A Realistic Camera Model for Real-time Rendering

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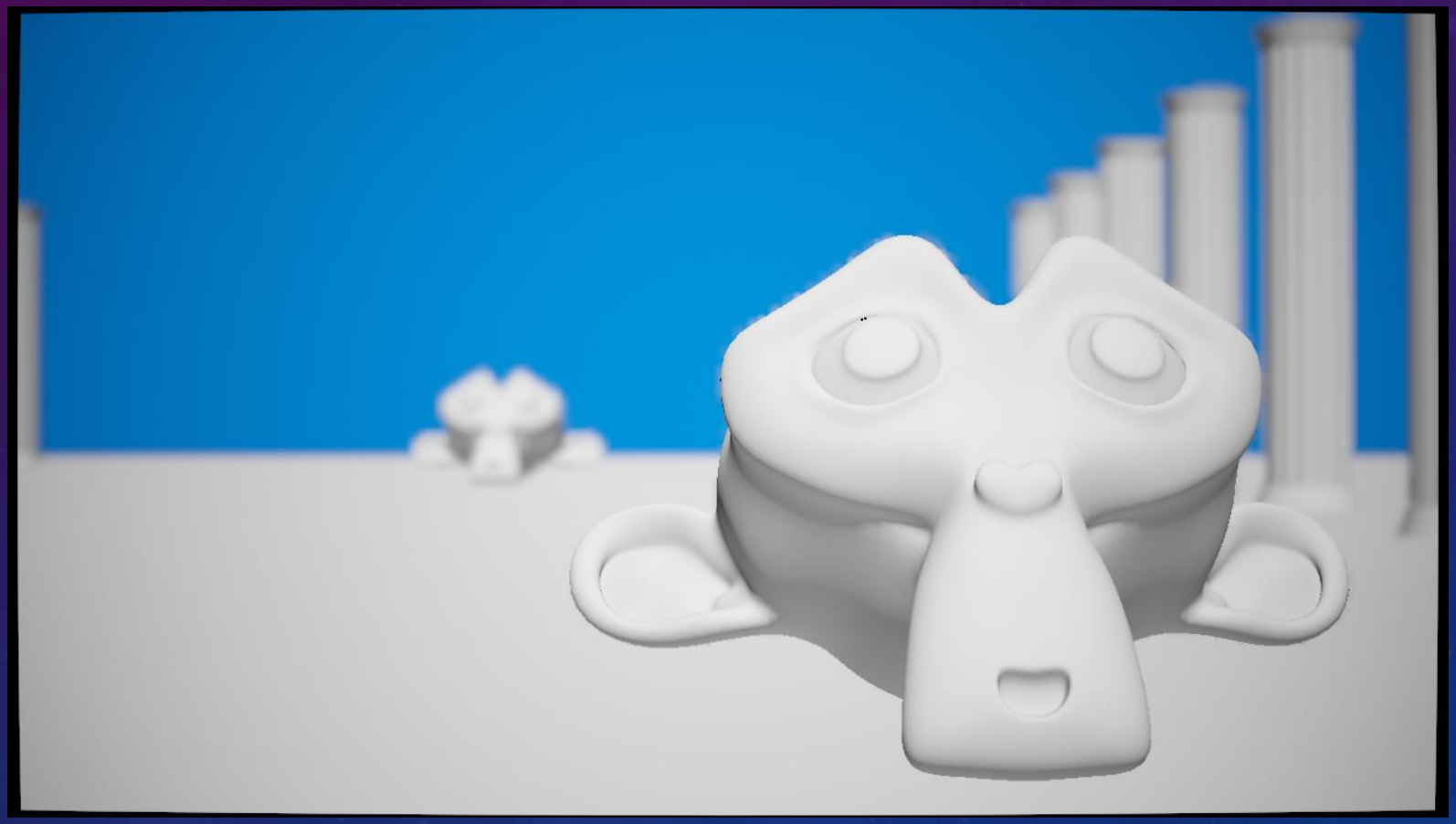
Results



Simulating a Zeiss Planar T* 1.4/50

Motivation

- A camera metaphor makes using 3D graphics systems easier for users who are already familiar with cameras
- The principles behind 3D graphics are easier to explain when related to real cameras
- Can be used when merging computer-generated imagery with recorded imagery (e.g. for augmented reality or special effects)
  - The computer-generated imagery needs to use a camera model similar to that of the real camera

Goal

- A realistic camera model for real-time computer graphics
  - Take in a set of parameters for the configuration of a real camera
  - Simulate defocus blur, motion blur, and third order lens aberrations simultaneously
  - Apply lens and exposure equations from photographic optics in a post-processing step to the output from a rasterizer

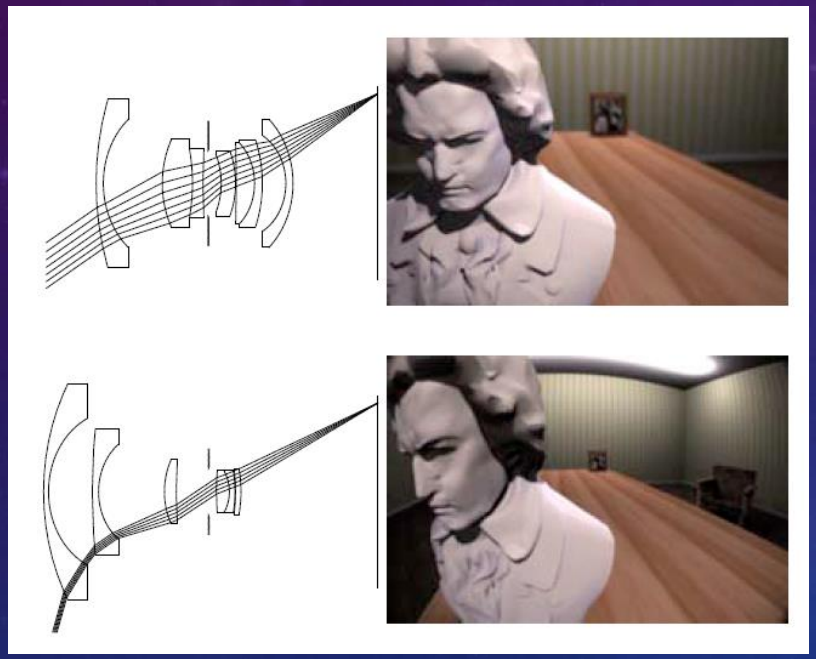
Previous Work

Raytracing

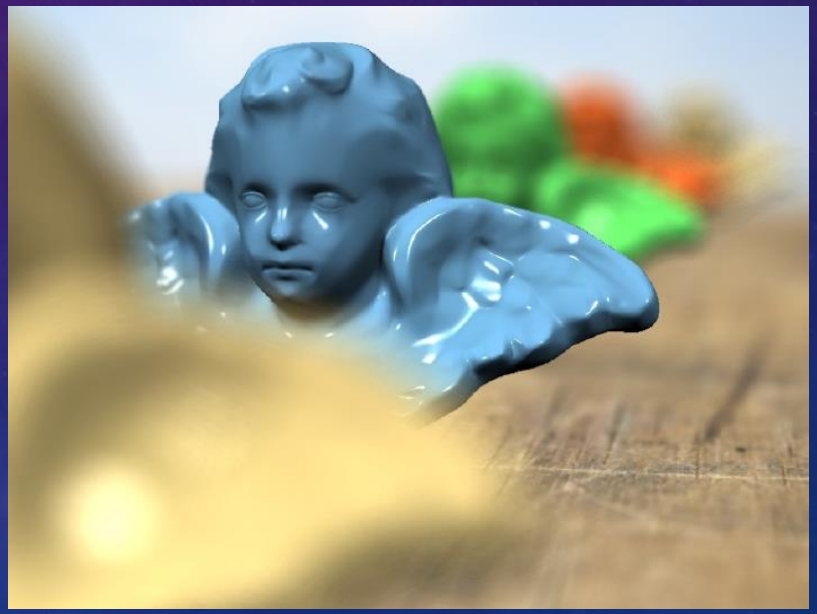
- Generate an image by tracing the path taken by light rays interacting with a scene
  - Usually traced from the camera into the scene as it is more efficient
- Simulating camera optics
  - Refract rays through the camera's lens system first
  - Adds a small, constant amount to rendering time

Raytracing

Kolb et al. (1995)



Lee et al. (2010)



Raytracing

- If the refraction through the lenses is calculated accurately, all of the expected aberrations will appear in the output
- Raytracing is computationally expensive
  - A large number of samples are required to simulate defocus and motion blur

Post-processing

- Take the output from a rasterizer, and modify it in a post-processing step
- Apply lens and optics equations to analytically determine the parameters for the post-processed effects

Post-processing

GPU Gems (2004)

McGuire et al. (2012)

Post-processing

- Each effect has to be manually simulated, and the effects have to be combined and applied in the right order
- Significantly faster than raytracing

