Image and Depth from a Conventional Camera with a Coded Aperture - 2007

Anat Levin, Rob Fergus, Fredo ´ Durand, William T. Freeman

Presented by
Vedavalli Krishnan

Modified slides from author's website
http://groups.csail.mit.edu/graphics/CodedAperture/

Desired bokeh

Topics

Undesired blur

Problem: Variable blur in sub image
Proposed Solution: defocus -> depth -> image
Limitations
Possible Applications
Present cameras- computational photography

Problem Statement

50mm Canon

Table front : 2m
Table back: 3m

Front in focus
Empty coke can,
the bottles at back
are at different
levels of defocus

Lens and defocus

Lens' aperture

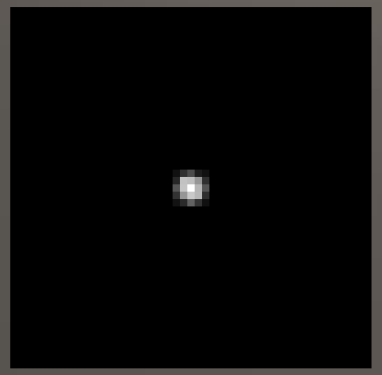
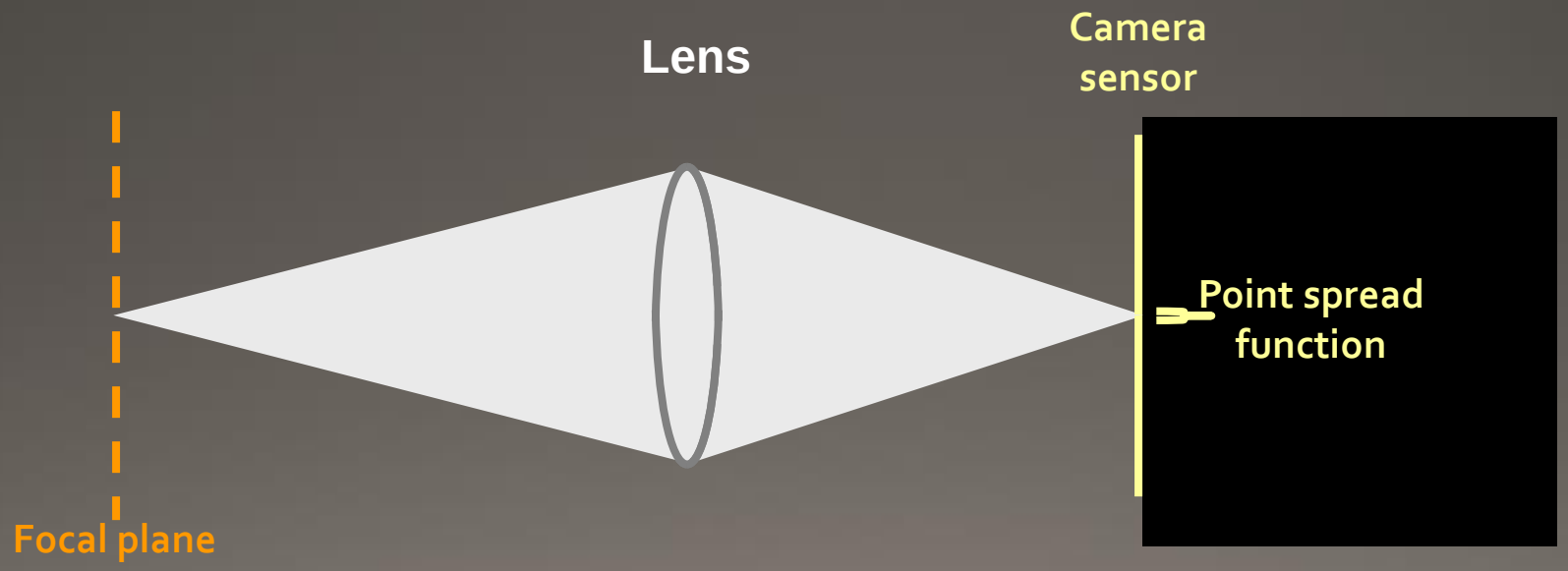


Image of a point light source



Lens and defocus

Lens' aperture

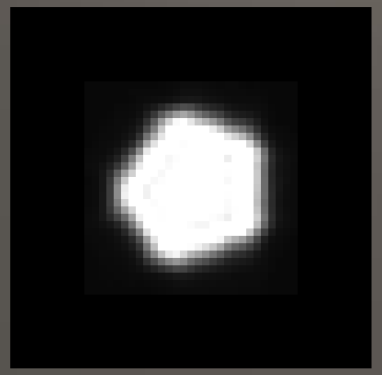
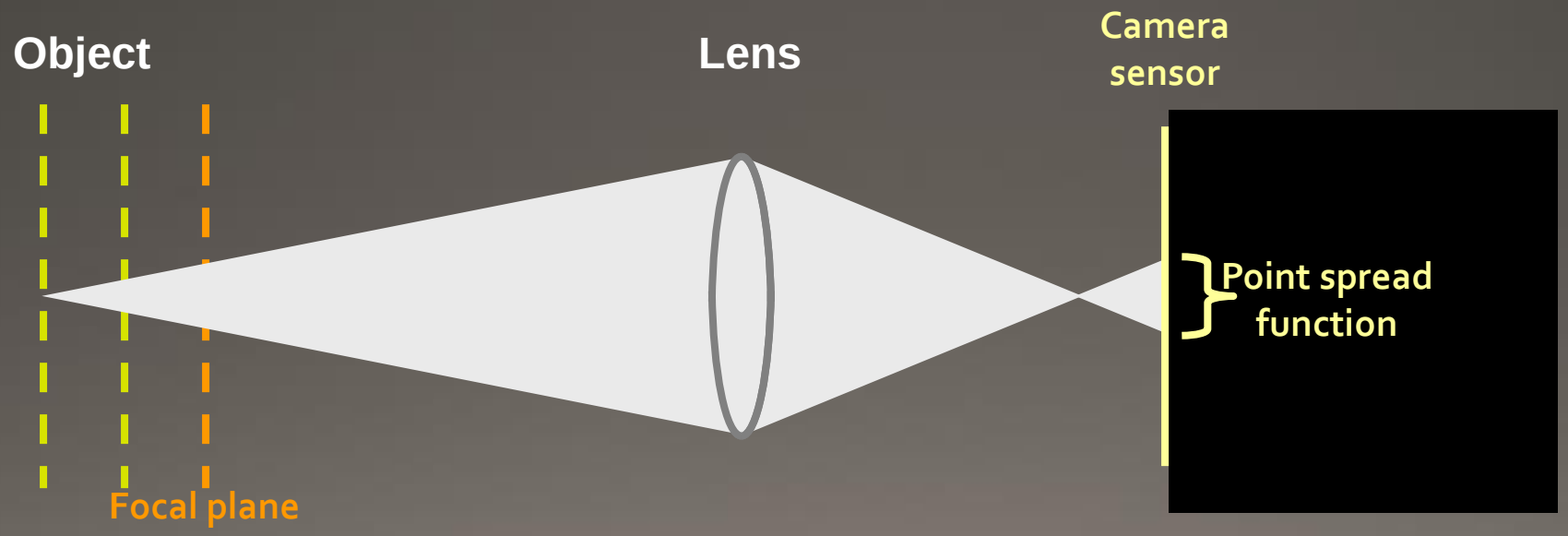


