02941 Physically Based Rendering

Camera and Eye Models

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Models needed for physically based rendering

Repetition from the first lecture:

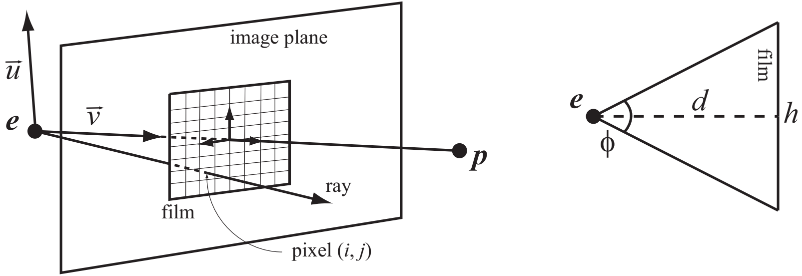
- Think of the experiment: “taking a picture”.
- What do we need to model it?
  - **Camera**
  - Scene geometry
  - Light sources
  - Light propagation
  - Light absorption and scattering
- Mathematical models for these physical phenomena are required as a minimum in order to render an image.
- We can use very simple models, but, if we desire a high level of realism, more complicated models are required.

Ray casting

- Camera description:

Extrinsic parameters		Intrinsic parameters	
$\boldsymbol{e}$	Eye point	ϕ	Vertical field of view
$\boldsymbol{p}$	View point	d	Camera constant
$\vec{u}$	Up direction	W, H	Camera resolution

- Sketch of ray generation:

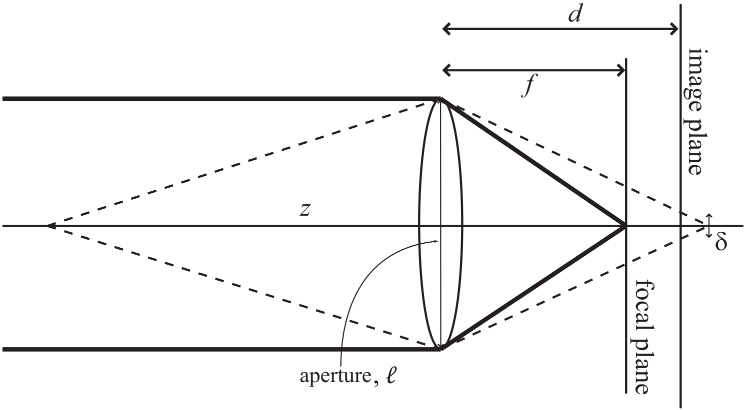


- For each ray, find the closest point where it intersects a triangle.

Photography and depth of field

- Small lens means large depth of field, but less incident light.
- Large lens means more incident light, but small depth of field.
- The focal length of a lens also has an influence. See more at https://en.wikipedia.org/wiki/Depth_of_field

A model for thin lenses



z is the distance to the photographed object.

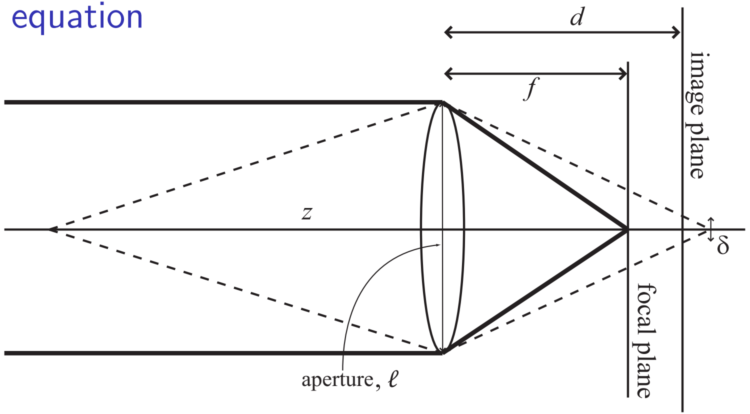
d is the *camera constant*: the distance between the lens and the image plane.

f is the *focal length*: the distance to the focal plane where collimated light is focused in a point.

ℓ is the *aperture*: the diameter of the lens.

δ is the diameter of the *circle of confusion* for objects at the distance z.

