Great Ideas in Computational Photography

HDR Imaging, Tone Mapping, Coded Apertures & Imaging

EE367/CS448I: Computational Imaging

stanford.edu/class/ee367

Lecture 6

Gordon Wetzstein

Stanford University

Computational Photography on your Phone

- High-dynamic-range (HDR) imaging
- Tone mapping
- Burst photography

wikipedia

-4 stops

wikipedia

exposure sequence

-2 stops

wikipedia

exposure sequence

2 stops

wikipedia

4 stops

Motivation

wikipedia

HDR
contrast
reduction
(scaling)

wikipedia

HDR
local tone
mapping

High Dynamic Range Imaging (HDRI)

Problems:

- Sensors have a limited full well capacity, pixels saturate for higher electron count
- Non-zero noise floor and ADC quantization further reduce precision

Terminology:

- dynamic range: ratio between brightest and darkest value
- quantization (i.e., precision) within that range is equally important

→ from 8 bits (256 values) to 32 bits floating point

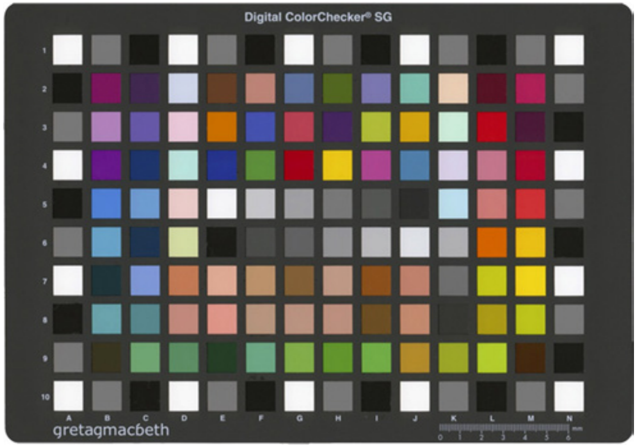
https://www.princetoninstruments.com/learn/camera-fundamentals/full-well-capacity-pixel-saturation

HDRI – Overview

1. estimate camera response curve
2. capture multiple low dynamic range (LDR) exposures
3. fuse LDR images into 32 bit HDR image
4. possibly convert to absolute radiance (global scaling)

HDRI – Estimating the Response Curve

- not required when working with linear RAW images
- easiest option: use calibration chart



HDRI – Estimating the Response Curve

- not required when working with linear RAW images
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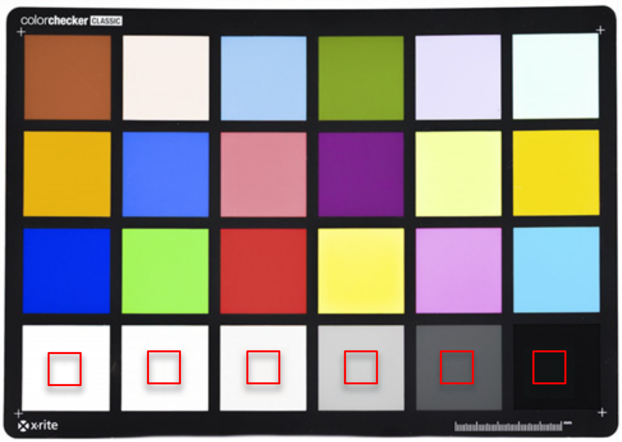
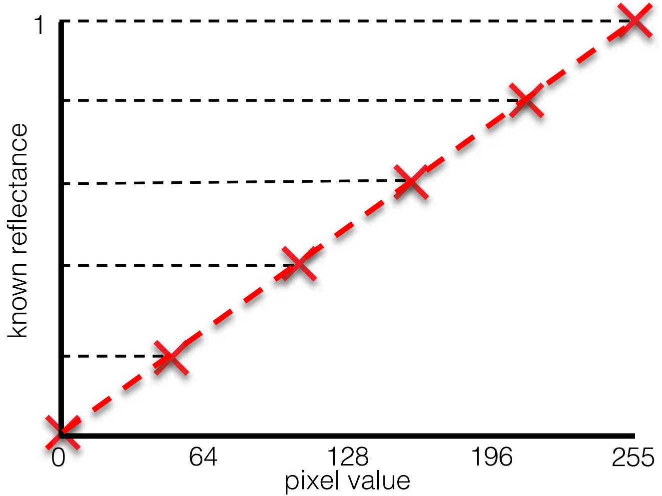


linear RAW



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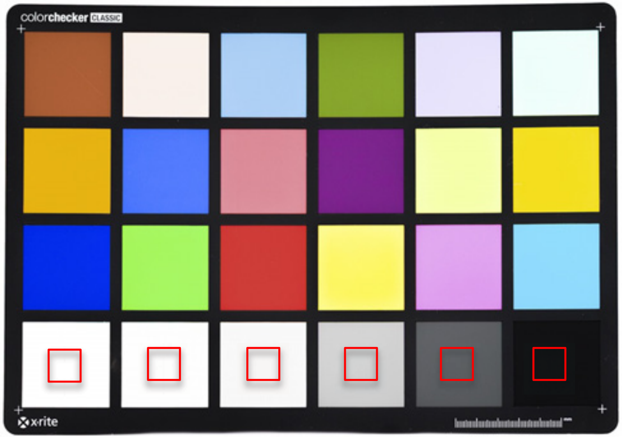
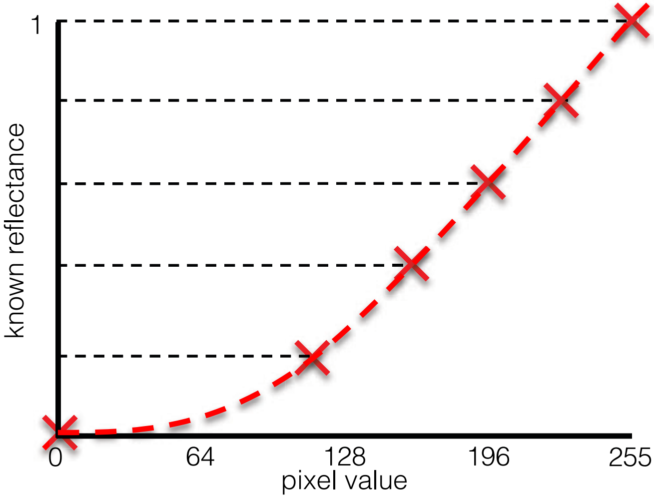


e.g. JPEG



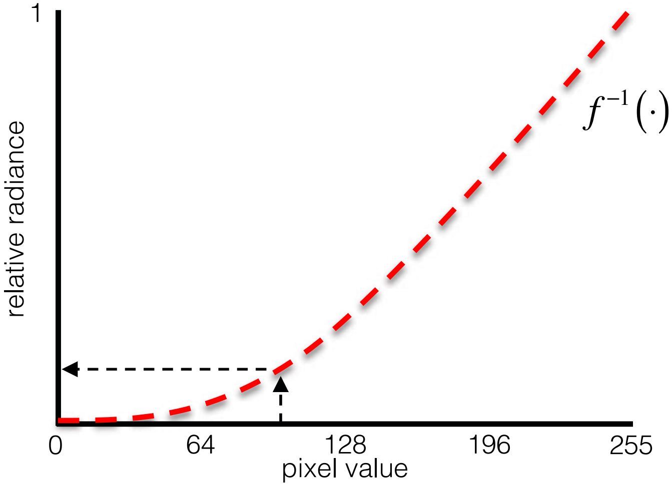
HDRI – Linearizing LDR Exposures

- capture exposure, apply lookup table

I

$I_{lin} = f^{-1}(I)$

e.g. JPEG



HDRI – Merging LDR Exposures

- start with LDR image sequence I_i (only exposure time t_i changes)
- individual exposure is: $I_i = f\left(t_i X\right)$, f is camera response function