Image of a defocused point light source



Lens and defocus

Lens' aperture

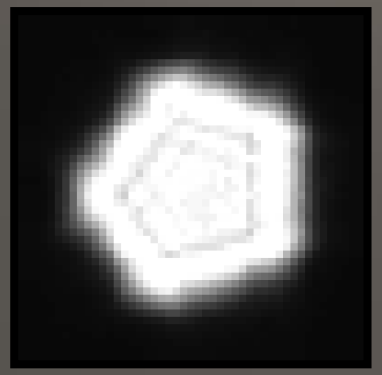
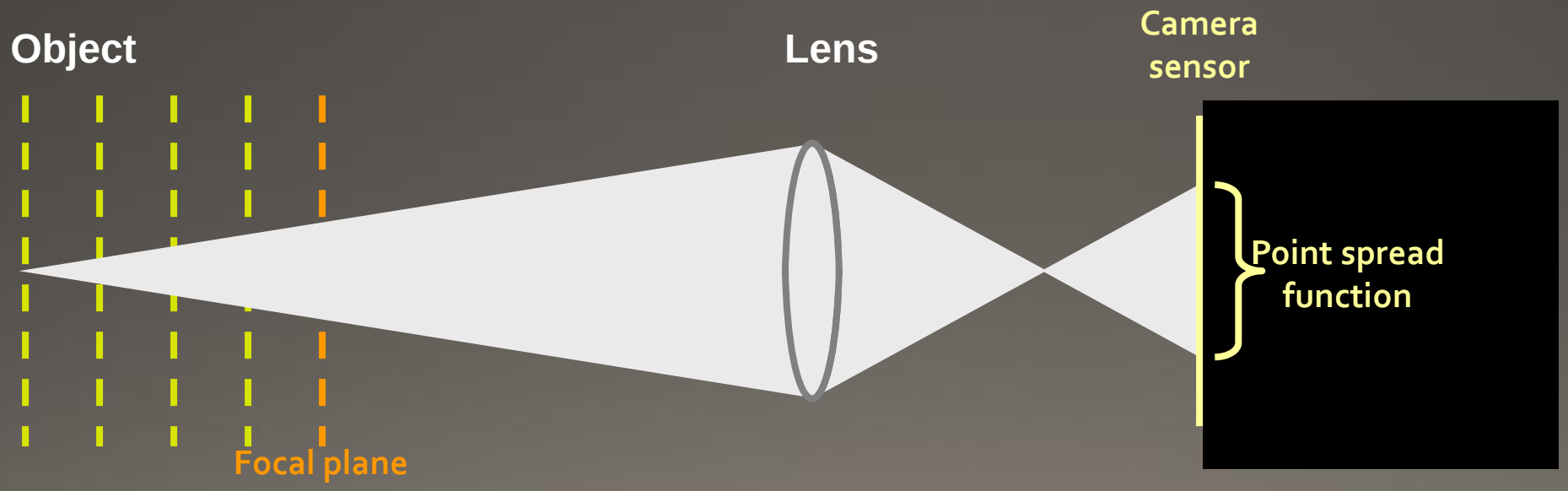
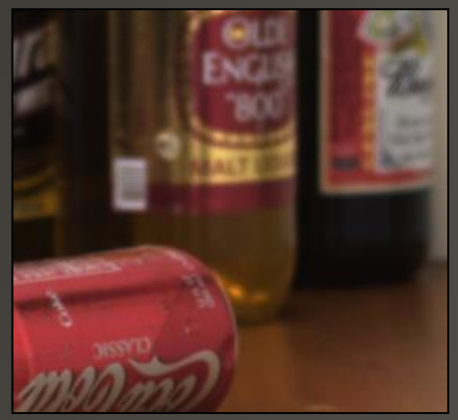


Image of a defocused point light source



Defocus as local convolution

Input defocused image

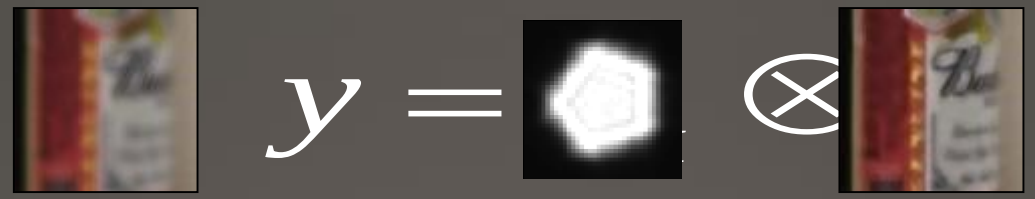


Local sub-window

Calibrated blur kernels at depth = ***k***

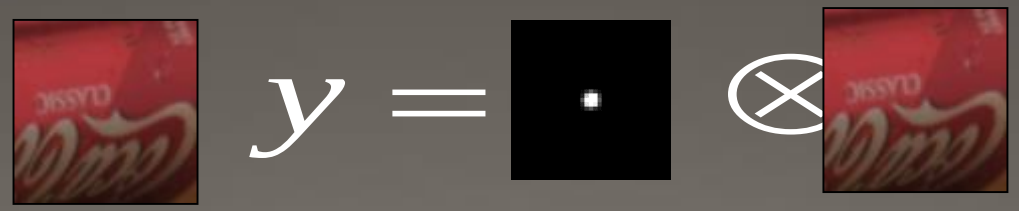
Sharp sub-window

Depth k=2.7m:



Depth k=2.5m:

Depth k=2.1m:



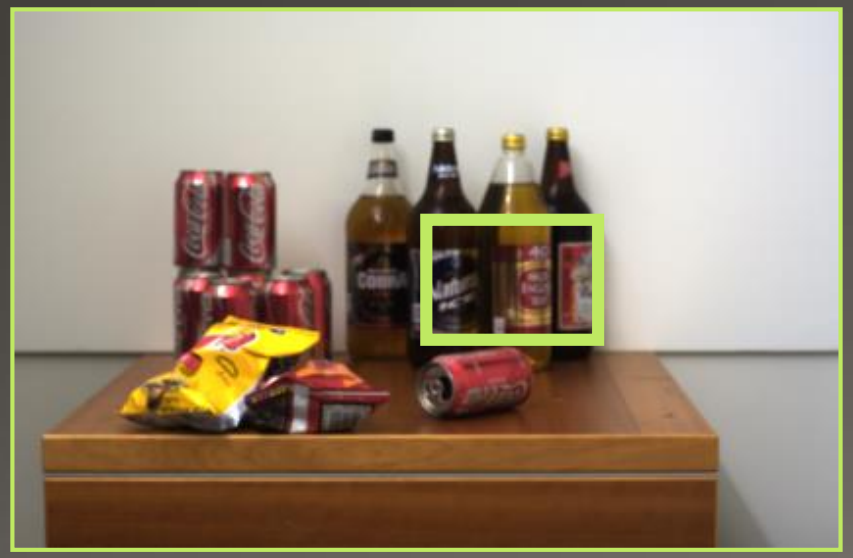
Solution Concept

evaluate local sections

derive Blur scale k

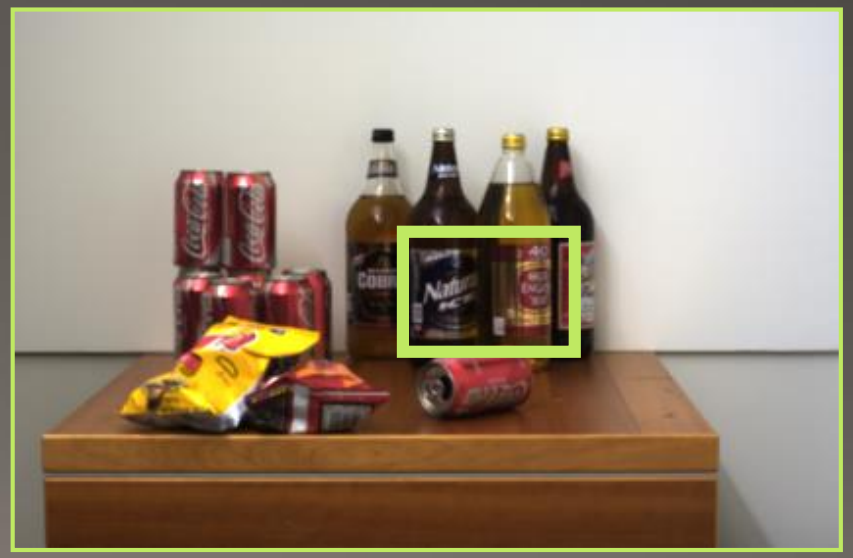
assemble depth map

single input image:



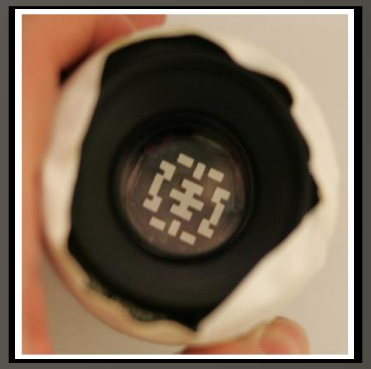
calibrate coded camera ‘k’

all-focused image



Contributions

- Coded aperture (mask inside lens)
  - make defocus patterns different from natural images
  - Select patterns with different frequency nulls for different depth.



- Exploit prior on natural images
  - Improve deconvolution
  - Improve depth discrimination

Coded Apertures

Build your own coded aperture

Voila!

Aperture filter design requirements

Algorithm:

- Reliable discrimination between the blurs that result from different scaling of the filter
- Easily invertible so that the sharp image may be recovered.

Other:

- Binary symmetric masks
- Simple construction
- Avoid radial distortion
- Minimum hole size diffraction limited

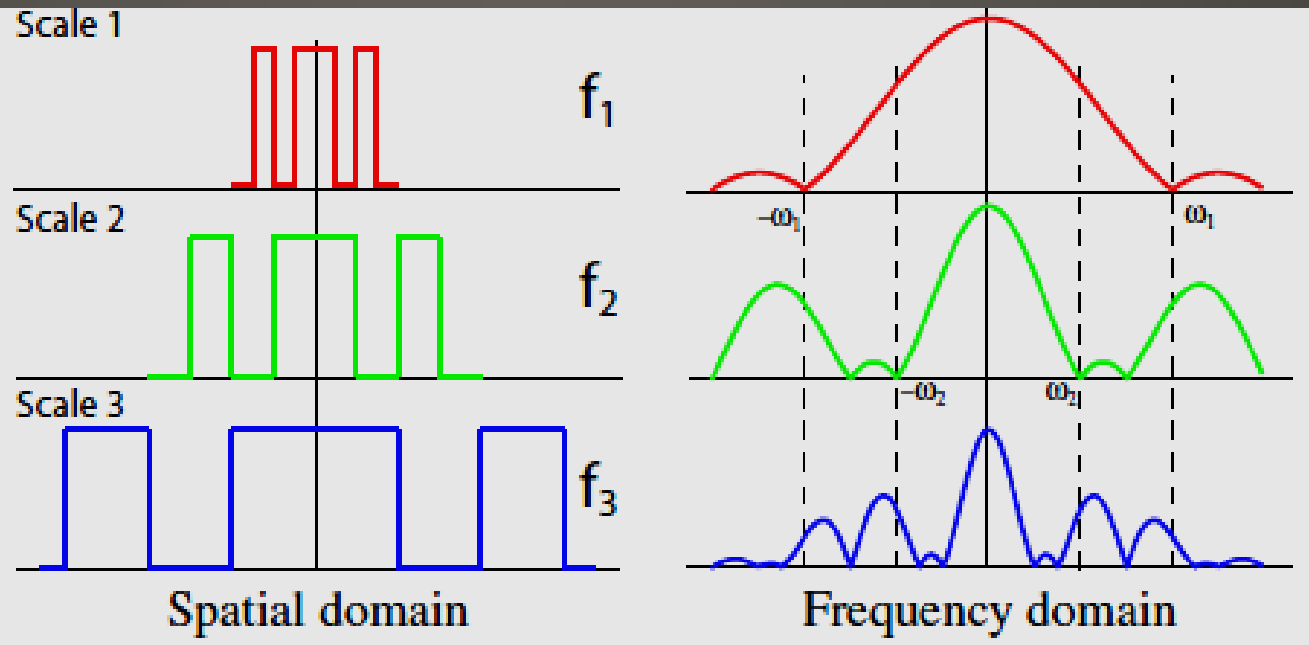
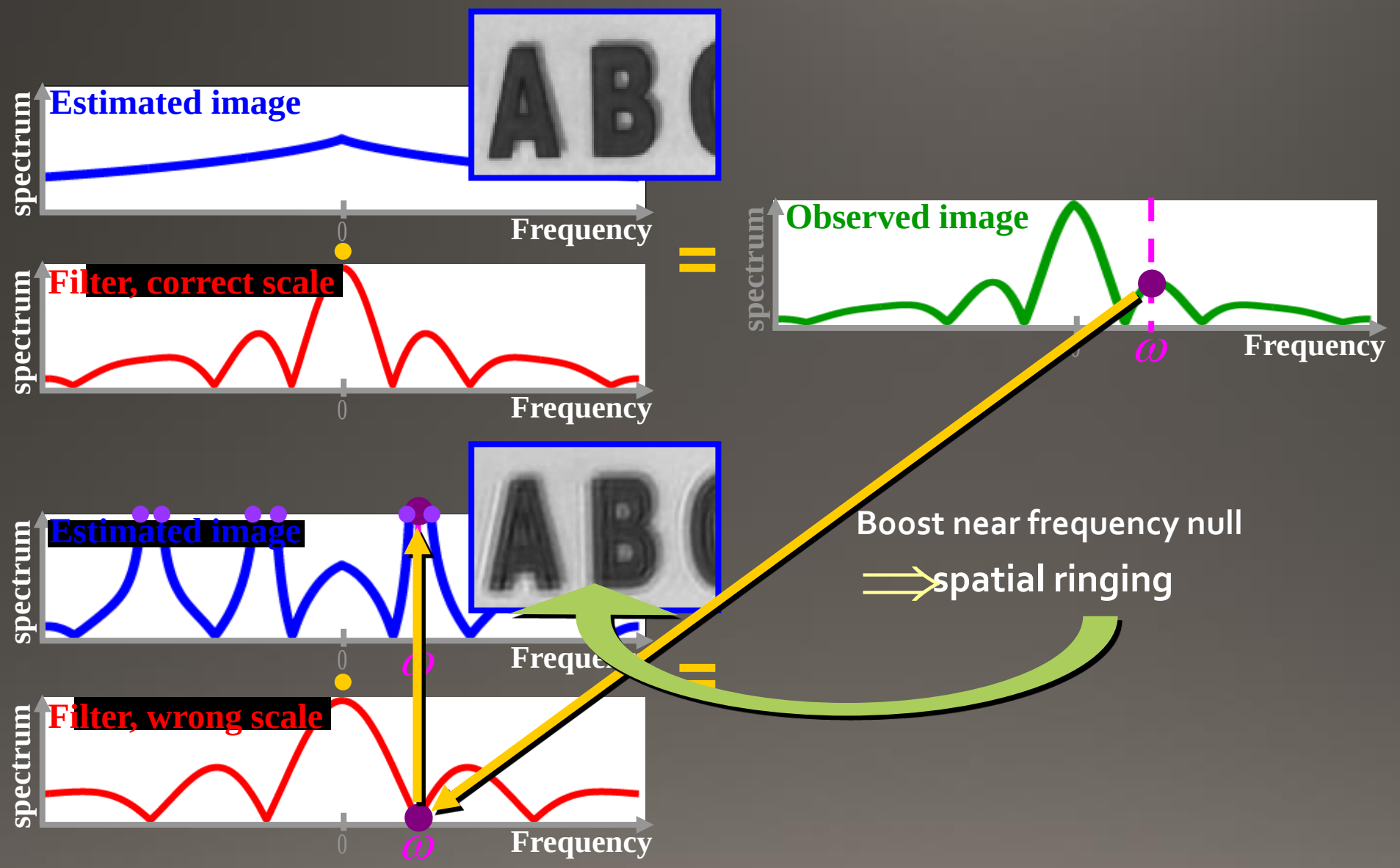


