General Spectral Camera Lens Simulation

• chromatic aberrations • spherical aberration • coma • astigmatism • distortion • aperture diffraction • lens flares • path generation

Overview

We present a camera lens simulation model capable of producing advanced photographic phenomena in a general spectral Monte Carlo image rendering system. Hereby, one generally solves the rendering equation by Kajiya. The actual image is formed by sampling a sensor plane and starting paths traversing an optical device. For efficiency reasons the camera model is handled separately instead of being part of the scene geometry. Our approach, based on Monte Carlo path generation methods, extends existing approaches by Kolb et al. [KMH95] by certain important aspects:

- **Wavelength** dependent events
- Usage of **real glass** data
- Consideration of dielectric **Fresnel** interaction
- Ray based **diffraction** simulation at the aperture
- **Efficient** path generation with pupil consideration per pixel
- Progressive approach to render specific artifacts

This leads to:

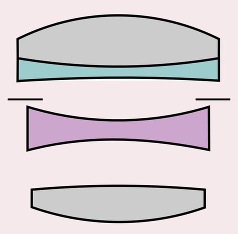
- **Chromatic aberration** verification
- Simulation of all monochromatic **Seidel aberrations**
- **Lens flare** simulation
- **Glare streaks** resulting from diffraction at the aperture
- Realistically shaped **Bokeh**
- All **advanced** effects caused by lens geometry such as barrel flare or vignetting

Implementation

Details about out reference implementation:

- Spectral Monte Carlo path tracer in both path directions
- Mono-ray bounding volume hierarchy for the scene
- Lens tracer with optimized methods for traversing lenses
- Spherical dome as main data structure for every lens surface
- Ray buffer for precomputing rays for the next rendering pass
- Geometric aperture or texture for intersection test
- Implementation of the diffraction process as specific material routines for the aperture

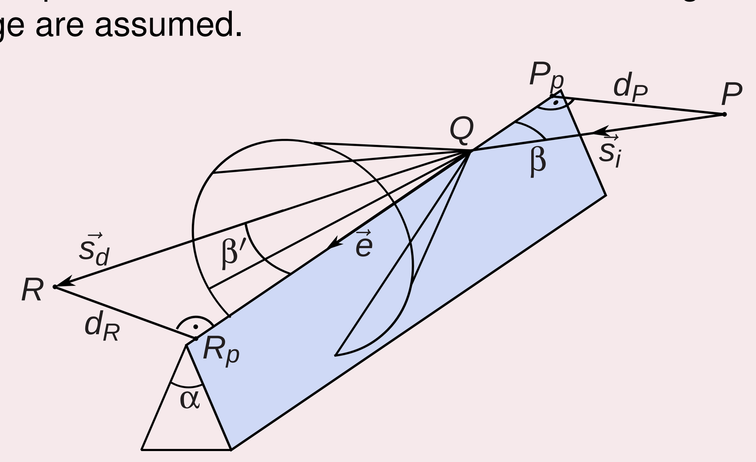
sphere radius	thickness	material	IOR	V-no	radius
42.970	9.8	LAK9	1.691	54.7	19.2
-115.33	2.1	LLF7	1.549	45.4	19.2
306.840	4.16	air			19.2
	4.0	air			15.0
-59.060	1.870	SF7	1.640	34.6	17.3
40.930	10.640	air			17.3
183.920	7.050	LAK9	1.691	54.7	16.5
-48.910	79.831	air			16.5



Real lens data from popular designs in the field of optical engineering specify all needed information to build up an analytic representation for intersection tests and refraction calculation. This definition of a Tessar [Smi05] lens design informs about used materials and element dimensions.

