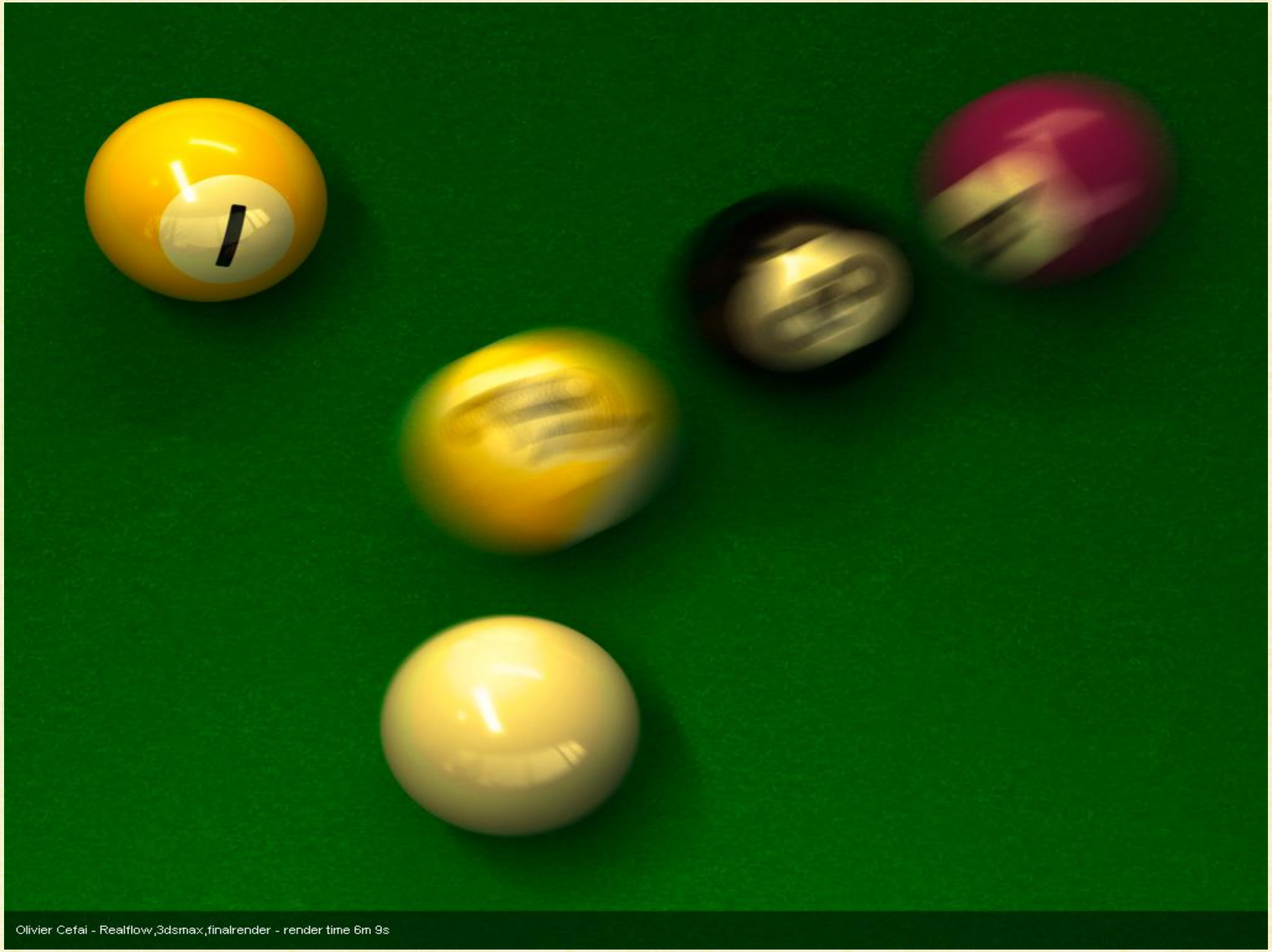
Advanced Rendering

Motion Blur


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

Shutter Speed

- The <u>shutter</u> limits the amount of light that hits the sensor
- While the shutter is open, moving objects create streaks on the sensor
- A faster shutter prevents motion blur, but limits the amount of entering light (often making the image too dark)

Ray Tracing Animated Geometry

- Animate objects during a time interval $[T_0, T_1]$, when the shutter is open
  - 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 $\alpha \in [0,1]$
  - Use $F(t_{ray})$ to place the object into its time t_{ray} location
  - Trace the ray to get a color
- Works significantly better when using many rays per pixel (to combat temporal aliasing)

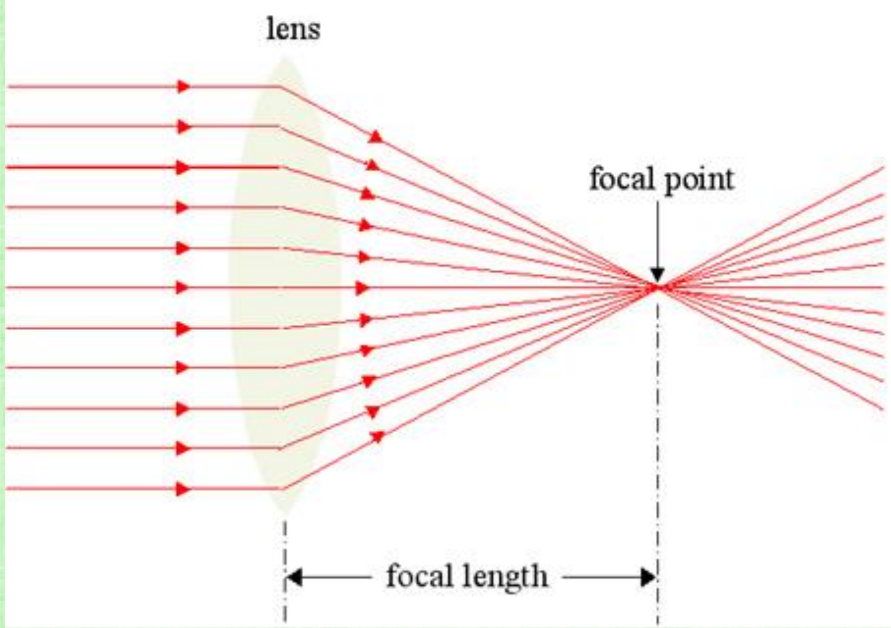
Fast shutter speed

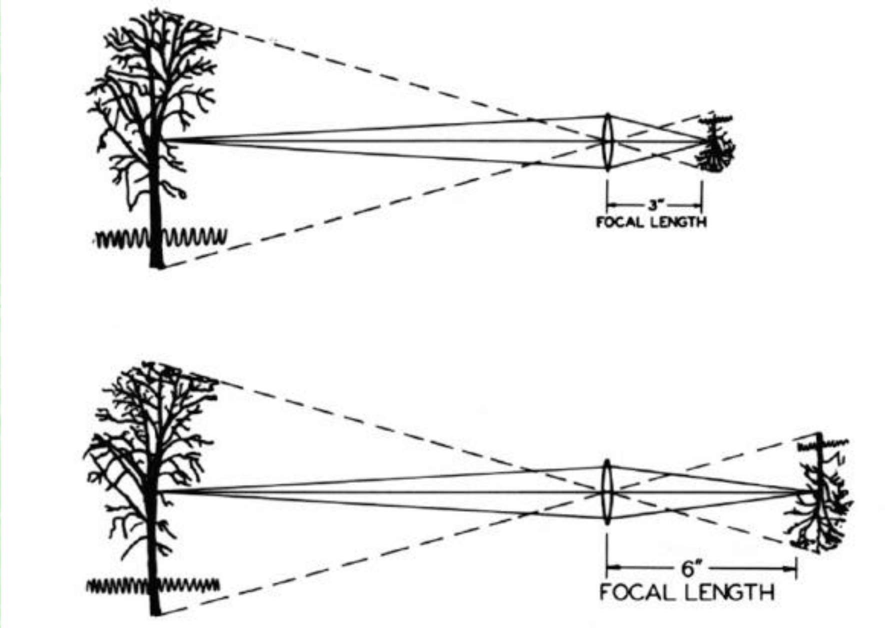
Slow shutter speed

Depth of Field

Focal Length

- The lens (or lens system) has to bring diverging rays back into focus
- The focal length is defined as the distance required to bring parallel rays into focus
    - Individual elements of a lens system can be adjusted to change the overall focal length, but each individual lens has a fixed focal length
- A stronger lens has a shorter focal length (bending rays more than a weaker lens)
- Farther away objects have more parallel diverging rays, so focusing them requires the image plane to be close to the focal point



