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

Sources: CMU 15-463

- Generalized optics encode world into intermediate representation.
- Generalized computation decodes representation into one or multiple images.

Sources: [CMU 15-463]

Credit: B.J. Mattson, L3/NASA/GSFC

source may be inferred

R. H. Dicke (1968). "Scatter-hole cameras for x-rays and gamma rays". The Astrophysical Journal. ***153****:L101.*

Adapted from: [Hasinoff 2008]

Adapted from: [Hasinoff 2008]

Adapted from: [Hasinoff 2008]

Point Spread Function (PSF): Response of a focused imaging system to a point source. Impulse response of an imaging system.

Adapted from: [Hasinoff 2008]

Adapted from: [Hasinoff 2008]

Adapted from: [Hasinoff 2008]

Adapted from: [Hasinoff 2008]

Adapted from: [Hasinoff 2008]

Adapted from: [Hasinoff 2008]

Adapted from: [Hasinoff 2008]

$$I \quad * \quad k \quad = \quad B$$

scene by the PSF of the imaging system.

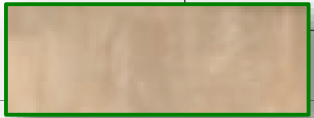

mputer bereits simulieren. Für Pro
irtuelles Mikroskop. *Foto: Brinkm*

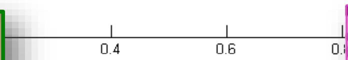
schichten auf dem bewährten C
Basis ial Silizium entwickelt
n beim herköm


0.4
0.6

Details

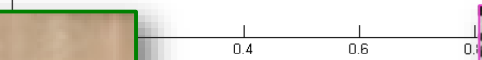

mputer bereits simulieren. Für Pro
irtuelles Mikroskop. Foto: Brinkm
schichten auf dem bewährten C
Silizium entwickelt
beim herköm

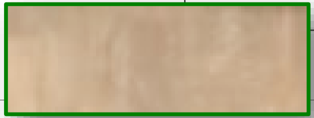



0.4
0.6

Details


mputer bereits simulieren. Für Pro
irtuelles Mikroskop. Foto: Brinkm
schichten auf dem bewährten C
Silizium entwickelt
beim herköm



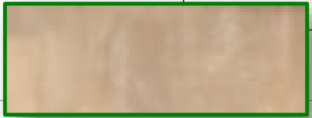


Details


mputer bereits simulieren. Für Pro
irtuelles Mikroskop. *Foto: Brinkm*

schichten auf dem bewährten C
Basis ial Silizium entwickelt
n beim herköm

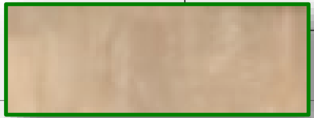
Details

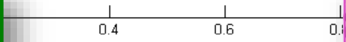



mputer bereits simulieren. Für Pro
irtuelles Mikroskop. *Foto: Brinkm*

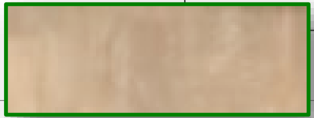
schichten auf dem bewährten C
Basis ial Silizium entwickelt
n beim herköm

Details




0.4
0.6


mputer bereits simulieren. Für Pro
irtuelles Mikroskop. Foto: Brinkm
schichten auf dem bewährten C
Silizium entwickelt
beim herköm