Approach

- Simulate each camera effect using post-processing
- Take advantage of hardware acceleration by implementing the effects as shaders
  - Uses DirectX and HLSL shaders, but the same approach could be implemented in OpenGL with GLSL

Agenda

- For each topic
  - Brief overview
  - Any implementation details
  - Images of what the output is supposed to look like
  - Images of the output from the renderer

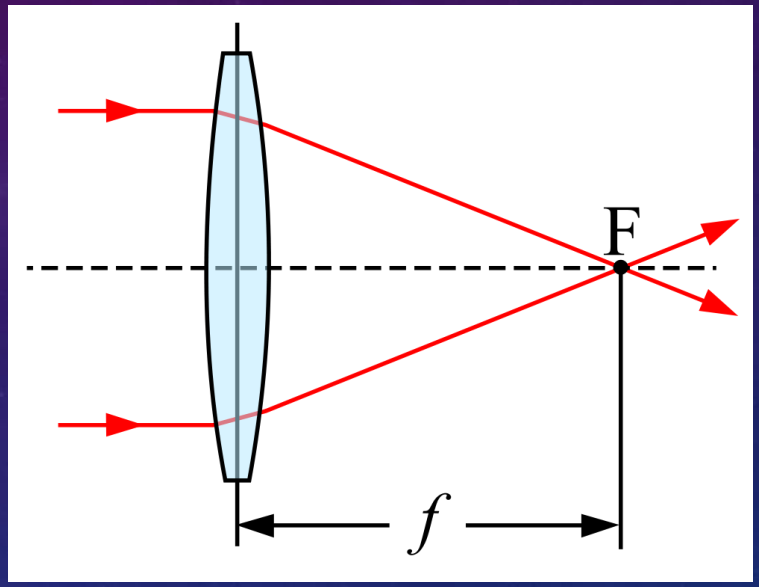
Photographic Optics

Lenses

- Most lenses are compound lenses, made up of several simple lenses
- The entire lens systems can be analyzed as a single entity

Focal Length

- f = focal length
- Distance from the lens to the point where incoming collimated light (light whose rays are parallel) is focused
- Describes how strongly the lens system converges light

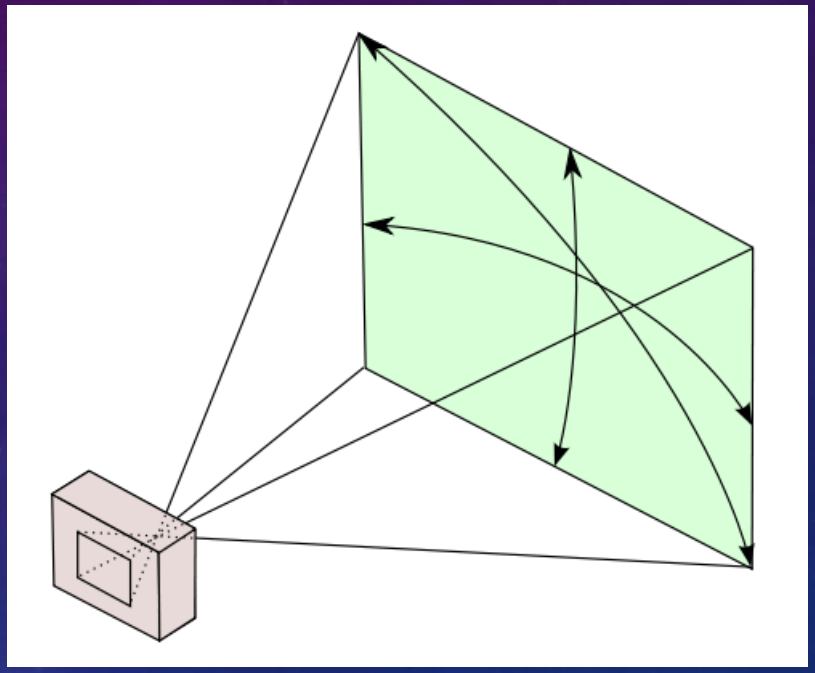


Field of View

- How much of the scene can be imaged by the camera

$$W = 2 \arctan\left(\frac{K}{2f}\right)$$

- Used to calculate the field of view for the projection matrix



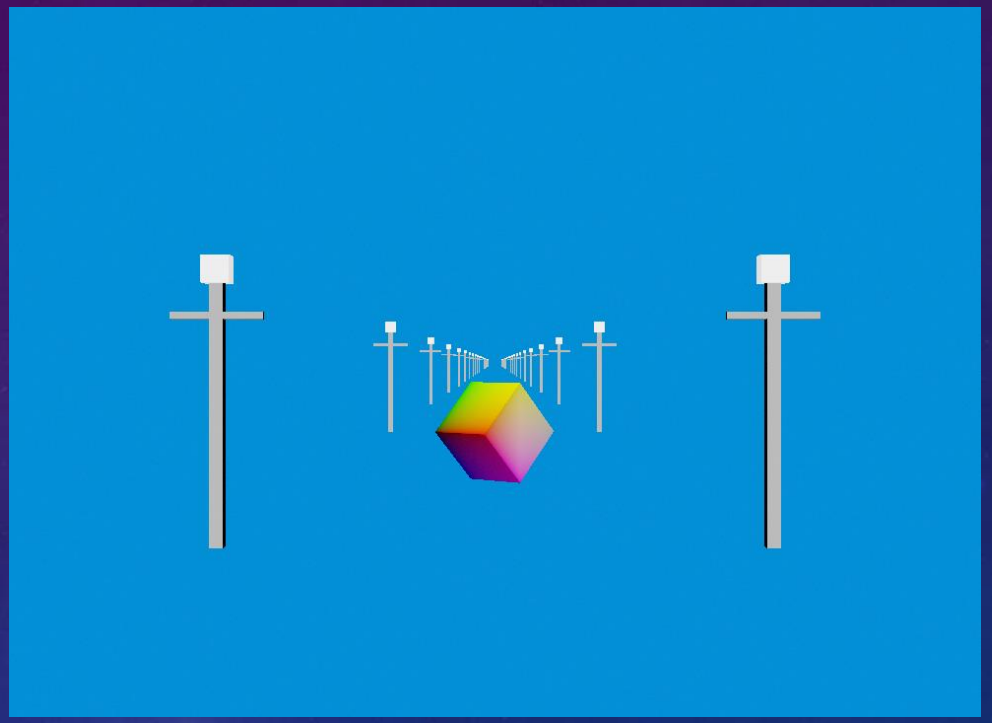
Focusing a Lens

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

- u = distance from lens to focal plane
- v = distance from lens to image plane
- When focused at infinity, $v = f$
- When focused closer to the lens, v increases and field of view will vary as a function of v instead of f
- Affects defocus blur

Focusing a Lens

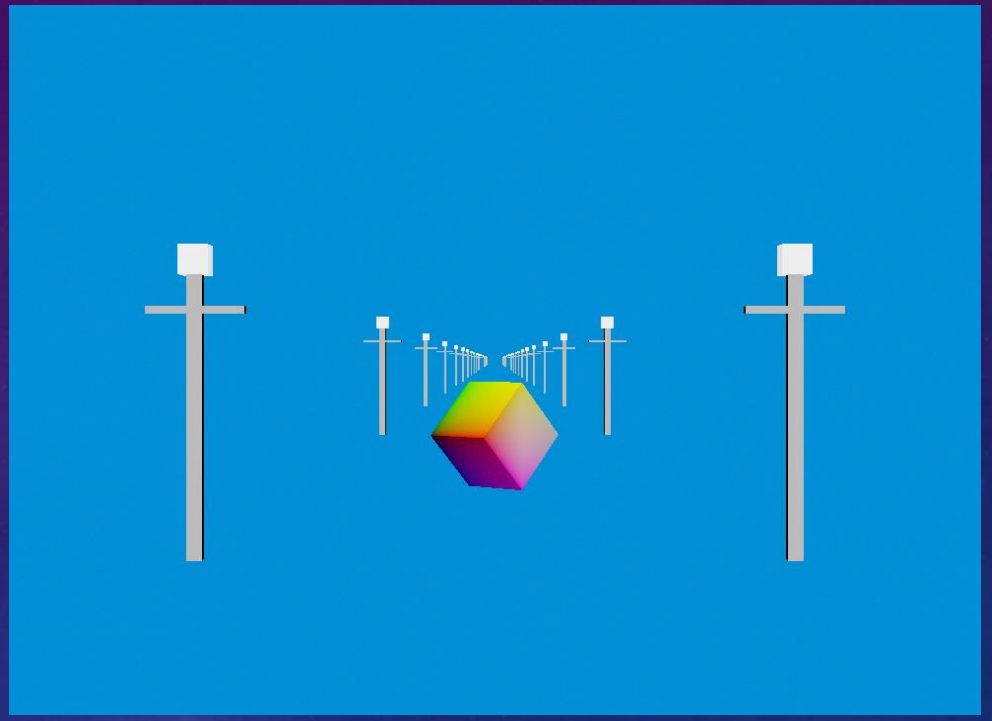
50mm lens focused at infinity



Focusing a Lens

50mm lens focused at 0.7 meters

(aperture of *f*/22 to keep everything in focus)