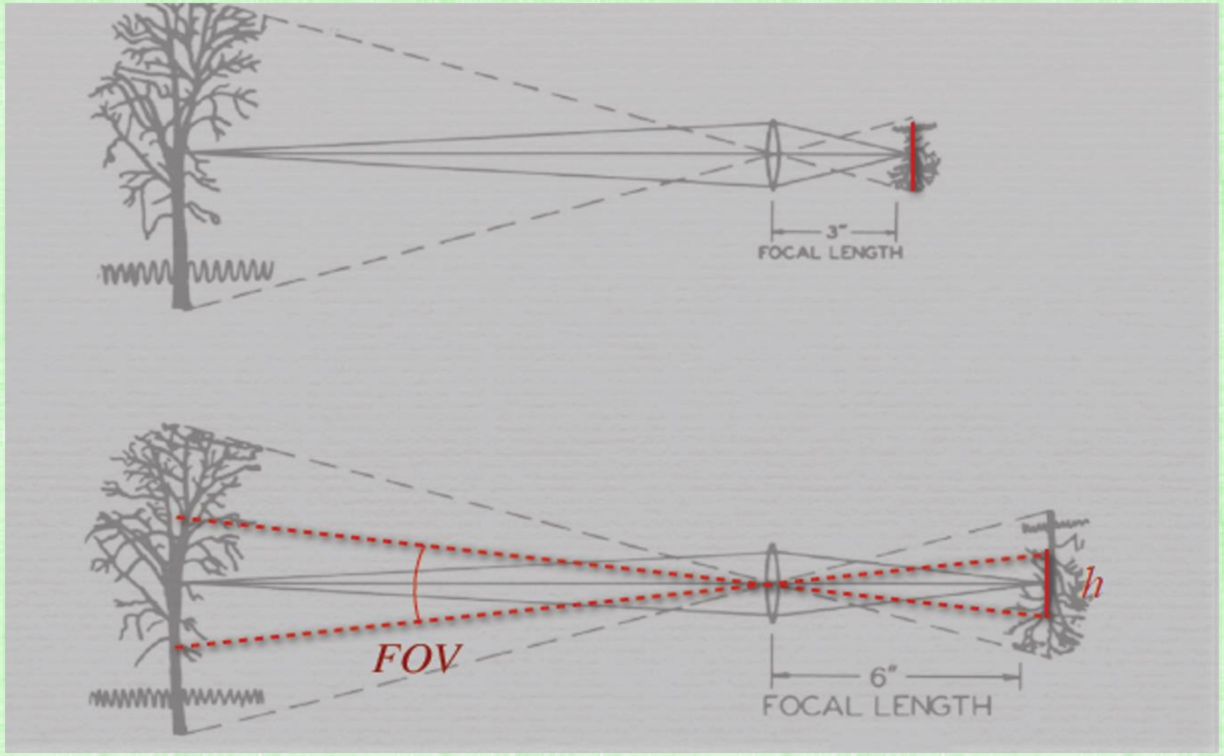


stronger lens

weaker lens

Field of View

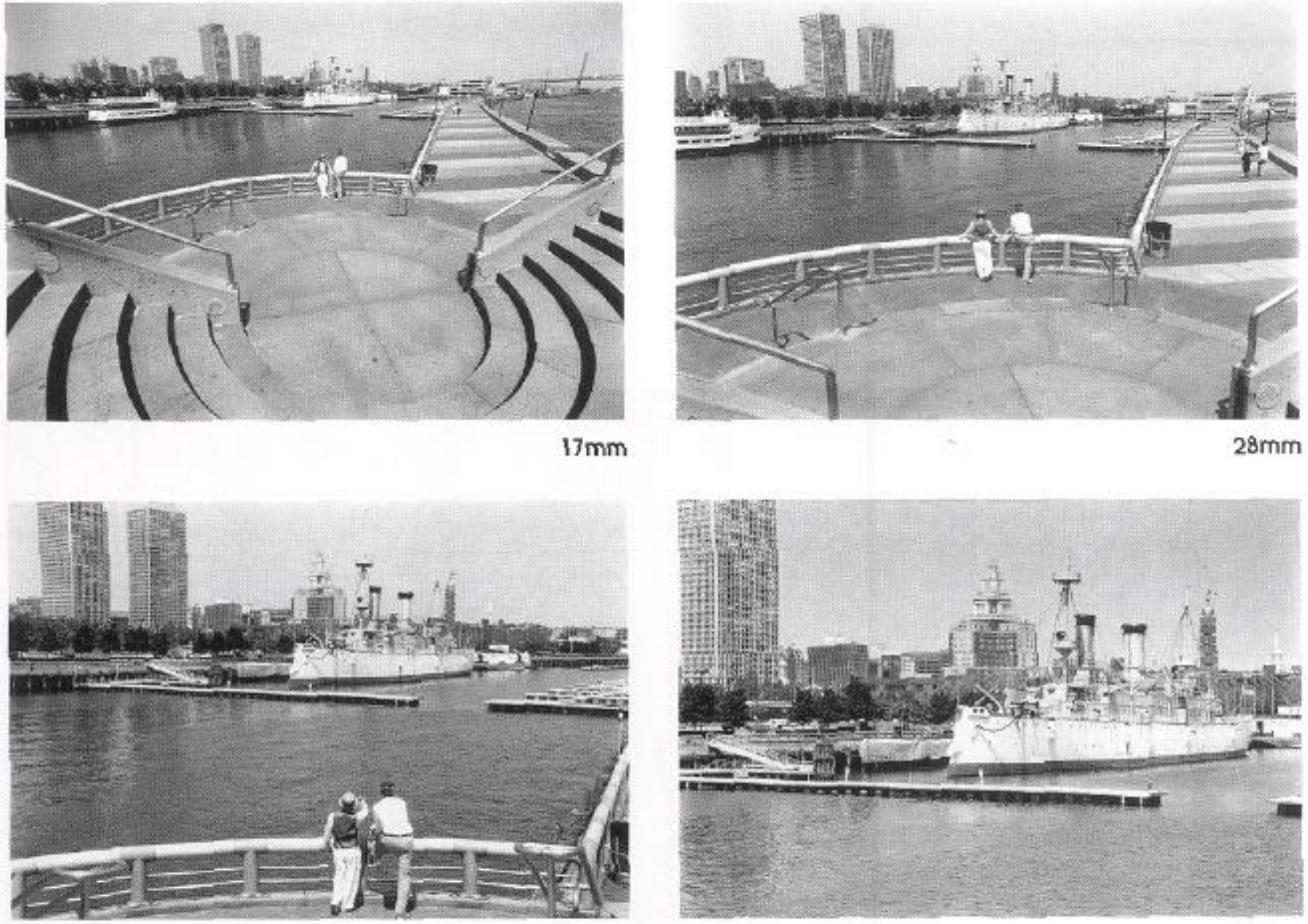
- Portion of the world visible to the sensor
- Zoom out/in by decreasing/increasing the focal length of a lens system
- Move the sensor in/out to adjust for the new focal length
- Since the sensor size doesn't change, the field of view expands/shrinks
- Get less/more pixels per feature, i.e. less/more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



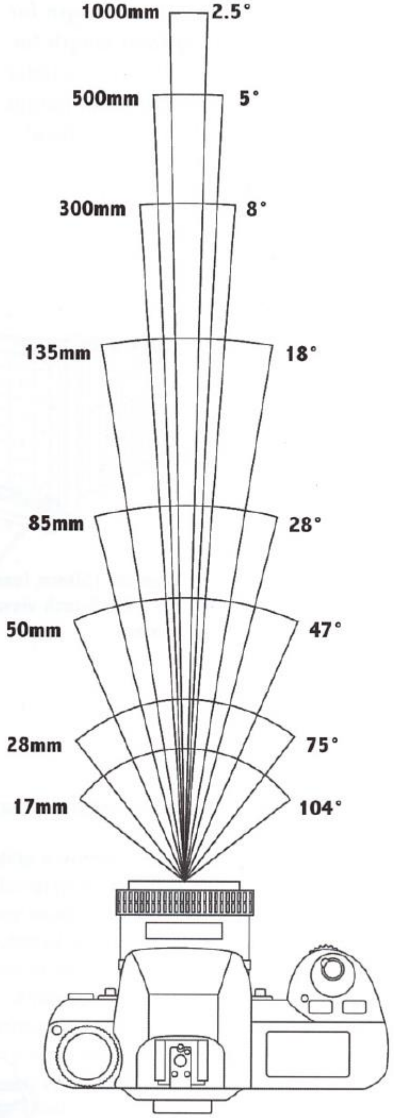
zoom out (decrease the distance)

zoom in (increase the distance)

