

COMP527

COMPUTATIONAL IMAGING

Lecture #08 – Deconvolution and Coded Photography



KOÇ
UNIVERSITY

Aykut Erdem // Koç University // Spring 2023

Previously on COMP527

- Quick reminder: pinhole vs lens cameras
- Focal stack
- Confocal stereo
- Lightfield
- Measuring lightfields
- Plenoptic camera
- Images from lightfields
- Some notes on (auto-)focusing



Today's Lecture

- Deconvolution
 - Sources of blur
 - Blind deconvolution
 - Non-blind deconvolution
- Coded photography
 - The coded photography paradigm
 - Dealing with depth blur
 - Dealing with motion blur

Disclaimer: The material and slides for this lecture were borrowed from

—Ioannis Gkioulekas' 15-463/15-663/15-862 "Computational Photography" class

—Seungyong Lee and Sunghyun Cho's "Recent Advances in Image Deblurring" course at SIGGRAPH Asia 2013

Today's Lecture

- Deconvolution
 - Sources of blur
 - Blind deconvolution
 - Non-blind deconvolution
- Coded photography
 - The coded photography paradigm
 - Dealing with depth blur
 - Dealing with motion blur

Sources of blur



blur [bl3:(r)]

- Long exposure
- Moving objects
- Camera motion
 - panning shot
- Lens imperfections
- Depth defocus



blur [bl3:(r)]

- Often degrades image/video quality severely
- Unavoidable under dim light circumstances

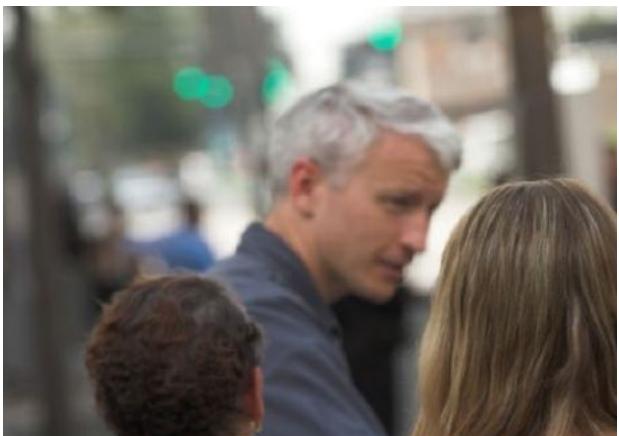
Various Kinds of Blurs



Camera shake (Camera motion blur)



Object movement (Object motion blur)



Out of focus (Defocus blur)



Combinations (vibration & motion, ...)

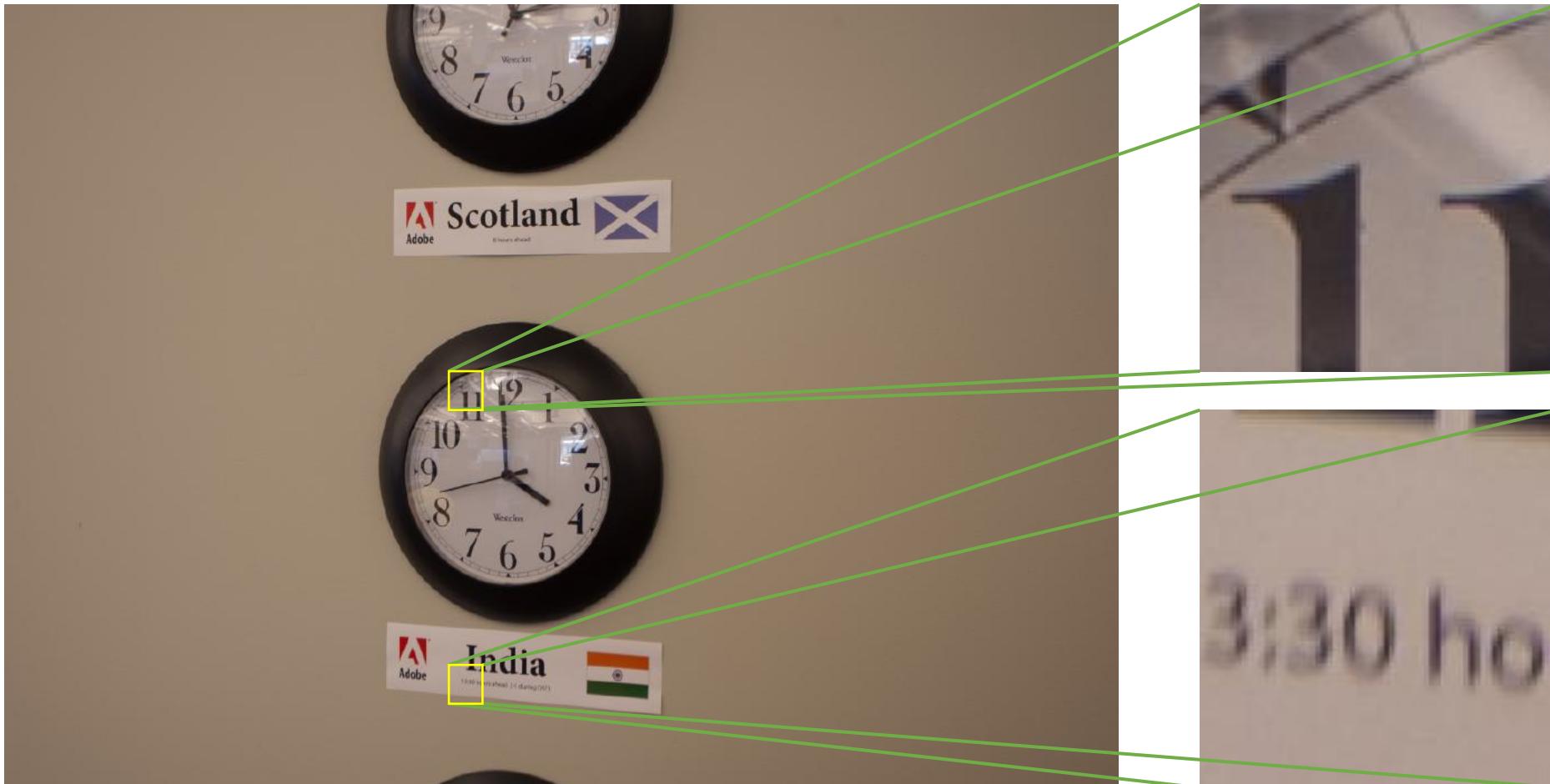
Object Motion Blur

- Caused by object motions during exposure time



Optical Lens Blur

- Caused by lens aberration



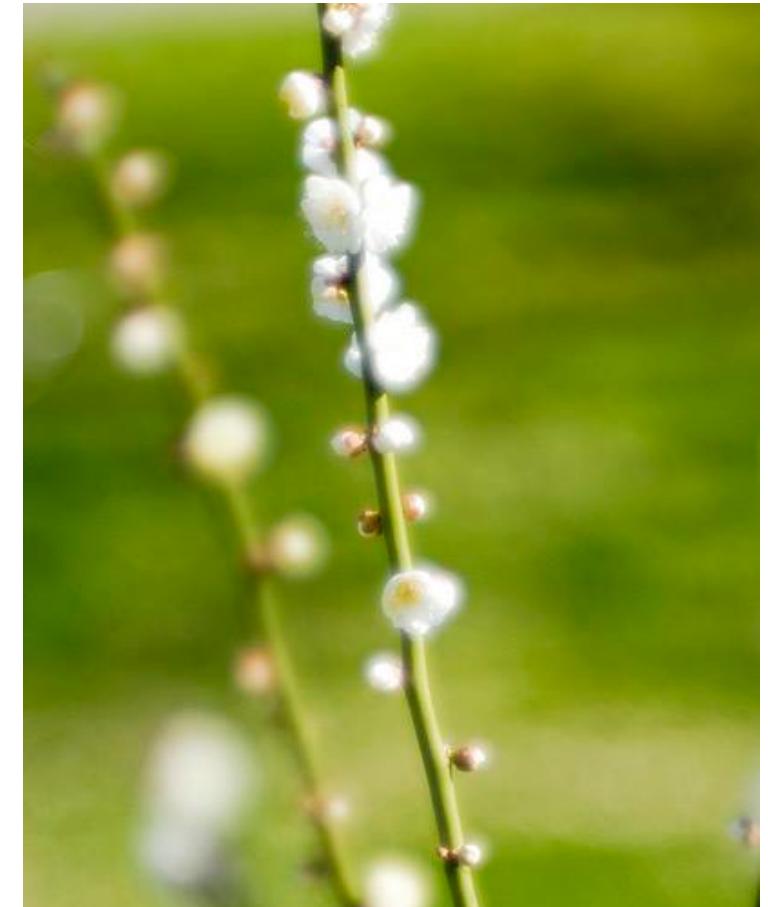
Camera Motion Blur

- Caused by camera shakes during exposure time
 - Motion can be represented as a camera trajectory



Defocus Blur

- Caused by the limited depth of field of a camera



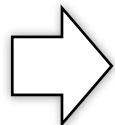
More on coded photography part

Deblurring?

- Remove blur and restore a latent sharp image



from a given blurred image



find its latent sharp image

Why is it important?

- Image/video in our daily lives
 - Sometimes a retake is difficult!

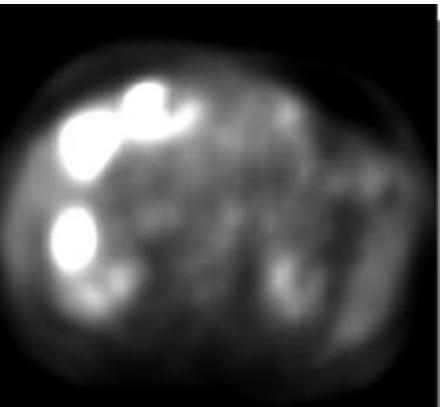


Why is it important?

- Strong demand for high quality deblurring



CCTV, car black box



Medical imaging



Aerial/satellite photography

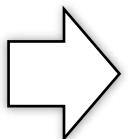


Robot vision

Deblurring



from a given blurred image



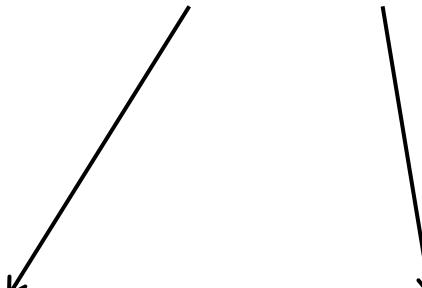
find its latent sharp image

Commonly Used Blur Model



Blurred image

$$= \text{ } \left[\begin{array}{c} \text{ } \\ \text{ } \end{array} \right] * \text{ }$$



Blur kernel or
Point Spread
Function (PSF)



Latent sharp image

Convolution
operator

Blind Deconvolution

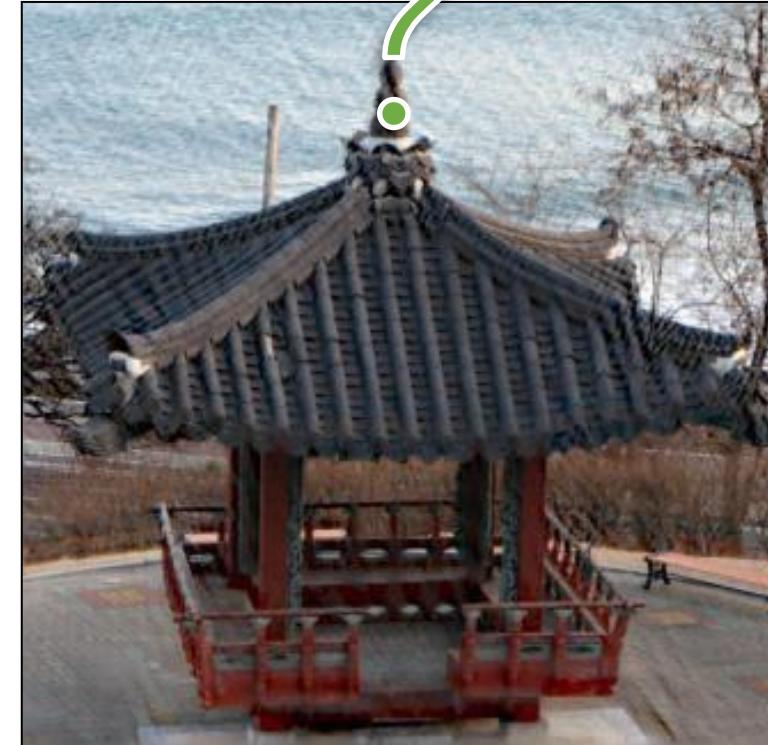


Blurred image

$$= \text{Blur kernel or Point Spread Function (PSF)} * \text{Latent sharp image}$$

Blur kernel or
Point Spread
Function (PSF)

Convolution
operator



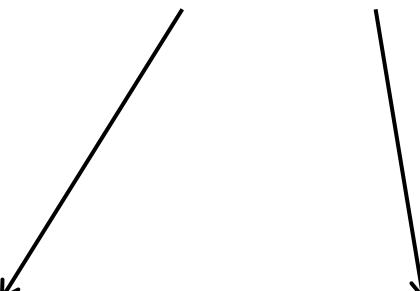
Latent sharp image

Non-blind Deconvolution



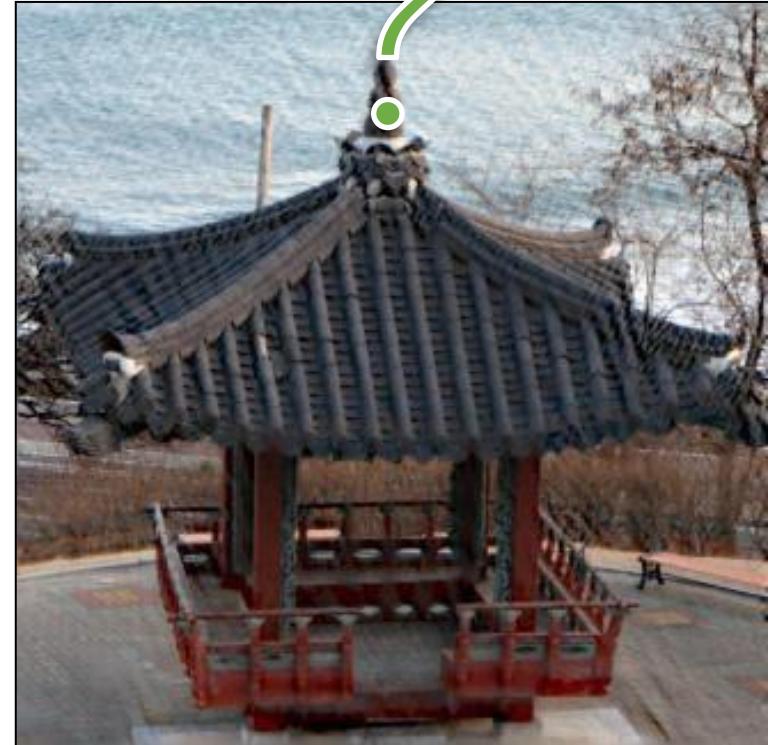
Blurred image

$$= \text{ } \left[\begin{array}{c} \text{ } \\ \text{ } \end{array} \right] * \text{ }$$



Blur kernel or
Point Spread
Function (PSF)

Convolution
operator



Latent sharp image

Uniform vs. Non-uniform Blur



Uniform blur

- Every pixel is blurred in the same way
- Convolution based blur model

Uniform vs. Non-uniform Blur



Non-uniform blur

- Spatially-varying blur
- Pixels are blurred differently
- More faithful to real camera shakes

Most Blurs Are Non-Uniform



Camera shake (Camera motion blur)



Object movement (Object motion blur)



Out of focus (Defocus blur)



Combinations (vibration & motion, ...)

Blind deconvolution

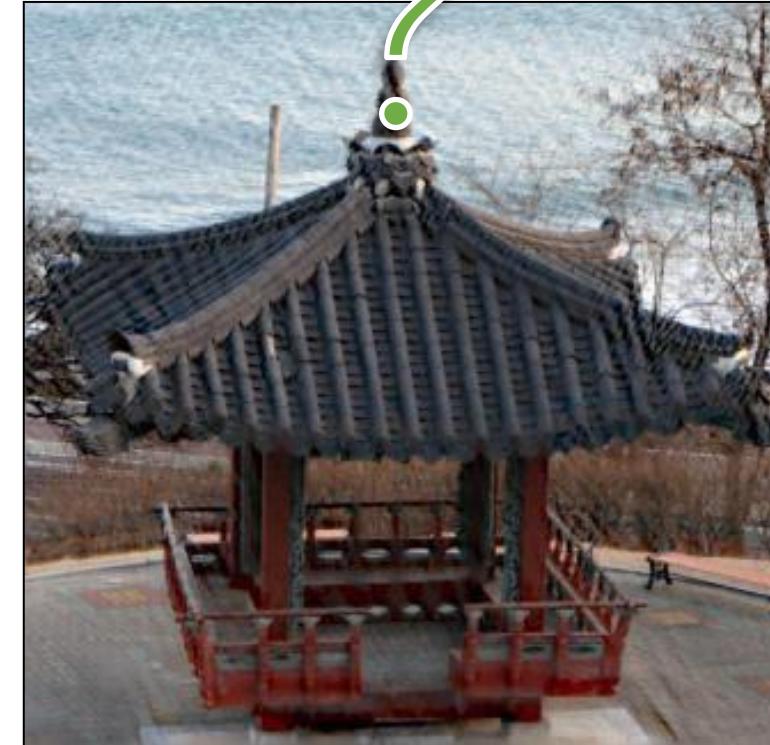
Blind Deconvolution (Uniform Blur)



Blurred image

$$= \text{Blur kernel or Point Spread Function (PSF)} * \text{Convolution operator}$$

Blur kernel or
Point Spread
Function (PSF)



Latent sharp image

Key challenge: Ill-posedness!



Blurred image

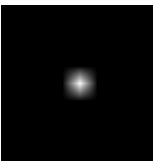
=



Possible solutions



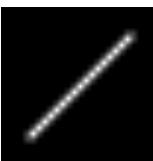
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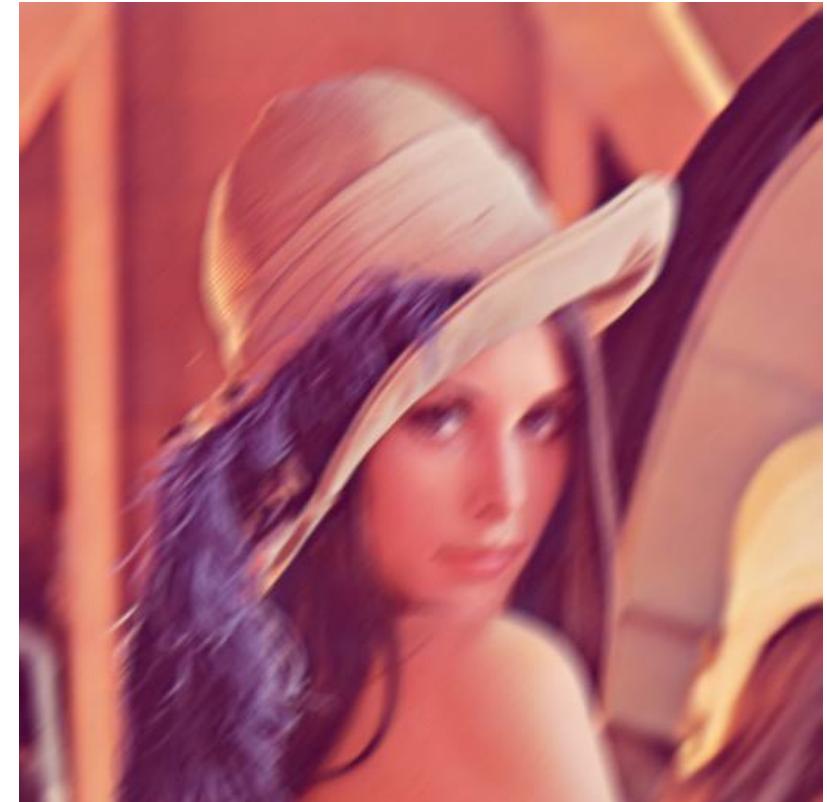
- Infinite number of solutions satisfy the blur model

- Analogous to

$$100 = \begin{cases} 2 \times 50 \\ 4 \times 25 \\ 3 \times 33.333 \dots \end{cases}$$

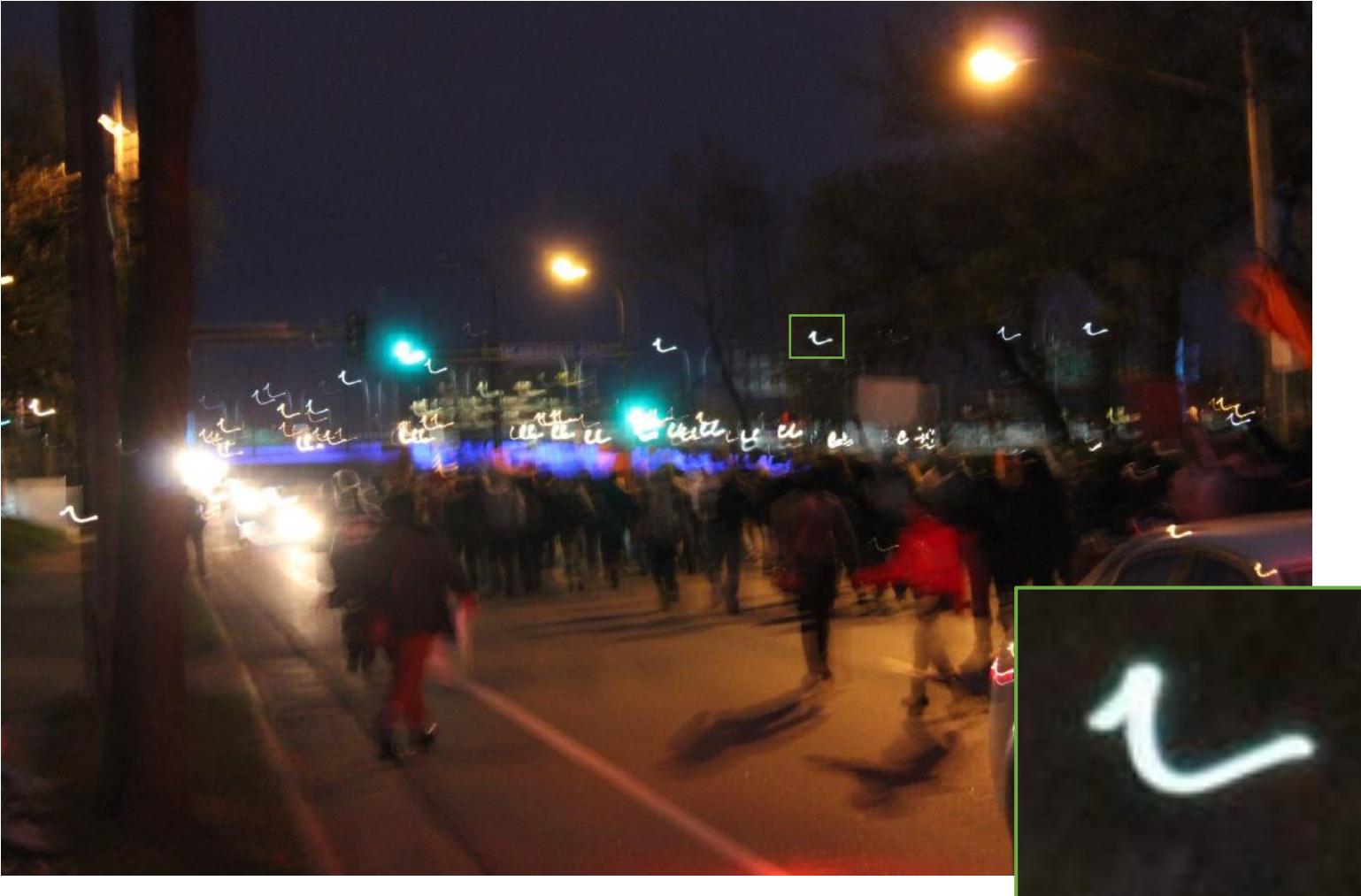
Early approaches

- Parametric blur kernels
 - [Yitzhaki et al. 1998], [Rav-Acha and Peleg 2005], ...
 - Directional blur kernels defined by (length, angle)



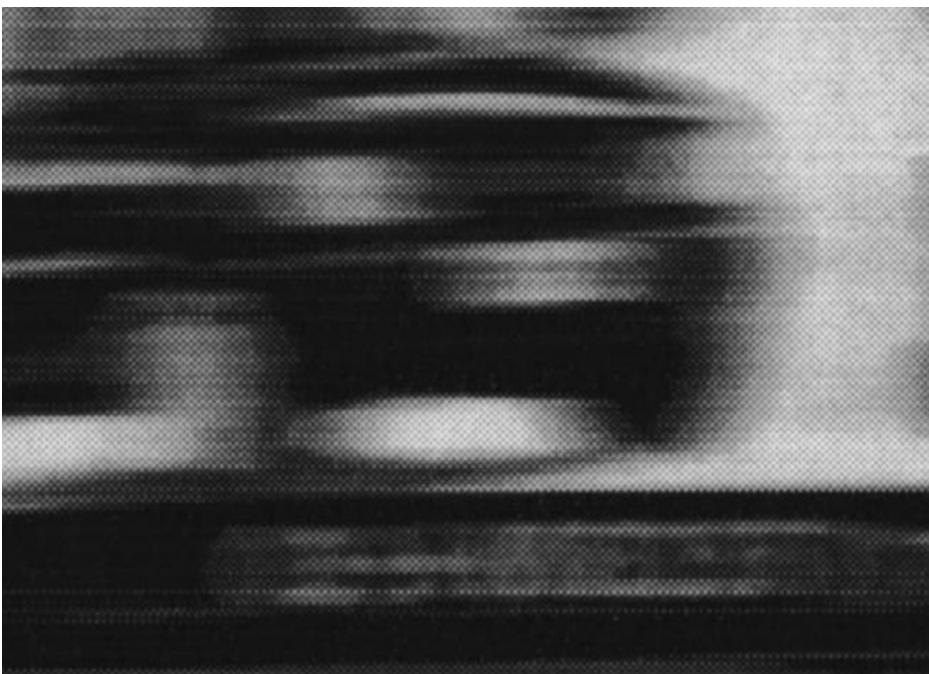
Early approaches

- But real camera shakes are much more complex

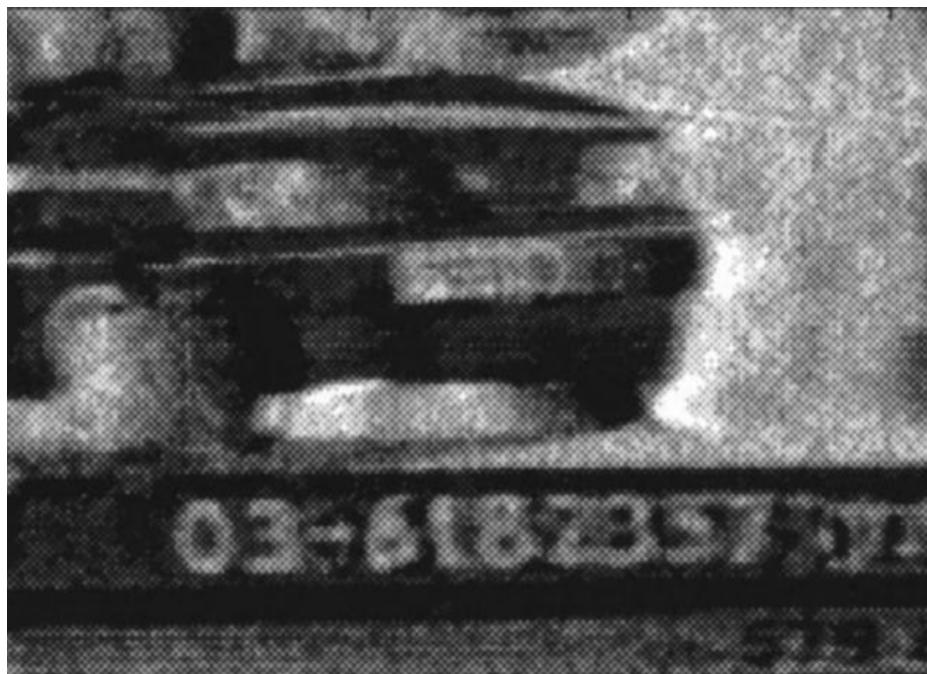


Early approaches

- Parametric blur kernels
 - Very restrictive assumption
 - Often failed, poor quality



Blurred image

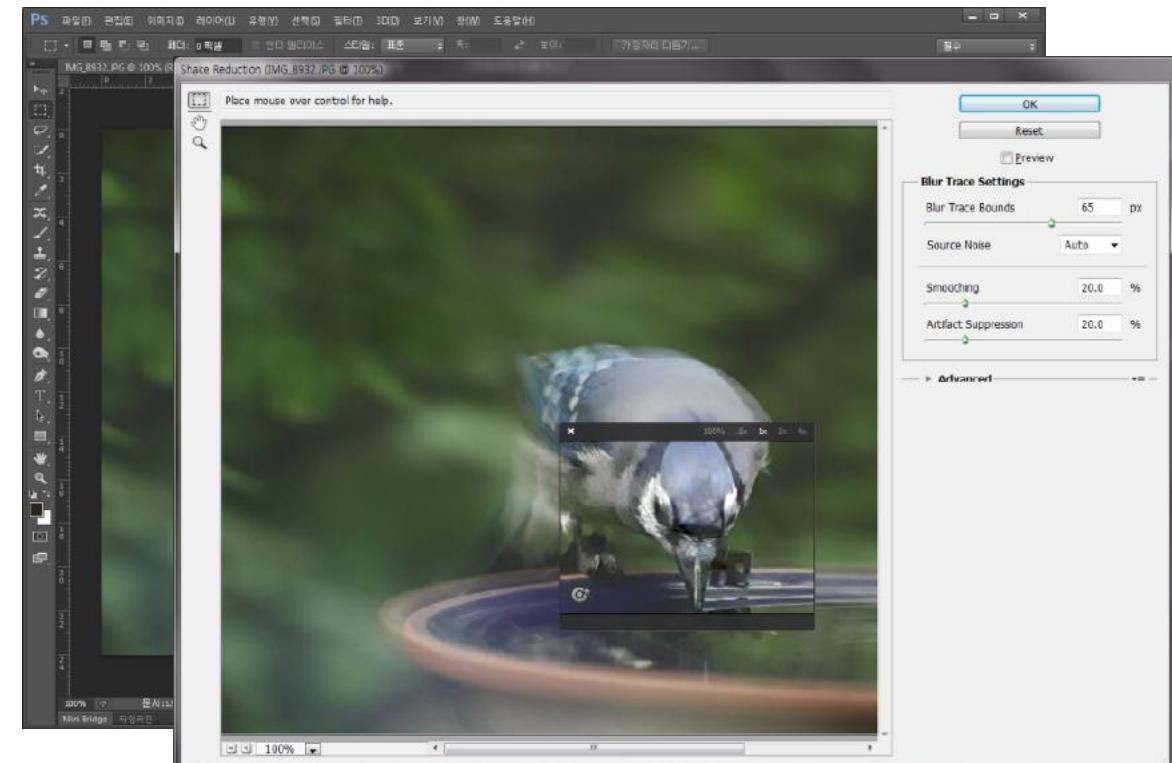


Latent sharp image

Yitzhaky et al. 1998]

More recent work

- Some successful approaches have been introduced...
 - [Fergus et al. SIGGRAPH 2006], [Shan et al. SIGGRAPH 2008], [Cho and Lee, SIGGRAPH Asia 2009], ...
 - More realistic blur kernels
 - Better quality
 - More robust
- Commercial software
 - Photoshop CC Shake reduction



Popular Approaches

- Maximum Posterior (MAP) based
- Variational Bayesian based
- Edge Prediction based

Popular Approaches

- Maximum Posterior (MAP) based
- Variational Bayesian based
- Edge Prediction based
- Deep-Learning based (not now, later on)

Popular Approaches

- Maximum Posterior (MAP) based
 - [Shan et al. SIGGRAPH 2008], [Krishnan et al. CVPR 2011], [Xu et al. CVPR 2013], ...
- Variational Bayesian based
- Edge Prediction based
 - Seek the most probable solution, which maximizes a posterior distribution
 - Easy to understand
 - Convergence problem

MAP based Approaches

Maximize a joint posterior probability with respect to k and l

Posterior distribution

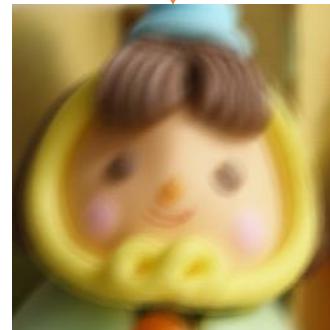
$$p(k, l | b)$$



Blur kernel k



Latent image l



Blurred image b

MAP based Approaches

Bayes rule:

$$\text{Posterior distribution} \quad \text{Likelihood} \quad \text{Prior on } l \quad \text{Prior on } k$$
$$p(k, l | b) \propto p(b|l, k) p(l) p(k)$$



Blur kernel k



Latent image l

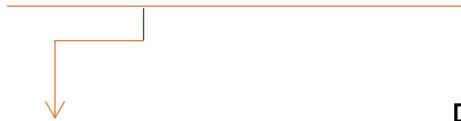


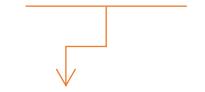
Blurred image b

MAP based Approaches

Negative log-posterior:

$$\begin{aligned} -\log p(k, l|b) &\Rightarrow -\log p(b|k, l) - \log p(l) - \log p(k) \\ &\Rightarrow \|k * l - b\|^2 + \rho_l(l) + \rho_k(k) \end{aligned}$$

 Data fitting term

 Regularization on
latent image l

 Regularization on
blur kernel k

MAP based Approaches

Negative log-posterior:

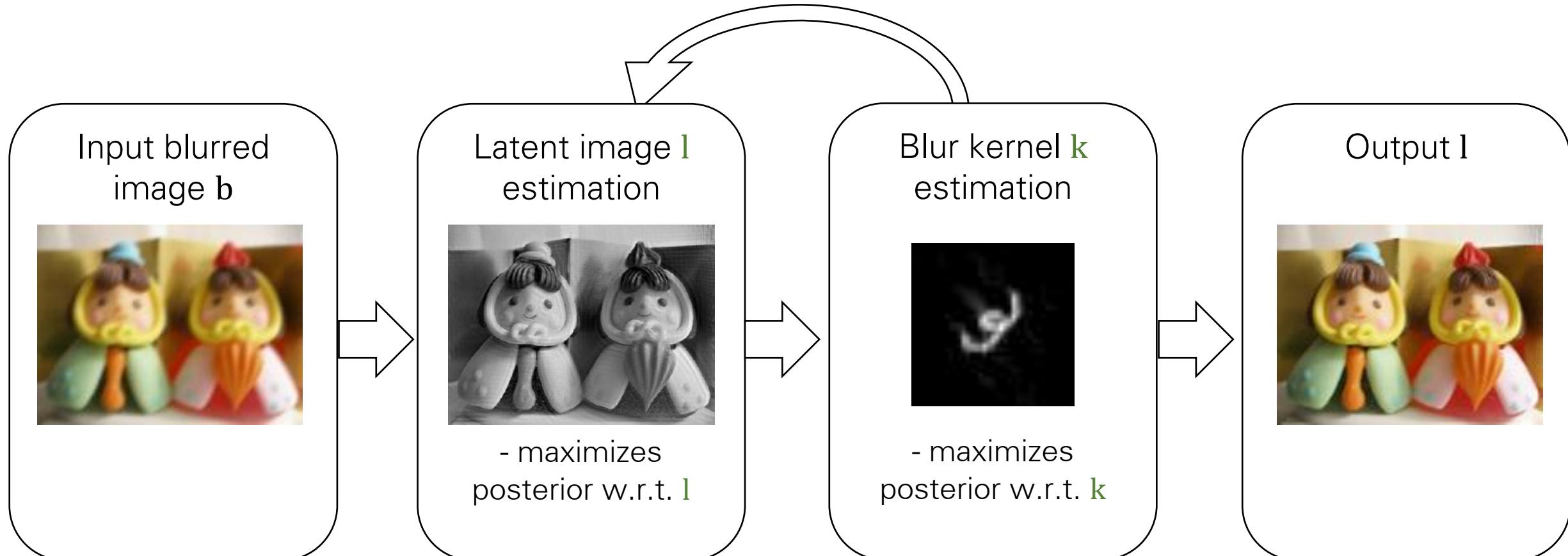
$$\begin{aligned} -\log p(k, l|b) &\Rightarrow -\log p(b|k, l) - \log p(l) - \log p(k) \\ &\Rightarrow \underbrace{\|k * l - b\|^2}_{\text{Data fitting term}} + \rho_l(l) + \rho_k(k) \end{aligned}$$

↓ ↓ ↓

Regularization on
latent image l Regularization on
blur kernel k

Alternately minimize the energy function w.r.t. k and l

MAP based Approaches



MAP based Approaches

- Chan and Wong, TIP 1998
 - Total variation based priors for estimating a parametric blur kernel
- Shan et al. SIGGRAPH 2008
 - First MAP based method to estimate a nonparametric blur kernel
- Krishnan et al. CVPR 2011
 - Normalized sparsity measure, a novel prior on latent images
- Xu et al. CVPR 2013
 - L0 norm based prior on latent images

Shan et al. SIGGRAPH 2008

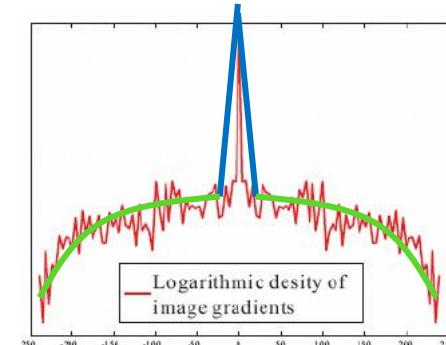
- Carefully designed likelihood & priors

$$p(k, l|b) \propto p(b|l, k)p(l)p(k)$$

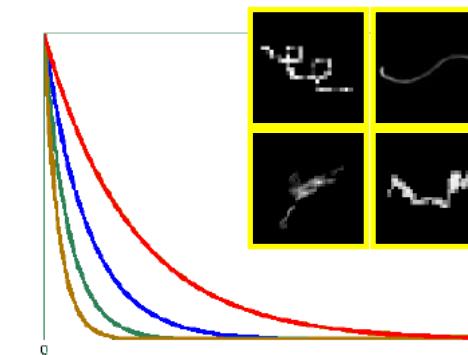
Likelihood based on
intensities & derivatives



Natural image
statistics based
prior on l

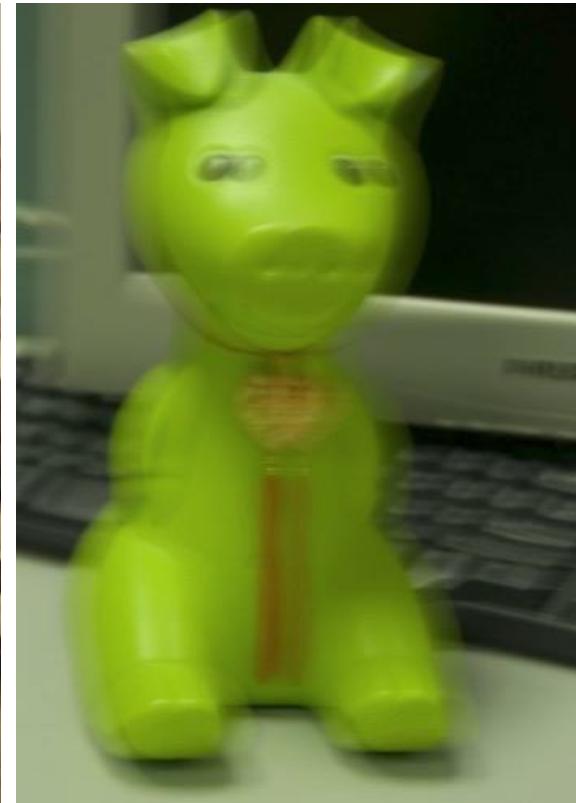


Kernel statistics
based prior on k



Shan et al. SIGGRAPH 2008

- A few minutes for a small image
- High-quality results



Shan et al. SIGGRAPH 2008

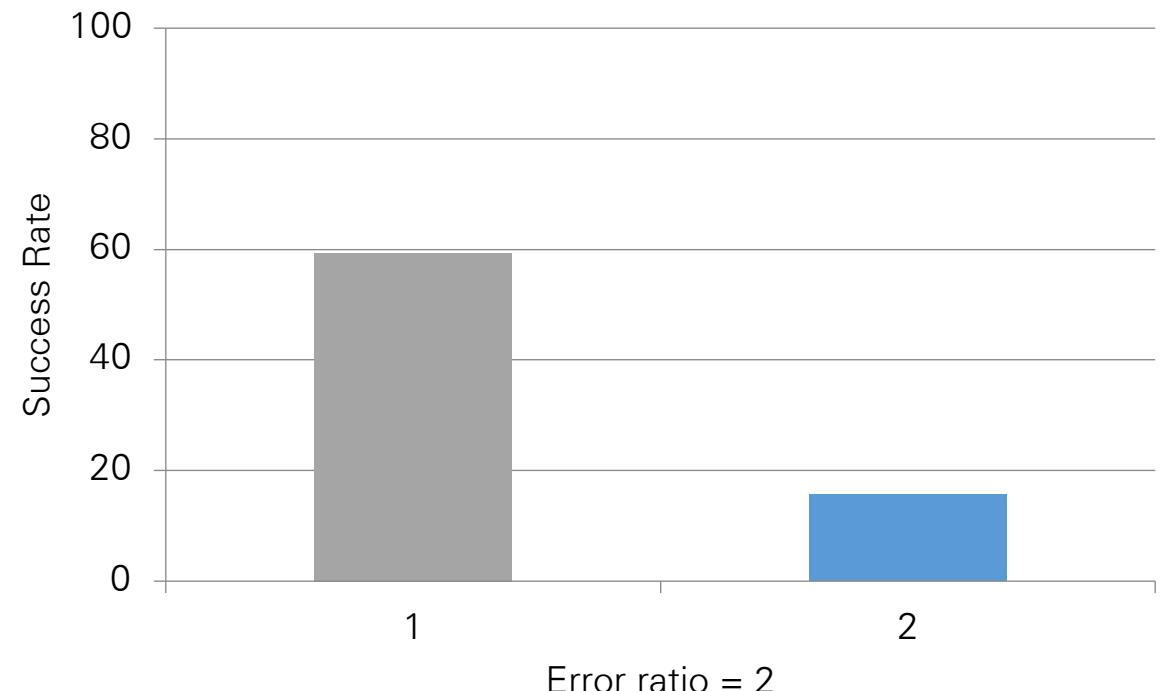
- Convergence problem
 - Often converge to the no-blur solution [Levin et al. CVPR 2009]
 - Natural image priors prefer blurry images



Shan et al. SIGGRAPH 2008



Fergus et al. SIGGRAPH 2006
(variational Bayesian based)

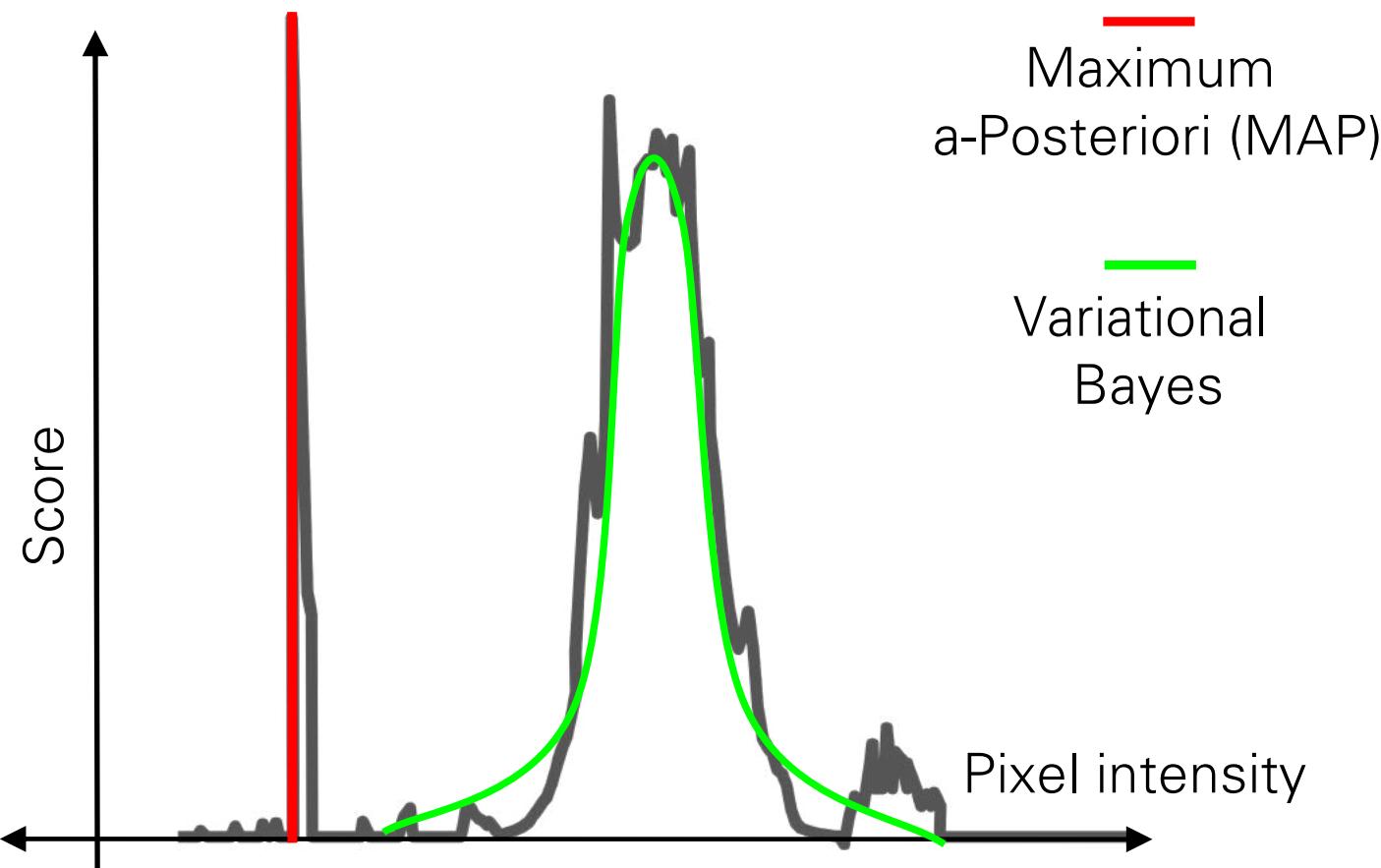


Popular Approaches

- Maximum Posterior (MAP) based
- **Variational Bayesian based**
 - [Fergus et al. SIGGRAPH 2006], [Levin et al. CVPR 2009], [Levin et al. CVPR 2011], ...
- Edge Prediction based
 - Not seek for one most probable solution, but consider all possible solutions
 - Theoretically more robust
 - Slow

Variational Bayesian

MAP v.s. Variational Bayes



- MAP
 - Find the most probable solution
 - May converge to a wrong solution
- Variational Bayesian
 - Approximate the underlying distribution and find the mean
 - More stable
 - Slower

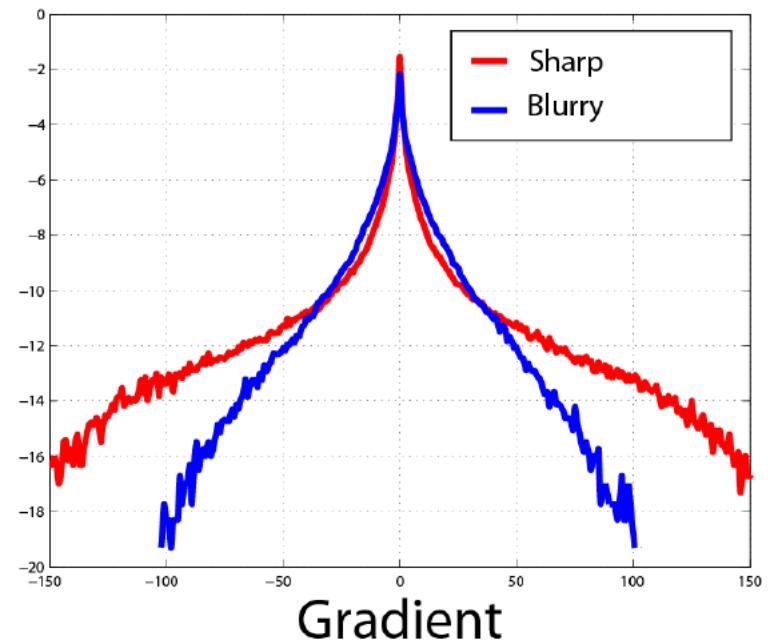
Variational Bayesian

- Fergus et al. SIGGRAPH 2006
 - First approach to handle non-parametric blur kernels
- Levin et al. CVPR 2009
 - Show that variational Bayesian approaches can perform more robustly than MAP based approaches
- Levin et al. CVPR 2010
 - EM based efficient approximation to variational Bayesian approach

Fergus et al. SIGGRAPH 2006

- Posterior distribution

$$p(k, l|b) \propto p(b|k, l)p(l)p(k)$$



Fergus et al. SIGGRAPH 2006

- Find an approximate distribution by minimizing Kullback-Leibler (KL) divergence

$$\arg \min_{q(k), q(l), q(\sigma^{-2})} KL(q(k)q(l)q(\sigma^{-2}) \| p(k, l|b))$$



approximate distributions for blur kernel k ,
latent image l , and noise variance σ^2

- cf MAP based approach:

$$\arg \min_{k,l} p(k, l|b)$$

Fergus et al. SIGGRAPH 2006

- First method to estimate a nonparametric blur kernel
- Complex optimization
- Slow: more than an hour for a small image



