
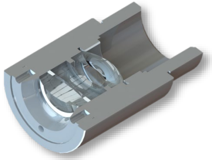



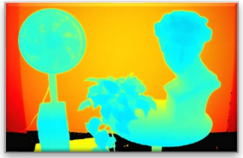


Computational Imaging

Lecture 13: Computing Toolbox: Image Blurry

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The Chinese University of Hong Kong, Shenzhen

Q:Why are Our Images Blurry?

Today's Topic

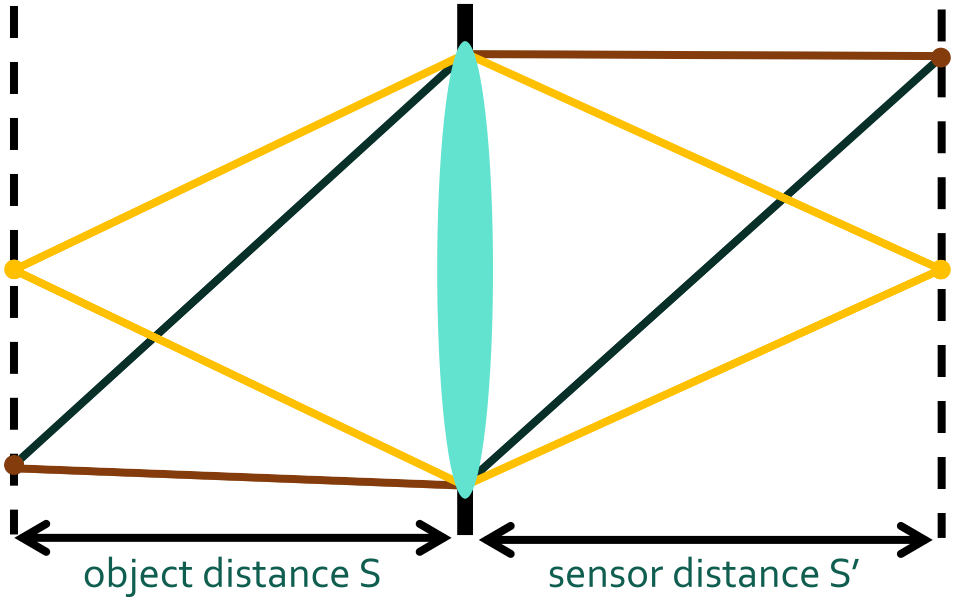
- Lens Imperfections and Physical Limit.
- Camera Shake.
- Scene Motion.
- Depth Defocus.

Lens Imperfections and Physical Limit

Lens Imperfections

- Ideal lens: A point maps to a point at a certain plane.

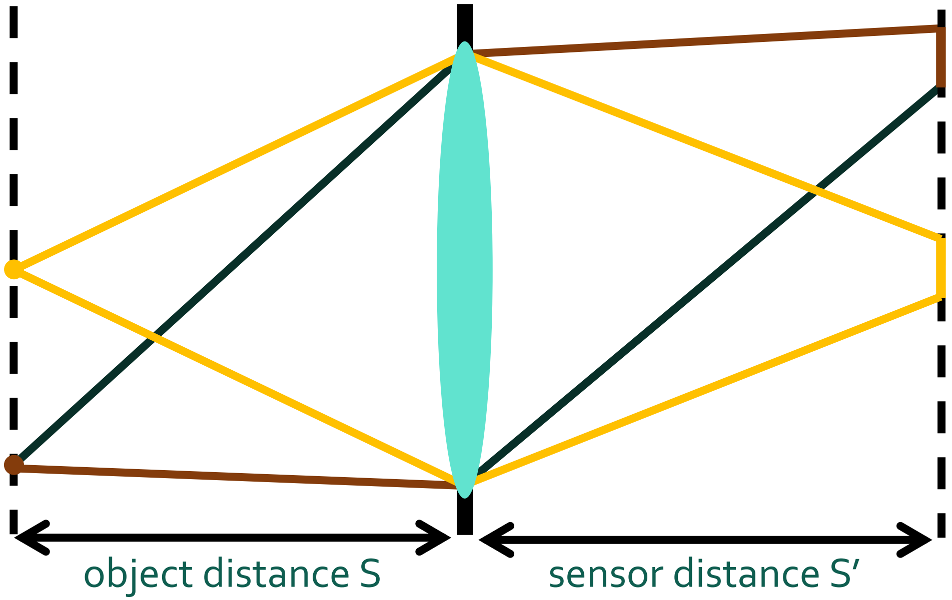
$$\boxed{\frac{1}{S'} + \frac{1}{S} = \frac{1}{f}}$$



Lens Imperfections

- Ideal lens: A point maps to a point at a certain plane.
- Real lens: A point maps to a circle that has non-zero minimum radius among all planes.

$$\boxed{\frac{1}{S'} + \frac{1}{S} = \frac{1}{f}}$$

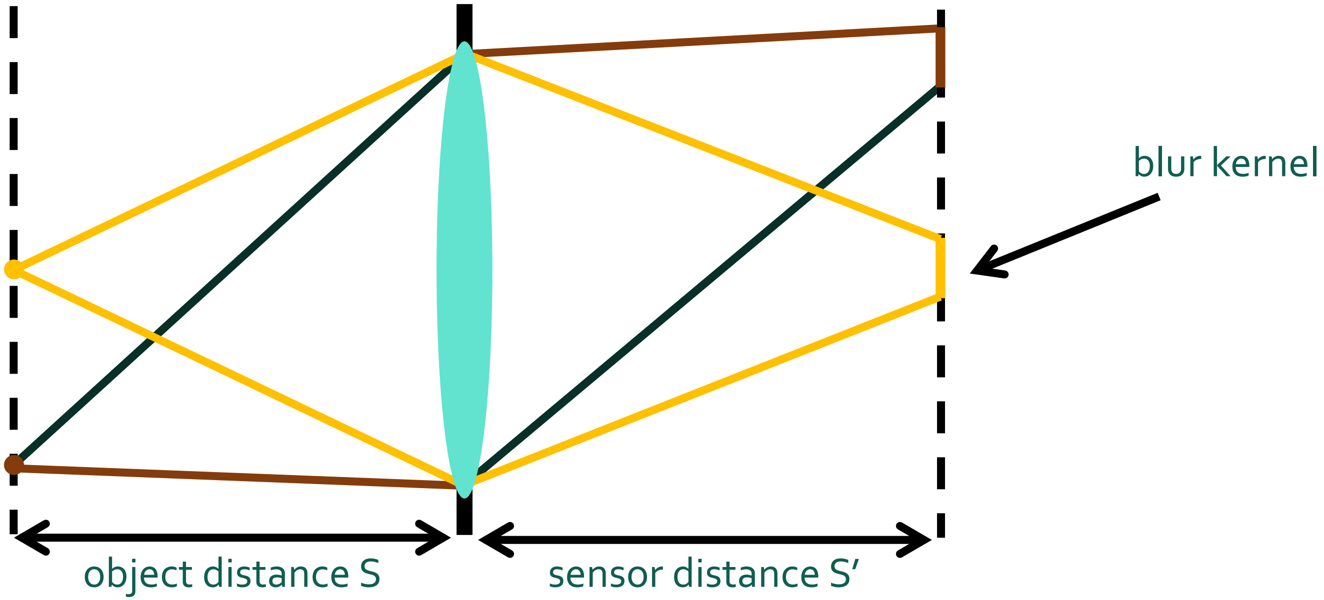


What is the effect of this on the images we capture?

Lens Imperfections

- Ideal lens: A point maps to a point at a certain plane.
- Real lens: A point maps to a circle that has non-zero minimum radius among all planes.

$$\boxed{\frac{1}{S'} + \frac{1}{S} = \frac{1}{f}}$$

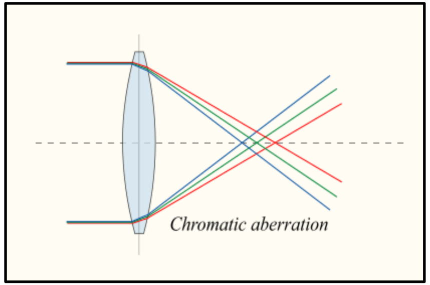


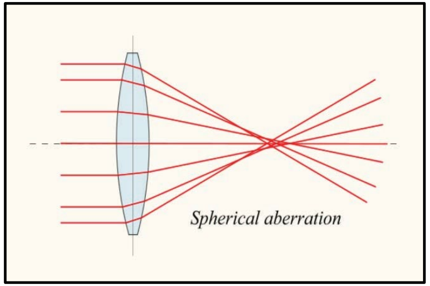
Shift-invariant blur.

Lens Imperfections

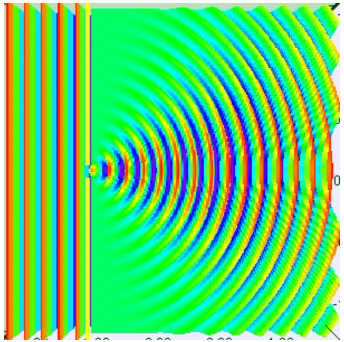
- What causes lens imperfections?
  - Aberrations.

(Important note: Oblique aberrations like coma and distortion are not shift-invariant blur and we do not consider them here!)