Exposure Control

- Aperture
  - Controls how much light passes through the lens system
  - Measured as the ratio of a lens' aperture diameter to its focal length
  - N = f-number
- Shutter
  - Controls how long the film or sensor is exposed

Exposure Calculation

$$E = \frac{TL}{4N^2}$$

- E = illuminance
- L = incoming luminance
- T = lens transmittance
- N = f-number

Exposure Calculation

$$H = Et$$

- H = exposure
- E = illuminance
- t = exposure duration

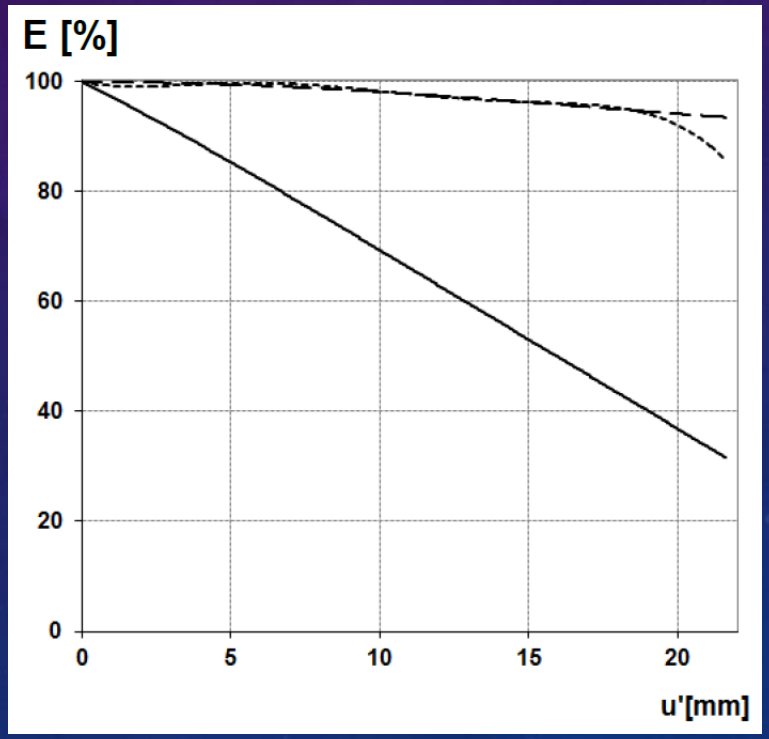
Vignetting

- Reduction in image brightness as you move away from the image center
- Natural vignetting
  - Illuminance is affected by the angle at which light enters the lens
  - $\cos^4 \theta$ law of illumination

$$E \propto cos^4\theta$$

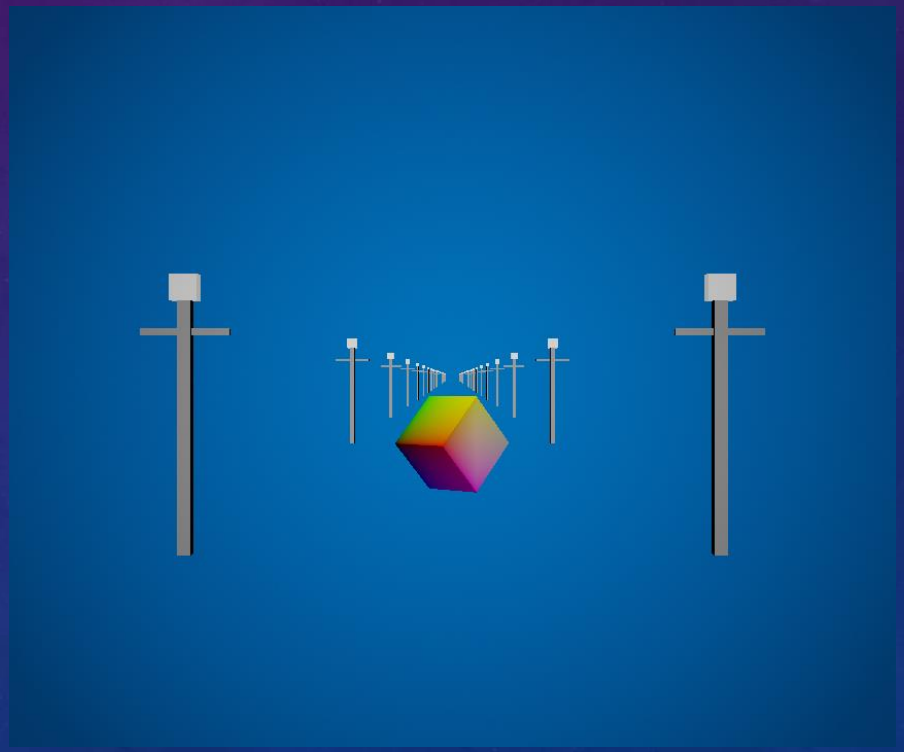
Natural Vignetting

- Provided by lens manufacturers as a plot of transmittance and off-axis distance



Natural Vignetting

- Use the transmittance graph to darken the output image



Film/Sensor

- Film has a non-linear response to light
- Characteristic curve
  - Plot of film opacity and log exposure

