Advanced Rendering
Shutter Speed

• The shutter allows light to hit the sensor for a finite duration of time
• Objects which move while the shutter is open create multiple images on the sensor, resulting in **motion blur**
• A faster shutter speed prevents motion blur, but can severely limit the amount of light available to the sensor making the resulting image too dark (especially when the aperture size is small)
Motion Blur

• Set up animations for moving objects during the time interval in which the shutter is open $[T_0, T_1]$
  – E.g. describe the transform of the object by a function $F(t)$ for $t \in [T_0, T_1]$

• For each ray:
  – Assign a random time $t_{\text{ray}} = (1-\alpha)T_0 + \alpha T_1$
  – All objects in the scene are placed in their time $t_{\text{ray}}$ locations
    • i.e. given by $F(t_{\text{ray}})$
  – Trace the ray with the time $t_{\text{ray}}$ scene and get a color for that ray

• This works significantly better when multiple rays per pixel are used to combat temporal aliasing
Depth of Field
Focal Length

• The distance over which initially parallel rays are brought into focus onto a focal point by a lens or lens system
• A stronger lens system has a shorter focal length
• Individual elements of a lens system can be adjusted to change the overall focal length of a camera (but each individual lens/element has a fixed focal length)
• If the object is “far” enough away (infinity), the image plane or sensor should be placed near (or at) the focal point
Field of View

- The part of the world that is visible to the sensor
- Zoom in/out by increasing/decreasing the focal length of the lens system
- The sensor needs to be moved out/in to adjust for the new focal length
- Since the size of the sensor does not change, the field of view will shrink/expand
Field of View

- Zooming in the camera shrinks the FOV
Field of View

- Zooming in the camera shrinks the FOV
Field of View

• The field of view for a ray tracer can be adjusted by changing the distance between the “eye” point and the image plane
• Alternatively, one can change the size of the sensor (unlike in a real camera)
• A common mistake in computer graphics is to place the film plane too close to the main objects in the scene
  – The desired field of view is then obtained by placing the “eye” point very close to the film plane or by making a very large film plane (resulting in an un-natural fish-eye lens effect)
Circle of confusion

- An optical spot caused by a cone of light rays from a lens not coming into perfect focus when imaging a point source
- When the spot is approximately equal to the size of a pixel on the sensor, the object seems to be “in focus”
- Objects at varying distances from the camera require the sensor to be paced at different distances from the lens in order for the object to be “in focus”
- **Depth of Field** - the distance between the nearest and farthest objects in a scene that appear roughly “in focus” (the circle of confusion is not too big)
Depth of Field

• A pinhole camera has infinite depth of field
• Making the aperture smaller improves the depth of field
  – However, this limits the amount of light entering the camera making the image darker
  – Decreasing the shutter speed to offset this can result in motion blur
  – Small apertures also cause undesirable light diffraction

\[ D_{TOT} \approx \frac{2NCU^2}{f^2} \]

– f is the focal length
– N=f/d is the F-Number (with d the aperture diameter)
– U is the real world object distance
– C is the allowable circle of confusion
Aperture & Depth of Field

Large aperture opening

Small aperture opening

LESS DEPTH OF FIELD

MORE DEPTH OF FIELD

Wider aperture

f/2

Smaller aperture

f/16
Depth of Field

• Specify a focal plane (red plane, below) where objects will be in focus
• For each pixel, the “focal point” is calculated as the intersection of the standard ray tracing ray (green ray, below) and the pre-specified focal plane
• For each pixel, replace the pinhole “eye” with a circular region
• Then to shade that pixel, shoot multiple rays from sampled points in the circular region through the focal point (and average the results)
• Objects further away from the focal plane will have more blurring
Depth of Field
Dispersion

- Dispersion occurs because the phase velocity (and thus the index of refraction) depends on the frequency/wavelength of light.
- Dispersive media: glass, raindrops.
- Index of refraction: Air $n_1(\lambda) \approx 1$; Glass/water $n_2(\lambda) > 1$.
- For visible light in most transparent materials, $n$ decreases towards 1 as the wavelength increases.
  - So 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 $A$, $B$, $C$. 