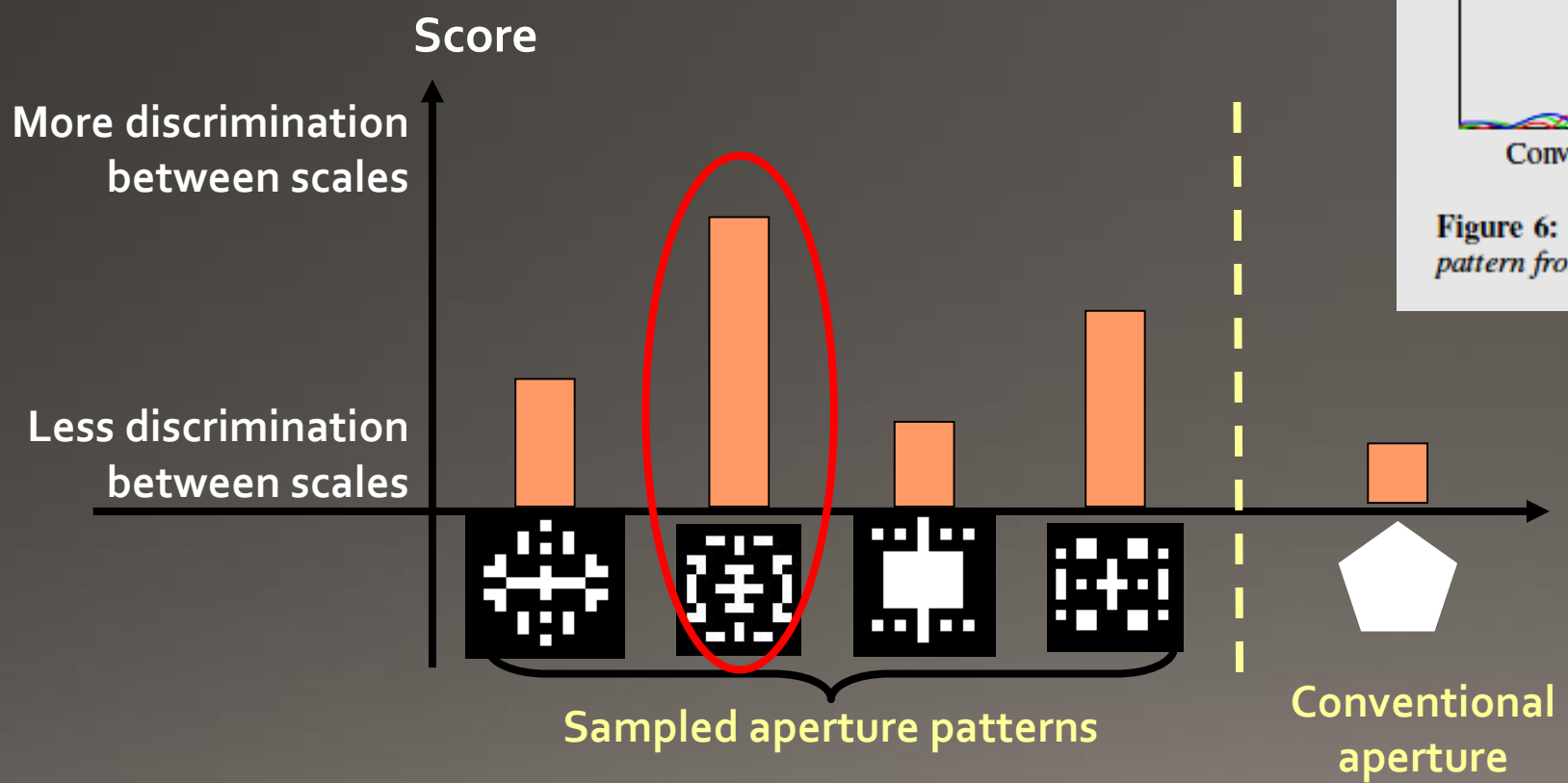
Figure 4: *A simple 1D example illustrating how the structure of zeros in the frequency domain shifts as a toy filter is scaled in the spatial domain.*

Scale estimation effect



Filter Design

Analytically search for a pattern maximizing discrimination between images at different defocus scales (Kullback Leibler-divergence)



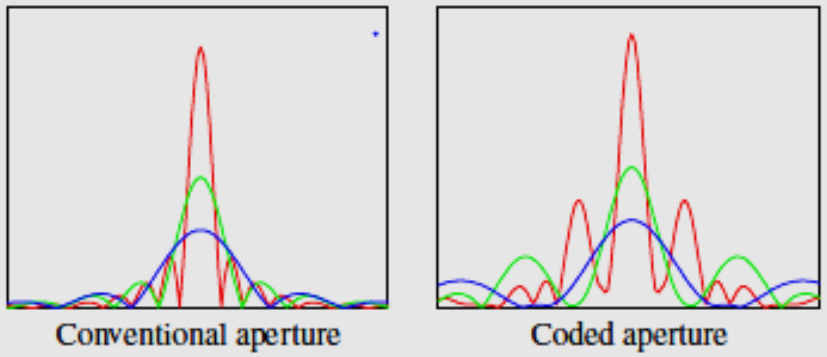


Figure 6: *The Fourier transforms of a 1D slide through the blur pattern from conventional and coded lenses at 3 different scales*