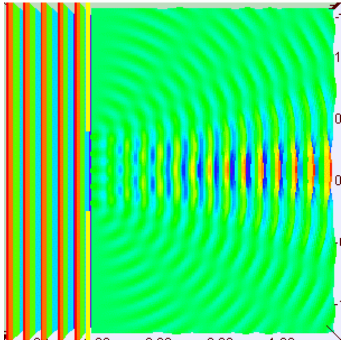




  - Diffraction



small aperture



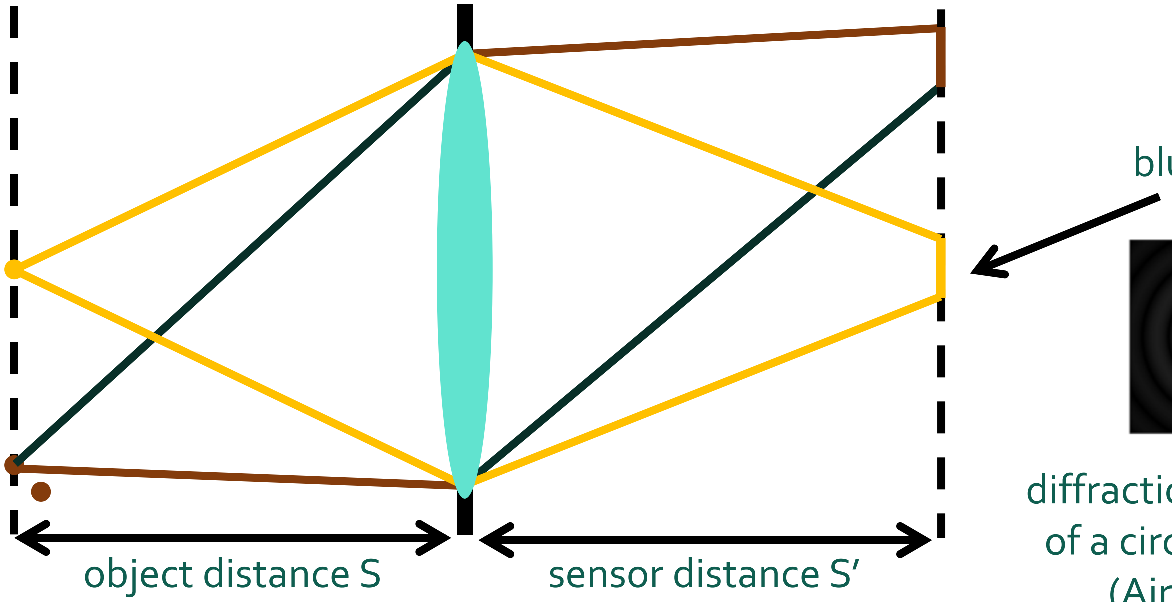
large aperture

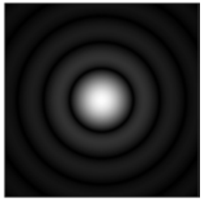
Lens: An Optical Low-pass Filter

Point spread function (PSF): The blur kernel of a lens.

➢ "Diffraction-limited" PSF: No aberrations, only diffraction. Determined by aperture shape.

$$\frac{1}{S'} + \frac{1}{S} = \frac{1}{f}$$





diffraction-limited PSF of a circular aperture (Airy pattern)

Basics of Diffraction Theory

Assume that we can use:

- ***Fraunhofer diffraction***

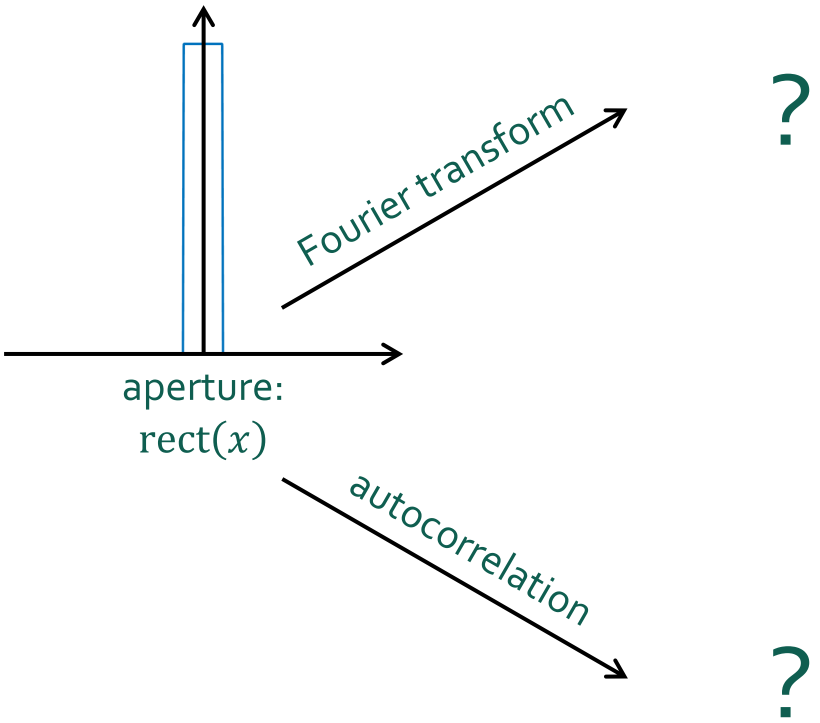
  i.e., distance of sensor and aperture is large relative to wavelength.

- ***Incoherent illumination***

  i.e., the light we are measuring is not laser light.

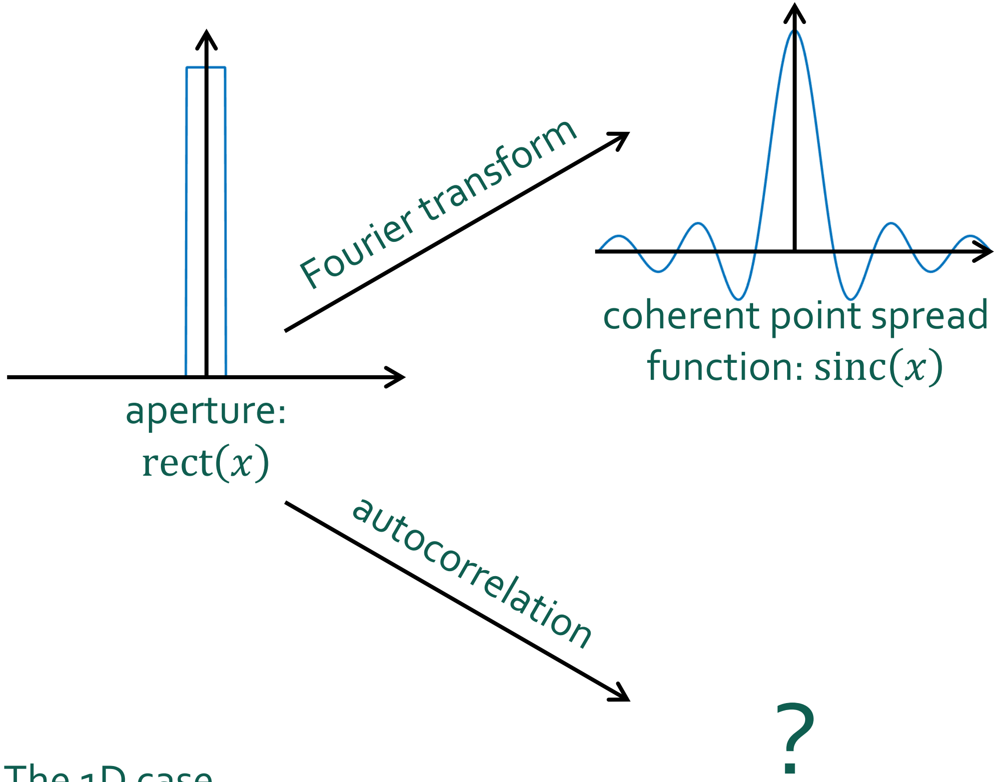
Ignore various scale factors. Different functions are not drawn to scale.