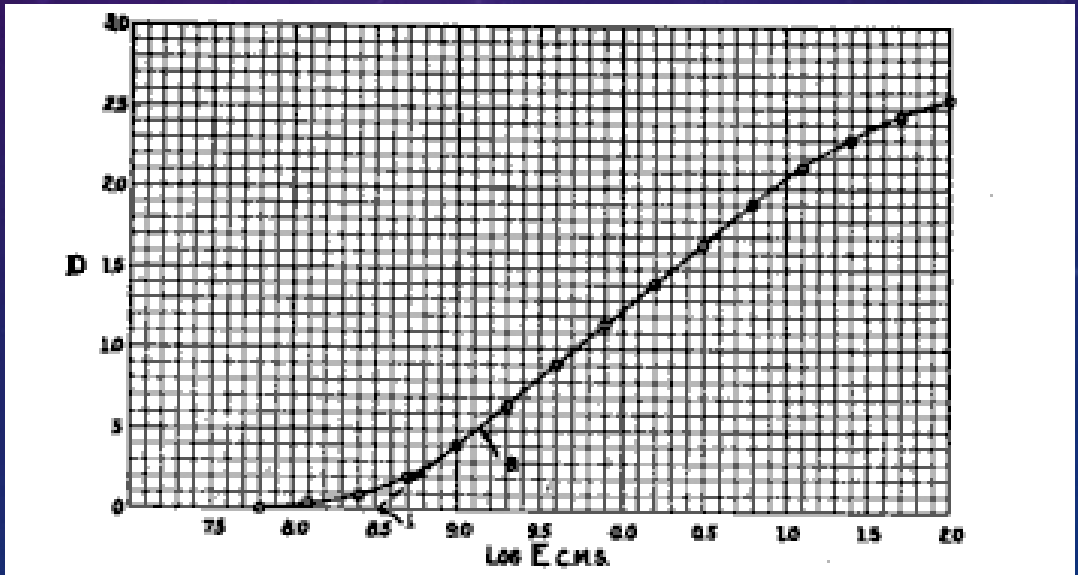


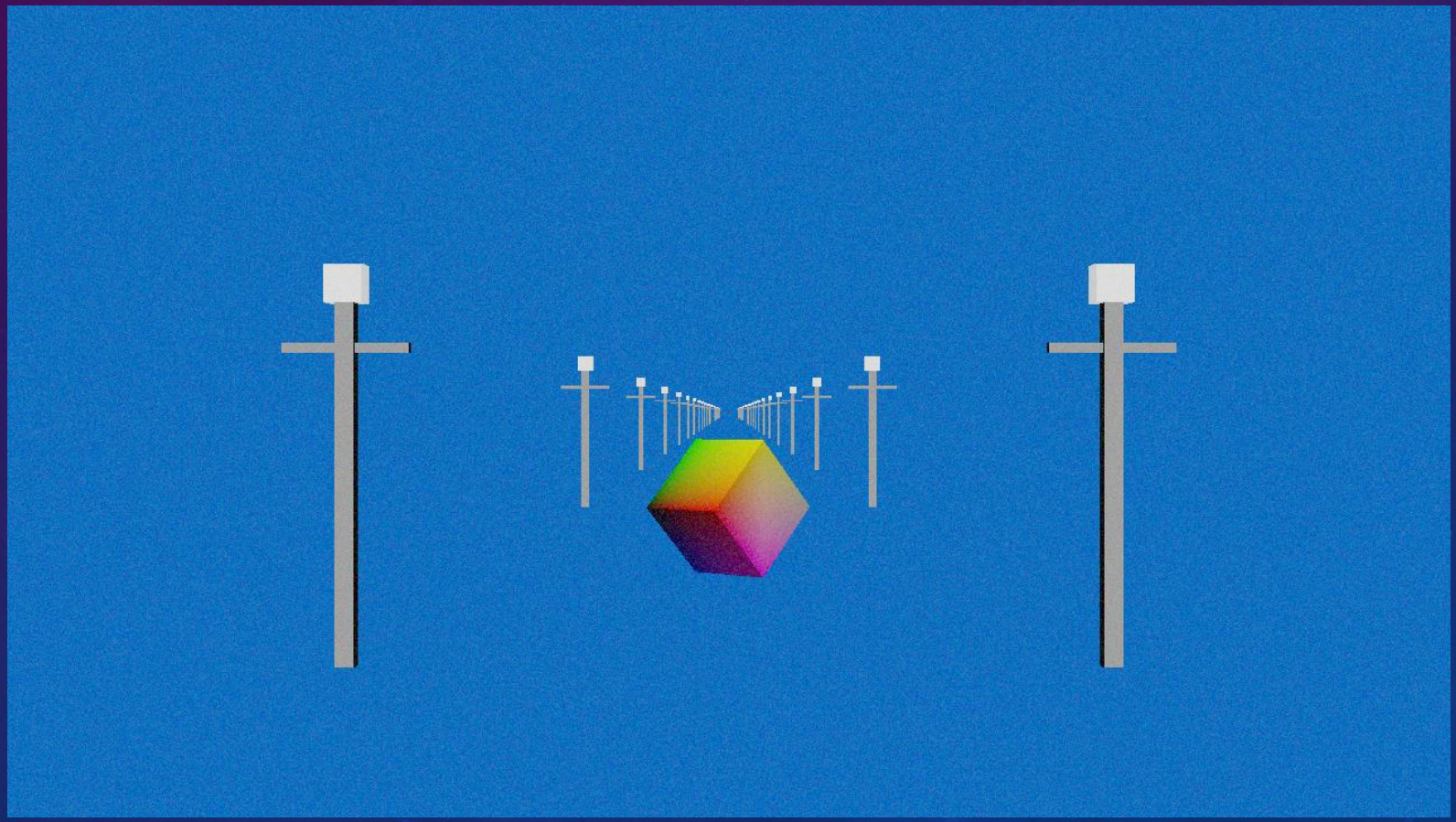
FIG. 6—*Density-exposure curve showing toe, straightline, and shoulder*

Film Grain

- More grain will be visible in film that is more sensitive in light
- Digital sensors don’t have physical grains, but they can have image noise

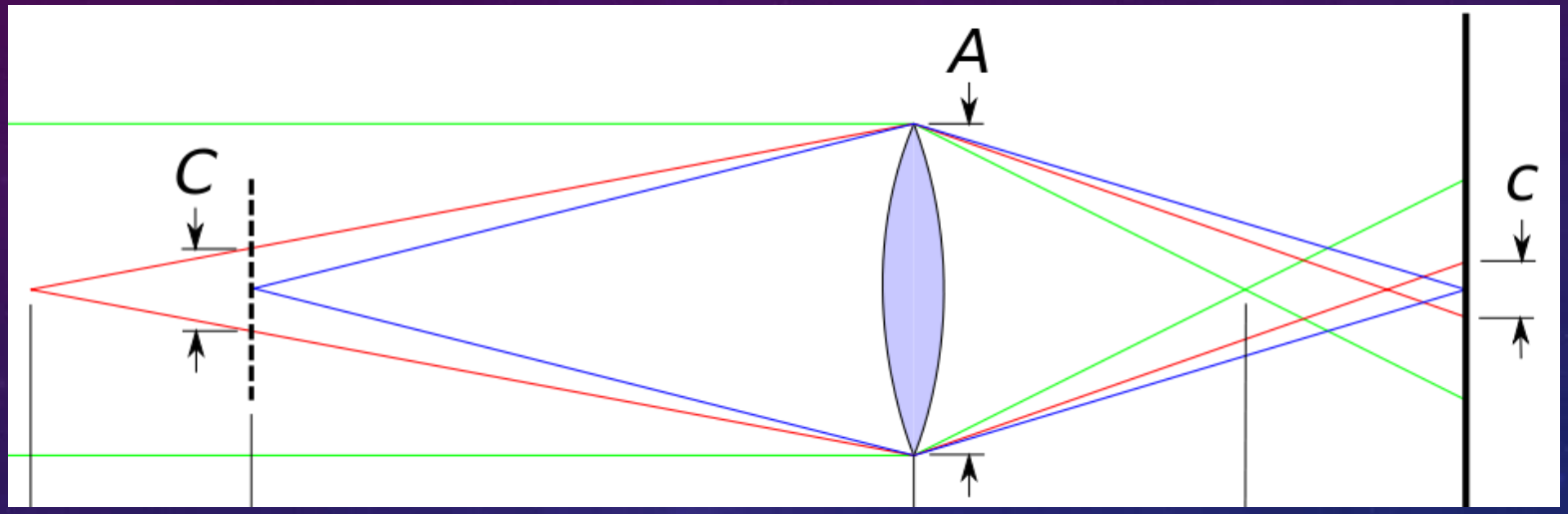
Film Grain

- Simulated with random noise



Defocus Blur and Motion Blur

Defocus Blur



- An object point that is not in focus is imaged as a blur patch (a circle of confusion)

Circle of Confusion Size

$$C = \frac{v^2|S - u|}{uSN}$$

- C = diameter of circle of confusion
- u = distance from lens to focal plane
- v = distance from lens to image plane
- S = distance from lens to defocused point
- N = f-number

Bokeh

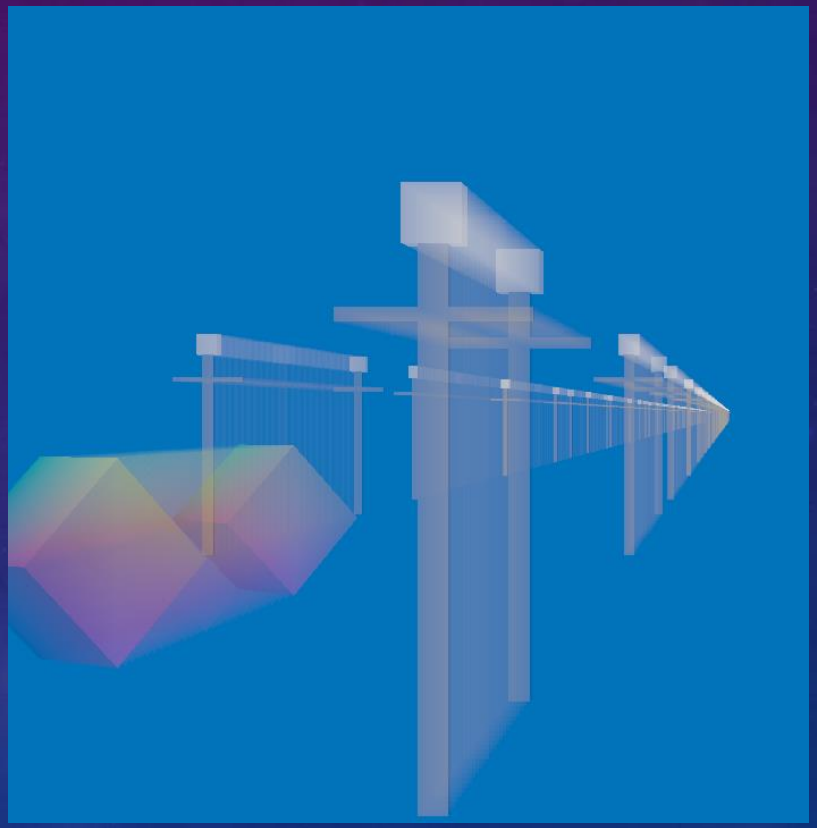
- The shape and quality of the defocused blur is known as bokeh
  - The bokeh shape is determined by the shape of the aperture
  - The distribution of light across the blur patch is affected by spherical aberration

Hexagonal Bokeh

Motion Blur

- Objects that are in motion for the duration of the exposure will be blurred in the output image
- Long exposure photography
  - Shutter can be left open for an extended period of time to capture motion trails
  - Simulated by accumulating the output images into a render target, applying an appropriate blend factor so that each frame is weighted correctly

Long Exposure Motion Blur



Optical Aberrations

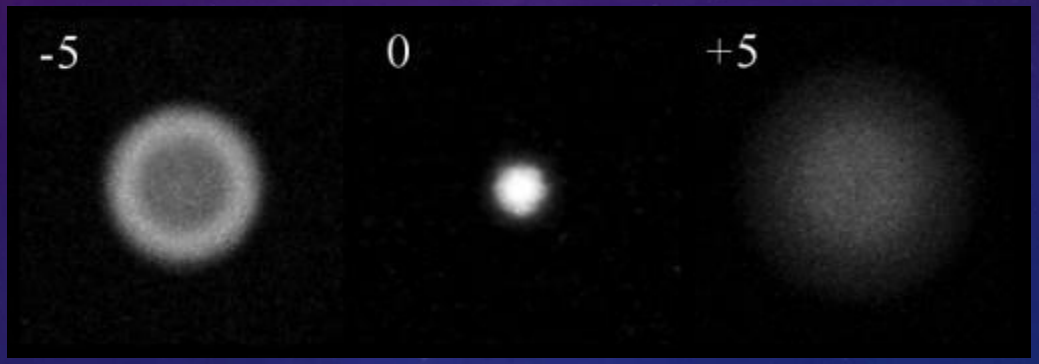
IMPERFECTIONS IN THE WAY LENSES REFRACT LIGHT