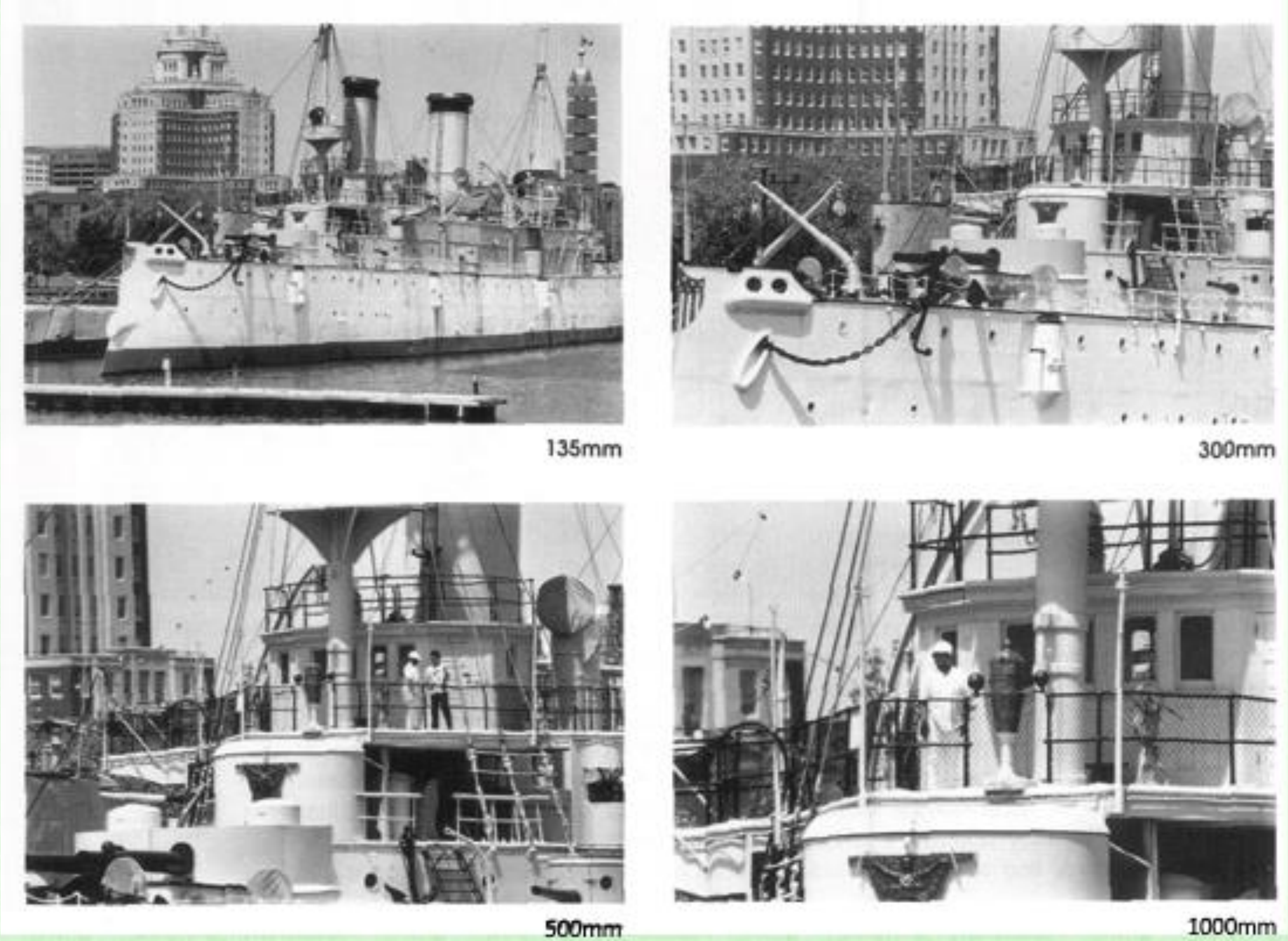
Zooming In shrinks the Field of View

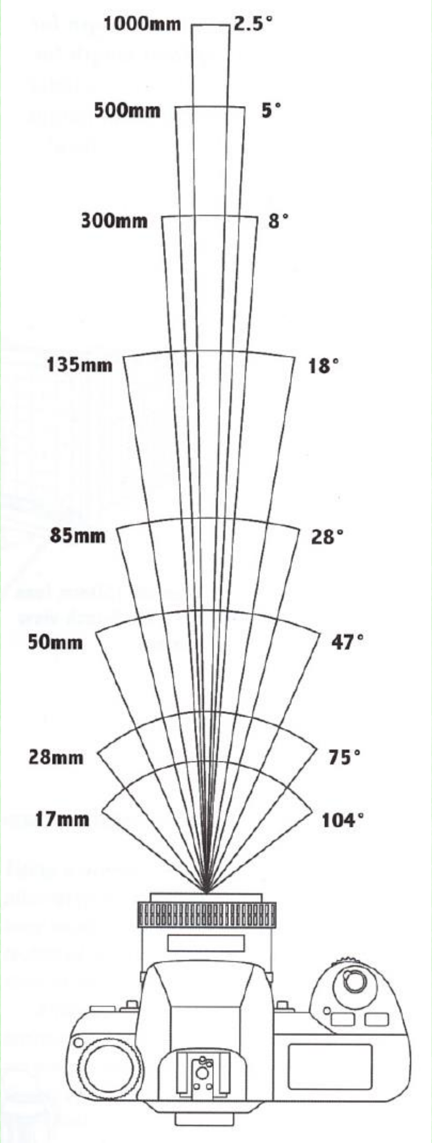


17mm 28mm 50mm 85mm



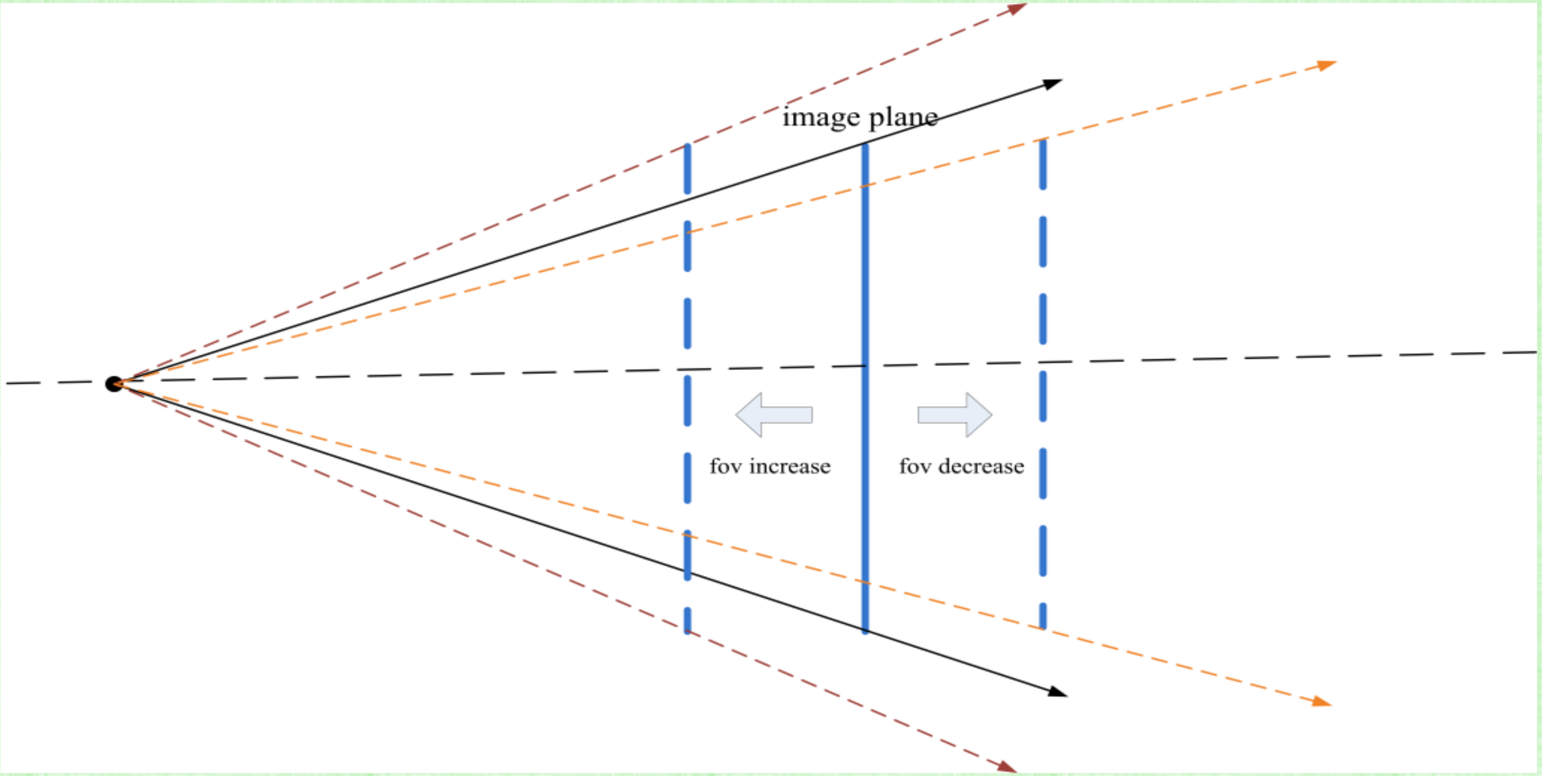
Zooming In shrinks the Field of View





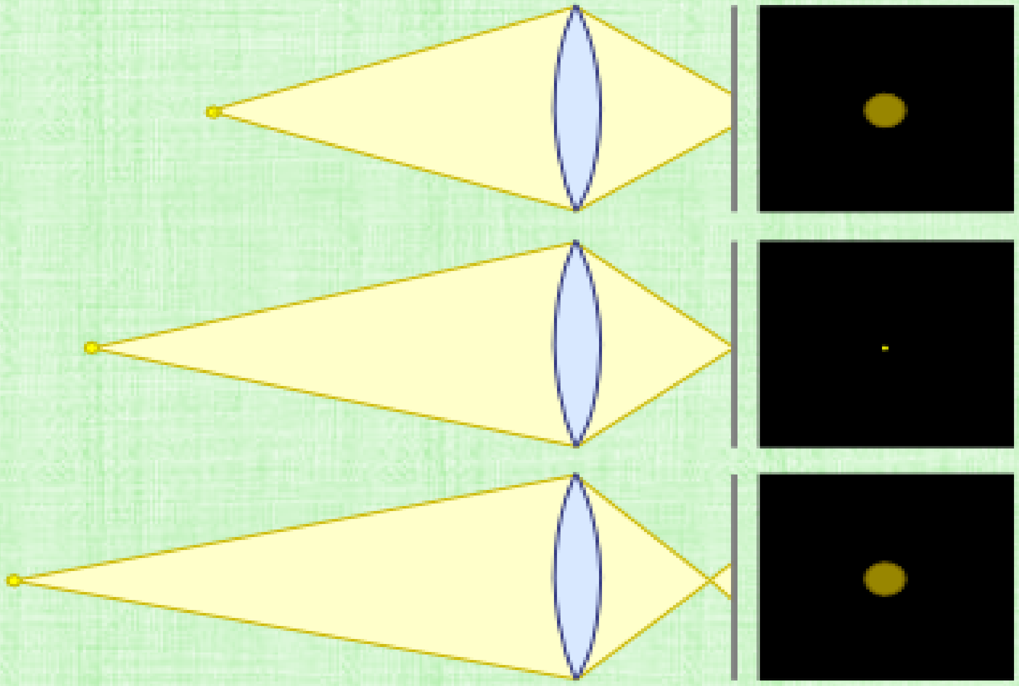
Virtual Camera Field of View (FOV)

- The 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)

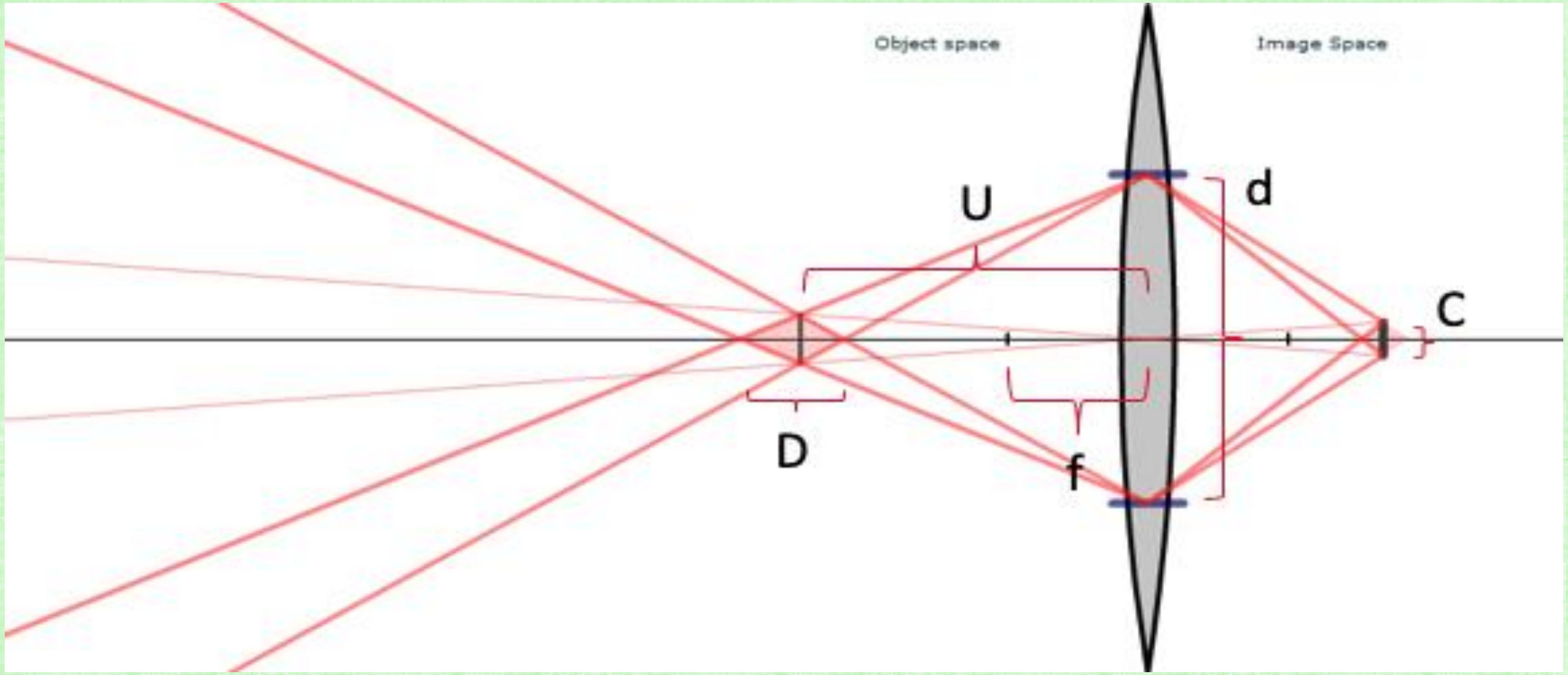


Circle of Confusion

- The "spot" caused by re-focusing light rays emanating from a single point
- When the spot is less than the size of a pixel, the object is sufficiently "in focus"
- Objects at varying distances require varying sensor placement to keep the objects "in focus"
- Depth of Field - distance between the nearest and farthest objects in a scene that appear to be "in focus" (i.e. the distance range with a small enough circle of confusion)