Basics of Diffraction Theory



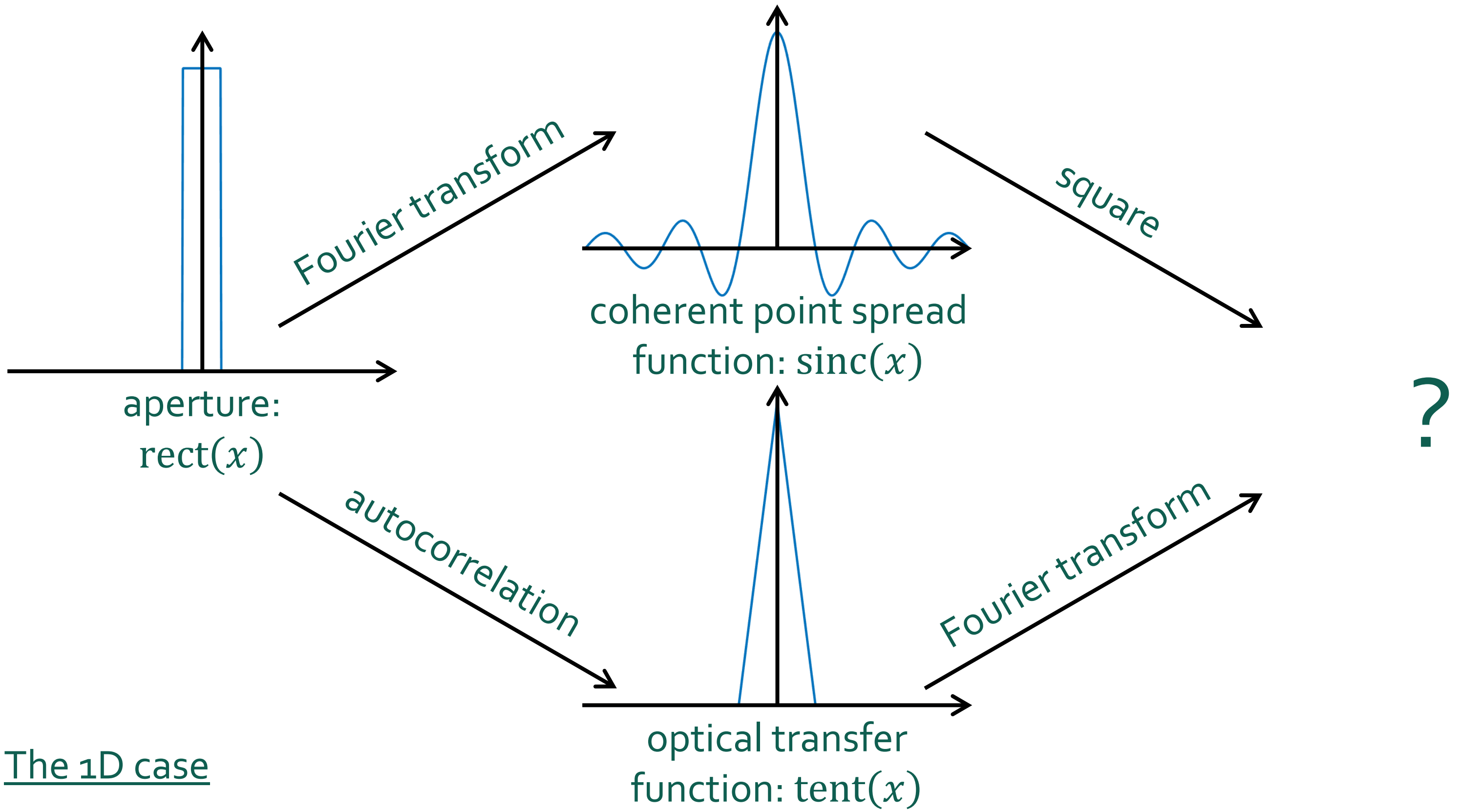
The 1D case

Basics of Diffraction Theory



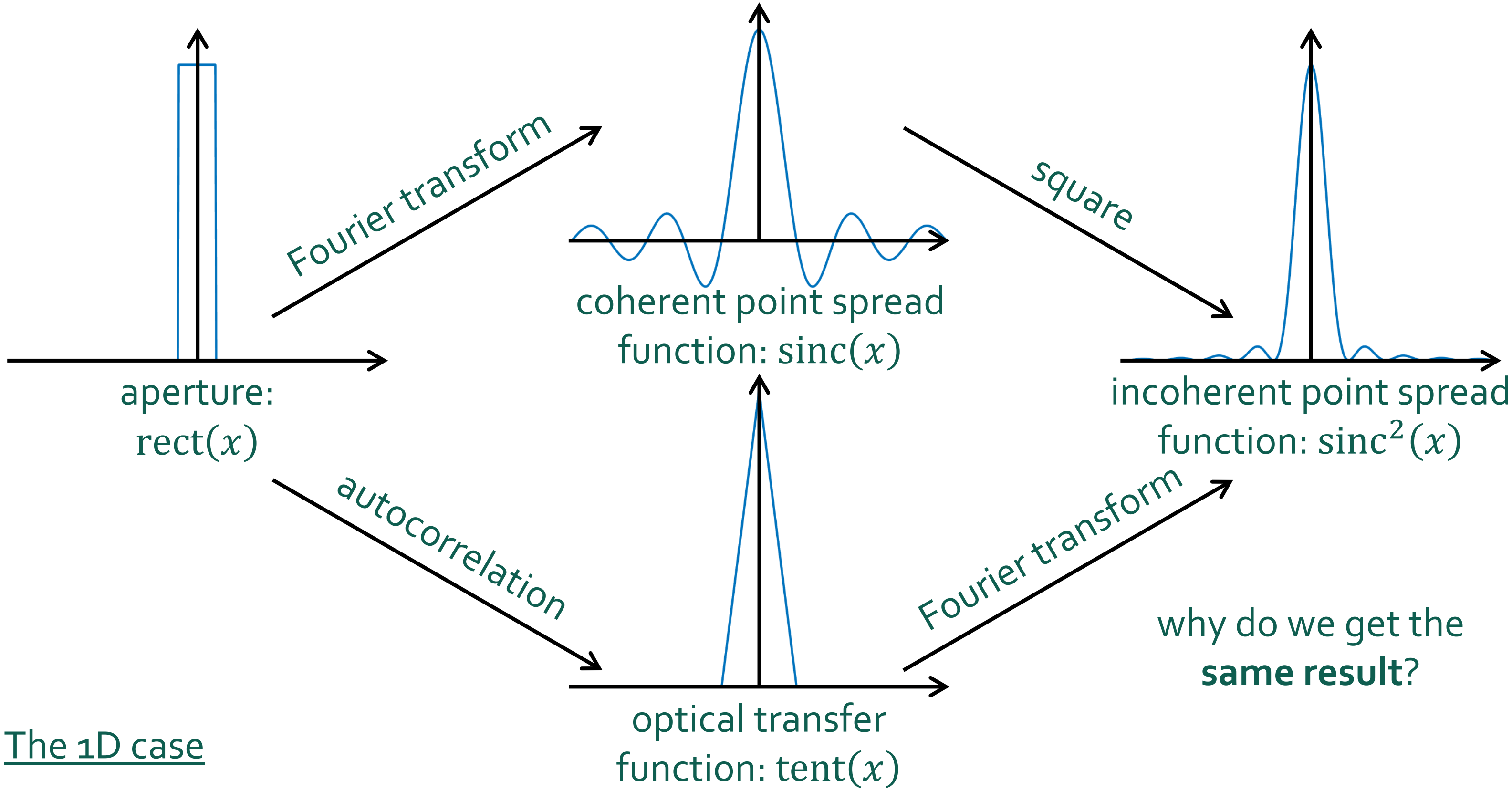
The 1D case

Basics of Diffraction Theory



The 1D case

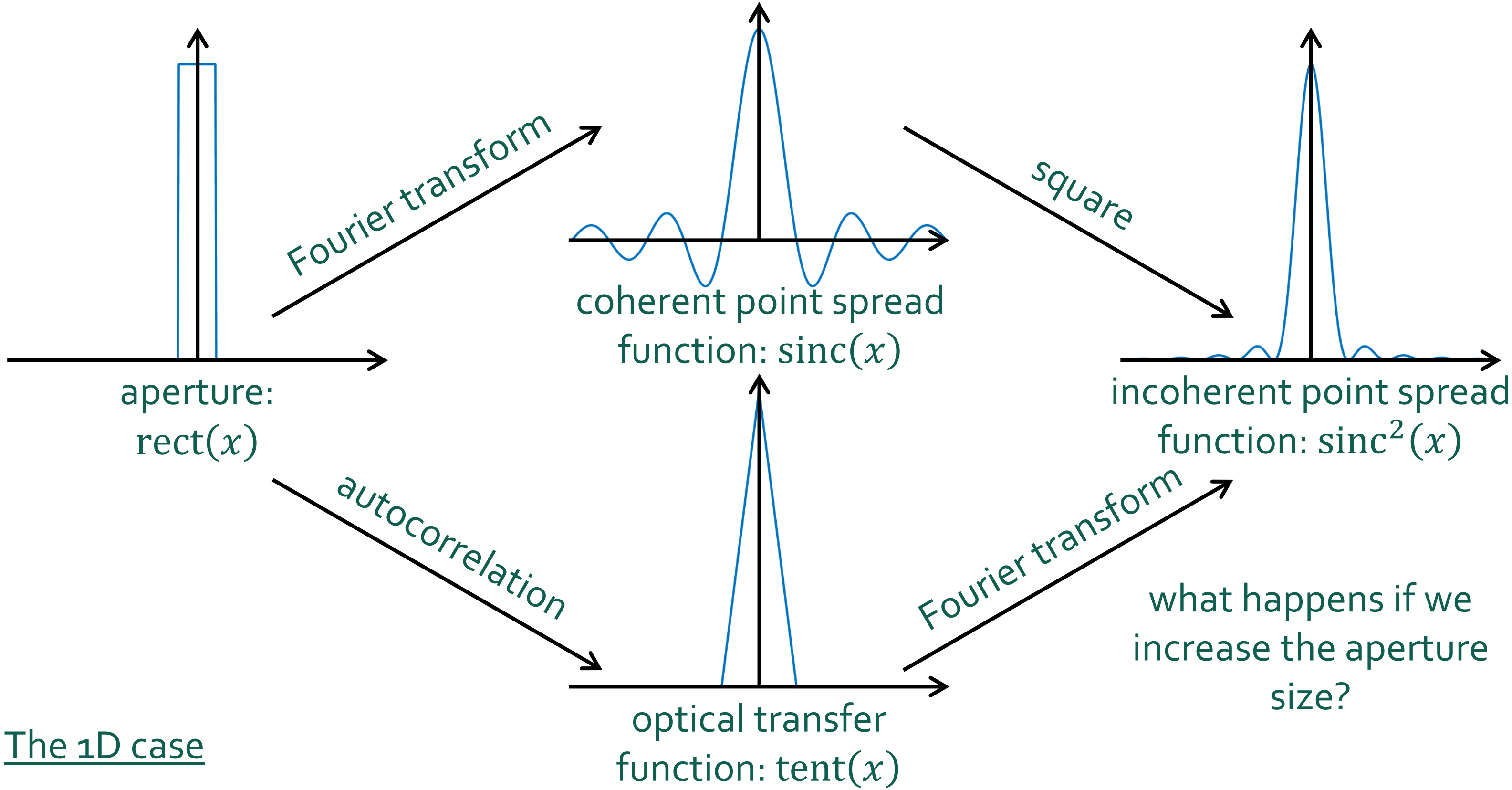
Basics of Diffraction Theory



why do we get the **same result**?