Diffraction Simulation

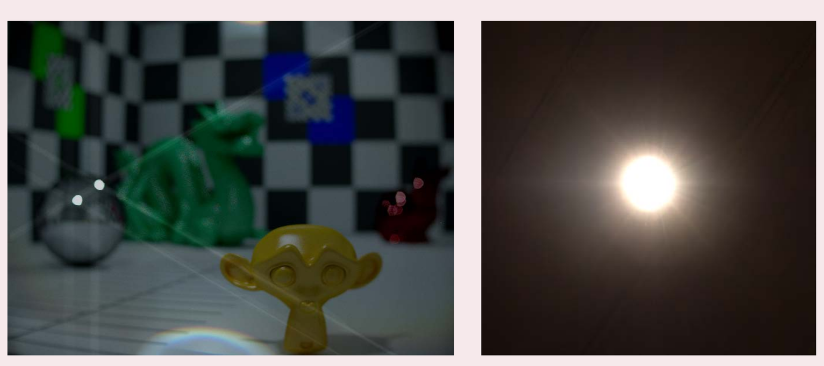
Spectral properties are accounted for by extending the Monte Carlo Simulation with a wavelength dimension. The complex wave property of light causes diffraction effects, not explainable with classic geometrical optics. Approaches by Joseph B. Keller on the Geometrical Theory of Diffraction [Kel62] adopted the wave behavior of light to a modified Fermat setting. Unpolarised spherical wave fronts with interference neglected, hitting a straight edge are assumed.



Aveneau and Mériaux proposed using Keller's Geometrical Theory of Diffraction in an image rendering setting. Contrary to their approach, we are explicitly sampling the diffracted path directions inside the Keller Cone, the space of all valid diffraction directions. An appropriate diffraction coefficient for unpolarised light can be found in [AM99].
The simulation steps are:

- For every ray passing the aperture choose, whether it is continued as diffracted ray or normal ray. The possibility decreases with distance to the edges.
- If ray becomes diffracted, sample a diffraction direction inside the surface of the Keller Cone.
- Continue ray and account for the diffraction coefficient.

Diffraction of incoming light at the aperture blades forms streaks perpendicular to the edges. Diffraction effects can be simulated separately and simply added to the rest of the light transport. The resulting light streaks have a significant impact on the brightness perception of light sources.

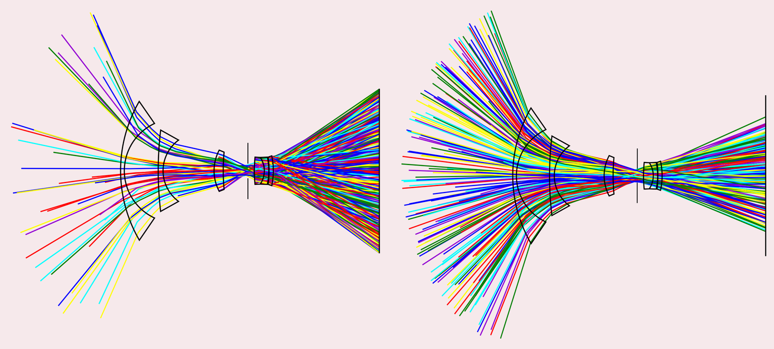


The left image is a result, rendered with out method. The right image is as real photograph of a light source, showing a clear halo and noticeable streaks originating from the source.

Path Generation Challenge

Effective path generation through a lens holds several challenges:

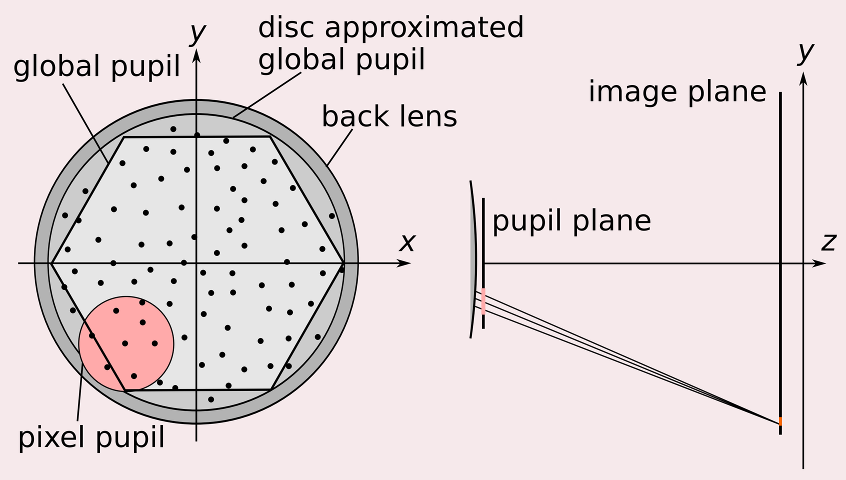
- Optical vignetting: Only paths passing through the effective aperture of a lens on both sides contribute to the image.
- During forward path tracing through the lens, only rays inside the field of view are of interest.
- The image of the aperture on both sides of the lens defines the region of passage.