Popular Approaches

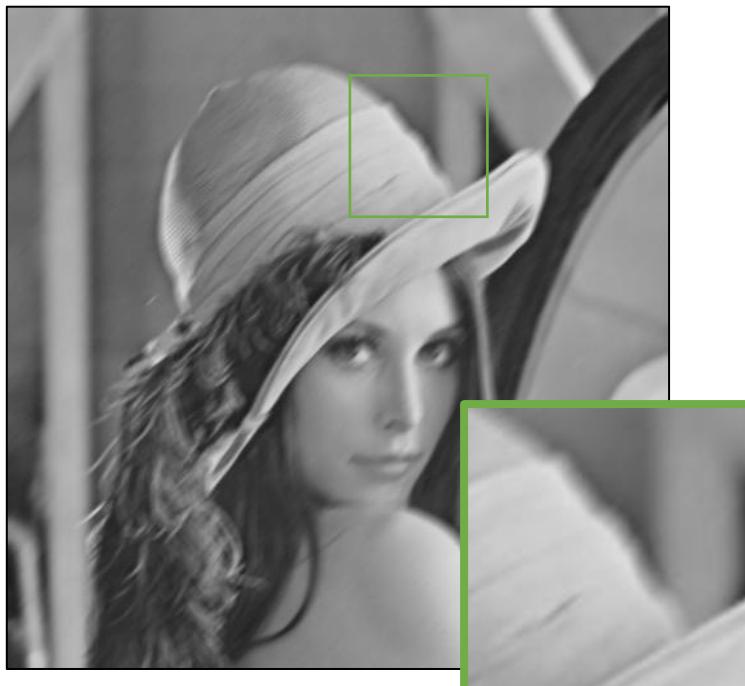
- Maximum Posterior (MAP) based
- Variational Bayesian based
- Edge Prediction based
 - [Cho & Lee. SIGGRAPH Asia 2009], [Xu et al. ECCV 2010], [Hirsch et al. ICCV 2011], ...
 - Explicitly try to recover sharp edges using heuristic image filters
 - Fast
 - Proven to be effective in practice, but hard to analyze because of heuristic steps

Edge Prediction based Approaches

- Joshi et al. CVPR 2008
 - Proposed sharp edge prediction to estimate blur kernels
 - No iterative estimation, limited to small scale blur kernels
- Cho & Lee, SIGGRAPH Asia 2009
 - Proposed sharp edge prediction to estimate large blur kernels
 - Iterative framework, very fast
- Cho et al. CVPR 2010
 - Applied Radon transform to estimate a blur kernel from blurry edge profiles
 - Small scale blur kernels
- Xu et al. ECCV 2010
 - Proposed a prediction scheme based on structure scales as well as gradient magnitudes
- Hirsch et al. ICCV 2011
 - Applied a prediction scheme to estimate spatially-varying camera shakes

Cho & Lee, SIGGRAPH Asia 2009

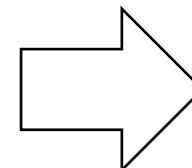
- Key idea: blur can be estimated from a few edges
→ No need to restore every detail for kernel estimation



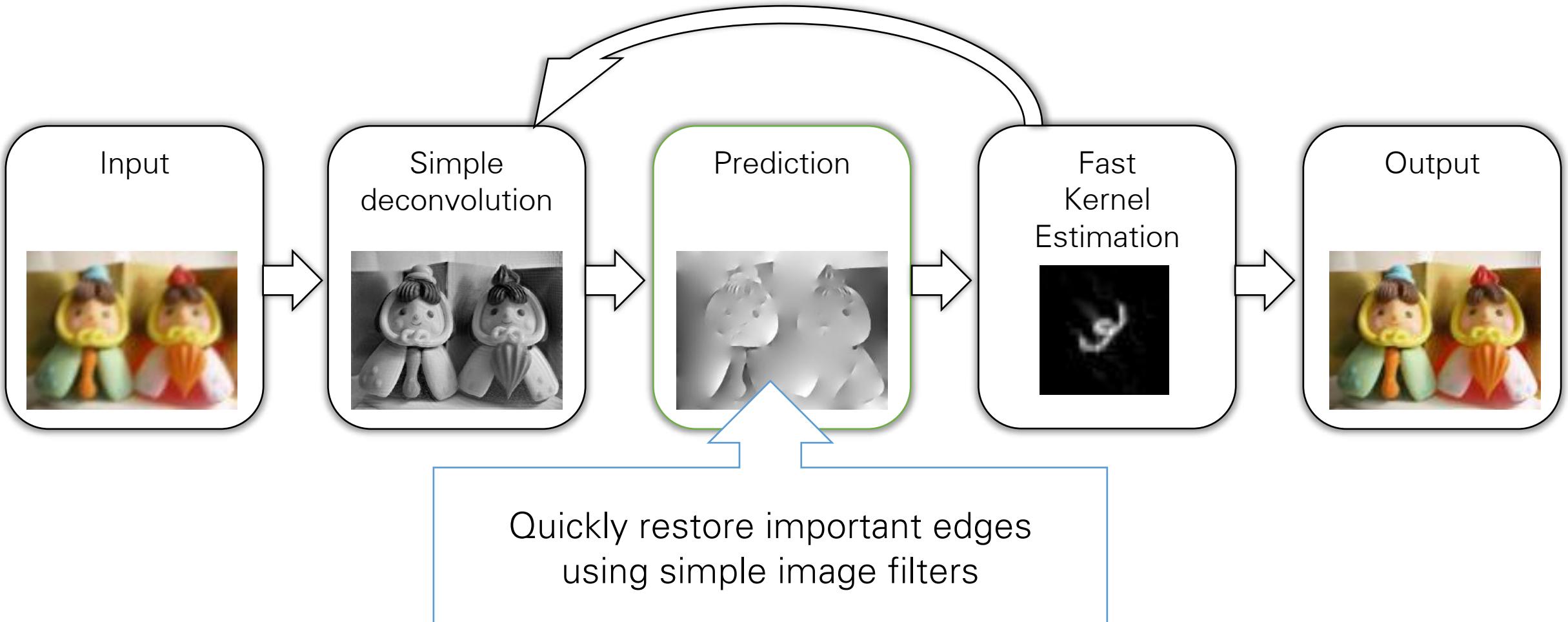
Blurred image



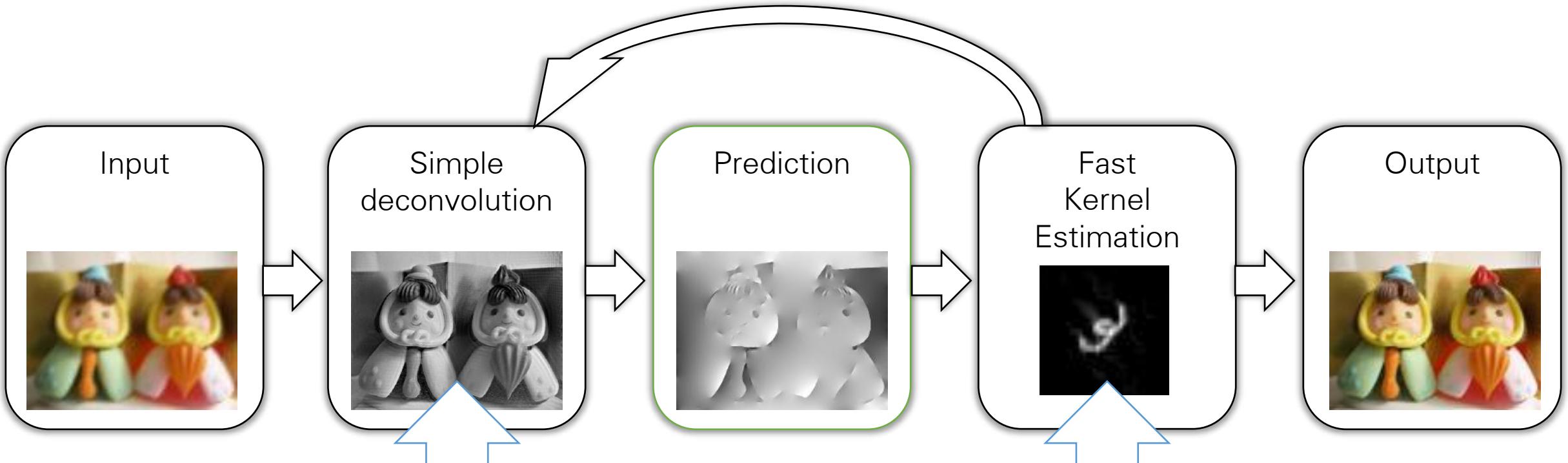
Latent image with only a few edges and no texture



Cho & Lee, SIGGRAPH Asia 2009



Cho & Lee, SIGGRAPH Asia 2009

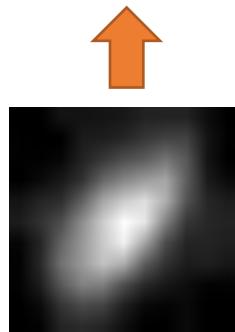


Do not need complex priors for the latent image and the blur kernel
→ Significantly reduce the computation time

Cho & Lee, SIGGRAPH Asia 2009

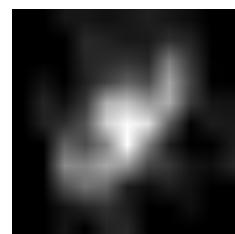


Fast but low quality deconvolution

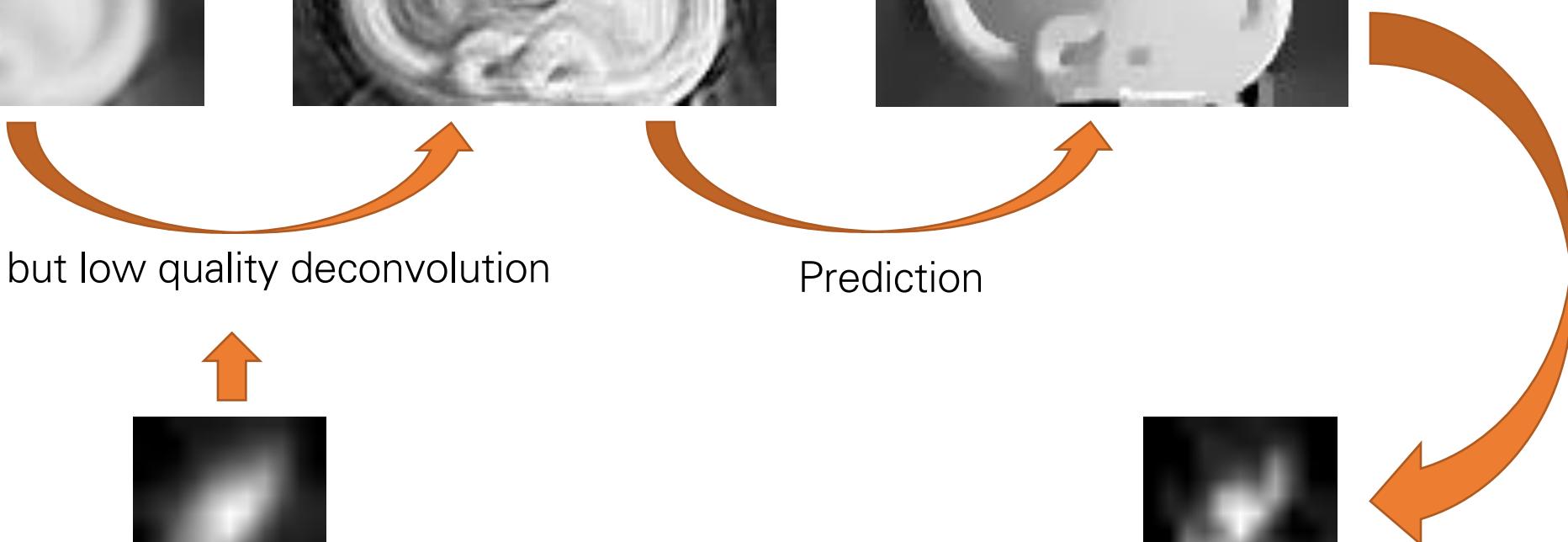


Previous kernel

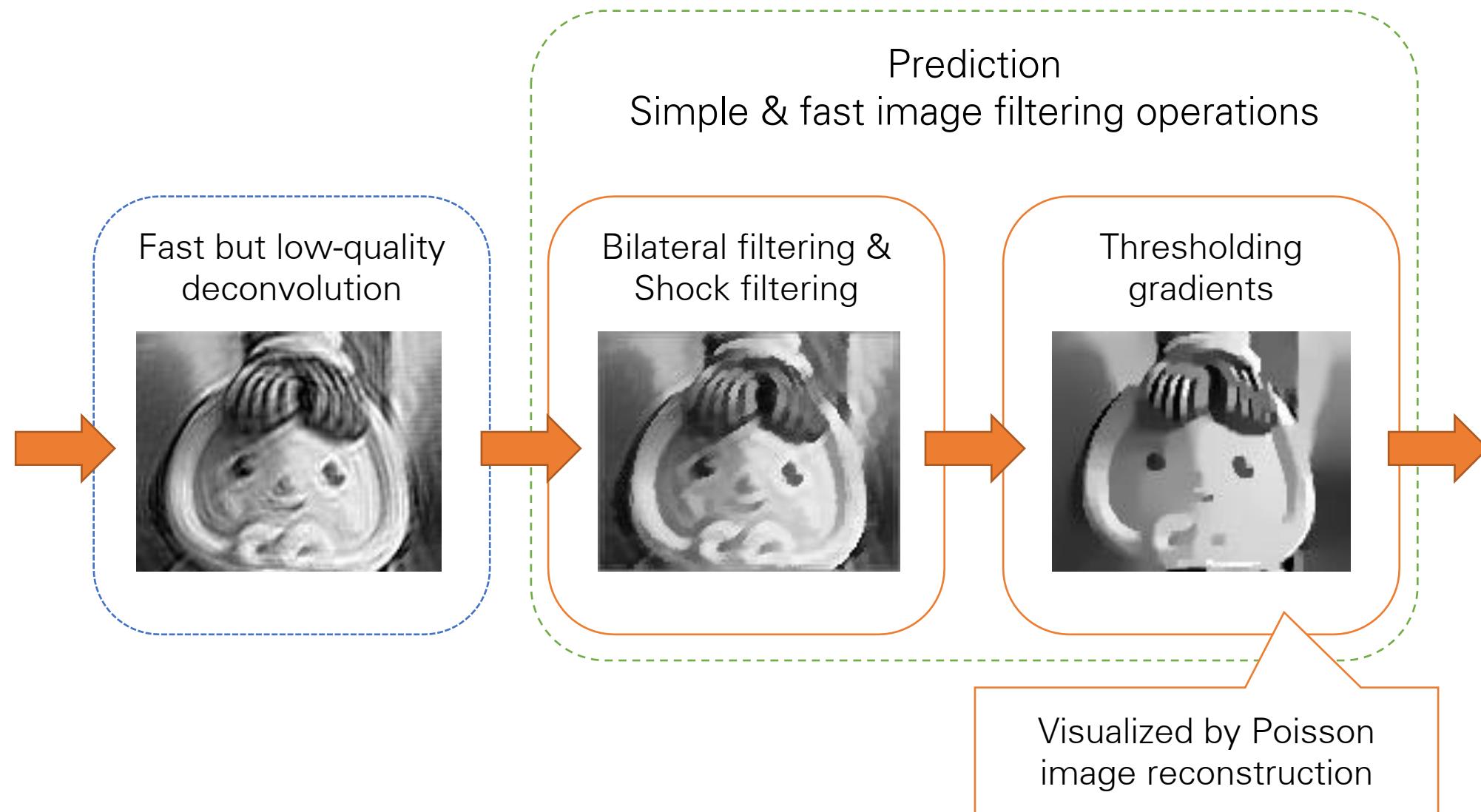
Prediction



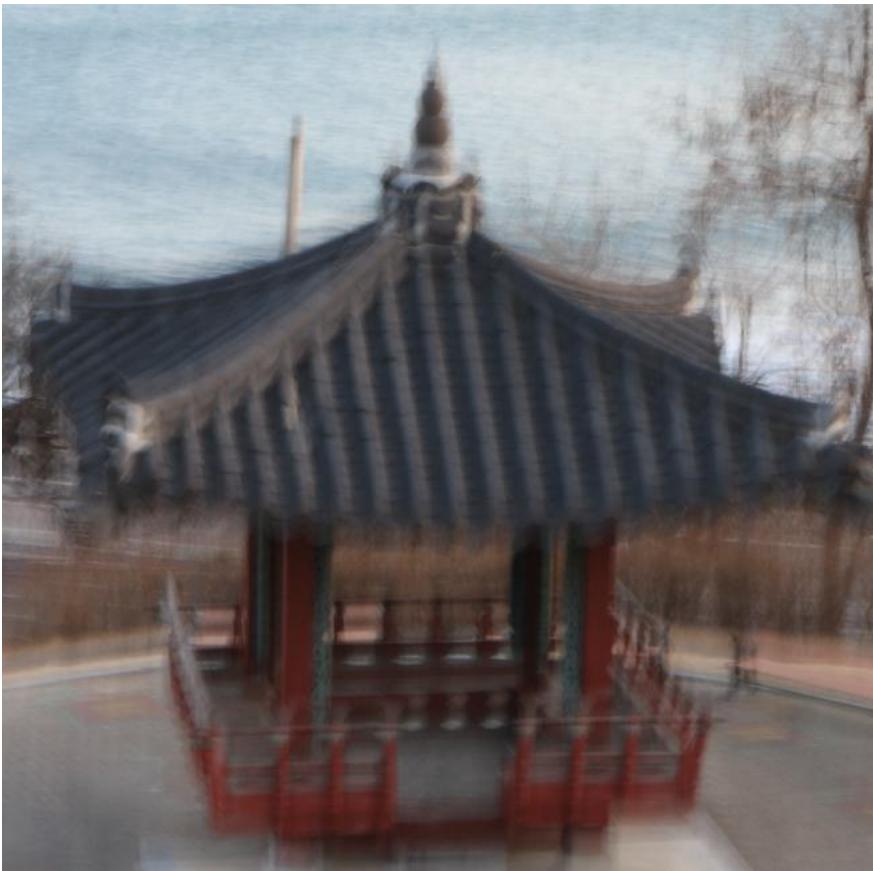
Updated kernel



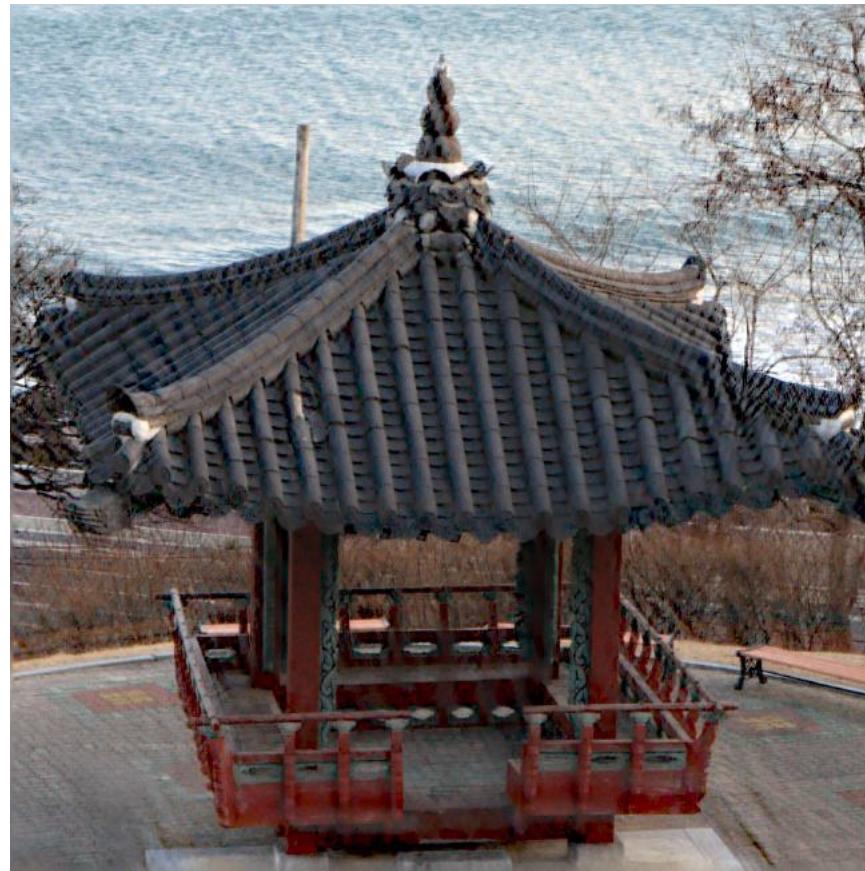
Cho & Lee, SIGGRAPH Asia 2009



Cho & Lee, SIGGRAPH Asia 2009



Blurry input



Deblurring result



Blur kernel

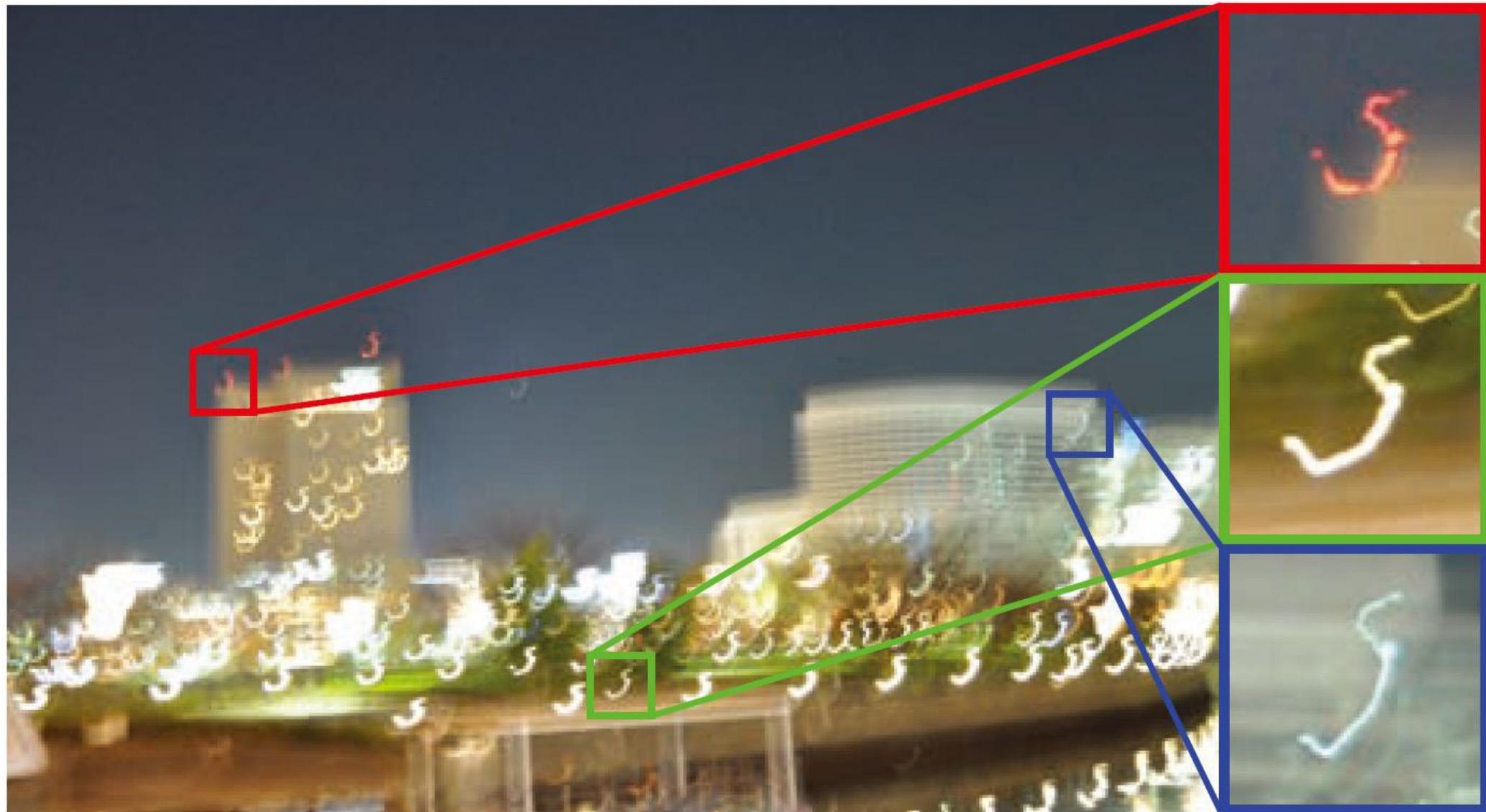
- State of the art results
- A few seconds
- 1Mpix image
- in C++

Convolution based Blur Model

- Uniform and spatially invariant blur



Real Camera Shakes: Spatially Variant!



Uniform Blur Model Assumes

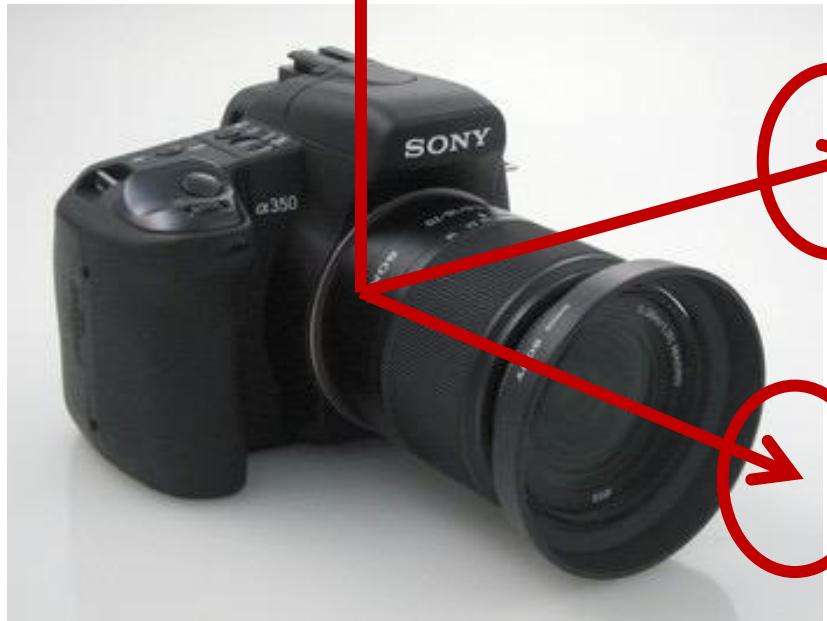


x & y translational
camera shakes



Planar scene

Real Camera Shakes

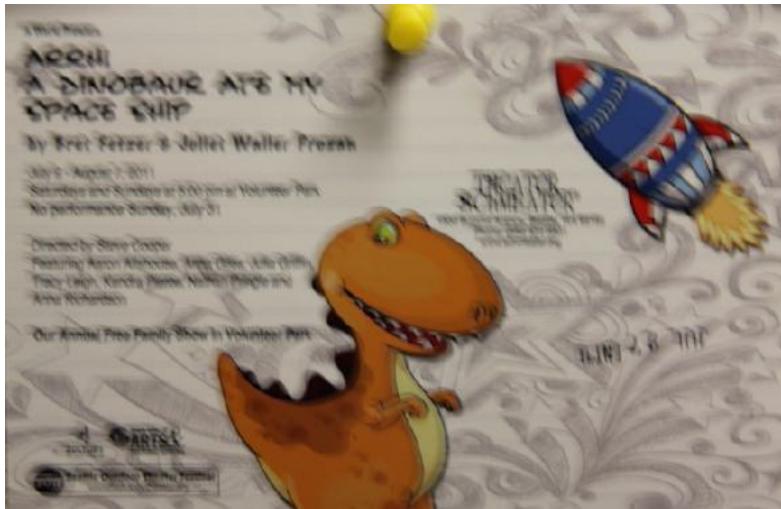


6D real camera motion

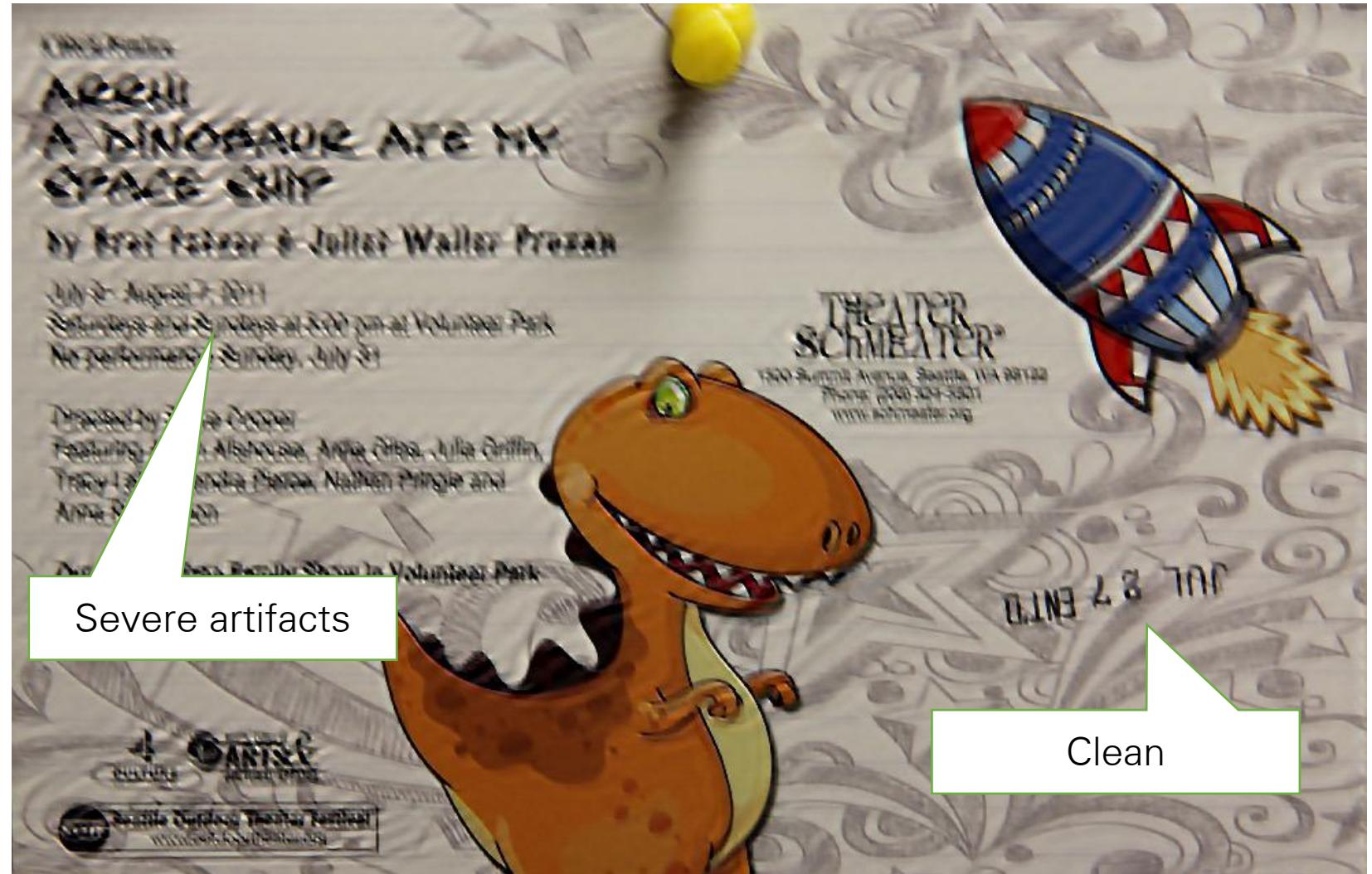


Different depths

Real Blurred Image



Non-uniformly blurred image



Uniform deblurring result

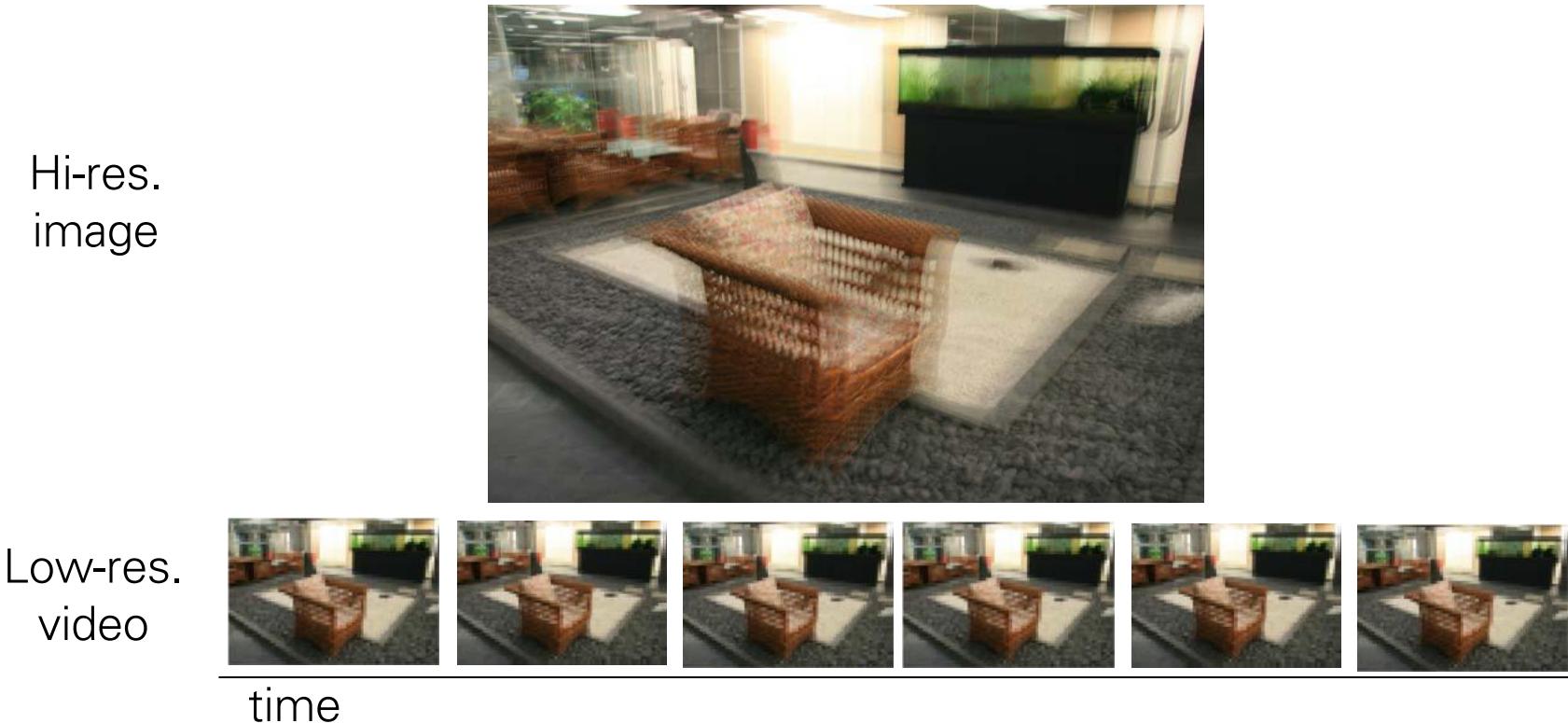
Pixel-wise Blur Model

- Dai and Wu, CVPR 2008
 - Estimate blur kernels for every pixel from a single image
 - Severely ill-posed
 - Parametric blur kernels



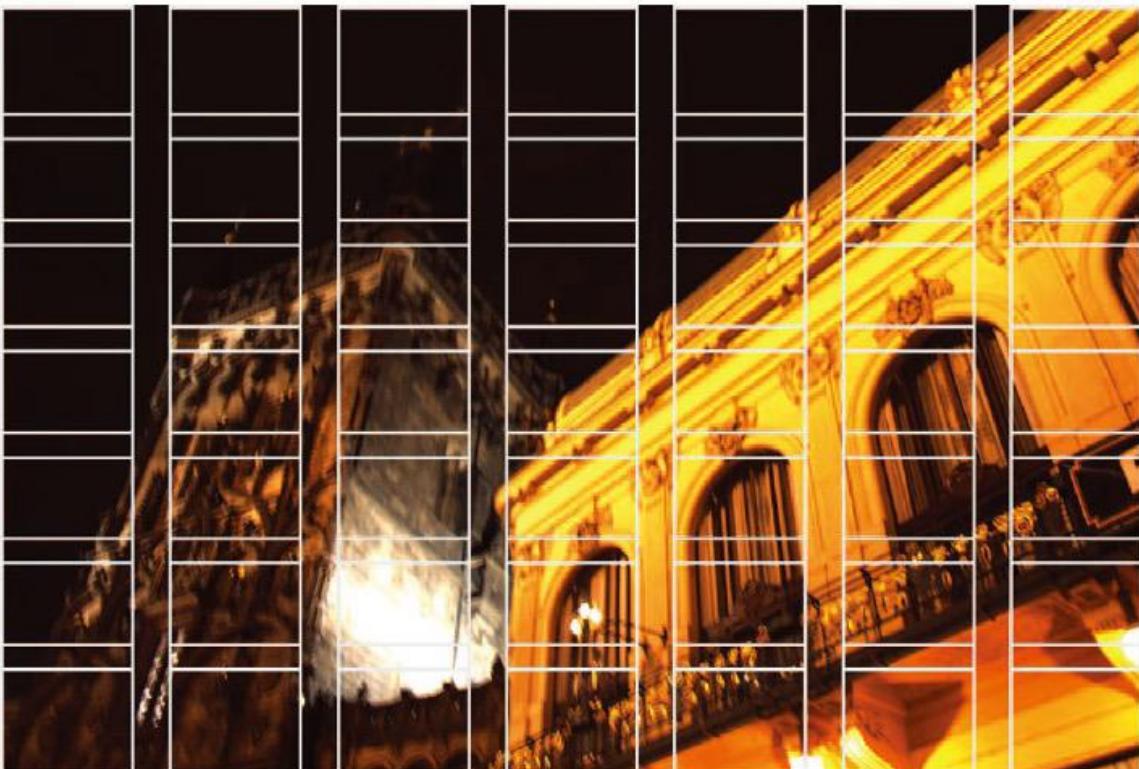
Pixel-wise Blur Model

- Tai et al. CVPR 2008
 - Hybrid camera to capture hi-res image & low-res video
 - Estimate per-pixel blur kernels using low-res video



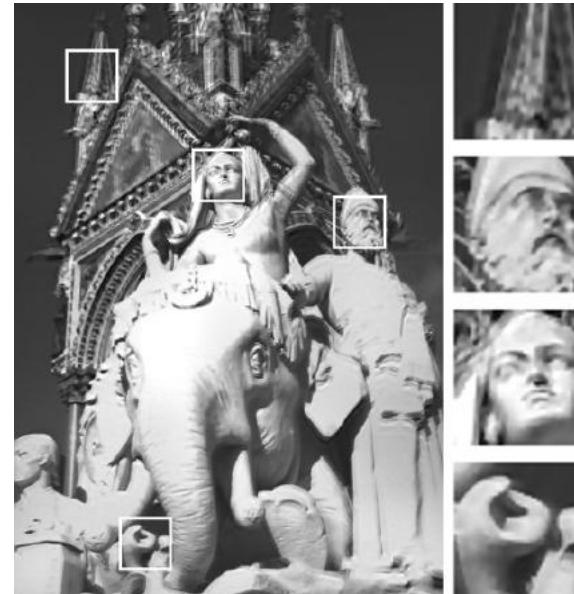
Patch-wise Blur Model

- Sorel and Sroubek, ICIP 2009
 - Estimate per-patch blur kernels from a blurred image and an underexposed noisy image



Patch-wise Blur Model

- Hirsch et al. CVPR 2010
 - Efficient filter flow (EFF) framework
 - More accurate approximation than the naïve patch-wise blur model
- Harmeling et al. NIPS 2010
 - Estimate per-patch blur kernels based on EFF from a single image



Patch-wise Blur Model

- Approximation
 - More patches → more accurate
- Computationally efficient
 - Patch-wise uniform blur
 - FFTs can be used
- Physically implausible blurs
 - Adjacent blur kernels cannot be very different from each other



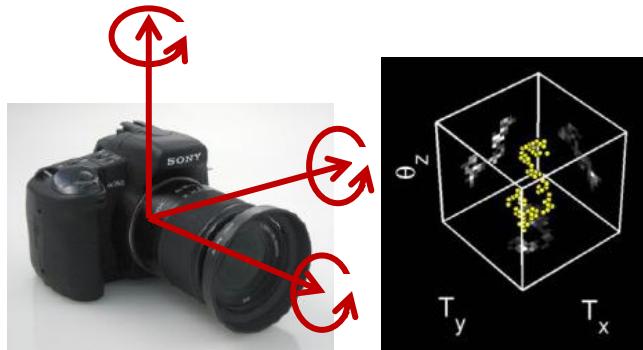
Summary

- Different blur models



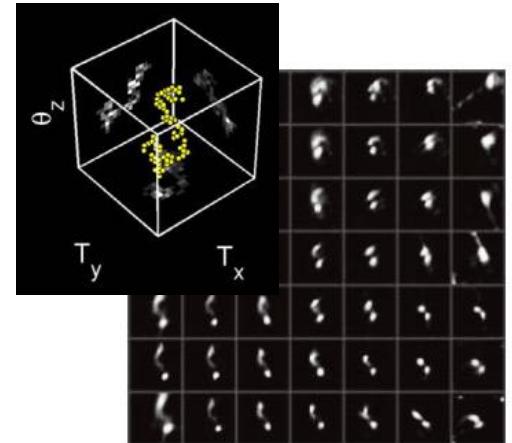
Patch based

Efficient but no global constraint



Projective Motion Path

Globally consistent but inefficient



Hybrid

Efficient & globally consistent

- More realistic than uniform blur model
- Still approximations
 - Real camera motions: 6 DoF + more (zoom-in, depth, etc...)
- High dimensionality
 - Less stable & slower than uniform blur model

Remaining Challenges



- All methods still fail quite often
- Noise
- Outliers
- Non-uniform blur
- Limited amount of edges
- Speed...
- Etc...

Non-blind deconvolution

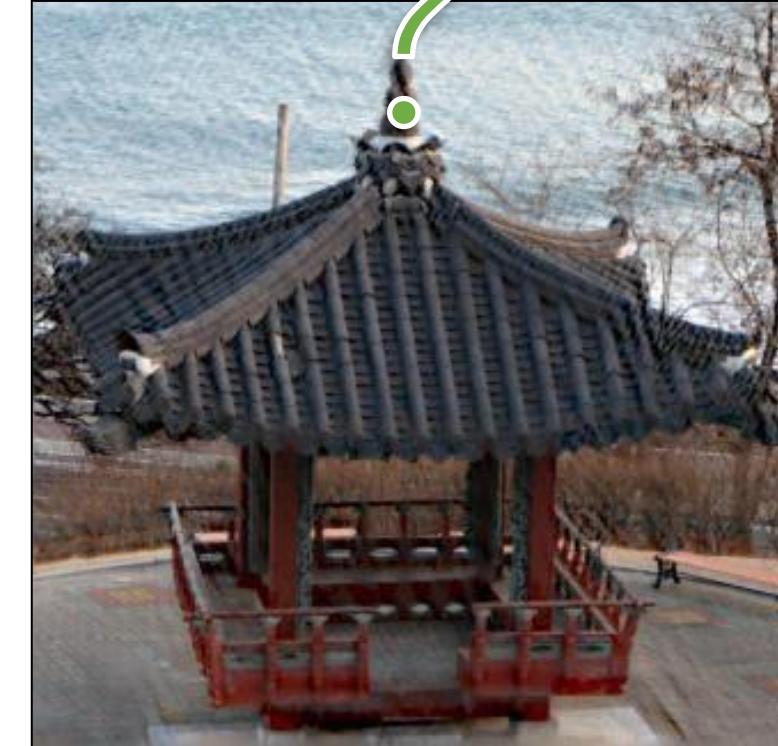
Non-blind Deconvolution (Uniform Blur)



Blurred image

$$= \quad \quad \quad *$$


Blur kernel



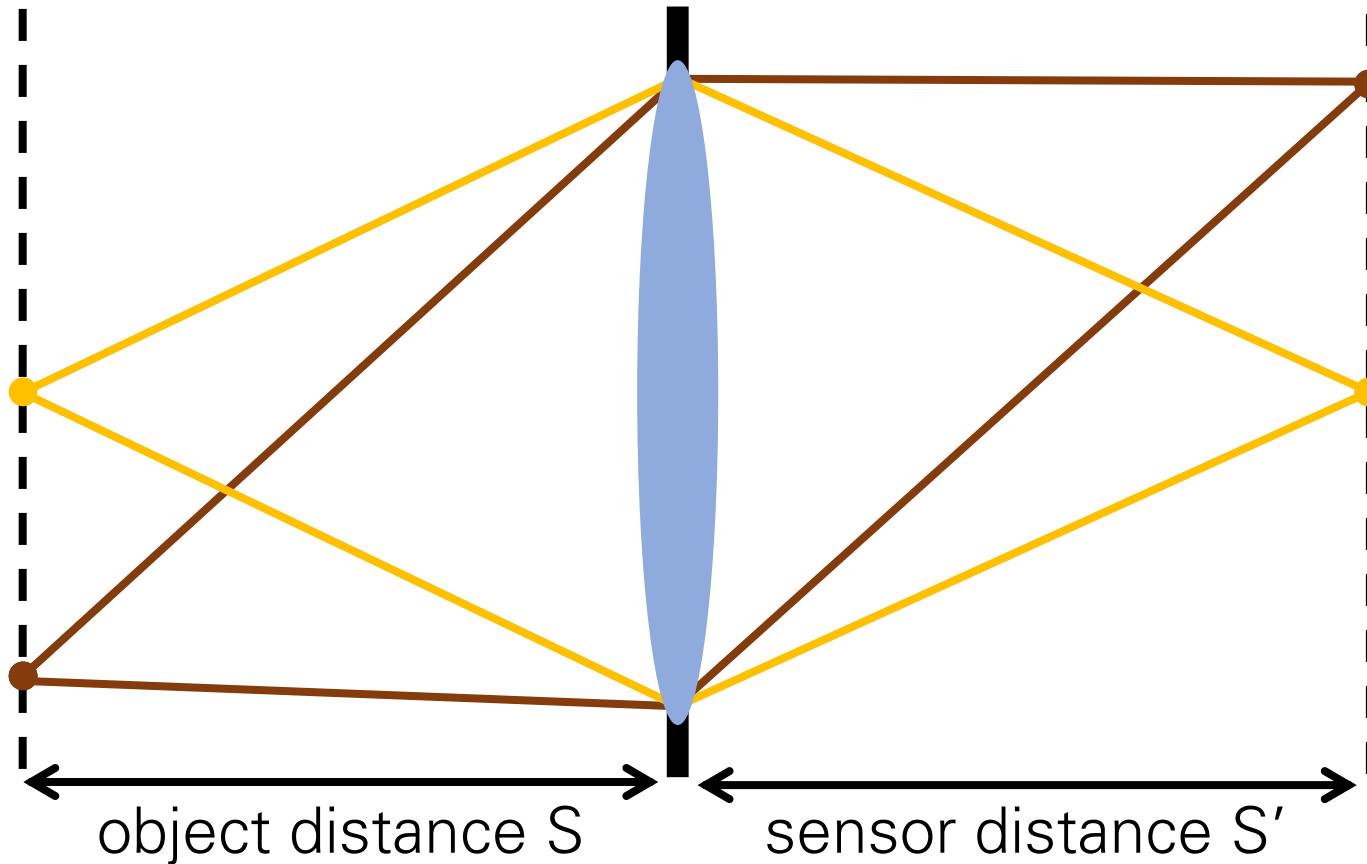
Latent sharp image

Convolution
operator

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.

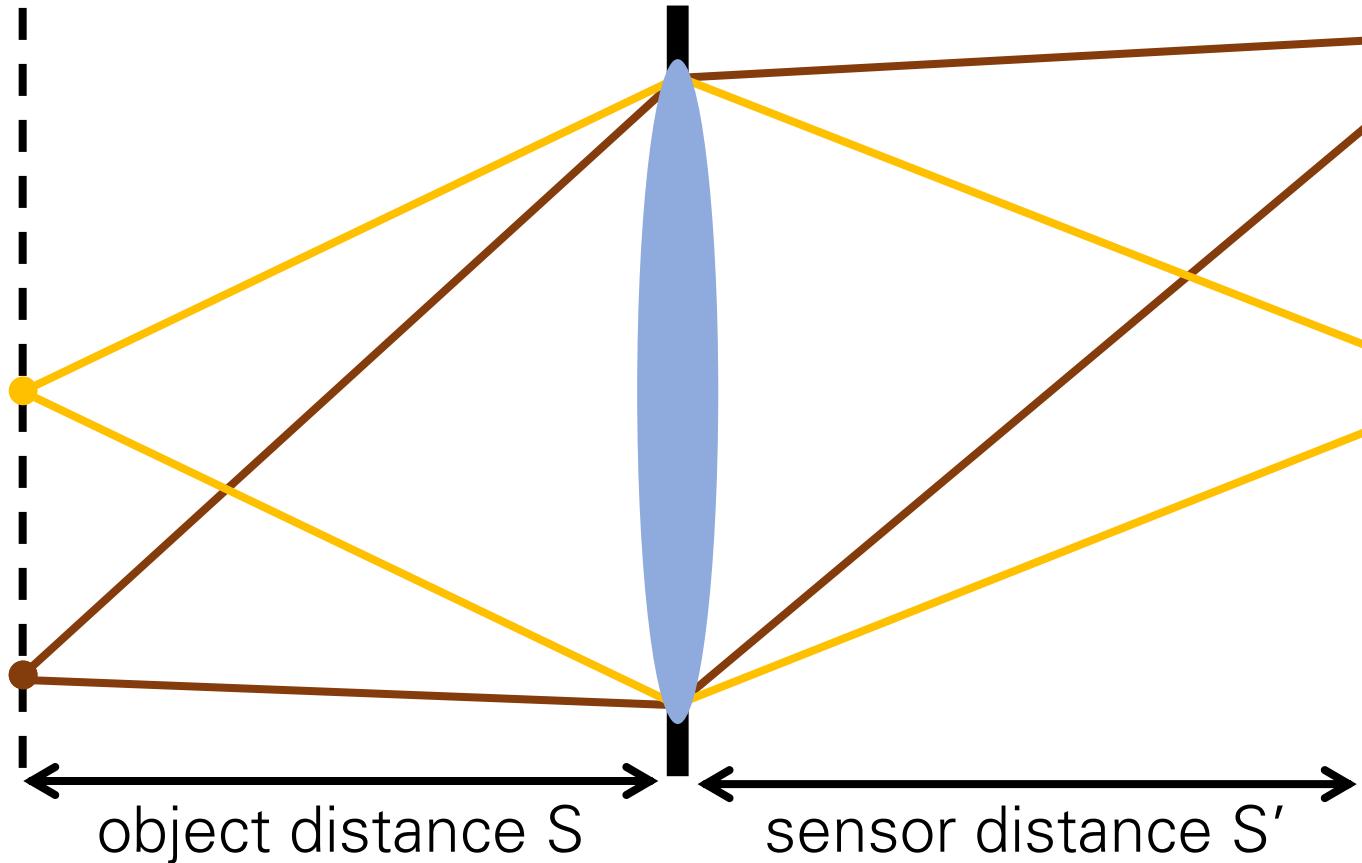
$$\frac{1}{S'} + \frac{1}{S} = \frac{1}{f}$$



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.