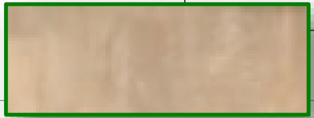


Details


mputer bereits simulieren. Für Pro
irtuelles Mikroskop. *Foto: Brinkm*

schichten auf dem bewährten C
Basis... Silizium entwickelt
...n beim herköm

Details

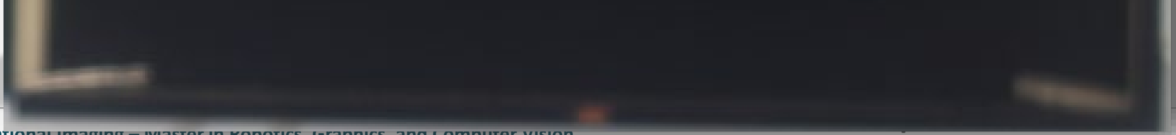



mputer bereits simulieren. Für Pro
irtuelles Mikroskop. *Foto: Brinkm*

schichten auf dem bewährten C
Basis ial Silizium entwickelt
n beim herköm

object distance D focus distance D

object distance D focus distance D



Calibrated kernels at a variety of depths from the focus plane

Captured Image

Captured Image

Normalized Frequency

Normalized Frequency

Normalized Frequency

Bad code

New code!

New code!

Levin, A., Fergus, R., Durand, F., & Freeman, W. T. (2007). Image and depth from a conventional camera with a coded aperture. *ACM transactions on graphics (TOG)*, *26*(3), 70-es.

Usually posed as an optimization problem, defining the appropriate objective function (& constraints).

object distance D

focus distance D’

object distance D

focus distance D’

object distance D focus distance D’

object distance D focus distance D’

object distance D focus distance D’

Sources: [CMU 15-463](CMU 15-463)


object distance D
focus distance D’

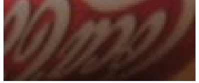
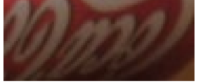
object distance D

focus distance D’

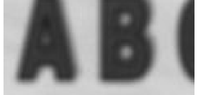
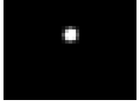
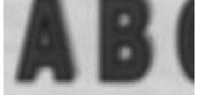
input defocused image

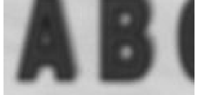
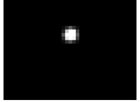
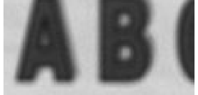
input defocused image

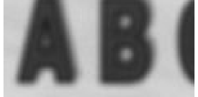
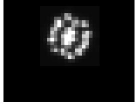
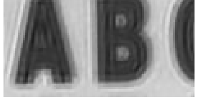
measured PSFs at different depths

 =  * 

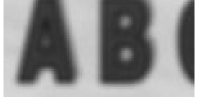
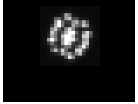
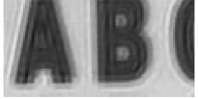
measured PSFs at different depths

 $*^{-1}$  $=$ 

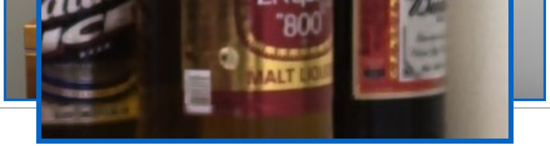
 $*^{-1}$  $=$  correct scale ?

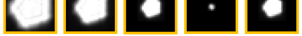
 $*^{-1}$  $=$ 

wrong scale

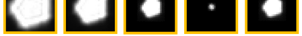
 $*^{-1}$  $=$ 

wrong scale ✗


"800"



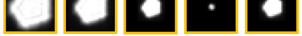
PSFs for object at depth 1



PSFs for object at depth 1

PSFs for object at depth 2

Sources: CMU 15-463

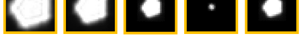


PSFs for object at depth 1

PSFs for object at depth 2

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

Sources: CMU 15-463

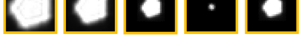


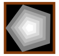
PSFs for object at depth 1

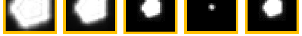
PSFs for object at depth 2

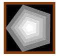
As we sweep through focus settings, each point is blurred by all possible PSFs.

Sources: CMU 15-463

$\int$  dt =  effective PSF for object at depth 1

$\int$  dt =  effective PSF for object at depth 2

$\int$  dt =  effective PSF for object at depth 1

$\int$  dt =  effective PSF for object at depth 2

Let's have a look at these PSFs...

Zhou, C., Miau, D., & Nayar, S. K. (2012). Focal sweep camera for space-time refocusing.