Path plot for a Muller [Smi05] fish-eye at f/8. The aperture has only 1.8mm diameter. Ray passage rate is 10% without (left) and 82% with pixel pupil sampling (right).

Our approach samples the effective pupil per pixel:

- Create paths per pixel, save whether ray leaves the other side or not.
- Average the hit-points on the back most lens of all positive paths. This is the center of a disc, approximating the pupil.
- The radius can be found by the block path with nearest distance from the pupil center.
- Compute pupil per pixel and use it from now on for path construction.
- By choosing a more precise representation, the passage ratio can be up to 100%.
- Source lens path calculation out to the GPU.

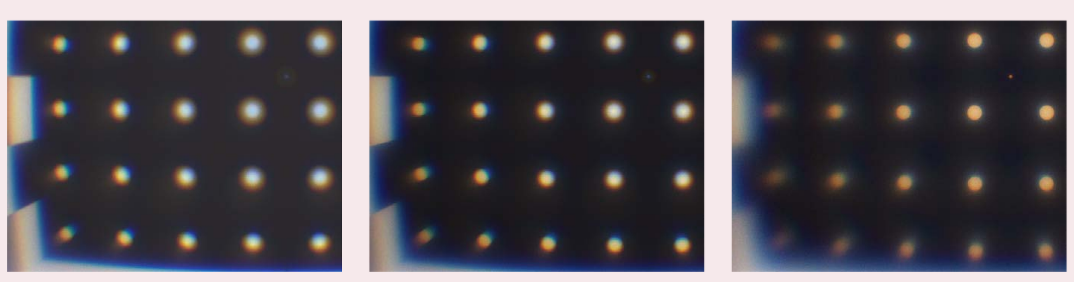


Bokeh

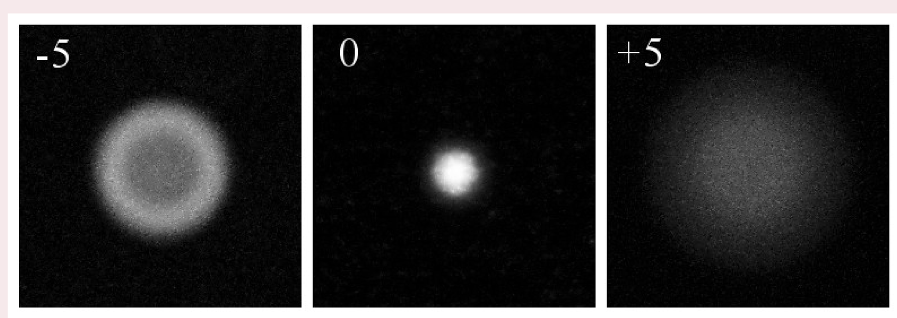
One direct consequence of using a real lens design is a limited depth of field, especially for high speed lenses. Bokeh is the term for the visual appeal of the out-of-focus region.

Here, the size and shape of the aperture is an important factor, as it influences the appearance of out-of-focus features. On the left our test scene, on the right a reference photograph.

Spherical Aberration and Lateral Color



Unequal focus near the border is caused by spherical aberration and field curvature. The color shift of the marginal circles in the defocussed left version is called lateral color originating from varying magnification over all wavelengths.

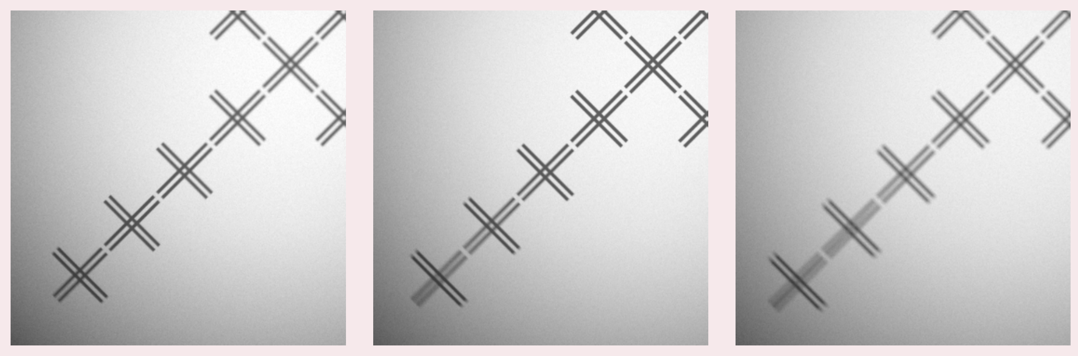


These reference pictures show the same pattern composition, here in gray-scale for the center dot. By courtesy of Paul van Walree ©.