The 1D case

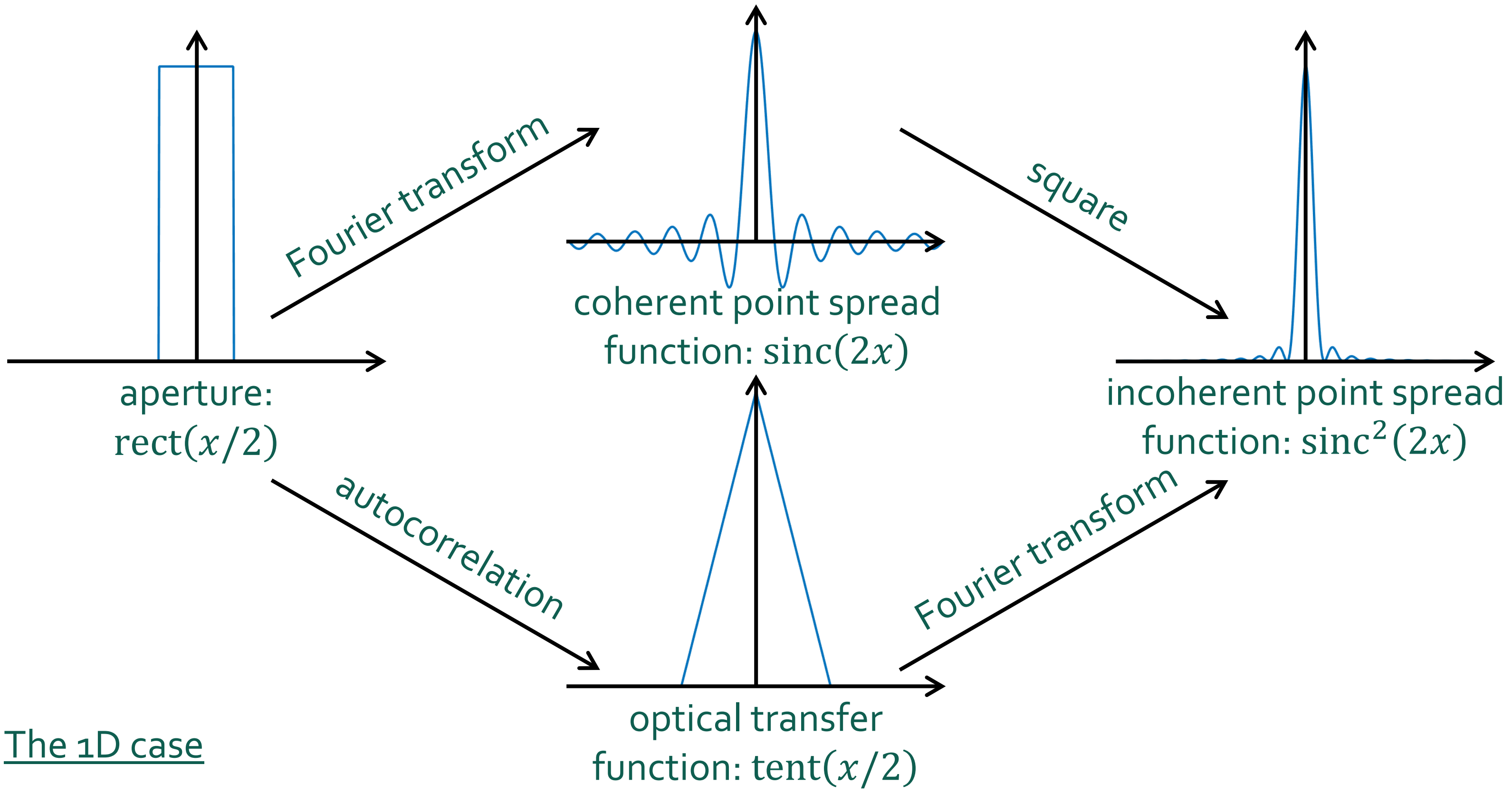
Basics of Diffraction Theory



what happens if we increase the aperture size?

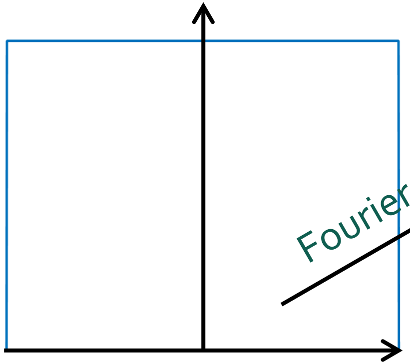
The 1D case

Basics of Diffraction Theory



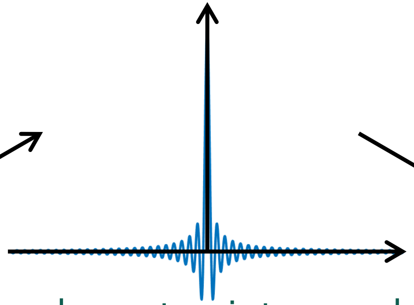
The 1D case

Basics of Diffraction Theory



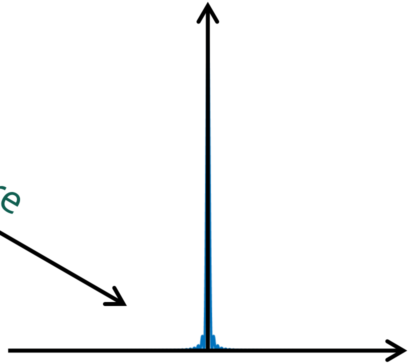
aperture: $\mathrm{rect}(x/10)$

Fourier transform



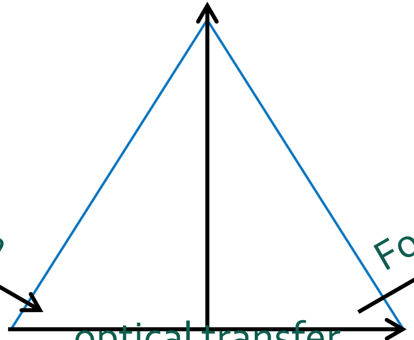
coherent point spread function: $\mathrm{sinc}(10x)$

square



incoherent point spread function: $\mathrm{sinc}^2(10x)$

autocorrelation



optical transfer function: $\mathrm{tent}(x/10)$

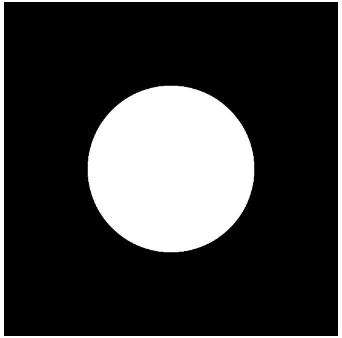
Fourier transform

As the aperture size increases…

… point spread function becomes smaller

The 1D case

Basics of Diffraction Theory

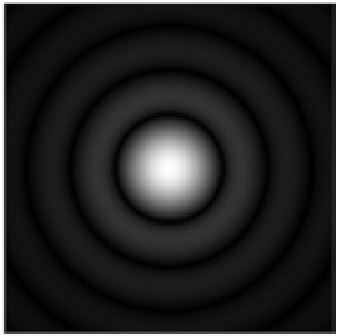


aperture

autocorrelation

optical transfer function

Fourier transform



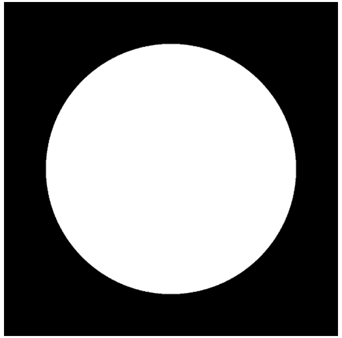
incoherent point spread function

As the aperture size increases...

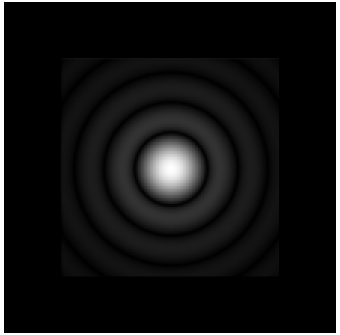
... point spread function becomes smaller

The 2D case

Basics of Diffraction Theory



aperture



incoherent point spread function

autocorrelation

Fourier transform

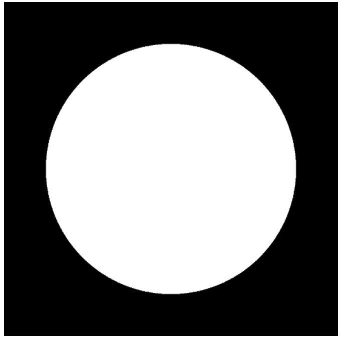
optical transfer function

As the aperture size increases…

… point spread function becomes smaller

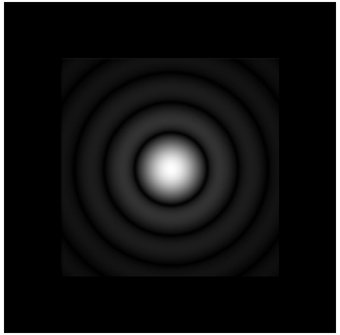
The 2D case

Basics of Diffraction Theory



aperture

Why do we prefer circular apertures?



incoherent point spread function

autocorrelation

optical transfer function

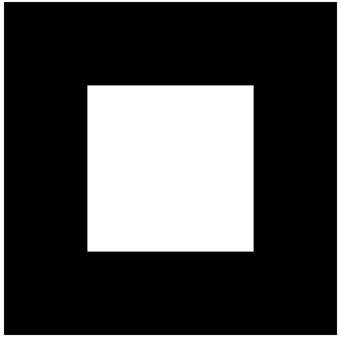
Fourier transform

As the aperture size increases…

… point spread function becomes smaller

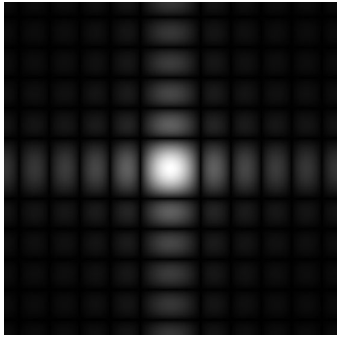
The 2D case

Basics of Diffraction Theory



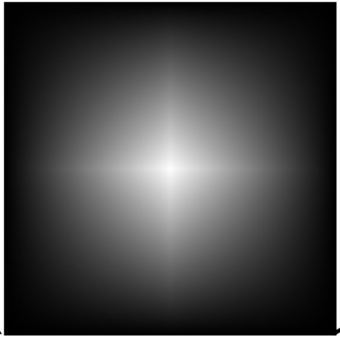
aperture

Other shapes produce very **anisotropic** blur.



incoherent point spread function

autocorrelation



optical transfer function

Fourier transform

As the aperture size increases…

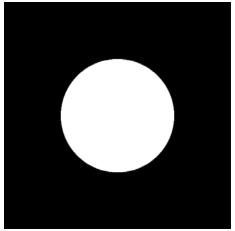
… point spread function becomes smaller

The 2D case

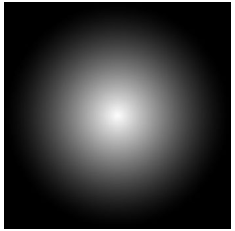
Lens: An Optical Low-pass Filter

Point spread function (PSF): The blur kernel of a lens.