The thin lens equation



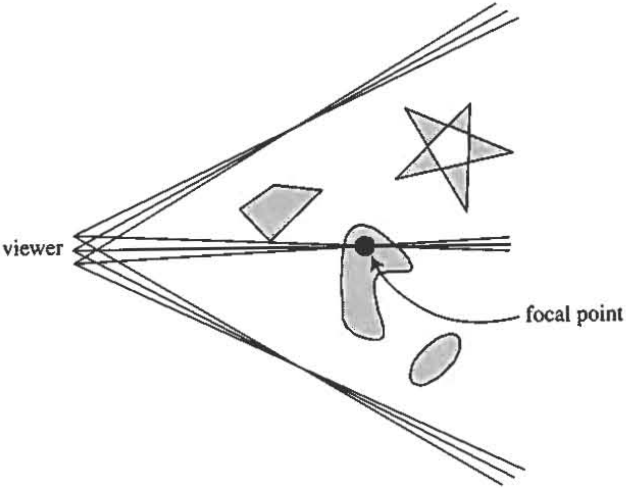
- An image will be perfectly sharp for objects at the distance z_d, where

$$\frac{1}{z_d} + \frac{1}{d} = \frac{1}{f} \quad .$$

- Using the concept of similar triangles, we may derive

$$\delta = \left| \frac{\Delta d}{d + \Delta d} \right| \ell = \left| \frac{\frac{z_d}{z} - 1}{z_d - f} \right| f \ell \quad .$$

Modelling depth of field



- Centering the circle of confusion around the eye point, we can simulate depth of field by sampling different eye positions within the circle of confusion.

Modelling depth of field

- Centering the circle of confusion around the eye point, we can simulate depth of field by sampling different eye positions within the circle of confusion.
- Then we need a circle of confusion that is independent of z.
- Suppose we let z go to infinity, then

$$\begin{aligned}\delta_\infty &= \lim_{z\to\infty} \delta = \lim_{z\to\infty} \left| \frac{\frac{z_d}{z} - 1}{z_d - f} \right| f\ell \\ &= \lim_{z\to\infty} \left| \frac{z_d}{z} - 1 \right| \frac{f\ell}{z_d - f} = \frac{f\ell}{z_d - f} \quad .\end{aligned}$$

- Now, we can sample an offset inside the circle of confusion with diameter δ_∞.
- Blending images seen from slightly displaced viewers that look at the same focal point will result in a depth of field effect.
- Error (considering similar triangles): $\frac{\delta_\infty}{z_d} = \frac{\delta_{\text{model}}}{|z_d - z|} \Leftrightarrow \delta_{\text{model}} = \frac{|z_d - z|}{z_d}\delta_\infty = \frac{z_d}{z}\delta$.
- Thus, since f is constant and zoom changes d, the camera has largest depth of field when zoomed out as much as possible.

Example

- A demo program used to be available in the OptiX SDK.

References

- Cook, R. L., Porter, T., and Carpenter, L. Distributed ray tracing. *Computer Graphics (SIGGRAPH '84) 18*(3), pp. 137–145. July 1984. https://doi.org/10.1145/800031.808590

02941 Physically Based Rendering

Glare and Fourier Optics

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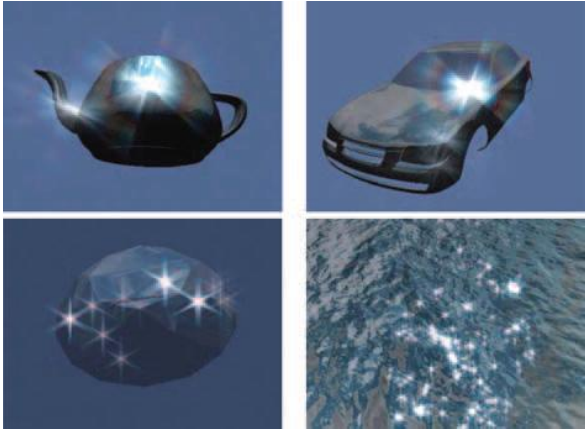
Ritschel, T., Ihrke, M., Frisvad, J. R., Coppens, J., Myszkowski, K., and Seidel, H.-P. Temporal glare: Real-time dynamic simulation of the scattering in the human eye. *Computer Graphics Forum (EG 2009) 28*(2), pp. 183-192. April 2009. https://doi.org/10.1111/j.1467-8659.2009.01357.x