Depth of Field



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

f - focal length

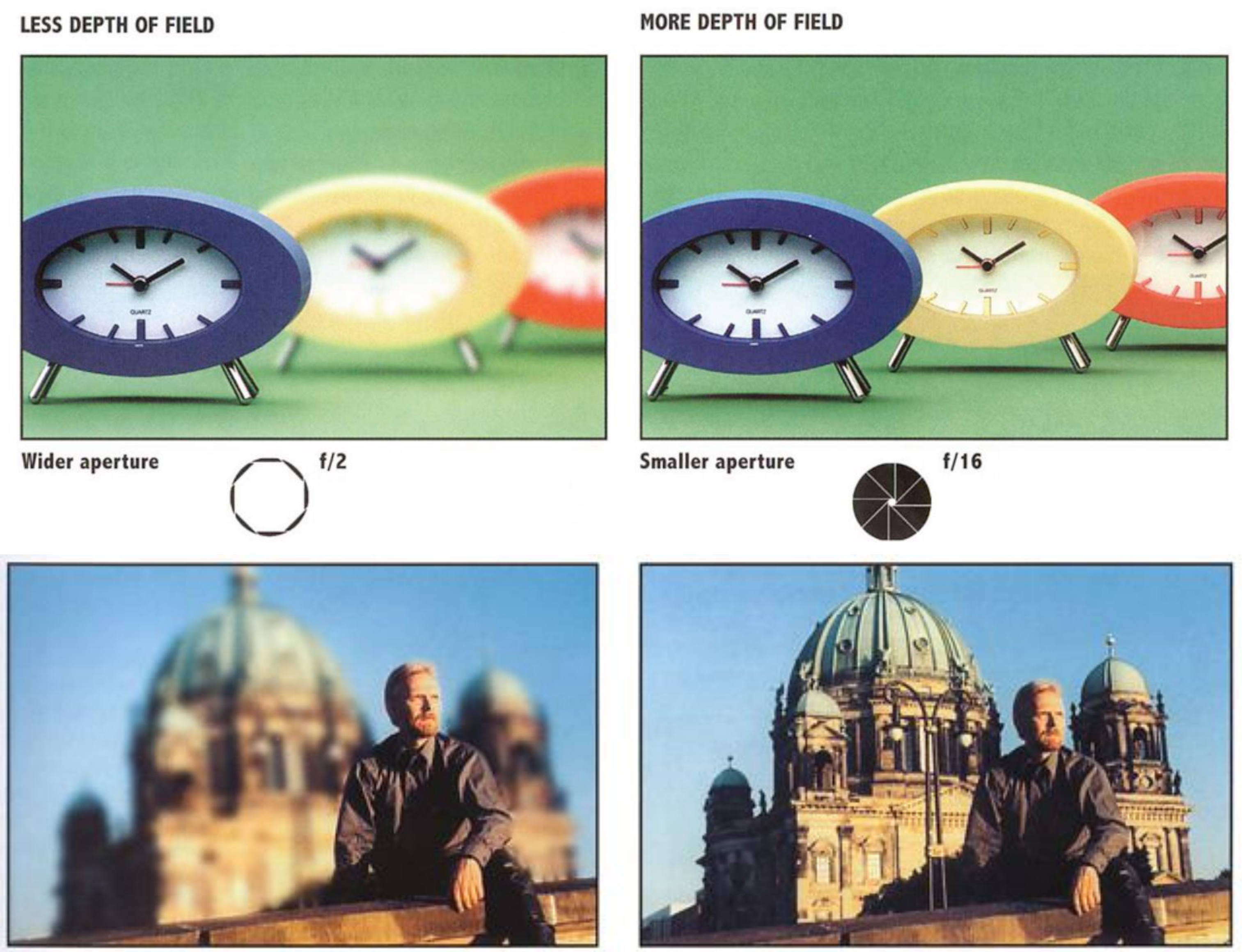
C - allowable circle of confusion

d - aperture diameter

U - distance to the center of focus

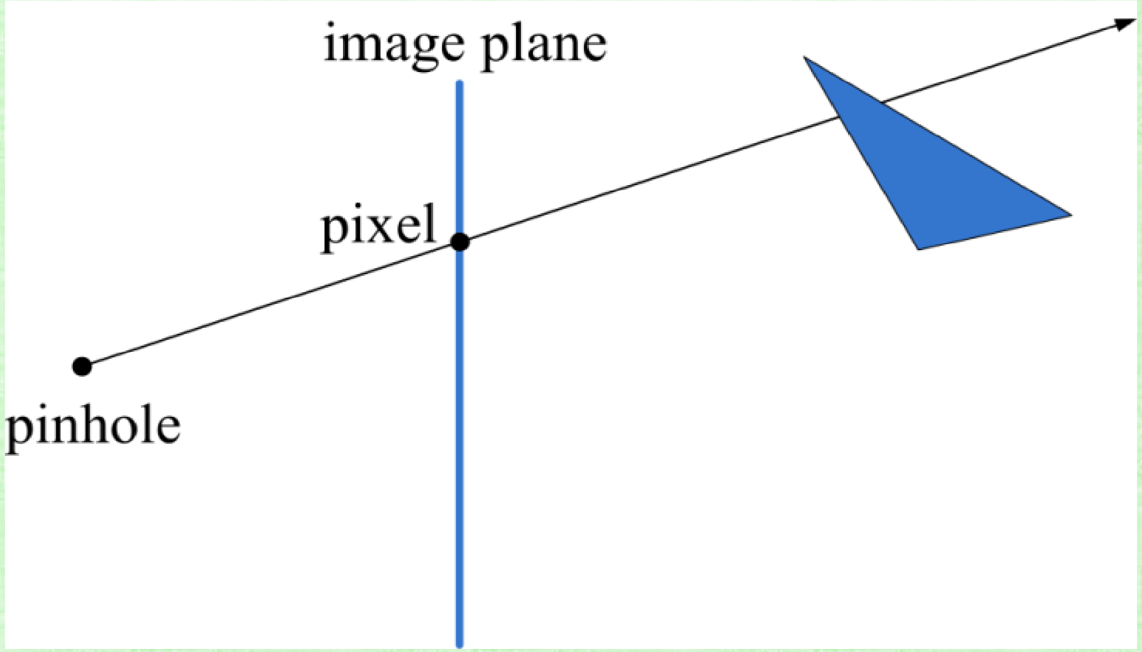
- Pinhole cameras have $d = 0$ and thus an infinite depth of field
- Shrinking the aperture increases the depth of field
  - However, it limits amount of light entering the camera (making the image too dark/noisy)
  - Decreasing shutter speed lets in more light (but creates motion blur)
  - Also, a small aperture causes undesirable light diffraction

Aperture vs. Depth of Field

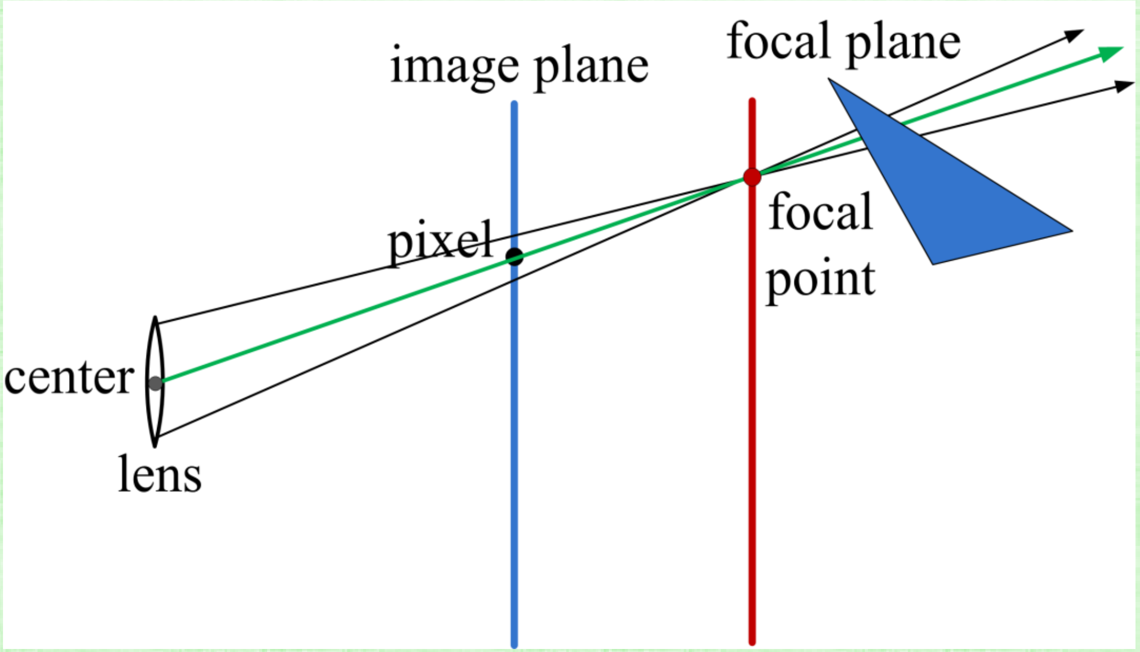


Implementing Depth of Field for a Ray Tracer

- Specify the focal plane (**red**) where objects are should be in focus
- For each pixel:
  - Calculate the “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 the circular region through the focal point (and average the results)
- Objects further away from the focal plane are more blurred