Spherical Aberration (SA)

- Positive SA: occurs in an uncorrected lens when the lens margins focus rays closer to the lens than the lens center
  - Foreground blur patch will have a dark core surrounded by a bright ring
  - Background blur patch will have a bright core fading out towards the edges
- When overcorrection is applied, the effect on foreground and background blurs are swapped

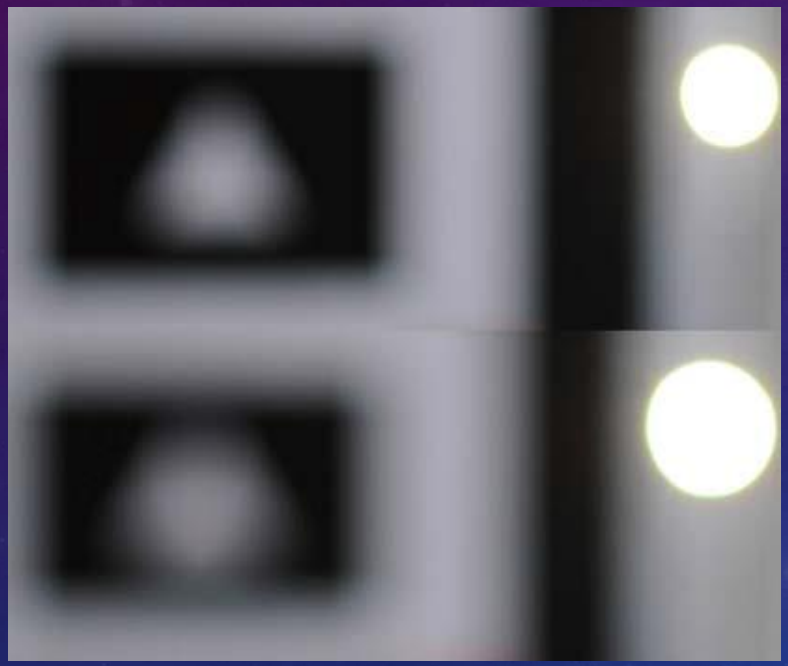
Spherical Aberration

- Simulated by modulating the bokeh with a texture representing the light distribution