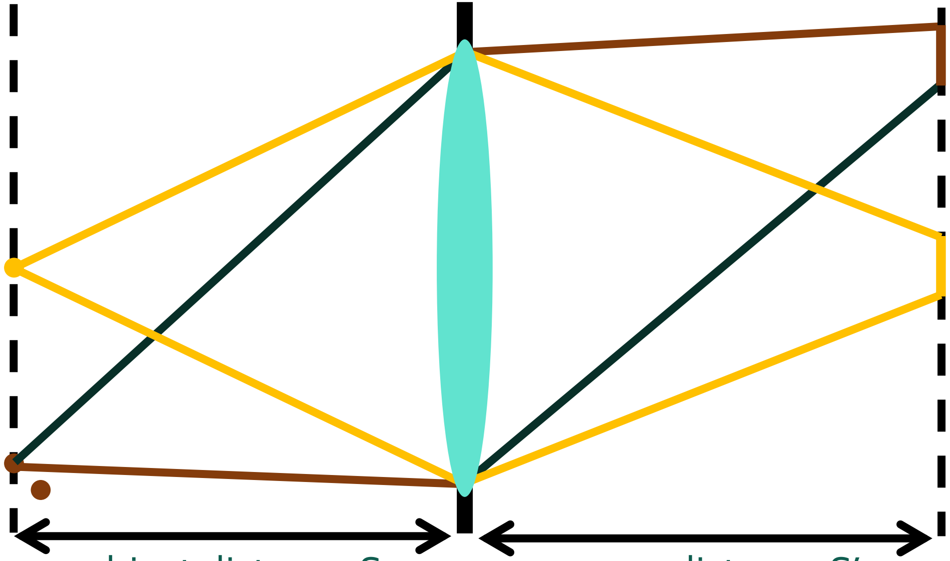
- “Diffraction-limited” PSF: No aberrations, only diffraction. Determined by aperture shape.



aperture



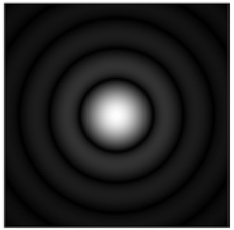
optical transfer function (OTF)



object distance S

sensor distance S’

blur kernel



diffraction-limited PSF of a circular aperture (Airy pattern)

Lens: An Optical Low-pass Filter

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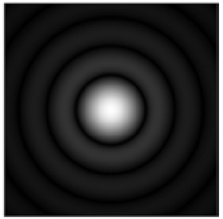


=

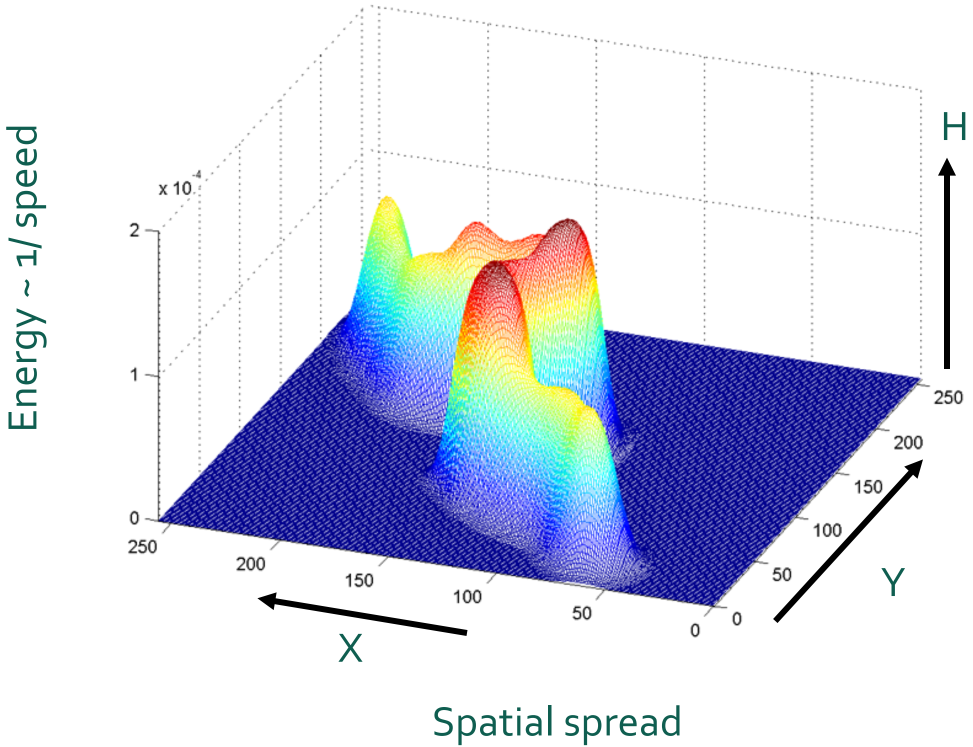
image from a perfect lens | imperfect lens PSF | image from imperfect lens

$$x * c = b$$

If we know b and c, can we recover x?

Camera Shake

Camera Shake: Motion PSF



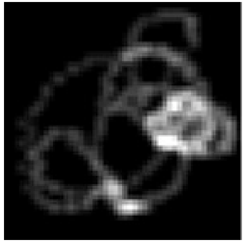
Motion PSF is a Function of:

- Motion path
- Motion speed

Camera Shake as A Filter

image from static camera

$*$



PSF
from camera motion

$=$

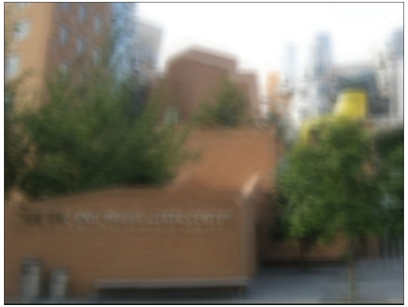
image from shaky camera

$$x \quad * \quad c \quad = \quad b$$

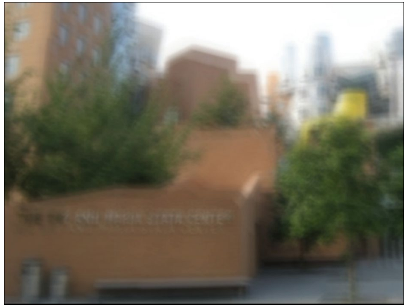
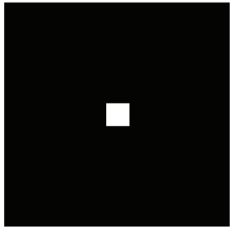
If we know b and c, can we recover x?

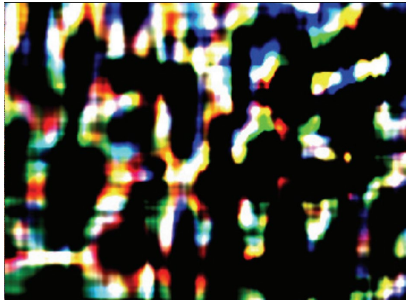
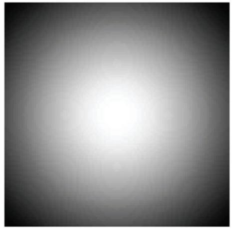
Multiple Possible Solutions

Sharp image



Blurry image

=  * 

=  * 

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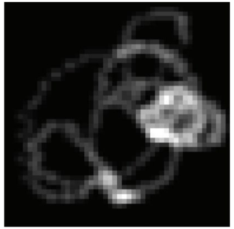
* 

How do we detect this PSF?

Use Prior Information

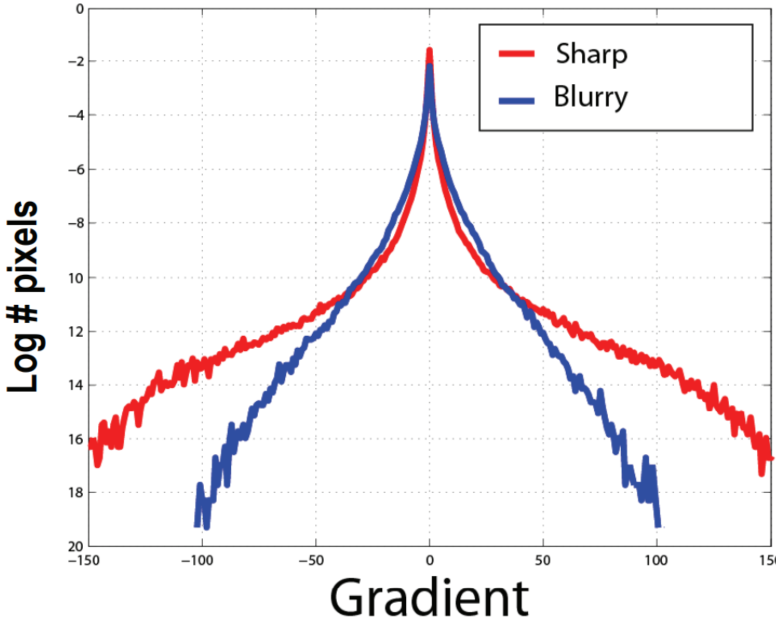
Among all the possible pairs of images and blur kernels, select the ones where:

- The image “looks like” a natural image.

