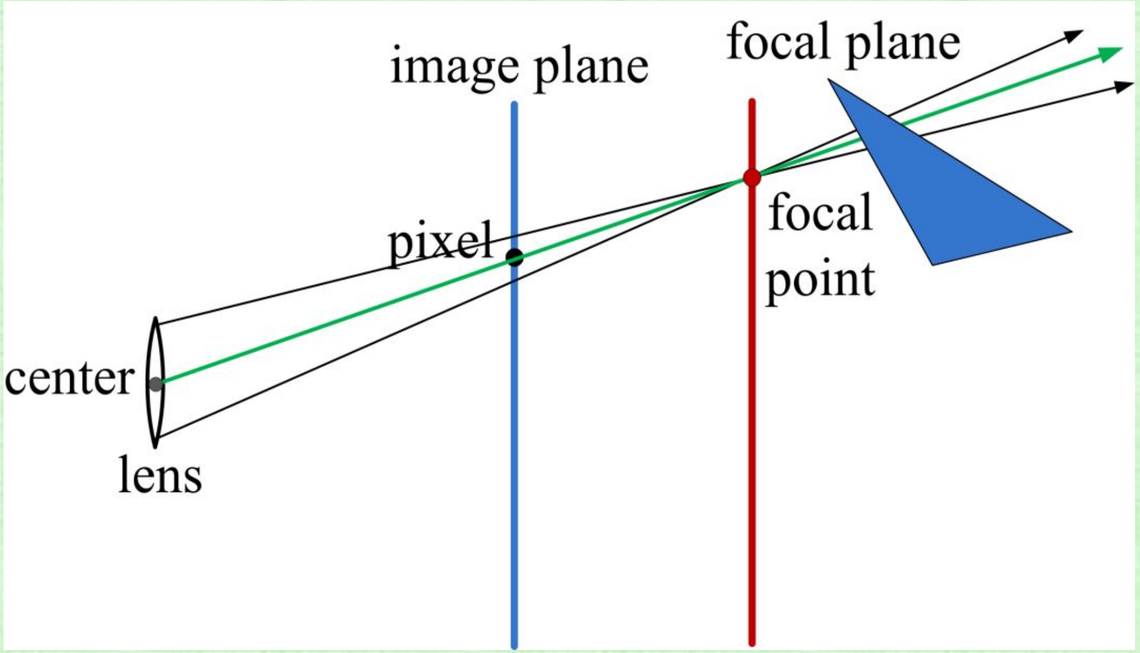


Depth of Field Ray Tracer

- Specify the focal plane (**red**) where objects are desired to be in focus
- For each pixel:
  - Calculate “focal point” by intersecting the standard ray (**green**) with the focal plane (**red**)
  - Replace the pinhole (aperture) with a circular region
  - Cast multiple rays from points sampled from the circular region through the focal point (average the results)
- Objects further away from the focal plane are more blurred