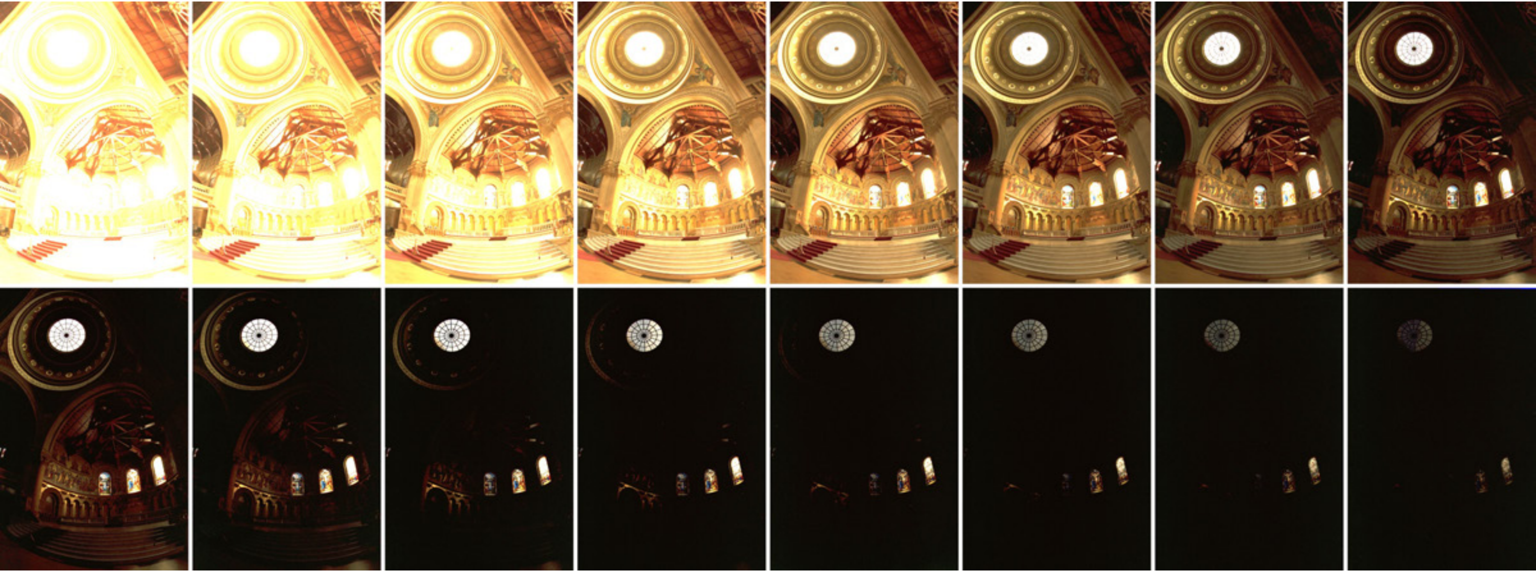


Image from Debevec & Malik, 1997

HDRI – Merging LDR Exposures

- undo the camera response: $I_{lin_i} = f^{-1}(I_i)$

  e.g., gamma function $f(I) = I^{1/\gamma} \quad \rightarrow \quad f^{-1}(I) = I^{\gamma}$

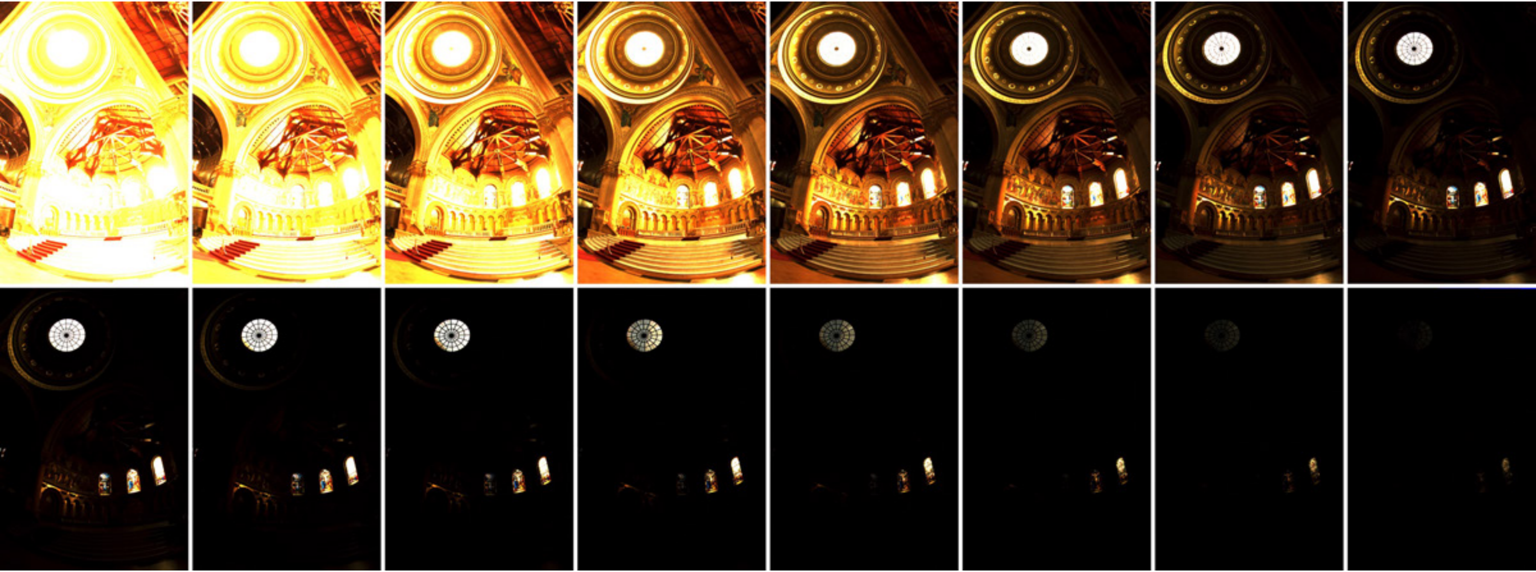


Image from Debevec & Malik, 1997

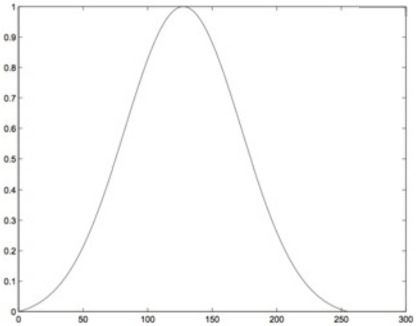
HDRI – Merging LDR Exposures

- compute a weight (confidence) that a pixel is well-exposed

  → (close to) saturated pixel = not confident, pixel in center of dynamic range = confident!

$$w_{ij} = \exp\left(-4 \frac{\left(I_{lin_{ij}} - 0.5 \right)^2}{0.5^2} \right)$$

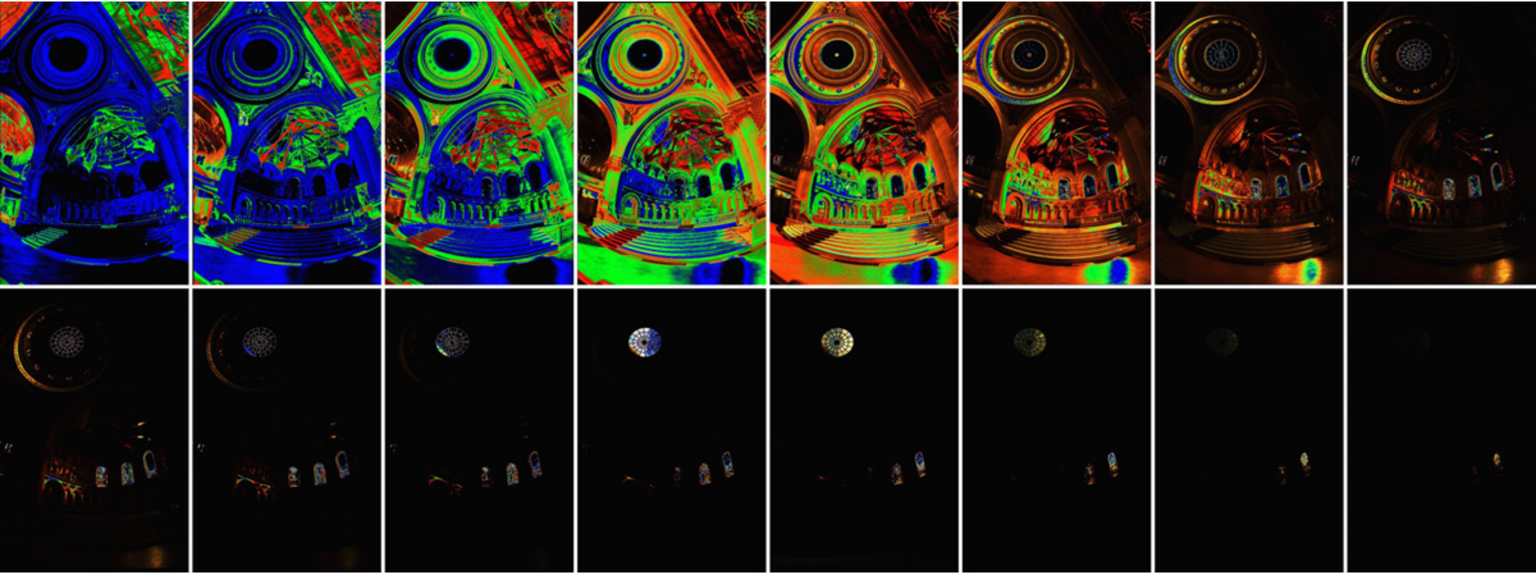
or mean pixel value, e.g. 127.5 if I in [0, 255]