Coded aperture advantage

Larger scale

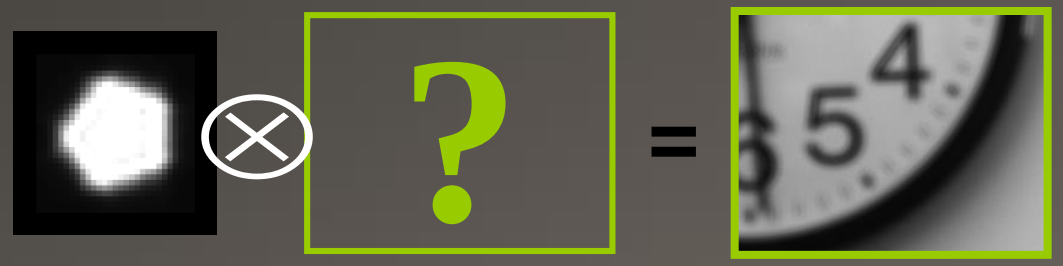
Correct **scale**

Smaller scale

Deconvolution

Deconvolution is ill posed

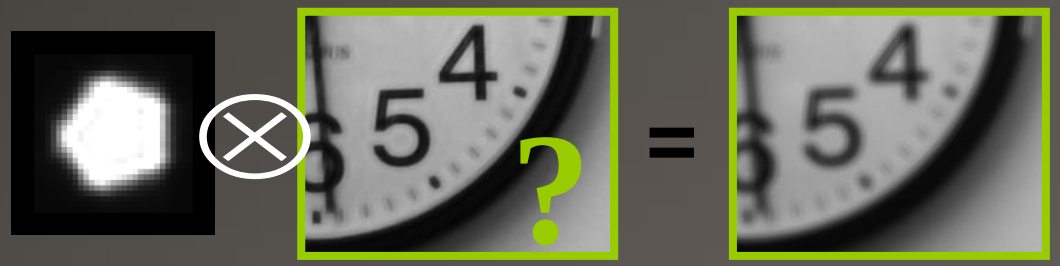
$$f \otimes x = y$$



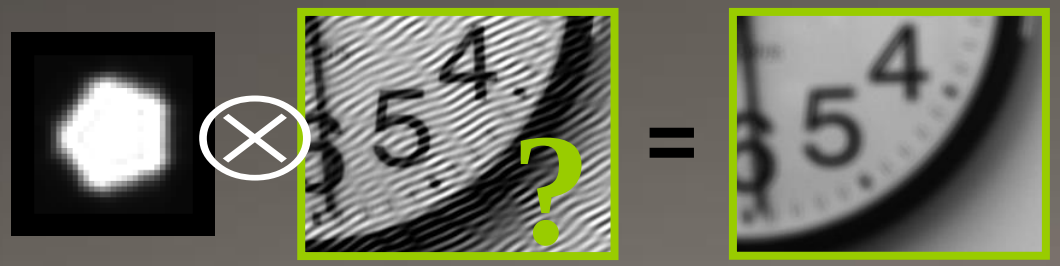
Deconvolution is ill posed

$$f \otimes x = y$$

Solution 1:

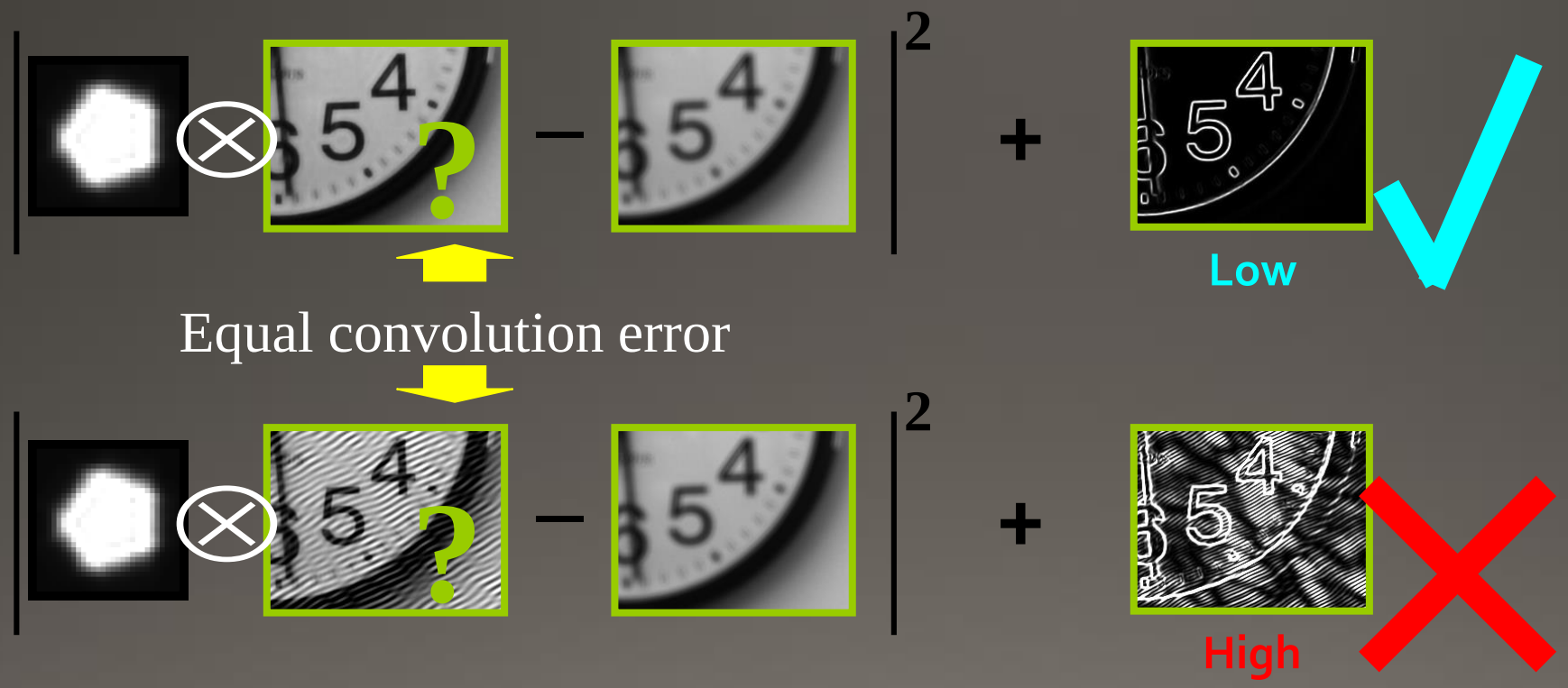


Solution 2:



Deconvolution with prior

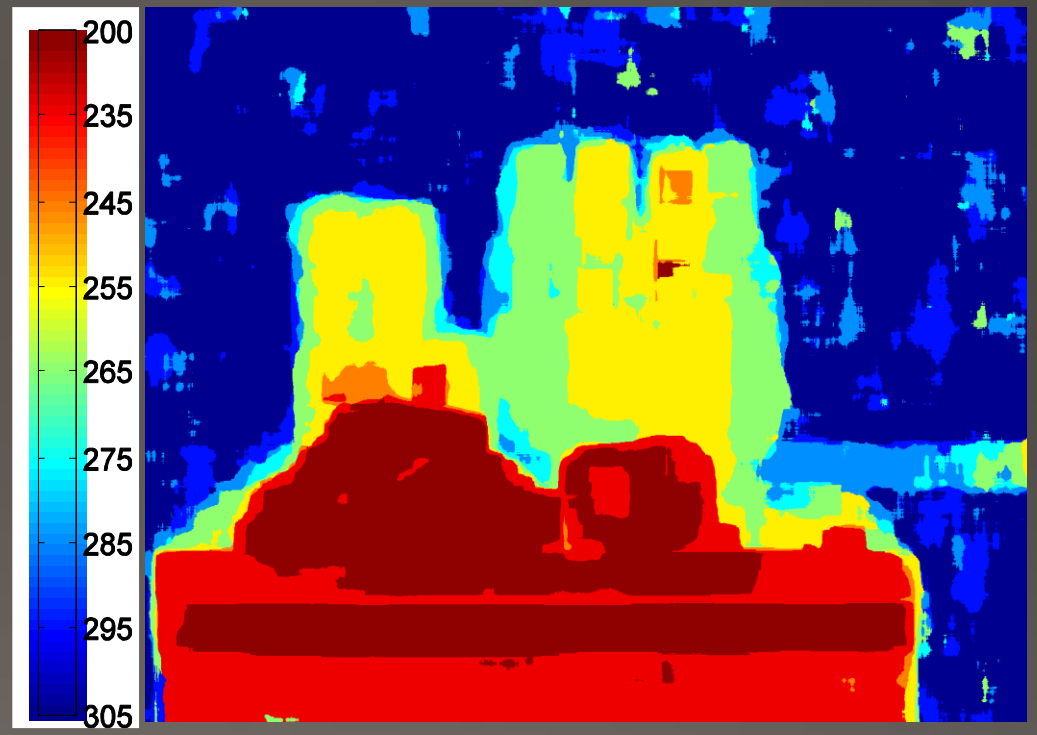
$$x = \arg\min \quad \underbrace{\left| f \otimes x - y \right|^2}_{\text{Convolution error}} + \lambda \underbrace{\sum_i \rho(\nabla x_i)}_{\text{Derivatives prior}}$$



Depth Map and Image Reconstruction

Depth estimate map

1. Deconvolve entire image “y” with all the “k” blur kernals - relults in “k” deconvolved estimation “x”
2. SubImage:
   1. derive reconstruction error for each blur kernel - results in “k” errors
   2. Derive corresponding “k” error energies in a window for each pixel.
   3. Minimum error energy “k” corresponds to the depth of pixel.