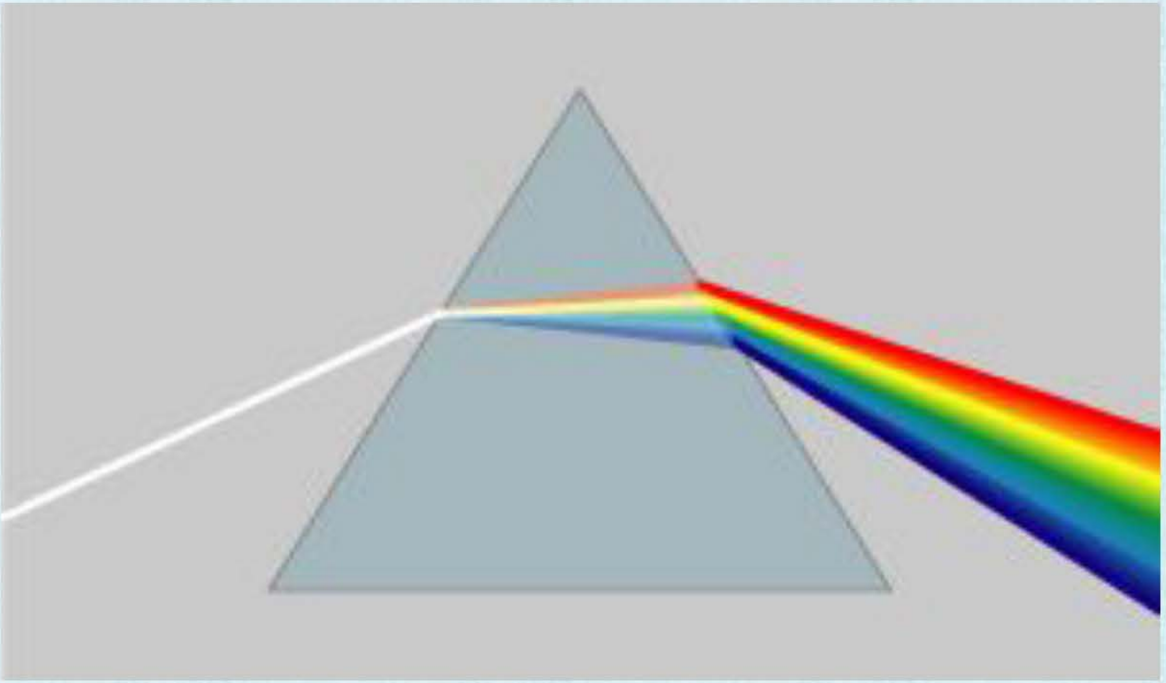
standard ray tracer



depth-of-field ray tracer

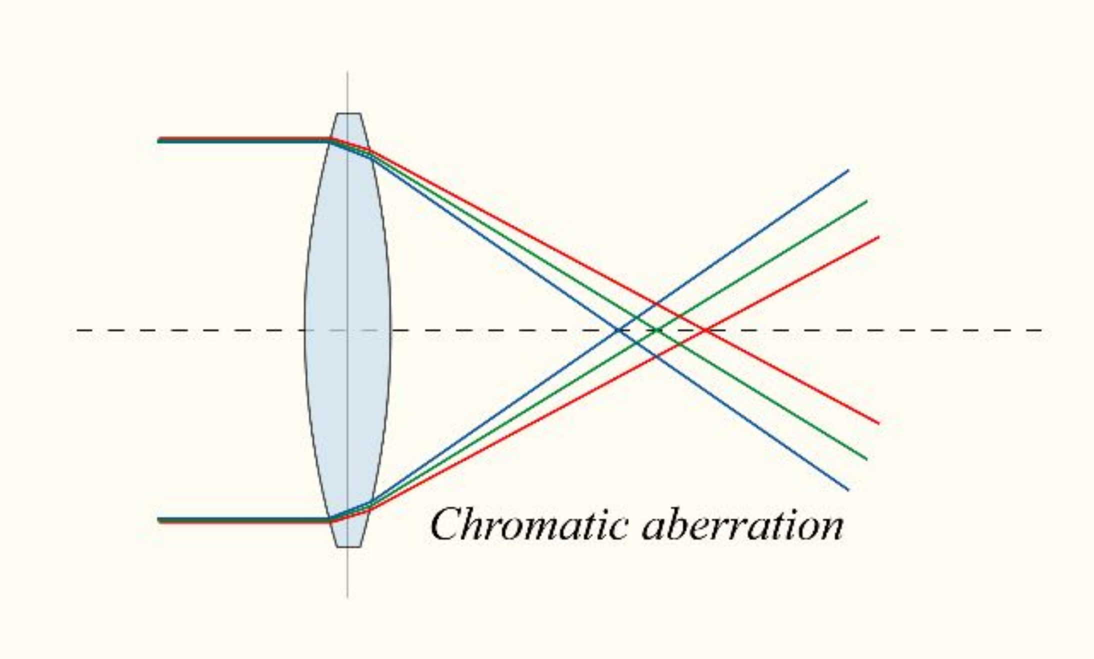
Dispersion

- Phase velocity (and thus index of refraction) depends on frequency/wavelength of the light
- Index of refraction: air $n_1(\lambda) \approx 1$, glass/water $n_2(\lambda) > 1$
- For most dispersive media (glass, water, etc.), n decreases towards 1 as wavelength increases
- That is, **blue light** ($\lambda \approx 400\text{nm}$) bends more than **red light** ($\lambda \approx 700\text{nm}$)
- Cauchy's approximation: $n(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4}$ with material parameters A, B, C



Chromatic Aberration

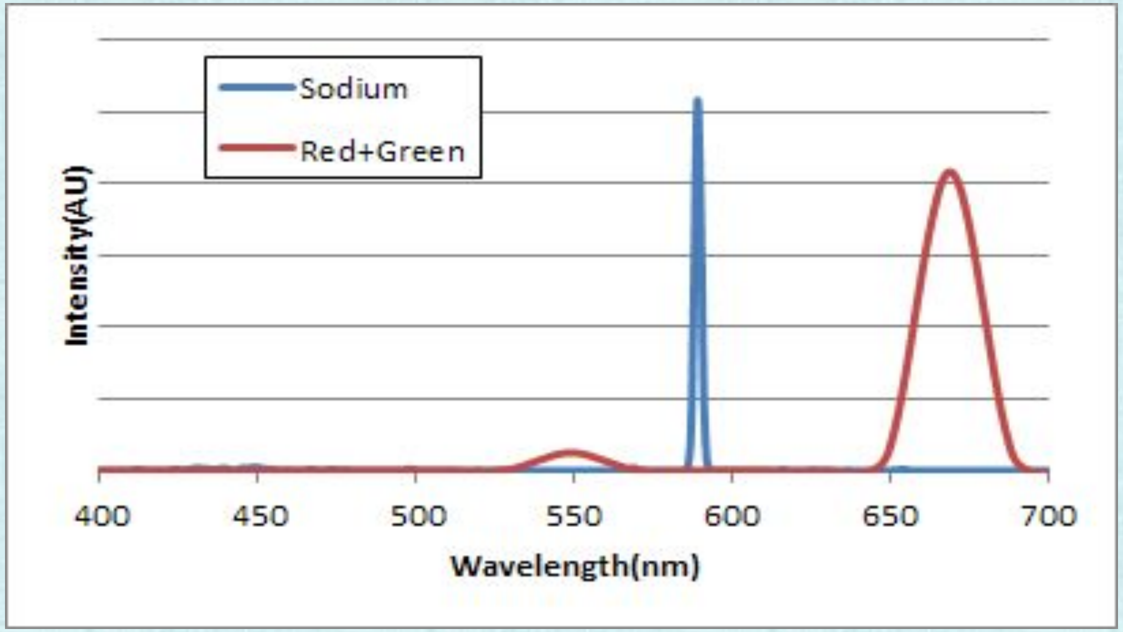
- Lens elements are characterized by the Abbe number which measures their dispersion
- Blue light bends more easily than red light, resulting in unequal focusing (and unwanted chromatic aberration)
- Focusing the blue light blurs the red light, and vice versa