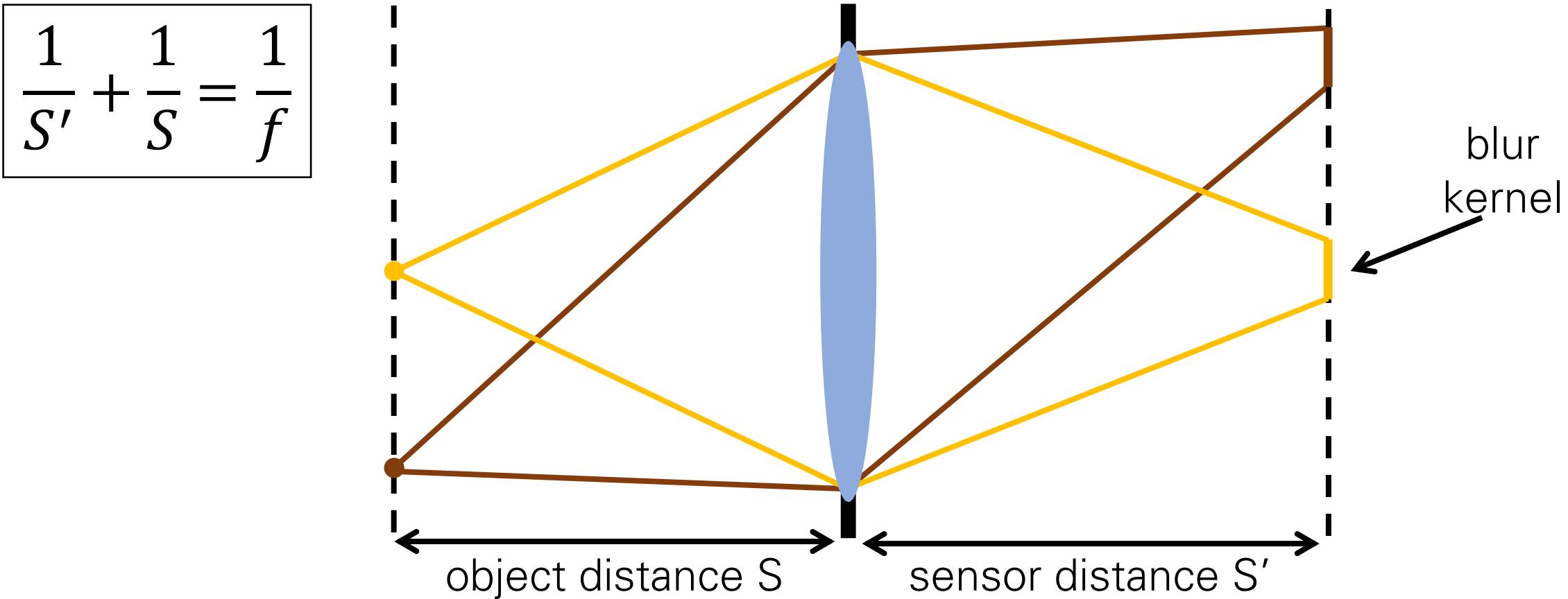
$$\frac{1}{S'} + \frac{1}{S} = \frac{1}{f}$$



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.



Shift-invariant blur.

Lens imperfections

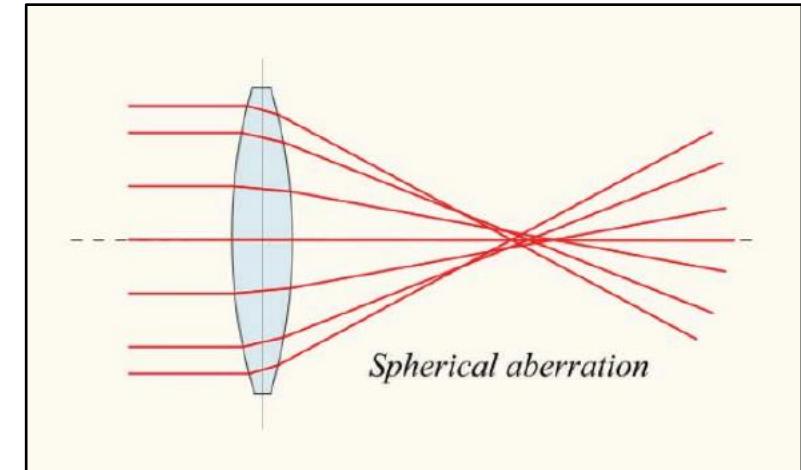
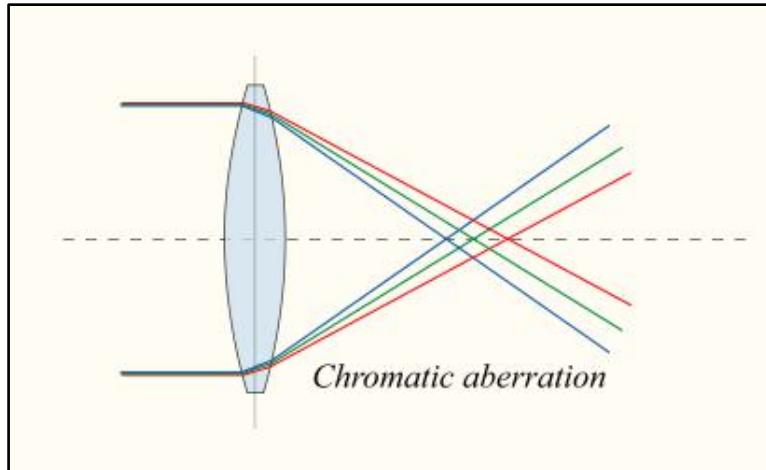
What causes lens imperfections?

Lens imperfections

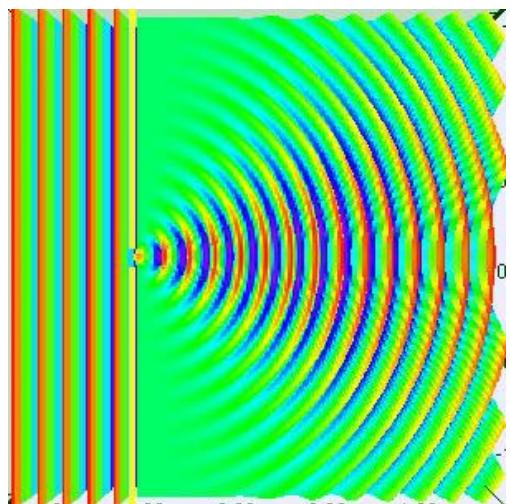
What causes lens imperfections?

- Aberrations.

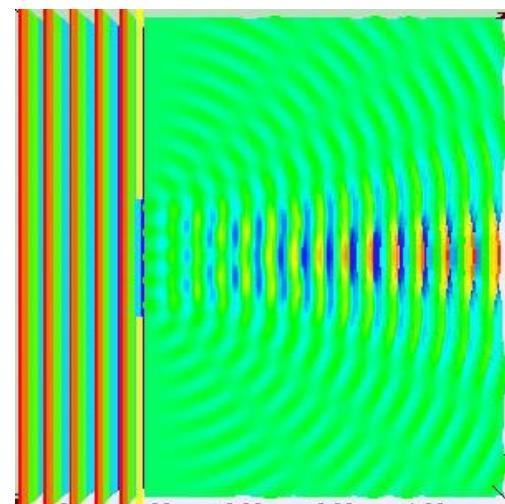
(Important note: Oblique aberrations like coma and distortion are not shift-invariant blur and we do not consider them here!)



- Diffraction.



small
aperture



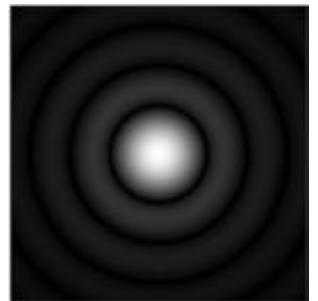
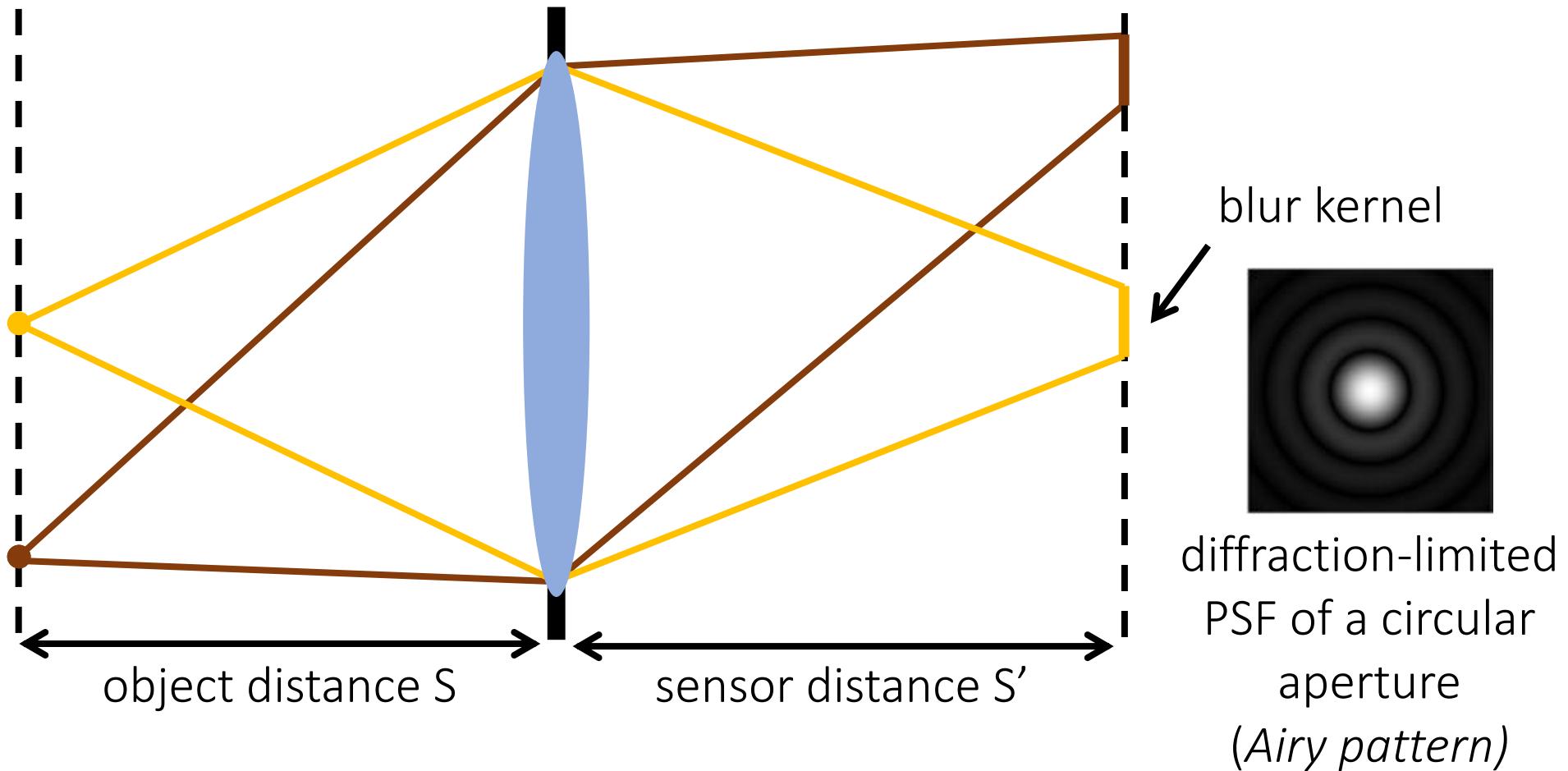
large
aperture

Lens as 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.

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

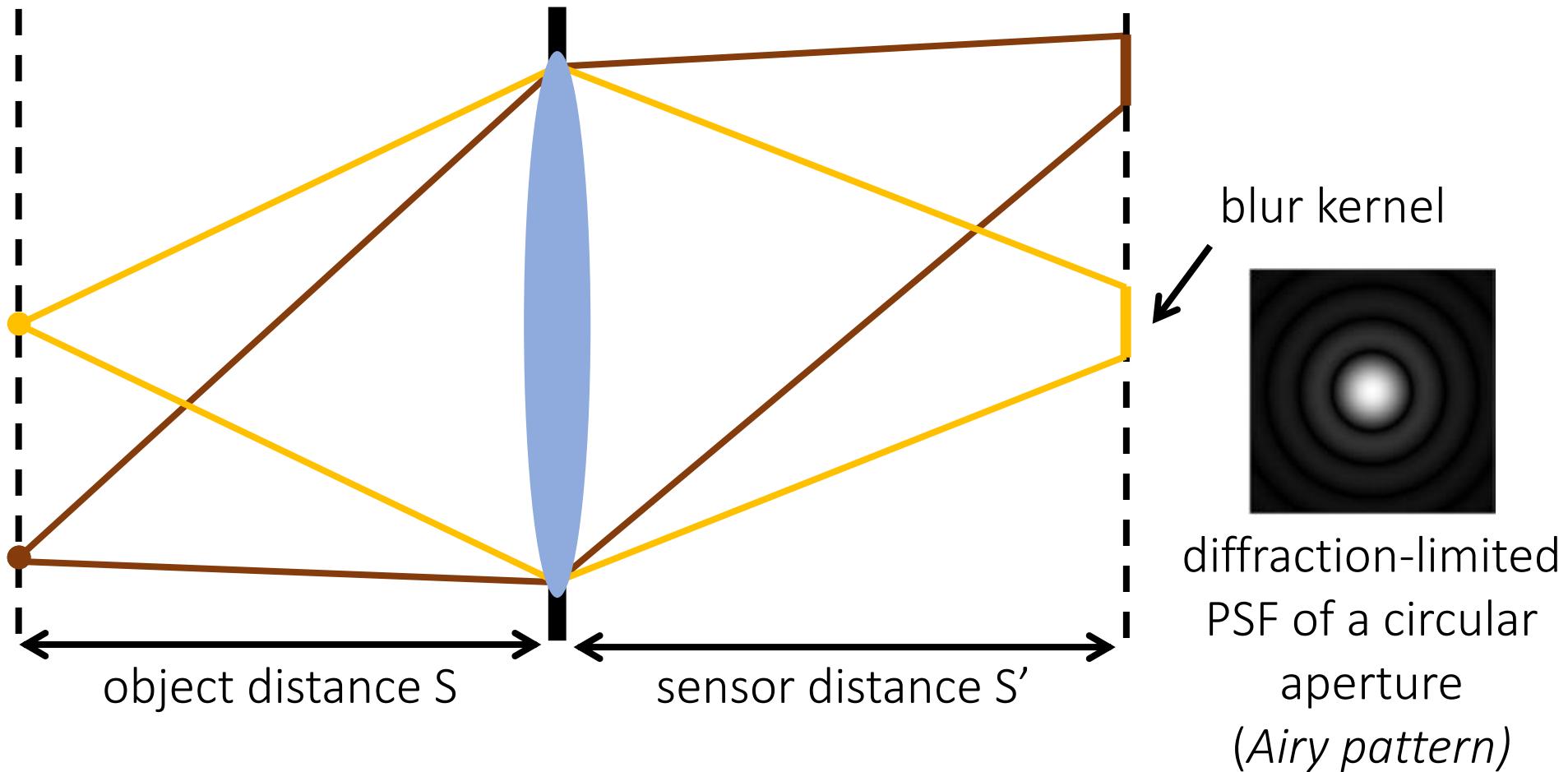


Lens as an optical low-pass filter

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

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



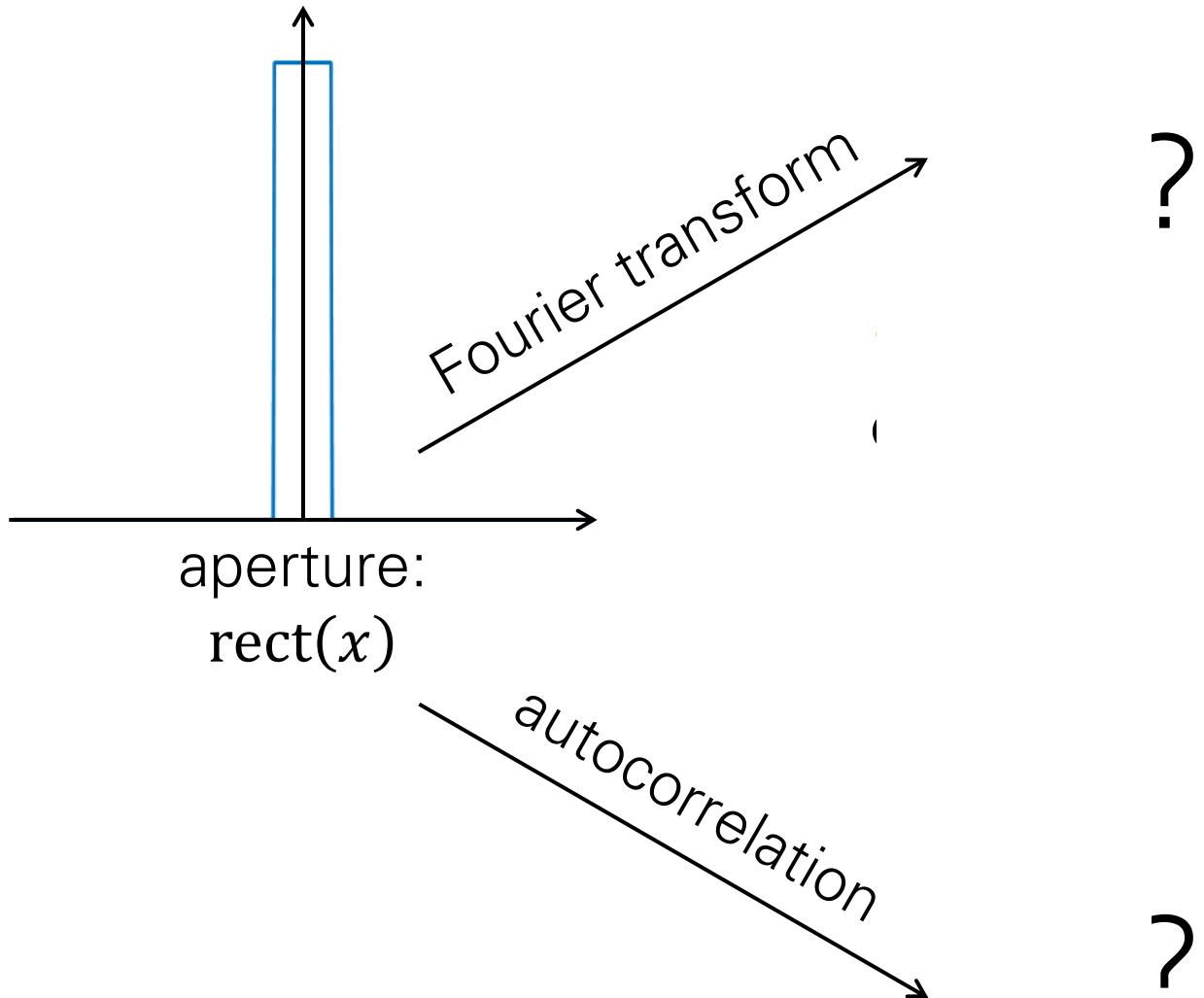
Some basics of diffraction theory

We will 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).

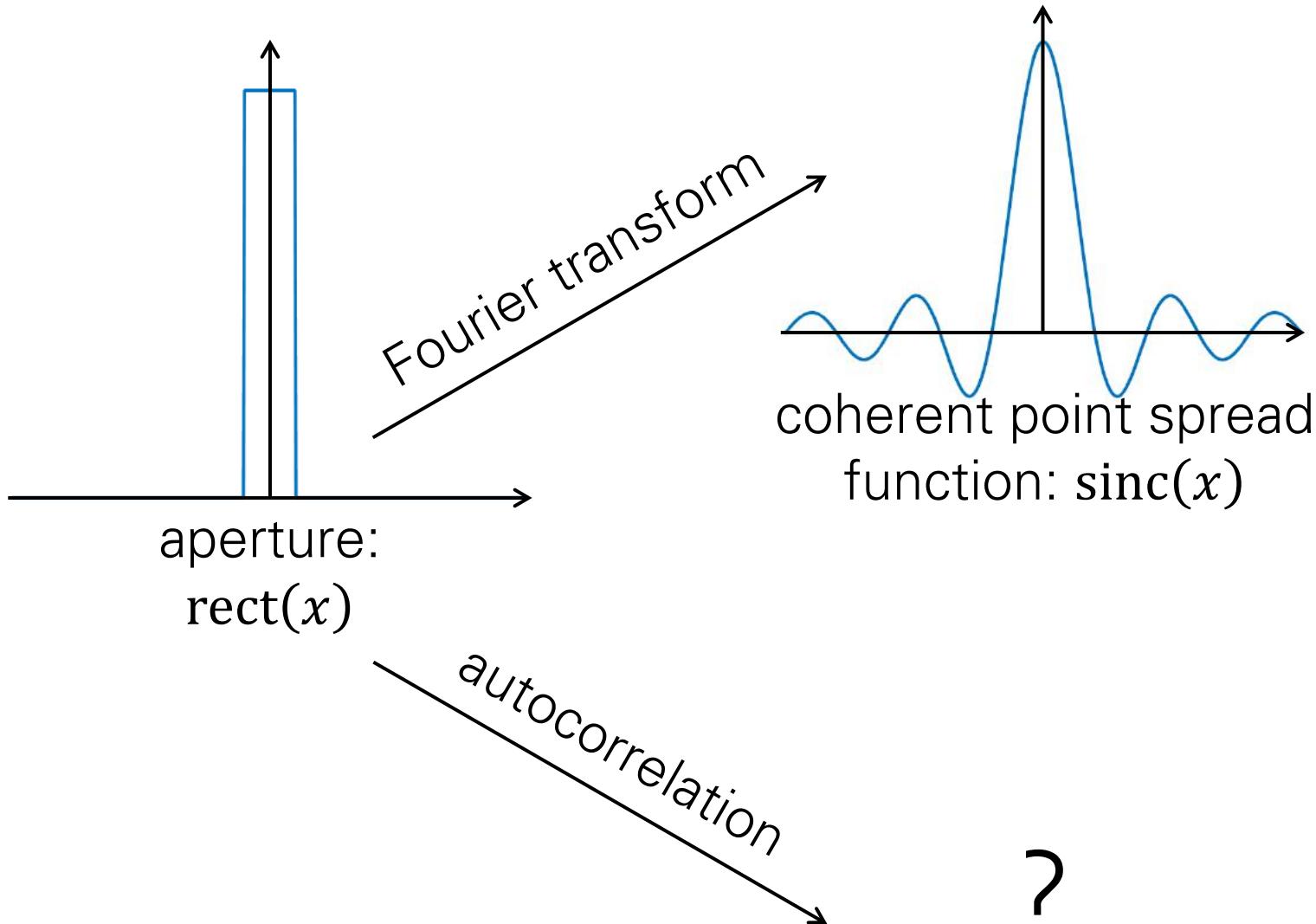
We will also be ignoring various scale factors. Different functions are not drawn to scale.

Some basics of diffraction theory



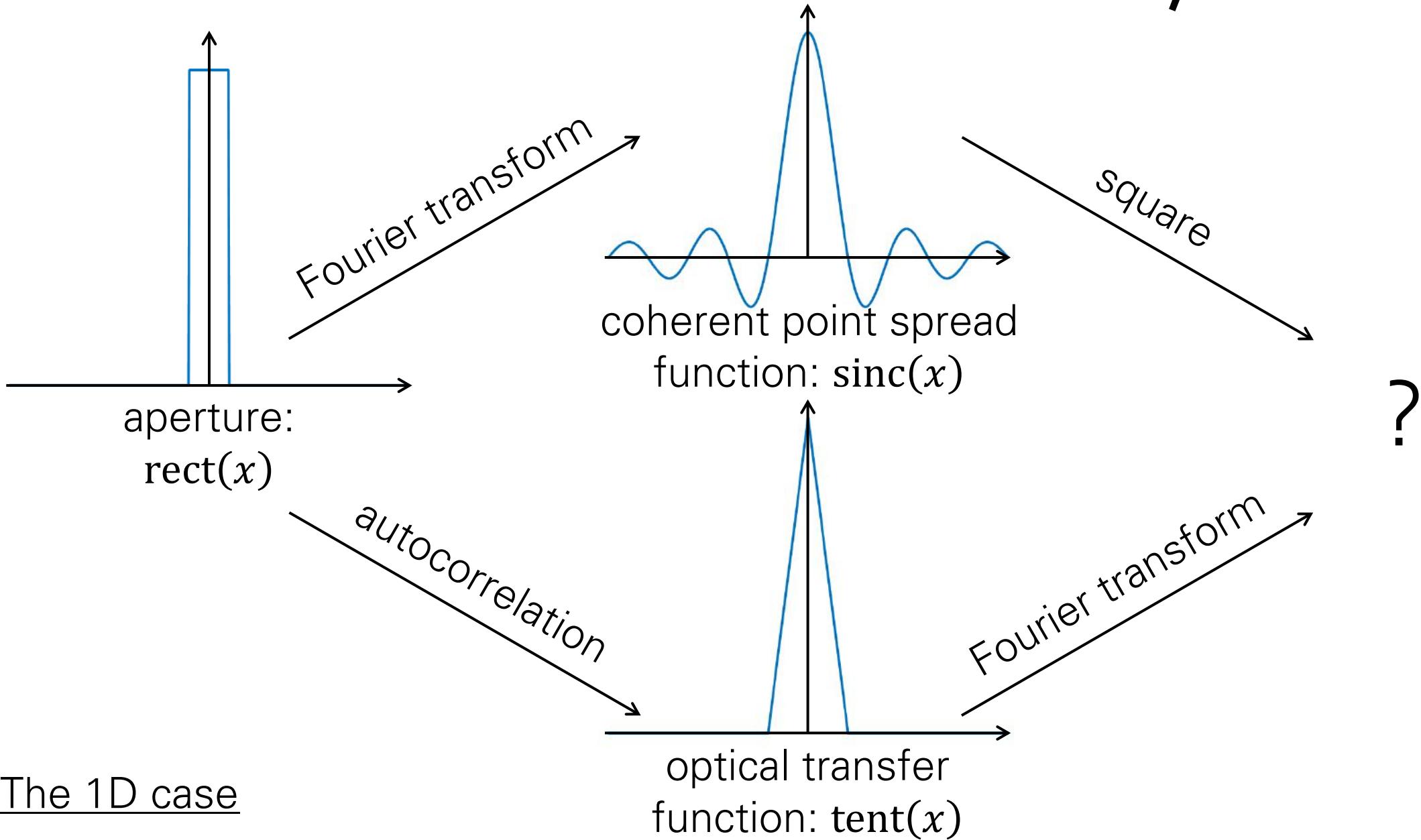
The 1D case

Some basics of diffraction theory

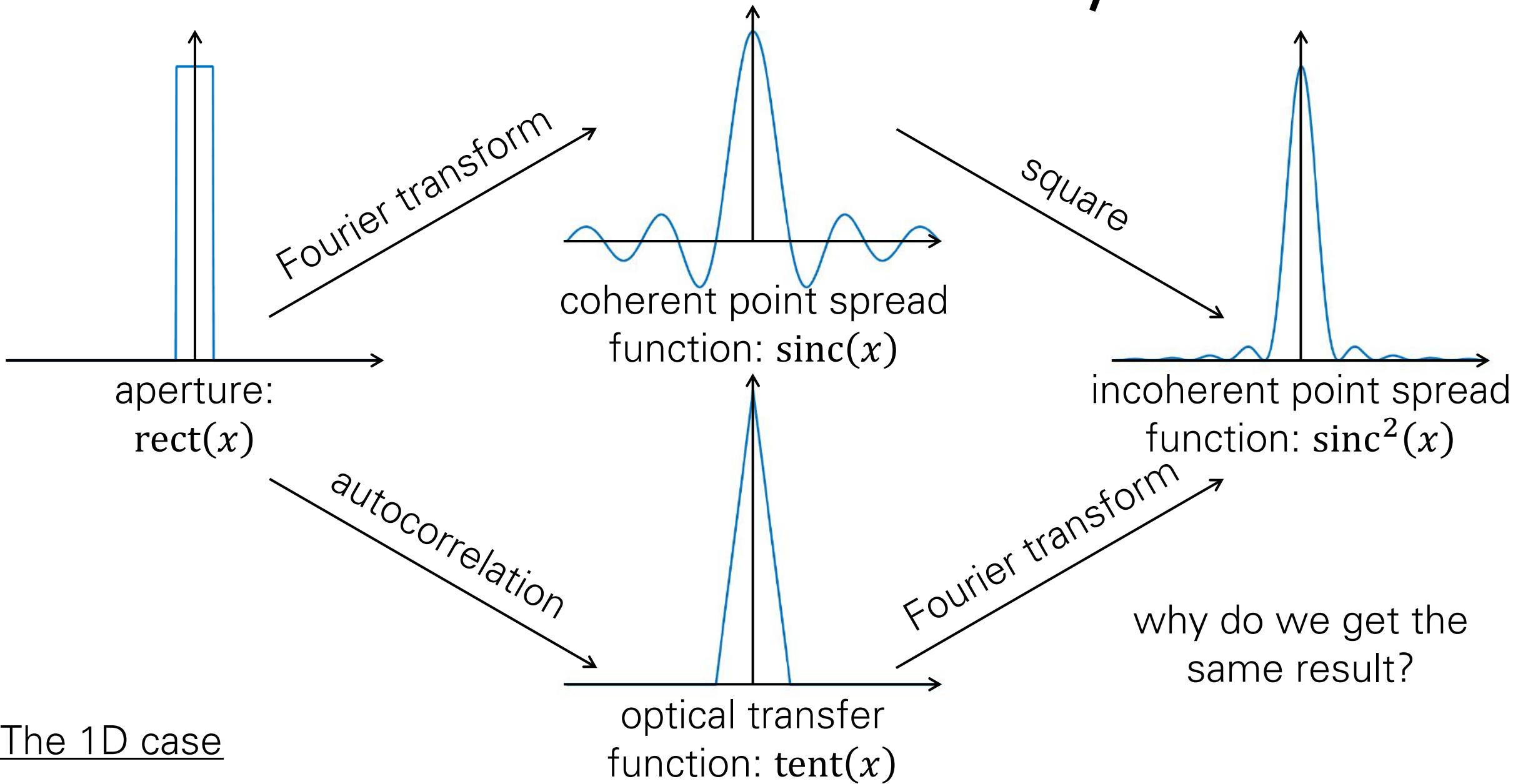


The 1D case

Some basics of diffraction theory

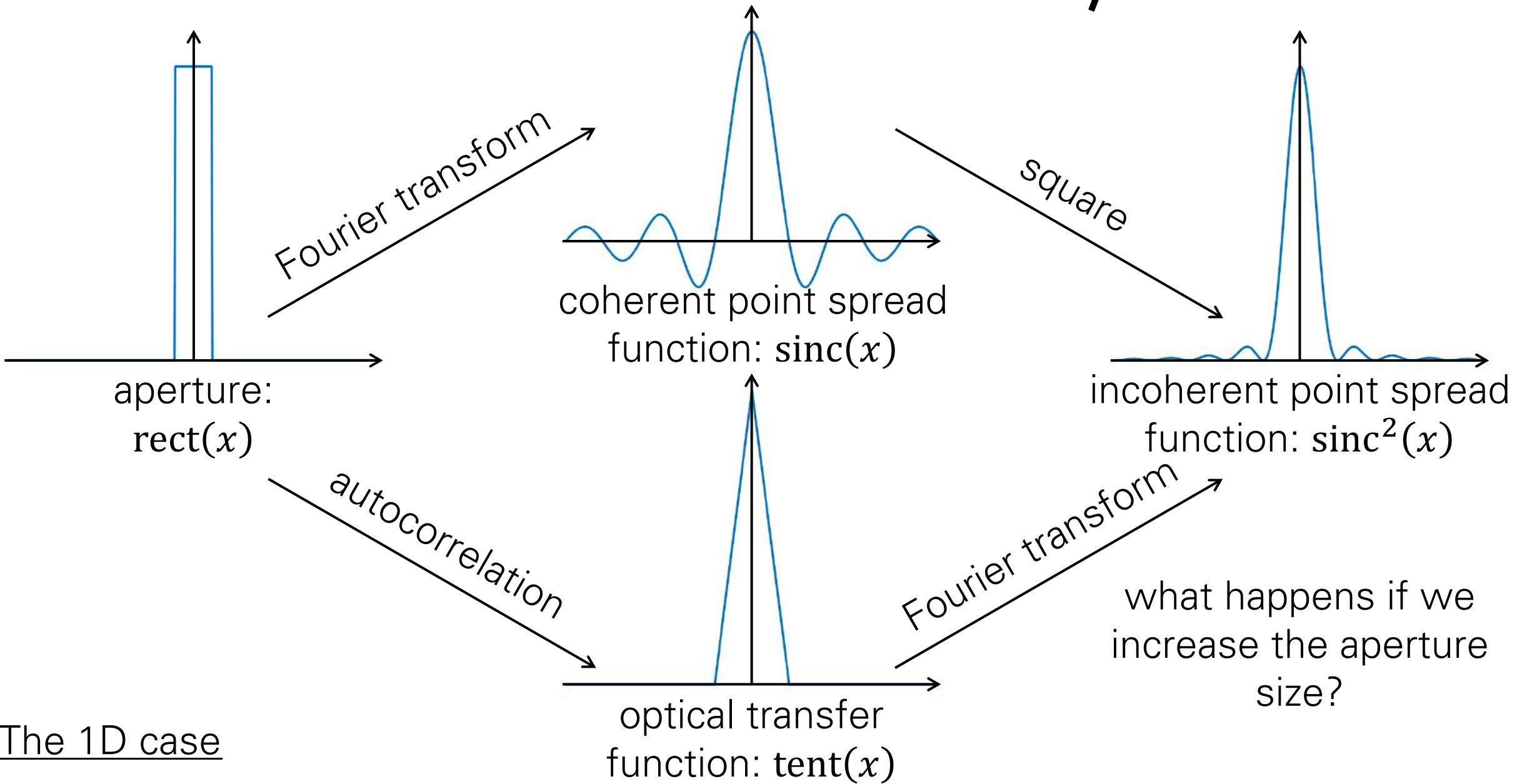


Some basics of diffraction theory

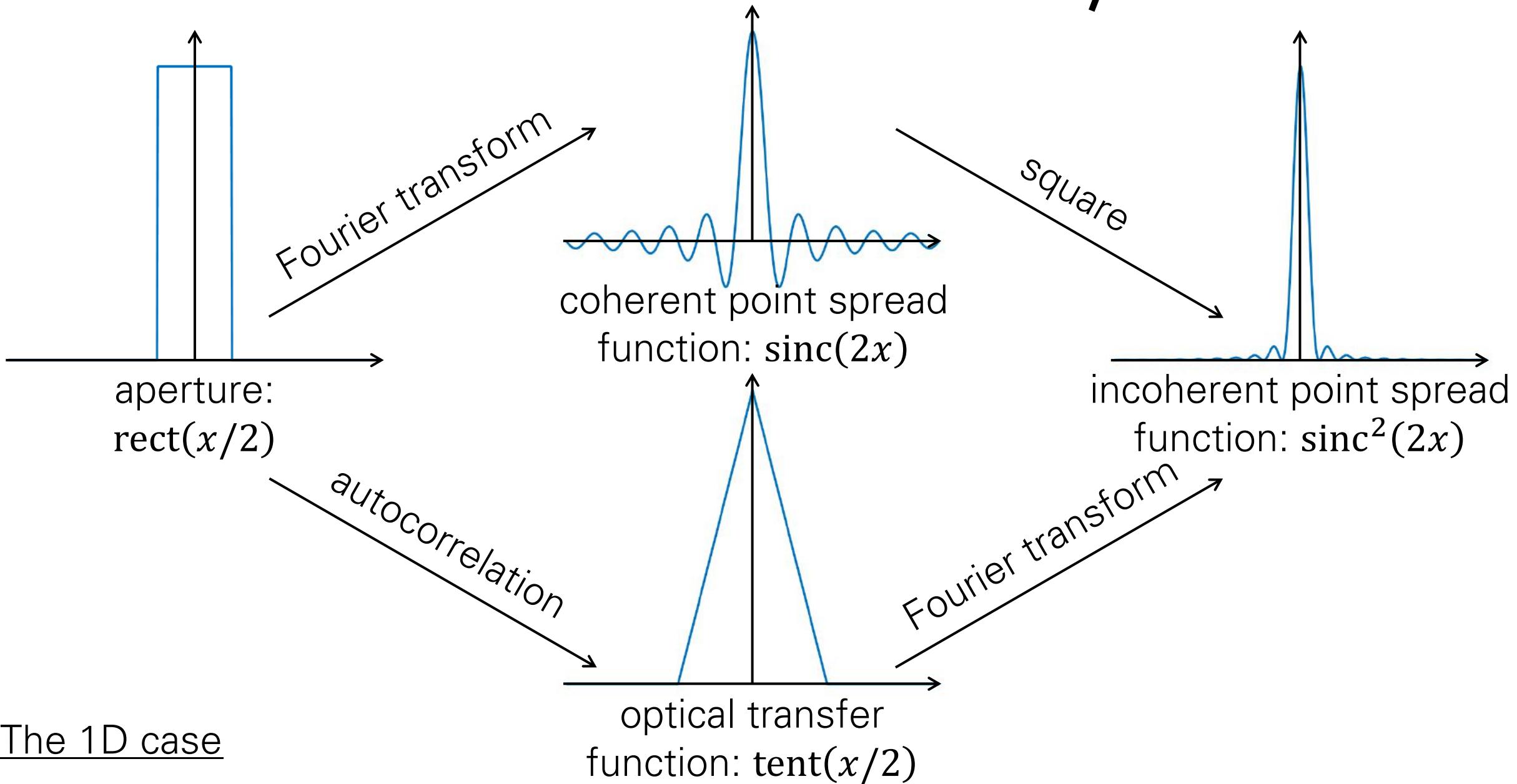


The 1D case

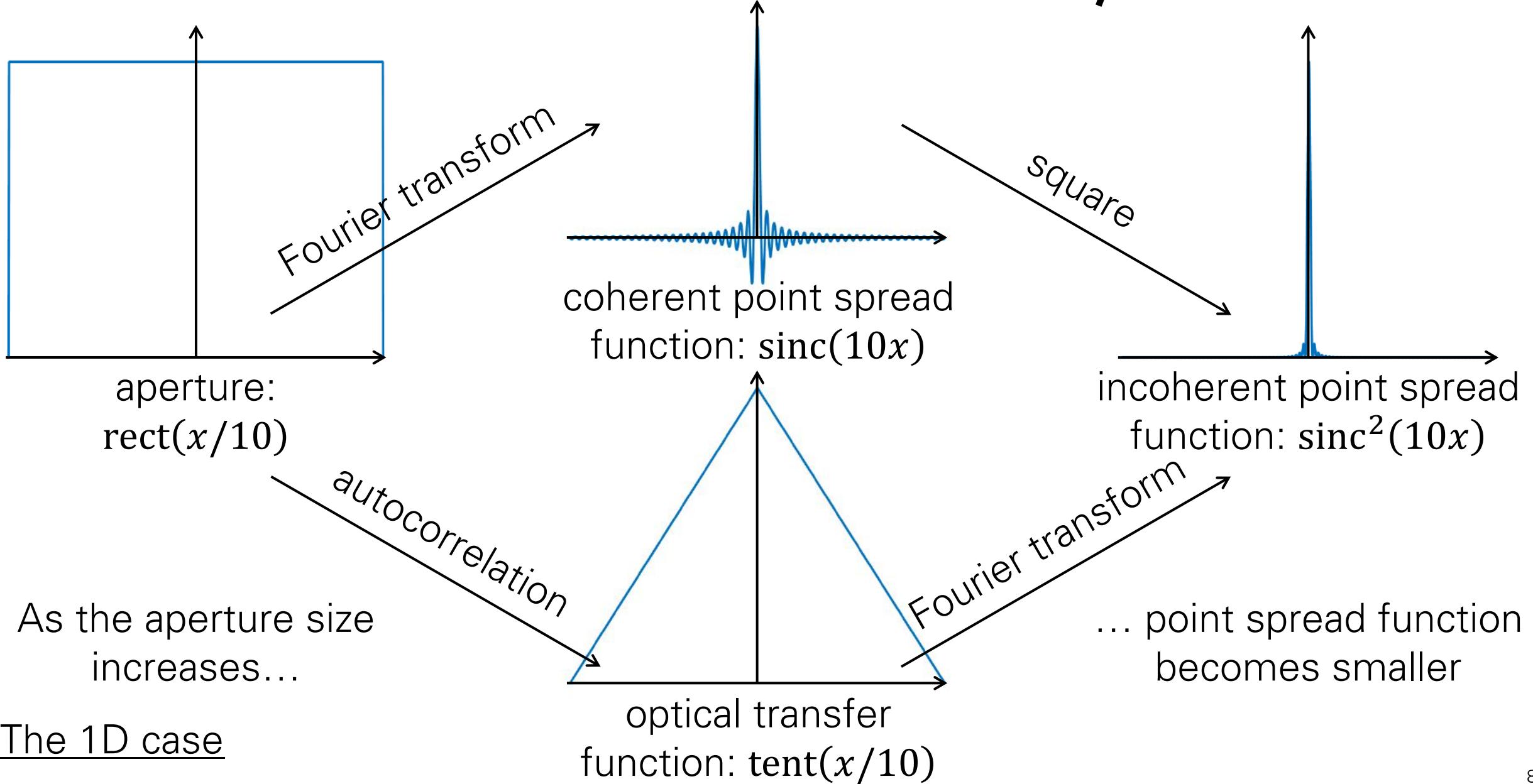
Some basics of diffraction theory



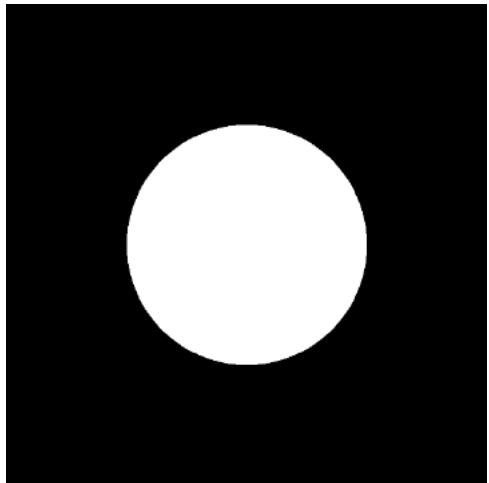
Some basics of diffraction theory



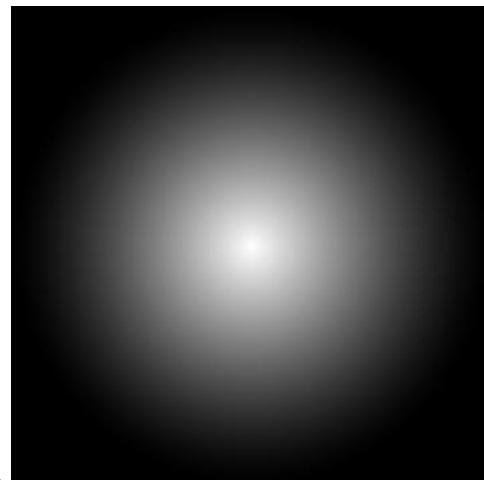
Some basics of diffraction theory



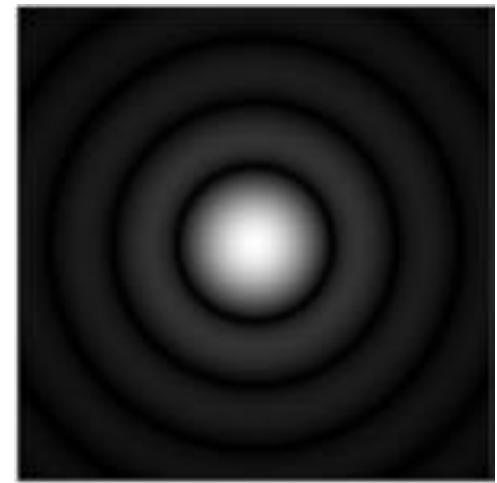
Some basics of diffraction theory



aperture



optical transfer
function



incoherent point spread
function

As the aperture size
increases...

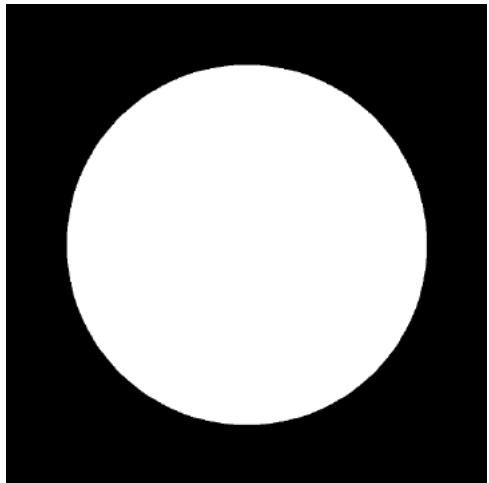
autocorrelation

The 2D case

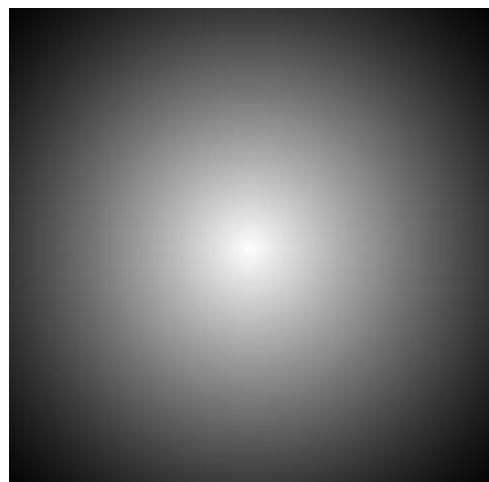
Fourier transform

... point spread function
becomes smaller

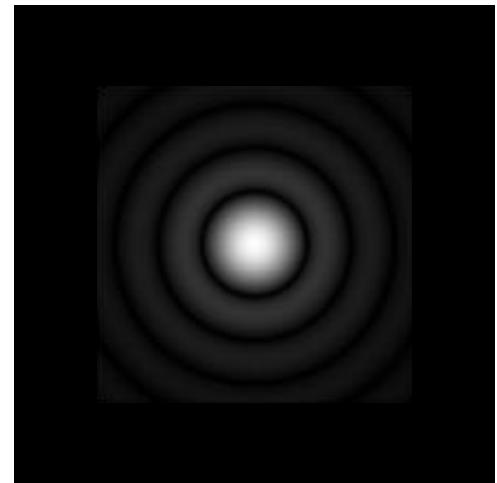
Some basics of diffraction theory



aperture



optical transfer
function



incoherent point spread
function

As the aperture size
increases...

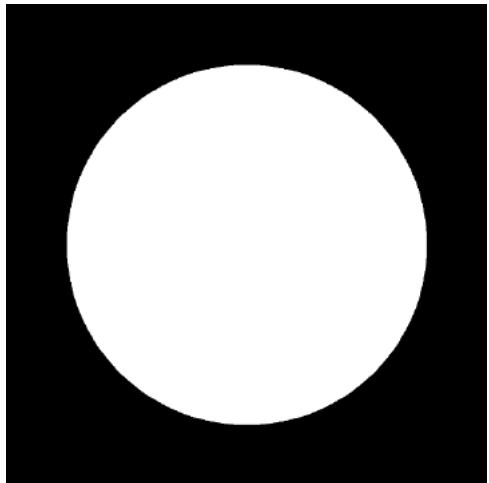
autocorrelation

The 2D case

Fourier transform

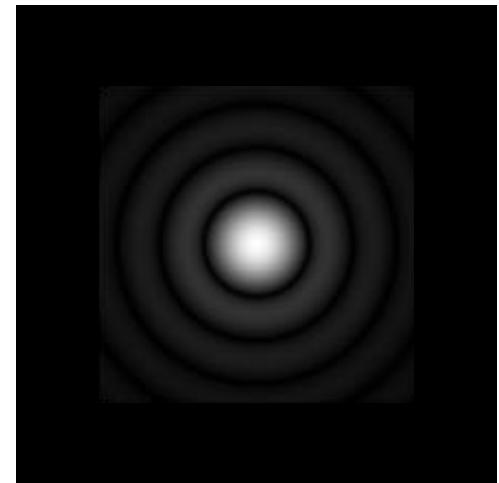
... point spread function
becomes smaller

Some basics of diffraction theory

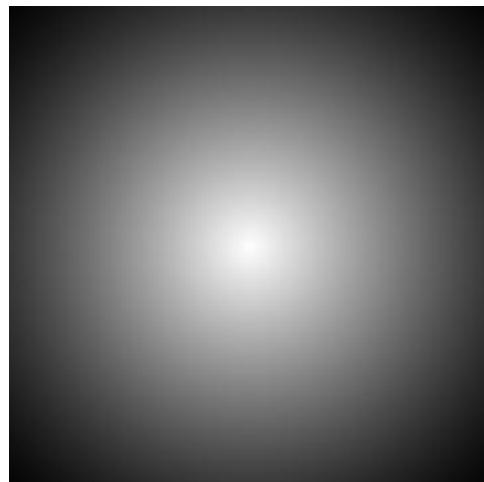


aperture

Why do we prefer circular apertures?



incoherent point spread function



optical transfer function

As the aperture size increases...