Examples of artistic and simulated glare

- All people experience glare to some degree

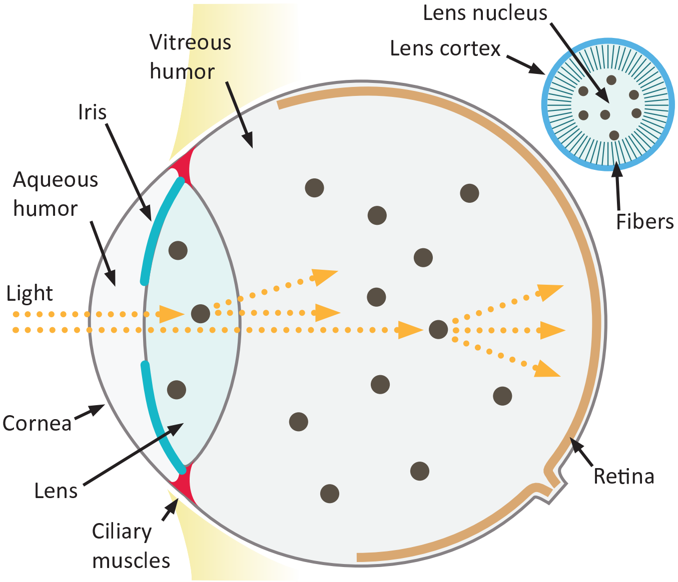


- Painting by Carl Saltzmann, 1884
- Renderings by Kakimoto et al. [2005]
- Columbia Pictures Intro Video
- Why is it not in photos?

Categories of glare

- Glare
  - An interference with visual perception caused by a bright light source or reflection.
  - A form of visual noise.
- Discomfort glare
  - Glare which is distracting or uncomfortable.
  - Does not significantly reduce the ability to see information needed for activities.
  - The sensation one experiences when the overall illumination is too bright e.g. on a snow field under bright sun.
- Disability glare
  - Glare which reduces the ability to perceive the visual information needed for a particular activity.
  - A haze of veiling luminance that decreases contrast and reduces visibility.
  - Typically caused by pathological defects in the eye.

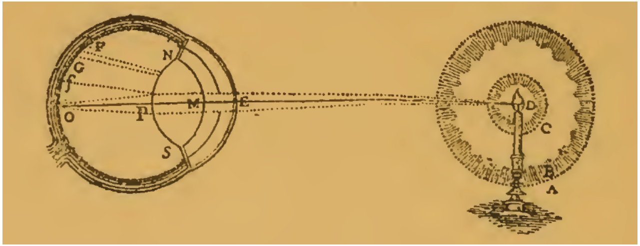
Anatomy of the human eye



- Glare is due to particle scattering.

Ocular haloes and coronas

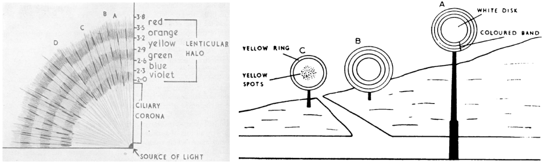
- The glare phenomenon as described by Descartes in 1637:



- This cannot be captured by a camera as it happens inside the eye, but could we simulate this?
- Fourier developed his transform to solve heat transfer problems. It is well-known that there are many other uses.
- In Fourier optics, it is used to compute the scattering of particles that we can model as obstacles in a plane.
- This is particularly useful for modelling lens systems such as the human eye.

Related Work

Simpson [1953]
“Occular Haloes and Coronas”

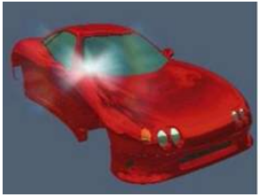


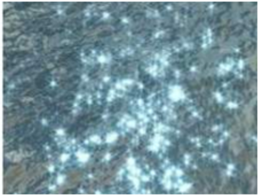
Nakamae *et al.* [1992]
“A Lighting Model Aiming at Drive Simulators”

Spencer *et al.* [1995]
“Physically-Based Glare Effects for Digital Images”

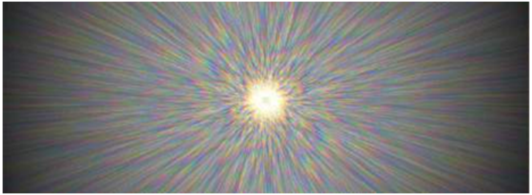
Related Work

Kakimoto *et al.* [2004]
"Glare Generation Based
on Wave Optics"