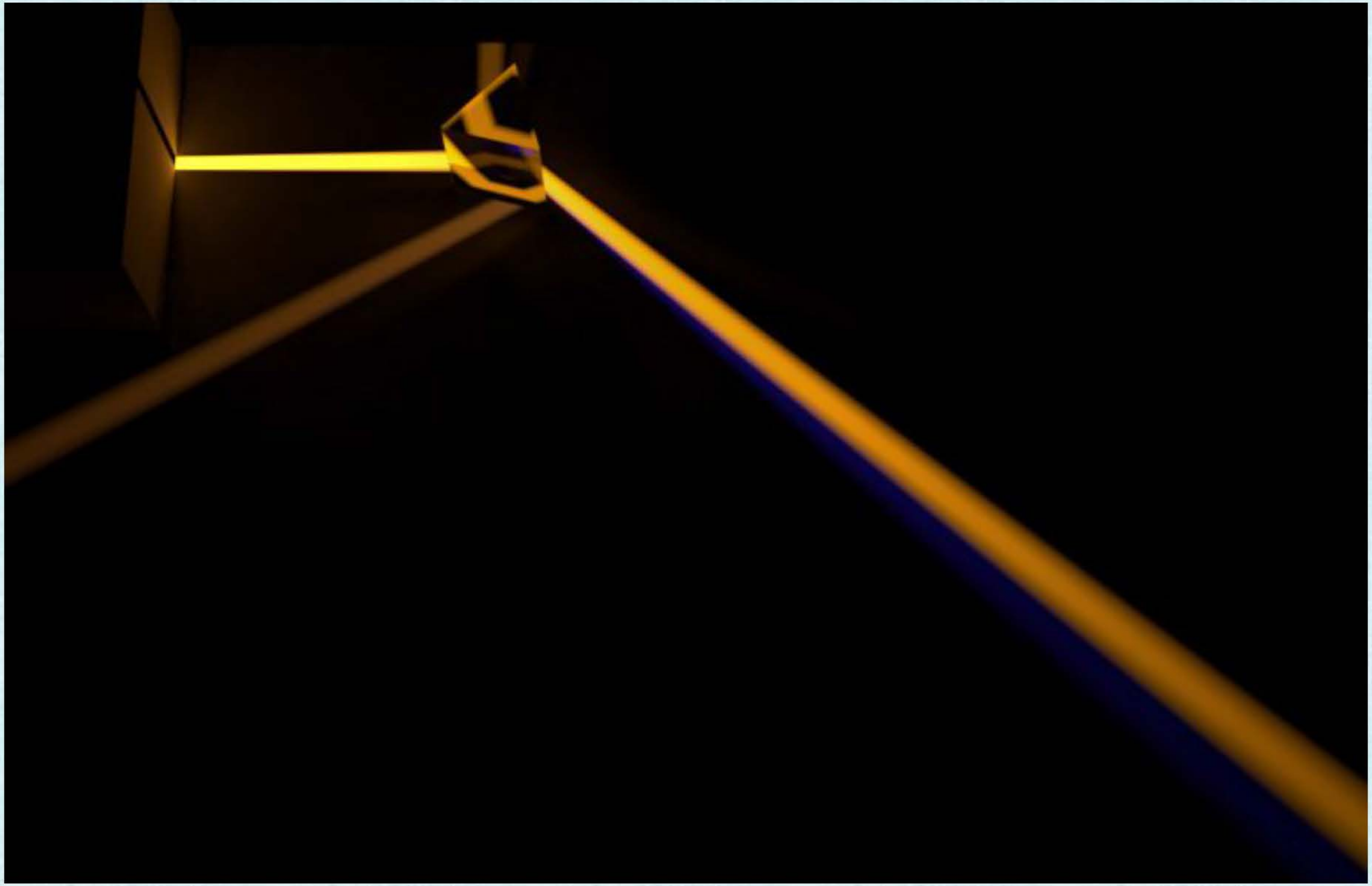
Spectral Power Distribution

- Light interaction with materials cannot (generally) be described using only RGB values
  - The same RGB values map to many different power distributions (as we have discussed)
- Need to describe light interaction with materials using full spectral power distributions