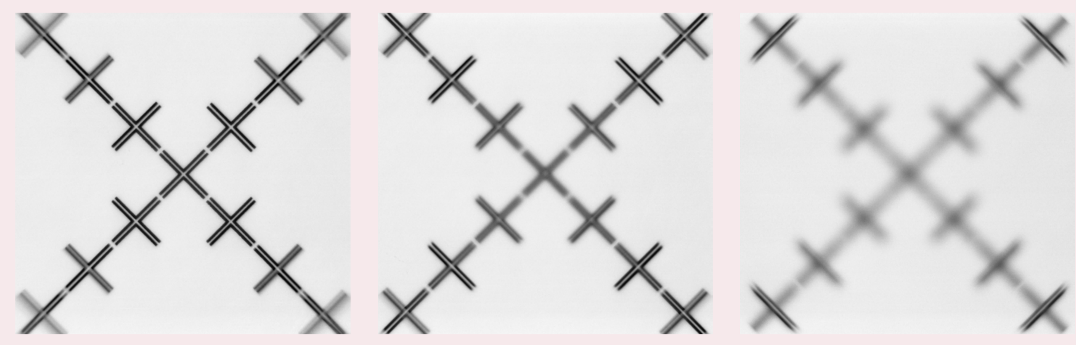
Distortion

Two shots with two different types of fish-eye lenses, 180° and 145° field of view. The scene *History Museum* is available at `http://www.3drender.com`. The right image is a comparison panorama of the Muensterplatz in Ulm.

Astigmatism and Field Curvature



Astigmatism and field curvature observed for a Petzval[Smi05] design lens at different image distances. The shown pictures are lower left corner crops of an astigmatism cross test pattern, in front of, in, and behind the plane of focus. Tangential structures in the marginal regions stay rather focused, the sagittal lines towards the center become blurred.



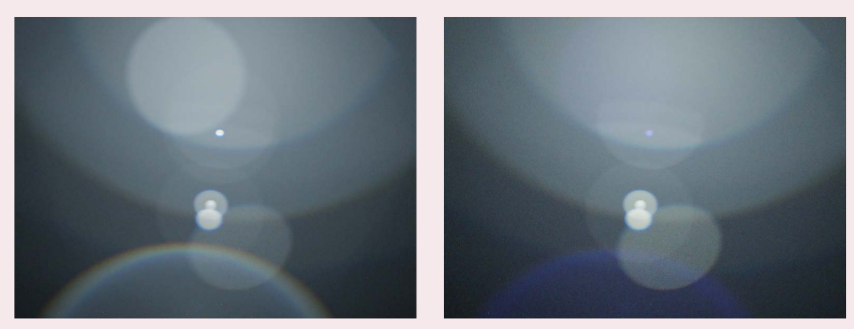
Comparison photographs, shot with a Zeiss Planar lens. By courtesy of Paul van Walree ©.

Lens Flare Simulation

Since a single ray-based rendering technique cannot sufficiently cover all possible effects, a progressive rendering method that combines several techniques is required. Central observations are:

- Lens flare paths are strictly singular.
- Only direct light from the source to the lens is important.
- Forward path tracing from the light source delivers much higher convergence rates.
- Neglecting direct light to the front most lens part in the backward path tracing stage allows both results to be simply summed up to one final image.
- Pixel pupil sampling cannot be used in combination with lens flare computation, because the relevant field of view is not limited here.

By saving the result in the forward light tracing pass, the lens flare can be examined separately from other effects.



Examples clearly showing how a single lens coating suppresses specific lens flare parts.

Reference photographs of typical flare light situations. By courtesy of Paul van Walree ©.

References

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