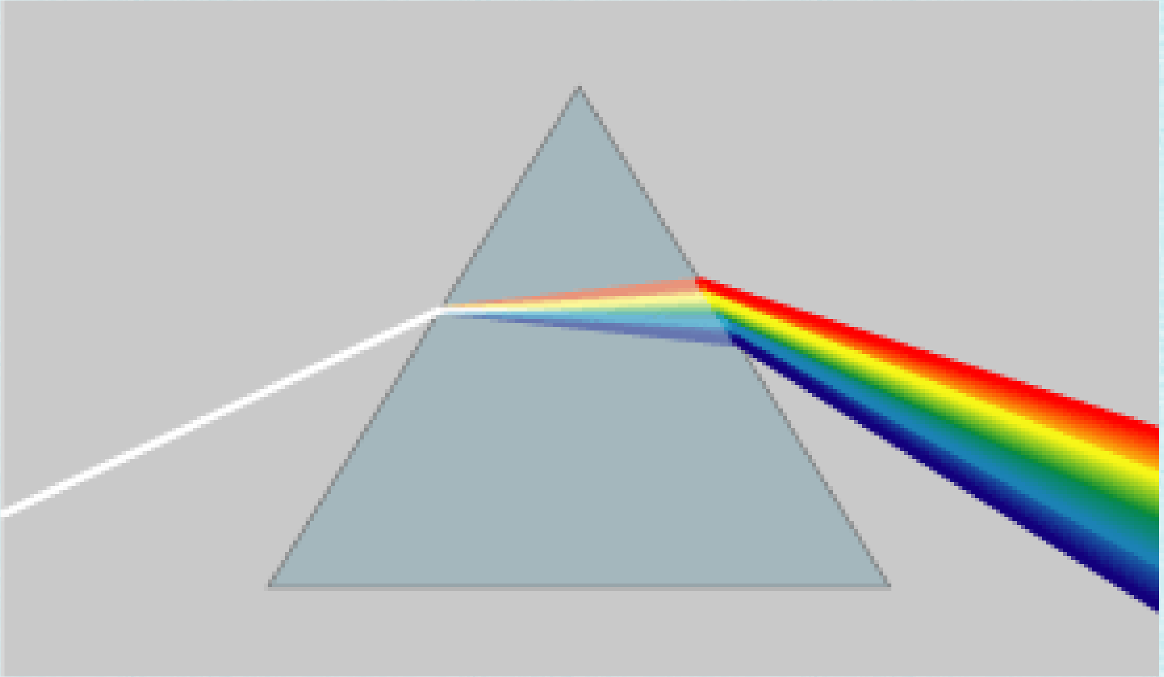
standard ray tracer



depth-of-field ray tracer

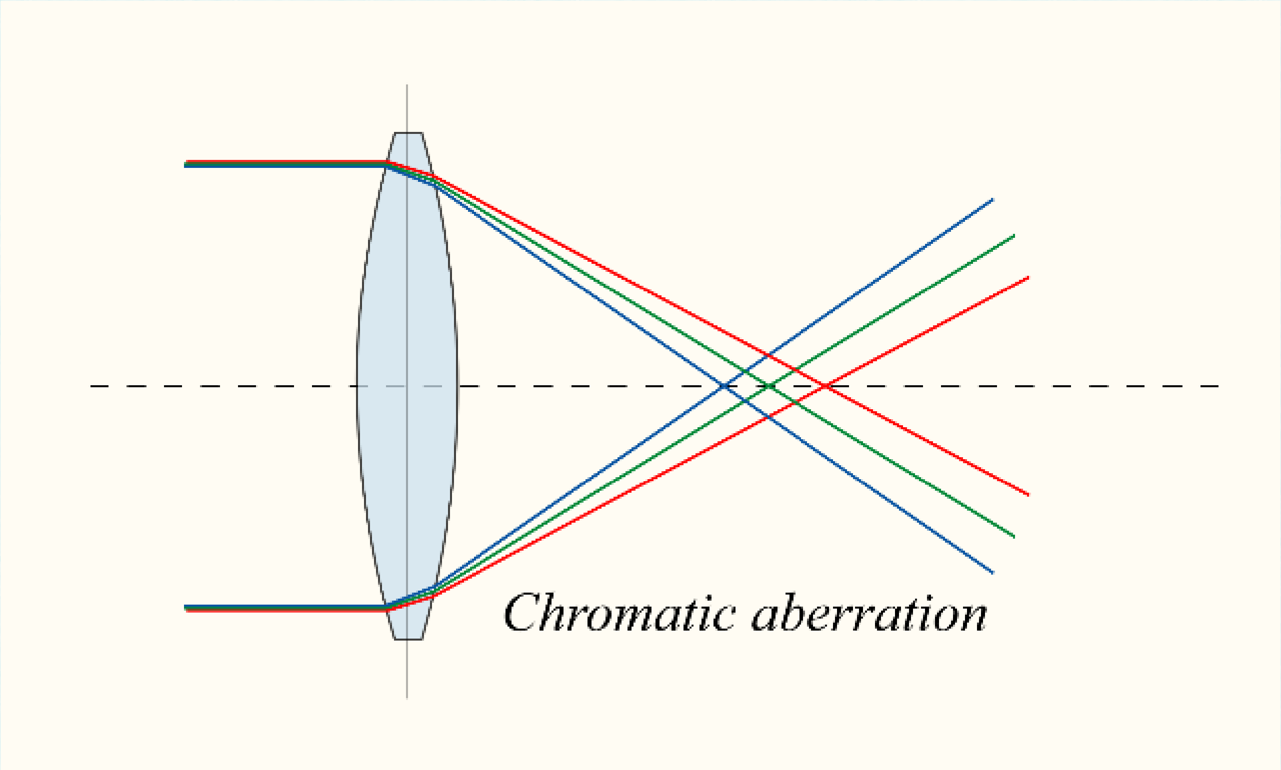
Dispersion

- The index of refraction depends on the frequency/wavelength of the light
- Index of refraction: air $n_1(\lambda) \approx 1$, glass/water $n_2(\lambda) > 1$
- Typically, n decreases as wavelength increases
  - Cauchy's approximation: $n(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4}$ with material parameters A, B, C
- So, **blue light** ($\lambda \approx 400\text{nm}$) bends more than **red light** ($\lambda \approx 700\text{nm}$)



Chromatic Aberration

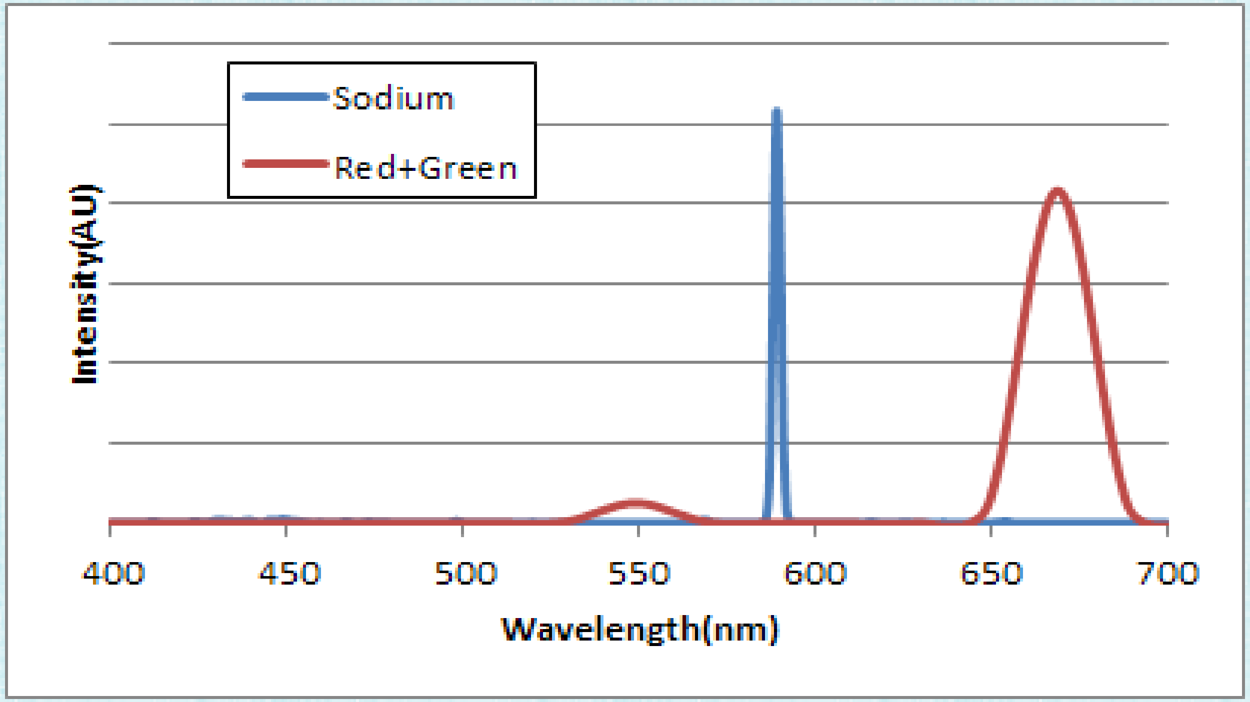
- Blue light bends more than red light, resulting in unequal focusing
- Focusing the blue light blurs the red light, and vice versa