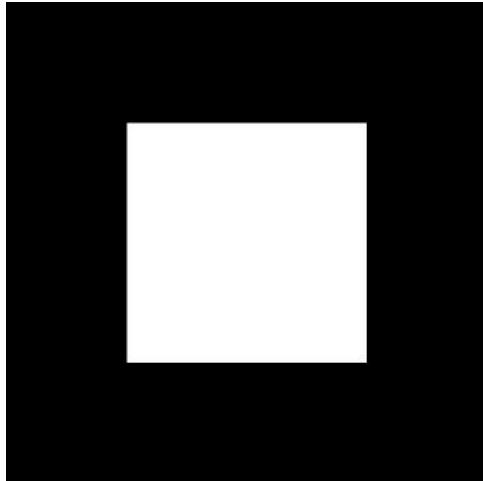
autocorrelation

The 2D case

Fourier transform

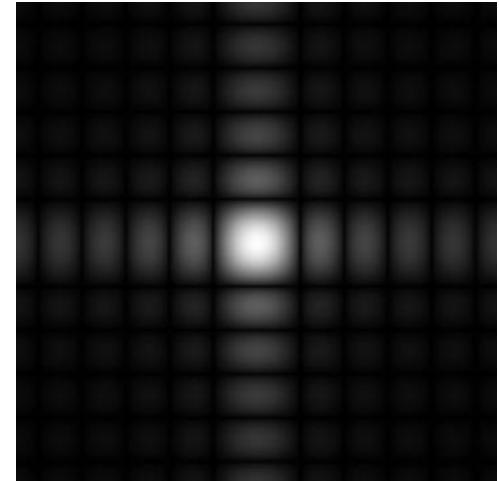
... point spread function becomes smaller

Some basics of diffraction theory

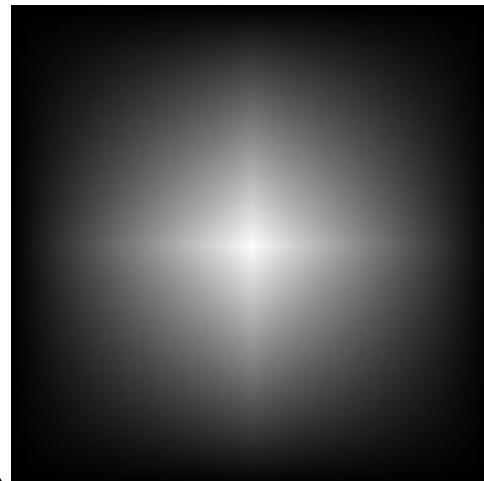


aperture

Other shapes produce very anisotropic blur.



incoherent point spread function



optical transfer function

As the aperture size increases...

autocorrelation

The 2D case

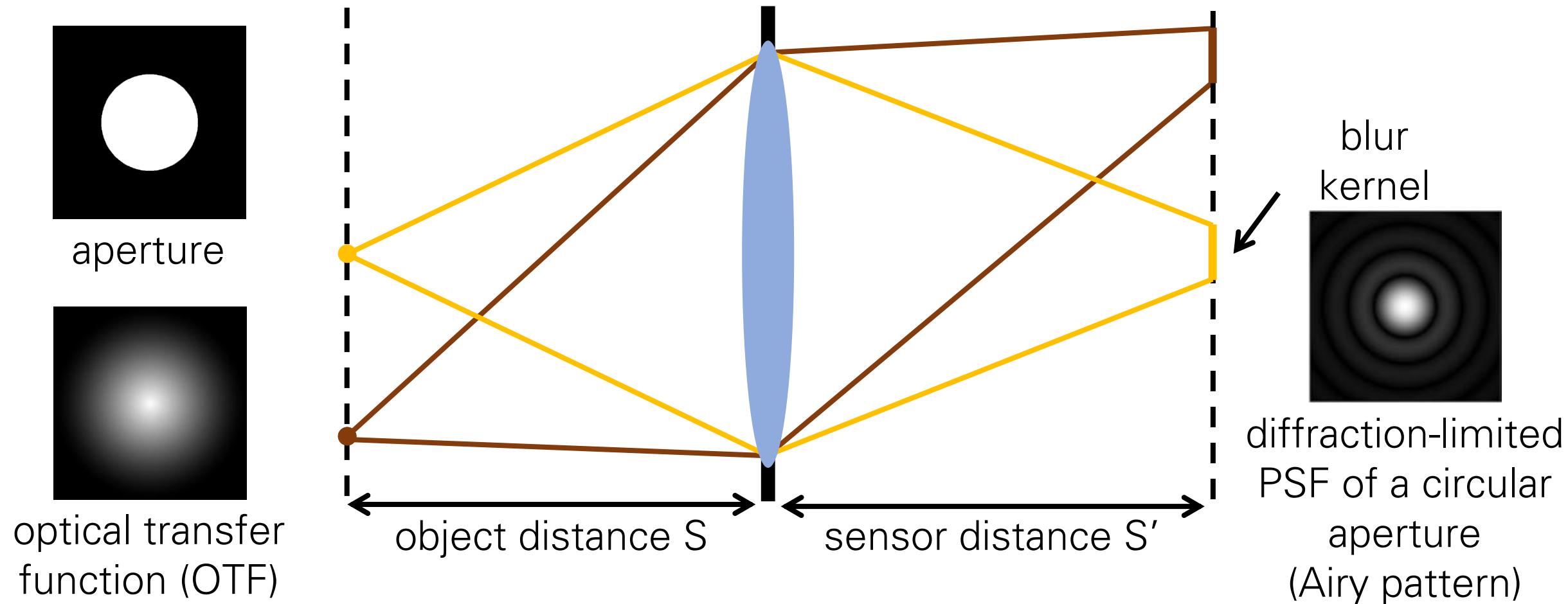
Fourier transform

... point spread function becomes smaller

Lens as 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.



Lens as an optical low-pass filter



image from a perfect lens

i

$$i * \text{imperfect lens PSF} = b$$



image from imperfect lens

b

Lens as an optical low-pass filter

If we know b and k , can we recover i ?



image from a perfect lens

i

$$* \quad \text{imperfect lens PSF} =$$
A grayscale plot of a diffraction pattern, showing concentric rings of varying intensity centered at the bottom left.



image from imperfect lens

b

Non-blind Deconvolution (Uniform Blur)

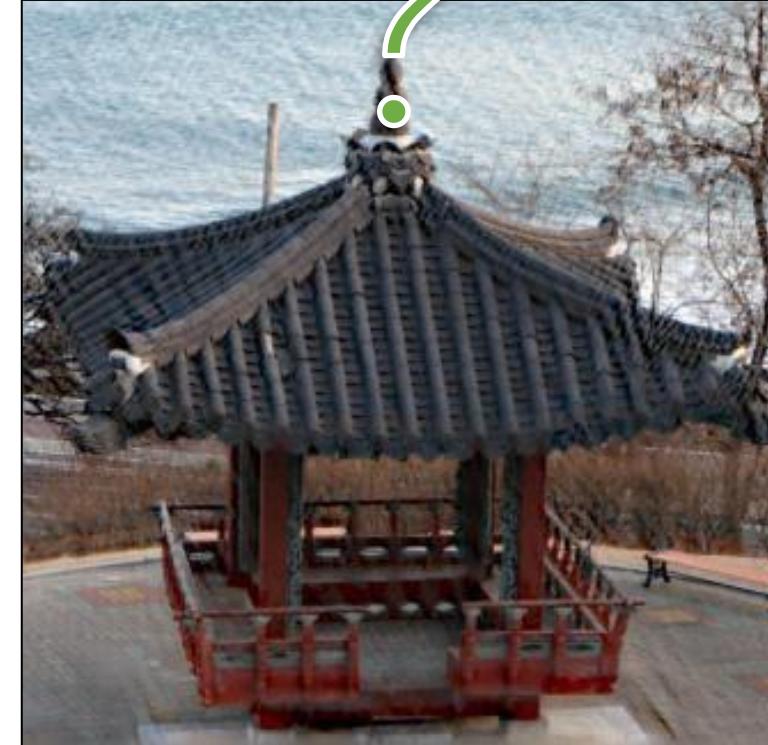


Blurred image

$$= \quad \quad \quad *$$


Blur kernel

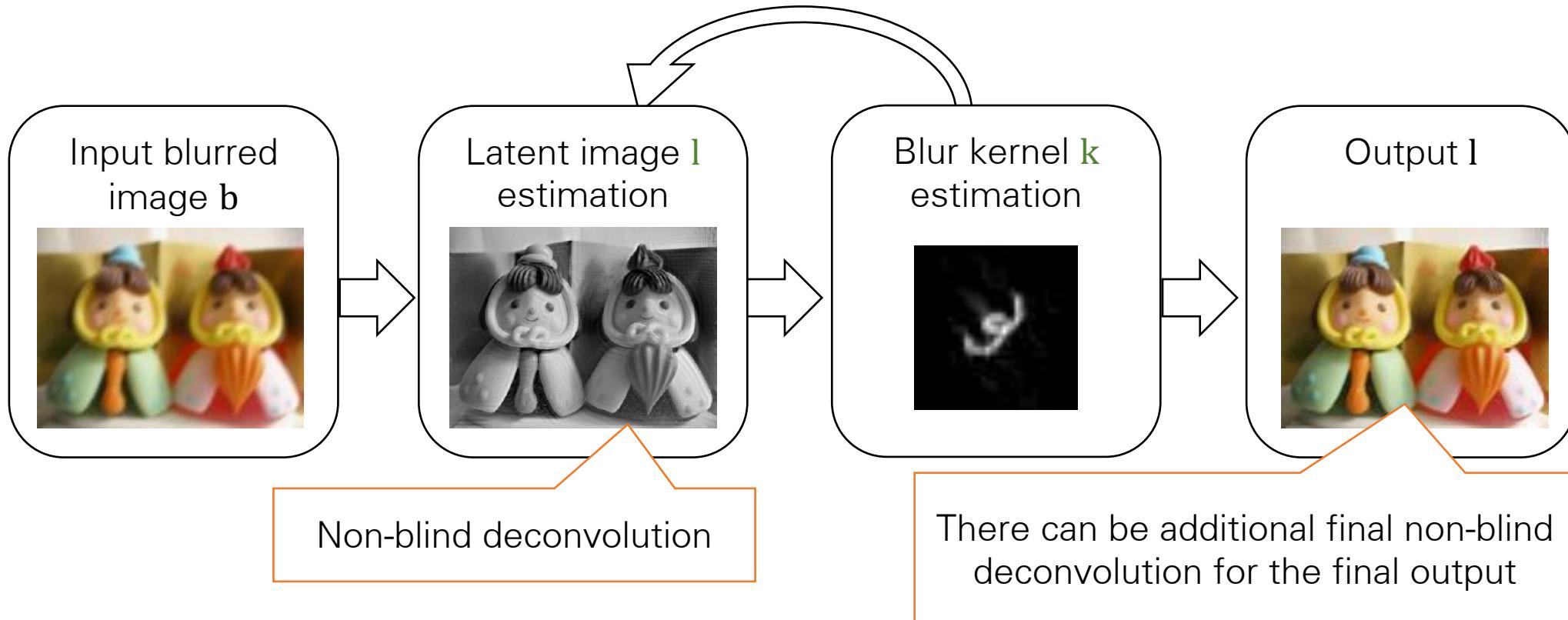
Convolution
operator



Latent sharp image

Non-blind Deconvolution

- Key component in many deblurring systems
 - For example, in MAP based blind deconvolution:



Non-blind Deconvolution



- Wiener filter
- Richardson-Lucy deconvolution
- Rudin et al. Physica 1992
- Bar et al. IJCV 2006
- Levin et al. SIGGRAPH 2007
- Shan et al. SIGGRAPH 2008
- Yuan et al. SIGGRAPH 2008
- Harmeling et al. ICIP 2010
- etc...

III-Posed Problem

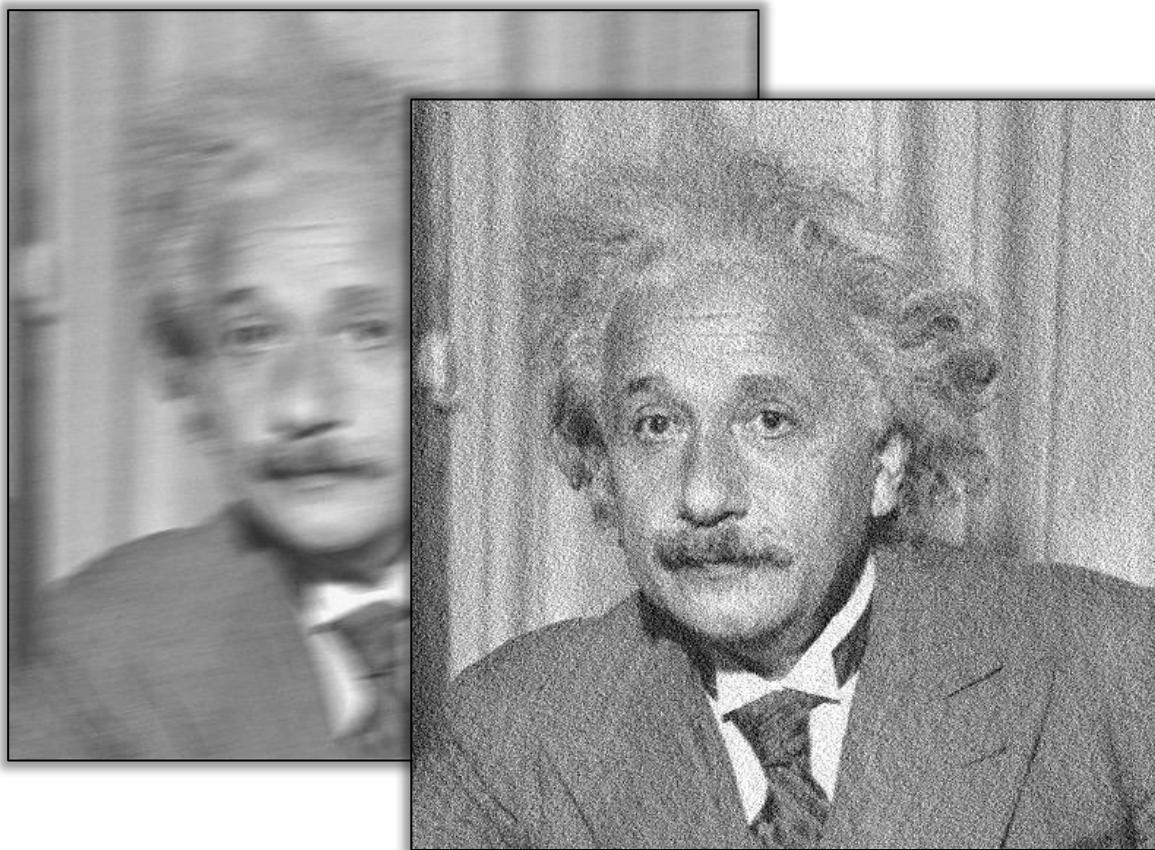
- Even if we know the true blur kernel, we cannot restore the latent image perfectly, because:



- Loss of high-freq info & noise \approx denoising & super-resolution

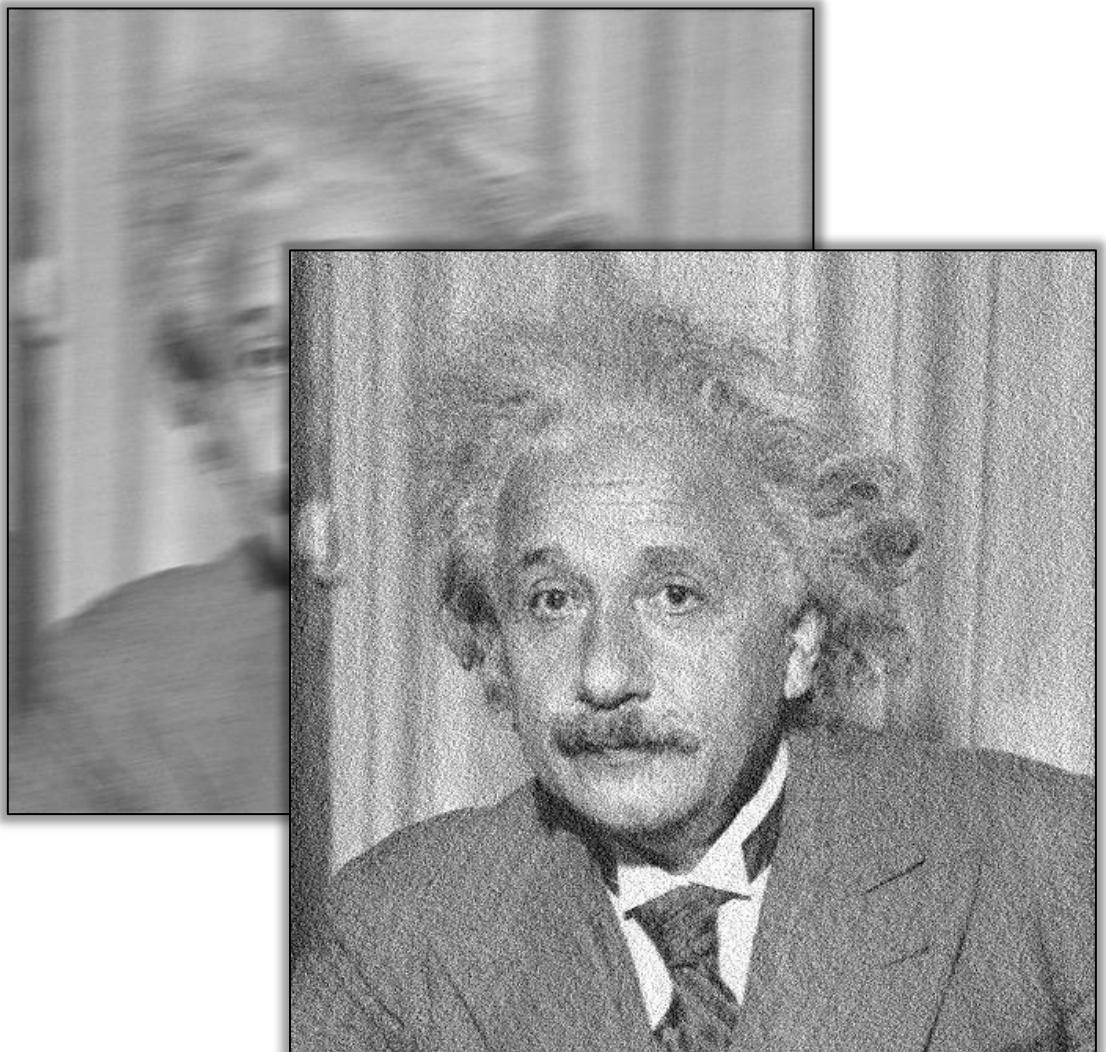
III-Posed Problem

- Deconvolution amplifies noise as well as sharpens edges
- Ringing artifacts
 - Inaccurate blur kernels, outliers cause ringing artifacts



Classical Methods

- Popular methods
 - Wiener filtering
 - Richardson-Lucy deconvolution
 - Constrained least squares
- Matlab Image Processing Toolbox
 - deconvwnr, deconvlucy, deconvreg
- Simple assumption on noise and latent images
 - Simple & fast
 - Prone to noise & artifacts



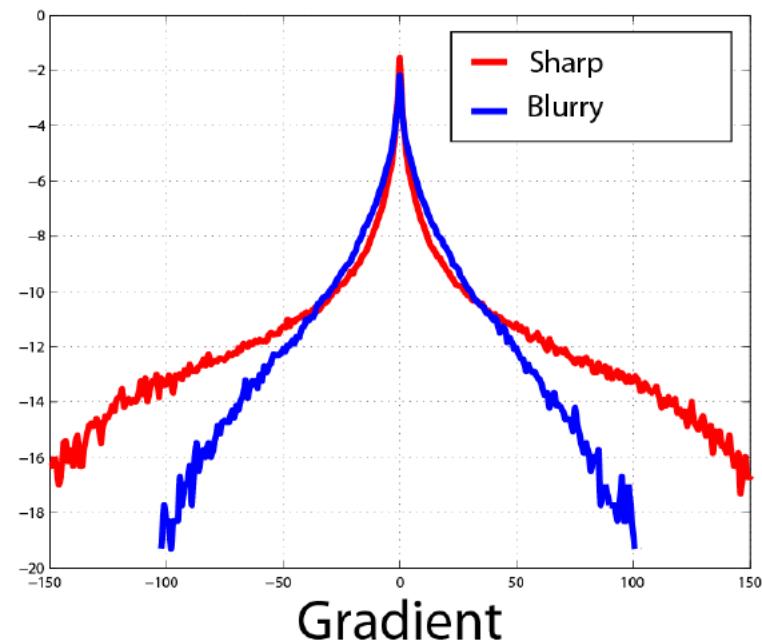
Natural Image Statistics

- Non-blind deconvolution: ill-posed problem
- We need to assume something on the latent image to constrain the problem.



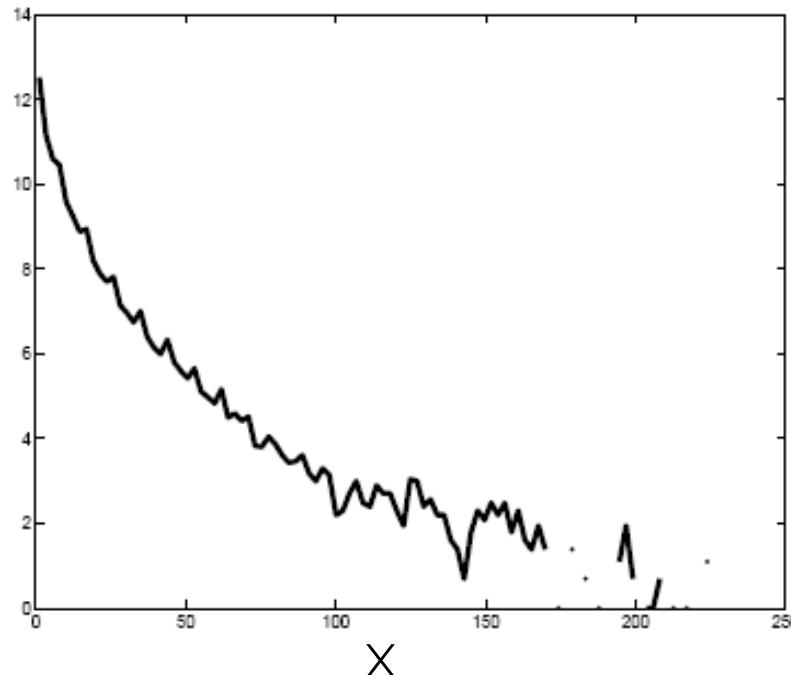
Natural Image Statistics

- Natural images have a heavy-tailed distribution on gradient magnitudes
 - Mostly zero & a few edges
 - Levin et al. SIGGRAPH 2007, Shan et al. SIGGRAPH 2008, Krishnan & Fergus, NIPS 2009

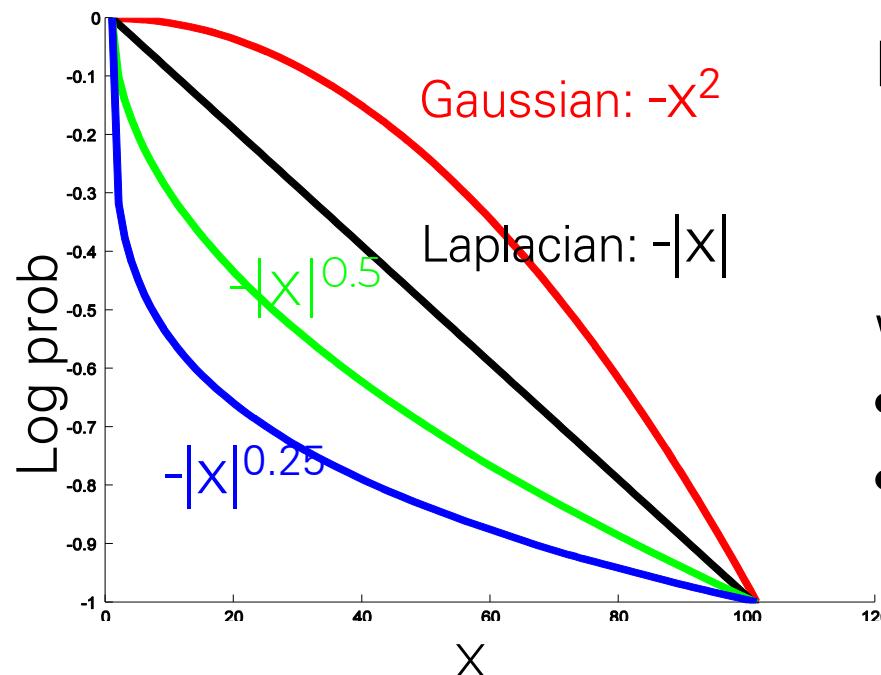


Natural Image Statistics

- Levin et al. SIGGRAPH 2007
 - Propose a parametric model for natural image priors based on image gradients



Derivative histogram from a natural image



Parametric models

Proposed prior

$$\log p(x) = - \sum_i |\nabla x_i|^\alpha$$

where:

- x : image
- α : model parameter, $\alpha < 1$

Natural Image Statistics

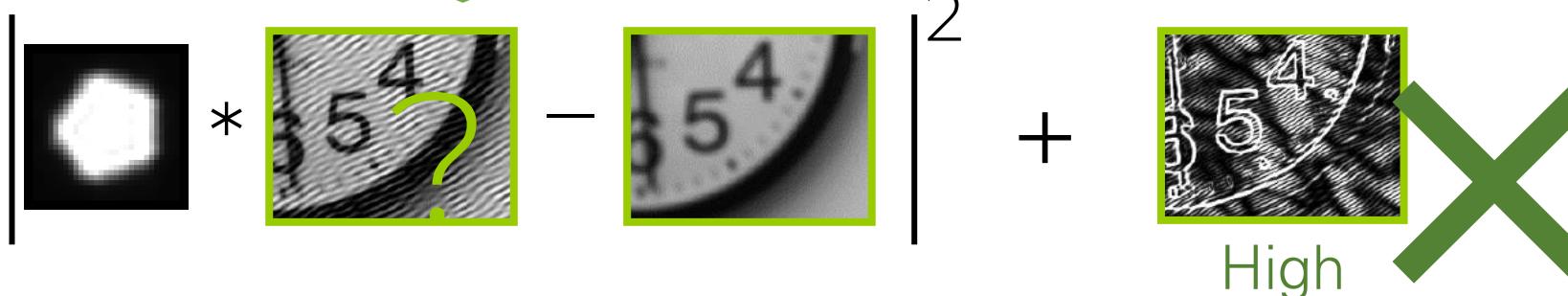
- Levin et al. SIGGRAPH 2007

$$l = \arg \min_l \{ \|k * l - b\|^2 + \lambda \sum_i |\nabla l_i|^\alpha \} \quad (\alpha < 1)$$

Data term Prior



Equal convolution error



Natural Image Statistics

- Levin et al. SIGGRAPH 2007

“spread” gradients

“localizes” gradients



Input



Richardson-Lucy



Gaussian prior

$$\sum_i |\nabla l_i|^2$$

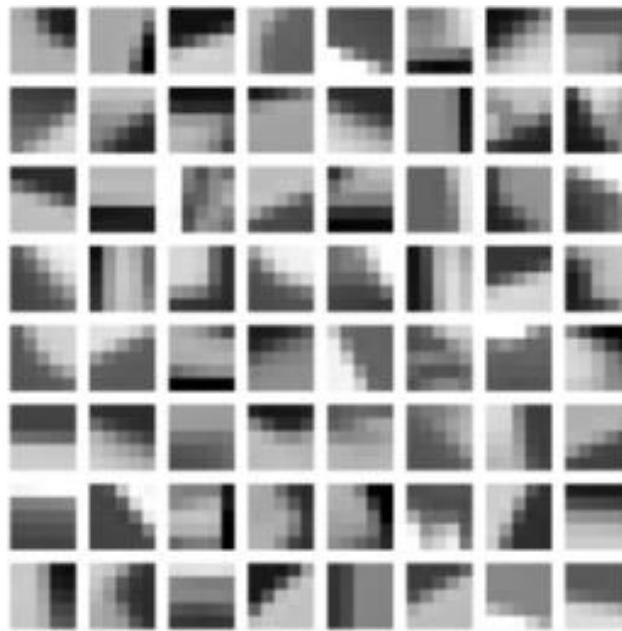


Sparse prior

$$\sum_i |\nabla l_i|^{0.8}$$

High-order Natural Image Priors

- Patches, large neighborhoods, ...
- Effective for various kinds of image restoration problems
 - Denoising, inpainting, super-resolution, deblurring, ...

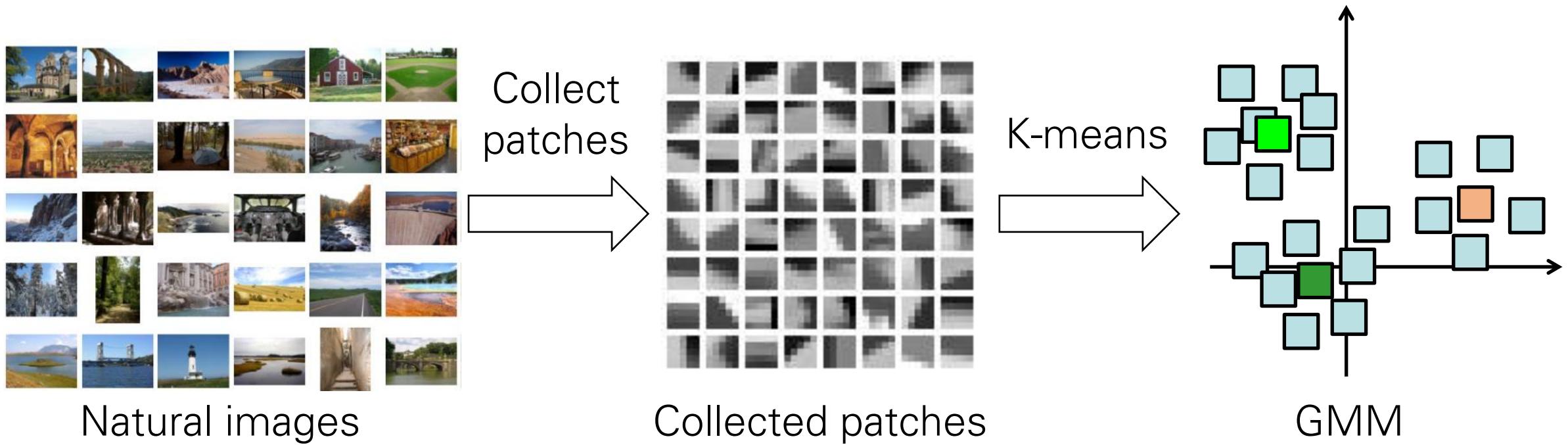


High-order Natural Image Priors

- Schmidt et al. CVPR 2011
 - Fields of Experts
- Zoran & Weiss, ICCV 2011
 - Trained Gaussian mixture model for natural image patches
- Schuler et al. CVPR 2013
 - Trained Multi-layer perceptron to remove artifacts and to restore sharp patches
- Schmidt et al. CVPR 2013
 - Trained regression tree fields for 5x5 neighborhoods

High-order Natural Image Priors

- Zoran & Weiss, ICCV 2011
 - Gaussian Mixture Model (GMM) learned from natural images



High-order Natural Image Priors

- Zoran & Weiss, ICCV 2011
 - Given a patch, we can compute its likelihood based on the GMM.
 - Deconvolution can be done by solving:

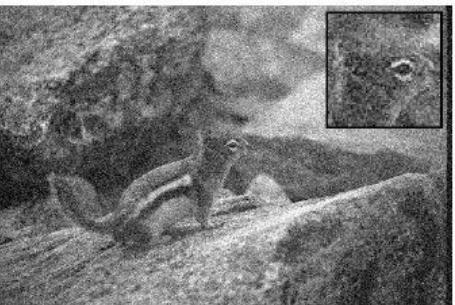
$$\arg \min_l \left\{ \|k * l - b\|^2 - \lambda \sum_i \log p(l_i) \right\}$$

Log-likelihood of a patch l_i at i -th pixel
based on GMM

High-order Natural Image Priors

- Zoran & Weiss, ICCV 2011

Denoising



(a) Noisy Image - PSNR: 20.17



(b) KSVD - PSNR: 28.72



(c) LLSC - PSNR: 29.30



(d) EPLL GMM - PSNR: 29.39

Deblurring



Blurred image



Krishnan & Fergus
PSNR: 26.38



Zoran & Weiss
PSNR: 27.70

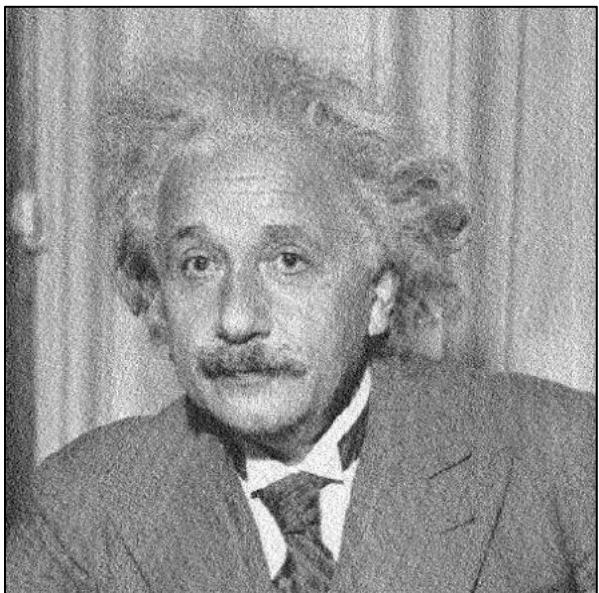
Ringing Artifacts

- Wave-like artifacts around strong edges
- Caused by
 - Inaccurate blur kernels
 - Nonlinear response curve
 - Etc...



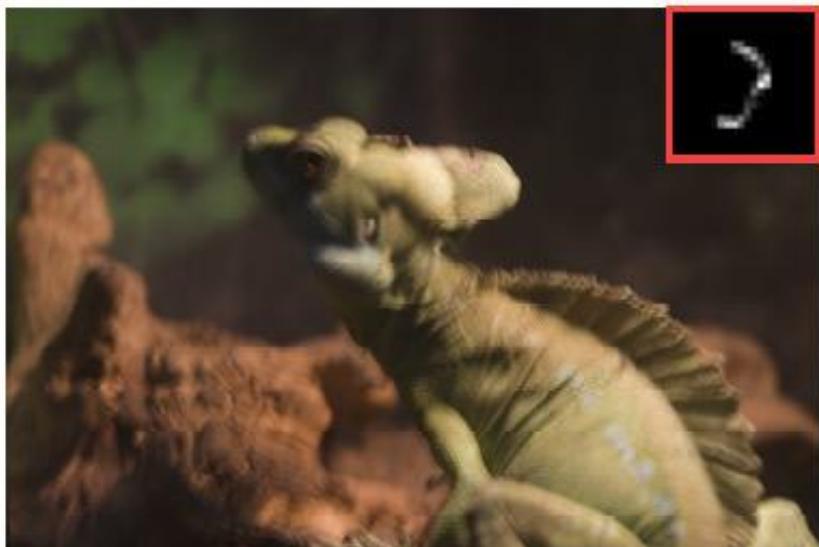
Ringing Artifacts

- Noise
 - High-freq
 - Independent and identical distribution
 - Priors on image gradients work well
- Ringing
 - Mid-freq
 - Spatial correlation
 - Priors on image gradients are not very effective



Ringing Artifacts

- Yuan et al. SIGGRAPH 2007
 - Residual deconvolution & de-ringing
- Yuan et al. SIGGRAPH 2008
 - Multi-scale deconvolution framework based on residual deconvolution



Blurred image



Richardson-Lucy



Yuan et al. SIGGRAPH 2008

Residual Deconvolution [Yuan et al. SIGGRAPH 2007, 2008]



Blurred image



Guide image



Residual deconvolution result
with less ringing artifacts

- Relatively accurate edges, but less details
- Obtained from a deconvolution result from a smaller scale

Residual Deconvolution [Yuan et al. SIGGRAPH 2007, 2008]

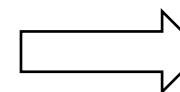


Blurred image

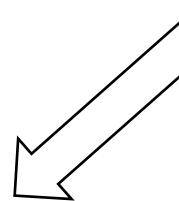
$$- \quad * \quad *$$



Guide image



Residual blur



Deconvolution

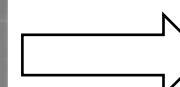


Guide image

$$+$$



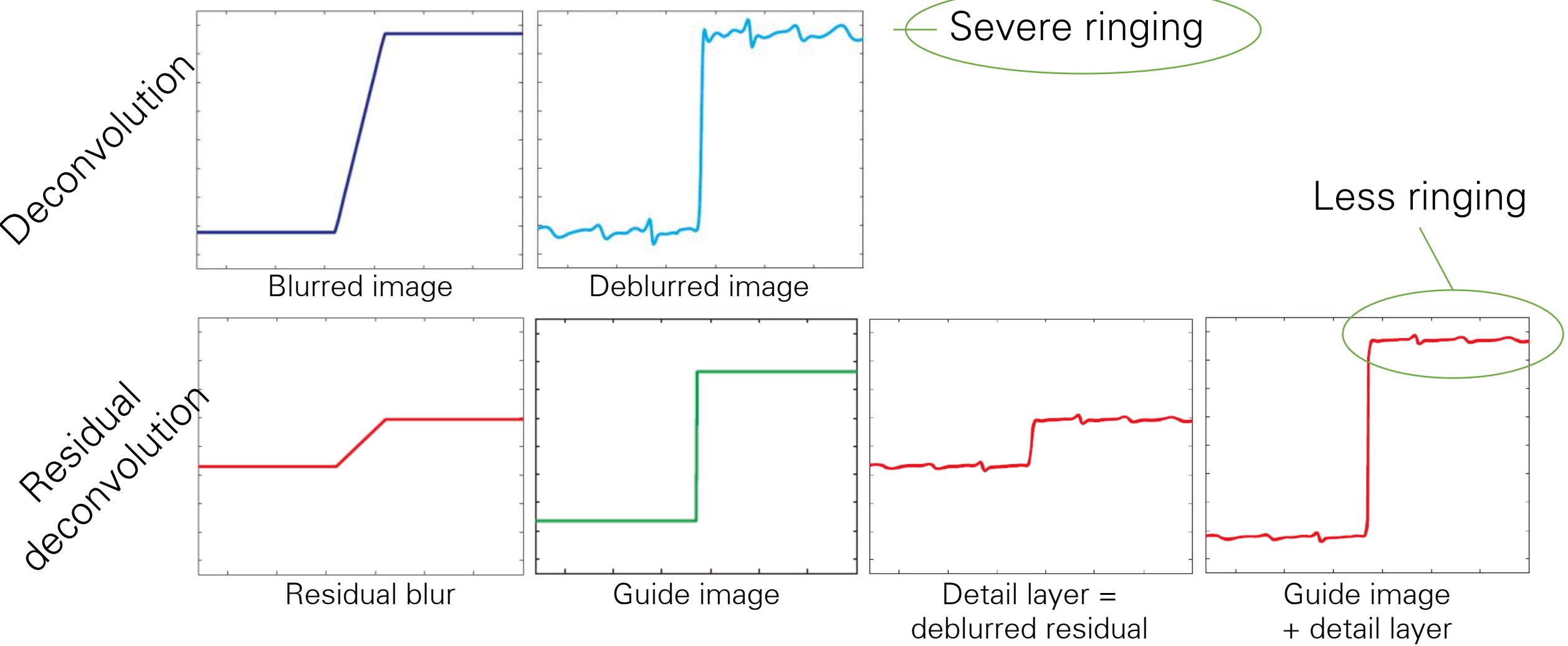
Detail layer



Result

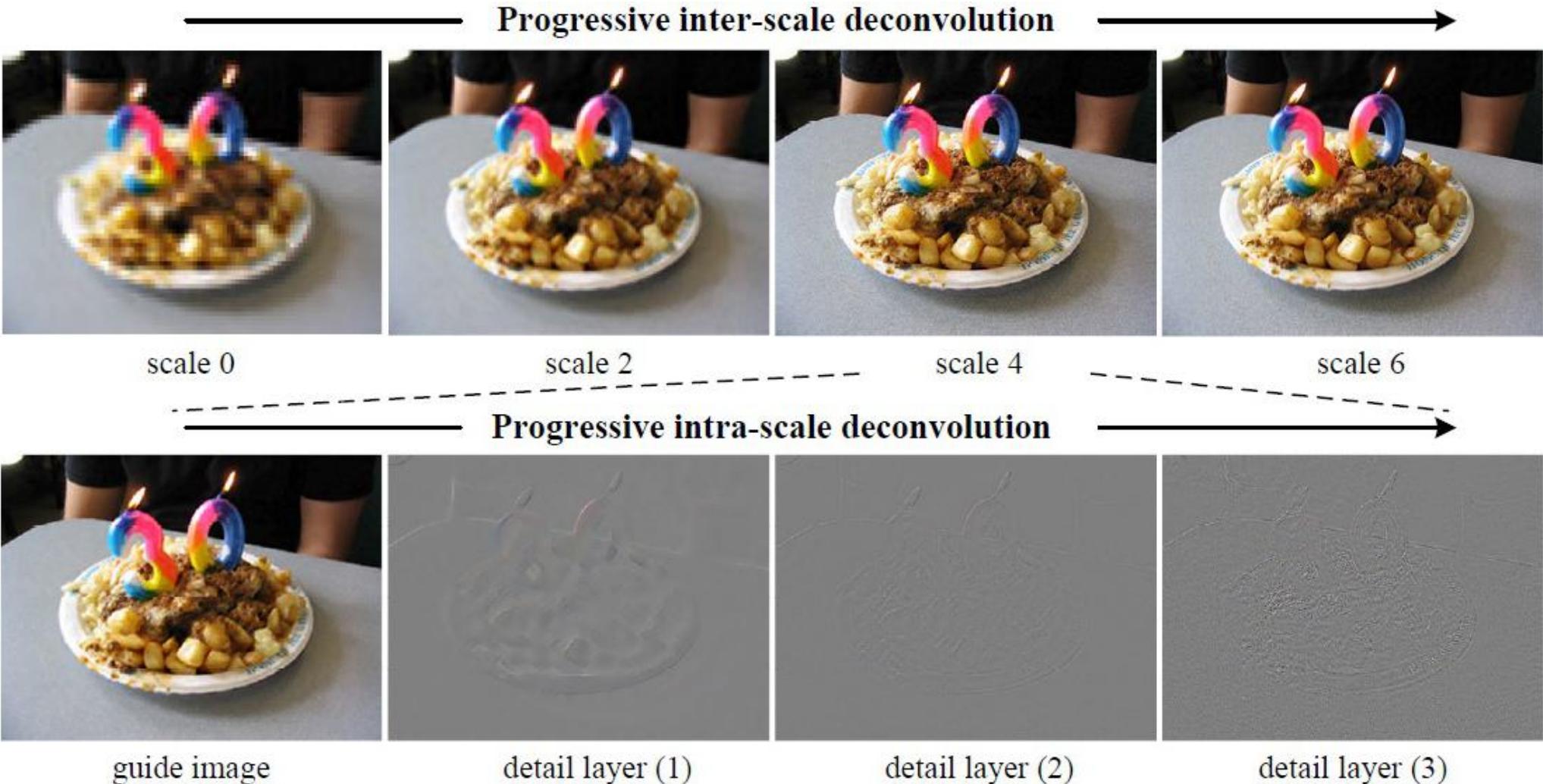
Residual Deconvolution [Yuan et al. SIGGRAPH 2007, 2008]

- Residual deconvolution



Progressive Inter-scale & Intra-scale Deconvolution [Yuan et al. SIGGRAPH 2008]

- Progressive inter-scale & intra-scale deconvolution





Blurred image



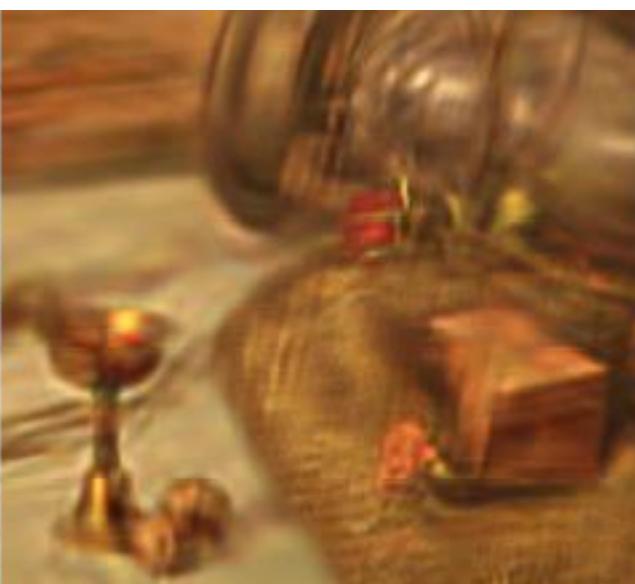
Richardson-Lucy



TV regularization



Levin et al. SIGGRAPH 2007



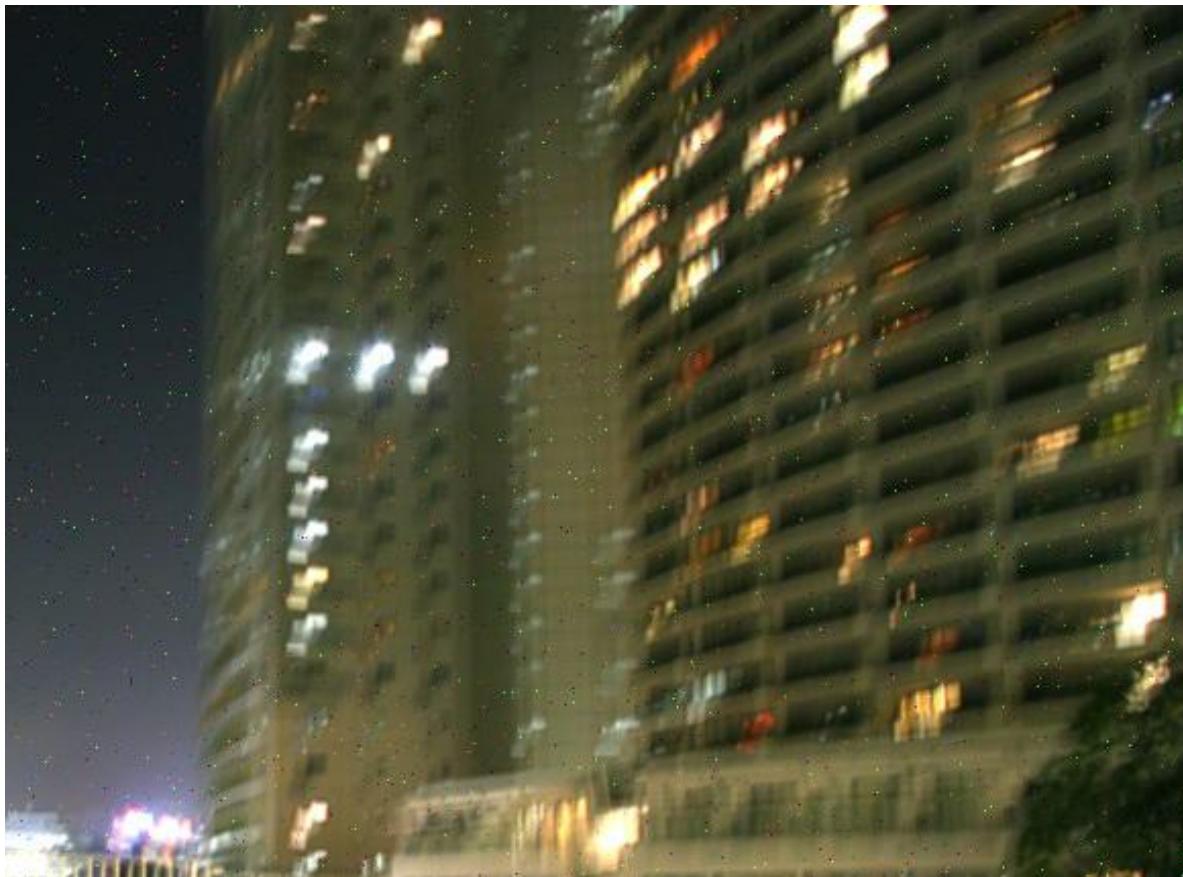
Wavelet regularization



Yuan et al. SIGGRAPH 2008

Outliers

- A main source of severe ringing artifacts



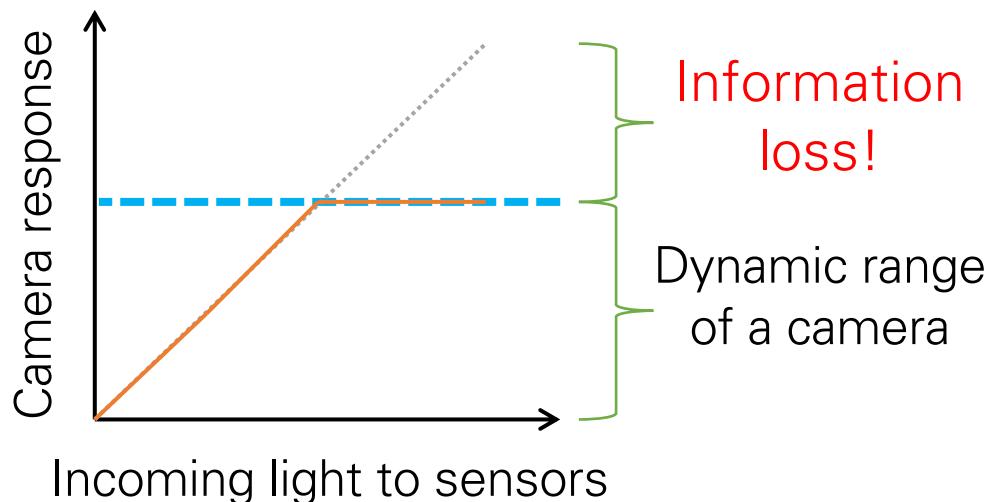
Blurred image with outliers



Deblurring result
[Levin et al. SIGGRAPH 2007]

Outliers

- Saturated pixels caused by limited dynamic range of sensors



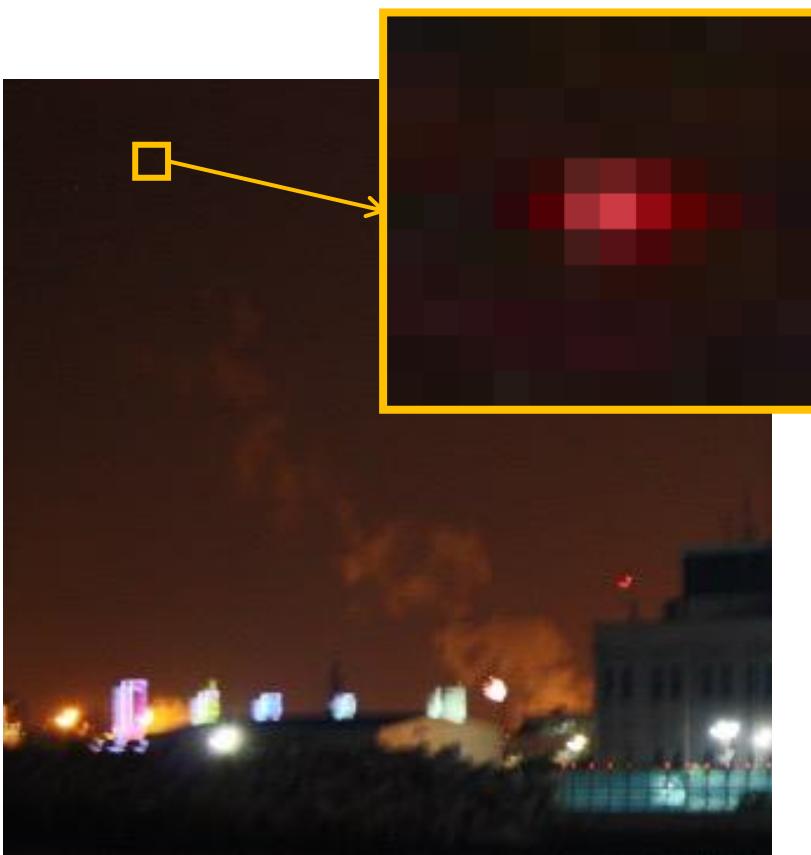
Blurred image



[Levin et al. 2007]

Outliers

- Hot pixels, dead pixels, compression artifacts, etc...