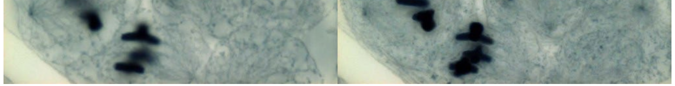
Sources: CMU 15-463

Zhou, C., Miau, D., & Nayar, S. K. (2012). Focal sweep camera for space-time refocusing.

Sources: [CMU 15-463]

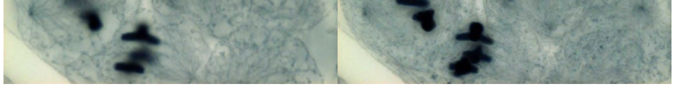
Zhou, C., Miau, D., & Nayar, S. K. (2012). Focal sweep camera for space-time refocusing.

Sources: CMU 15-463



Images: Meyer Inst.

Sources: CMU 15-463



Images: Meyer Inst.

Sources: CMU 15-463

=> Focal sweep enables EDOF while maintaining high SNR.

Sources: CMU 15-463

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

Sources: [CMU 15-463]

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

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

Sources: CMU 15-463

conver
(sm

conver
(large

conver
(sm

conver
(large

Sources: CMU 15-463

Sources: CMU 15-463 [Ortega-Sánchez et al. 2019].

C. Wang, A. Serrano, X. Pan, K. Wolski, B. Chen, K. Myszkowski, & T. Leimkühler (2023). **An Implicit Neural Representation for the Image Stack: Depth, All in Focus, and High Dynamic Range**. *ACM Transactions on Graphics (TOG)*, *42*(6), 1-11.

Sources: CMU 15-463

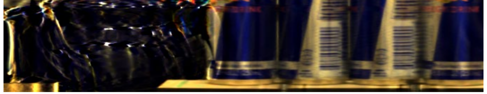
Can is moving linearly from left to right

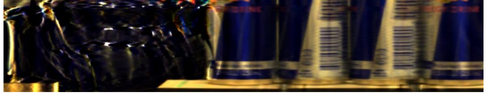
Source: ExpertPhotography.

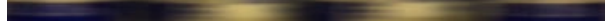
Source: OpenCV.

Source: ExpertPhotography.

Spatially-varying kernel (velocity-dependent).





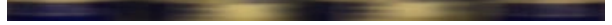


blurry image of moving object

motion blur kernel

sharp image of static object

Sources: [CMU 15-463](CMU 15-463)



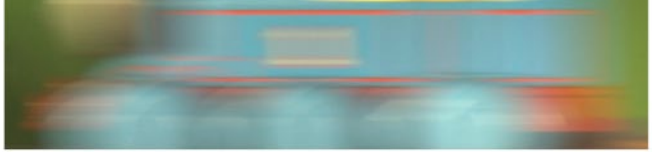
blurry image of moving object

motion blur kernel

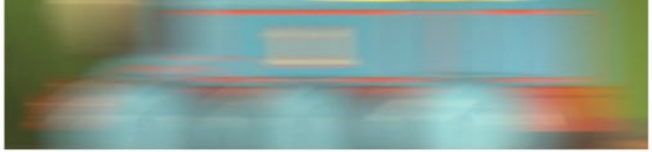
sharp image of static object

Sources: CMU 15-463

Why is flutter-shutter better?



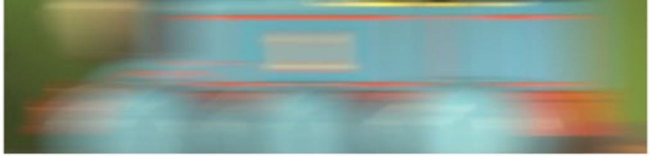
Why is flutter-shutter better?