Regularizing Depth Estimate

Estimating best depth for each sub image windows is noisy

- Passive depth estimates needs texture
- Deconvolution may not result in unique solution

Markov random field is used to regularize the local depth map

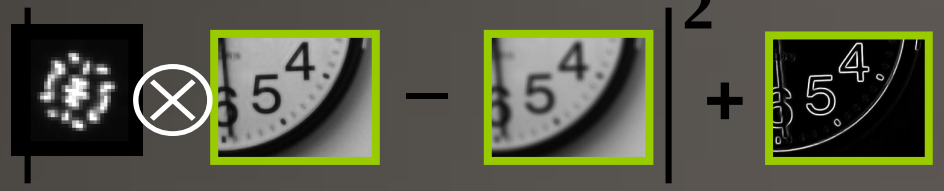
Concept: Energy minimization ; iterative concept

- depth to be piece-wise constant ; present depends only on previous
- depth discontinuities should align with image discontinuities

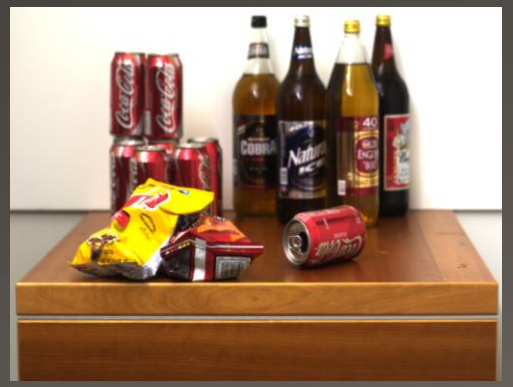
Summary

deblurring with 10 different aperture scales

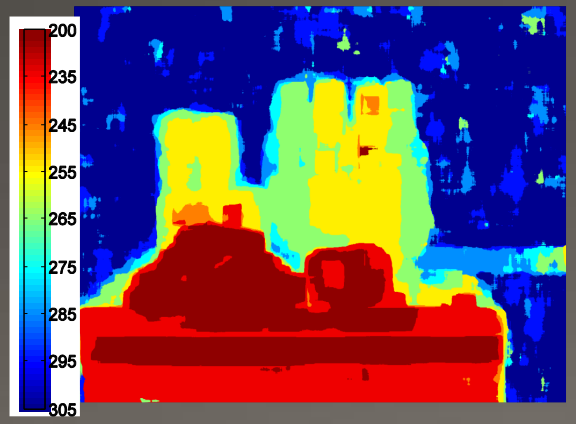
$$x = \arg\min \underbrace{|f \otimes x - y|^2}_{\text{Convolution error}} + \underbrace{\lambda \sum_i \rho(\nabla x_i)}_{\text{Derivatives prior}}$$



Keep minimal error scale in each local window + regularization



Blurred Input



Local depth estimation

Regularized depth

Recovered output

Observations

Limitations & contributions

Coded aperture reduces the amount of light

PSF is calculated at discrete depths and is not an analytical function

PSF is assumed constant at a depth irrespective of the angle (lens distortions are not taken into account)

Segmentation method is not robust and needs manual intervention sometimes

The above topics are actively researched and new algorithms for PSF engineering and segmentations are reported.

The camera manufacturers use blur calculations for passive auto focus

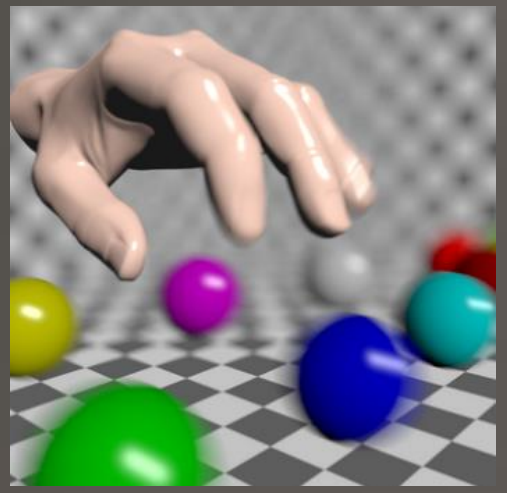
Application: Digital refocusing from a single image