Hot pixel



Blurred image with outliers [Levin et al. 2007]



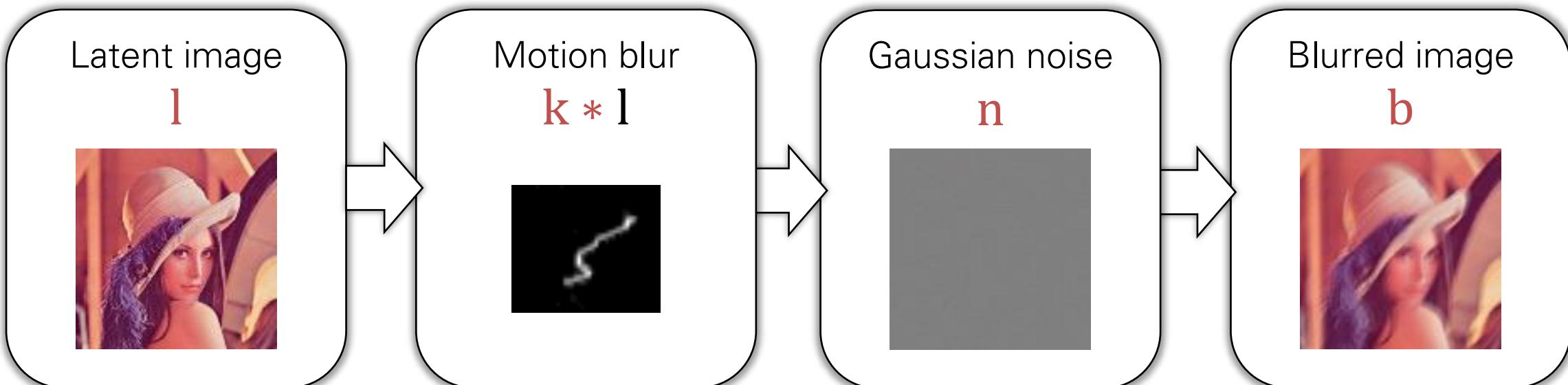
Outlier Handling

- Most common blur model:

$$b = k * l + n$$

Equivalent to

small amount of Gaussian noise



Outlier Handling

- An energy function derived from this model:

$$E(l) = \underbrace{\|k * l - b\|^2}_{L^2\text{-norm based data term: known to be vulnerable to outliers}} + \underbrace{\rho(l)}_{\text{Regularization term on a latent image } l}$$

- More robust norms to outliers
 - L^1 -norm, other robust statistics...

$$E(l) = \underbrace{\|k * l - b\|_1}_{L^1\text{-norm based data term}} + \rho(l)$$

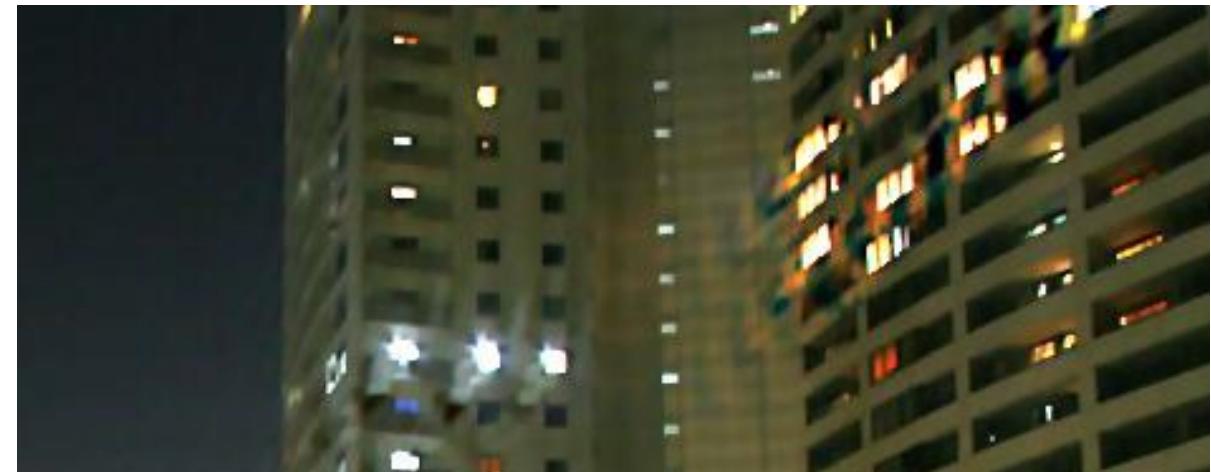
- Bar et al. IJCV 2006, Xu et al. ECCV 2010, ...

Outlier Handling

- L^1 -norm based data term
 - Simple & efficient
 - Effective on salt & pepper noise
 - Not effective on saturated pixels



L^2 -norm based data term



L^1 -norm based data term

Modern Approaches

DeblurGAN: Blind Motion Deblurring Using Conditional Adversarial Networks

Orest Kupyn^{1,3}, Volodymyr Budzan^{1,3}, Mykola Mykhailych¹, Dmytro Mishkin², Jiří Matas²

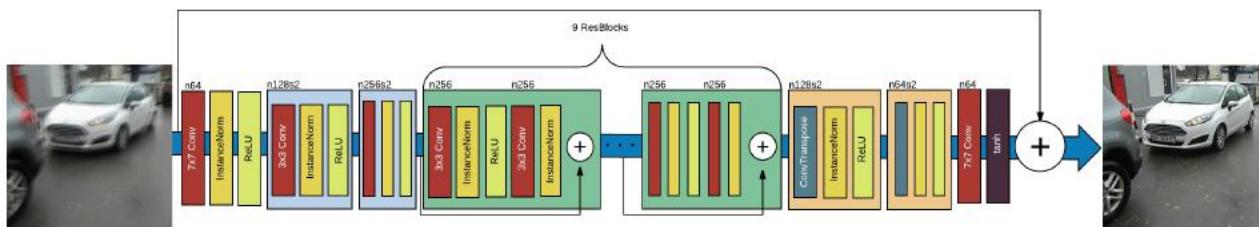
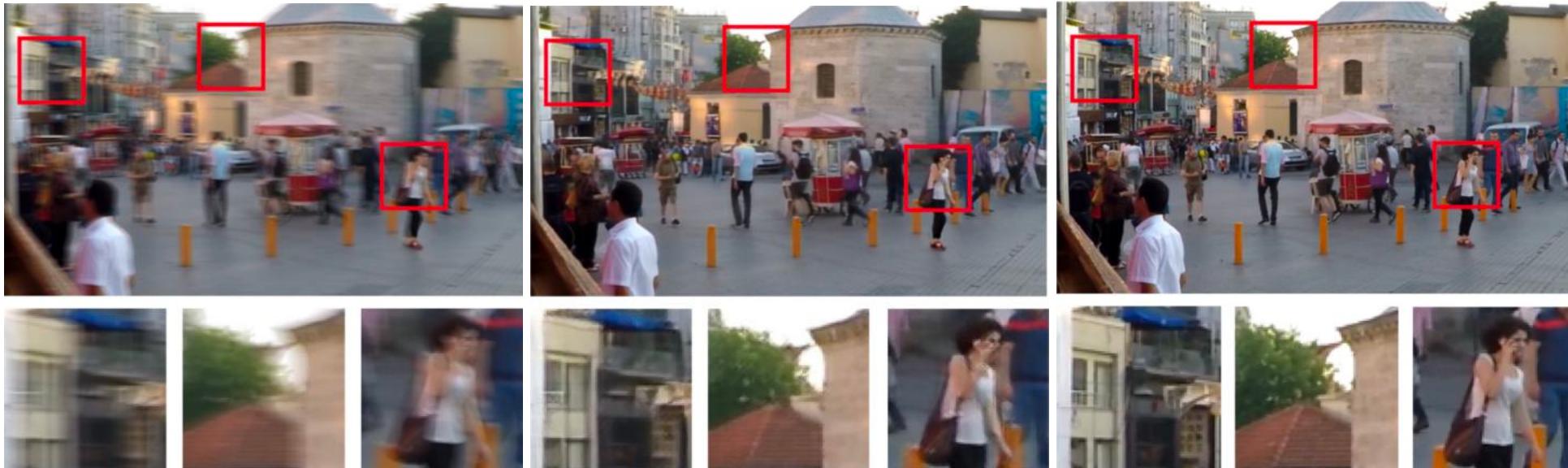
¹ Ukrainian Catholic University, Lviv, Ukraine

{kupyn, budzan, mykhailych}@ucu.edu.ua

² Visual Recognition Group, Center for Machine Perception, FEE, CTU in Prague

{mishkdmy, matas}@cmp.felk.cvut.cz

³ ELEKS Ltd.



Modern Approaches

Universal and Flexible Optical Aberration Correction Using Deep-Prior Based Deconvolution

Xiu Li^{1*}, Jinli Suo¹, Weihang Zhang¹, Xin Yuan², Qionghai Dai¹

¹Tsinghua University, ²Westlake University



Modern Approaches

Deblurring via Stochastic Refinement

Jay Whang^{†*}

Mauricio Delbracio[‡]

Hossein Talebi[‡]

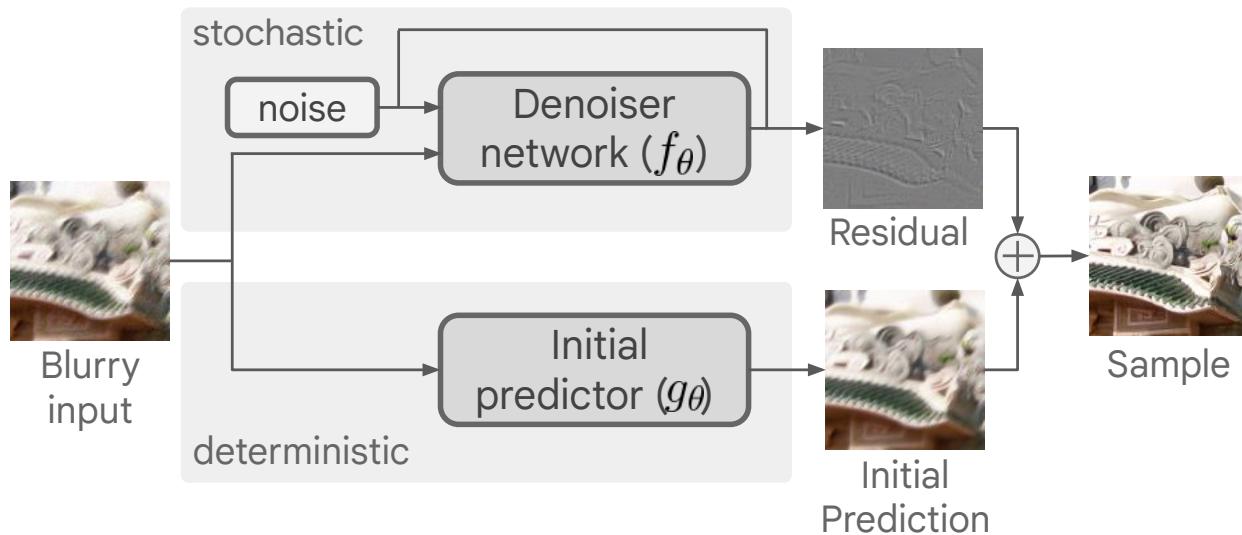
Chitwan Saharia[‡]

Alexandros G. Dimakis[†]

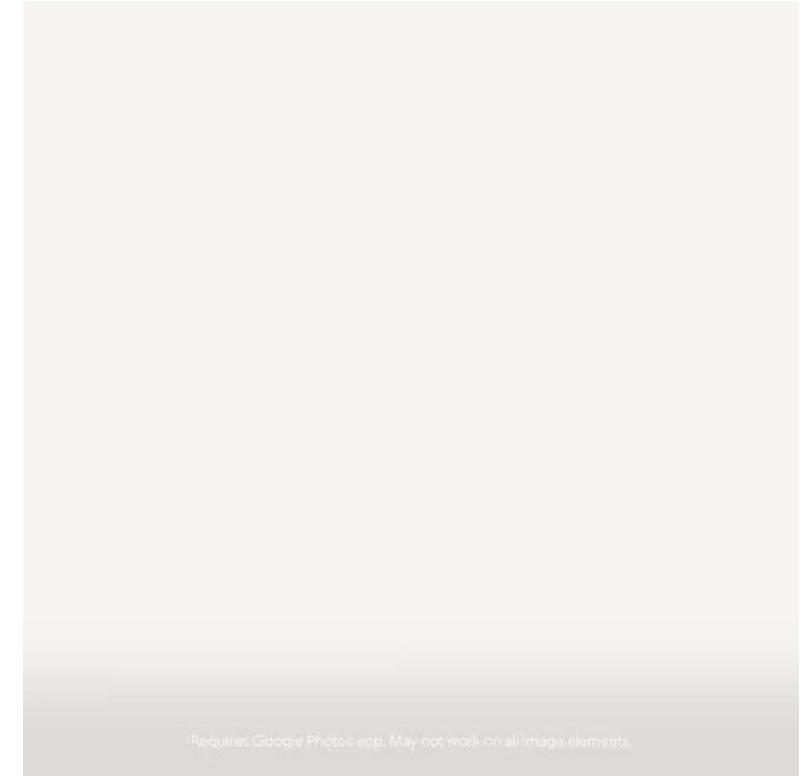
Peyman Milanfar[‡]

[†]University of Texas at Austin

[‡]Google Research



Modern Technology



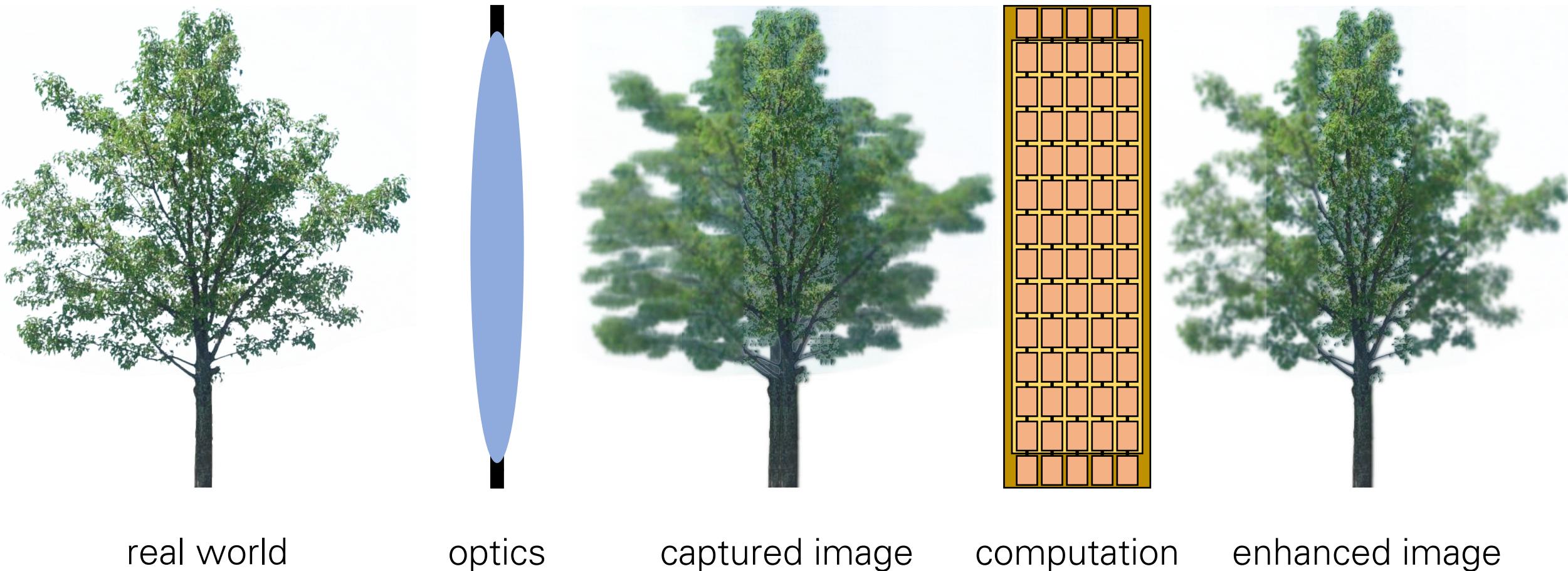
Requires Google Photos app. May not work on all image elements.

Today's Lecture

- Deconvolution
 - Sources of blur
 - Blind deconvolution
 - Non-blind deconvolution
- Coded photography
 - The coded photography paradigm
 - Dealing with depth blur
 - Dealing with motion blur

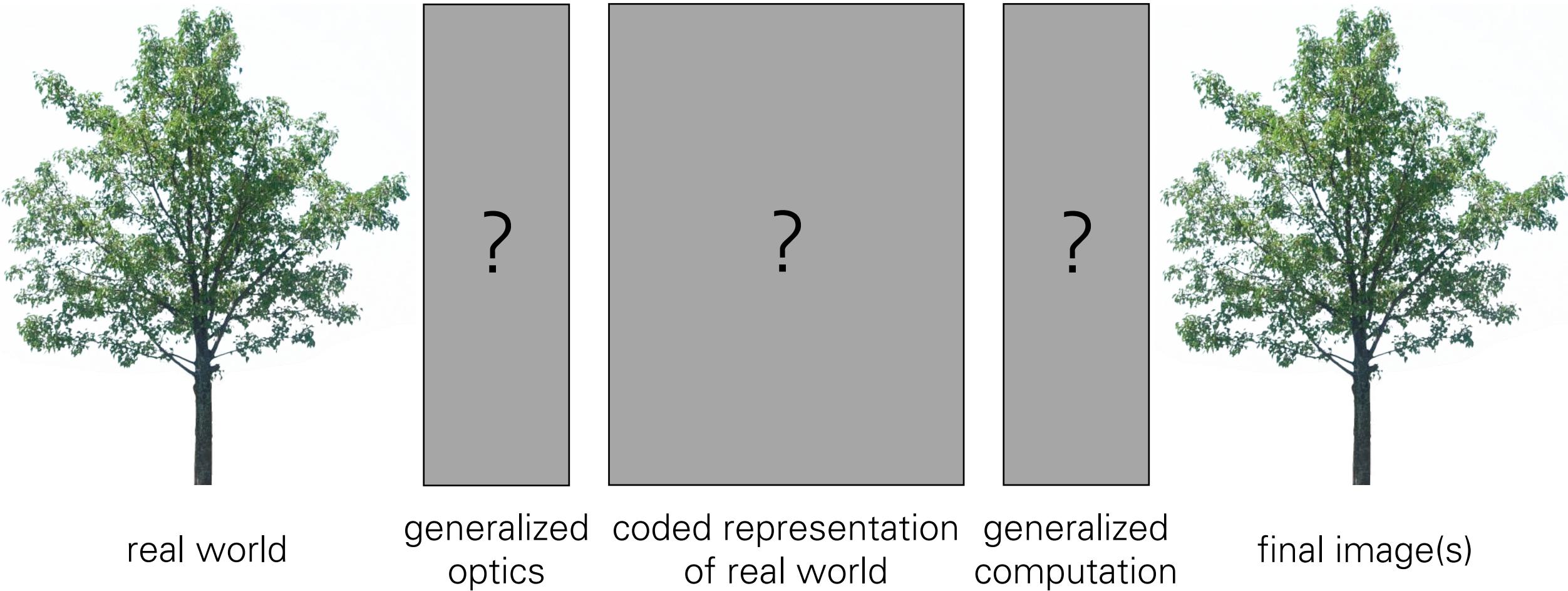
The coded photography paradigm

Conventional photography



- Optics capture something that is (close to) the final image.
- Computation mostly “enhances” captured image (e.g., deblur).

Coded photography

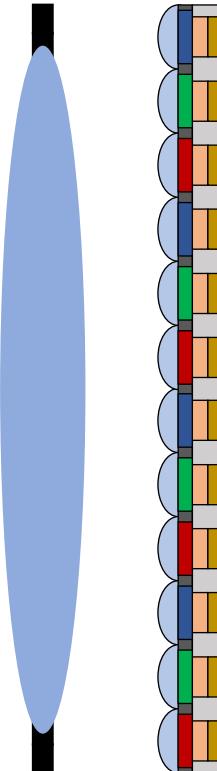


- Generalized optics encode world into intermediate representation.
 - Generalized computation decodes representation into multiple images.
- Can you think of any examples?

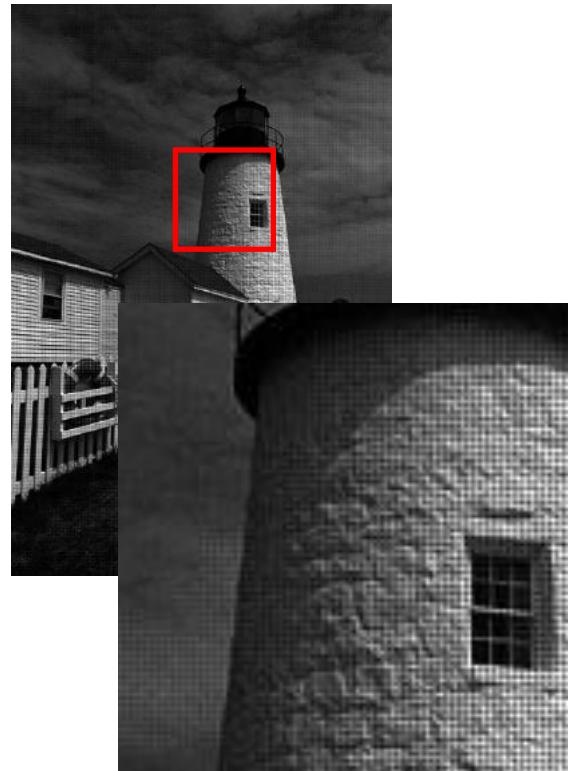
Early example: mosaicing



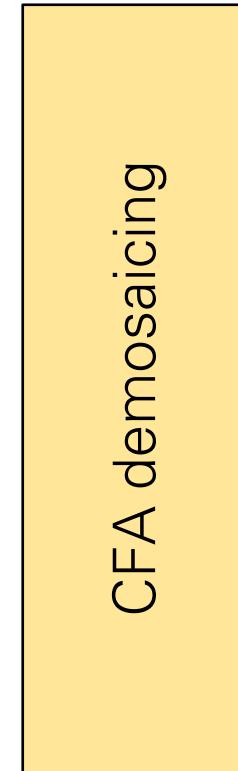
real world



generalized
optics



coded representation
of real world



generalized
computation



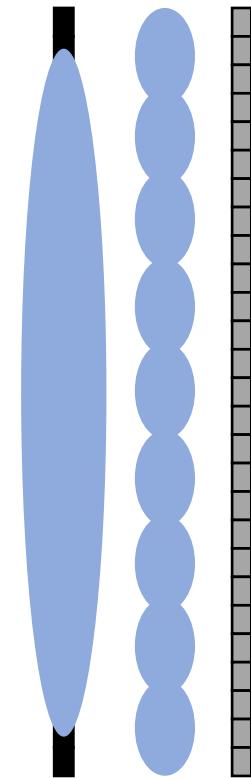
final image(s)

- Color filter array encodes color into a mosaic.
- Demosaicing decodes color into RGB image.

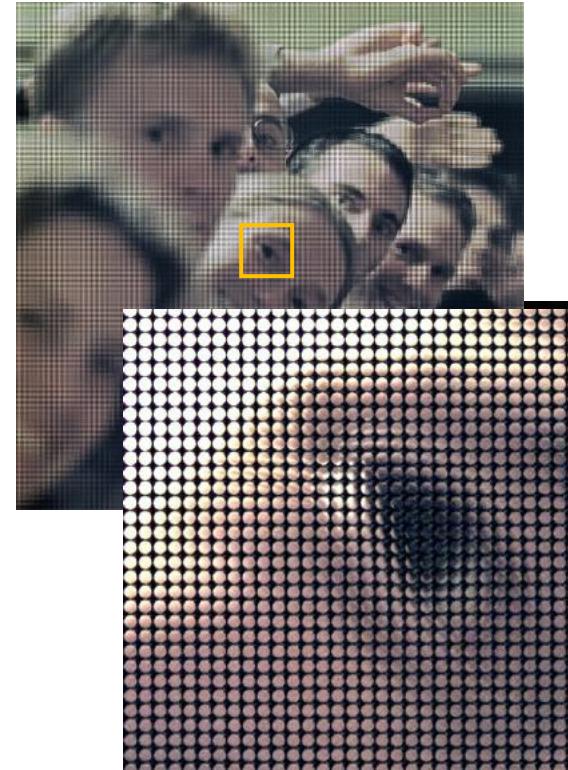
Recent example: plenoptic camera



real world



generalized
optics



coded representation
of real world



generalized
computation



final image(s)

- Plenoptic camera encodes world into lightfield.
- Lightfield rendering decodes lightfield into refocused or multi-viewpoint images.

Why are our images blurry?

- Lens imperfections. ← non-blind deconvolution
 - Camera shake. ← blind deconvolution
 - Scene motion. ← flutter shutter, motion-invariant photo
 - Depth defocus. ← coded aperture, focal sweep, lattice lens
-
- The diagram illustrates four causes of blurry images, each associated with a specific deconvolution method. A vertical bracket on the right side groups the first two causes under the heading 'conventional photography'. Another vertical bracket on the right side groups the last two causes under the heading 'coded photography'.

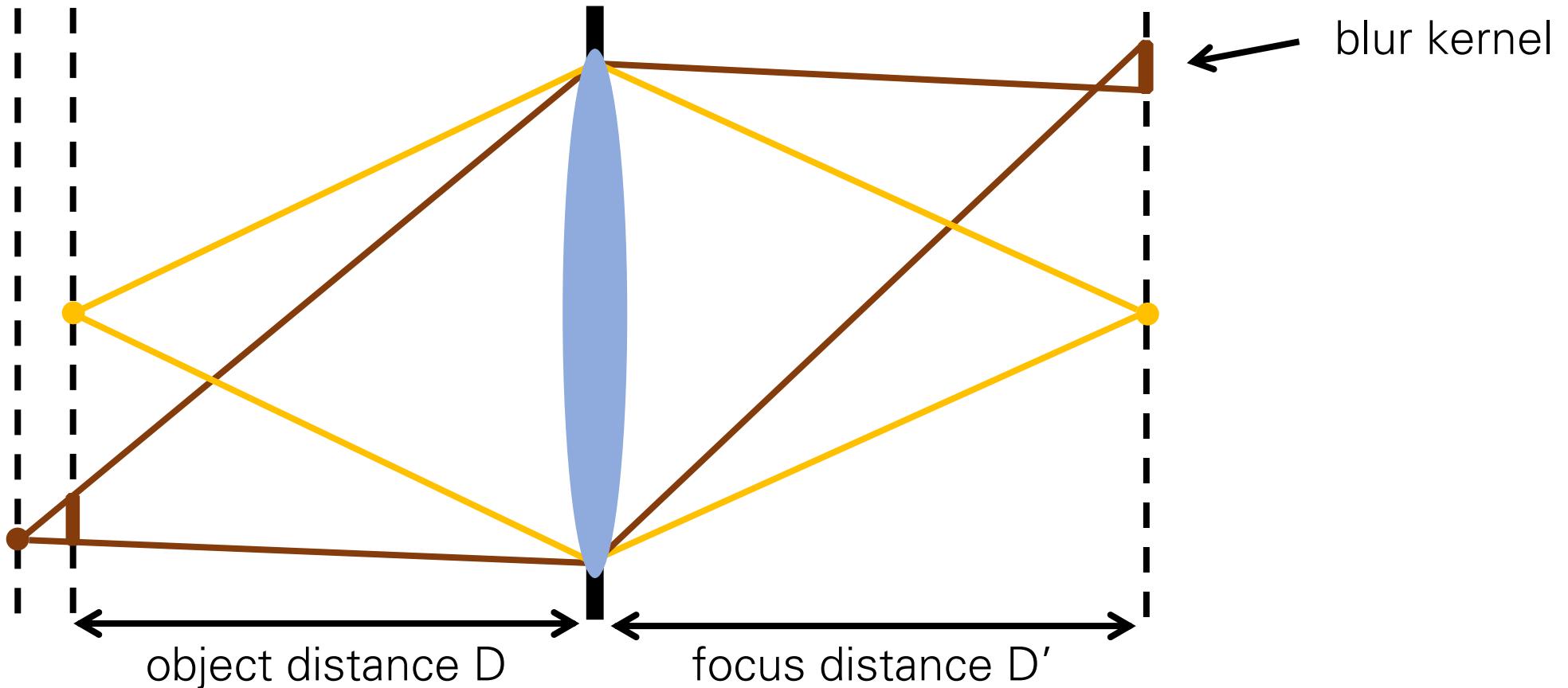
Why are our images blurry?

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 - Scene motion. ← flutter shutter, motion-invariant photo
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-
- conventional
photography
- coded
photography

Dealing with depth blur: coded aperture

Defocus blur

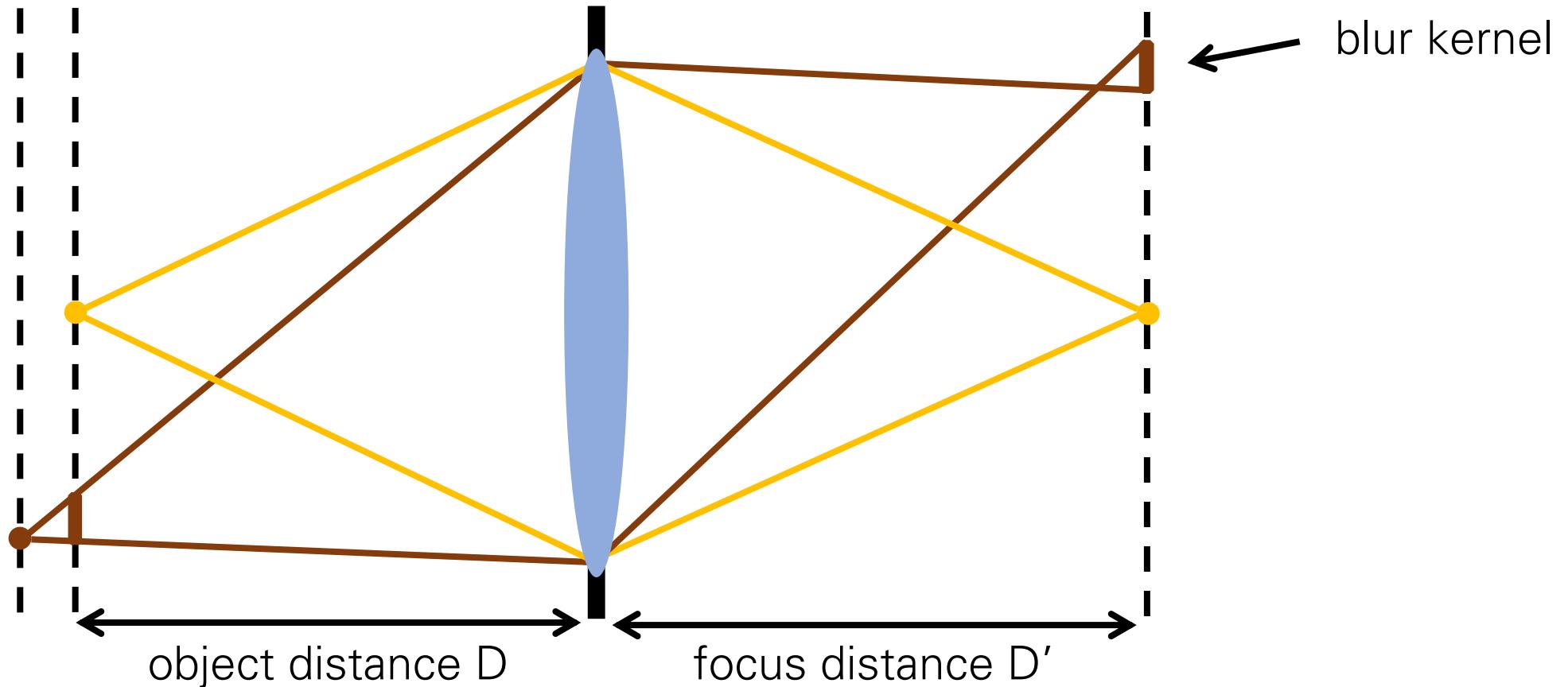
Point spread function (PSF): The blur kernel of a (perfect) lens at some out-of-focus depth.



What does the blur kernel depend on?

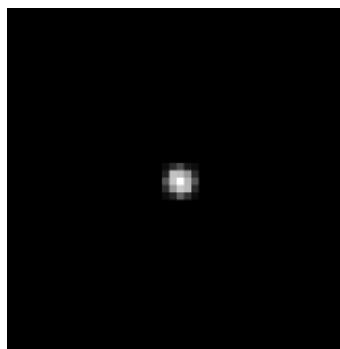
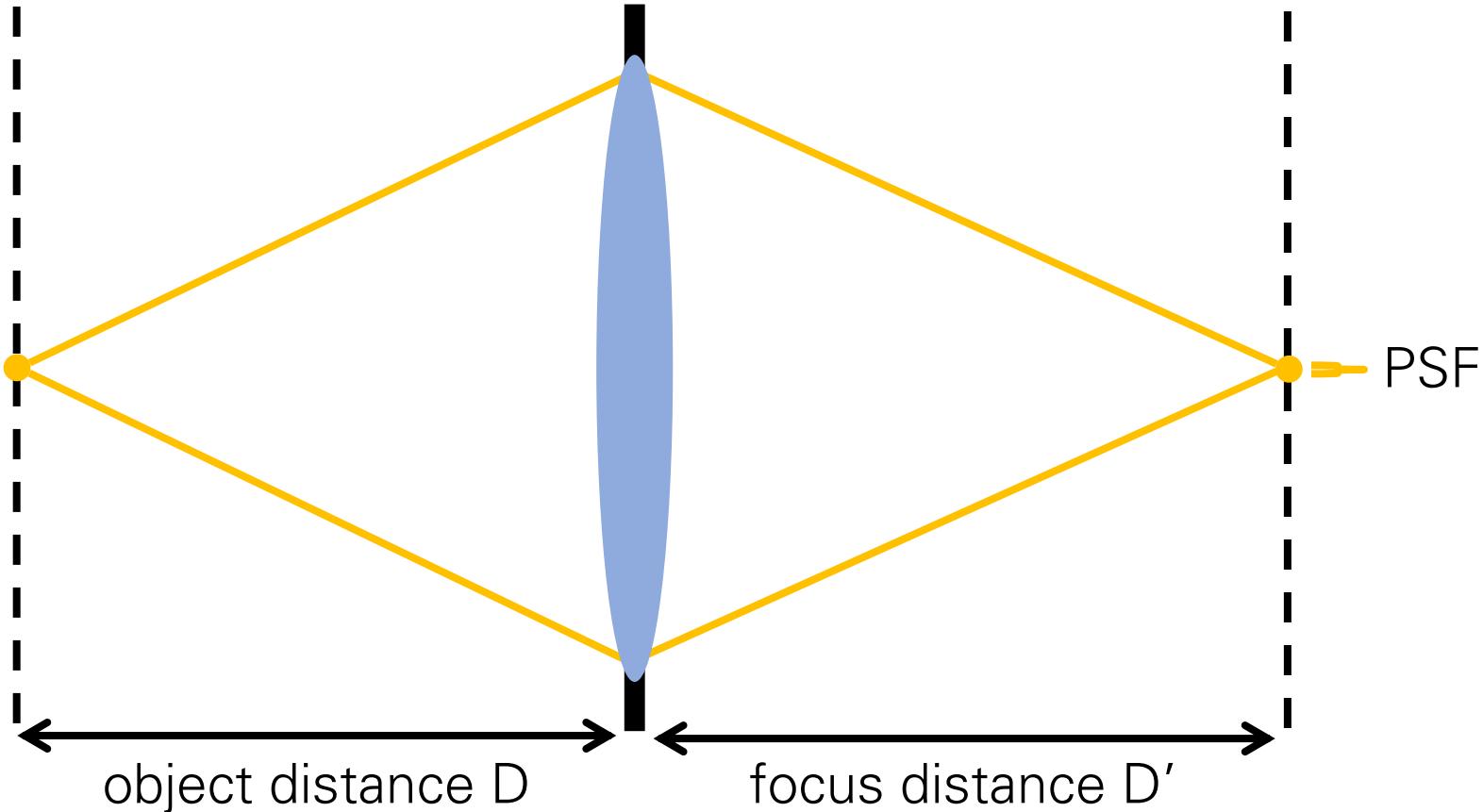
Defocus blur

Point spread function (PSF): The blur kernel of a (perfect) lens at some out-of-focus depth.

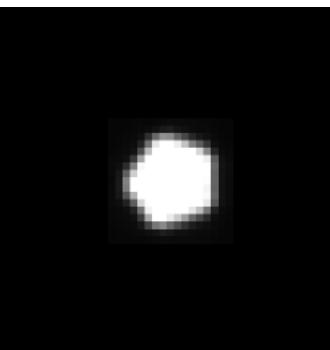
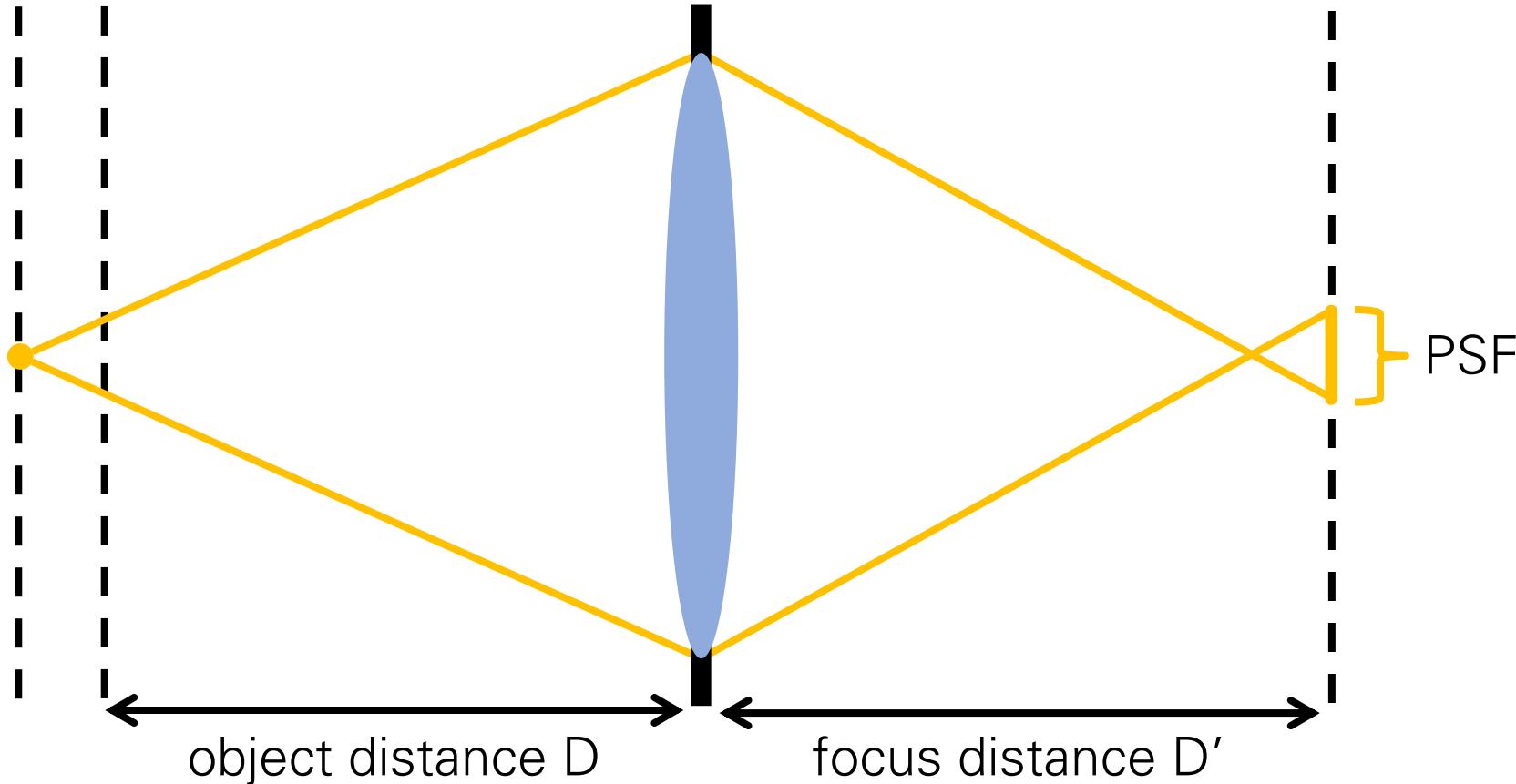


- Aperture determines shape of kernel.
- Depth determines scale of blur kernel.

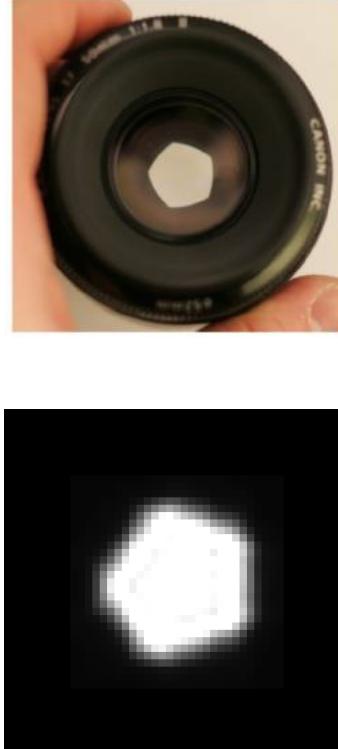
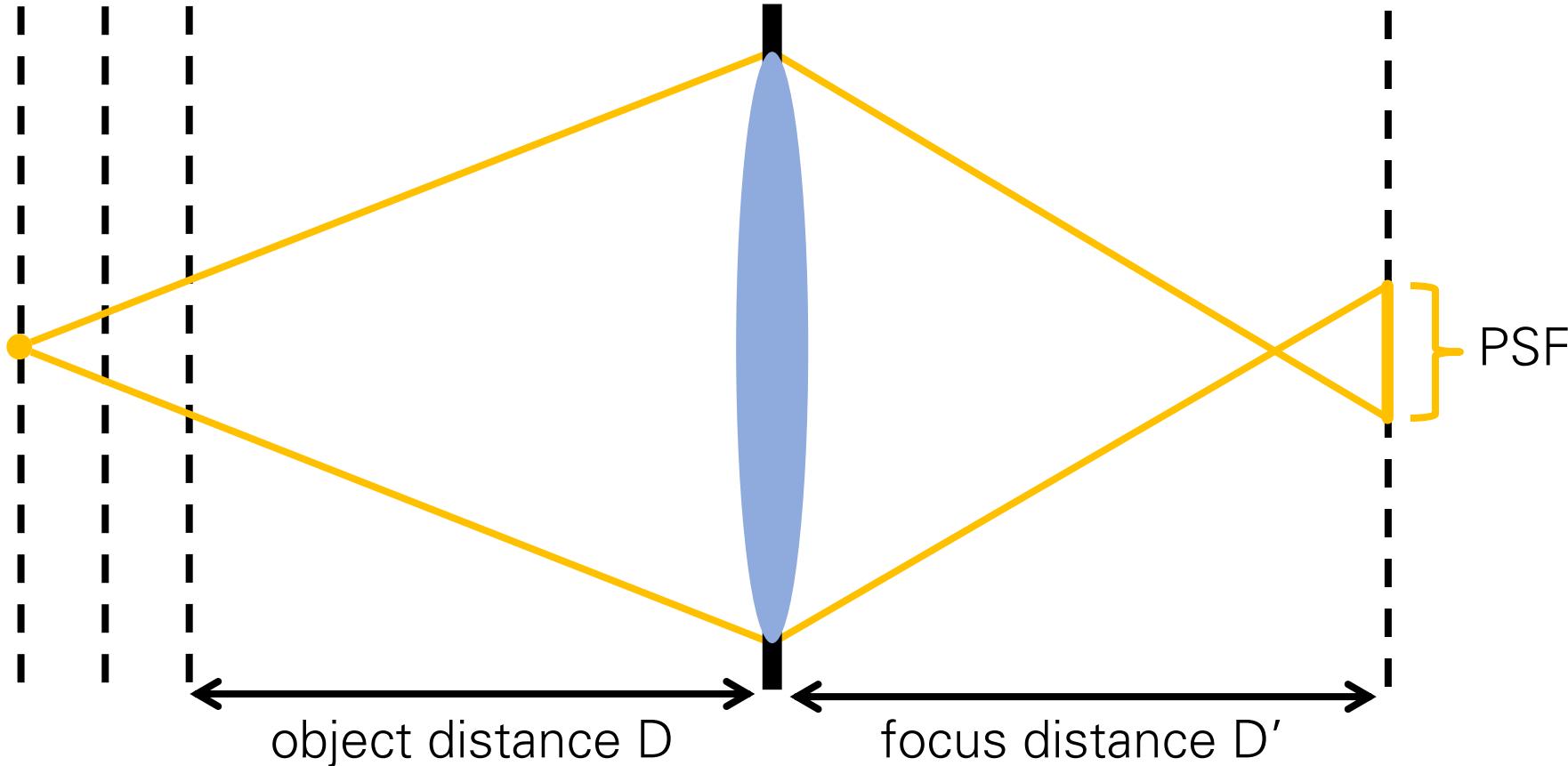
Depth determines scale of blur kernel



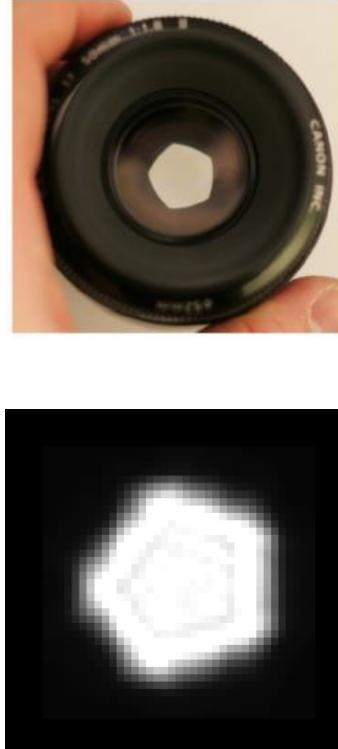
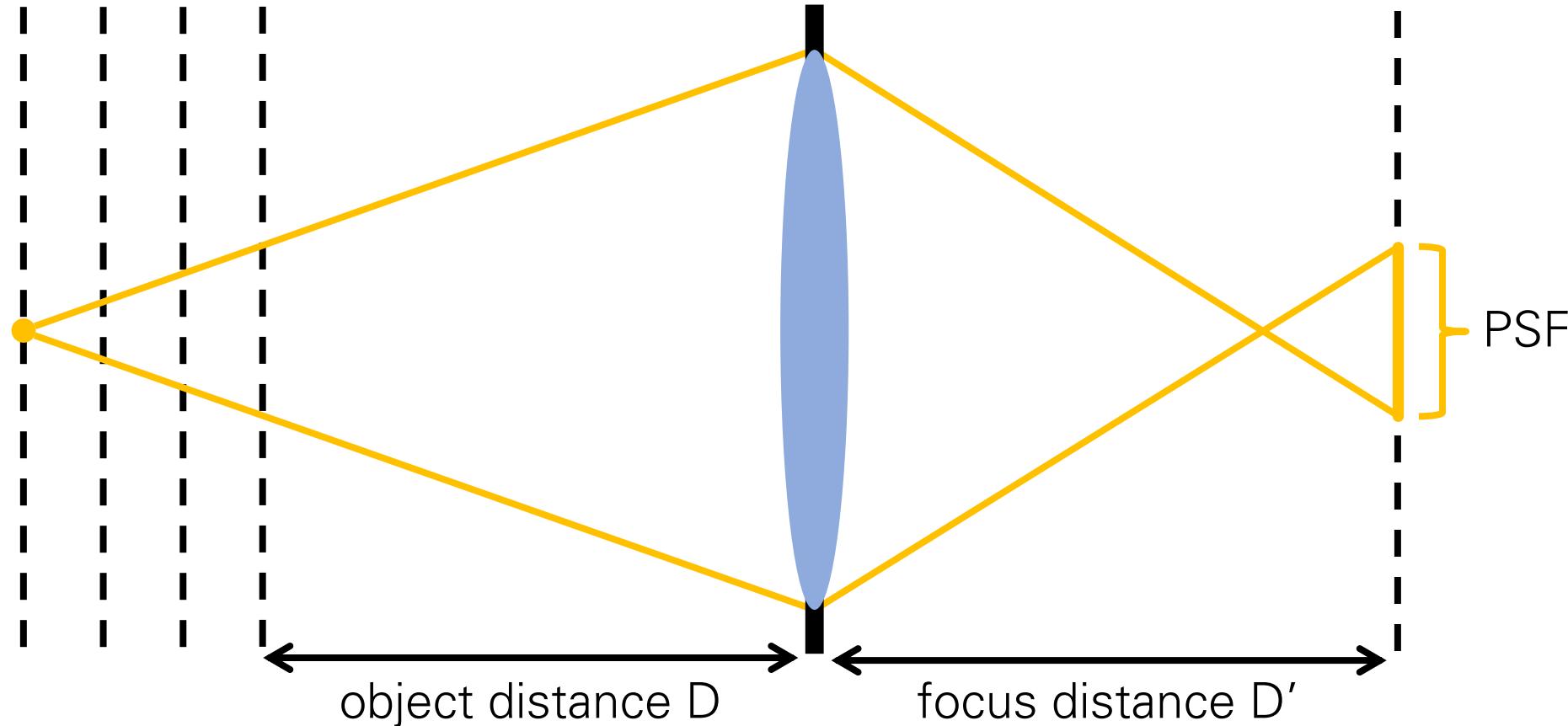
Depth determines scale of blur kernel