HDRI – Merging LDR Exposures

- compute per-color-channel-per-LDR-pixel weights

$$w_{ij} = \exp\left(-4 \frac{\left(I_{lin_{ij}} - 0.5\right)^2}{0.5^2} \right)$$



HDRI – Merging LDR Exposures

- define least-squares objective function in log-space → perceptually linear: $$\underset{X}{\text{minimize}} \quad \text{O} = \sum_i w_i \left(\log\left(I_{lin_i}\right) - \log\left(t_i X\right) \right)^2$$

- equate gradient to zero:

$$\frac{\partial O}{\partial \log(X)} = -2 \sum_i w_i \left(\log\left(I_{lin_i}\right) - \log\left(t_i\right) - \log\left(X\right) \right) = 0$$

- gives: $$\widehat{X} = \exp\left(\frac{\sum_i w_i \left(\log\left(I_{lin_i}\right) - \log\left(t_i\right) \right)}{\sum_i w_i} \right)$$

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- gives:

$$\hat{X} = \exp\left(\frac{\sum_i w_i \left(\log\left(I_{lin_i}\right) - \log\left(t_i\right)\right)}{\sum_i w_i} \right)$$

HDRI – Relative v Absolute Radiance

- LDR to HDR only gives relative radiance
- scale by reference radiance to get absolute!

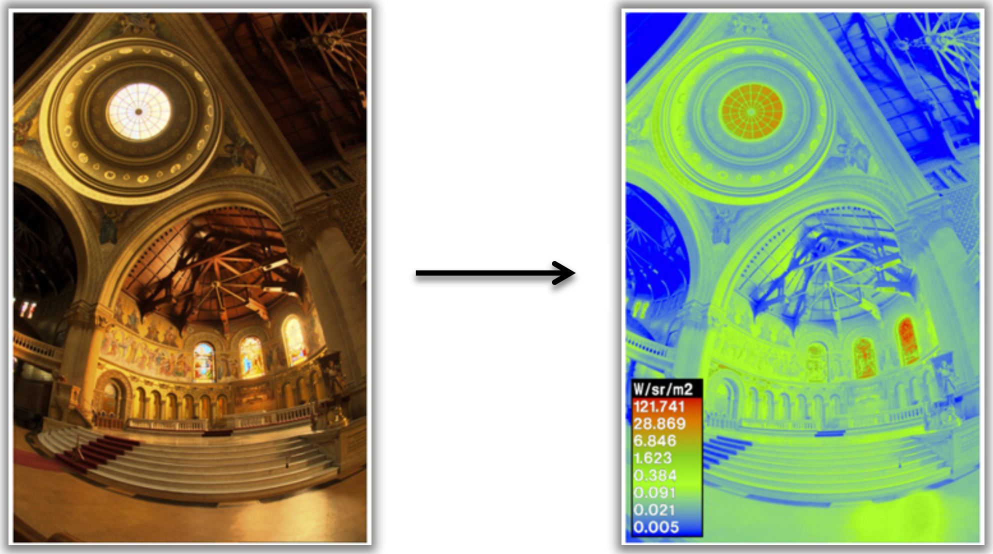


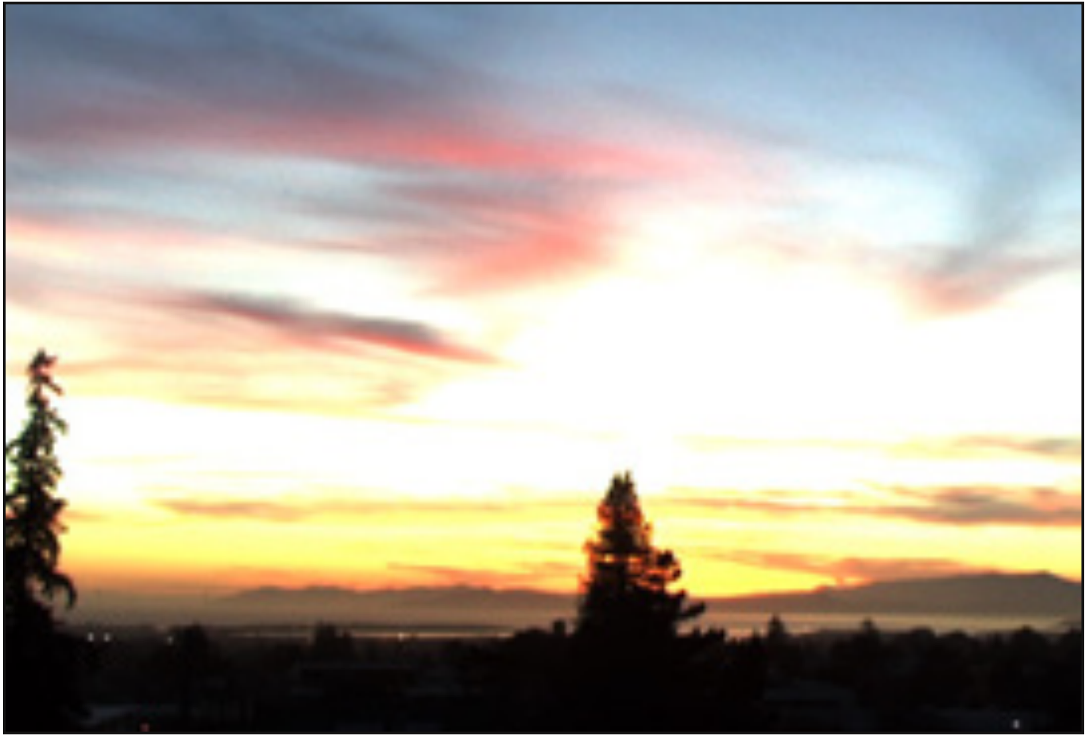
Image from Debevec & Malik, 1997

HDRI – Tone Mapping

- Problem: how to display a 32 bit HDR image on an 8 bit LDR display?
- Solution: tone mapping, i.e., “scale” into luminance range of display (or 0-255), while preserving high-contrast image details

Saturation

- sun overexposed
- foreground too dark



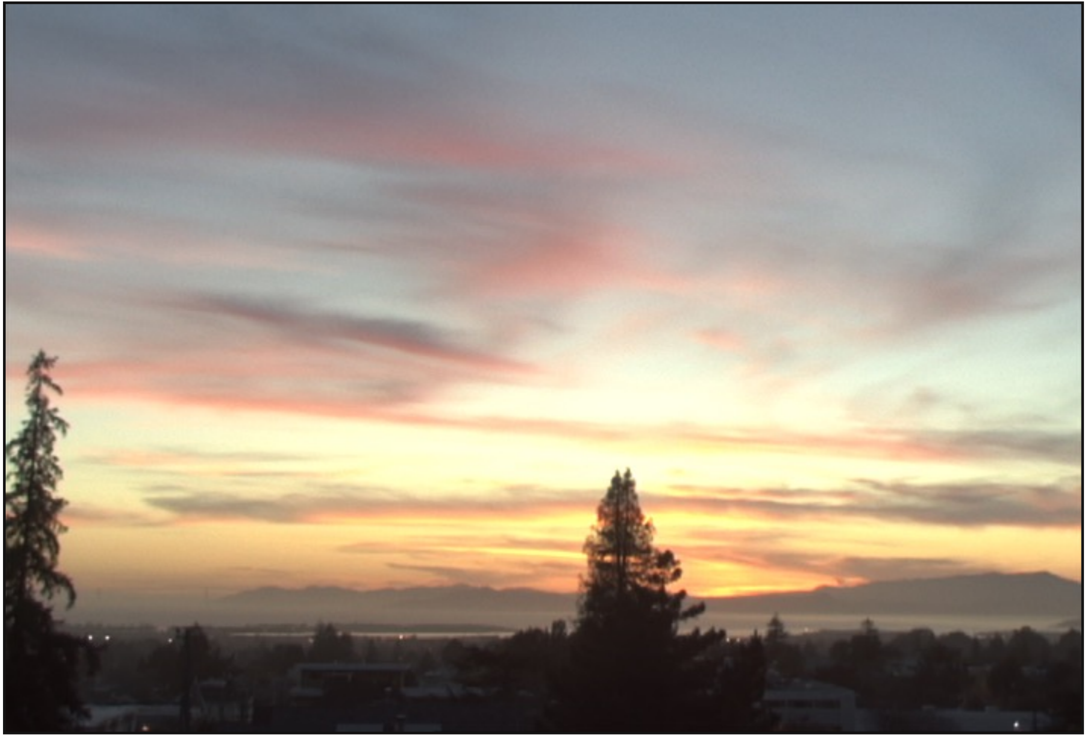
[Durand and Dorsey, 2002]