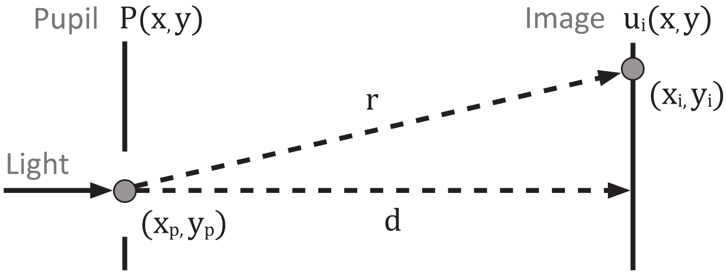
van den Berg *et al.* [2005]
"Physical Model and
Simulation of the Fine
Needles Radiating from
Point Light Sources"



Yoshida *et al.* [2008]
"Brightness of the Glare
Illusion"

Wave optics

- Huygen's principle:
  - Every element of a wave front gives rise to a spherical wave.
  - The envelope of the secondary waves determines the subsequent positions of the wave front.
- Simplistic eye model:



- Mathematically:

$$u_\mathrm{i}(x_\mathrm{i}, y_\mathrm{i}) = \frac{d}{i\lambda} \iint_P u_\mathrm{p}(x_\mathrm{p}, y_\mathrm{p}) \frac{\exp(ikr)}{r^2}\, \mathrm{d}x_\mathrm{p} \mathrm{d}y_\mathrm{p} \quad .$$

Fresnel's approximation

- Huygen's principle:

$$u_{\mathrm{i}}(x_{\mathrm{i}}, y_{\mathrm{i}}) = \frac{d}{i\lambda} \iint_P u_{\mathrm{p}}(x_{\mathrm{p}}, y_{\mathrm{p}}) \frac{\exp(ikr)}{r^2} \, \mathrm{d}x_{\mathrm{p}} \mathrm{d}y_{\mathrm{p}} \quad .$$

- Fresnel's approximation:

(Taylor expansion of the square root in the Pythagorean theorem)

$$\begin{aligned} r &\approx d + \frac{x_i^2 + y_i^2}{2d} + \frac{x_p^2 + y_p^2}{2d} - \frac{x_i x_p + y_i y_p}{d} \\ r^2 &\approx d^2 \end{aligned}$$

- Inserted:

$$u_i(x_i, y_i) = K(x_i, y_i) \iint_{-\infty}^{+\infty} u_p(x_p, y_p) E(x_p, y_p) \exp\left(-i\frac{k}{d}(x_i x_p + y_i y_p)\right) \mathrm{d}x_p \mathrm{d}y_p \quad ,$$

where

$$K(x_i, y_i) = \frac{1}{i\lambda d} \exp\left(ik\left(d + \frac{x_i^2 + y_i^2}{2d}\right)\right) \quad \text{and} \quad E(x_p, y_p) = \exp\left(i\frac{\pi}{\lambda d}(x_p^2 + y_p^2)\right) \quad .$$

What we want is light intensity

- The diffracted light wave:

$$u_i(x_i, y_i) = K(x_i, y_i) \iint_{-\infty}^{+\infty} u_p(x_p, y_p) E(x_p, y_p) \exp\left(-i\frac{k}{d}(x_i x_p + y_i y_p)\right) \mathrm{d}x_p \mathrm{d}y_p \quad ,$$

- This leads to Fourier optics, since

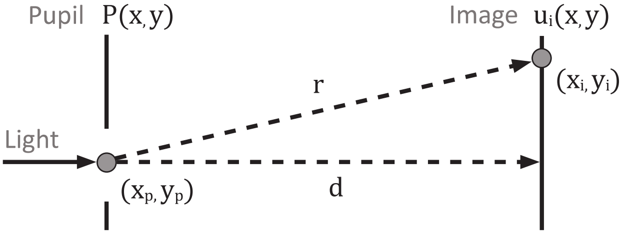
$$u_i(x_i, y_i) = K(x_i, y_i) \mathcal{F}\left\{u_p(x_p, y_p) E(x_p, y_p)\right\}_{p=x_i/(\lambda d), q=y_i/(\lambda d)} \quad .$$

  where $\mathcal{F}\{\dots\}$ is the Fourier transform.
- The light intensity is the squared absolute value of the wave:

$$\begin{aligned} L(x_i, y_i) &= |u_i(x_i, y_i)|^2 \\ &= \left|K(x_i, y_i) \mathcal{F}\left\{u_p(x_p, y_p) E(x_p, y_p)\right\}_{p=x_i/(\lambda d), q=y_i/(\lambda d)}\right|^2 \\ &= \frac{1}{(\lambda d)^2} \left|\mathcal{F}\left\{u_p(x_p, y_p) E(x_p, y_p)\right\}_{p=x_i/(\lambda d), q=y_i/(\lambda d)}\right|^2 \quad . \end{aligned}$$