- The kernel “looks like” a motion PSF.

Shake Kernel Statistics

Gradients in natural images follow a characteristic "heavy-tail" distribution.



Can be approximated by $\|\nabla x\|^{0.8}$

sharp natural image

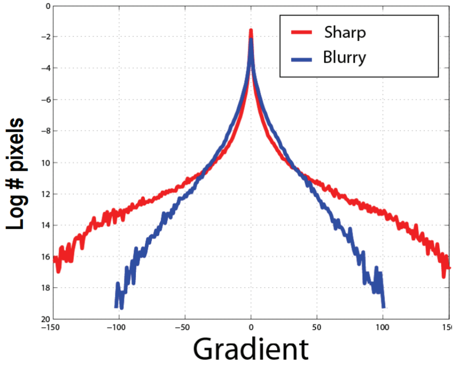
blurry natural image

Use Prior Information

Among all the possible pairs of images and blur kernels, select the ones where:

➢ The image "looks like" a natural image.

Gradients in natural images follow a characteristic "**heavy-tail**" distribution.



➢ The kernel "looks like" a motion PSF.

Shake **kernels** are very **sparse**, have continuous contours, and are always **positive**

How to use this information for blind deconvolution?

Three Sources of Information

b = observed image   c = blur kernel   x = sharp image

$$p(c, x|b) = k\, p(b|c, x)\, p(x)\, p(b)$$

Posterior

1. Likelihood (Reconstruction constraint)

2. Image prior

3. Blur prior

Regularized Blind Deconvolution

Solve regularized least-squares optimization

$$\min_{x,c} \|b - c * x\|^2 + \|\nabla x\|^{0.8} + \| c \|_1$$

What does each term in this summation correspond to?

Regularized Blind Deconvolution

Solve regularized least-squares optimization

$$\min_{x,c} \|b - c * x\|^2 + \|\nabla x\|^{0.8} + \| c \|_1$$

data term

nature image prior

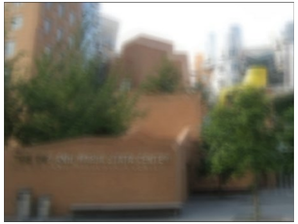
shake kernel prior

Sharp image

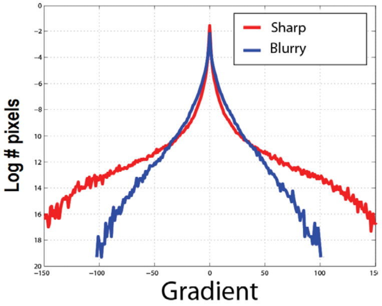
*

Estimated Blur kernel

=



Blurry image



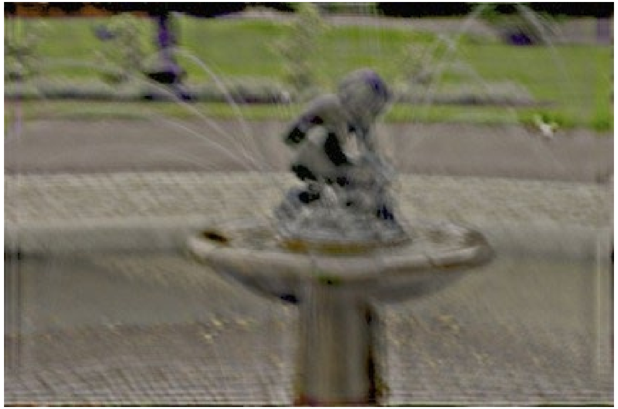
Note: Solving such optimization problems is complicated (no longer *linear* least squares).

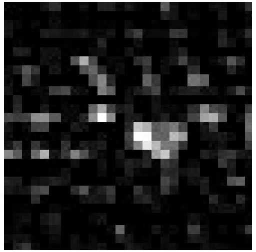
A Demonstration

香港中文大學(深圳)
The Chinese University of Hong Kong, Shenzhen

input

deconvolved image and kernel





This image looks worse than the original...

This doesn't look like a plausible shake kernel...

Regularized Blind Deconvolution

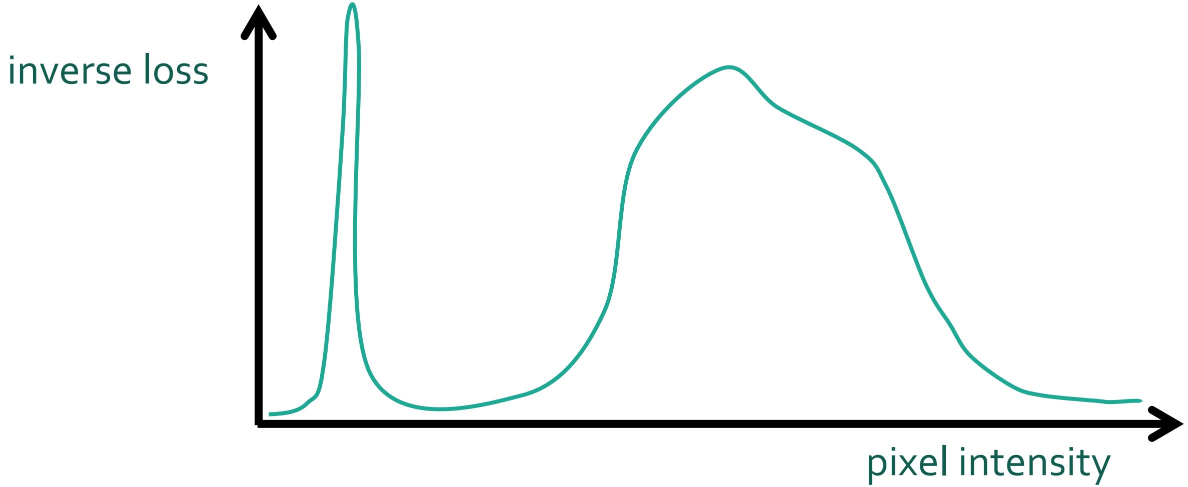
Solve regularized least-squares optimization

$$\min_{x,c} \underbrace{\|b - c * x\|^2 + \|\nabla x\|^{0.8} + \| c \|_1}_{\text{cost function}}$$

Regularized Blind Deconvolution

Solve regularized least-squares optimization

$$\min_{x,c} \underbrace{\|b - c * x\|^2 + \|\nabla x\|^{0.8} + \| c \|_1}_{\text{cost function}}$$

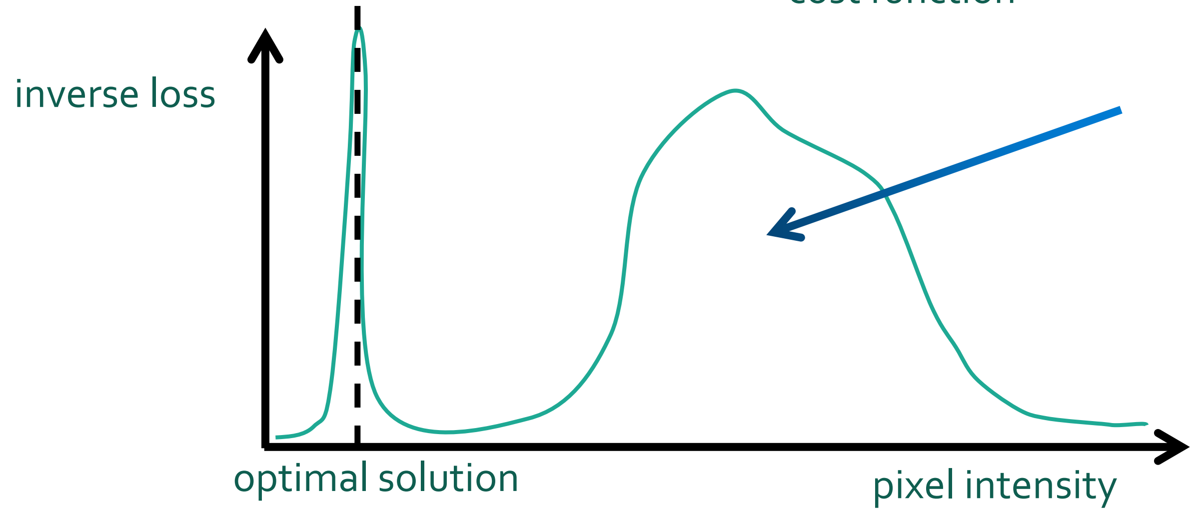


Where in this graph is the solution we find?