Limited Camera models

Adequate computational power

Unlimited blur / cluttered images

Limitless imagination

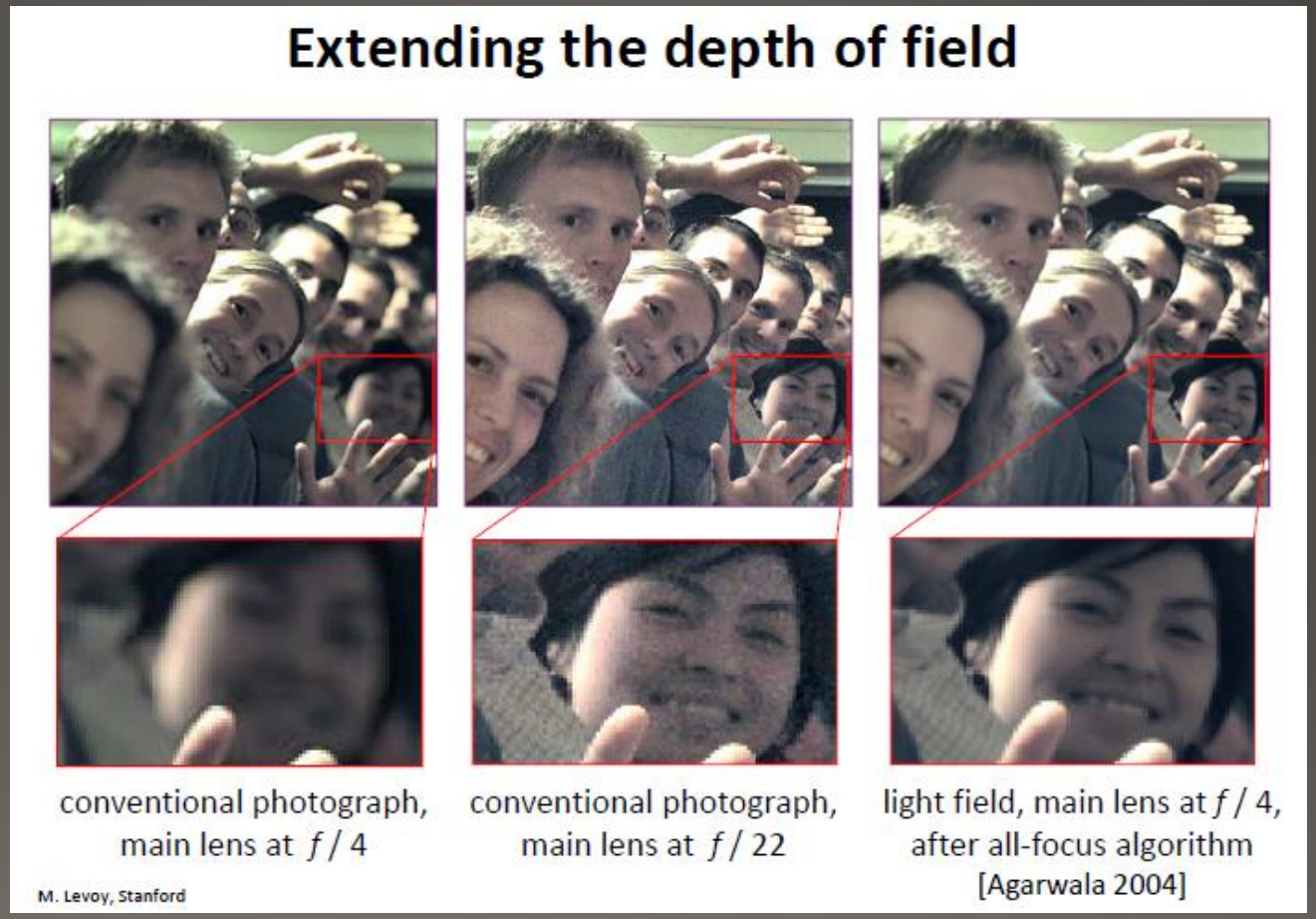


Now: Flexible Camera
Image enhancements applications

1. Variable Focal length :
   Wide angle to Tele photo

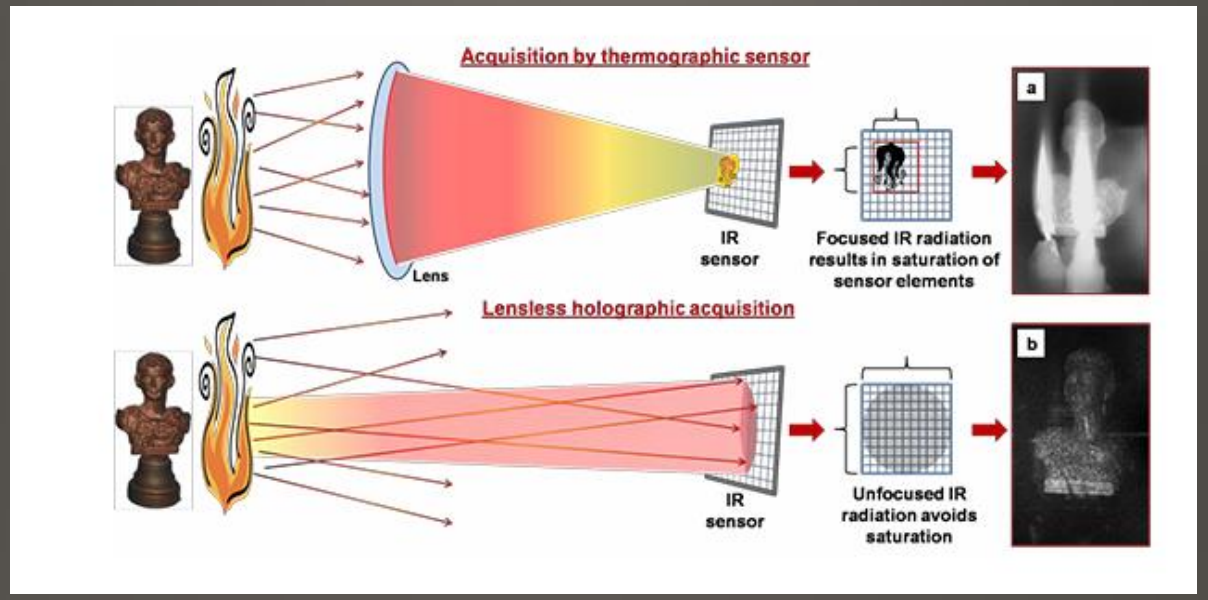
2. Manual Setting control:
   Aperture , Shutter speed, ISO control