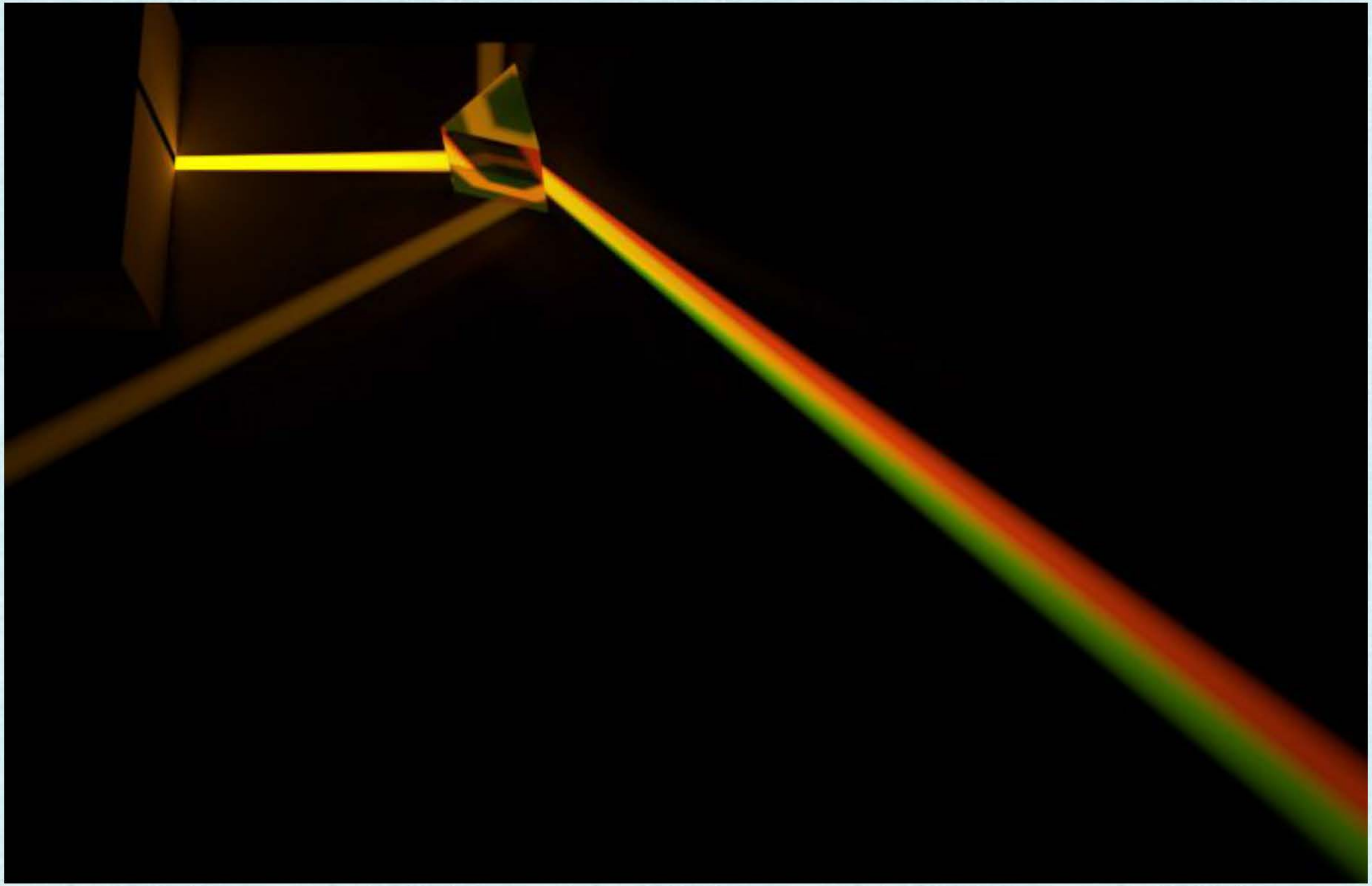
- Consider a prism dispersion setup with two lights, having **identical RGB values** but **different spectral power distributions**:



Sodium Light



Red/Green Light



Wavelength Light Map

- When tracing photons from a light source, importance sample the spectral power distribution (instead of R,G,B values) to obtain a λ for each photon
- Use the photon's λ and the reflectance/transmittance spectrum data at each intersection point to trace the photon throughout the scene
- Store incident power and wavelength of the photon in the photon map (λ-colored lights)

Gathering (from a Wavelength Light Map)

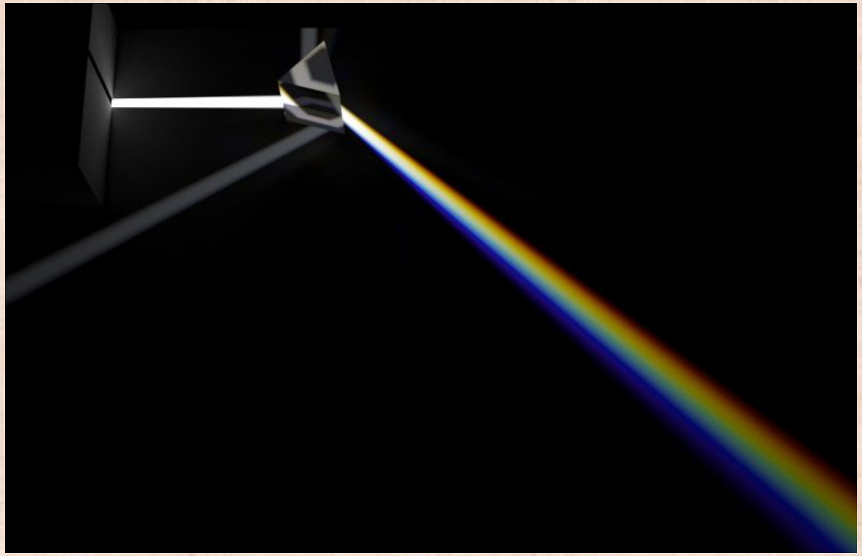
- When tracing rays from the camera, calculate the spectral power distribution at an intersection point using the nearby photon samples (which are now λ-colored) and the BRDF (as usual)
- Multiply/Integrate the calculated spectral power distribution by the tristimulus response functions to obtain R, G, B values (to store in the image, as usual)
- Requires significantly more samples in the photon map

Participating Media

- Light is scattered towards the camera/eye by dust, mist, etc.

Participating Media

- That's how one can see the light from the prism experiment (above), or a rainbow



Absorption

- When traveling through participating media, light can be absorbed (and converted into another form of non-visible energy, e.g. heat)
- As light moves a distance dx (along a ray), a fraction (<u>absorption coefficient</u> $\sigma_a(x)$) of the radiance $L(x,\omega)$ given by $\sigma_a(x)L(x,\omega)$ is absorbed: $dL(x,\omega) = -\sigma_a(x)L(x,\omega)dx$

Out-Scattering

- When traveling through participating media, light can be scattered off in various directions
- The atmosphere scatters blue light much more readily than red light, which makes the sunset red (the light travels through a lot of atmosphere to reach your eyes)
- As light moves a distance dx (along a ray), a fraction (scattering coefficient $\sigma_S(x)$) of the radiance $L(x,\omega)$ given by $\sigma_S(x)L(x,\omega)$ is scattered off in another direction (and no longer travels along the ray): $\mathrm{d}L(x,\omega) = -\sigma_S(x)L(x,\omega)\mathrm{d}x$