Tone Mapping w/ Simple Gamma

- gamma correction:

$$I = I^{\gamma}$$

- colors are washed out



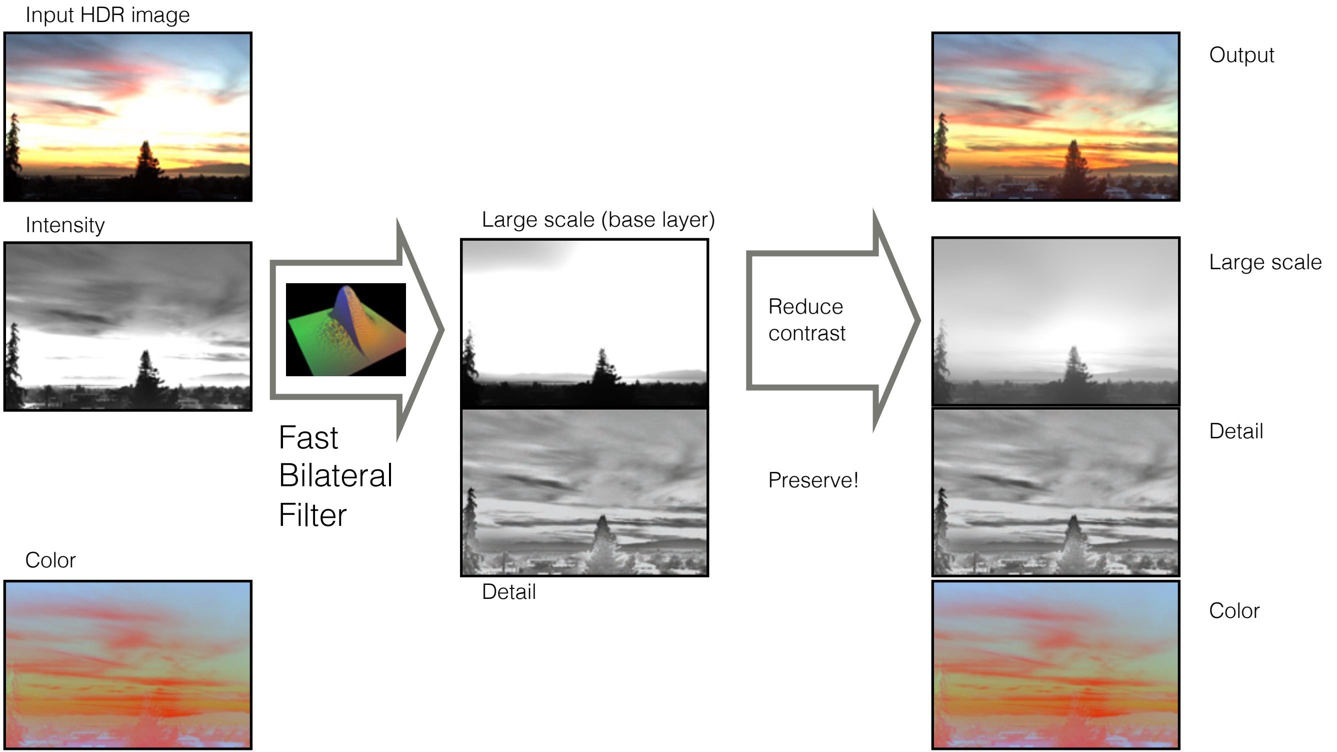
[Durand and Dorsey, 2002]

Tone Mapping w/ Simple Gamma

- gamma in intensity only!
- intensity details lost

[Durand and Dorsey, 2002]

Tone Mapping w/ Bilateral Filter



[Durand and Dorsey, 2002]

Tone Mapping w/ Bilateral Filter

[Durand et al., 2002]

Tone Mapping w/ Local Laplacian Filters

- Many many more and more complicated tone mapping algorithms out there (too many to discuss here)
- Local Laplacian Filters is one of the state-of-the-art approaches

(a) input HDR image tone-mapped with a simple gamma curve (details are compressed)

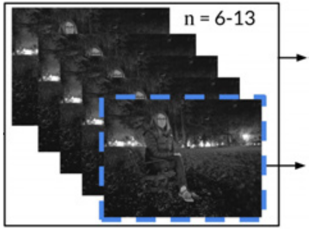
(b) our pyramid-based tone mapping, set to preserve details without increasing them

(c) our pyramid-based tone mapping, set to strongly enhance the contrast of details

[Paris et al., 2011]

Burst Denoising for Low-light Imaging

- Problem: too much (Poisson) noise in low-light conditions
- Solution: capture, align, and average multiple short exposures



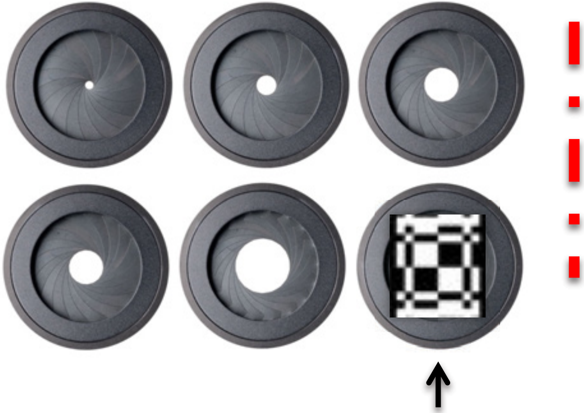
Guest lecture by Dr. Orly Liba from Google

Coded (Aperture) Computational Imaging

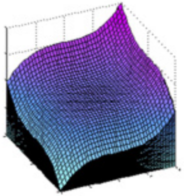
Camera Aperture Revisited

A camera aperture has (at least) two parts that can be "coded":

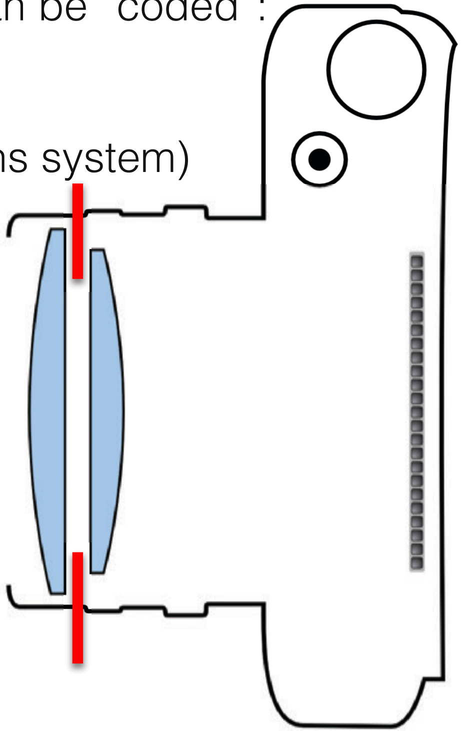
1. aperture stop – attenuating pattern
2. refractive elements (lens or compound lens system)



1. attenuating coded aperture

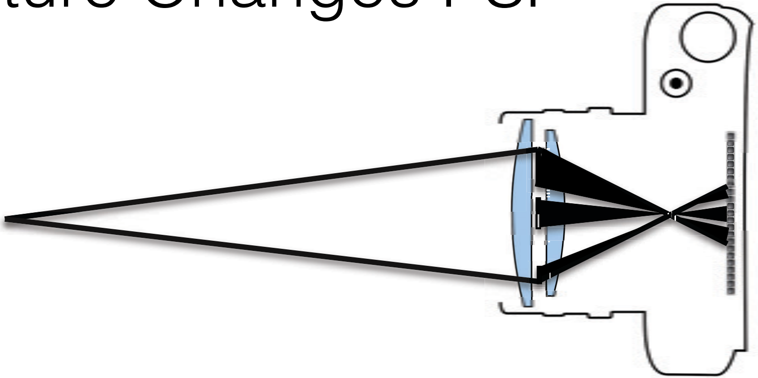


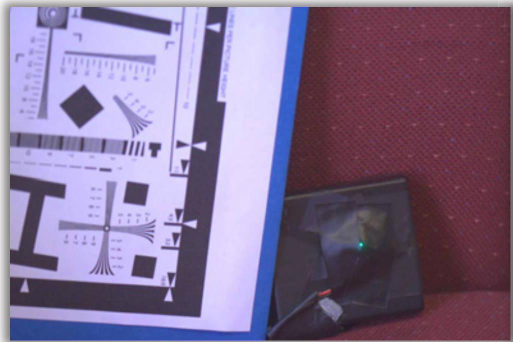
2. refractive or diffractive coded aperture or lens system