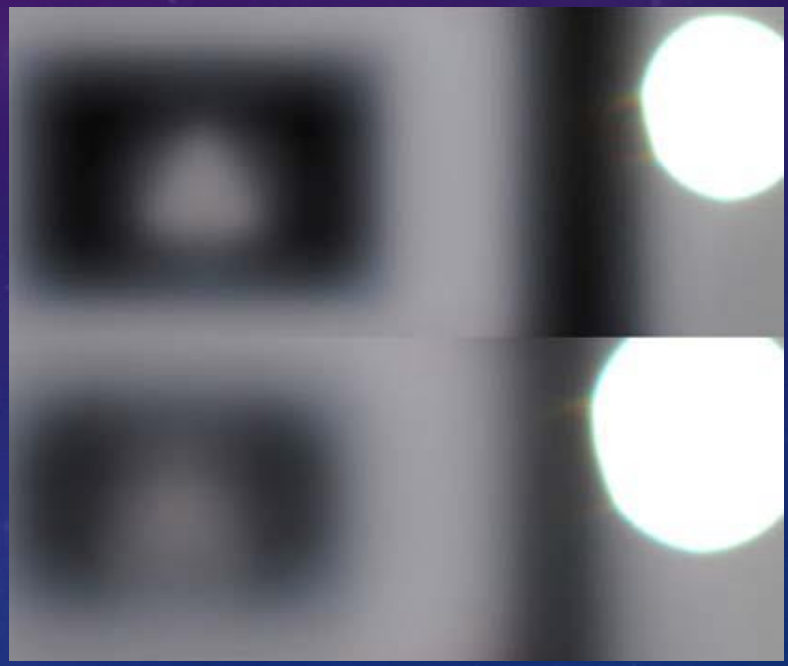


Background Defocus

Zero SA

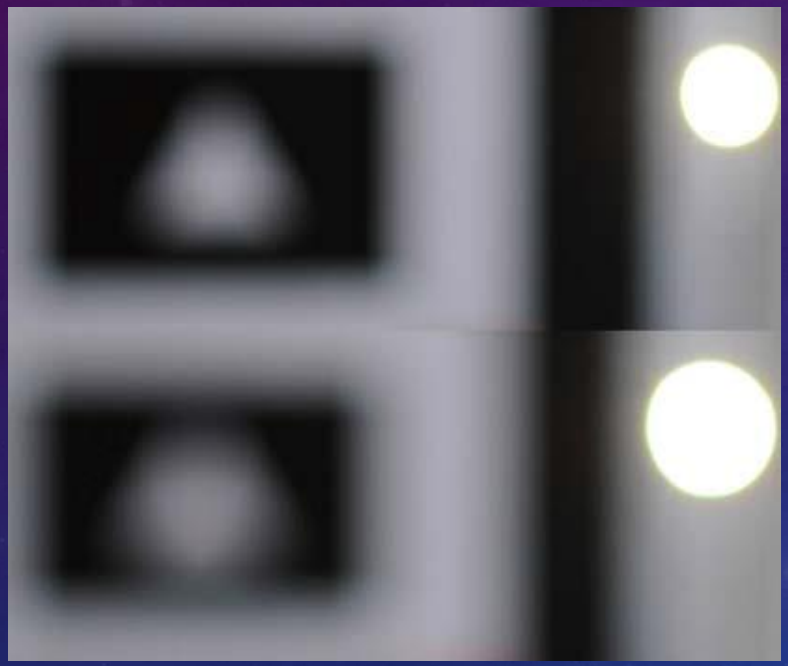


Positive SA

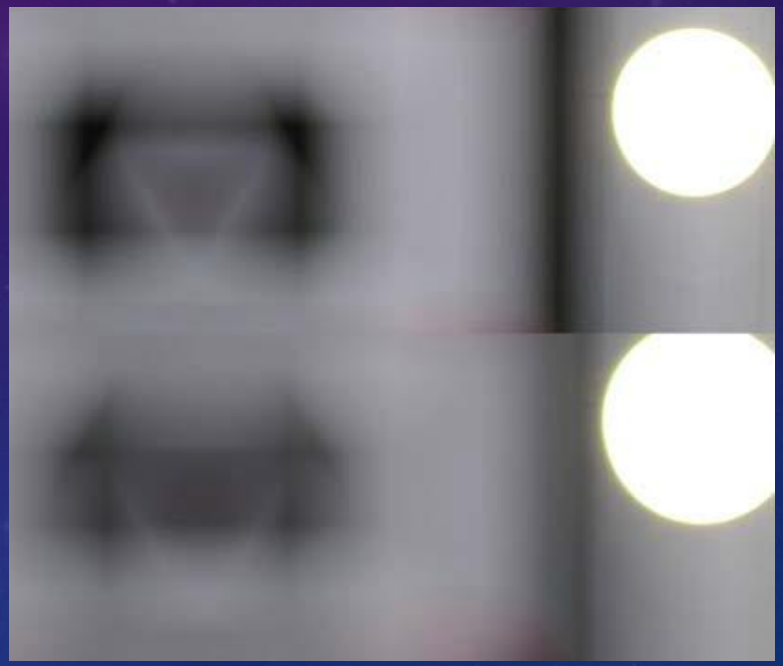


Background Defocus

Zero SA



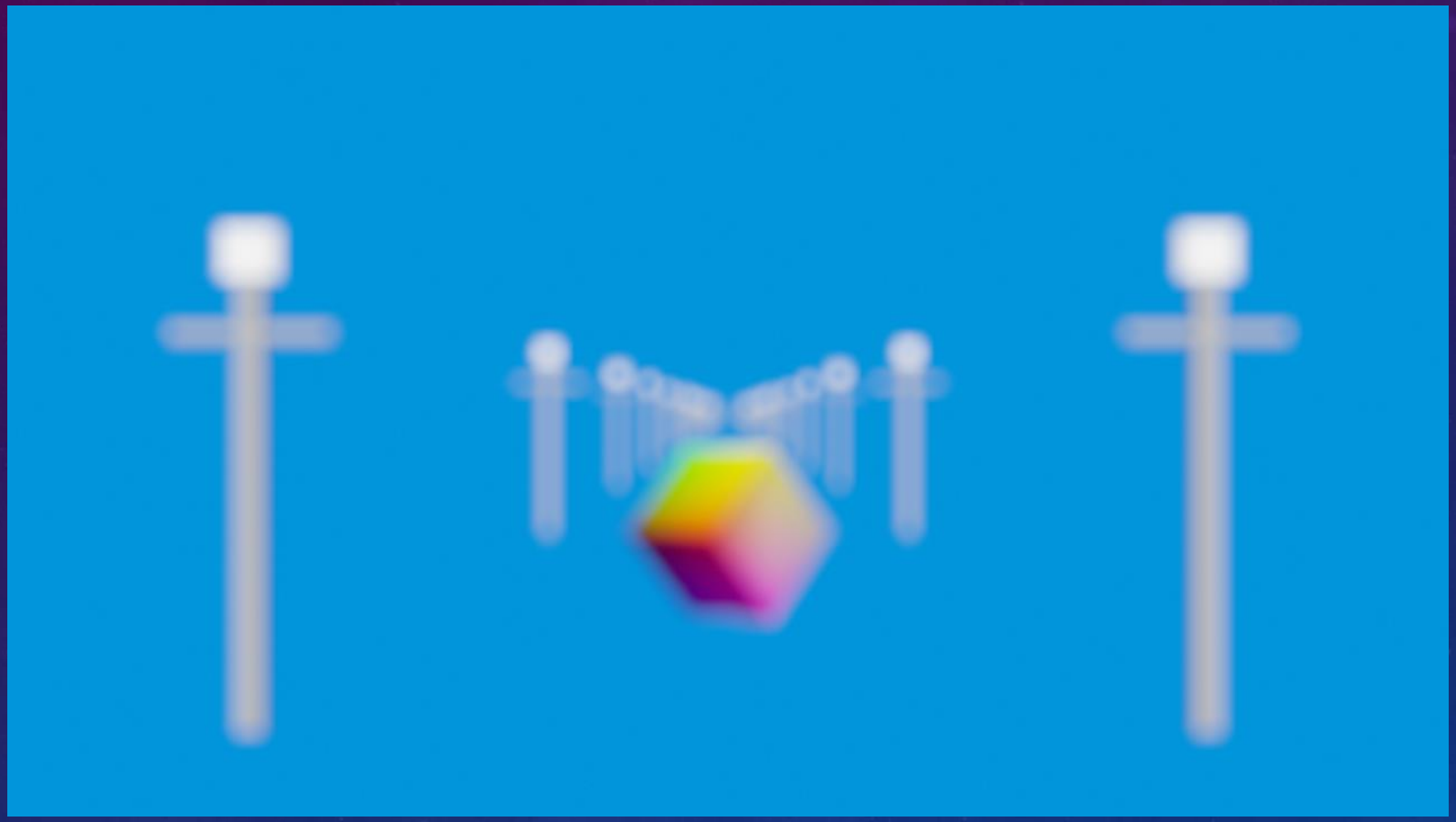
Negative SA



Zero Spherical Aberration

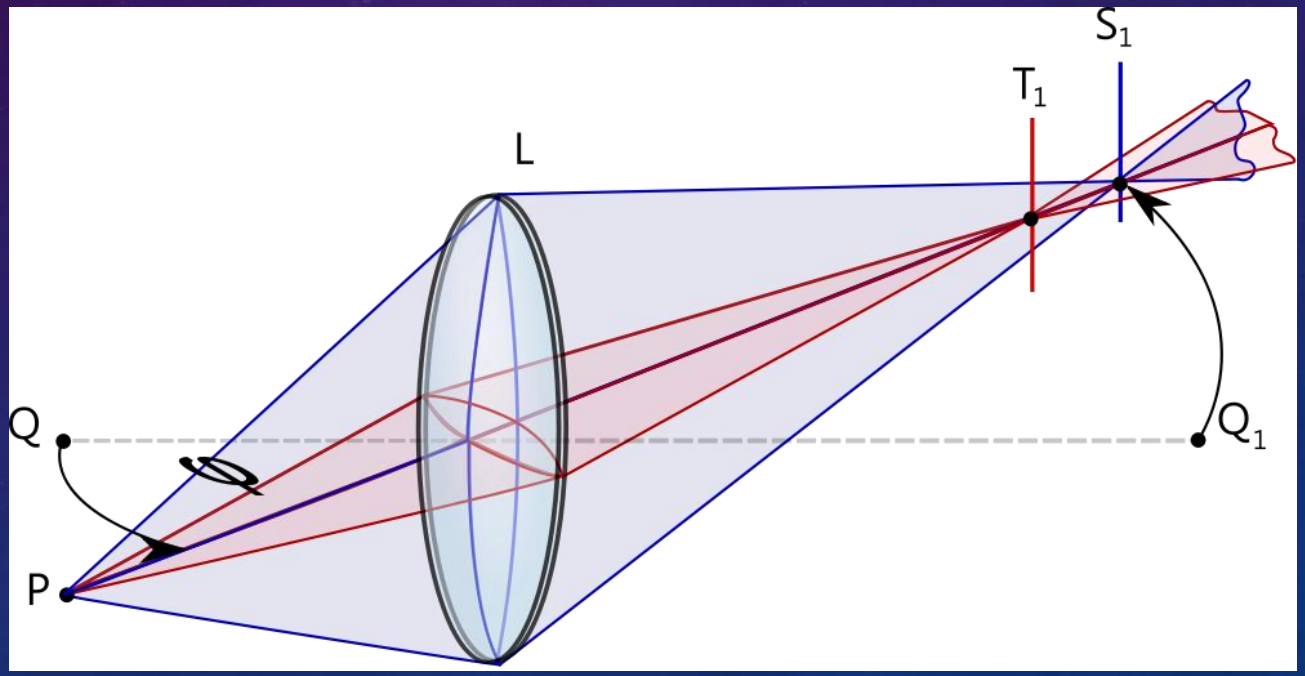
Positive Spherical Aberration

Negative Spherical Aberration



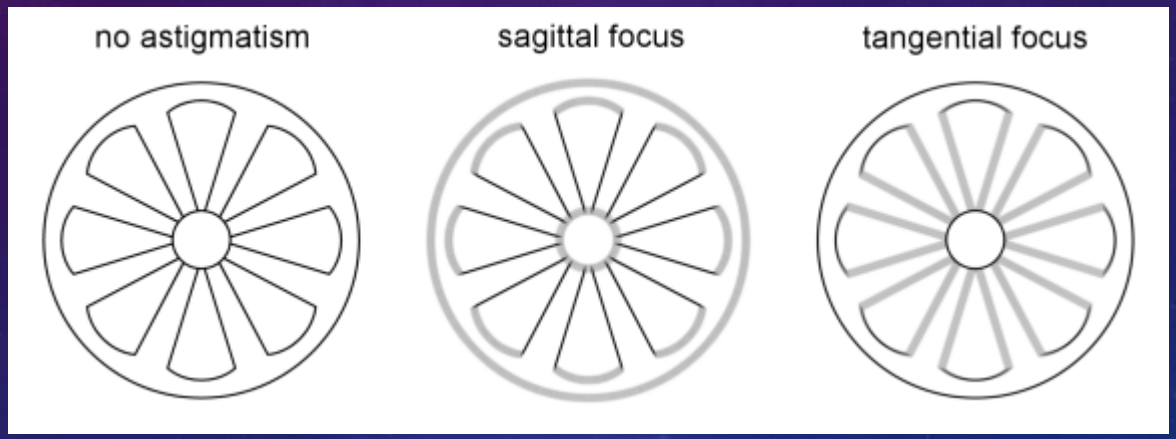
Astigmatism

- Occurs when rays traveling along the plane containing the optical axis (tangential rays) focus at a different distance than rays along the plane orthogonal to that (sagittal rays)