Fresnel diffraction (in summary)

- Simplistic eye model:



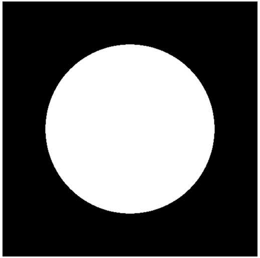
- Fresnel diffraction of the particles in the eye when modelled as obstacles in the pupil plane:

$$|u_i(x_i, y_i)|^2 = \frac{1}{(\lambda d)^2} \left| \mathcal{F}\left\{u_p(x_p, y_p) E(x_p, y_p)\right\}_{p=x_i/(\lambda d), q=y_i/(\lambda d)} \right|^2 ,$$

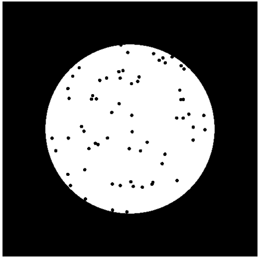
where $\mathcal{F}\{\dots\}$ is the Fourier transform, u_p is the light passing the pupil, E is a complex exponential term, λ is the wavelength, and d is the distance between pupil and retina.

Input for the Fourier transform

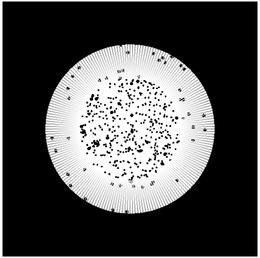
- The FFT is an obvious choice. The input is a simplified “image” of the obstacles in the eye that cause diffraction.



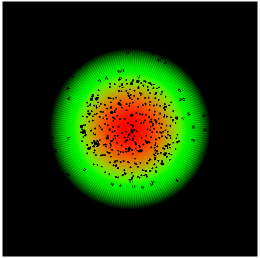
Pupil



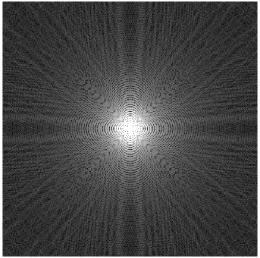
Cornea

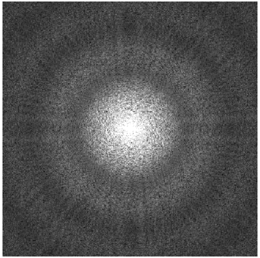


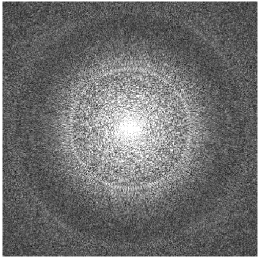
Lens

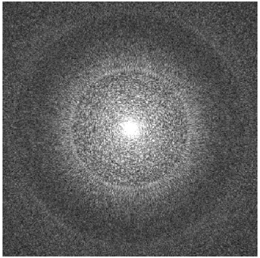


Exponential term









Chromatic blur

- Recall the dispersive properties of scattering by particles (Newton's discovery).
- We need FFTs for several wavelengths to get colours.
- Coordinates in frequency space involve the wavelength:

$$p = x_i/(\lambda d) \quad , \quad q = y_i/(\lambda d) \ .$$

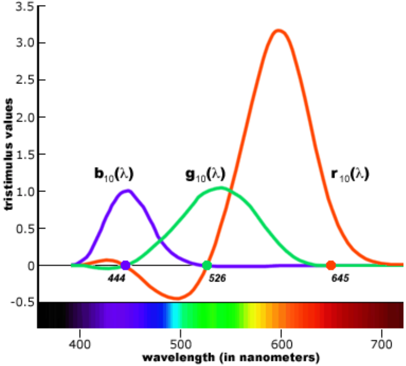
- This means that we can find the result for a different wavelength λ_{new} by simply scaling the result from one FFT:

$$F_{\lambda_{\text{new}}}(x_i, y_i) = F_\lambda\left(\frac{\lambda}{\lambda_{\text{new}}} x_i, \frac{\lambda}{\lambda_{\text{new}}} y_i\right) \ .$$