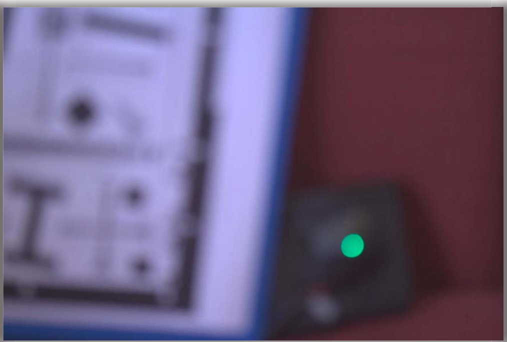
Coded Aperture Changes PSF

[Veeraragharavan et al. 2007]

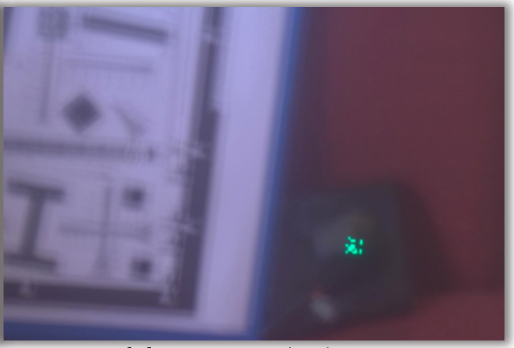




in-focus photo



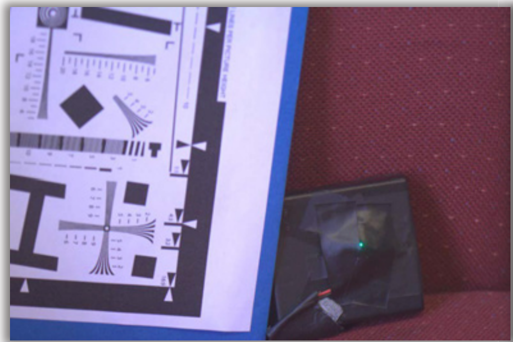
out-of-focus, circular aperture



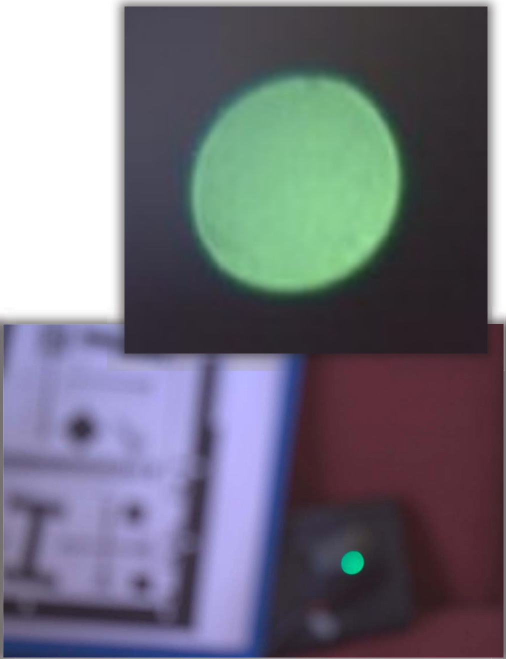
out-of-focus, coded aperture

Coded Aperture Changes PSF

[Veeraraghavan et al. 2007]



in-focus photo



out-of-focus, circular aperture

out-of-focus, coded aperture

Coded (Aperture) Imaging

Applications of *Coded Aperture Imaging*:

- Extended depth of field
- Monocular depth estimation

Applications of *Coded Imaging* in General:

- Motion deblurring
- High-speed, hyperspectral, light field, single-pixel imaging …

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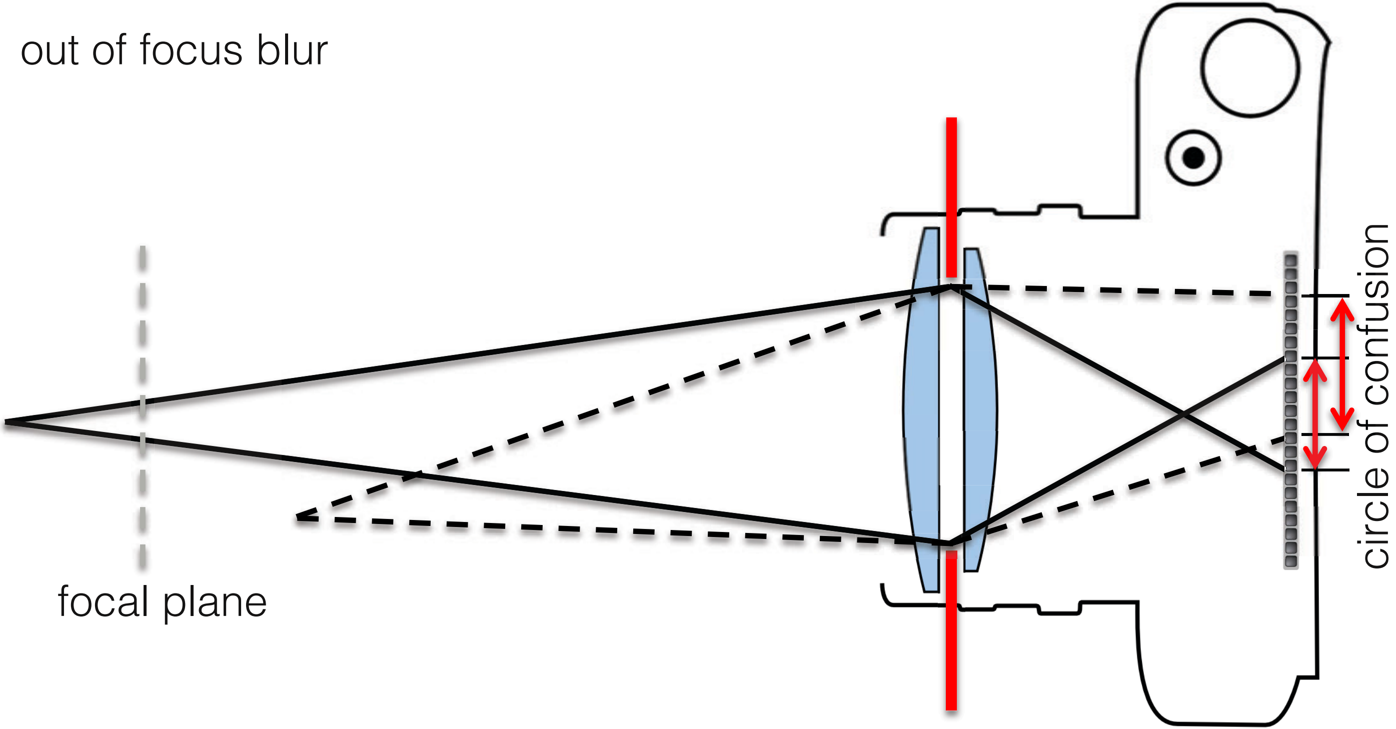
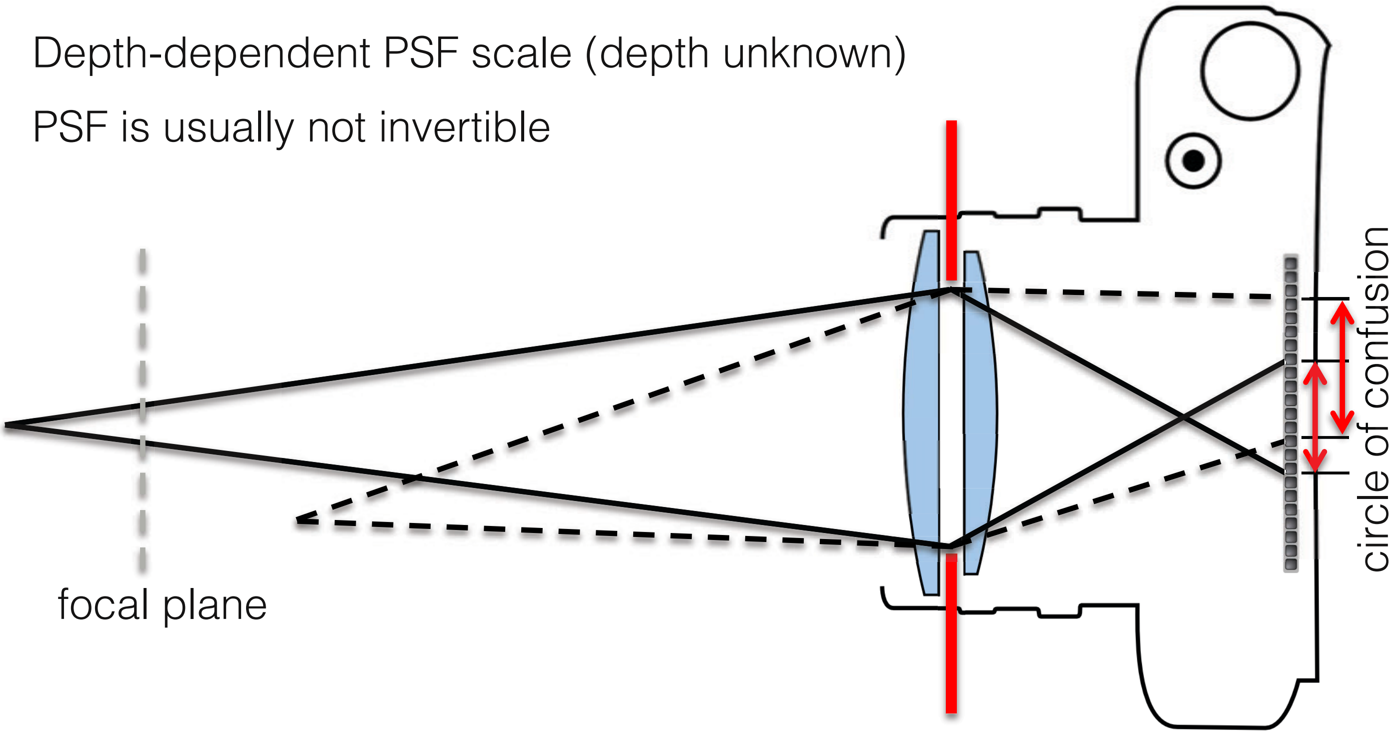
What makes Defocus Deblurring Hard?