3. Digital enhancement software:
   Photo shop, …etc

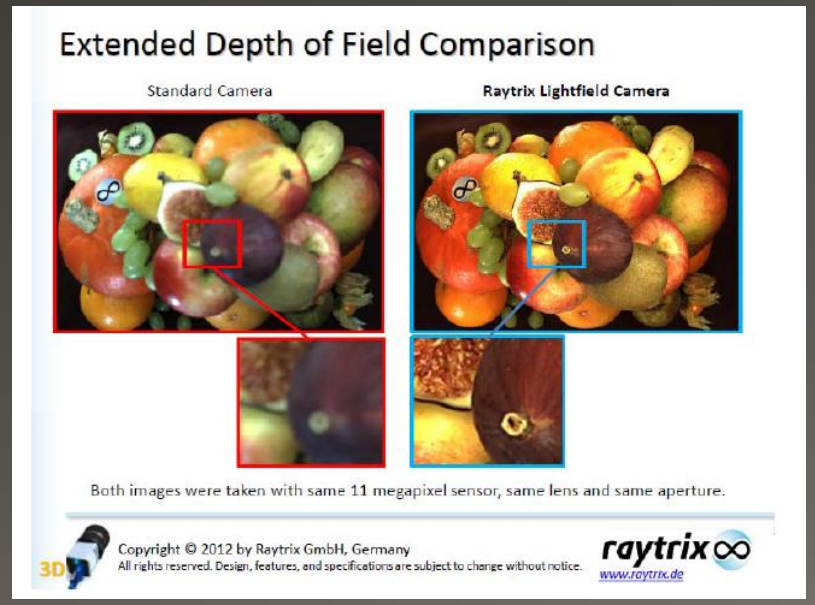


Emerging: Computational Photography

Holographic Reconstruction - 2013



Light field (Lenslet) camera - 2012

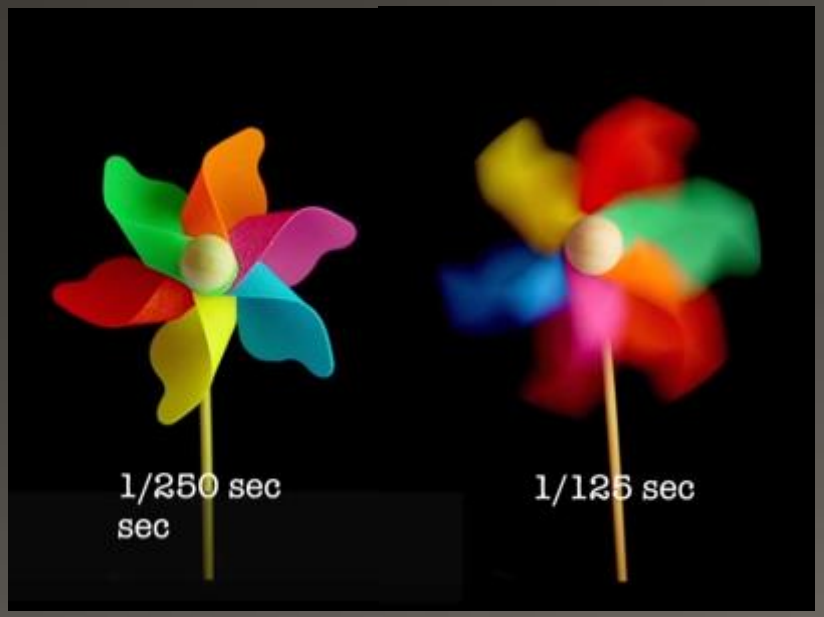


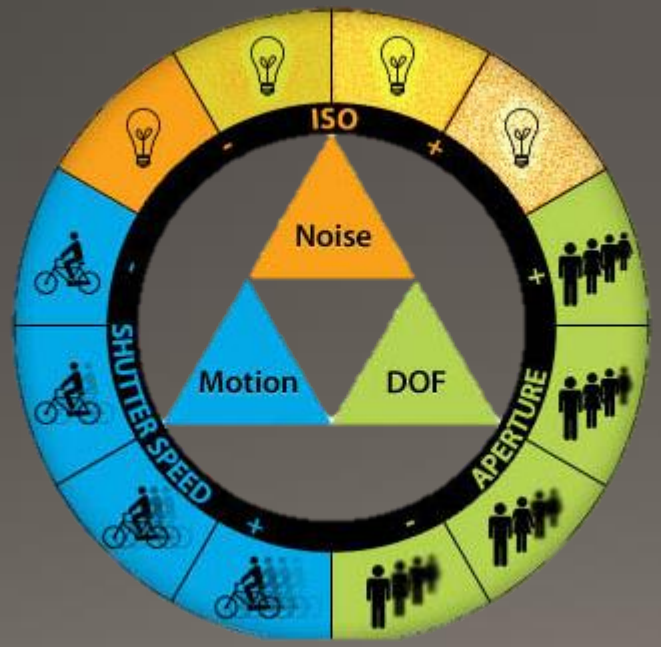
Pin hole revisited – Ansel Adams - 1941

Stereo camera - 2012

Thank you

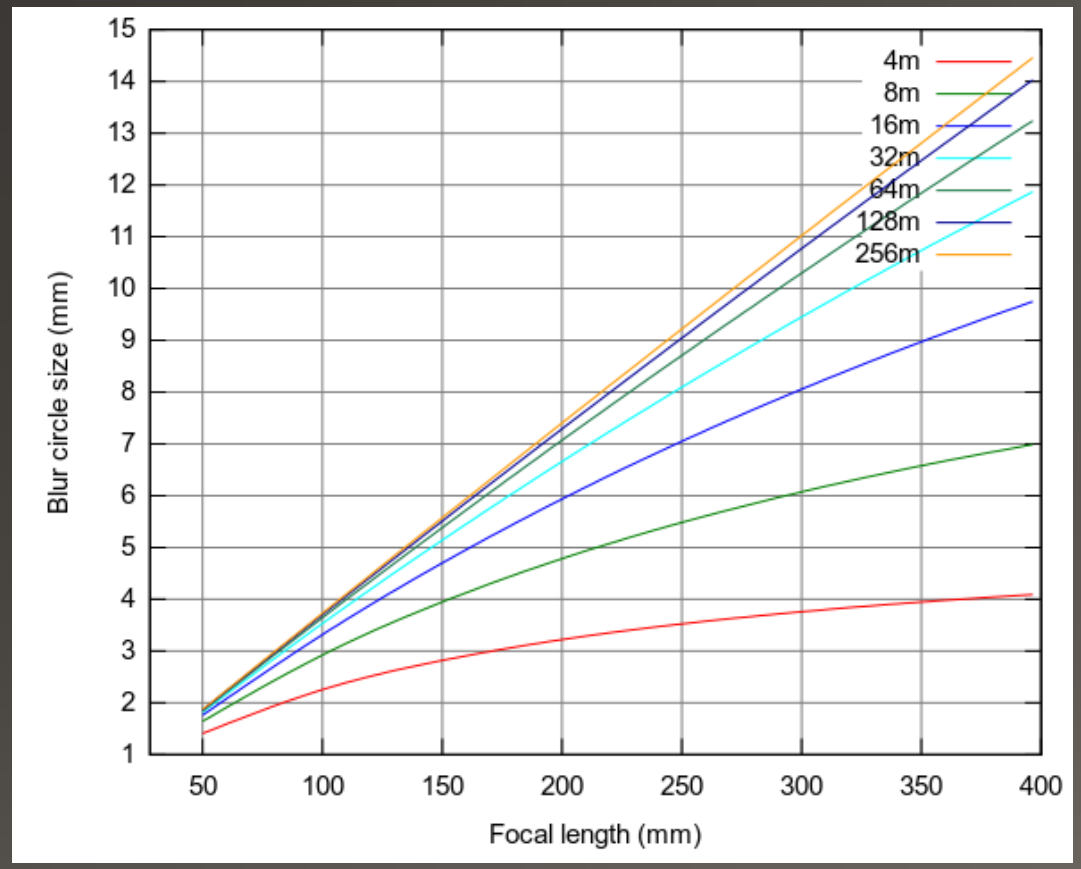
motion blur , noise , defocus blur



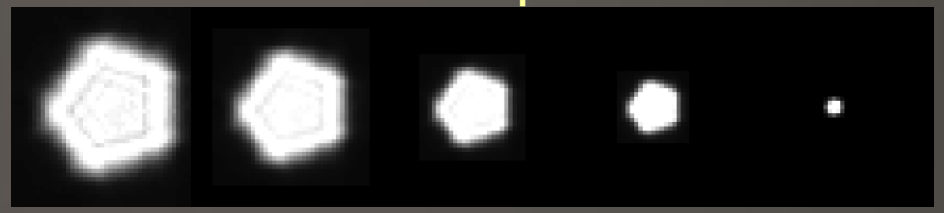


http://petapixel.com/2012/10/03/a-great-graphic-for-understanding-how-iso-aperture-and-shutter-speed-work/ Michael zhang

Circle of Confusion (blur diameter)



Calibrated blur kernels at different depths



Aperture : f/1.4
Subject : 1 meter distance
Background: 4 meter – 256 meter
Focal length : 50mm to 400 mm
Blur diameter: 1.2 mm – 15 mm

http://lewiscollard.com/technical/background-blur/

scale discrimination

$$D_{KL}(P_{k_1}, P_{k_2}) = \sum_{v,\omega} \left(\frac{\sigma_{k_1}(v,\omega)}{\sigma_{k_2}(v,\omega)} - log \left(\frac{\sigma_{k_1}(v,\omega)}{\sigma_{k_2}(v,\omega)} \right) \right) \quad (8)$$

$$D_{KL}(P_{k_1}(y), P_{k_2}(y)) = \int_y P_{k_1}(y)(logP_{k_1}(y) - logP_{k_2}(y))\, dy$$

Deconvolution Norms

$$x^* = argmin \frac{1}{\eta^2} |C_{f_k} x - y|^2 + \alpha |C_{g_x} x|^2 + \alpha |C_{g_y} x|^2 \qquad (10)$$

$$A = \frac{1}{\eta^2} C_{f_k}^T C_{f_k} + \alpha C_{g_x}^T C_{g_x} + \alpha C_{g_y}^T C_{g_y} \qquad b = \frac{1}{\eta^2} C_{f_k}^T y \qquad (11)$$

$$|C_{f_k} x - y| + \sum_{ij} \rho(x(i,j) - x(i+1,j)) + \rho(x(i,j) - x(i,j+1)) \quad (12)$$

MRF: Minimize energy

$$E(\bar{d}) = \sum_i E_1(\bar{d}_i) + v \sum_{i,j} E_2(\bar{d}_i, \bar{d}_j) \qquad (16)$$

where the local energy term is set to

$$E_1(\bar{d}_i) = \begin{cases} 0 & \bar{d}_i = d_i \\ 1 & \bar{d}_i \neq d_i \end{cases}$$

Penalize noisy variations - smoothen depth map - depth to be piece-wise constant

$$E_2(\bar{d}_i, \bar{d}_j) = \begin{cases} 0 & \bar{d}_i = \bar{d}_j \\ e^{-(y_i - y_j)^2/\sigma^2} & \bar{d}_i \neq \bar{d}_j \end{cases}$$

Penalize changes that do not coincide with the image edges