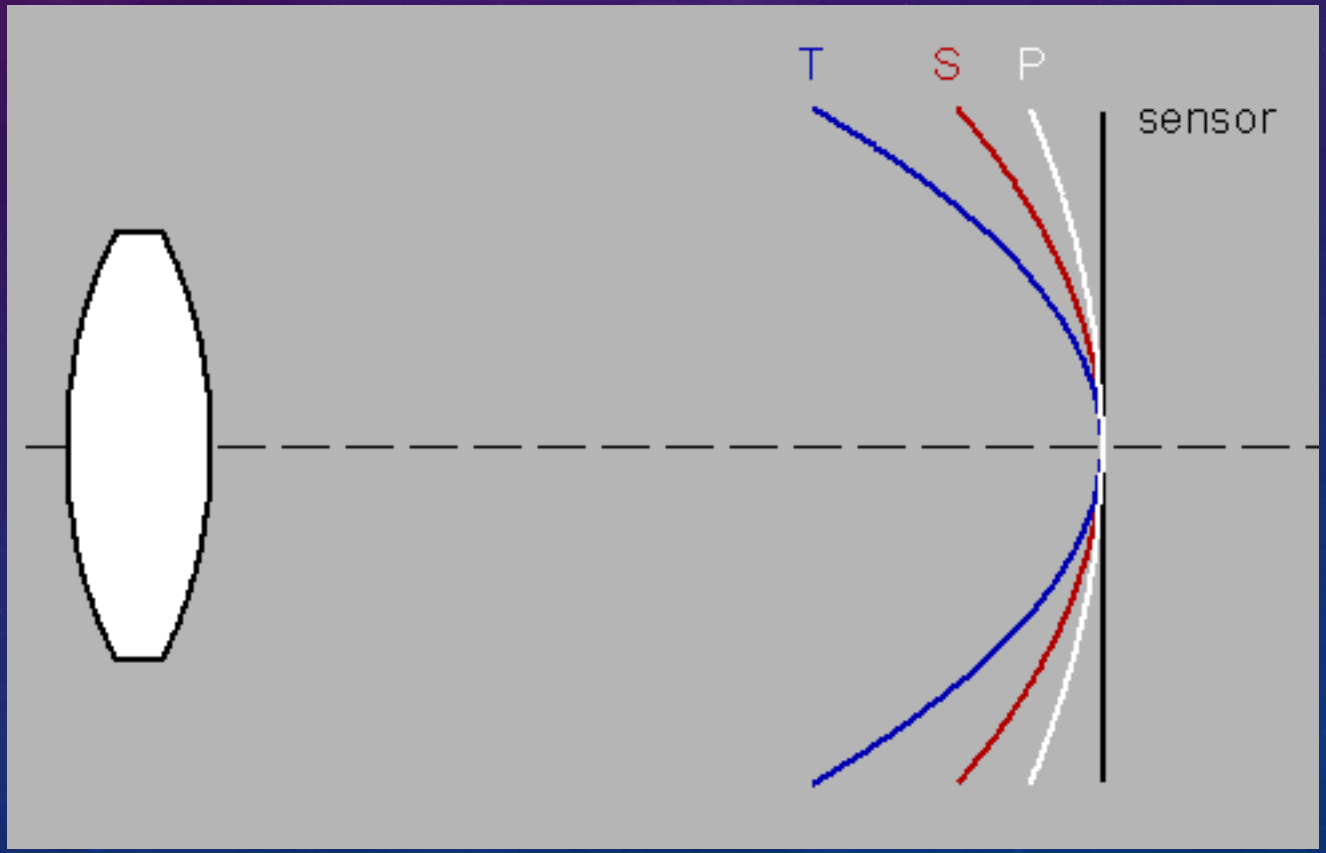
Astigmatism

- Visualized on a wheel, either the rims or the spokes are in focus, but not both at the same time



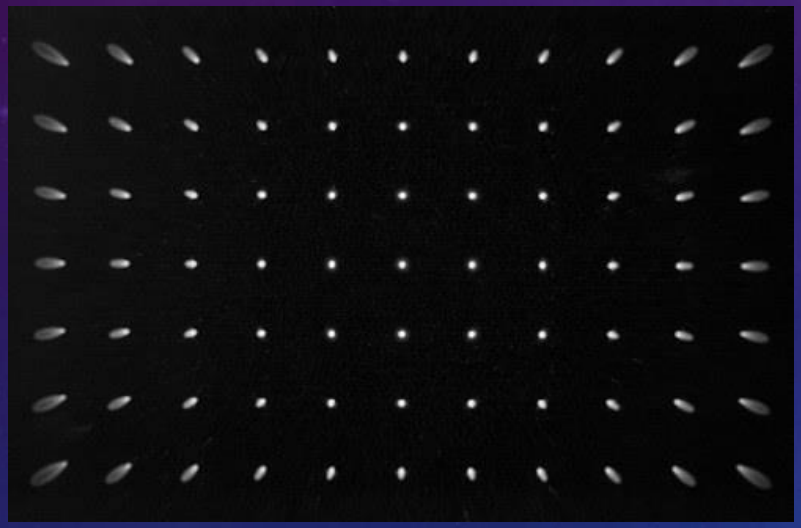
Astigmatism

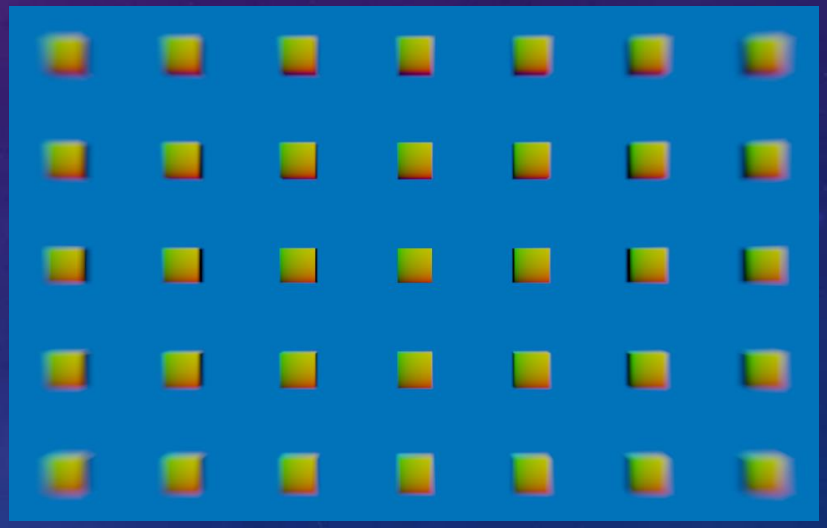
- Measured on a plot of focal offset from the image plane and off-axis distance



Astigmatism

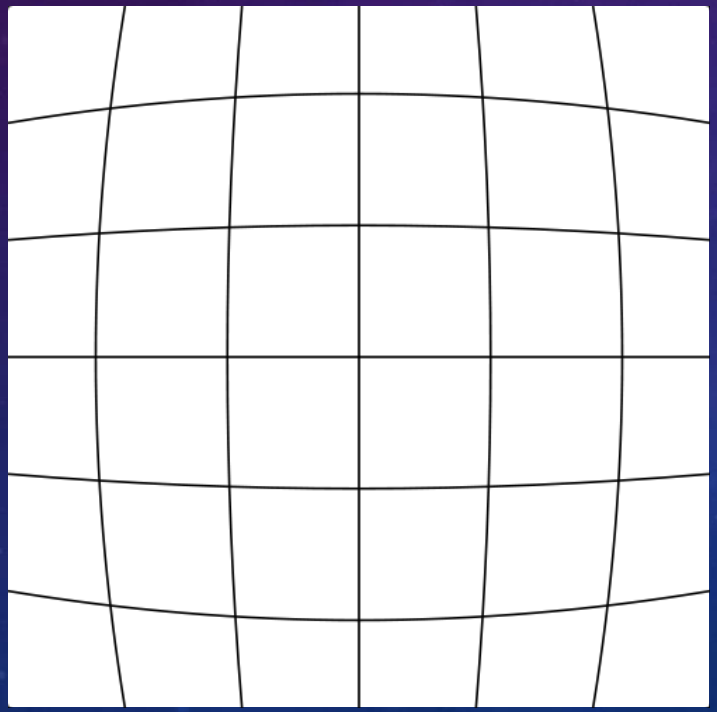
- Simulated by applying the appropriate amount of radial blur along the sagittal and tangential vectors