- out of focus blur



What makes Defocus Deblurring Hard?

1. Depth-dependent PSF scale (depth unknown)
2. PSF is usually not invertible



Extended Depth of Field

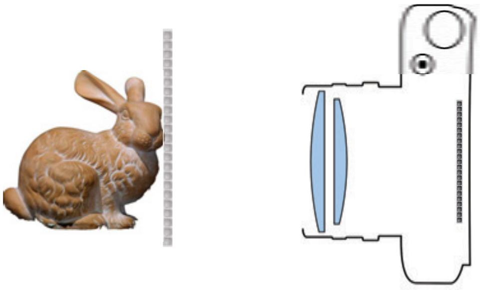
1. Problem: depth-dependent PSF scale (depth unknown)
    - engineer PSF to be depth invariant
    - resulting shift-invariant deconvolution is much easier!

2. Problem: circular / Airy PSF is usually not invertible: ill-posed problem
    - engineer PSF to be broadband (flat Fourier magnitudes)
    - resulting inverse problem becomes well-posed

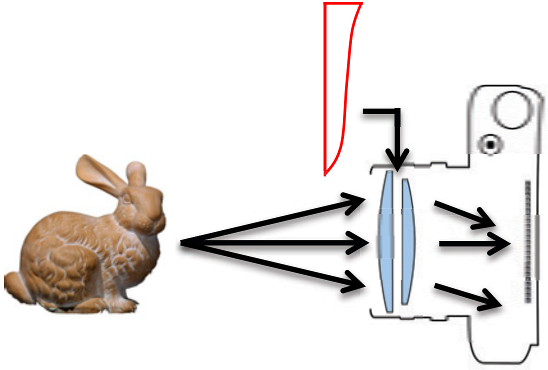
Extended Depth of Field

- Two general approaches for engineering depth-invariant PSFs:

1. <u>move sensor / object</u>
(known as focal sweep)



2. <u>change optics</u>
(e.g., wavefront coding)



Extended Depth of Field – Focal Sweep

captured focal sweep
always blurry!

EDOF image

conventional photo
(small DOF)

conventional photo
(large DOF, noisy)

[Nagahara et al. 2008]

Extended Depth of Field – Focal Sweep

- noise characteristics are main benefit of EDOF
- may change for different sensor noise characteristics

SNR should be evaluation metric!

EDOF image

conventional photo (large DOF, noisy)

[Nagahara et al. 2008]

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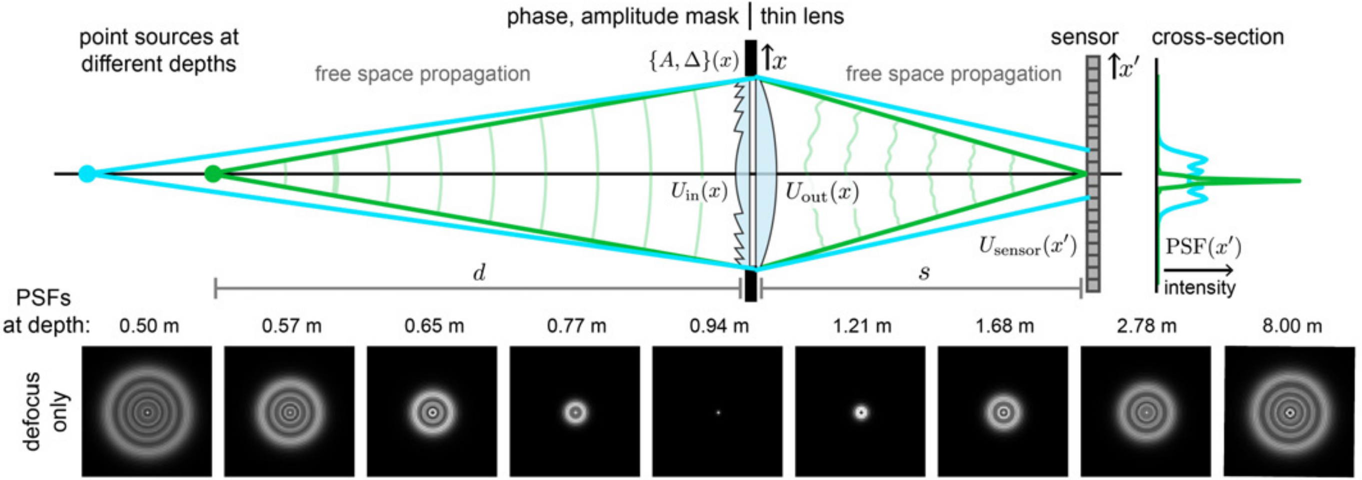
Monocular Depth Estimation

[Godard et al., 2017]

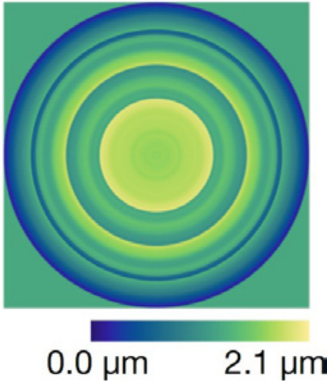
- Problem: 3D/depth cameras are hard
- Solution: a single image contains a lot of depth cues – learn to use them for depth estimation (like humans)

Coded Apertures for Depth Estimation



[Chang and Wetzstein, 2019]