![Dispersion diagram](image)
Humans have tri-stimulus color perception
- Allowed us to optimize rendering by only working with R, G, B

However, interaction of light with an arbitrary surface cannot (in general) be described correctly using only three components
- Same RGB value could map to many different power distributions (and therefore wavelengths)

Need to more accurately describe light and its interactions with surfaces using spectral power distributions

Consider a prism dispersion setup with two orange light sources that have identical RGB values but different spectral power distributions:

![Dispersion Graph](image-url)
Dispersion

Glass prism lit by “sodium” light source
Dispersion

Glass prism lit by "red+green" light source
Wavelength Light Map

- When tracing photons from the light source, importance sample the light’s spectral power distribution to obtain a $\lambda$ for each photon.
- Use $\lambda$ and the reflectance/transmittance spectrum at each intersection point to trace the photon throughout the scene.
- Store the incident power of the photon along with the wavelength of the photon in the photon map.
**Gathering (Camera Rays)**

- When tracing rays from the camera, estimate the spectral power distribution at an intersection point using the nearby photon samples.
- Multiply/Integrate this estimated spectral power distribution by the tristimulus response functions to obtain R, G, B values.
- Requires significantly more samples in the photon map, although many optimization strategies exist.
Participating Media
Atmospheric Effects

- Caused by light being scattered towards the camera by mist or dust
Absorption

- Light traveling through a medium may interact with the medium in such a way that the light energy is converted to another form of non-visible energy (such as heat).
- Define an absorption coefficient, $\sigma_a(x)$.
- As we move a small distance $dx$ along a ray, a fraction of the current 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

• Light traveling through a medium in a straight line may interact with the medium and be scattered to travel off in a different direction
• At sunset, the atmosphere scatters away most of the blue light leaving mostly red light traveling to our eyes from the sun
• Define a scattering coefficient, \( \sigma_s(x) \)
• As we move a small distance \( dx \) along a ray, a fraction 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):

\[
dL(x, \omega) = -\sigma_s(x)L(x, \omega)dx
\]
Total Attenuation

- The probability light is attenuated (either absorbed or out-scattered) per unit length is \( c(x) = \sigma_a(x) + \sigma_s(x) \)
- As we move a small distance \( dx \) along a ray, a fraction of the radiance \( L(x, \omega) \) given by \( c(x)L(x, \omega) \) is attenuated
  \[ dL(x, \omega) = -c(x)L(x, \omega)dx \]
- Both the primary rays shot from a camera pixel and the secondary shadow rays used in lighting calculations can pass through transparent objects or participating media
- The lighting contribution along these rays needs to be attenuated
- Attenuation in a participating medium can be modeled using Beer’s law
Recall: Beer’s Law

- If the media is homogeneous, the attenuation along the ray can be described using Beer’s Law:
  \[
  \frac{dI}{dx} = -cI
  \]
  where \( I \) is the light intensity, \( x \) is the distance along the ray, and \( c \) is the attenuation constant (which varies based on color/wavelength)

- Solving this Ordinary Differential Equation (ODE) with the initial value \( I(0) = I_0 \), results in:
  \[
  I(x) = I_0 e^{-cx}
  \]
Inhomogeneous Beer’s Law

- For non-homogeneous media, the attenuation constant varies spatially based on the concentration of the inhomogeneities.
- Discretize the ray into $N$ small segments, and treat the attenuation as constant over each small segment.
  - Converges to the correct answer as the number of segments is increased.
- The attenuation along the $i$-th segment is set to be $e^{-c(.5(x_{i-1}+x_i))\Delta x}$ where $\Delta x = (x_N-x_0)/N$ is the segment length, $c(.5(x_{i-1}+x_i))$ is the attenuation constant evaluated at the center of the segment, and $x_i = x_0 + i\Delta x$.
- The total attenuation along the ray is computed via multiplication:
  $$e^{-c(.5(x_0+x_1))\Delta x} e^{-c(.5(x_1+x_2))\Delta x} ... e^{-c(.5(x_{N-1}+x_N))\Delta x}$$
Attenuation

- Note how the smoke, acting as a participating media, casts a shadow on the ground.
- The shadow rays cast from the ground plane to the light source have their light attenuated by the smoke volume.
- The shadow is not completely black, since some light passes through the smoke volume.
Camera Rays

• Send out rays from the camera into the scene intersecting objects and calculating their lighting as usual

• For any ray that travels through participating media on the way from the camera to the object, the radiance along that ray needs to be attenuated
  - Just like as for shadow rays

• An objects color could be partially attenuated or completely attenuated (not visible - occluded) by the participating media
Volumetric Light Map

- Represent a 3D light map with a uniform grid enclosing the participating media
  - Could also use an octree, or any other spatial partition with sample points
- For each sample point that lies within the participating medium, send out a shadow ray to the light source and compute the attenuated radiance that reaches that sample point
  - This computes and stores self-shadowing effects (e.g., LEFT: clouds appear darker on the side away from the light; RIGHT: smoke has light and dark regions from self-shadowing)
In-Scattering

- At each point along a ray, some light will be in-scattered from the surrounding medium into the direction of the ray
- In-scattering increases the radiance along the direction of the ray
- The sky appears blue because the particles in the atmosphere scatter blue light in every direction (and some of it towards our eyes)
  - Without in-scattering, the sky would appear black
In-Scattering

• The radiance contribution due to in-scattering from the participating media needs to be added along the rays from the camera to the objects.