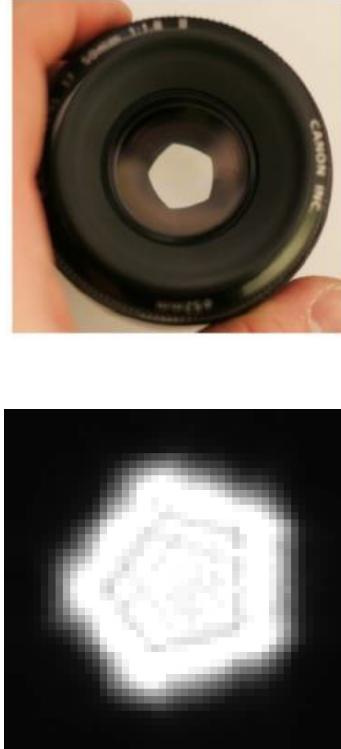
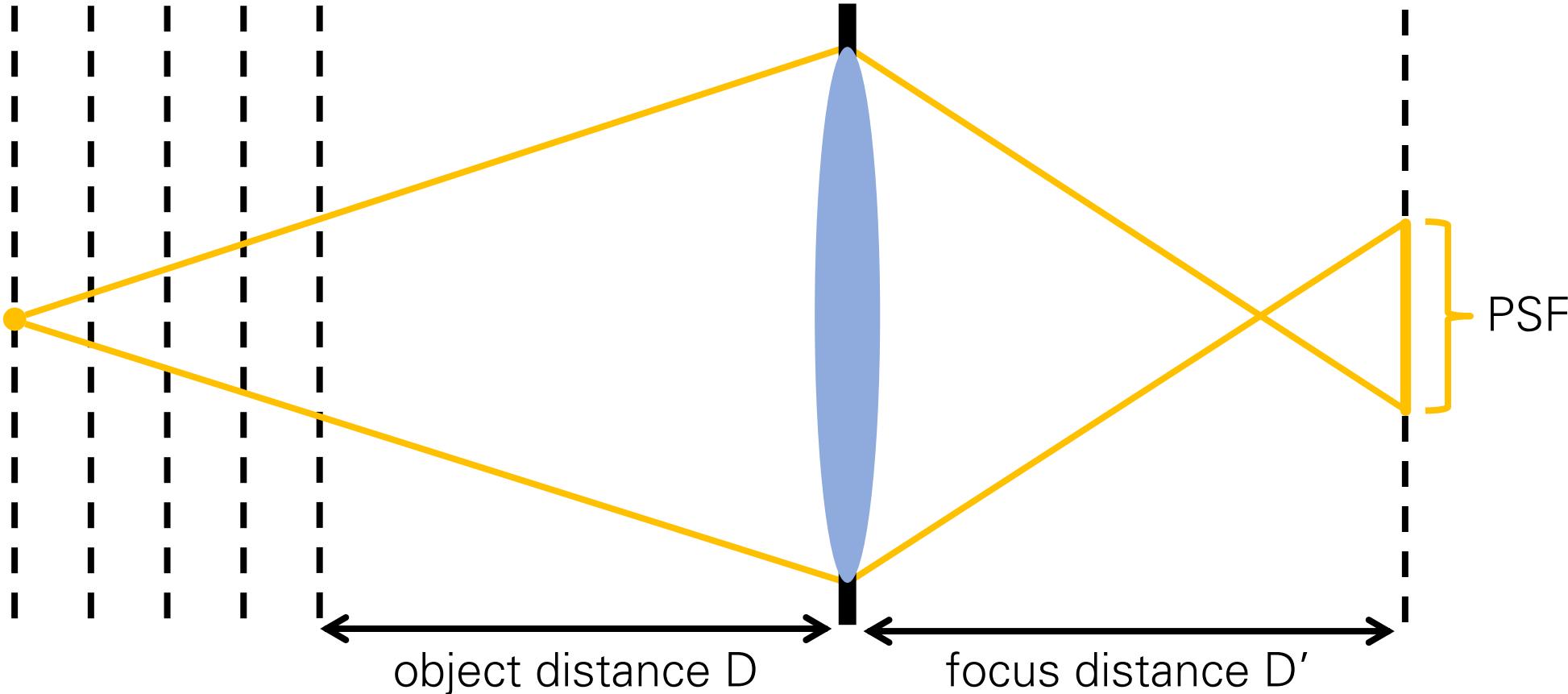
Depth determines scale of blur kernel



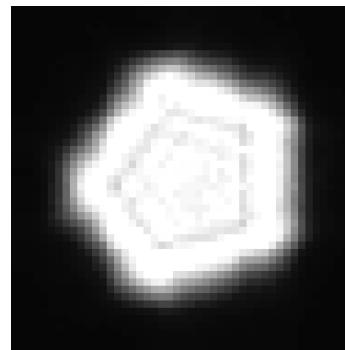
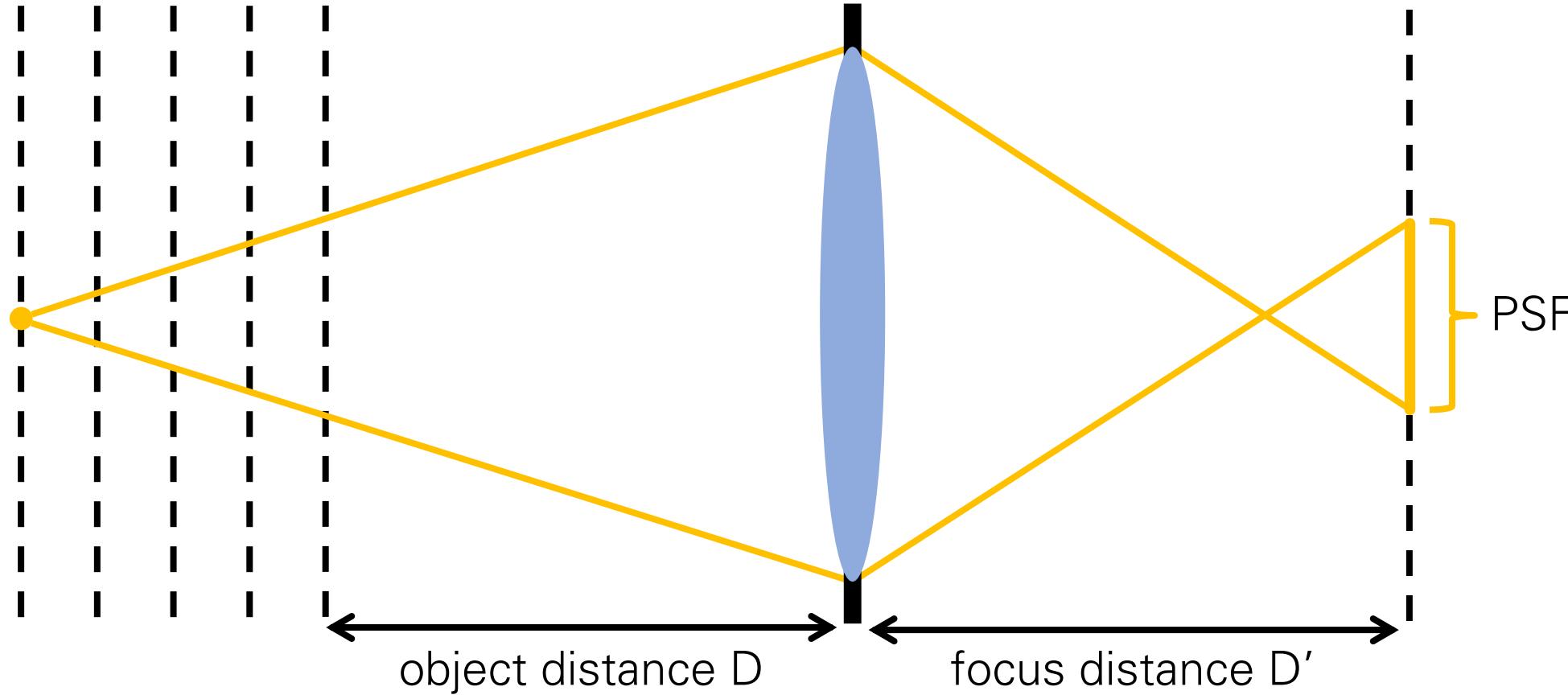
Depth determines scale of blur kernel



Depth determines scale of blur kernel



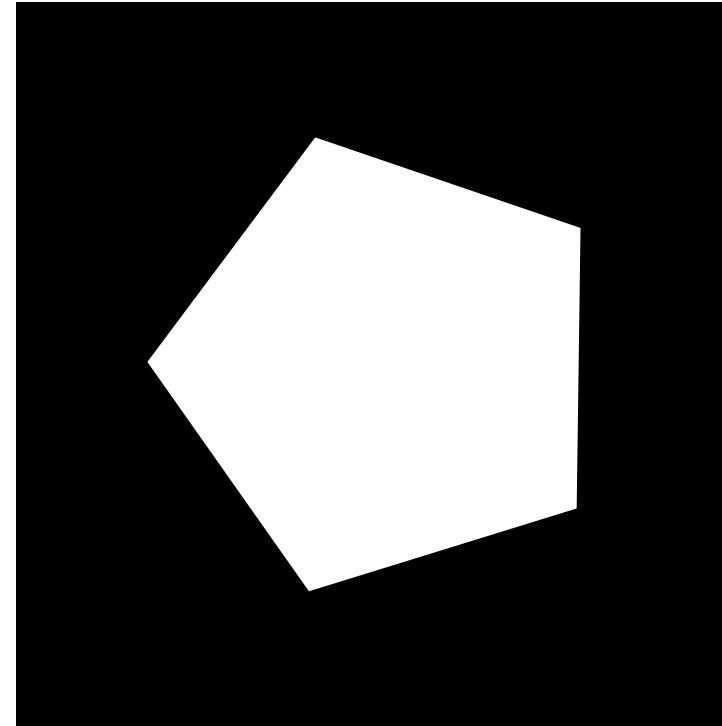
Aperture determines shape of blur kernel



Aperture determines shape of blur kernel

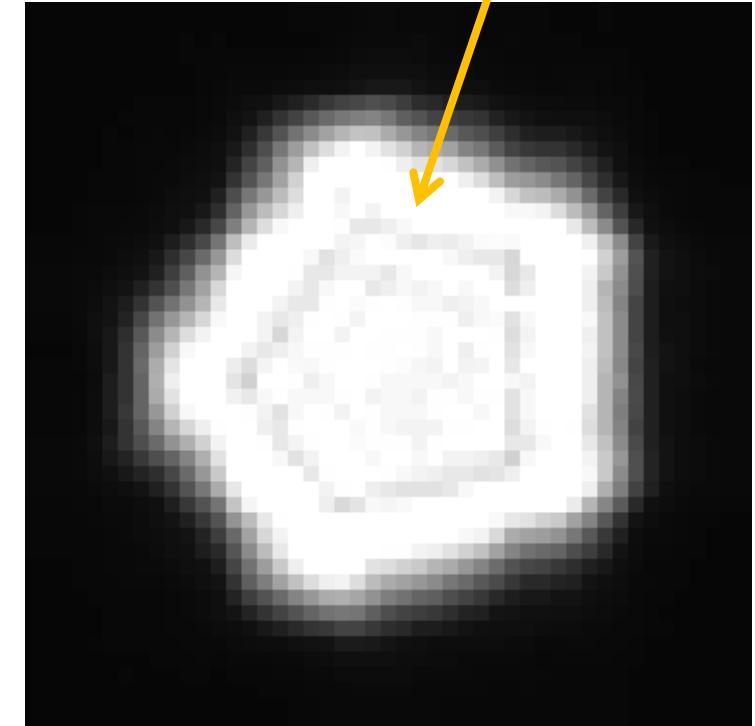


photo of aperture



shape of aperture
(optical transfer function, OTF)

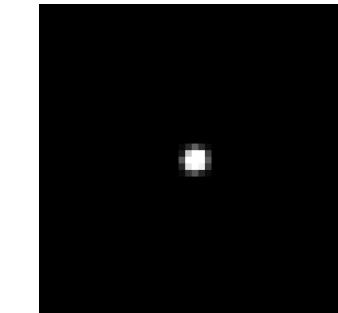
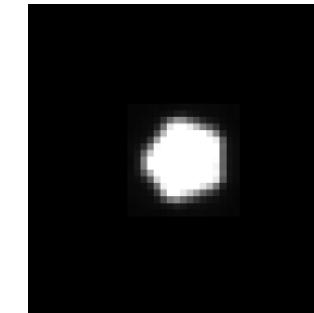
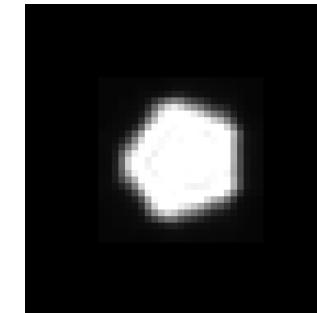
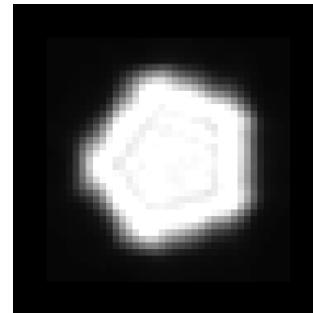
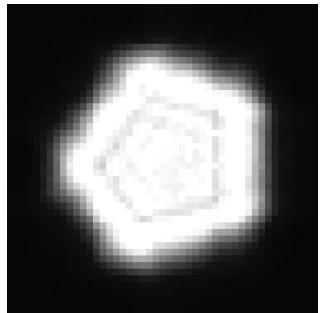
What causes these lines?



blur kernel
(point spread function, PSF)

How do the OTF and PSF relate to each other?

Removing depth defocus



measured PSFs at different depths



input defocused image

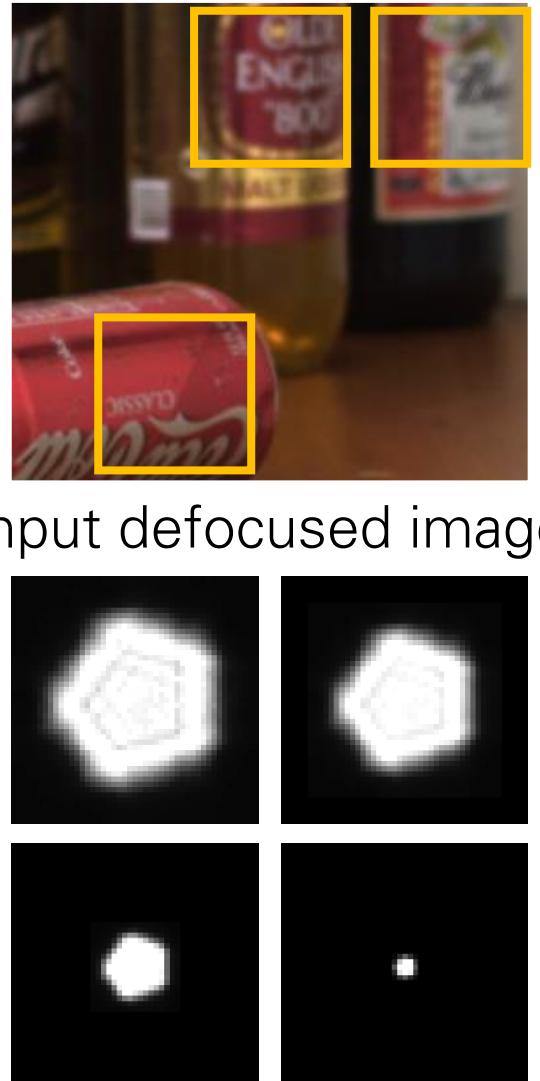
How would you create an all in-focus image given the above?

Removing depth defocus

Defocus is local convolution with a depth-dependent kernel

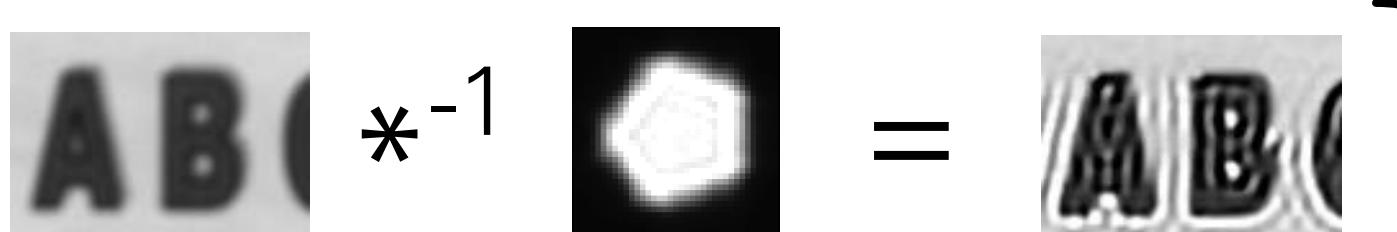
$$\begin{array}{c} \text{depth 3} \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{depth 2} \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{depth 1} \end{array} = \begin{array}{c} \text{PSF at depth 3} \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{PSF at depth 2} \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{PSF at depth 1} \end{array} * \begin{array}{c} \text{in-focus image at depth 3} \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{in-focus image at depth 2} \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{in-focus image at depth 1} \end{array}$$

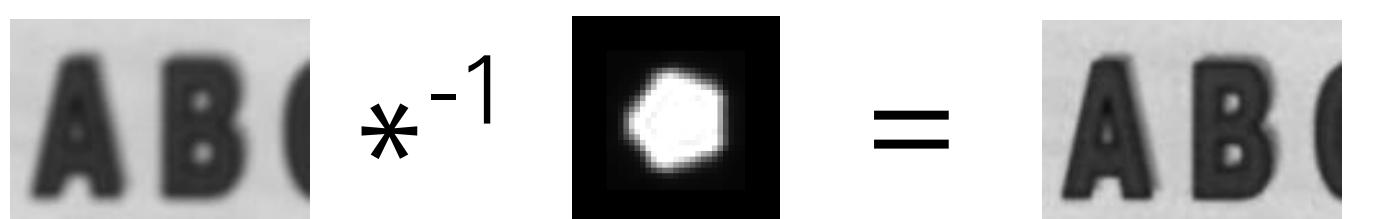
How would you create an all in-focus image given the above?

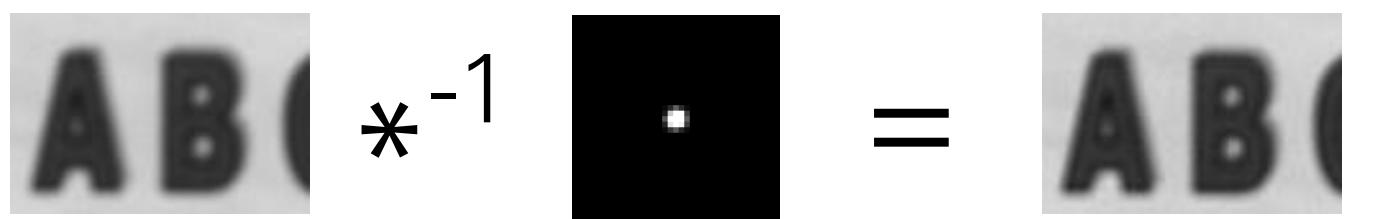


Removing depth defocus

- Deconvolve each image patch with all kernels
- Select the right scale by evaluating the deconvolution results

$$\text{Image} \otimes^{-1} \text{Kernel} = \text{Reconstructed Image}$$


$$\text{Image} \otimes^{-1} \text{Kernel} = \text{Reconstructed Image}$$


$$\text{Image} \otimes^{-1} \text{Kernel} = \text{Reconstructed Image}$$


How do we
select the
correct
scale?

Removing depth defocus

Problem: With standard aperture, results at different scales look very similar.

$$\text{ABC} \quad *^{-1} \quad \text{hexagonal diffraction pattern} \quad = \quad \text{ABC}$$

wrong scale X

$$\text{ABC} \quad *^{-1} \quad \text{square diffraction pattern} \quad = \quad \text{ABC}$$

correct scale ?

$$\text{ABC} \quad *^{-1} \quad \text{dot diffraction pattern} \quad = \quad \text{ABC}$$

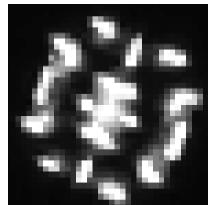
correct scale ?

Coded aperture

Solution: Change aperture so that it is easier to pick the correct scale



$$*^{-1}$$



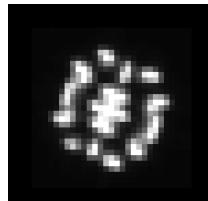
=



wrong scale



$$*^{-1}$$



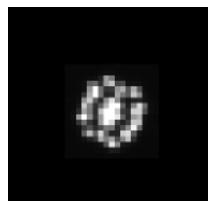
=



correct scale



$$*^{-1}$$



=



wrong scale



Build your own coded aperture

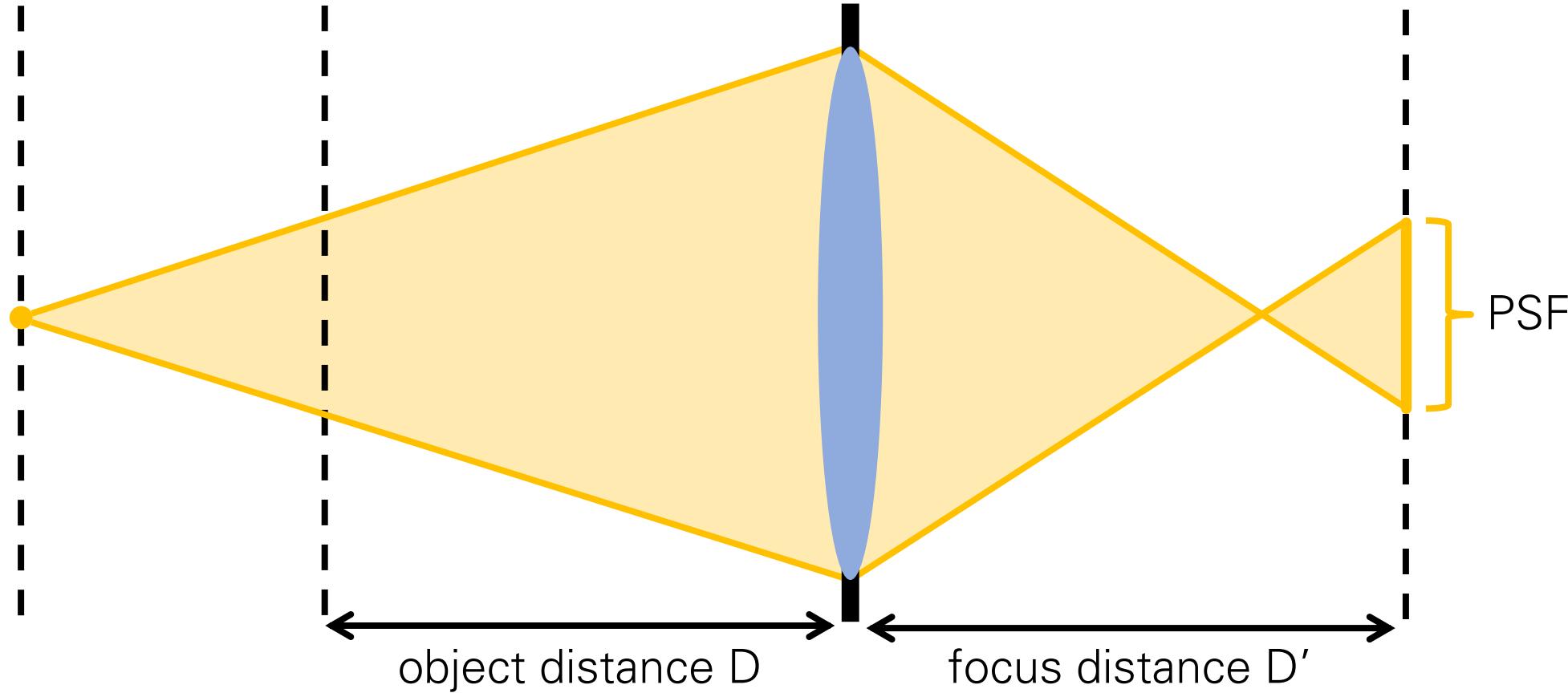


Build your own coded aperture

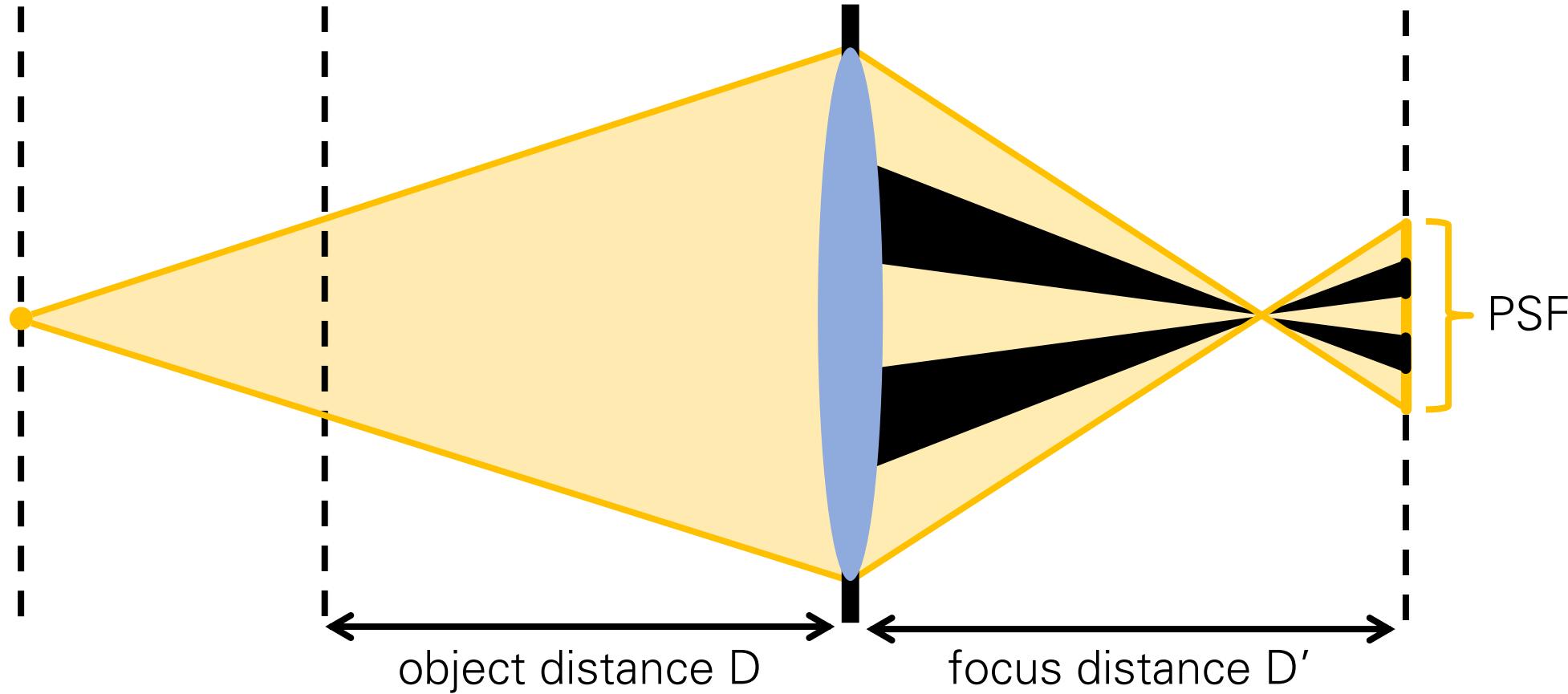
Voila!



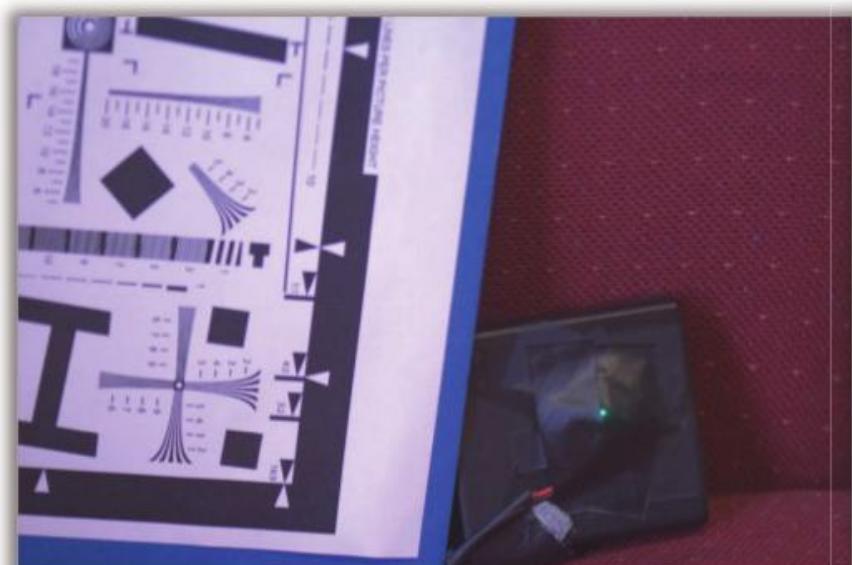
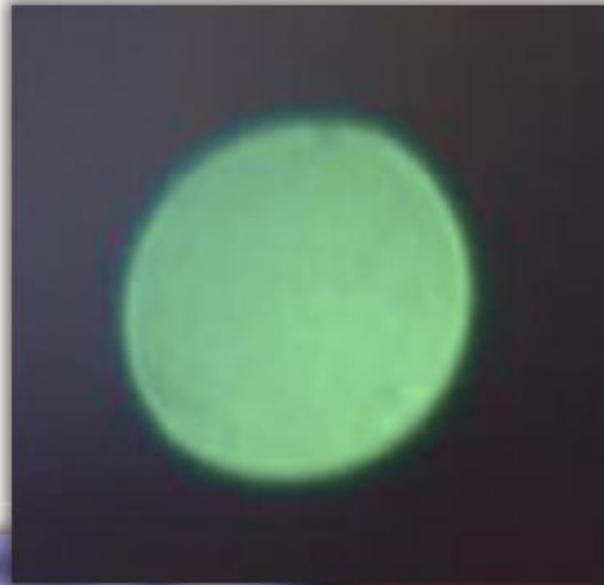
Coded aperture changes shape of kernel



Coded aperture changes shape of kernel



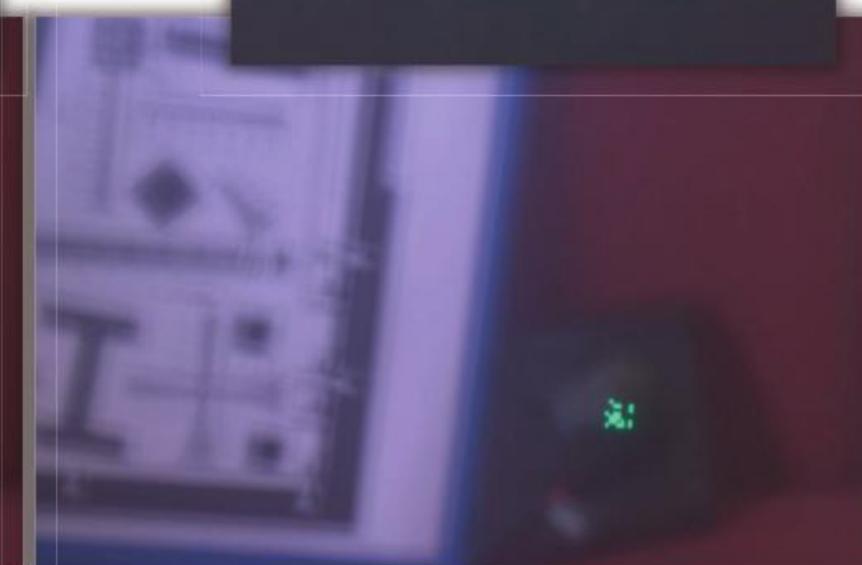
Coded aperture changes shape of PSF



in-focus photo

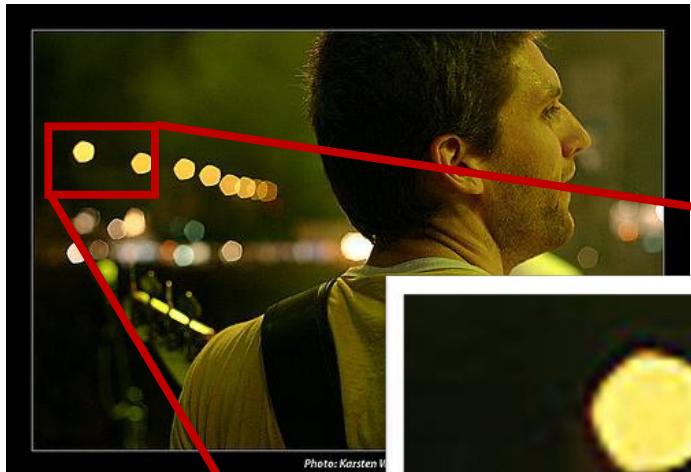


out-of-focus, circular aperture



out-of-focus, coded aperture

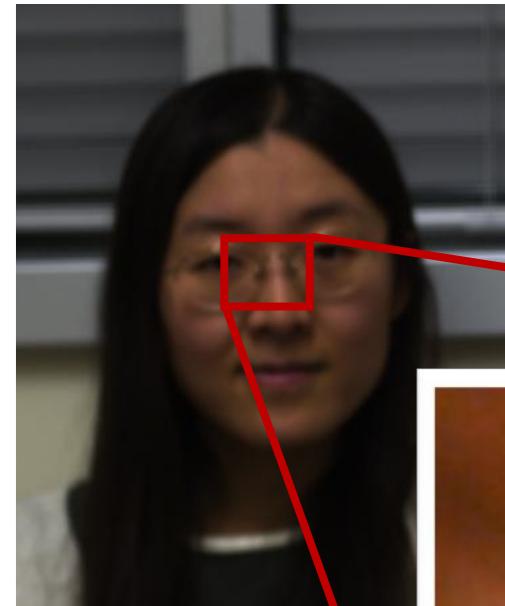
Image of a point light source



Conventional Aperture



Captured Image



Coded Aperture

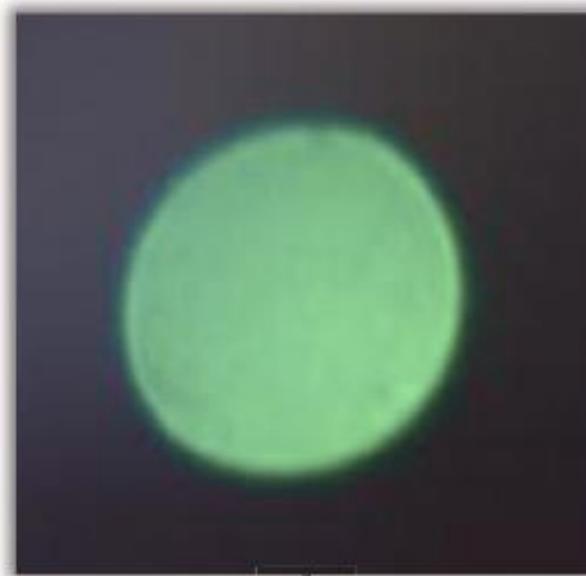
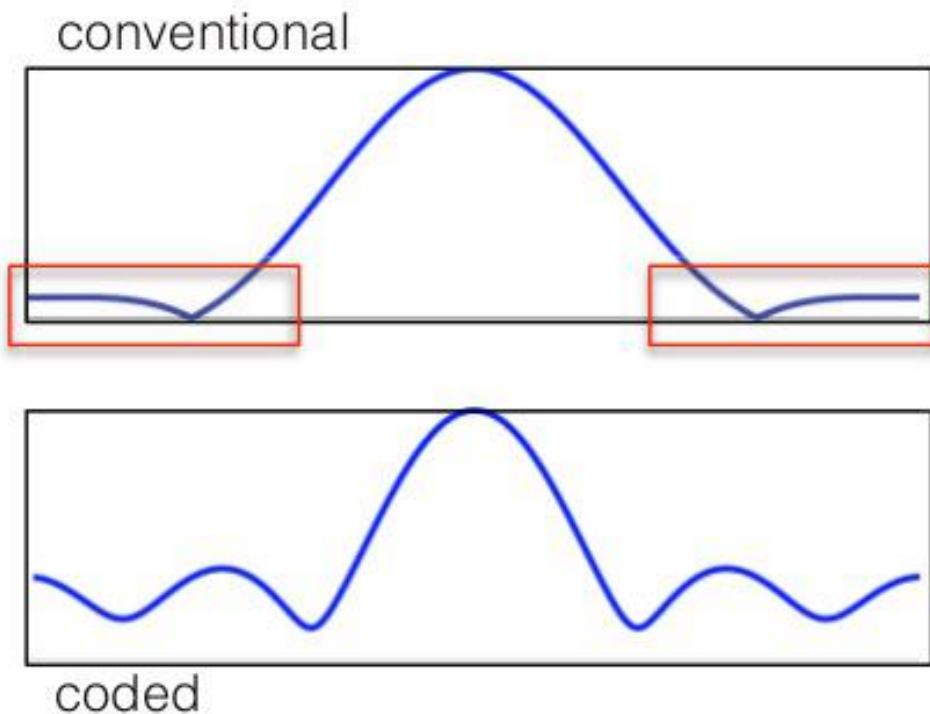


Captured Image

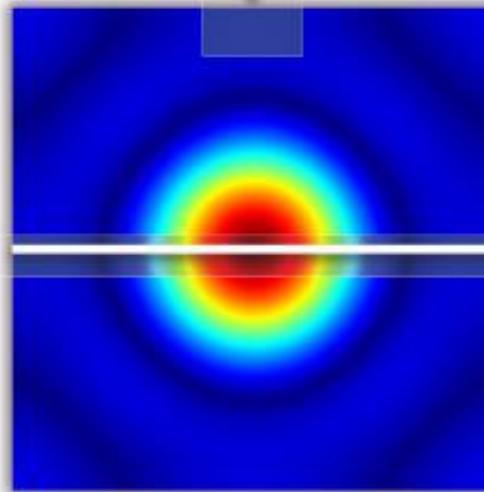
Coded aperture changes shape of PSF

New PSF preserves high frequencies

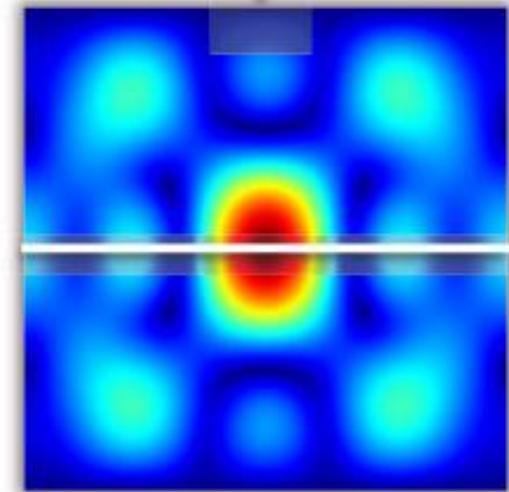
- More content available to help us determine correct depth



FFT



FFT



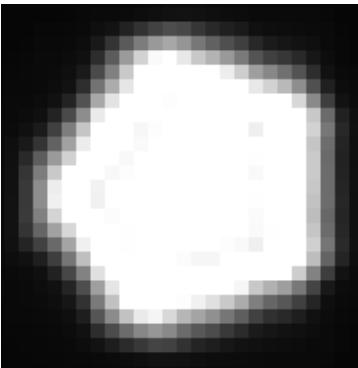
Input



All-focused (deconvolved)



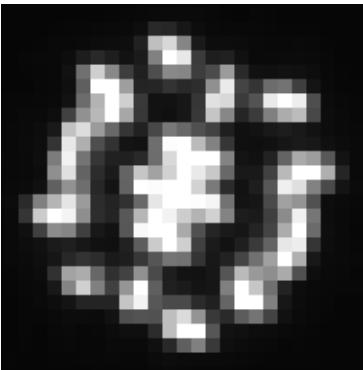
Comparison between standard and coded aperture



Ringing due to wrong scale estimation



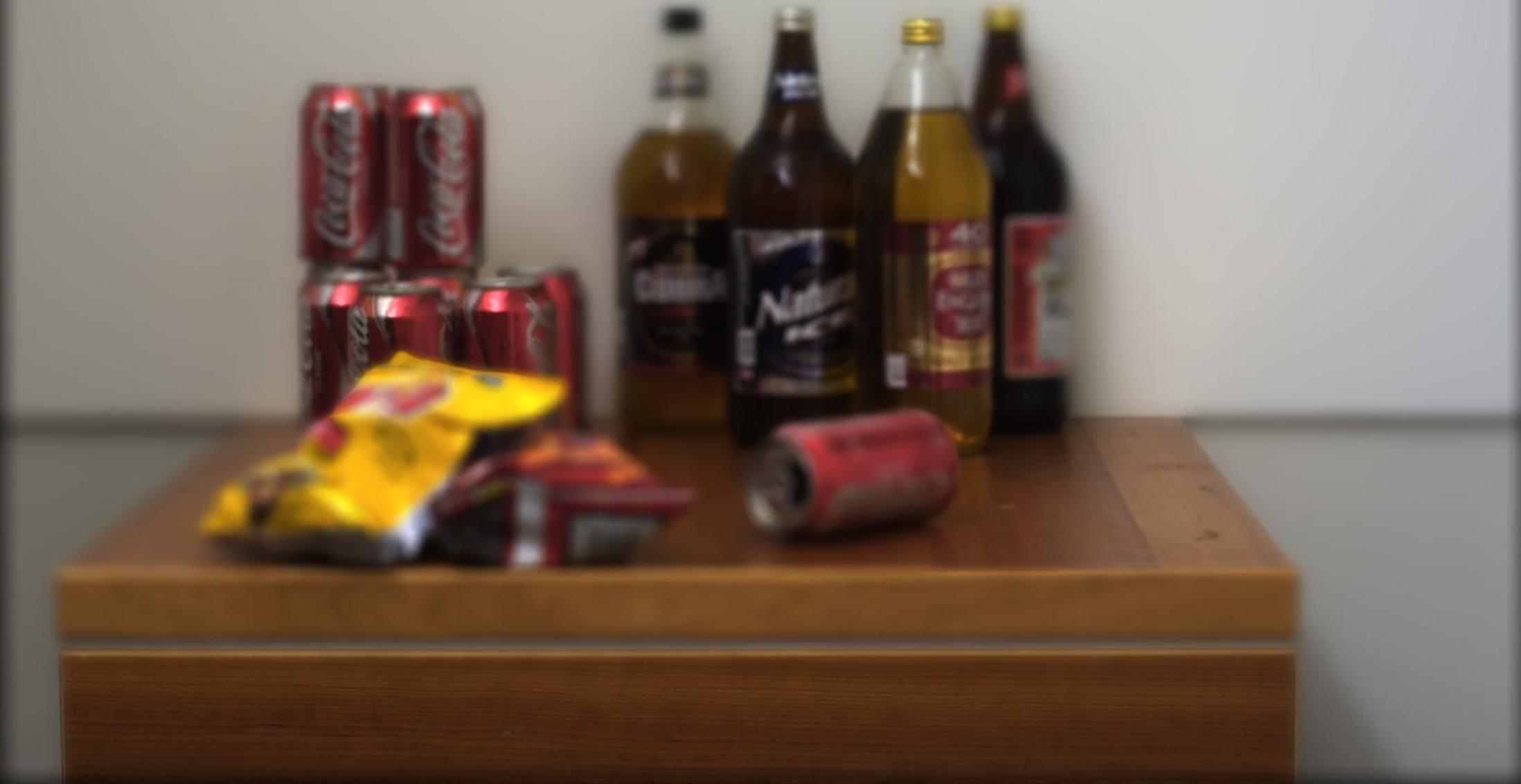
Comparison between standard and coded aperture



Refocusing



Refocusing



Refocusing



Depth estimation



Input



All-focused
(deconvolved)



Refocusing



Refocusing



Refocusing



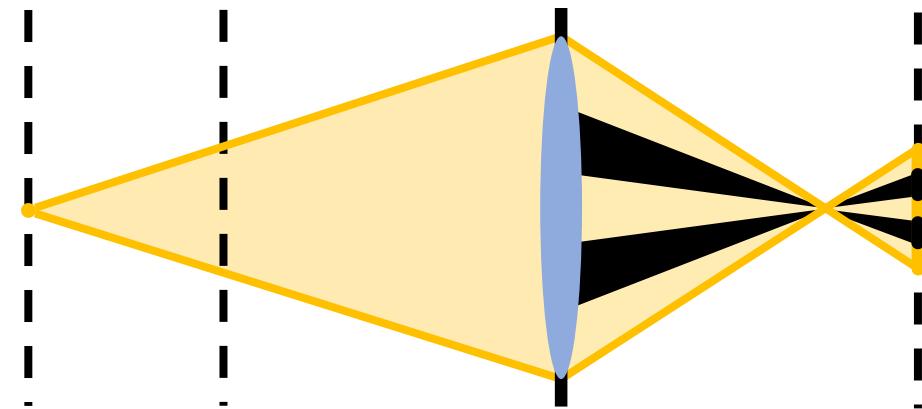
Depth estimation



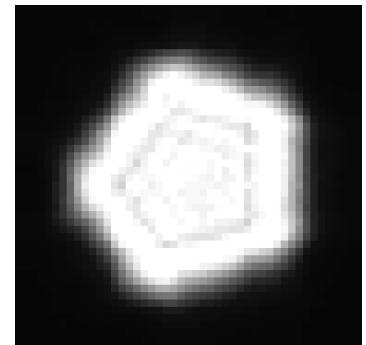
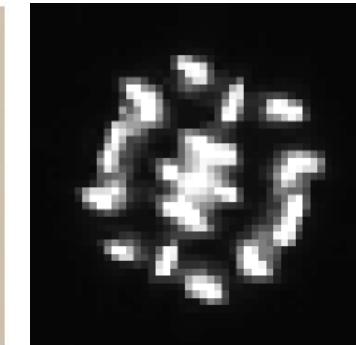
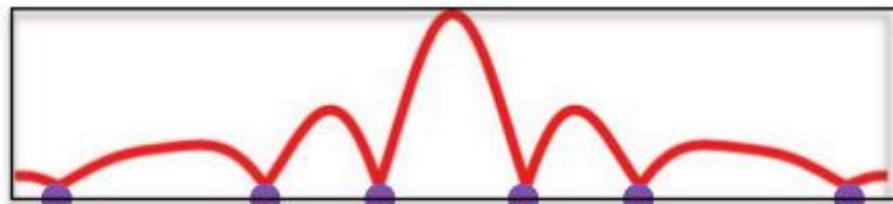
Any problems with using a coded aperture?

Any problems with using a coded aperture?

- We lose a lot of light due to blocking.



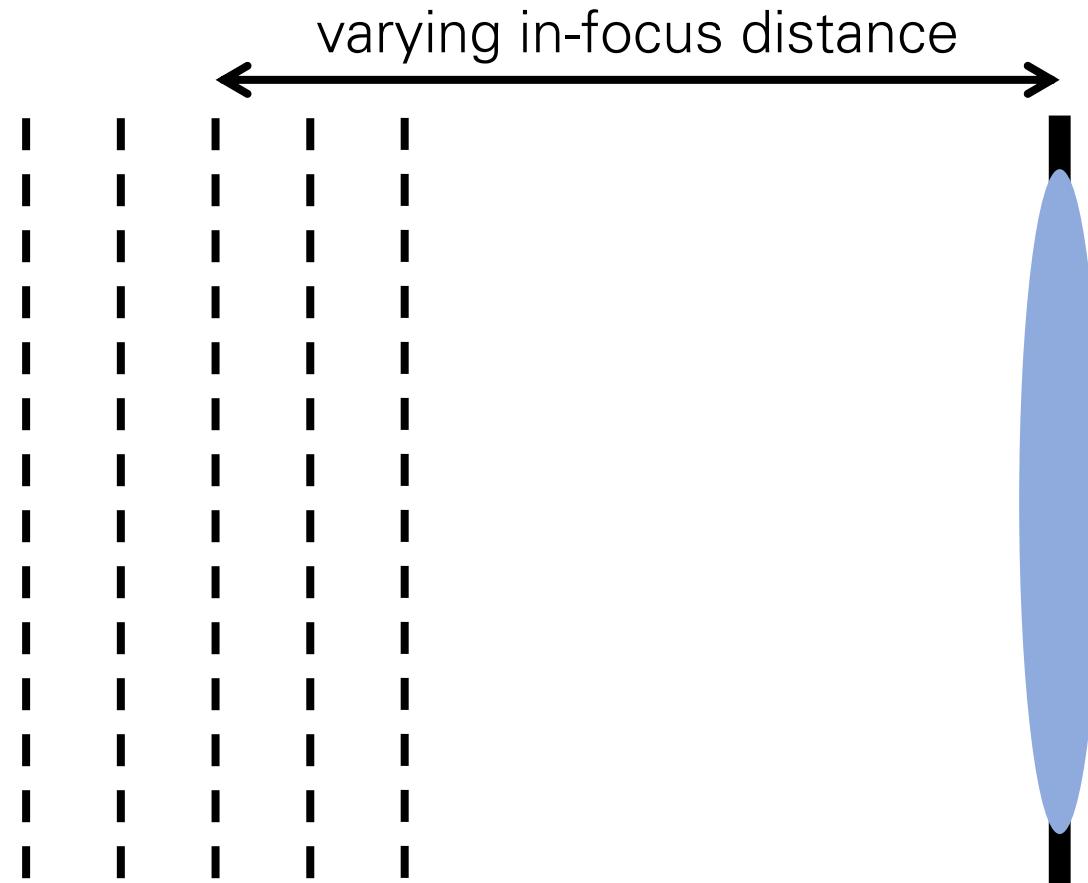
- The deconvolution becomes harder due to more diffraction/zeros in frequency domain.



- We still need to select correct scale.