Regularized Blind Deconvolution

Solve regularized least-squares optimization

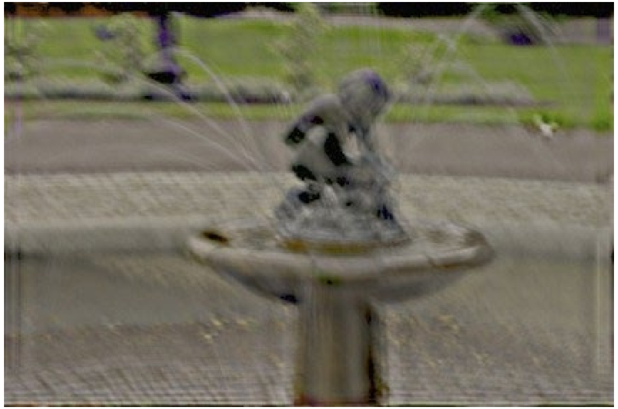
$$\min_{x,c} \underbrace{\|b - c * x\|^2 + \|\nabla x\|^{0.8} + \| c \|_1}_{\text{cost function}}$$



Rather than keep just maximum, do a weighted average of all solutions

A Demonstration

input	maximum-only	average

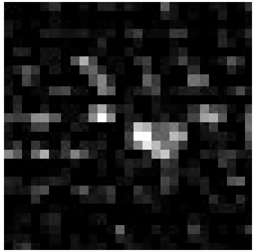
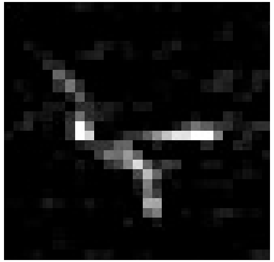



Image Artifacts & Estimated Kernels

Blur kernels

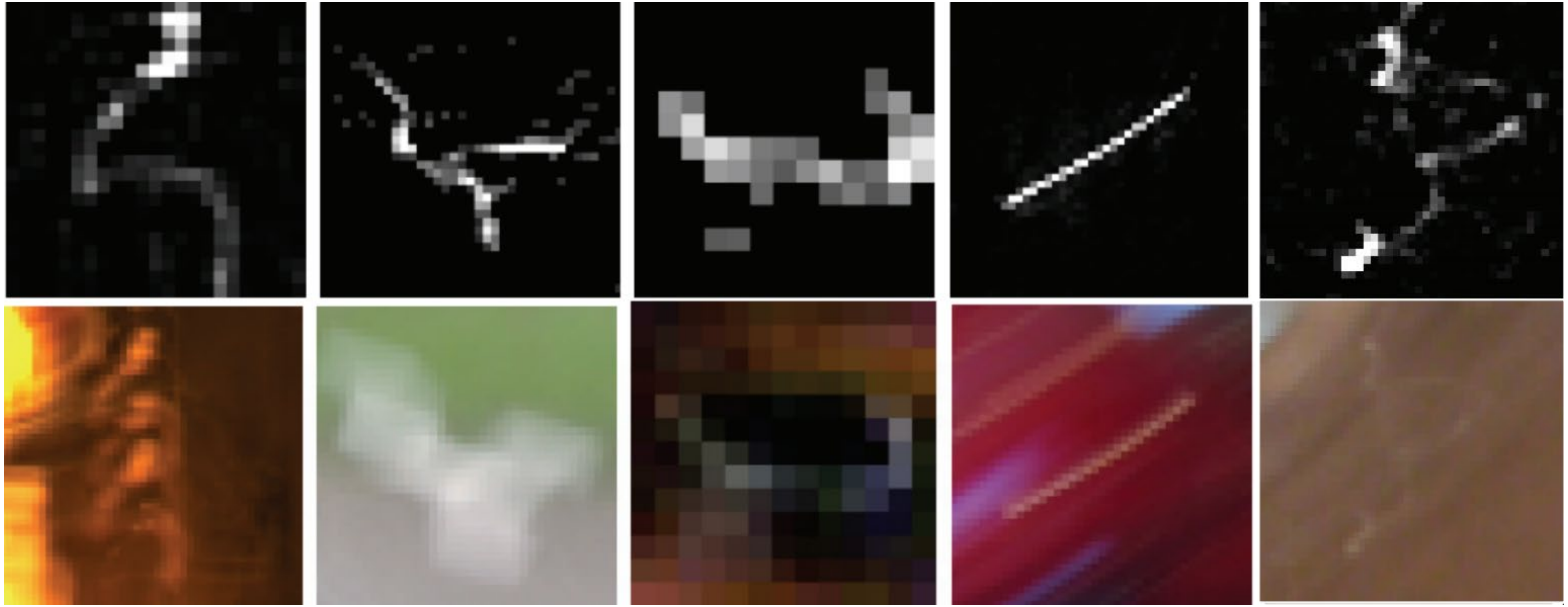


Image patterns

Note: blur kernels were inferred from large image patches,NOT the image patterns shown