Total Attenuation

- The total fraction of light absorbed or out-scattered per unit length is: $c(x) = \sigma_a(x) + \sigma_s(x)$
- As light moves a distance dx (along a ray), a fraction of the radiance is attenuated (and no longer travels along the ray): $dL(x, \omega) = -c(x)L(x, \omega)dx$
- This affects all rays, e.g. both primary rays from the camera pixels and secondary shadow rays (as we saw in Beer's law)

Recall: Beer’s Law

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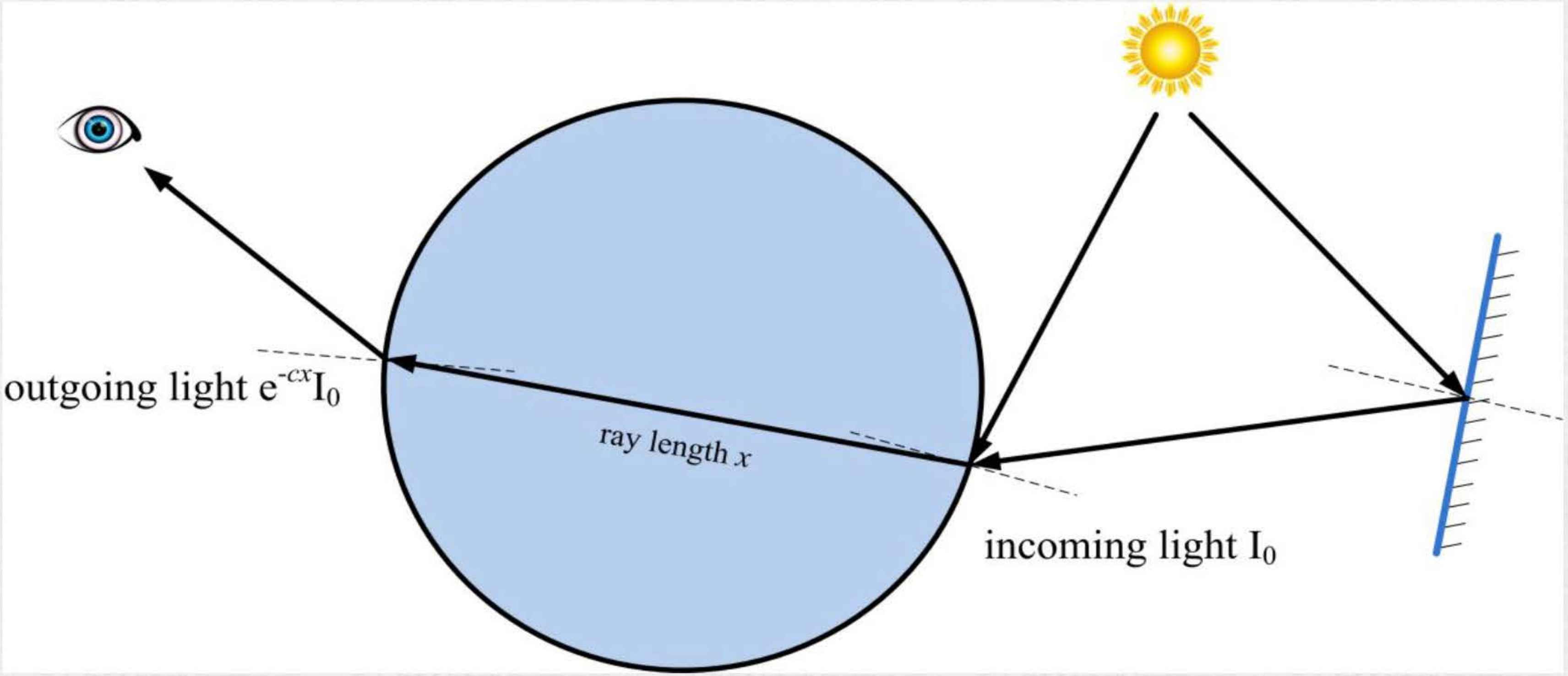
Recall: Beer's Law

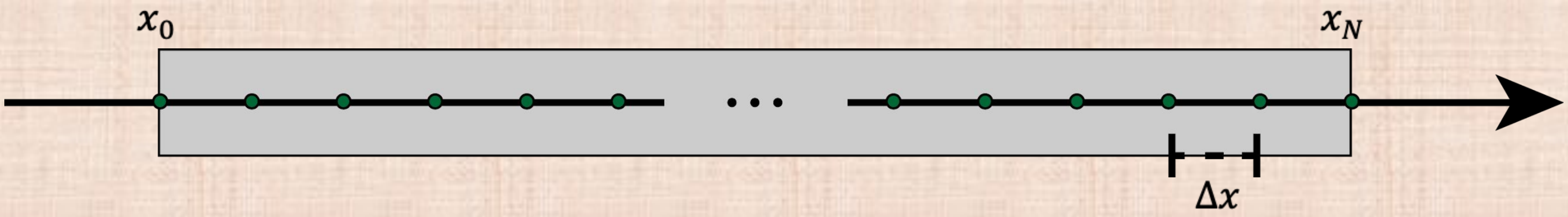
- If the media is homogeneous, attenuation along a ray can be described by Beer's Law
- Light with intensity I is attenuated over a distance x via the Ordinary Differential Equation (ODE): $\frac{dI}{dx} = -cI$ where c is the coefficient of attenuation
- The exact solution to this ODE is $I(x) = I_o e^{-cx}$ where I_o is the original unattenuated amount of light