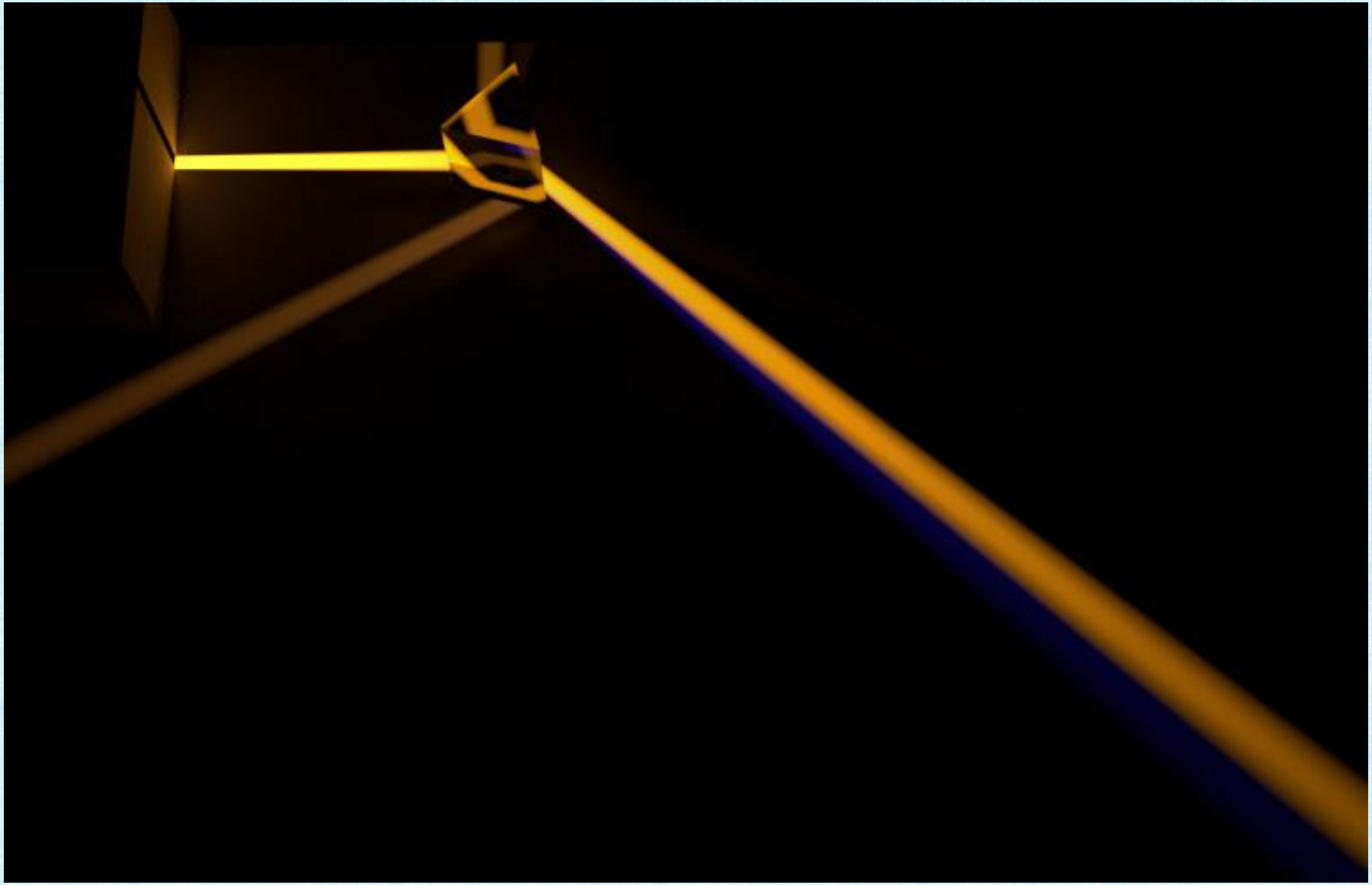
Spectral Power Distribution Matters

- Light's 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)
- Light's interaction with materials (often) requires the use of spectral power distributions

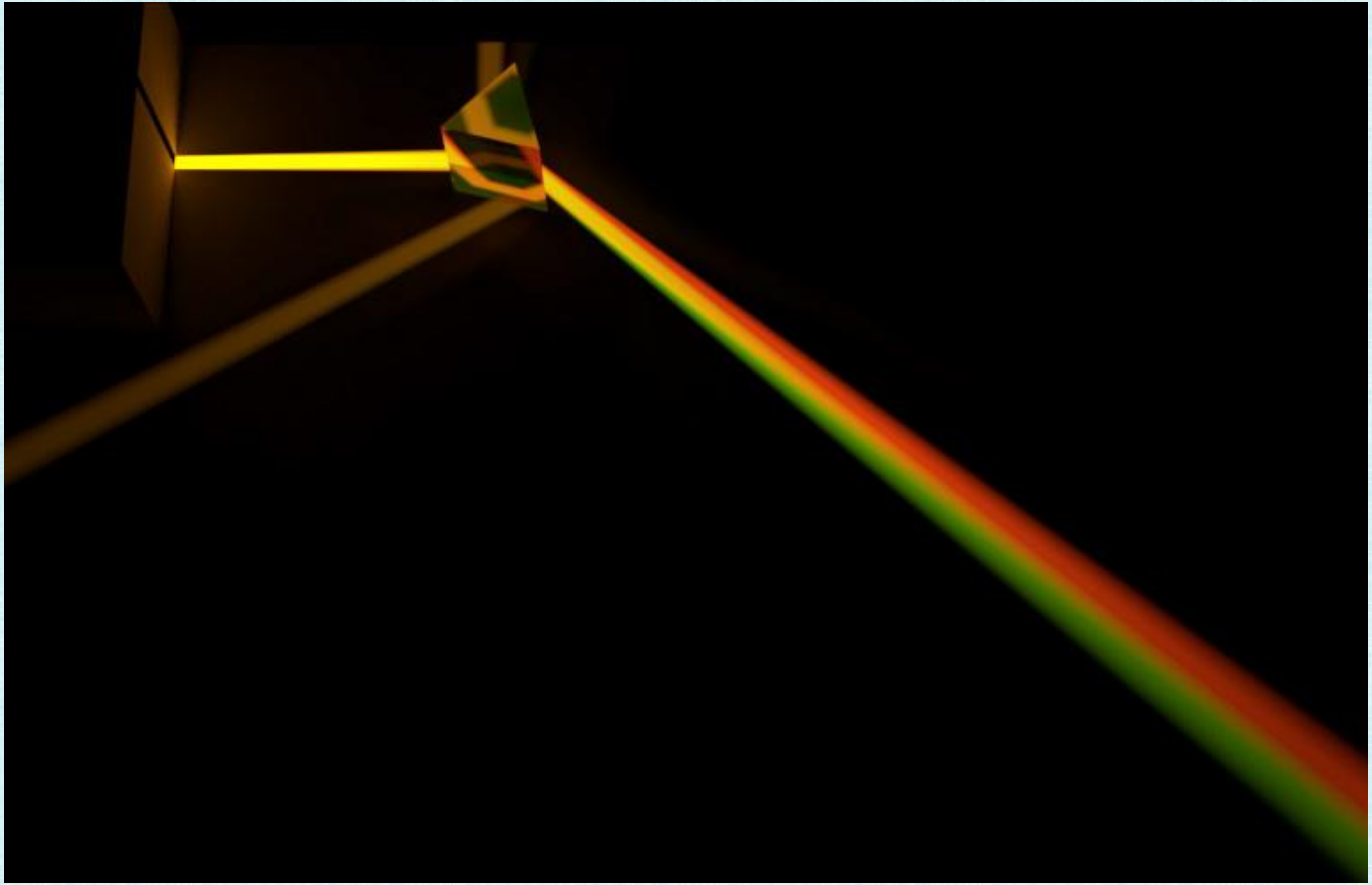
- Consider 2 different lights, with **identical RGB values** but **different spectral power distributions**:



Sodium Light through a Prism



Red/Green Light through a Prism



Wavelength Light Map

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

Gathering (from a Wavelength Light Map)

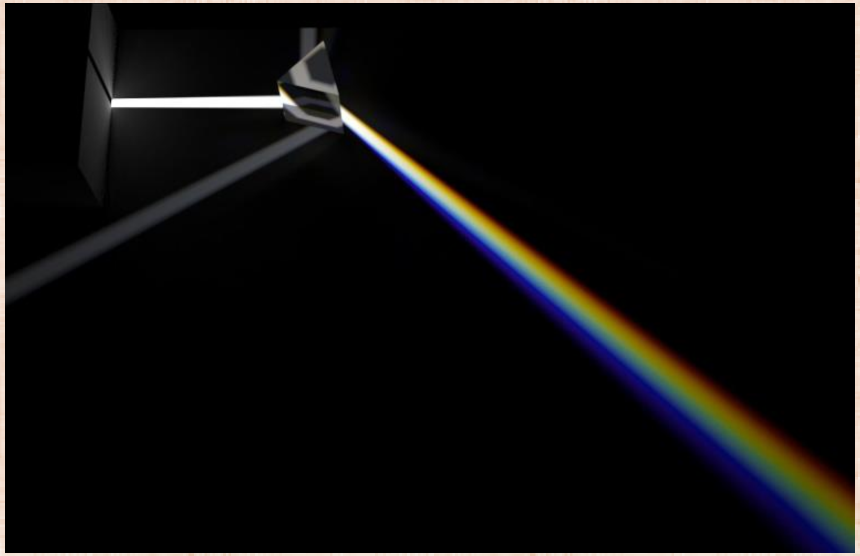
- When tracing rays from the camera, calculate the spectral power distribution at an intersection point using the nearby λ-colored photons and the BRDF
- Multiply/Integrate the calculated spectral power distribution by the tristimulus response functions to obtain R, G, B values (to store in the image,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

Participating Media

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

Participating Media

- That’s how we see the light from the prism experiment (in the previous slides), or a rainbow



Absorption

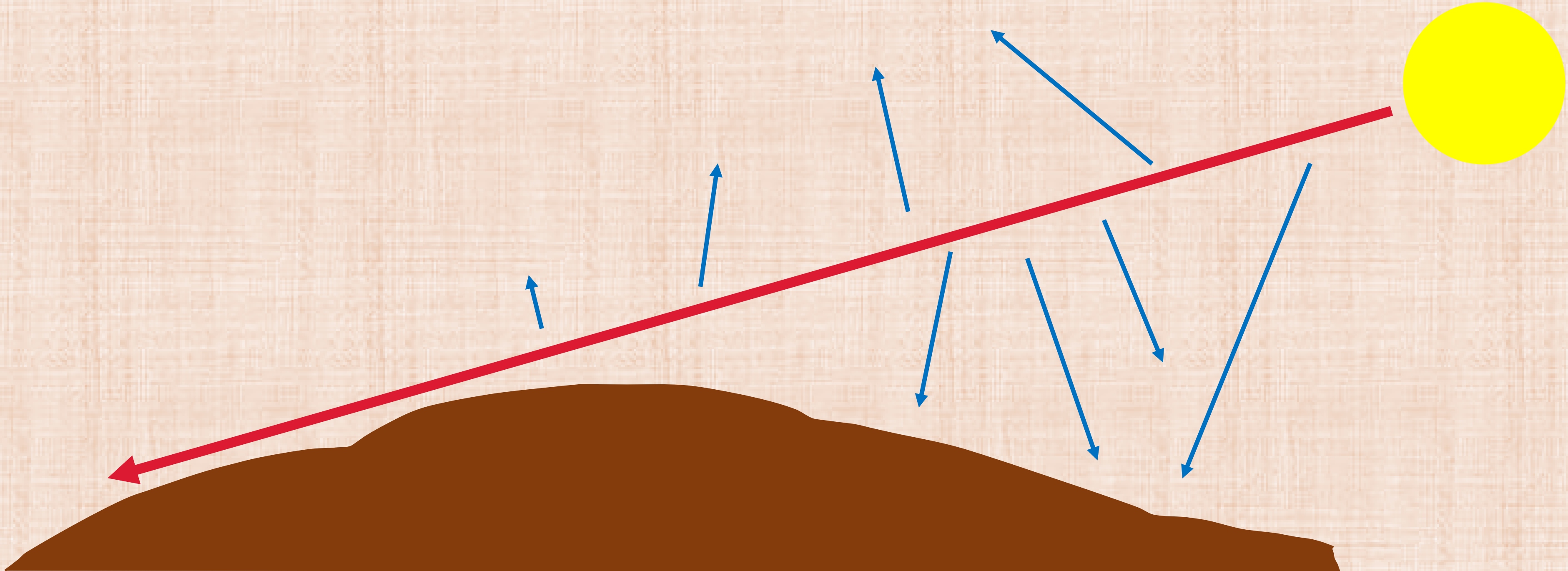
- While traveling through participating media, light can be absorbed (and converted into other forms of energy, e.g. heat)
- As light moves a distance dx (along a ray), a fraction (absorption coefficient $\sigma_a(x)$) of the radiance $L(x,\omega)$ given by $\sigma_a(x)L(x,\omega)$ is absorbed: $dL(x,\omega) = -\sigma_a(x)L(x,\omega)dx$