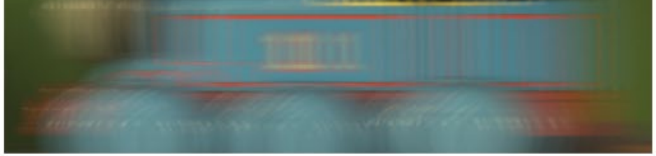


Graphics and Imaging Lab

Computatior

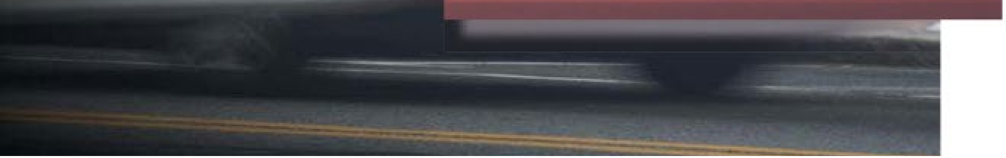
Input

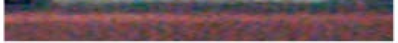




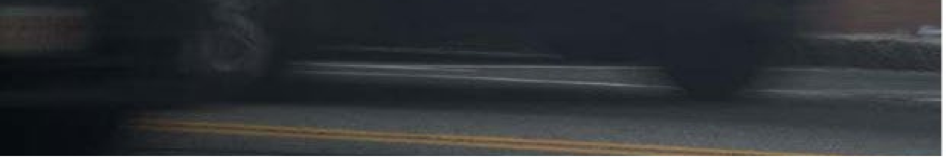
shutter

Sources: CMU 15-463

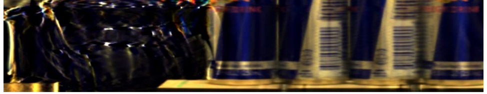




License Plate Retrieval



License Plate Retrieval



$$X \quad * \quad c \quad = \quad b$$

$$X \quad * \quad c \quad = \quad b$$

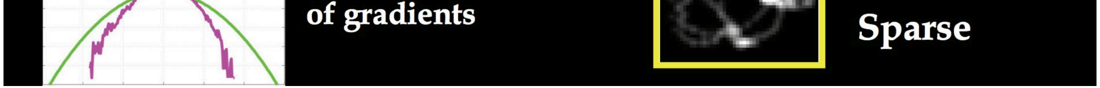
$$X \quad * \quad c \quad = \quad b$$

$$X \quad * \quad c \quad = \quad b$$

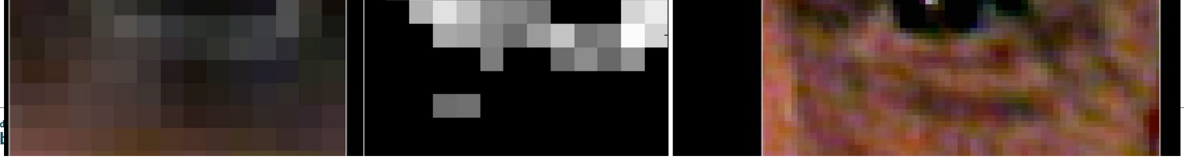
How do we detect this one?

continuous contours, and are always positive

How do we use this information?


of gradients
Sparse

Note: Solving such optimization problems is complicated.



Graphics and Imaging Lab

motion-invariant kernel at the cost of capturing everything blurry
(introducing additional motion)
→ Out of the scope of the course.

Levin, A., Sand, P., Cho, T. S., Durand, F., & Freeman, W. T. (2008). Motion-invariant photography. *ACM Transactions on Graphics (TOG)*, *27*(3), 1-9.

Graphics
Imaging

taken of a particular space-time chunk of the world (neglecting polarization and other wave-based effects)."

The Plenoptic Function and the Elements of Early Vision [Adelson and Bergen 1991]

- An observer takes **samples** from this function.

Compressive sensing (Lecture #[illegible])
Computational illumination (Lecture #7)

Source: Wetzstein et al. Plenoptic imaging.

May involve one or more cameras, and one or more captured images.

Different techniques for each – often there is *feedback* between dimensions.

Fergus et al., "Removing camera shake from a single image", SIGGRAPH 2006

Example of motion deblurring covered in this talk

Zhou et al., "Coded aperture pairs for depth from defocus", ICCV 2009.

Both papers show how to build on the basic approach to extract depth (also: see next topic in the course)