Heterogeneous Beer's Law

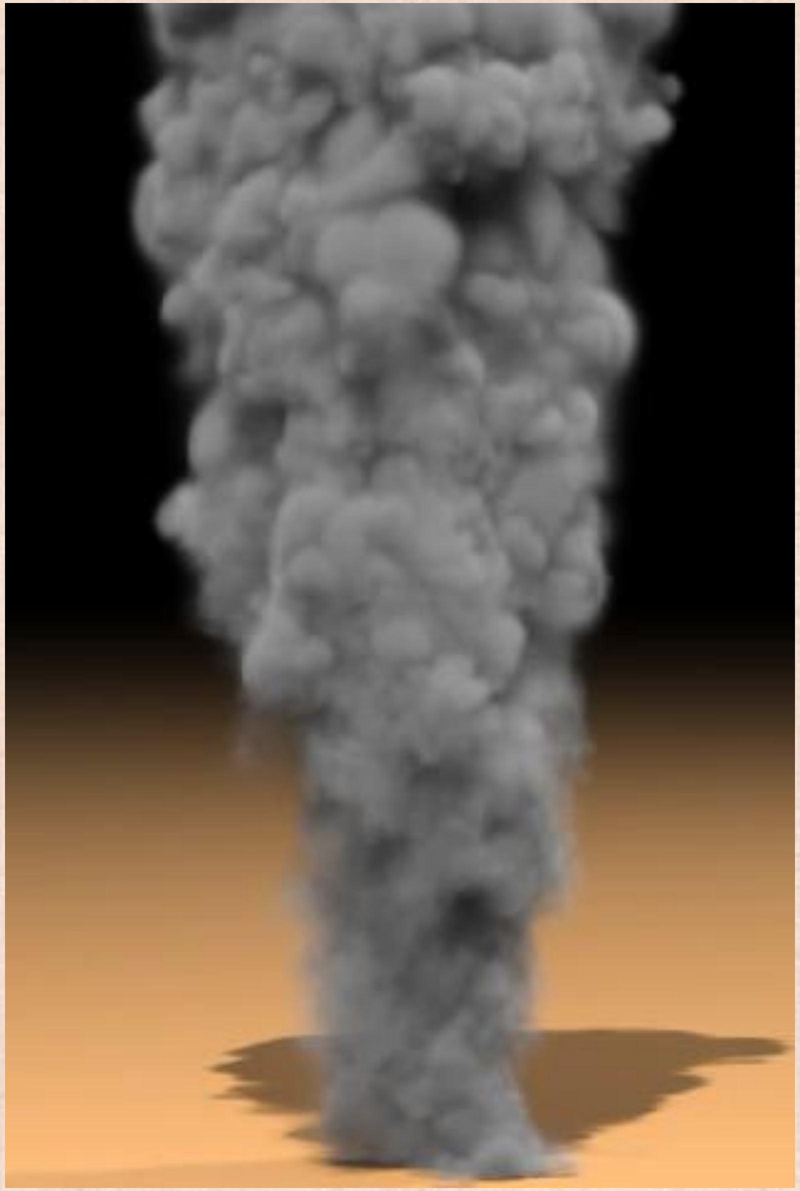
- For non-homogeneous media, the attenuation varies spatially (based on the concentration of the inhomogeneities)
- Discretize the ray into N smaller segments, and treat the attenuation as constant over each segment (converges as $N \to \infty$)
- Given $\Delta x = (x_N - x_0)/N$ and segment endpoints $x_i = x_0 + i\Delta x$ for $i \in [0, N]$, the total attenuation along the ray is:

$$I_o e^{-c\left(\frac{x_0+x_1}{2}\right)\Delta x} e^{-c\left(\frac{x_1+x_2}{2}\right)\Delta x} \cdots e^{-c\left(\frac{x_{N-1}+x_N}{2}\right)\Delta x}$$



Shadow Ray Attenuation

- Shadow rays cast from the ground plane to the light source have their light attenuated by the smoke volume
- Thus, smoke casts a shadow onto the ground plane
- The shadow is not completely black, since some light makes it through the smoke to the ground plane



Camera Ray Attenuation

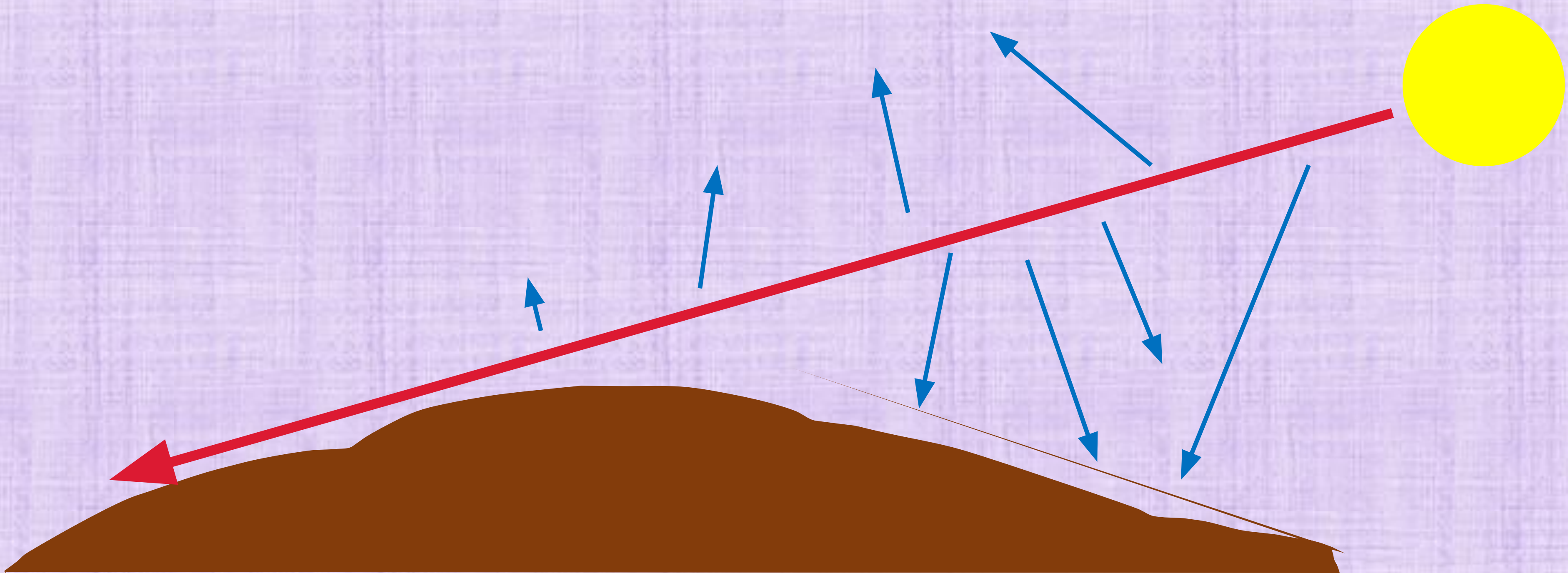
- Rays from the camera intersect objects, and a color is calculated (as usual, e.g. blue here)
- That color is attenuated by the participating media intersecting the ray
- The object color (blue here) could be partially or completely attenuated
- Complete attenuation would cause black pixels if the smoke itself had no color (which we discuss next)