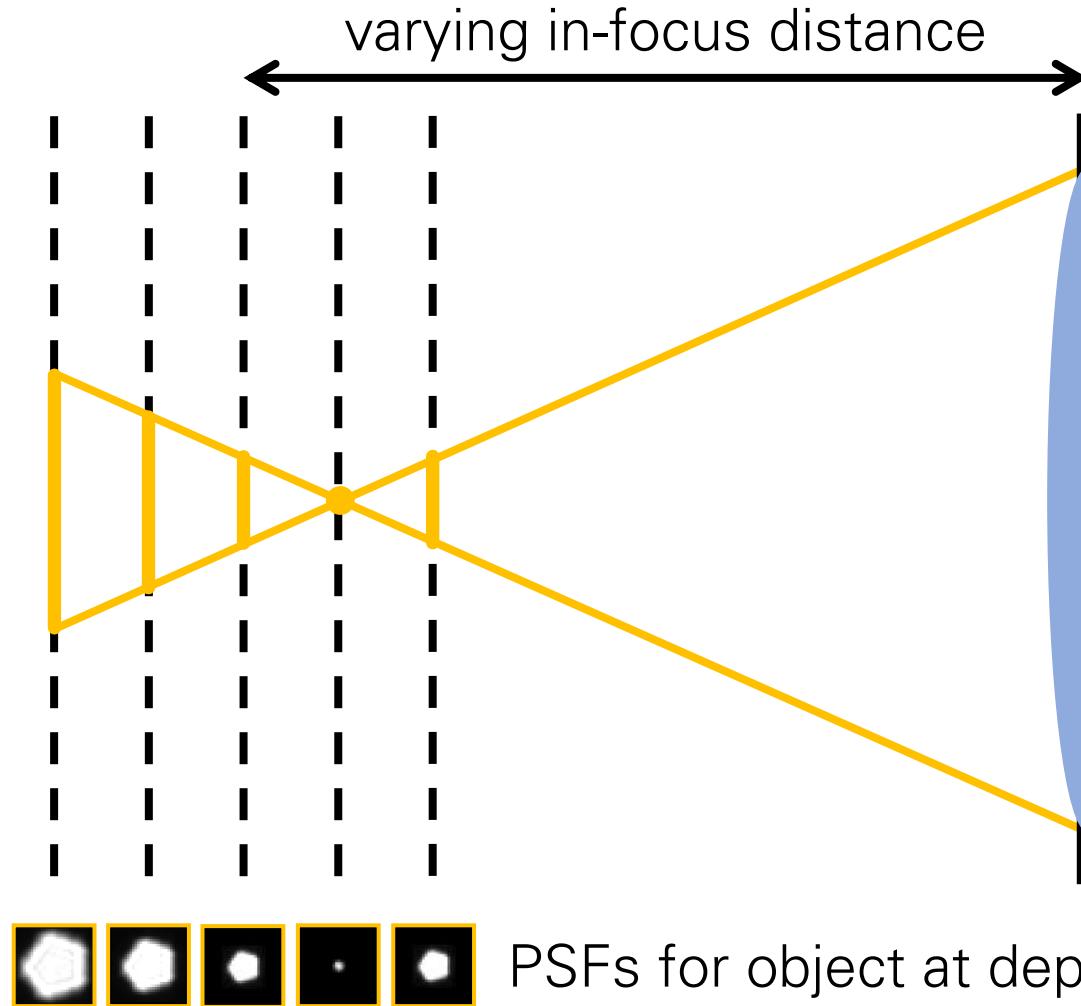
Dealing with depth blur: focal sweep

The difficulty of dealing with depth defocus



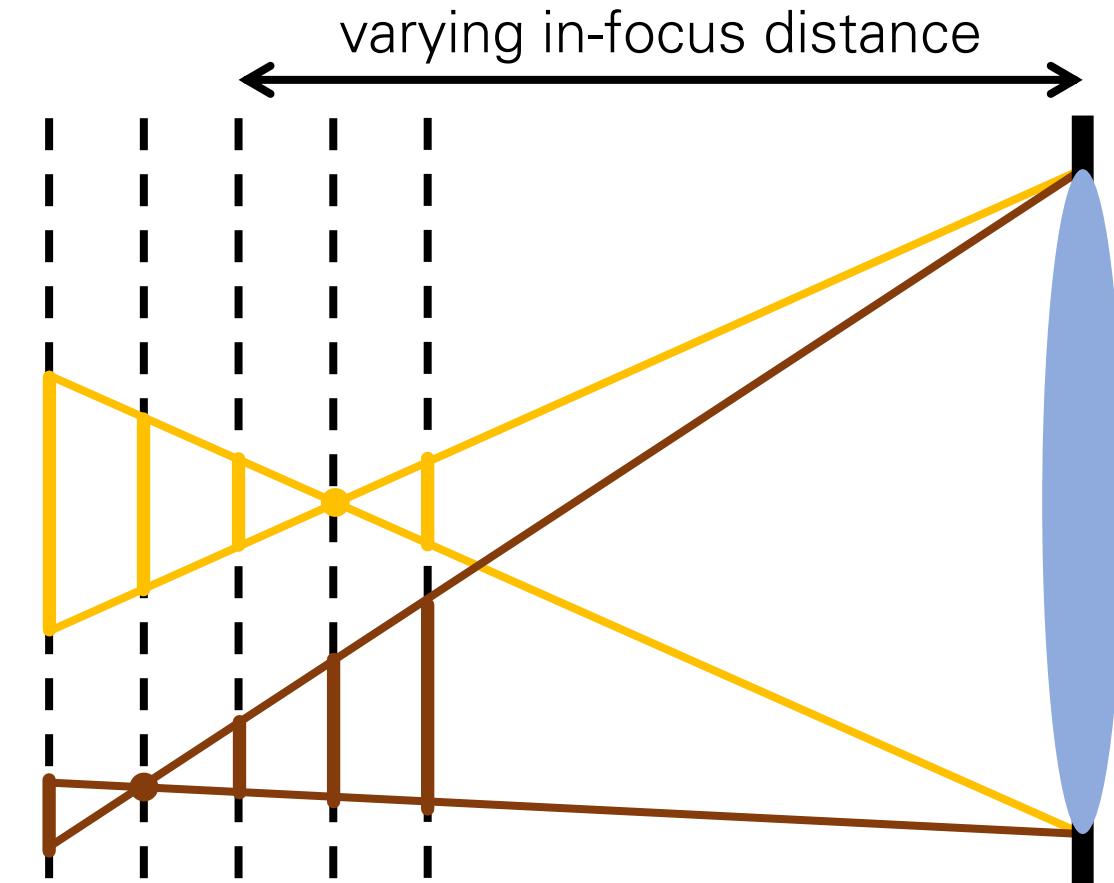
At every focus setting, objects at different depths are blurred by different PSF

The difficulty of dealing with depth defocus



At every focus setting, objects at different depths are blurred by different PSF

The difficulty of dealing with depth defocus



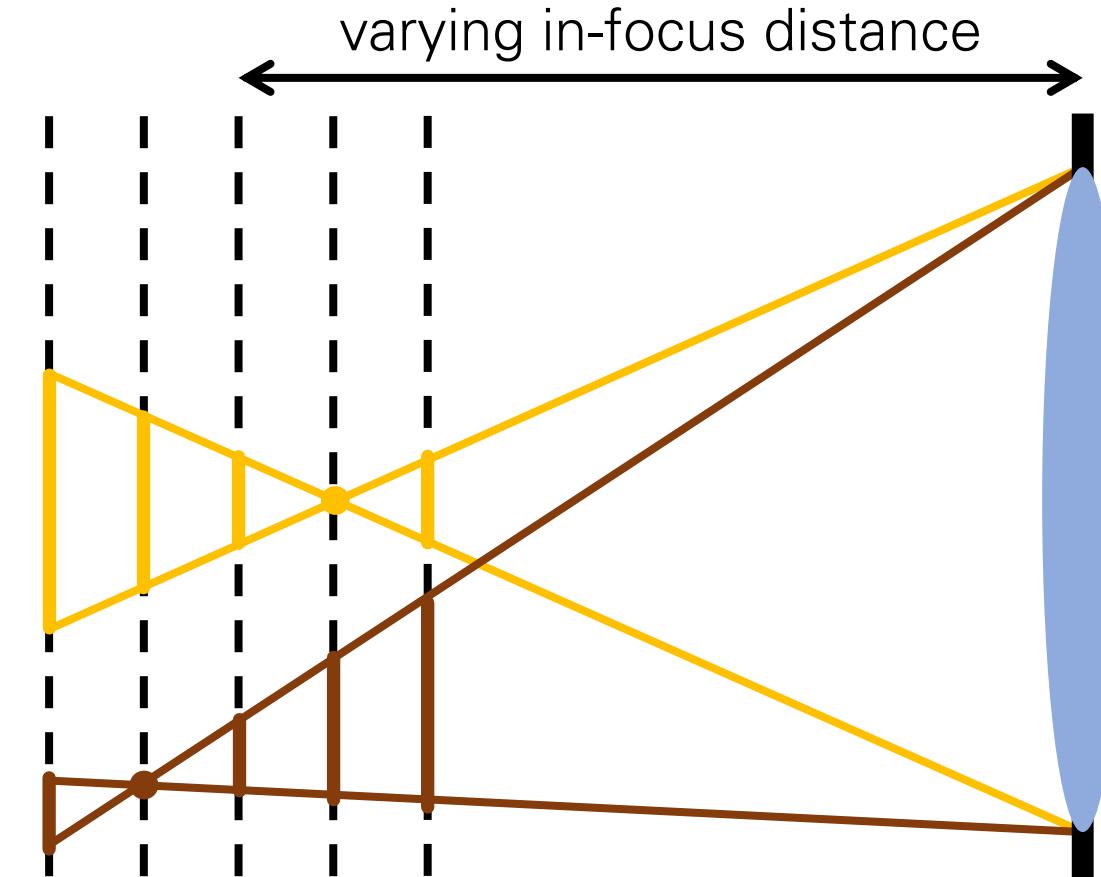
PSFs for object at depth 1



PSFs for object at depth 2

At every focus setting, objects at different depths are blurred by different PSF

The difficulty of dealing with depth defocus



PSFs for object at depth 1

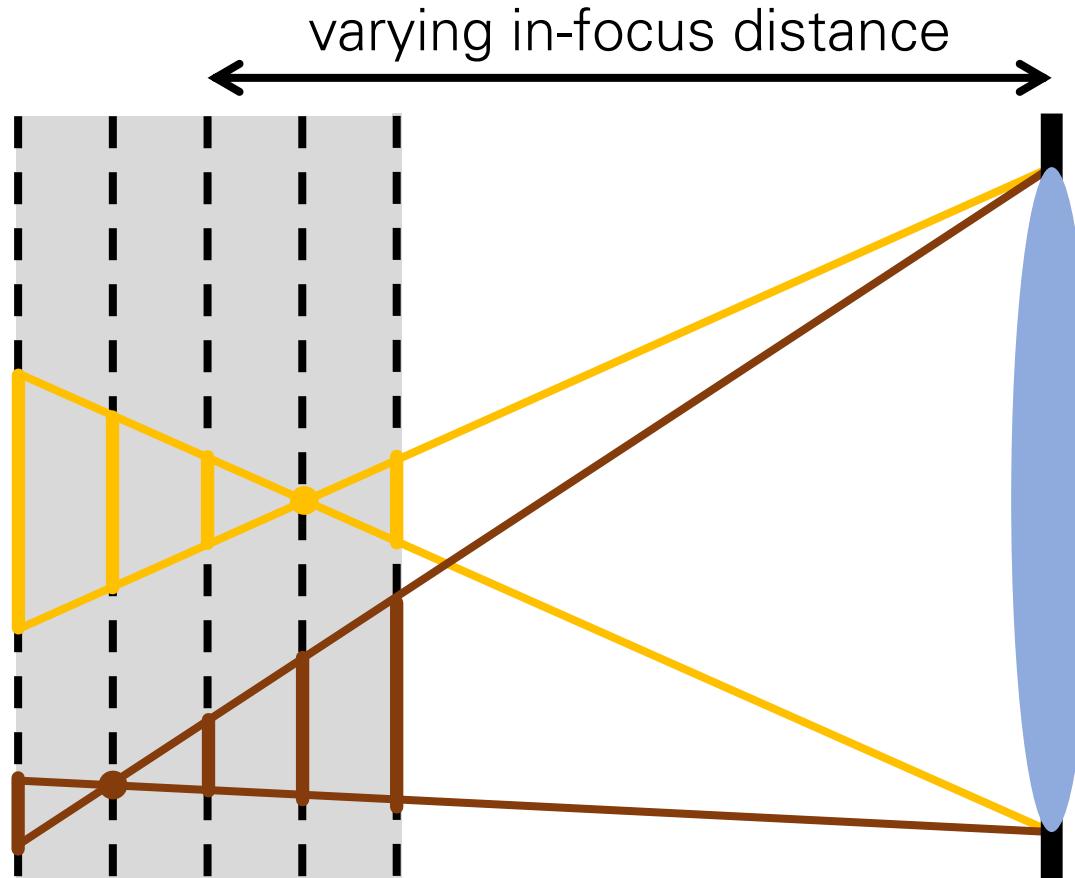


PSFs for object at depth 2

At every focus setting, objects at different depths are blurred by different PSF

As we sweep through focus settings, each point every object is blurred by all possible PSFs

Focal sweep

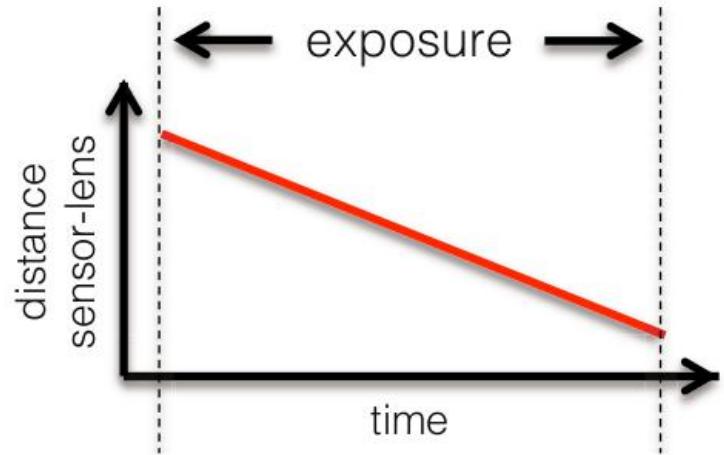


PSFs for object at depth 1



PSFs for object at depth 2

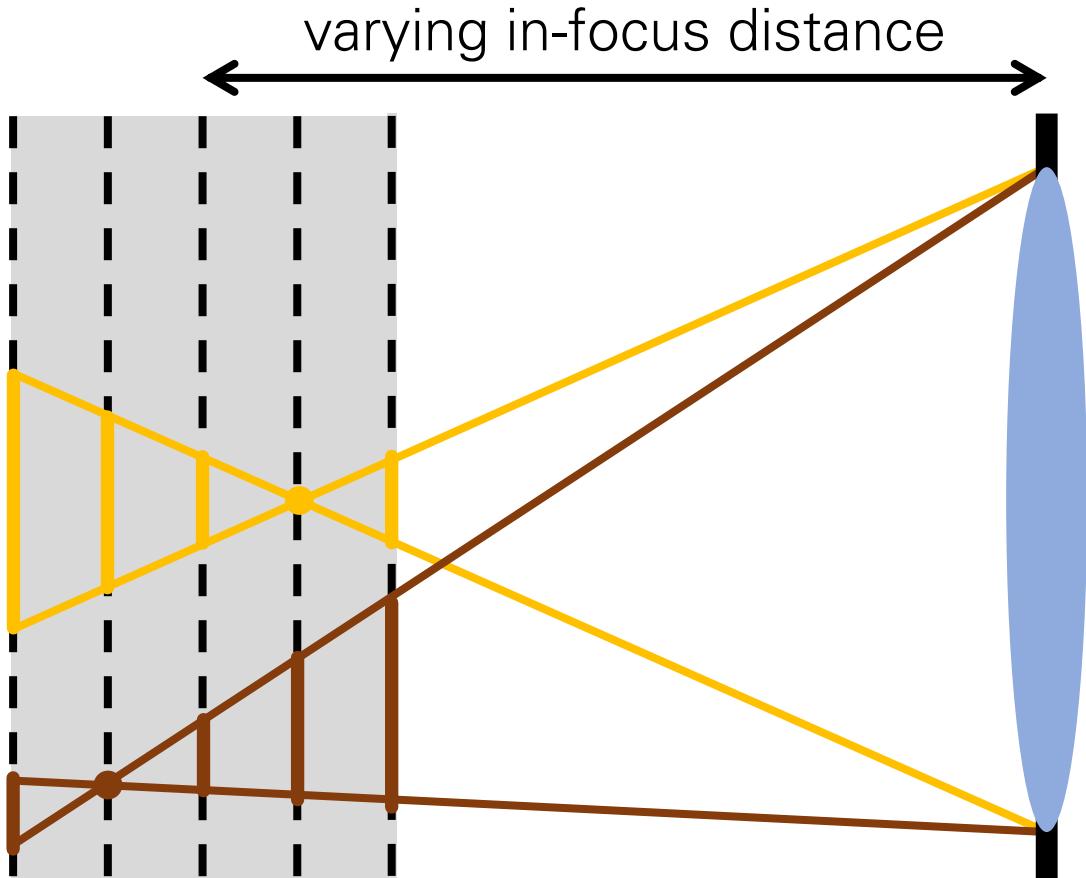
linear motion:



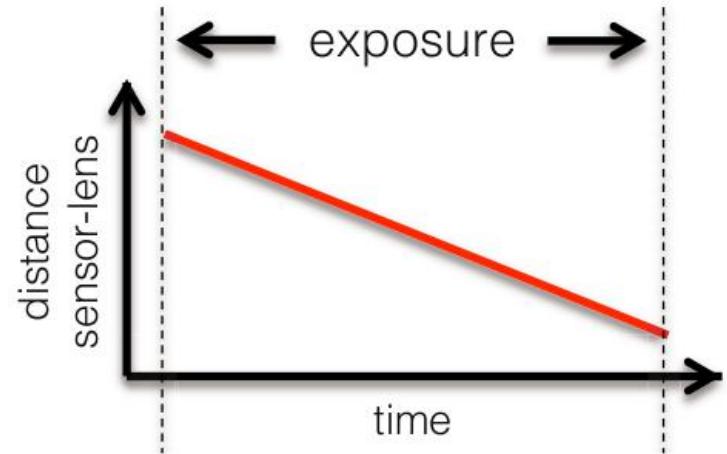
Go through all focus settings during a single exposure

What is the effective PSF in this case?

Focal sweep



linear motion:



Go through all focus
settings during a single
exposure

$$\int [\text{PSF}_1 \text{ PSF}_2 \text{ PSF}_3 \text{ PSF}_4 \text{ PSF}_5] dt = [\text{Effective PSF}] \text{ effective PSF for object at depth 1}$$

$$\int [\text{PSF}_1 \text{ PSF}_2 \text{ PSF}_3 \text{ PSF}_4 \text{ PSF}_5] dt = [\text{Effective PSF}] \text{ effective PSF for object at depth 2}$$

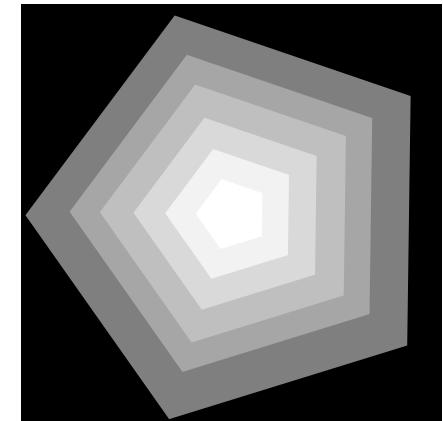
Anything special
about these effective
PSFs?

Focal sweep

The effective PSF is:

1. Depth-invariant – all points are blurred the same way regardless of depth.
2. Never sharp – all points will be blurry regardless of depth.

What are the implications of this?



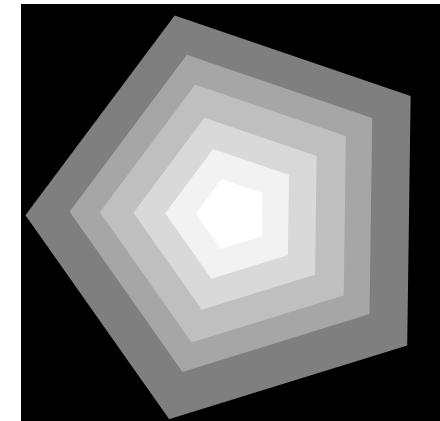
Focal sweep

The effective PSF is:

1. Depth-invariant – all points are blurred the same way regardless of depth.
2. Never sharp – all points will be blurry regardless of depth.

What are the implications of this?

1. The image we capture will not be sharp anywhere; but
2. We can use simple (global) deconvolution to sharpen parts we want



1. Can we estimate depth from this?
2. Can we do refocusing from this?

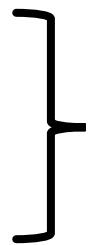
Focal sweep

The effective PSF is:

1. Depth-invariant – all points are blurred the same way regardless of depth.
2. Never sharp – all points will be blurry regardless of depth.

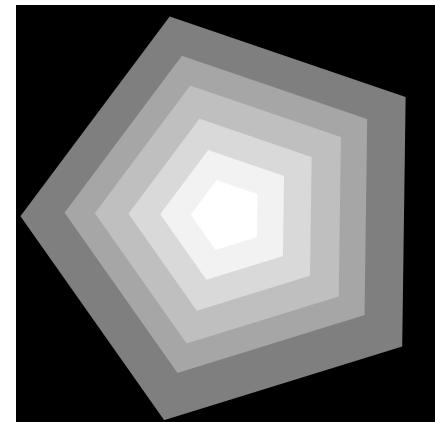
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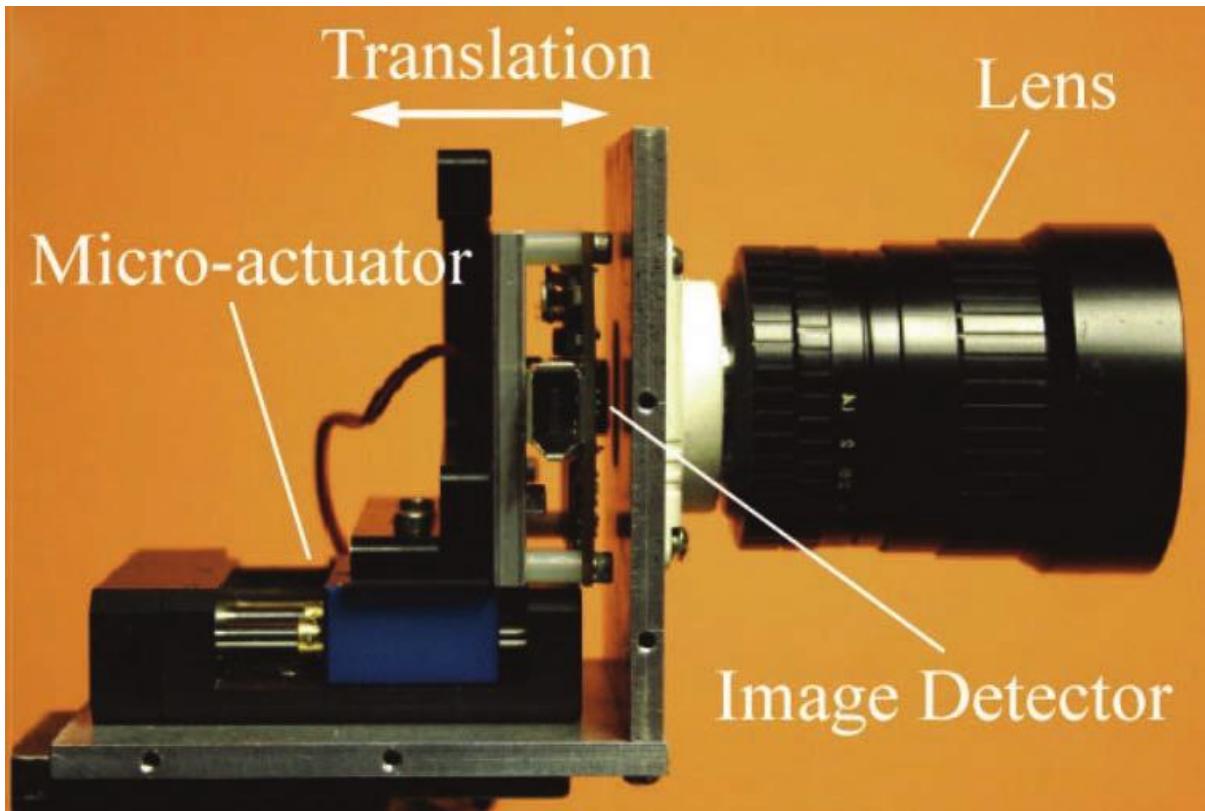
1. Can we estimate depth from this?
2. Can we do refocusing from this?

Depth-invariance of the PSF means that we have lost all depth information



How can you implement focal sweep?

How can you implement focal sweep?

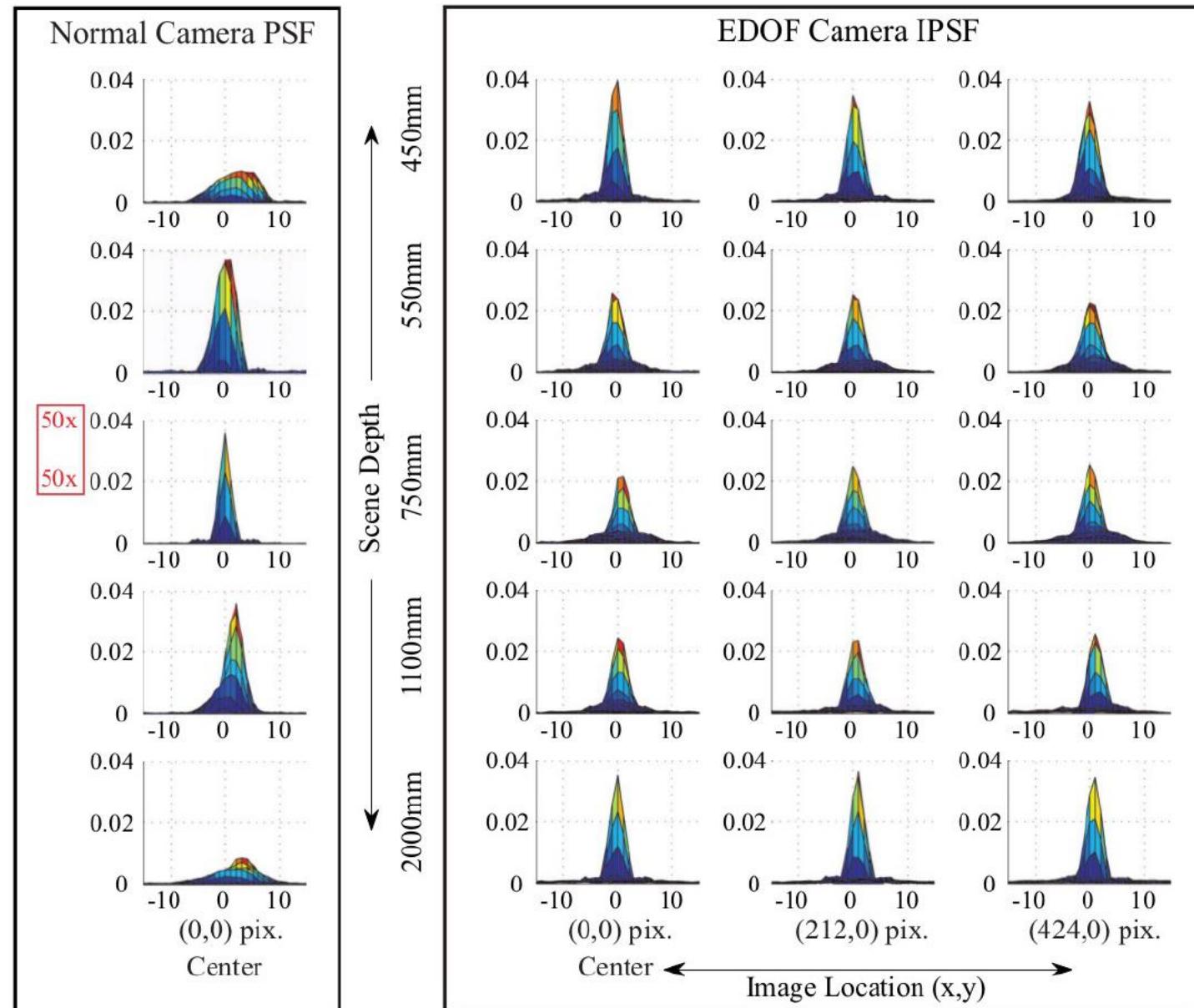


Use translation stage to move sensor relative to fixed lens during exposure



Rotate focusing ring to move lens relative to fixed sensor during exposure

Comparison of different PSFs



Depth of field comparisons

conventional photo
(small DOF)



captured focal sweep
always blurry!



conventional photo
(large DOF, noisy)



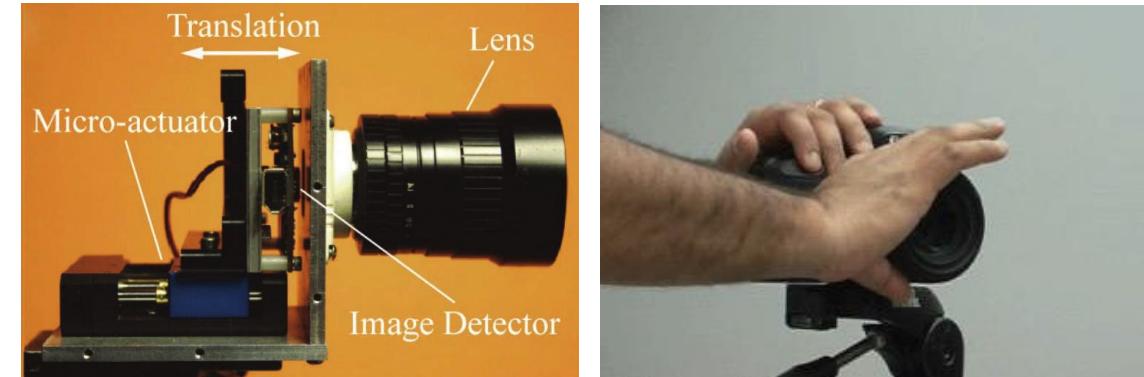
EDOF image



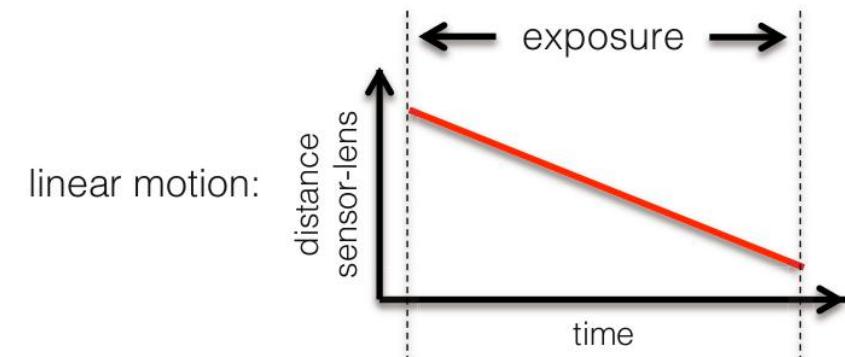
Any problems with using focal sweep?

Any problems with using focal sweep?

- We have moving parts (vibrations, motion blur).



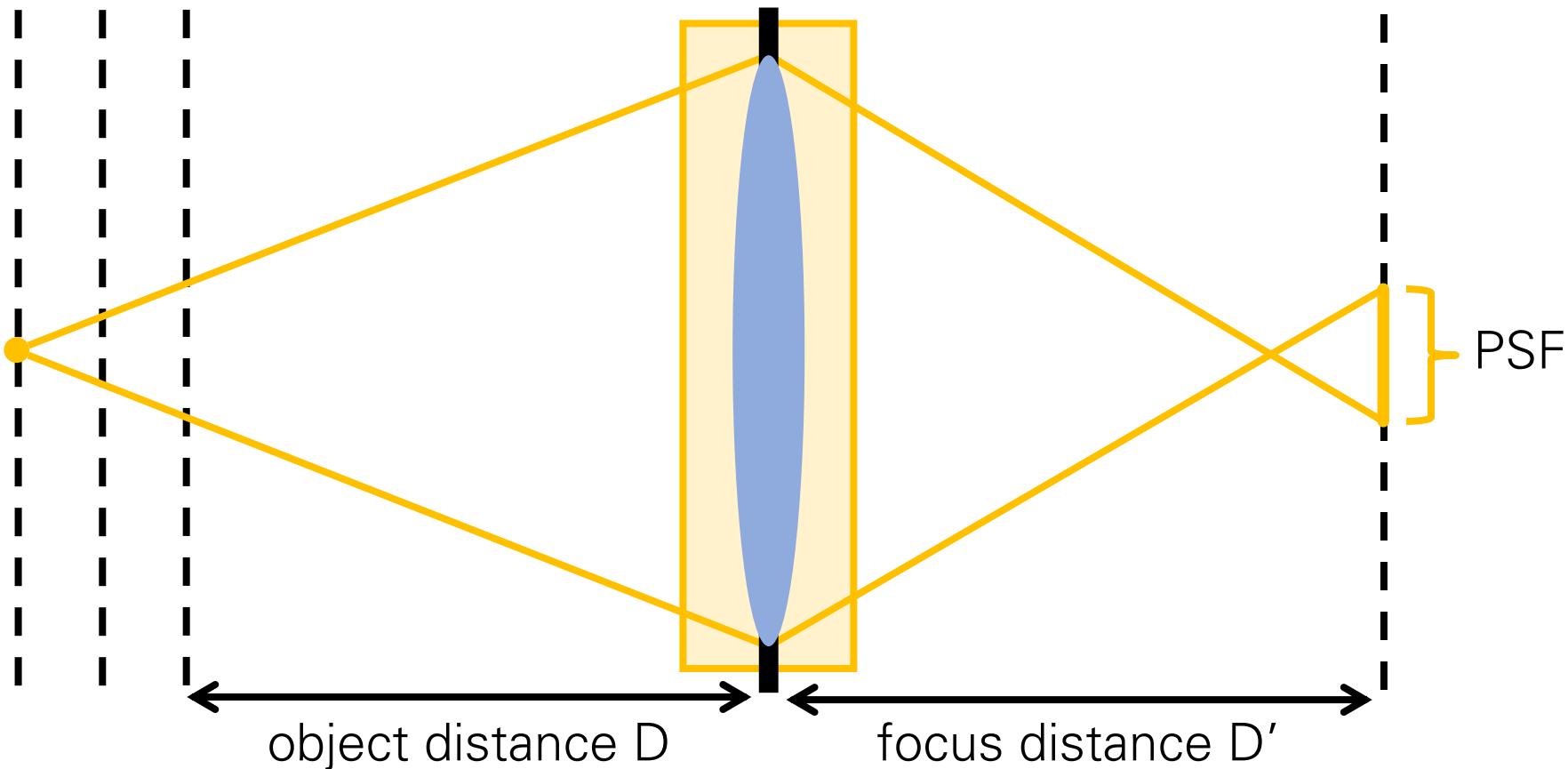
- Perfect depth invariance requires very constant speed.



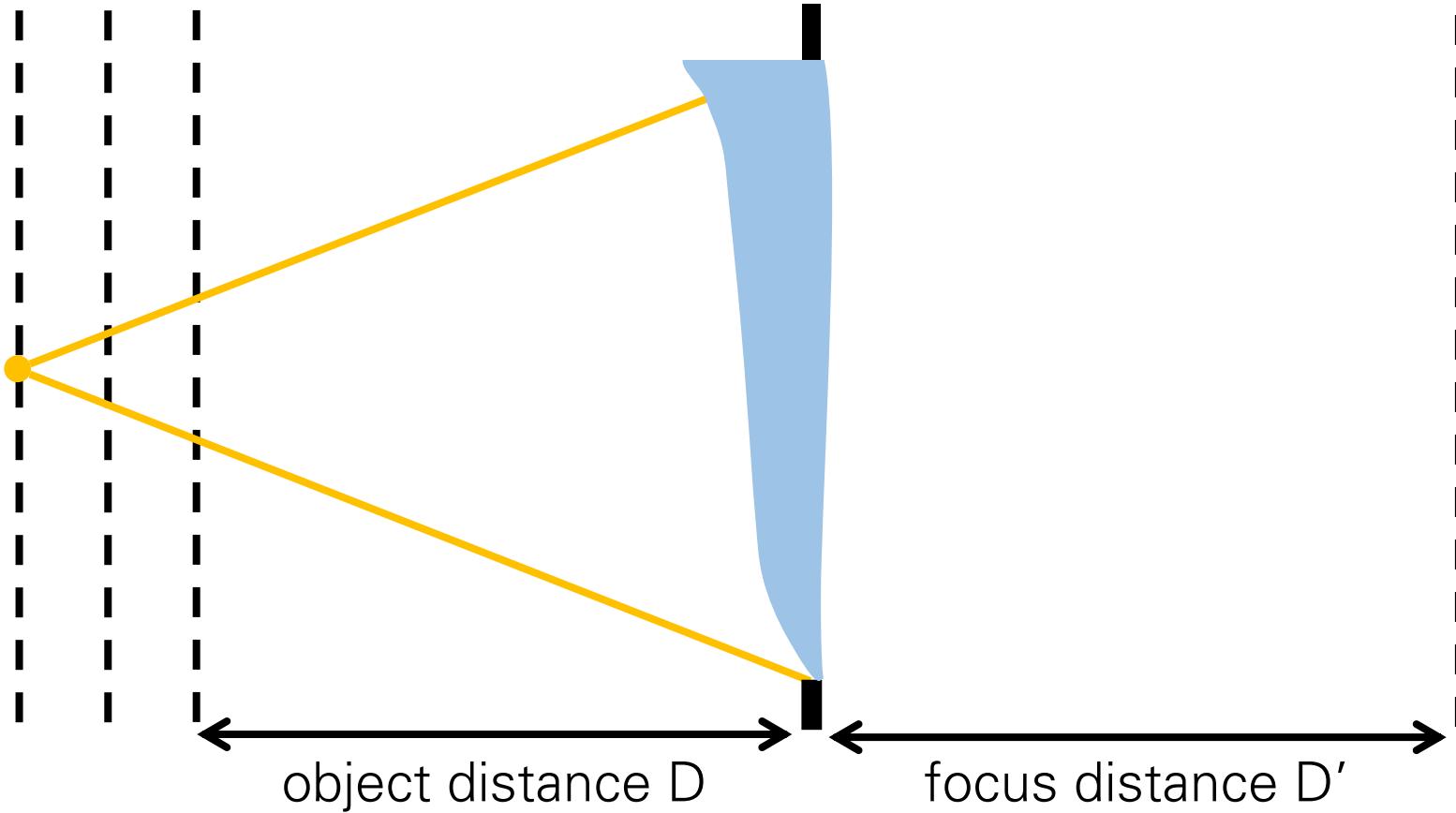
- We lose depth information.

Dealing with depth blur: generalized optics

Change optics, not aperture



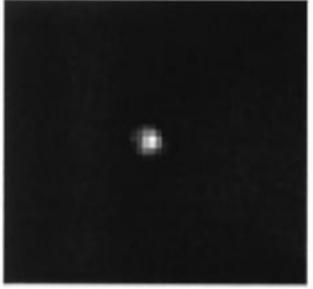
Wavefront coding



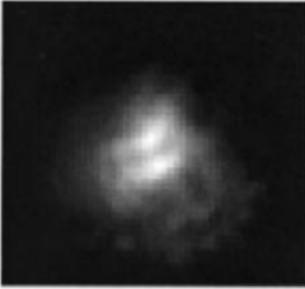
Replace lens with a cubic phase plate

Wavefront coding

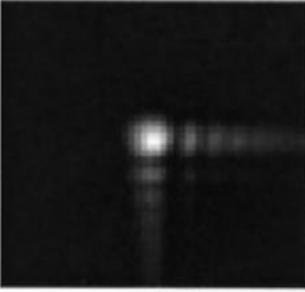
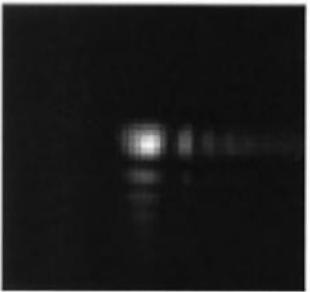
In focus



Out of focus

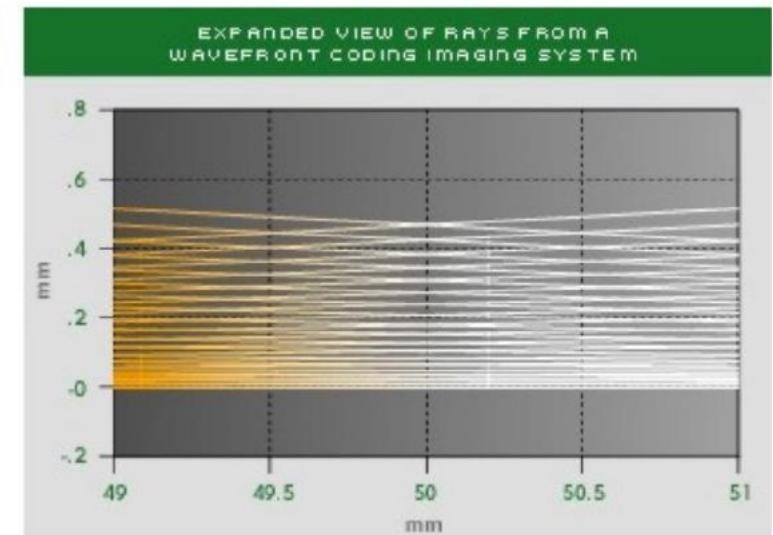
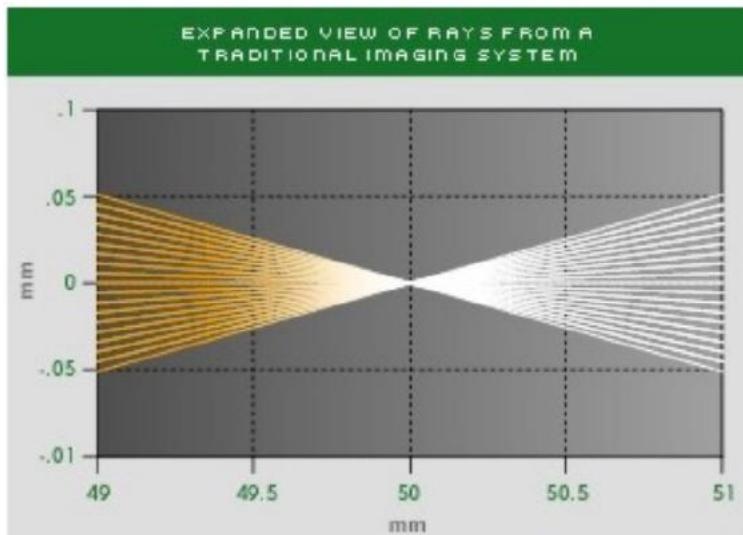
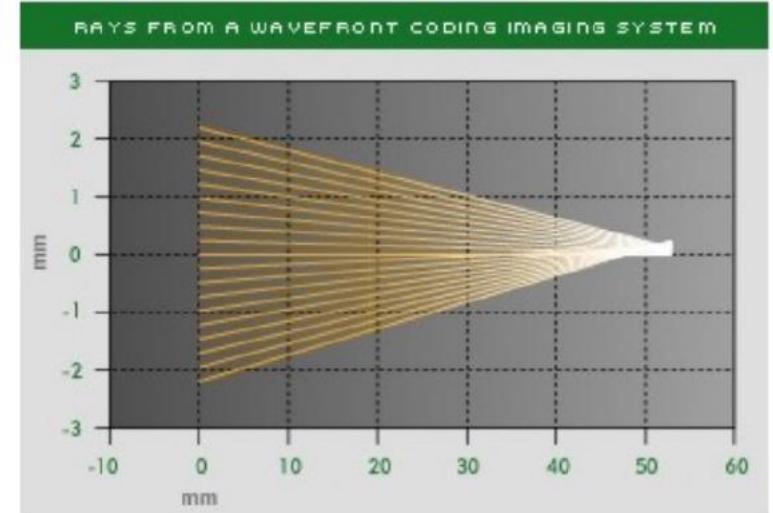
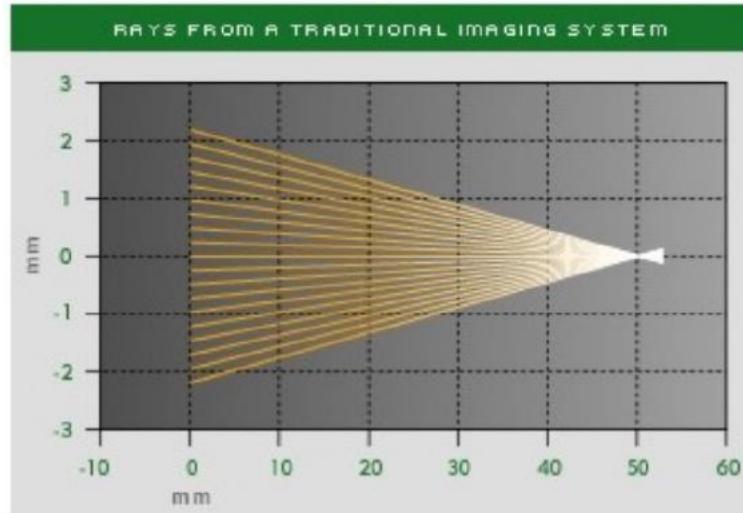


standard lens

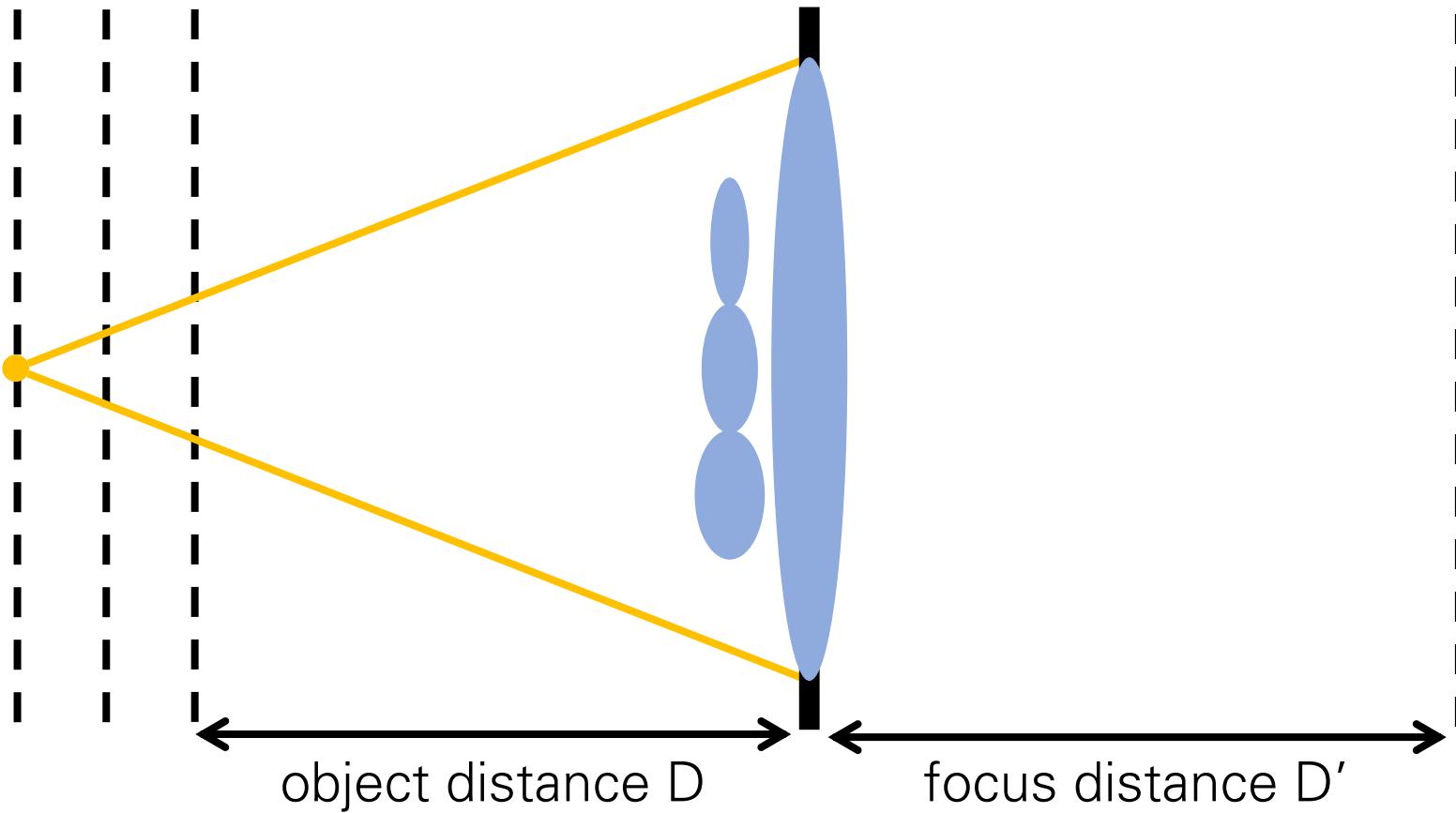


wavefront coding

- Rays no longer converge.
- Approximately depth-invariant PSF for certain range of depths.



Lattice lens

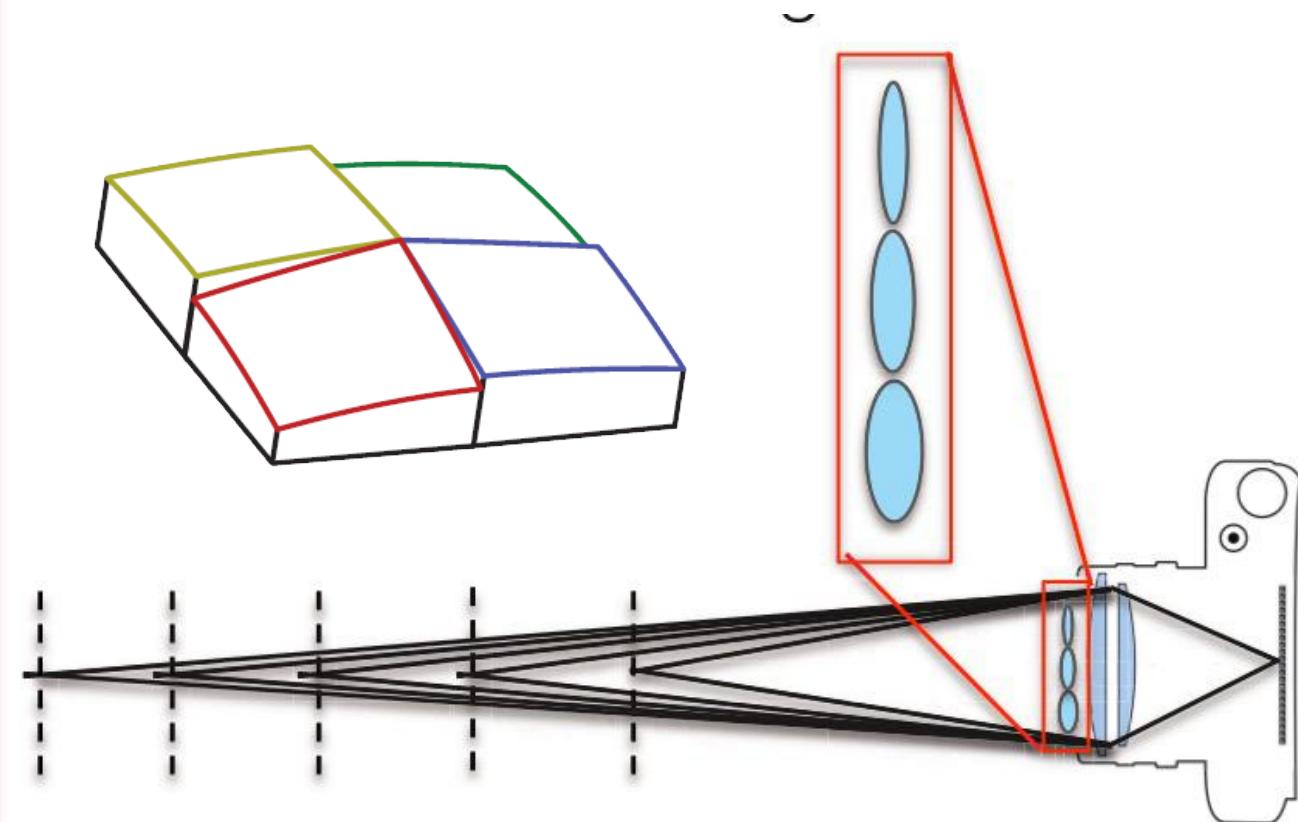


Add lenslet array with varying focal length in front of lens

Lattice lens



Does this remind you of something?