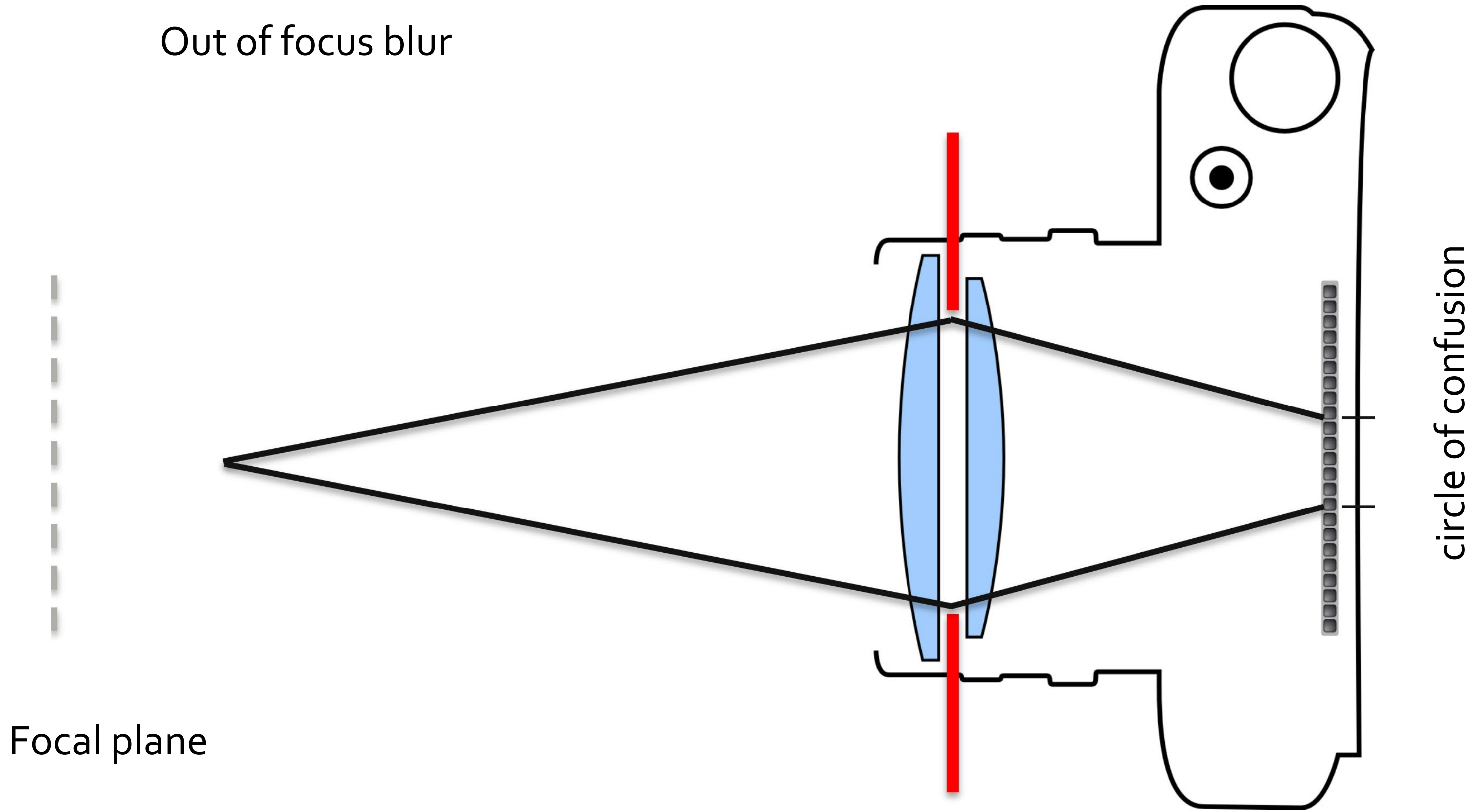
Scene Motion

Scene Motion Blur

Moshe Ben-Ezra and Shree K. Nayar Motion Deblurring Using Hybrid Imaging

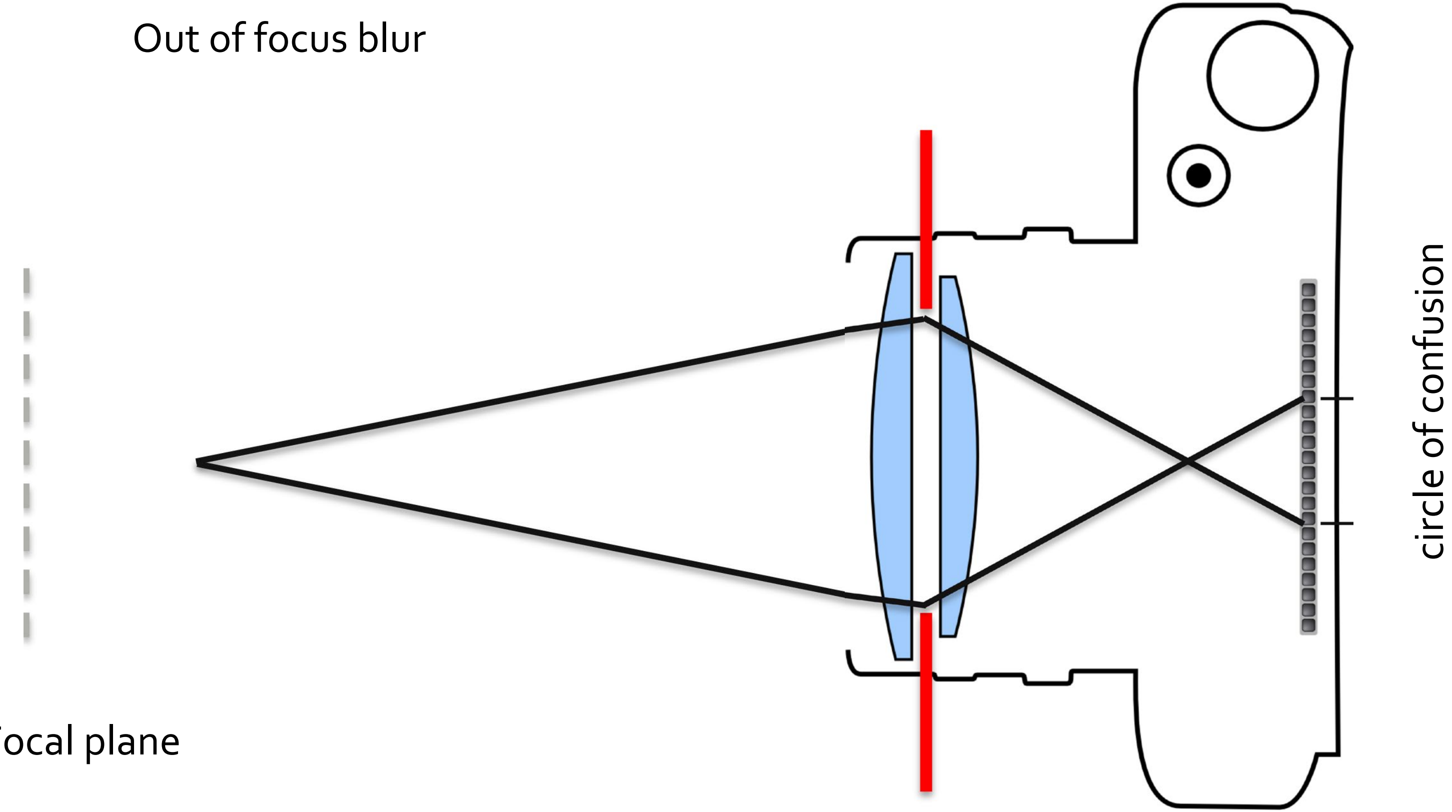
Depth Defocus

Recall: Out of Focus Blur



Recall: Out of Focus Blur

Out of focus blur



Focal plane

Recall: Out of Focus Blur

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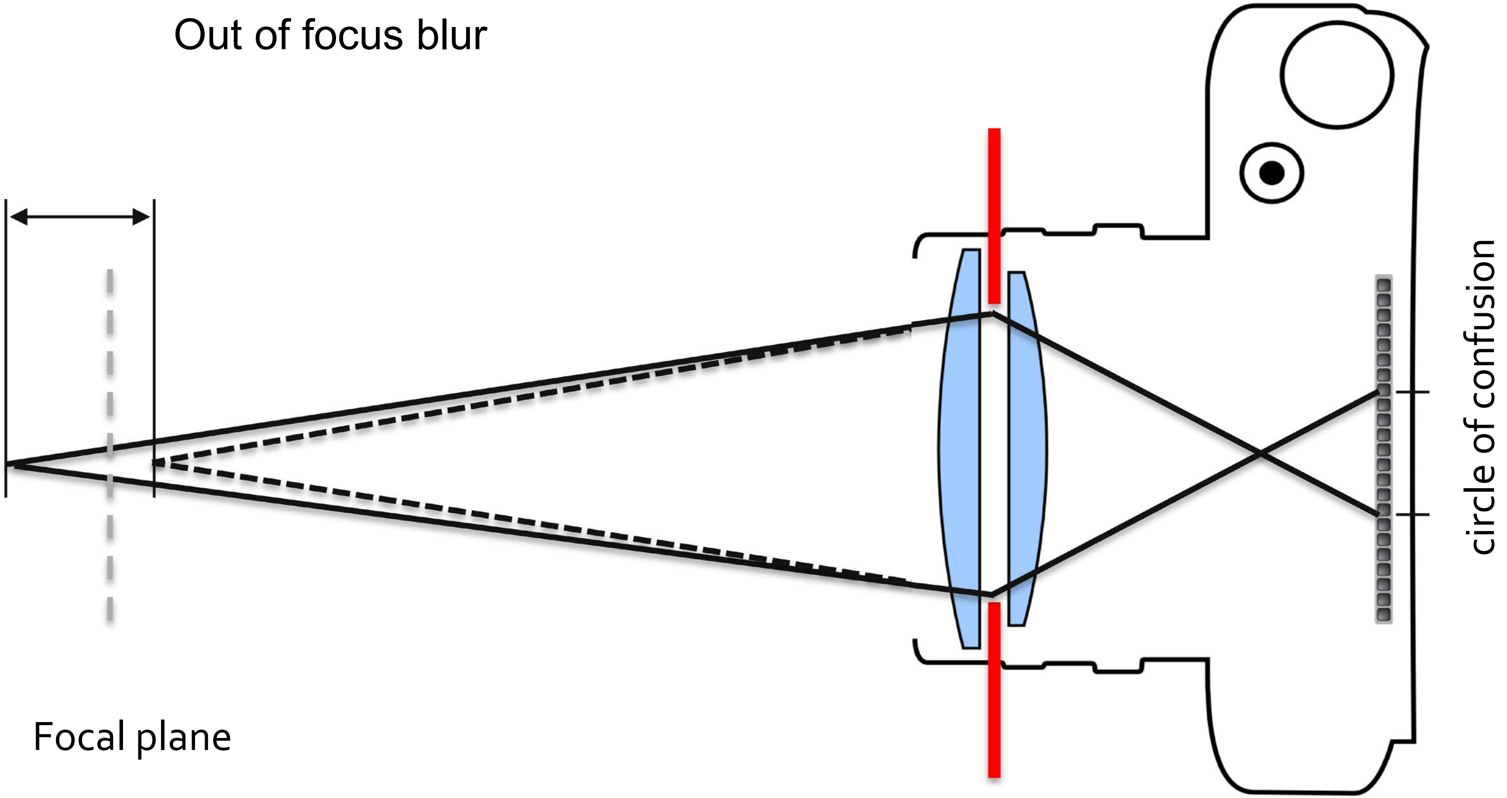
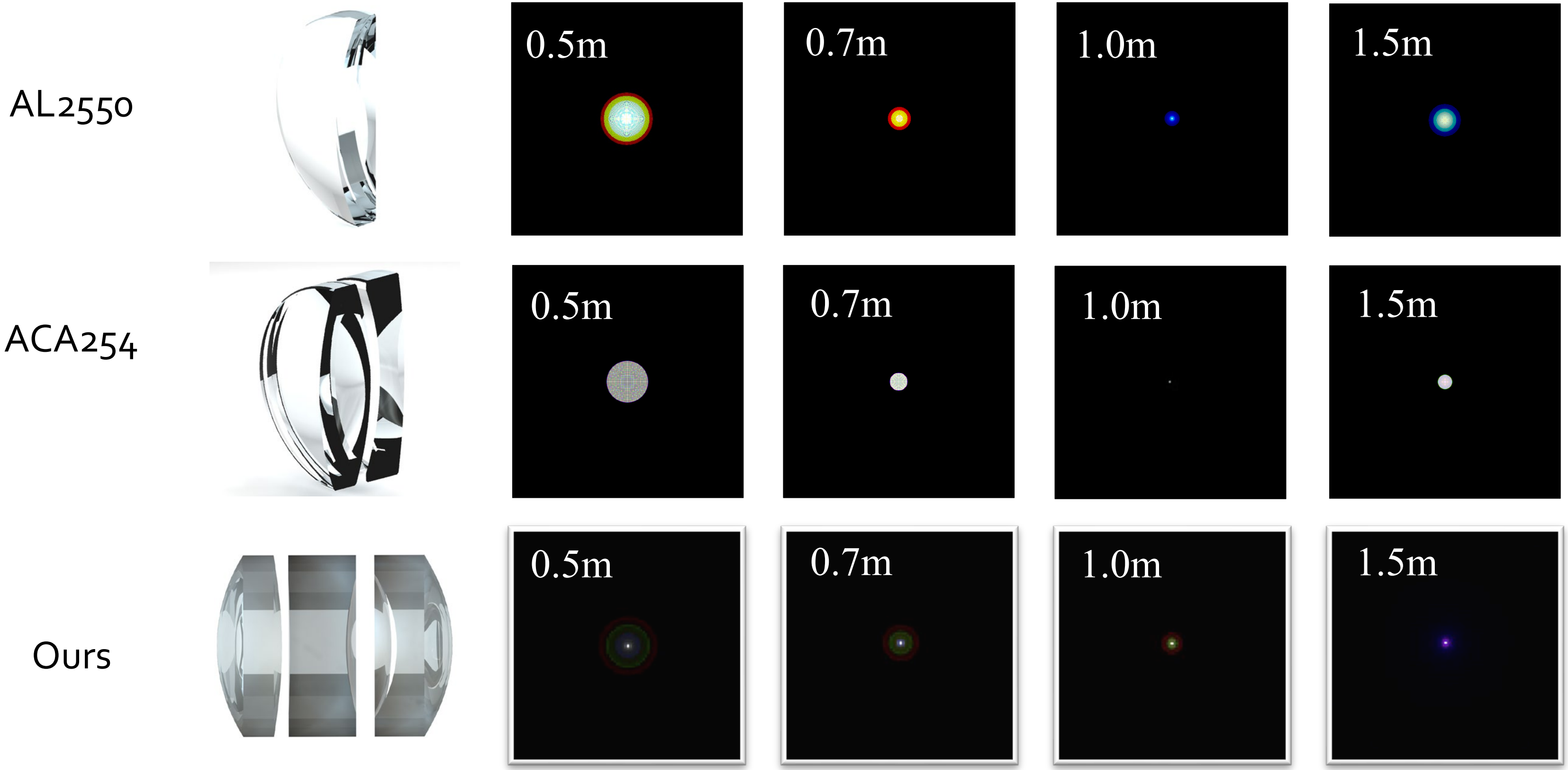


PSF Behavior of Different Depths



Qilin Sun et.al End-to-end Complex Lens Design with Differentiable Ray Tracing

Depth Defocus Examples

https://digital-photography-school.com/out-of-focus-photos/

Today's Topic

- Lens Imperfections and Physical Limit.
- Camera Shake.
- Scene Motion.
- Depth Defocus.

Thank You!

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