In-Scattering

- At each point along a ray, participating media can out-scatter light traveling in other directions such that it is in-scattered into the ray direction
  - This in-scattering <u>increases</u> the radiance in the direction of the ray
  - The sky appears blue because atmospheric particles scatter blue light in every direction, and thus scatter some towards our eyes (otherwise, the sky would appear black)

In-Scattering

- The sky appears blue because atmospheric particles scatter blue light in every direction, and thus scatter some towards our eyes (otherwise, the sky would appear black)
- Recall: The atmosphere scatters blue light much more readily than red light, which makes the sunset red (the light travels through a lot of atmosphere to reach your eyes)



In-Scattering

- Add the radiance contribution from participating media in-scattering to the color of the rays from cameras to objects (as well as to shadow rays)
  - Without this in-scattering, complete attenuation of object color by participating media would result in a black pixel
  - Instead, in-scattered light gives participating media its own appearance (clouds, smoke, etc.)
  - The darker underside of a cloud has less light available to in-scatter, because the top of the cloud absorbs much of the light (from the sun)

Volumetric Light Map

- At each of many sample points along a ray, cast a shadow ray to the light source to compute how much light is available for in-scattering
- These shadow rays are expensive to compute, since they use inhomogeneous Beer's law to attenuate light with the participating media along the ray

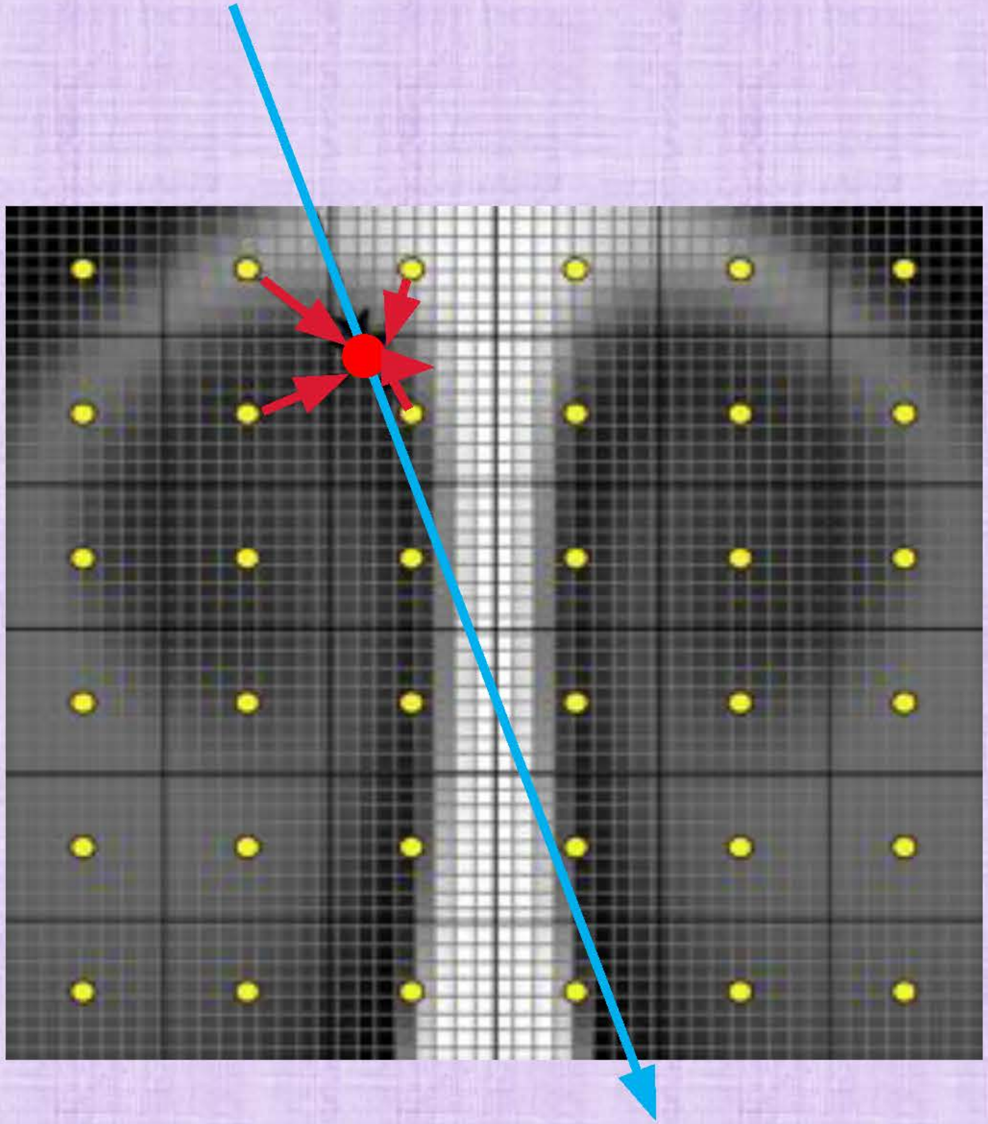
- For efficiency, precompute a volumetric light map:
  - Enclose the participating media with a uniform grid (or octree, or other spatial partition)
  - At each grid point, cast a shadow ray to the light source to compute how much light is available for in-scattering