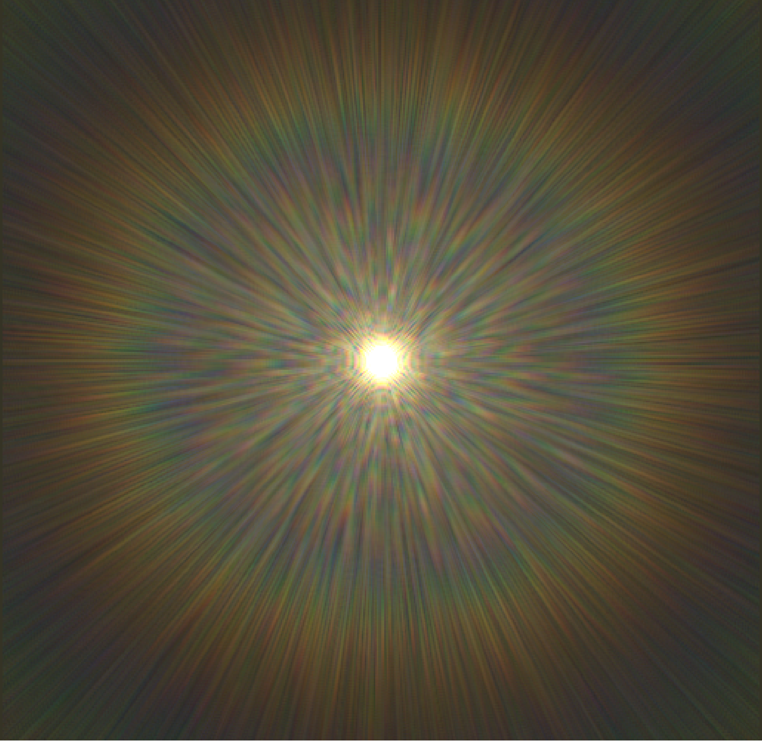
- Unfortunately, λ is also part of the expression for the complex exponential E, so the scaling introduces a small error.
- Accepting this small error saves many FFT computations.

Wavelengths to RGB

- To go from wavelengths to RGB we integrate over the CIE RGB color matching functions

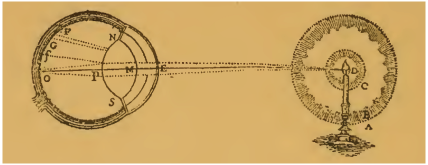


- After this "chromatic blur" of the monochromatic scattering result, we have a simulation of the glare from a point source.



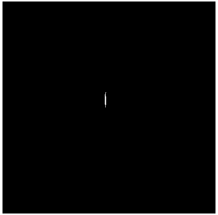
The point spread function of the eye

- We can think of the simulated glare from a point source as the point spread function (PSF) of the eye.
- Suppose we are looking at a candle:



- We should convolve the PSF of the eye with the pixels that are bright enough to result in a visible glare effect.