Out-Scattering

- While traveling through participating media, light can be scattered off in various directions
- The atmosphere scatters blue light more readily than red light, making the sunset red (at sunset, light has to travel through a lot of atmosphere to reach our 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 into other directions (and no longer travels along the ray): $\mathrm{d}L(x,\omega) = -\sigma_s(x)L(x,\omega)\mathrm{d}x$

Out-Scattering

- The atmosphere scatters blue light more readily than red light
- This makes sunsets red
- At sunset, the light travels through a lot of atmosphere to reach our eyes

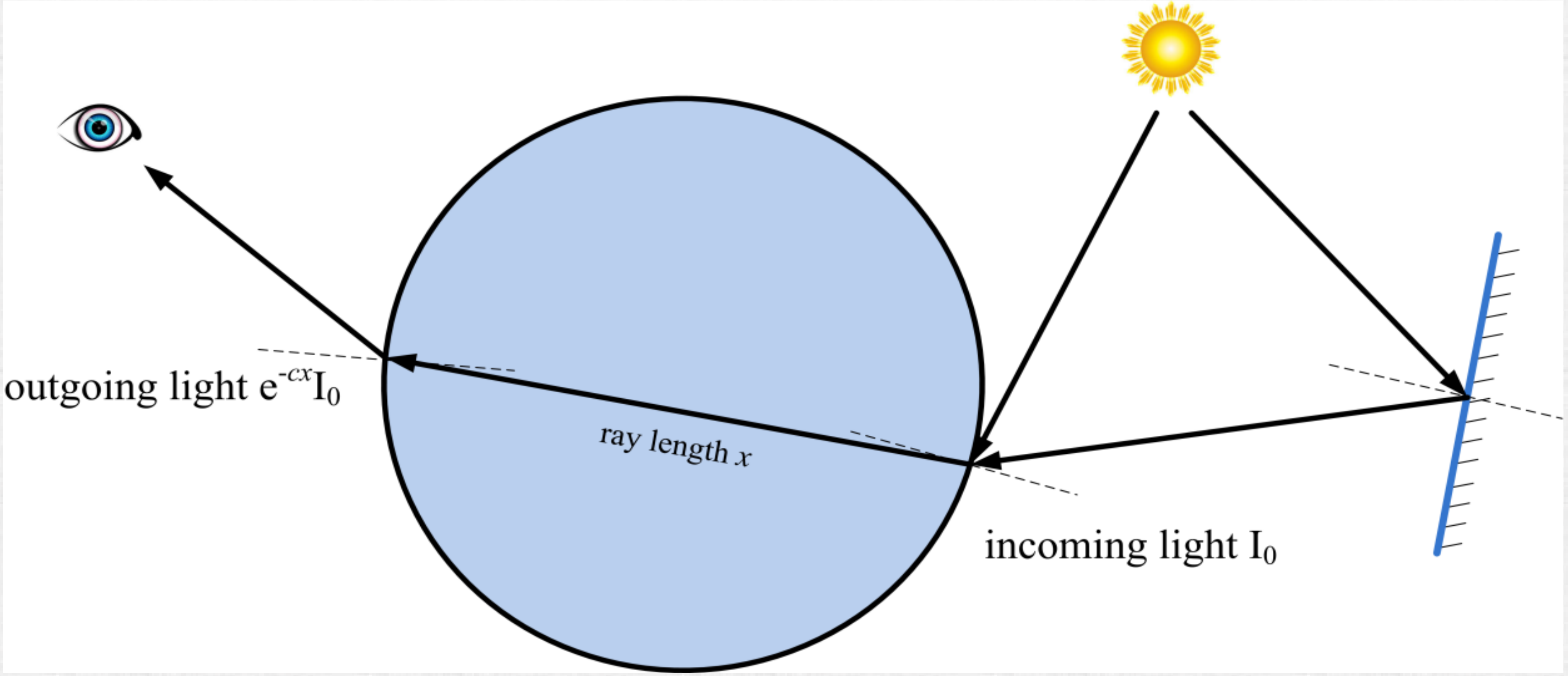


Attenuation

- 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: primary rays from the camera, shadow rays, reflected/transmitted rays

Recall: Beer's Law

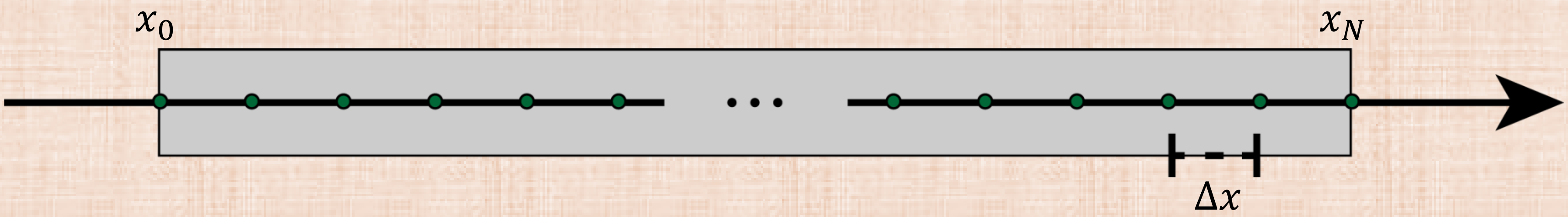
- For homogeneous media, attenuation can be approximated by Beer's Law
- Light with intensity I is attenuated over a distance x via the Ordinary Differential Equation (ODE): $\frac{dI}{dx} = -cI$ where c is the attenuation coefficient
- This ODE has an exact solution: $I(x) = I_o e^{-cx}$ where I_o is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



Heterogeneous Beer's Law

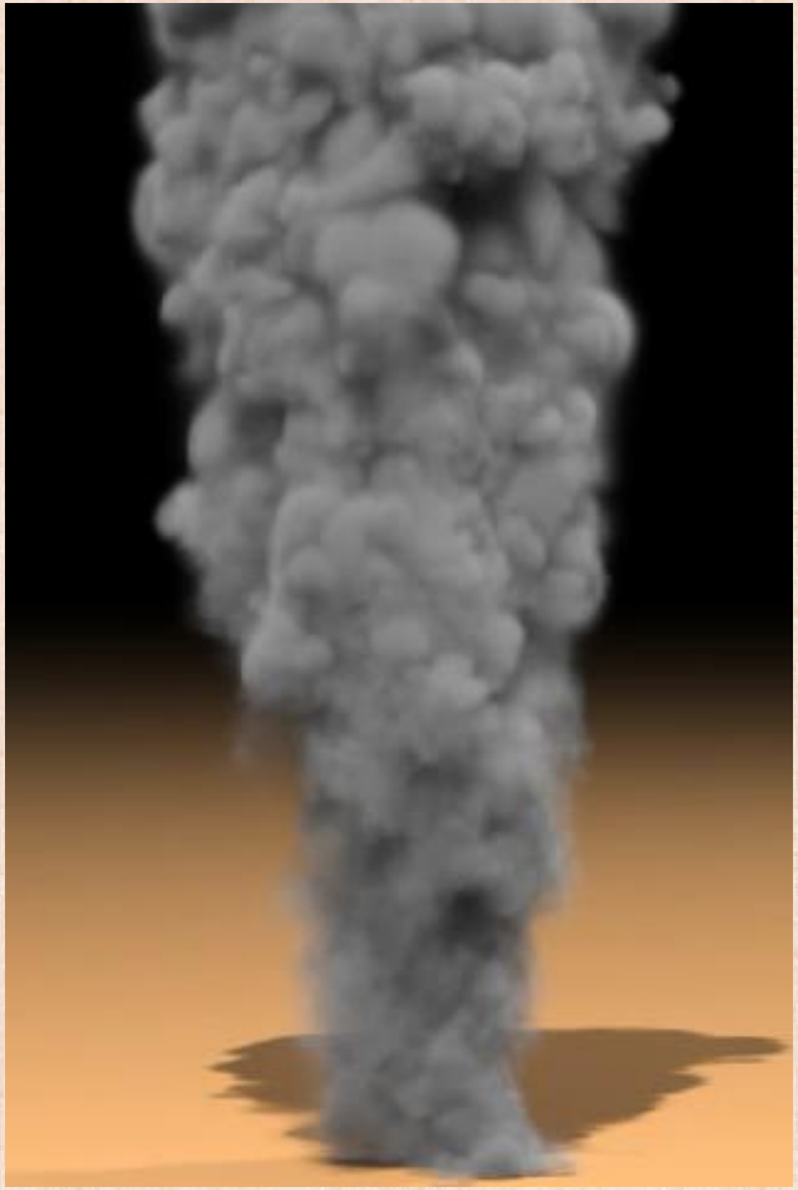
- For non-homogeneous media, $c(x)$ varies spatially (based on the concentration of the participating media)
- Discretize the ray into N smaller segments
- Treat c as a constant over each smaller segment (converges as $N \to \infty$)
- Given $\Delta x = (x_N - x_0)/N$ and segment endpoints $x_i = x_0 + i\Delta x$ 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
- This allows smoke to cast a shadow onto the ground plane
- The shadow is not completely black, since some light makes it through the smoke to the other side