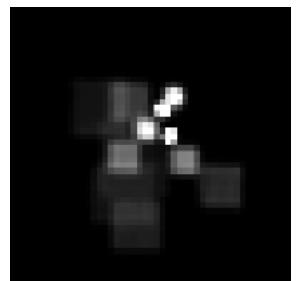
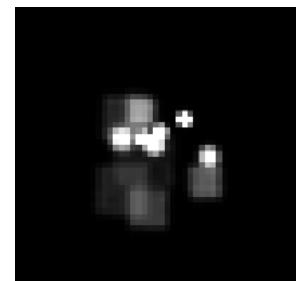
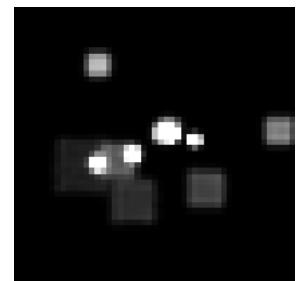
Lattice lens

- Effectively captures only the “useful” subset of the 4D lightfield.

Light field spectrum: 4D
Image spectrum: 2D
Depth: 1D } 3D
→ Dimensionality gap (Ng 05)
Only the 3D manifold corresponding to physical focusing distance is useful

- PSF is not depth-invariant, so local deconvolution as in coded aperture.

PSFs at different depths



Results



Results



Results



Results



Results



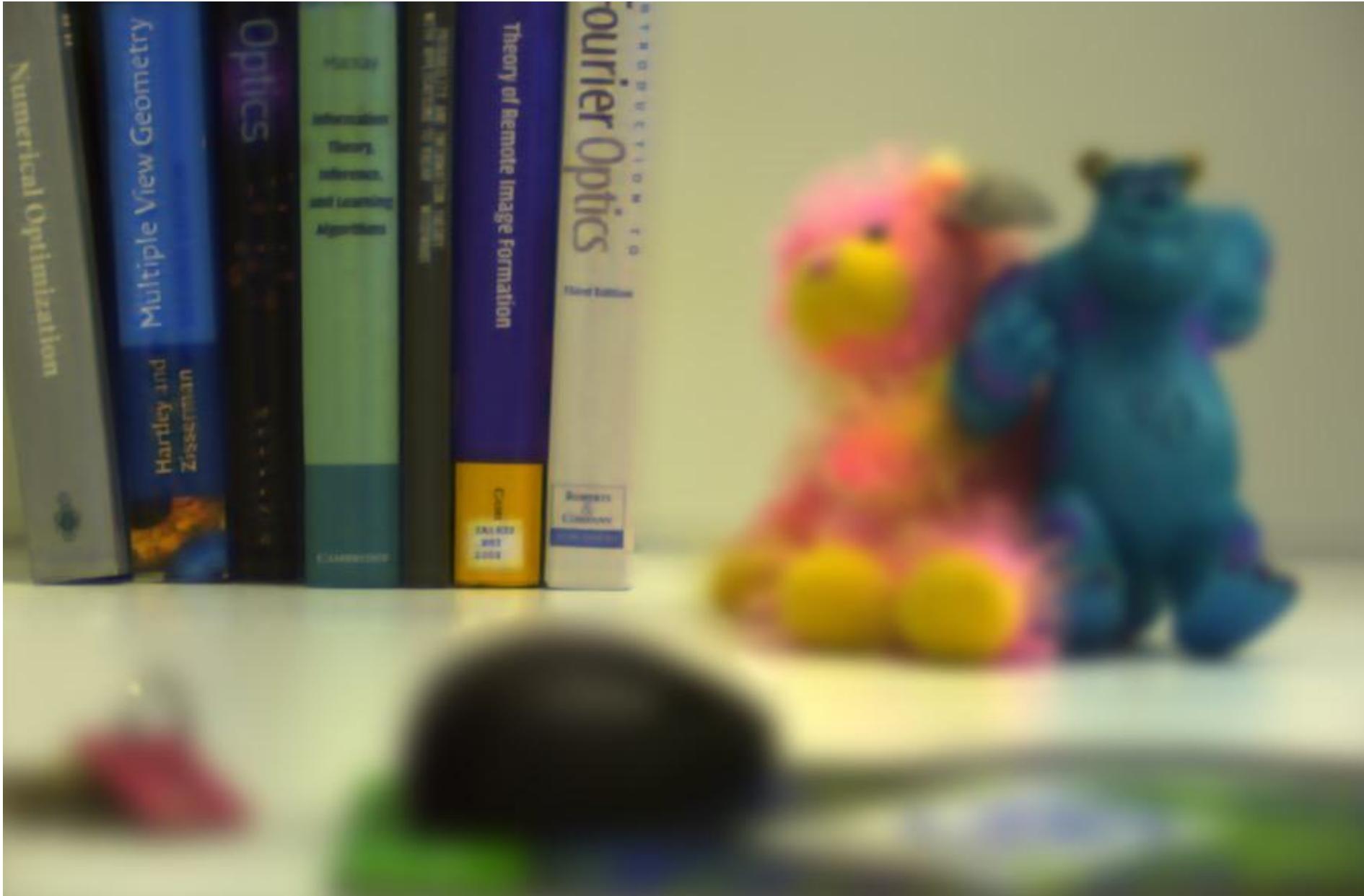
Results



Refocusing example



Refocusing example



Refocusing example



Comparison of different techniques

Depth of field
comparison:



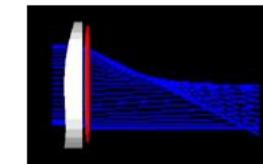
standard
lens



coded
aperture



focal
sweep



wavefront
coding

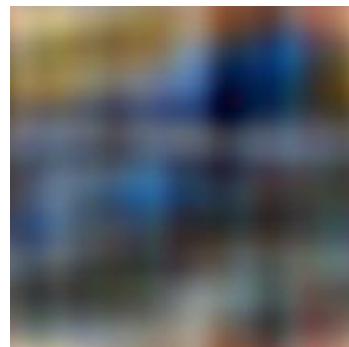
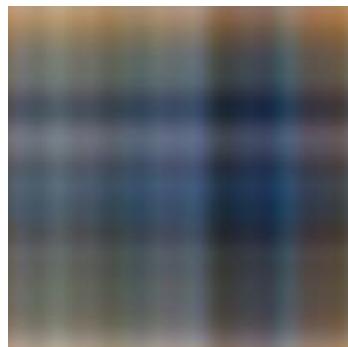


lattice
lens

Object at in-focus depth



Object at extreme depth



Diffusion coded photography

- can also do EDOF with diffuser as coded aperture, has better inversion characteristics than lattice focal lens



Conventional Camera



Diffusion Coded Camera

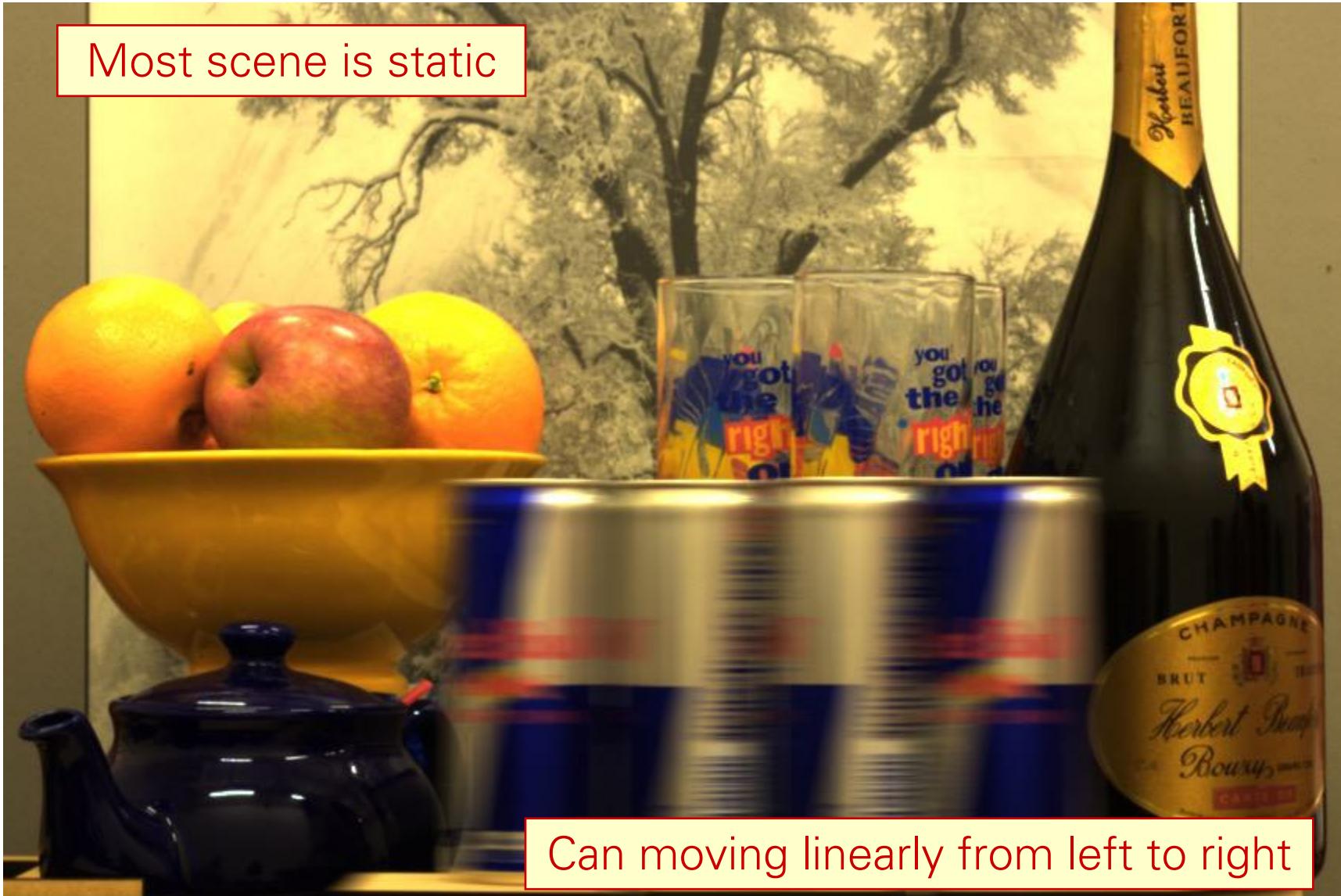
Can you think of any issues?

Dealing with motion blur

Why are our images blurry?

- Lens imperfections. ← non-blind deconvolution
 - Camera shake. ← blind deconvolution
 - Scene motion. ← flutter shutter, motion-invariant photo
 - Depth defocus. ← coded aperture, focal sweep, lattice lens
-
- The diagram illustrates four causes of blurry images, each associated with a specific deconvolution method. A vertical bracket on the right groups the first two causes under 'conventional photography', and another bracket groups the last two under 'coded photography'. A yellow horizontal box highlights the 'Scene motion' row.
- | Blur Cause | Deconvolution Method | Photography Type |
|--------------------|-------------------------------------------|--------------------------|
| Lens imperfections | non-blind deconvolution | conventional photography |
| Camera shake | blind deconvolution | conventional photography |
| Scene motion | flutter shutter, motion-invariant photo | coded photography |
| Depth defocus | coded aperture, focal sweep, lattice lens | coded photography |

Motion blur



Motion blur



blurry image of
moving object

$$= \text{ [] } *$$

motion blur kernel



sharp image of
static object

What does the motion blur kernel depend on?

Motion blur



blurry image of
moving object

$$= \text{motion blur kernel} *$$



sharp image of
static object

What does the motion blur kernel depend on?

- Motion velocity determines direction of kernel.
- Shutter speed determines width of kernel.

Can we use deconvolution to remove motion blur?

Challenges of motion deblurring

- Blur kernel is not invertible.
- Blur kernel is unknown.
- Blur kernel is different for different objects.



Challenges of motion deblurring

- Blur kernel is not invertible.
- Blur kernel is unknown.
- Blur kernel is different for different objects.



How would you deal with this?



Dealing with motion blur: coded exposure

Coded exposure a.k.a. flutter shutter

Code exposure (i.e., shutter speed) to make motion blur kernel better conditioned.

traditional
camera



blurry image of
moving object

$$= \text{---} \square \ast$$

motion blur kernel



sharp image of
static object

flutter-shutter
camera



blurry image of
moving object

$$= \text{---} \square\!\square\!\square \ast$$

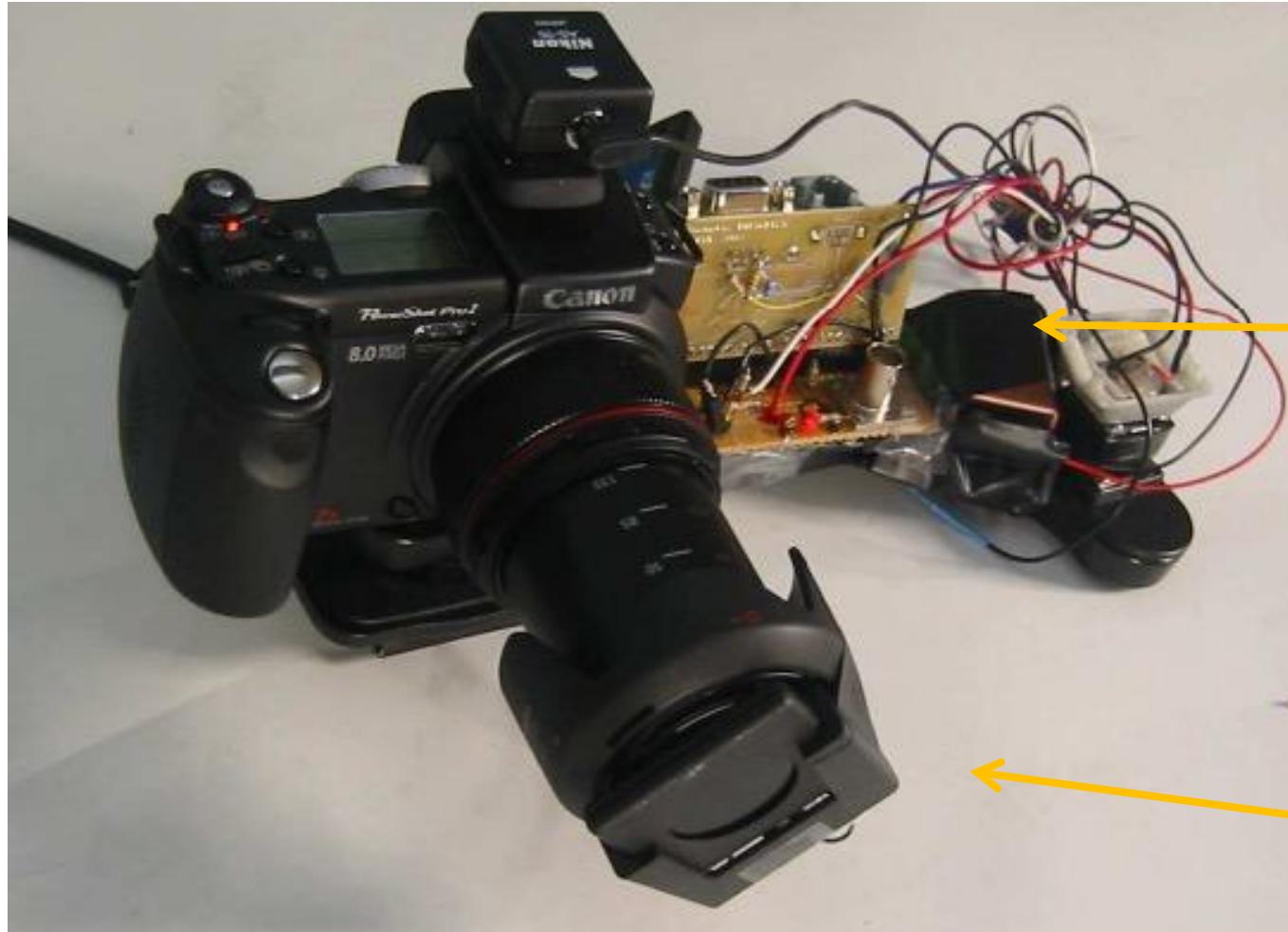
motion blur kernel



sharp image of
static object

How would you implement coded exposure?

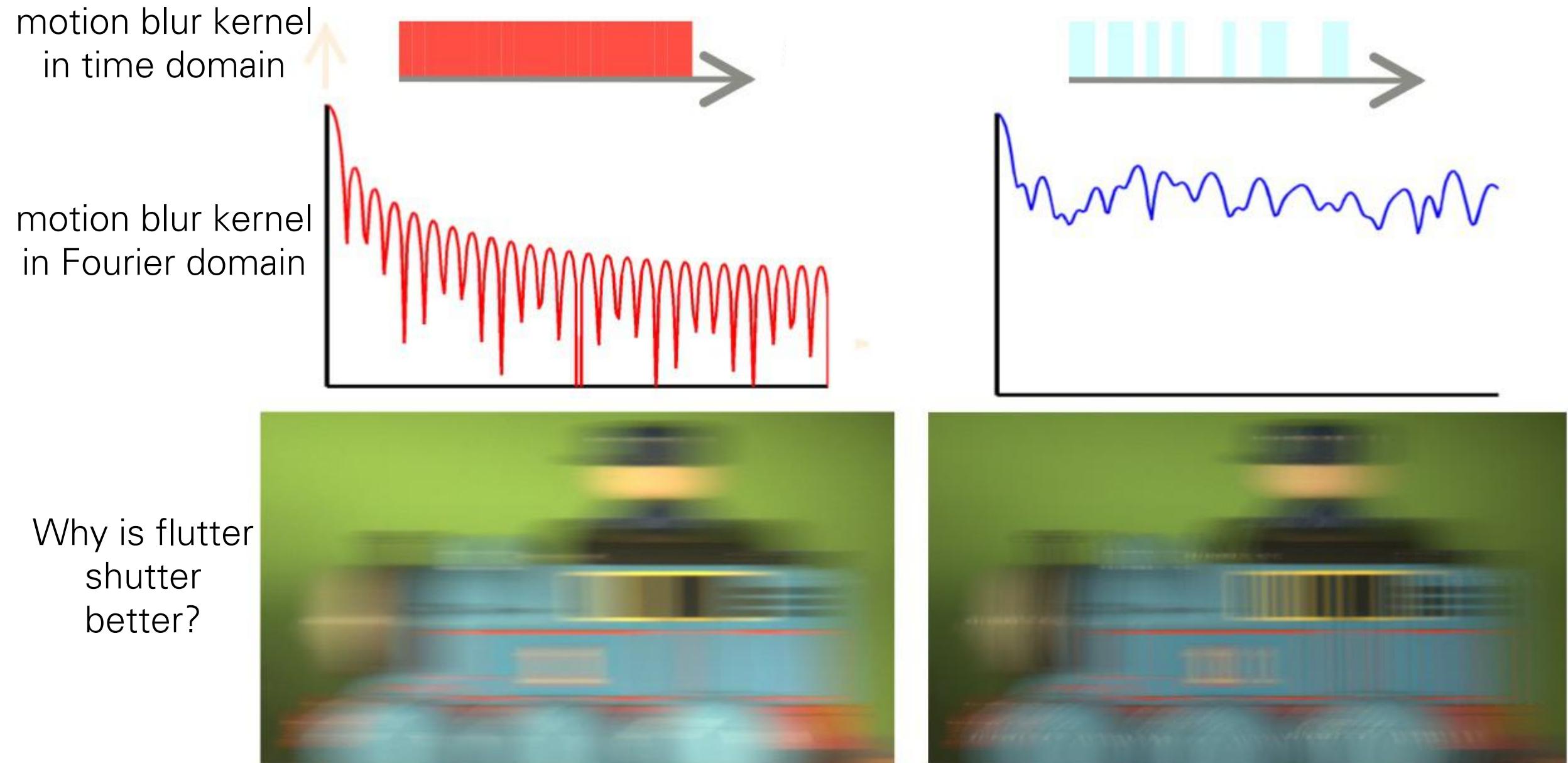
How would you implement coded exposure?



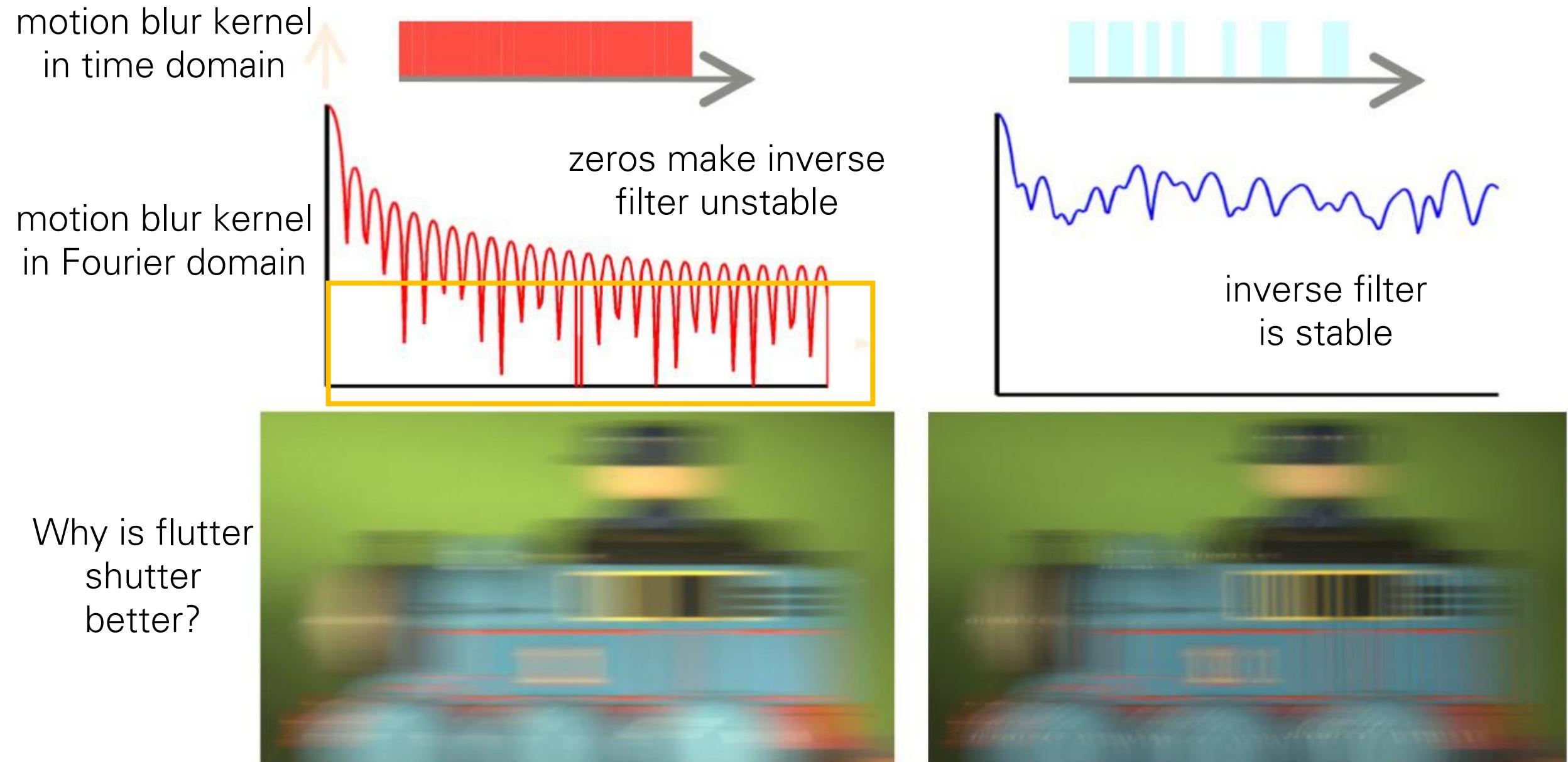
electronics for external
shutter control

very fast external
shutter

Coded exposure a.k.a. flutter shutter



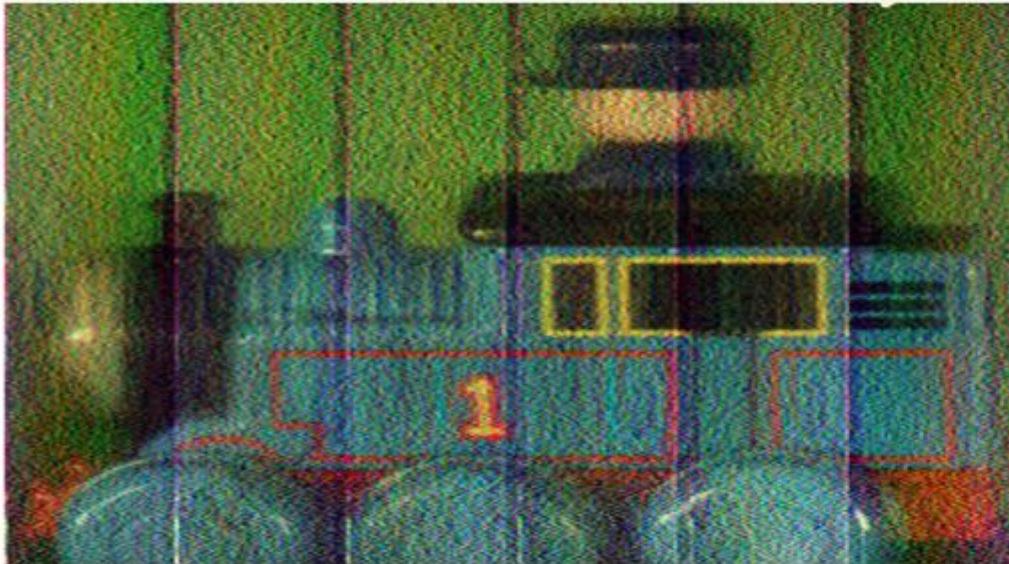
Coded exposure a.k.a. flutter shutter



Motion deblurring comparison

conventional photography

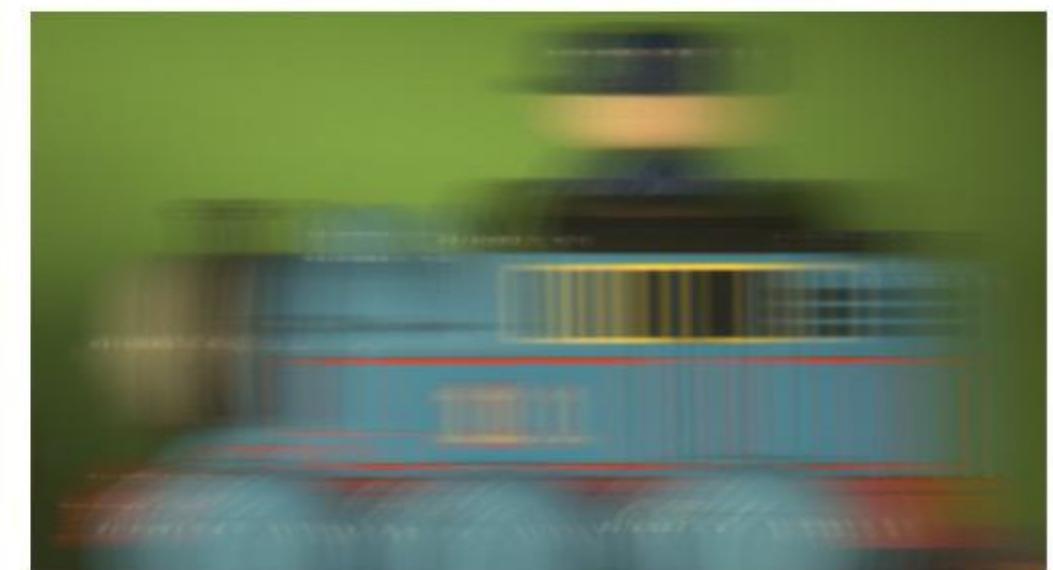
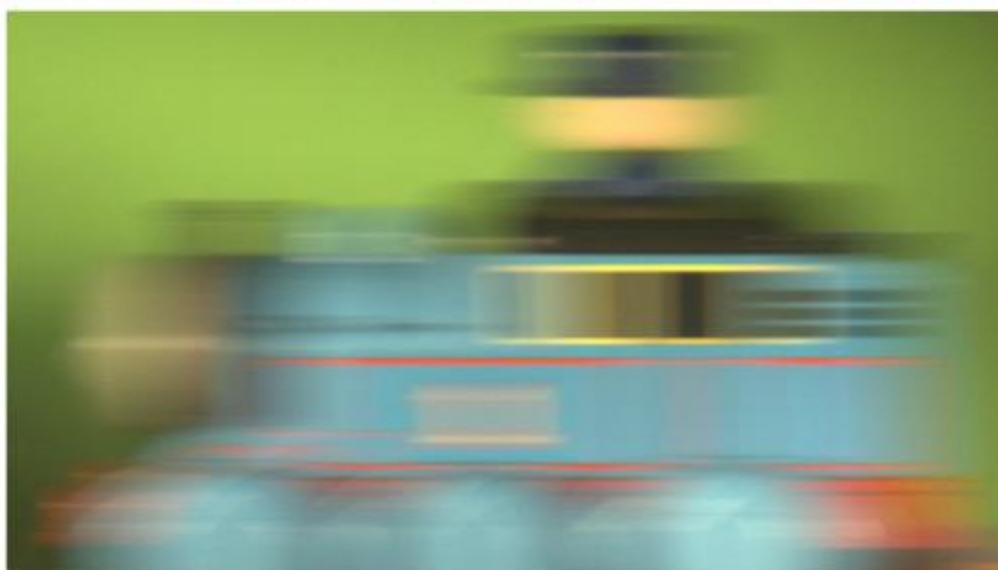
deconvolved
output

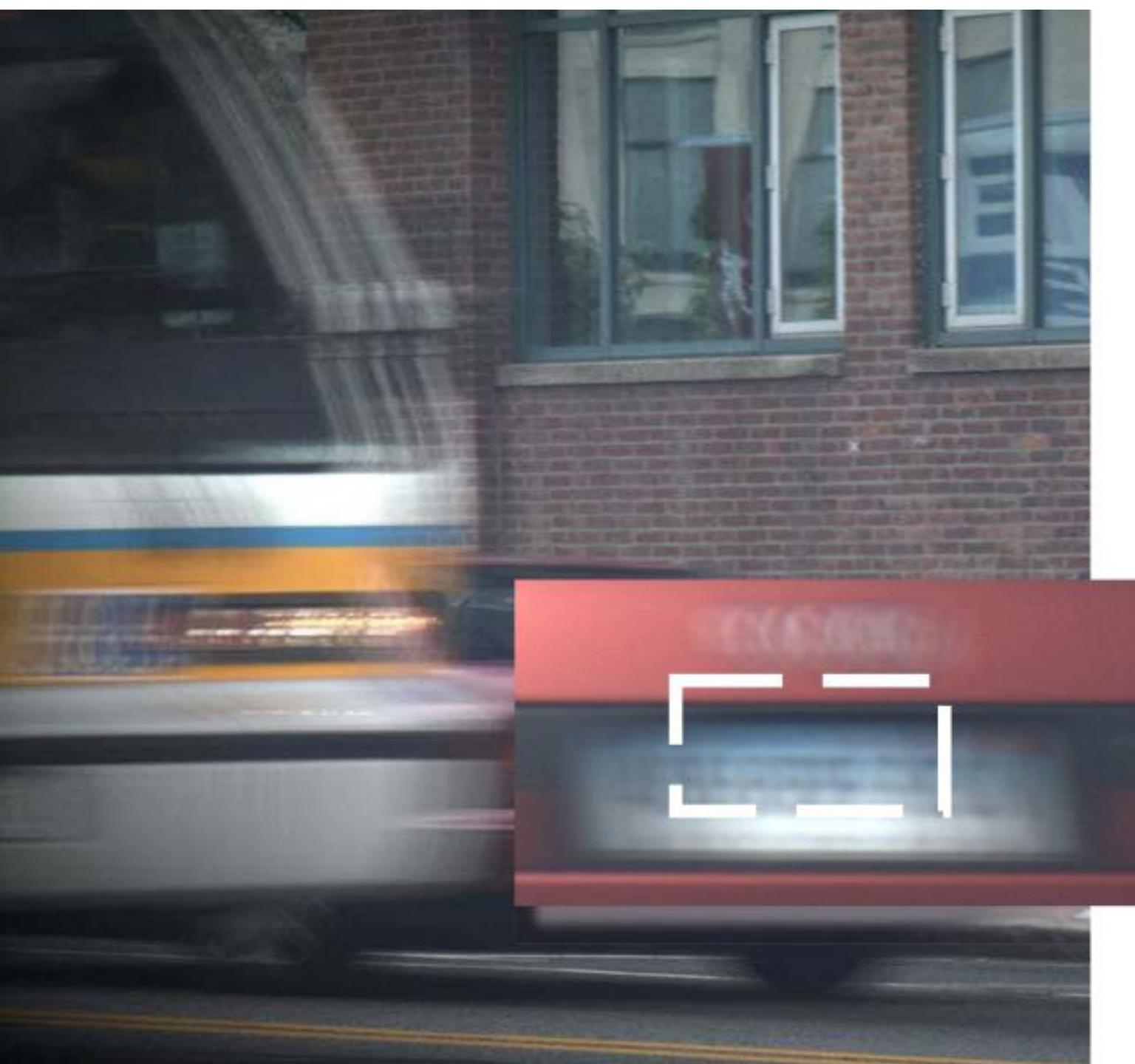


flutter-shutter photography

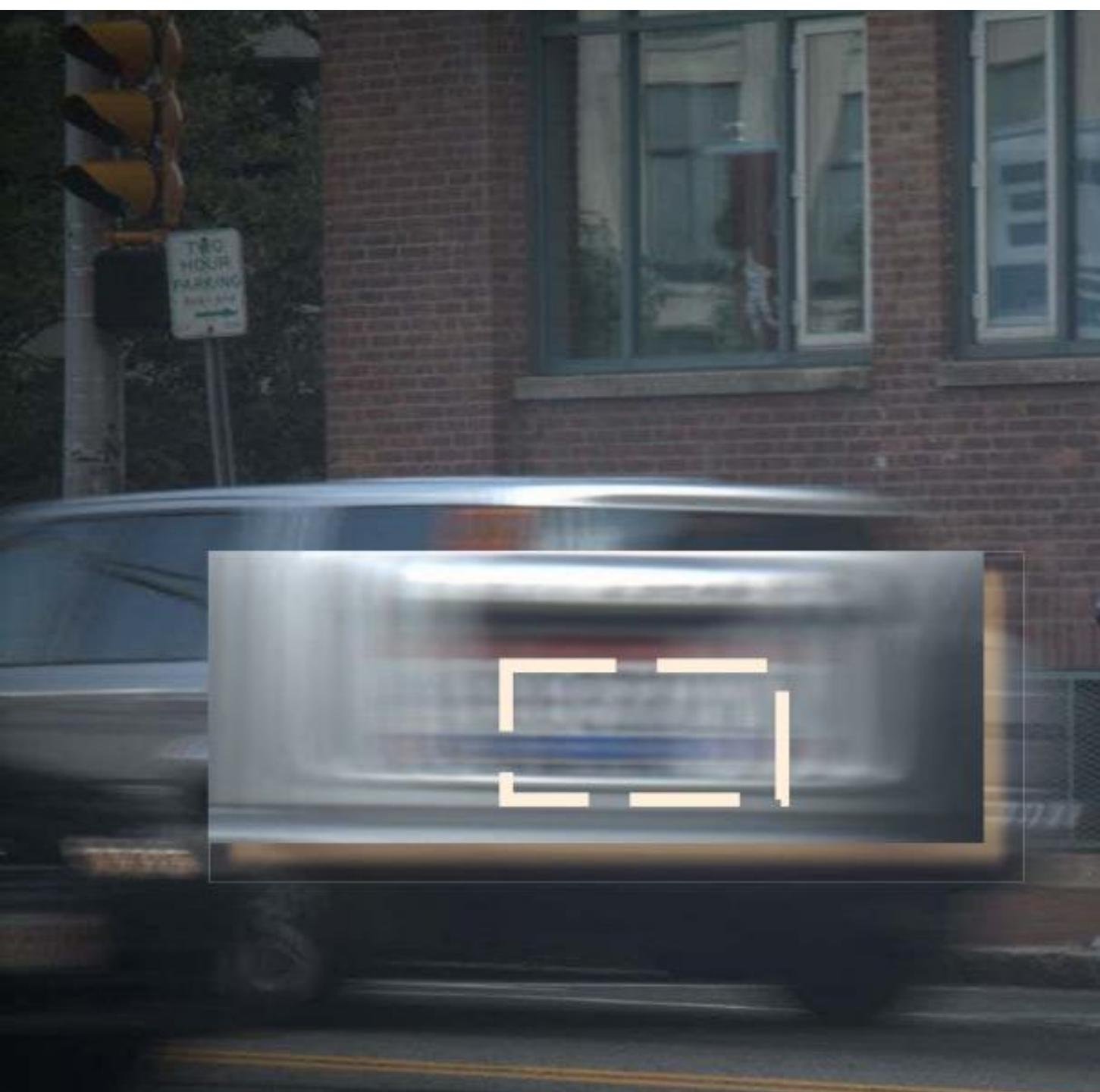


blurry
input





License Plate Retrieval

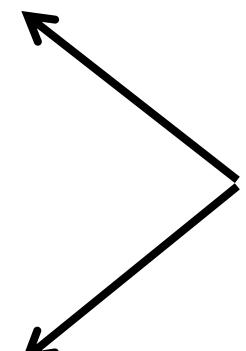


License Plate Retrieval

Challenges of motion deblurring

- Blur kernel is not invertible.

- Blur kernel is unknown.



How would you deal
with these two?

- Blur kernel is different for different objects.



Dealing with motion blur: parabolic sweep

Motion-invariant photography

Introduce extra motion so that:

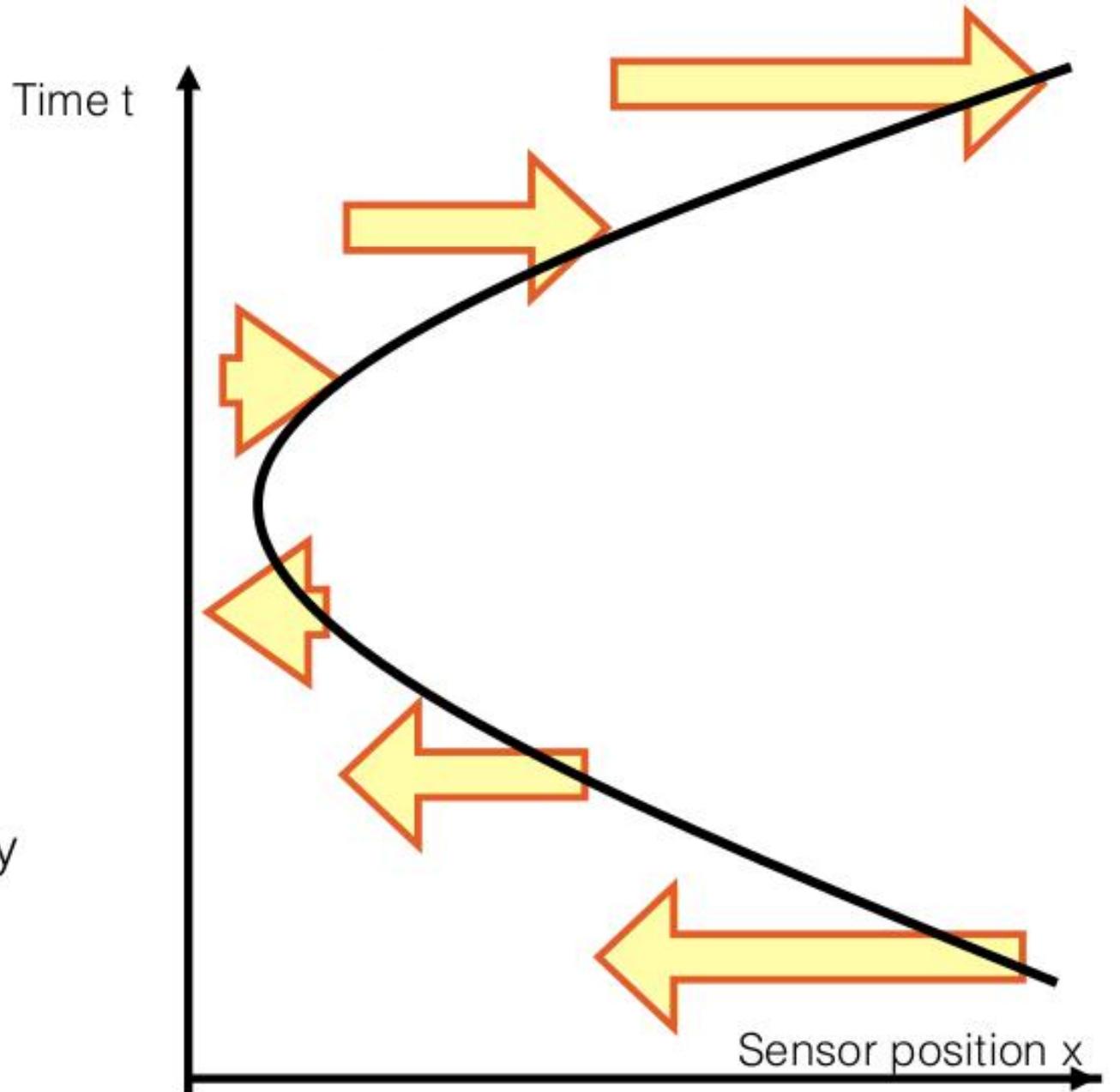
- Everything is blurry; and
- The blur kernel is motion invariant (same for all objects).

How would you achieve this?

Parabolic sweep

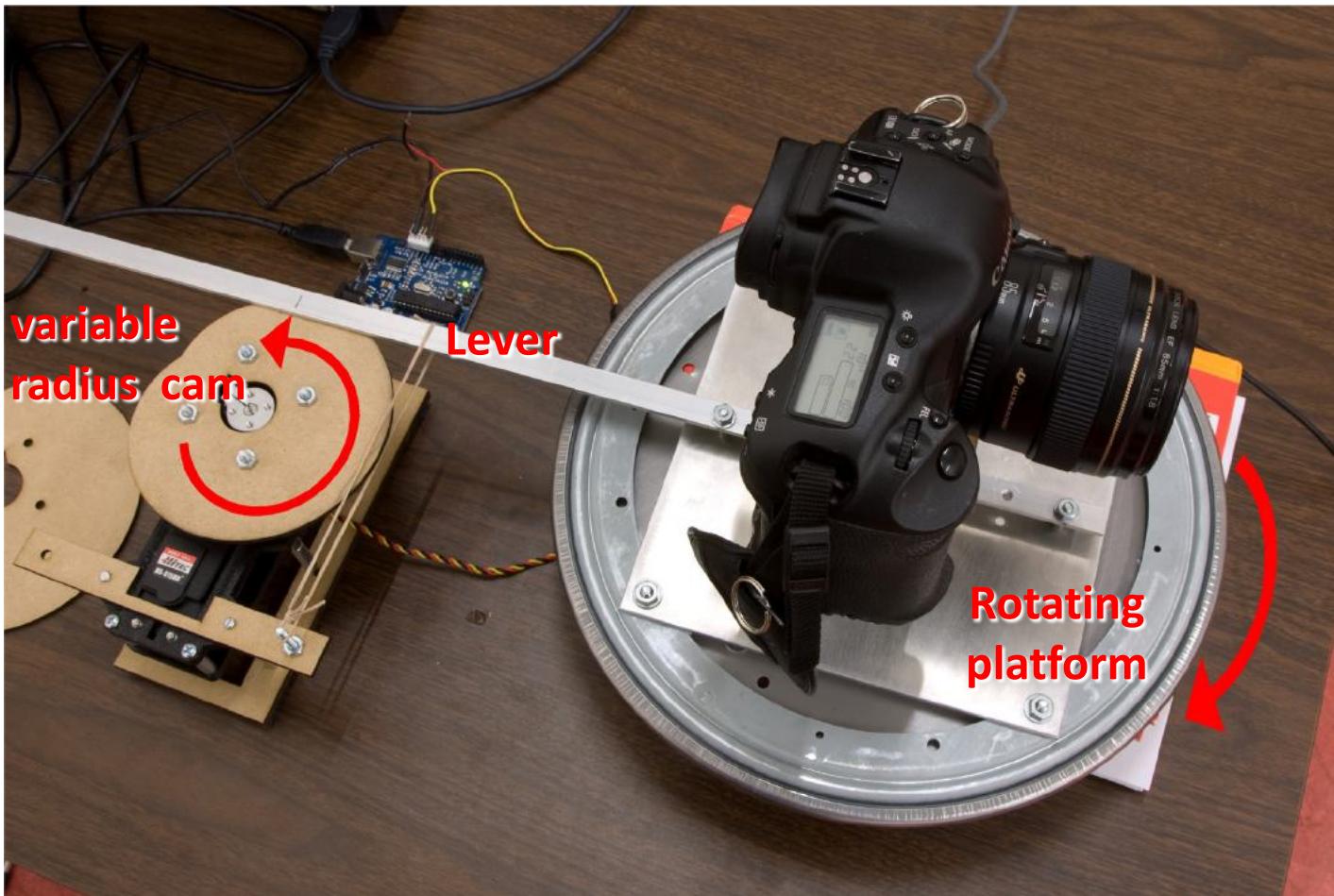
Sensor position $x(t)=a t^2$

- start by moving very fast to the right
 - continuously slow down until stop
 - continuously accelerate to the left
-
- Intuition:
 - for any velocity, there is one instant where we track perfectly
 - all velocities captured same amount of time



Hardware implementation

Approximate small translation by small rotation



Some results



static camera input -
unknown and variable blur



parabolic input - blur is
invariant to velocity

Some results



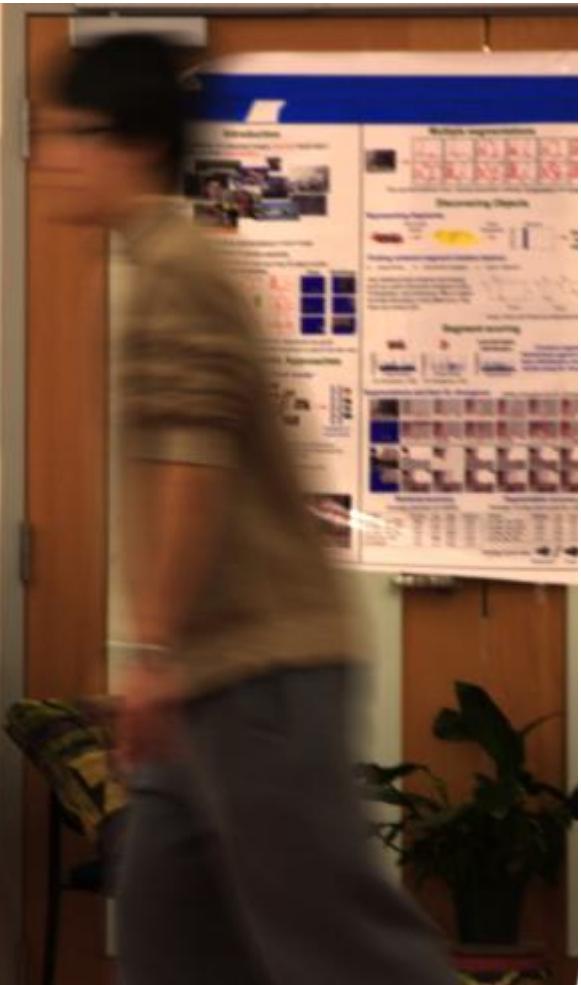
static camera input -
unknown and variable blur



output after deconvolution

Is this blind or non-blind deconvolution?

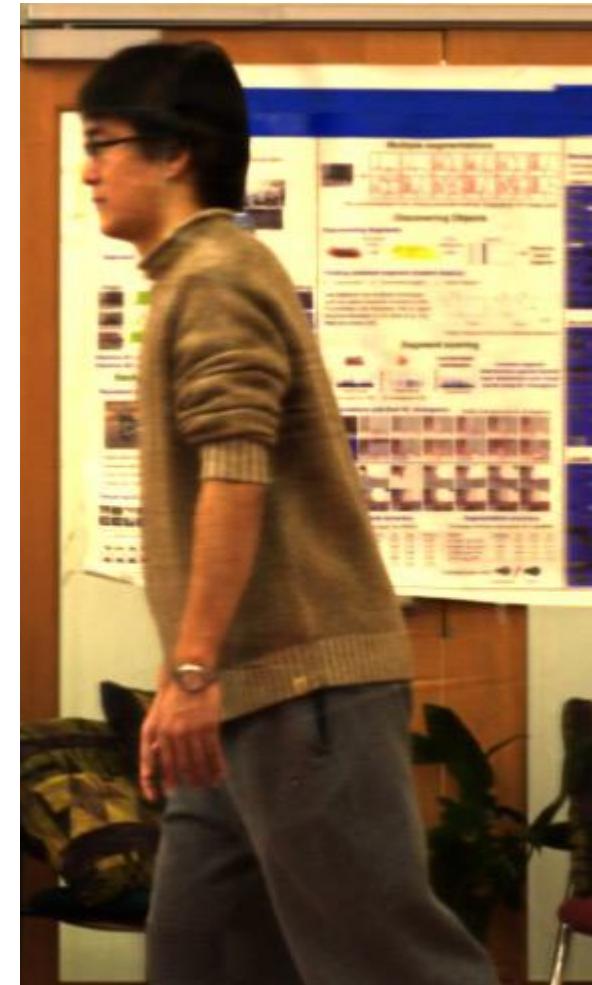
Some results



static camera input



parabolic camera input



deconvolution output

Next Lecture:

Convolutional Neural Networks