$+$



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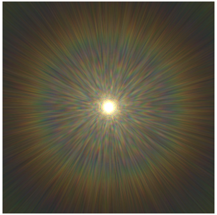
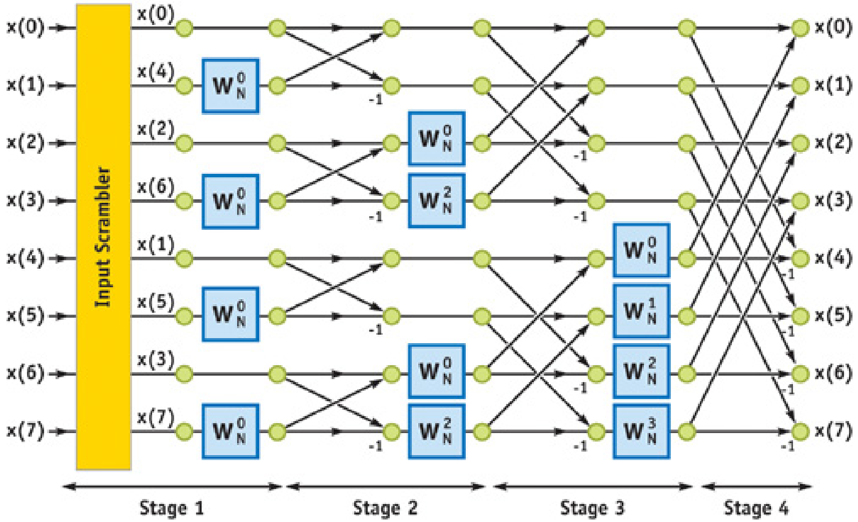
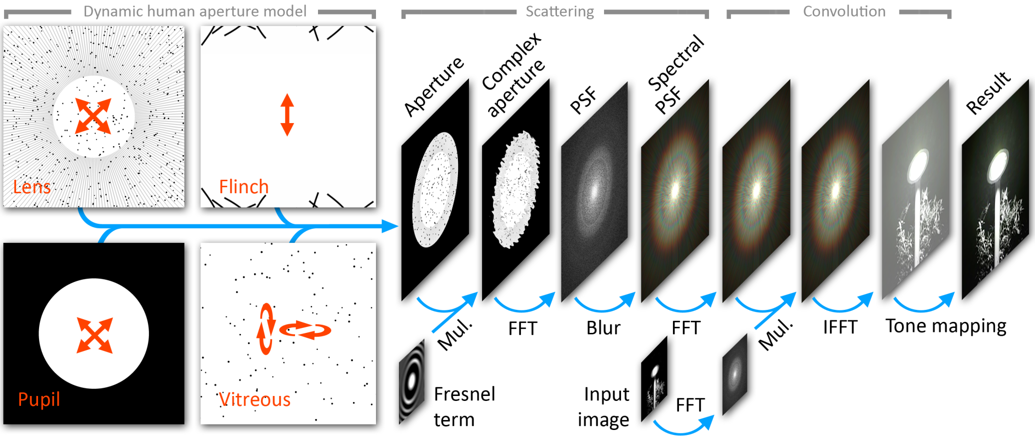


FFT on the GPU



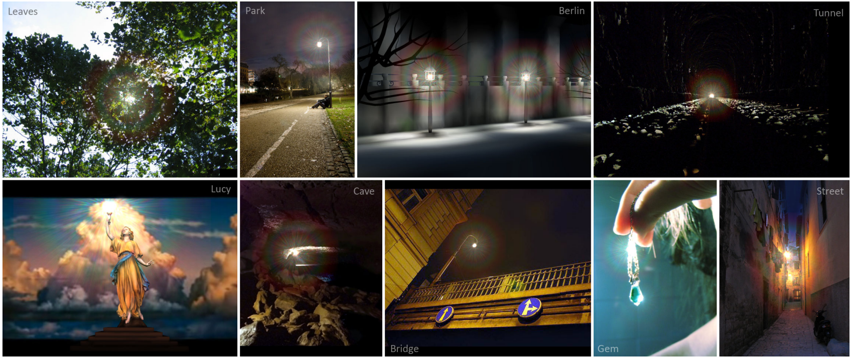
- Only $2\log_2(N)$ passes for two 2D FFTs
- This is fast enough for real-time simulation of dynamic effects

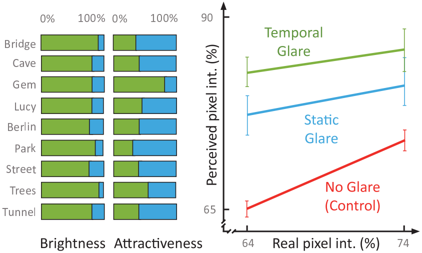
Temporal Glare



- Noise model for pupil
- Mass-spring system for lens
- Damped random forces for vitreous humor
- Simple up-down motion for squint/blink/flinch

Perceptual study





Model overview

- The eye model includes

Eye part	Scatter	Dyn.	Incl.
Eyelashes	varies	yes	yes
Cornea	25-30%	no	yes
Aqueous humor	none	no	no
Lens	40%	yes	yes
Iris	$\leq$1%	yes	no
Pupil	aperture	yes	yes
Vitreous humor	10%	yes	yes
Retina	20%	no	yes

- This is the first model to simulate the dynamical aspects of glare.
- Convolution ensures that the model works for area sources.

Example

- A demo program is available online at https://people.compute.dtu.dk/jerf/code/.
- Provide input images to this program to add glare effects.