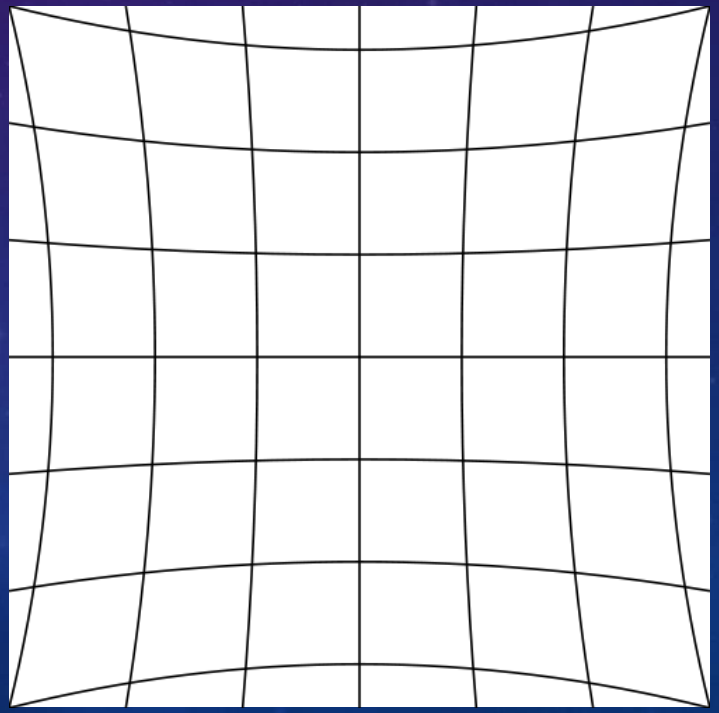




Distortion

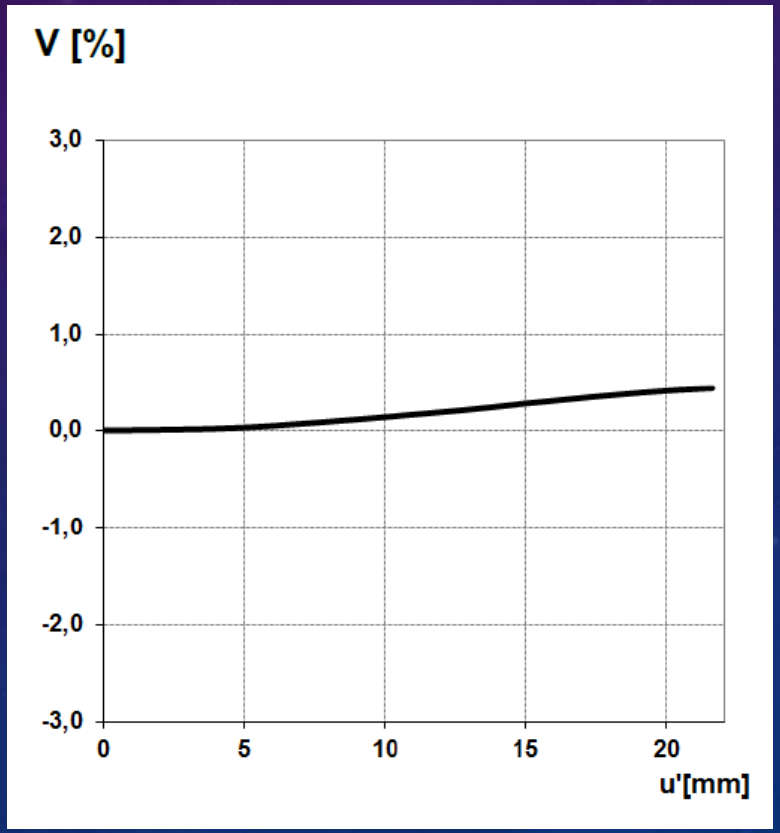
- Occurs when image magnification changes as a function of off-axis distance
- Mainly causes straight lines to appear curved





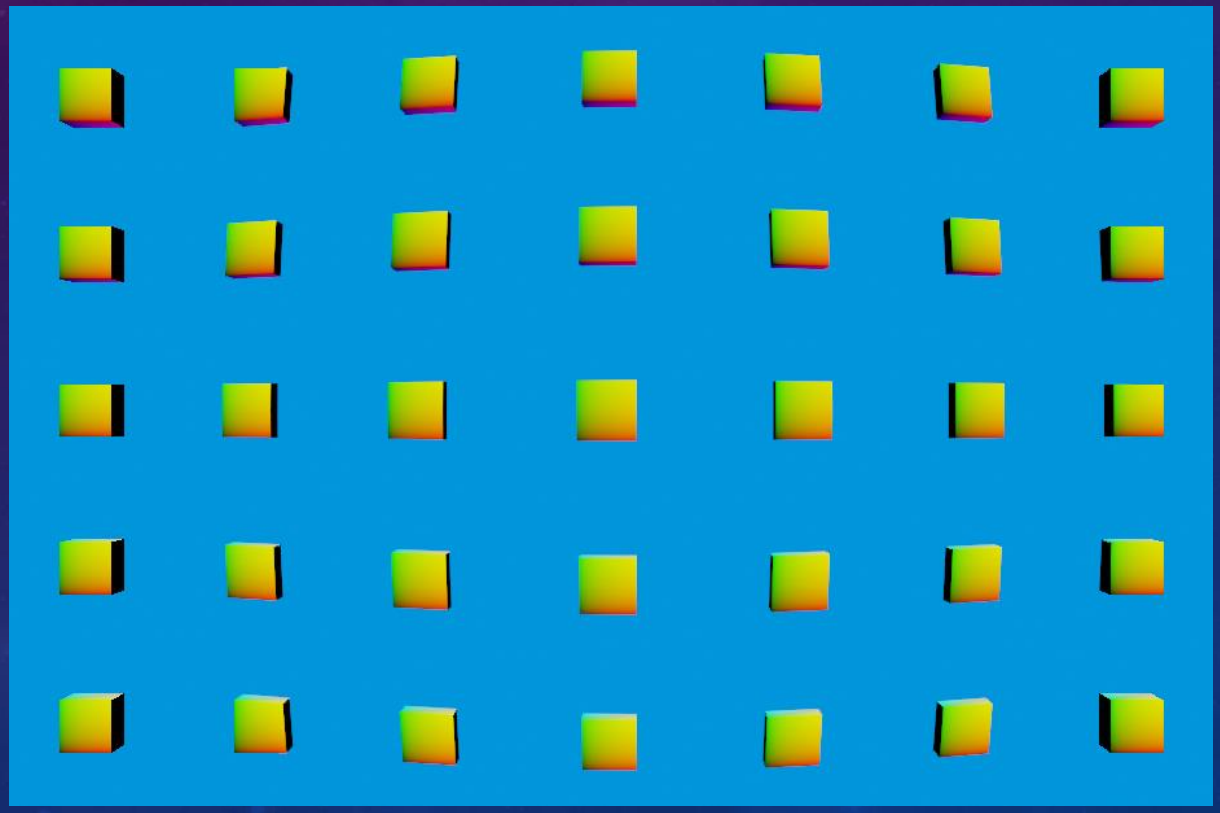
Distortion

- Provided by lens manufacturers as a plot of transmittance and off-axis distance



Distortion

- Simulated by applying an offset along the radial vector when sampling the source image for postprocessing



Analysis and Conclusion

Performance

- Intel Core i7-3635QM
  - 2.40 GHz (four cores)
  - Intel HD Graphics 4000
    - Approximately equivalent to a mid-range laptop graphics card
- Worst case performance test
  - Defocus blur on the entire image, with astigmatic blur, distortion, and vignetting applied

Performance

- 1280x720
  - All effects except defocus blur: 60 frames per second
  - Worst case: 28 frames per second
- 1920x1080
  - All effects except defocus blur: 30 frames per second
  - Worst case: 15 frames per second

Contributions

- A condensed set of optics equations that are directly applicable to virtual camera models
- A parameter-based model for describing and reproducing third order lens aberrations
- A flexible long-exposure model that allows the exposure to be started and stopped arbitrarily while allowing for easy control over the final exposure

Future Work

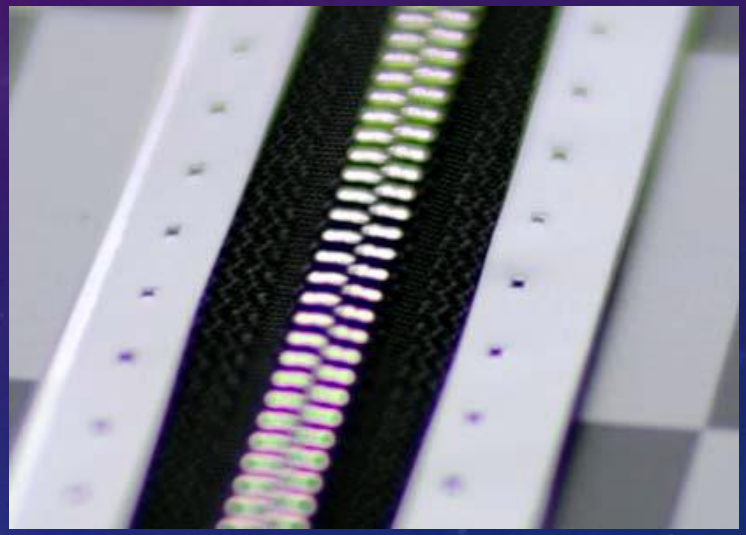
Unimplemented Aberrations

- Coma

- Field curvature

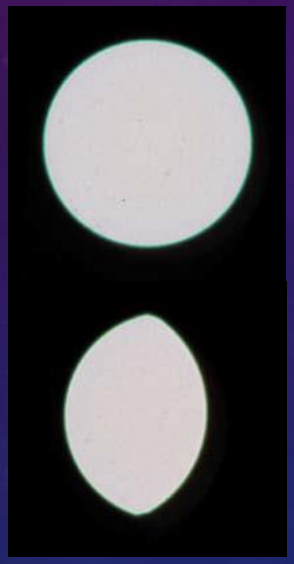
Unimplemented Aberrations

- Chromatic (and spherochromatic) aberration



Optical Vignetting

- Causes a cat's eye effect on the defocus blur



Further Reading

- Sidney F. Ray. *Applied Photographic Optics*. Focal Press, 2002.
- H. H. Nasse. Depth of Field and Bokeh. 2010. URL: http://www.zeiss.com/C12567A8003B8B6F/EmbedTitelIntern/CLN_35_Bokeh_EN/$File/CLN35_Bokeh_en.pdf

Image Sources

- http://en.wikipedia.org/
- http://toothwalker.org/optics.html
- Additional resources: See paper

Questions?