• Without in-scattering, an object whose outgoing radiance was completely attenuated by participating media produces black pixels—since there would be zero radiance along those rays.

• In order to add the in-scattering contribution, add in-scattered light along each segment of the ray discretization already used for attenuation.

• In-scattered light is added to the total light at each point, and thus gets attenuated by subsequent segments along the discretized ray—Thus the calculation needs to be done from object to camera.

• The precomputed volumetric light map stores candidate light for in-scattering.
In-Scattering

- At the center of each discretized segment of the camera ray, interpolate the radiance $L(x, \omega)$ from the sample points of the volumetric light map.
- The direction of the incoming light, $\omega$, is the direction from the light source to the center of the discretized segment.
  - a separate light map is needed for each light source.
- A phase function $p(\omega, \omega')$ gives the probability that an incoming ray from the light source with direction $\omega$ is scattered into the direction of the camera ray $\omega'$.
- The radiance at this point $x$ scattered towards the camera along direction $\omega'$ is $p(\omega, \omega')L(x, \omega)\sigma_s(x)$.
- The in-scattered radiance contribution from the entire discretized segment is then $p(\omega, \omega')L(x, \omega)\sigma_s(x)\Delta x$.
- N.B. $\sigma_s$ is the probability of any scattering in any direction, and $p$ selects the subset of these that scatter in the desired direction.
Phase Functions

- Energy conservation: $\int_{\text{sphere}} p(\omega, \omega') d\omega' = 1$
- Many phase functions are parameterized by the 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**: $p(\cos\theta) = \frac{\frac{1}{4\pi} (1 - g^2)}{(1 + g^2 - 2g \cos\theta)^{1.5}}$
   - $g$ denotes the average phase angle and 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. 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 lighting information can be added as a separate volumetric light map

- Note that this volumetric emission is in every direction, as opposed to the previously calculated information for self-shadowing

- Thus when calculating the in-scattering contribution, need to integrate the product of the phase function and incoming radiance over all incoming directions
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 for the hot carbon soot and light energy from electrons to cast shadows and light the scene.
- To do this, need to treat this region as a volume light.
- Often modeled by breaking it up into many small point lights:
  - similar to an area light.
- These point lights are then 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.
Lens Flare

• Light can be reflected and scattered by lenses in the lens system, resulting in generally unwanted but impressive effects
• This is caused in part by material inhomogeneities in the lens
• Model and ray trace a full optical model of the entire camera lens system
  – Geometry of lens surfaces and characteristic planes (entrance, aperture, sensor plane)
  – Absorption and dispersion of lens elements
  – Antireflective coatings
  – Diffraction
Camera Lens Geometry

- The camera “lens” consists of a large number of elements
- Specify the geometry of lens elements with parameters such as radius (for spherical elements), diameter, distance between elements, index of refraction, etc.
- Trace rays through these elements
  - Use Snell’s law to compute the reflected/transmitted ray directions
  - Use Fresnel Equations to compute the transmission and reflection components
Absorption and Dispersion

• Light is attenuated as it moves through each lens element
  – Treat each lens element as a participating medium with an absorption probability

• Lens elements are characterized by the Abbe number which measures the material’s dispersion
  – Results in chromatic aberration
  – Model these effects using spectral rendering techniques
Antireflective Coatings

- Optical coatings are applied to the surfaces of lenses to reduce reflection
- Characterized by a residual reflectivity $R(\lambda, \theta)$ where $\lambda$ is the wavelength of the light and $\theta$ is the incident angle
- Residual reflectivity denotes the amount of light reflected after the destructive interference of the coating is taken into account
- Requires spectral rendering techniques and multiple evaluations of the Fresnel equations
Diffraction

- Light tends to spread out as it goes through small openings
- Happens when your aperture gets too small
  - we call this diffraction limited
- Tends to create constructive and destructive interference
  - Airy disk
- Difficult to account for in a ray tracer due to geometric optics assumptions
  - can fake with a texture
Ray Tracing Lens Flare

- Trace rays from the lights into the camera lens
- Intersect the rays with the camera lens elements
- Use spectral rendering to compute reflection and transmission in a physically accurate manner
- Store wavelength-dependent illumination samples on the film
- Estimate the spectral power distribution on each pixel of the film to obtain the image

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