- Later, when tracing camera/shadow rays, the volumetric light map is used to compute how much light is available for in-scattering (along each segment of any ray passing through it)
- Add in-scattered light to the total light at each point, noting that it too gets attenuated by subsequent segments along the discretized ray
  - Thus, this calculation needs to be done from object to camera

In-Scattering (with a Volumetric Light Map)

- At the midpoint of each segment of the discretized ray, interpolate available radiance $L(x, \omega)$ from the grid nodes of the volumetric light map
- Also, compute the incoming direction ω from the light source to the interpolation point (a separate light map is required for each light source)
- A <u>phase function</u> $p(\omega, \omega')$ gives the probability that incoming light from direction ω is scattered into direction ω' of the camera ray (or shadow ray)
- Thus, the radiance at this point x scattered into the ray direction is $p(\omega, \omega')\sigma_s(x)L(x, \omega)$
  - σ_s is the probability of <u>any</u> scattering in <u>any</u> direction, and p selects the subset of these that scatter into the ray direction

- Finally, the entire in-scattered radiance from a segment of length Δx is approximated by $p(\omega, \omega')\sigma_s(x)L(x, \omega)\Delta x$



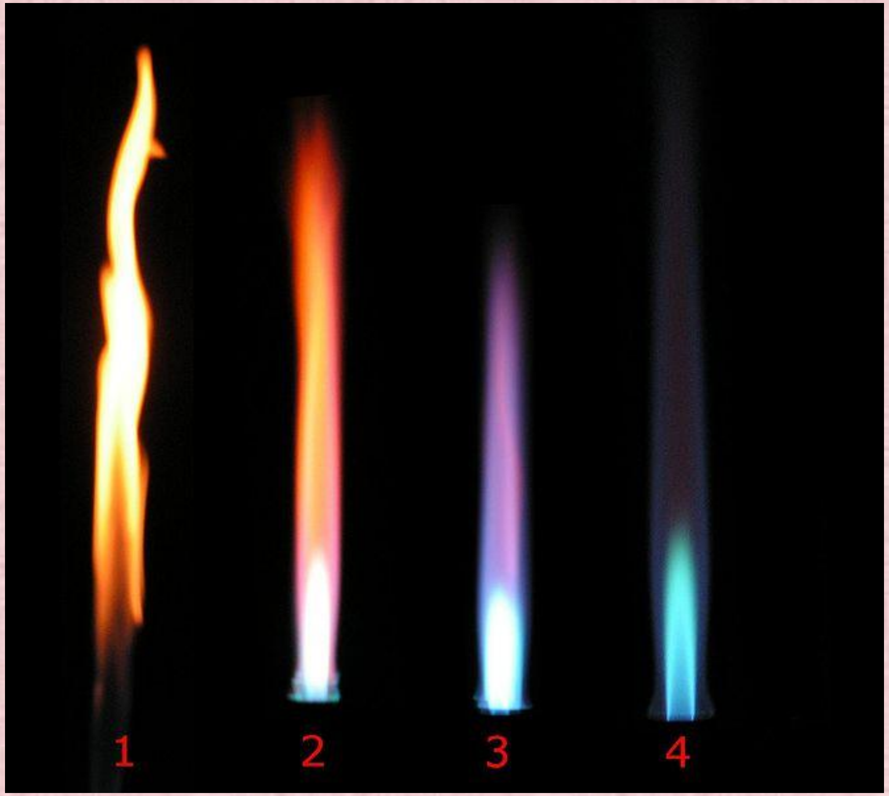
Phase Functions

- Everything goes somewhere: $\int_{\text{sphere}} p(\omega, \omega')\mathrm{d}\omega' = 1$
- Phase angle: $\cos\theta = \omega \cdot \omega'$

1. Isotropic: $p(\cos\theta) = \frac{1}{4\pi}$
2. Rayleigh: $p(\cos\theta) = \frac{3}{8}(1 + \cos^2\theta)$
    - Models scattering due to particles smaller than the wavelength of light, such as in the atmosphere
3. Henyey-Greenstein: $p(\cos\theta) = \frac{\frac{1}{4\pi}(1-g^2)}{(1+g^2-2g\cos\theta)^{1.5}}$
    - g can be treated as a tunable parameter, which allows one to adjust the appearance of a medium
    - $g = 0$ results in the isotropic phase function

Volumetric Emission

- Some participating media emit light (e.g. hot smoke and fire)
  - Hot carbon soot emits blackbody radiation based on temperature
  - Electrons emit light energy as they fall from higher energy excited states to lower energy states
- This light information can be added as a separate volumetric light map
- This volumetric emission is in <u>every</u> direction



Volumetric Emission

- Adding volumetric emission to the light map gives the desired orange/blue/etc. colors
- But only adding it to the light map doesn't allow it to cast shadows and light the scene
- To do this, treat this region as a volume light
  - Model volume light as many small point lights (similar to an area light)
  - These point lights are used just like every other light in the scene in regards to shadow rays, creating photon maps, etc.
  - And participate in the creation of the volumetric light map for the self shadowing of the participating media