Camera Ray Attenuation

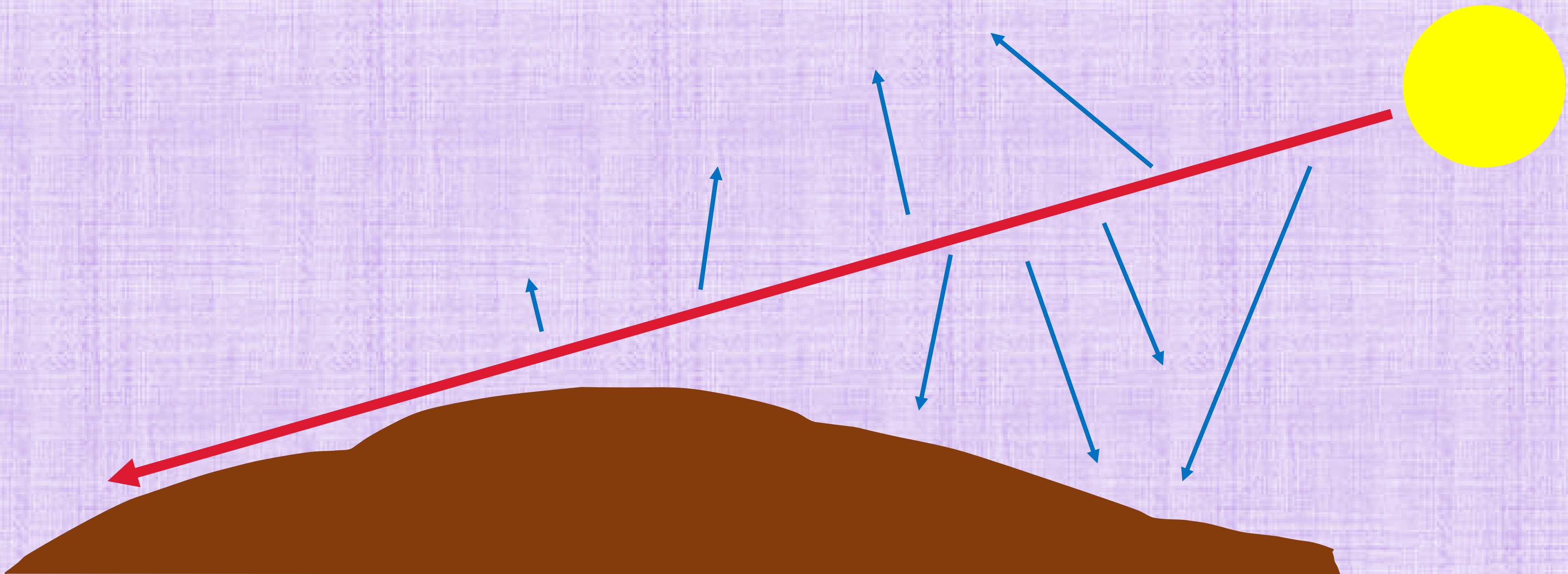
- Rays from the camera intersect objects, and a color is calculated (as usual, e.g. blue here)
- That color is attenuated by the participating media intersecting the ray
- The object color could be partially or completely attenuated
- Complete attenuation leads to black pixels, if the smoke itself added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

In-Scattering

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

In-Scattering

- The atmosphere scatters blue light more readily than red light
- Some of it is scattered towards your eyes
- This makes the sky appear to be blue (instead of black, as it appears at night)



In-Scattering

- Add the radiance contribution from in-scattering to the color of camera rays and shadow rays
- Without in-scattering, complete attenuation of object color (by participating media) results in a black pixel
- In-scattered light gives participating media its own appearance (e.g., clouds, smoke, etc.)

The darker underside of a cloud has less light available to in-scatter, because the top of the cloud absorbs and out-scatters much of the light (from the sun)

Volumetric Light Maps

- At each sample point along a ray, need to 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

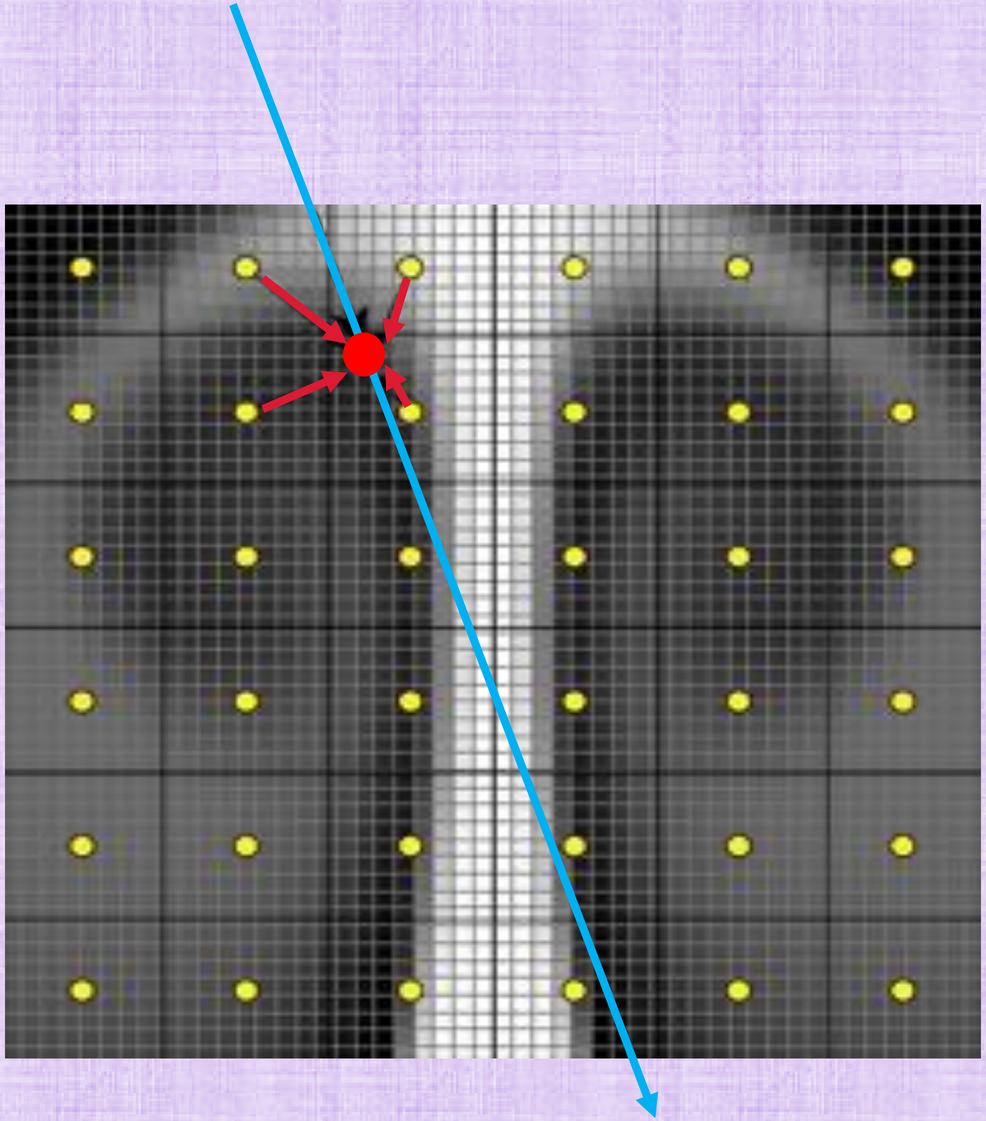
- For efficiency, <u>precompute</u> a volumetric light map:
  - Enclose the participating media with a grid (uniform, octree, etc.)
  - At each grid point, cast a shadow ray to the light source to precompute how much light is available for in-scattering

- Later, when tracing camera/shadow rays, use the precomputed light map to determine 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 on subsequent segments along the 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 volumetric light map
- 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/shadow ray
- The radiance at this point x scattered into the ray direction is $p(\omega, \omega')\sigma_s(x)L(x, \omega)$
  - σ_s represents the fraction scattered in <u>any</u> direction, and p selects the subset that scatters into the ray direction

- The total in-scattered radiance from a segment of length Δx is $p(\omega, \omega')\sigma_s(x)L(x, \omega)\Delta x$



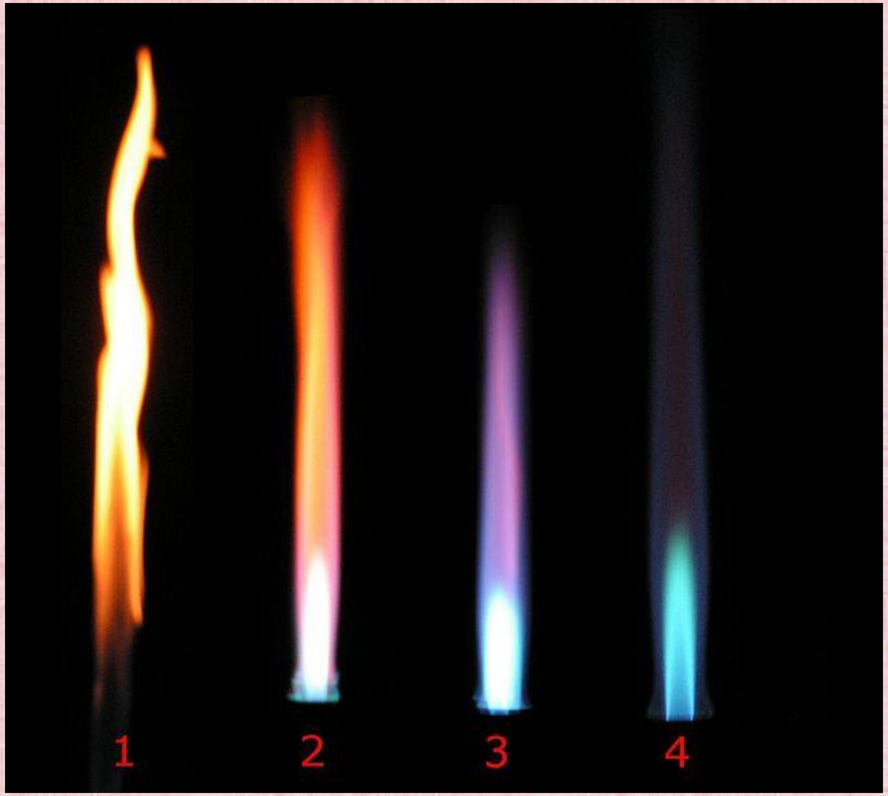
Phase Functions

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

1. Isotropic: $p(\cos\theta) = \frac{1}{4\pi}$ 4π steradians in a sphere
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

Volumetric Emission

- Participating media can emit light
  - 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 every 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
- Treat this region as a volume light:
  - Model a volume light with many small point lights (similar to an area light)
  - These point lights are used just like every other light in the scene: shadow rays, creating photon maps, etc.
  - They also participate in the creation of the volumetric light map (for self shadowing of participating media)