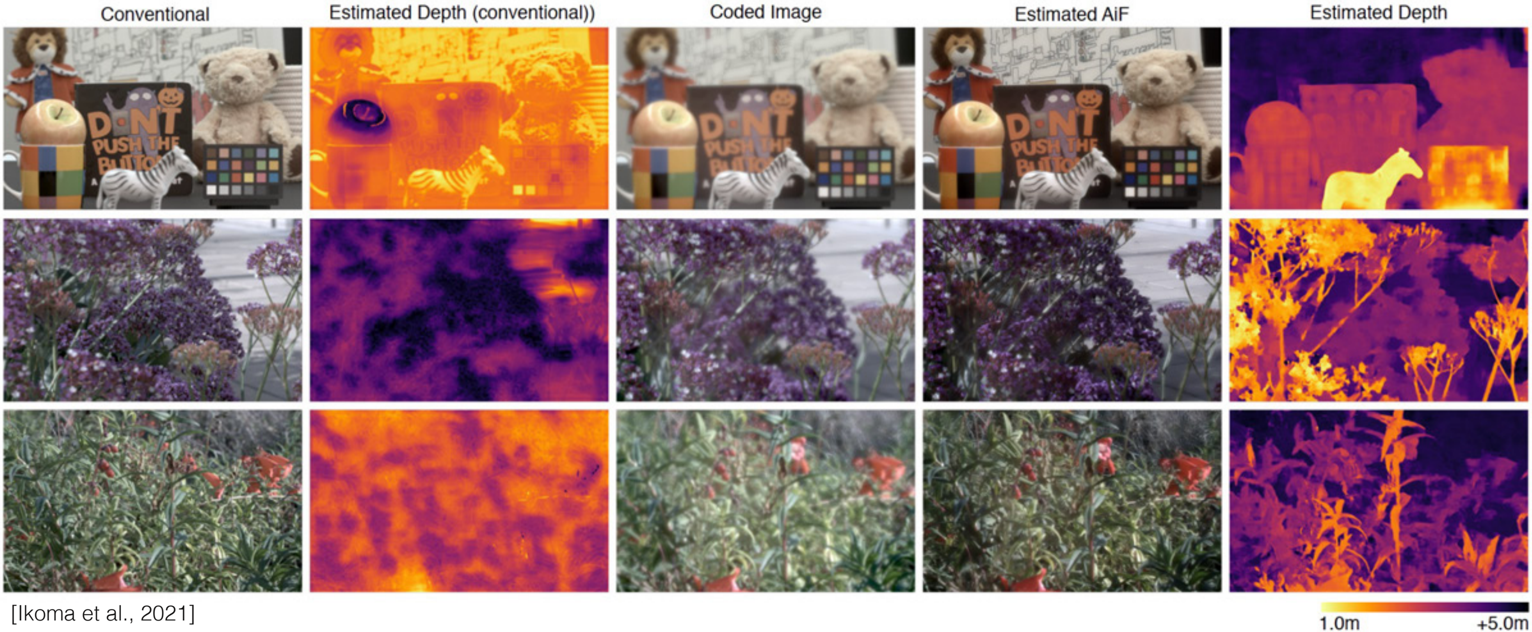
Coded Apertures for Depth Estimation



[Ikoma et al., 2021]

Coded Apertures for Depth Estimation

- PSF engineering can make depth estimation more robust by encoding low-level depth information in the PSF (rather than just pictorial cues)



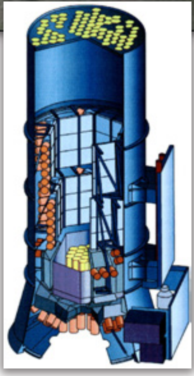
[Ikoma et al., 2021]

Coded Apertures in Astronomy

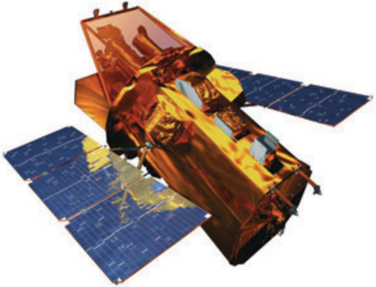
- some wavelengths are difficult to focus

→ no "lenses" available

- coded apertures for x-rays and gamma rays



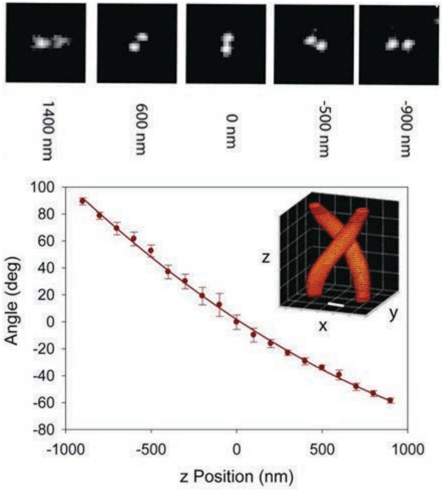
ESA SPI / INTEGRAL



NASA Swift

Coded Apertures in Microscopy

- for low-light, coding of refraction is better (less light loss)



e.g., rotating double helix PSF
Stanford Moerner lab

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Applications of *Coded Imaging* in General:

- Motion deblurring
- High-speed, hyperspectral, light field, single-pixel imaging …

Motion Blur and Deblurring

- Problem: objects that move throughout exposure time will be blurred
- Motion deblurring is hard because:
    1. Motion PSF may be unknown and different for different object
    2. Motion PSF is difficult to invert

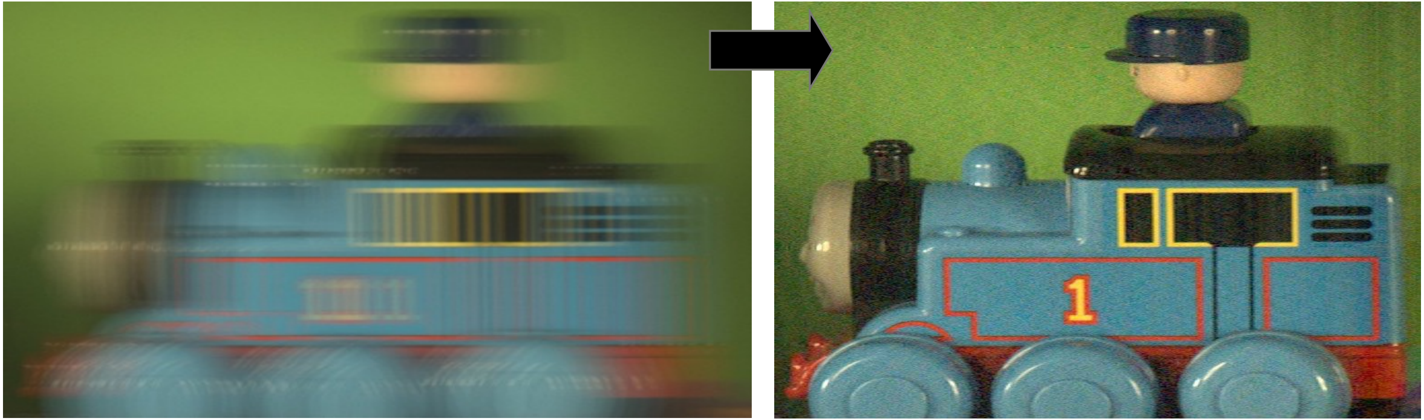
Blurred input image

Deblurred image

[Shan et al. 2008]

Motion Deblurring w/ Flutter Shutter

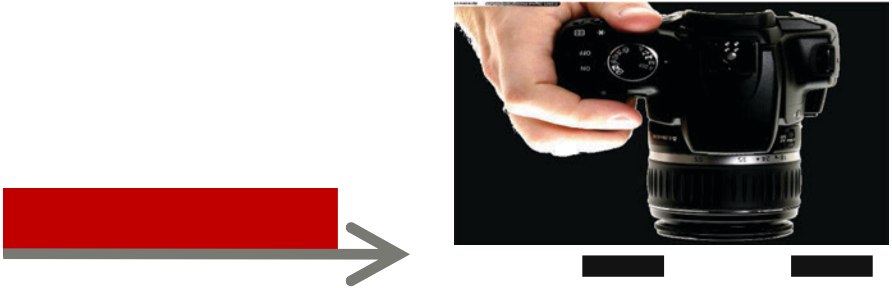
- engineer motion PSF (coding exposure time) so it becomes invertible!



Input Photo

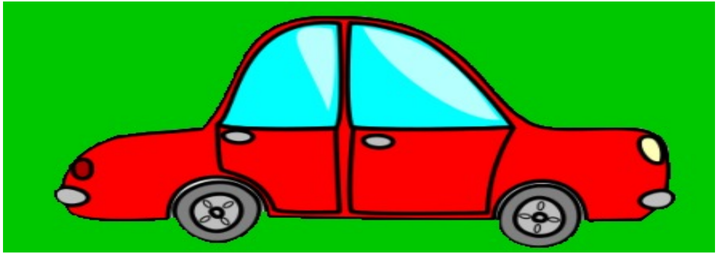
Deblurred Result

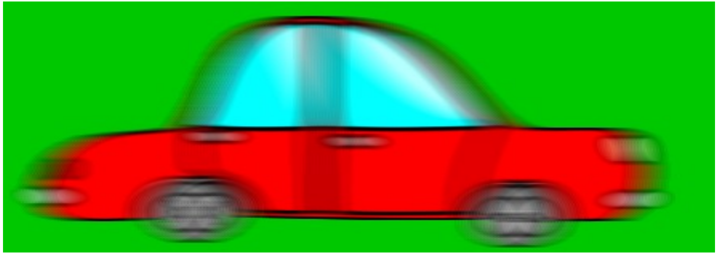
[Raskar et al. 2006]



Traditional Camera:

Shutter is OPEN

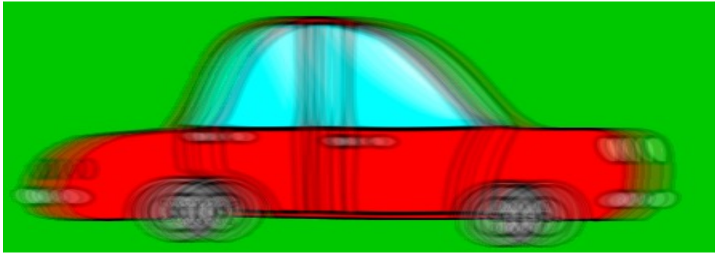




[Raskar et al. 2006]

Flutter Shutter Camera:

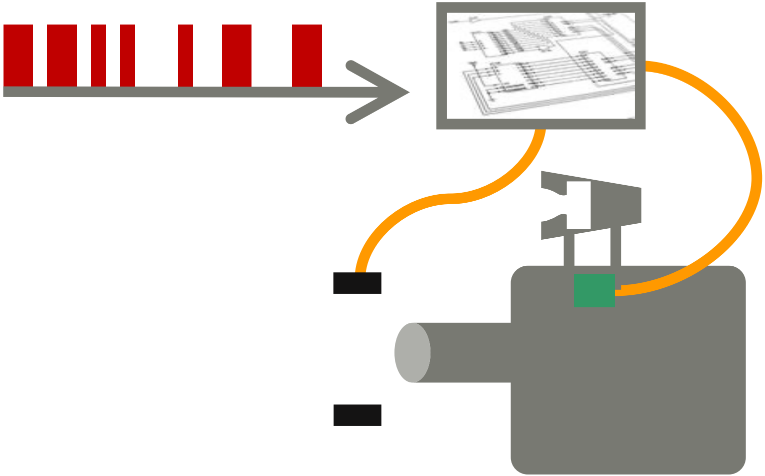
Shutter is OPEN & CLOSED



[Raskar et al. 2006]

Inspired by Harold “Doc” Edgerton

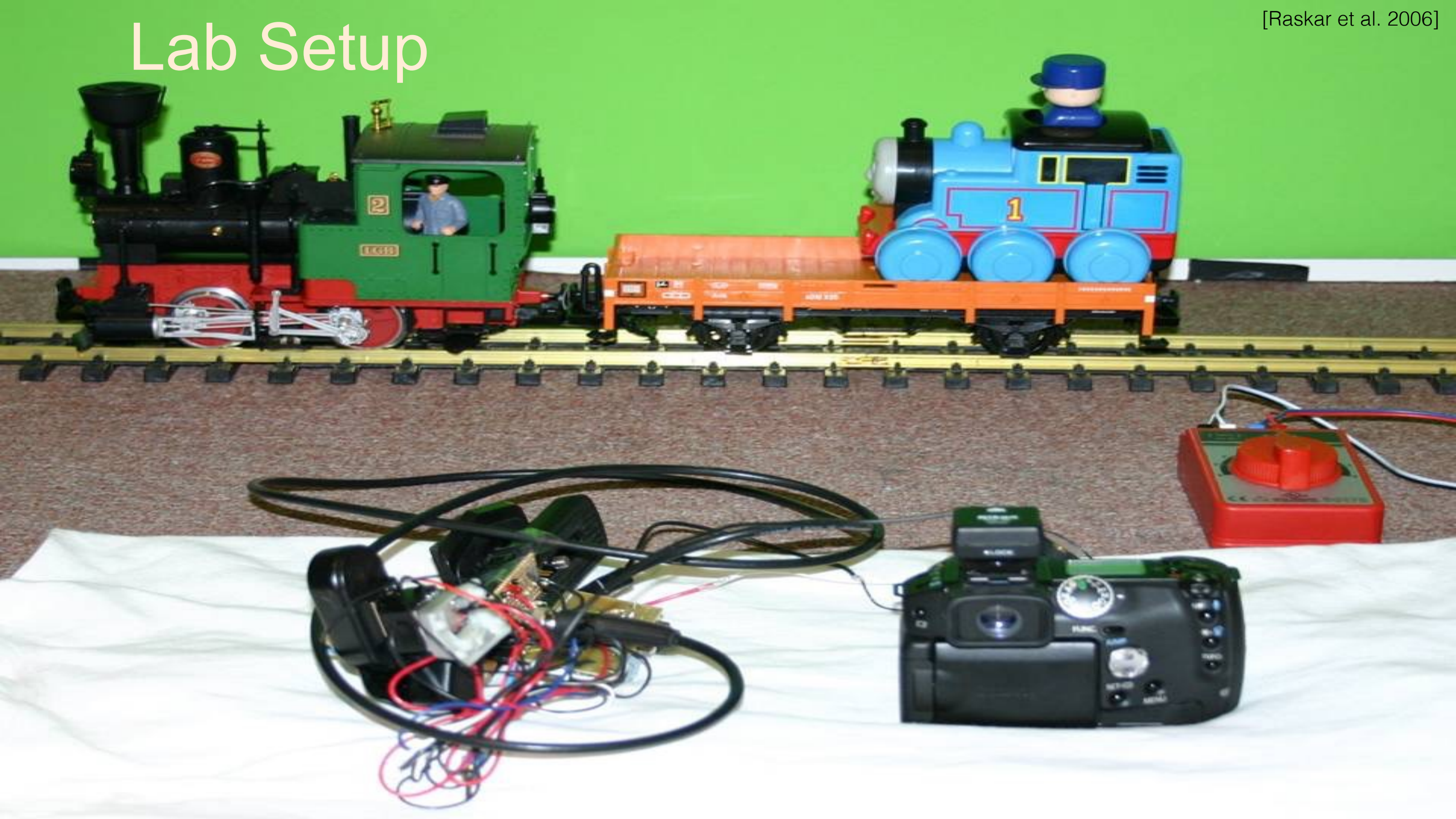
[Raskar et al. 2006]



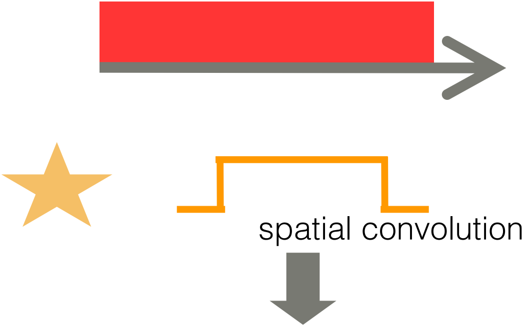
[Raskar et al. 2006]

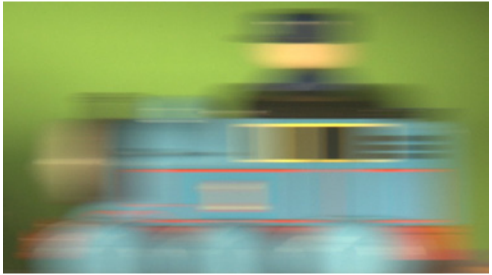
Lab Setup

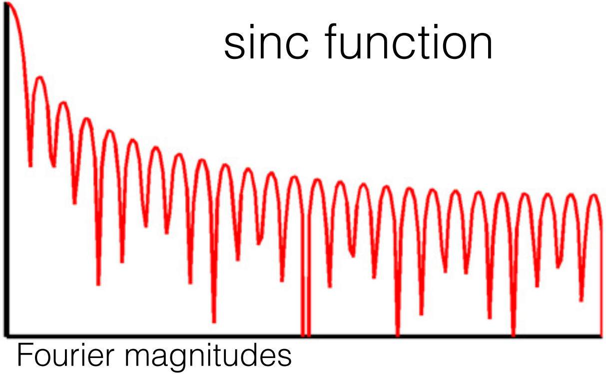
[Raskar et al. 2006]



[Raskar et al. 2006]







Blurring

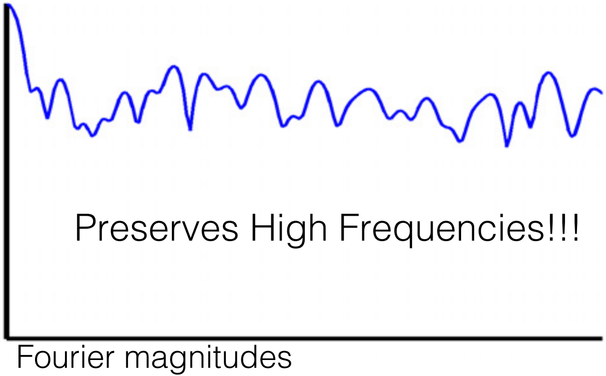
=

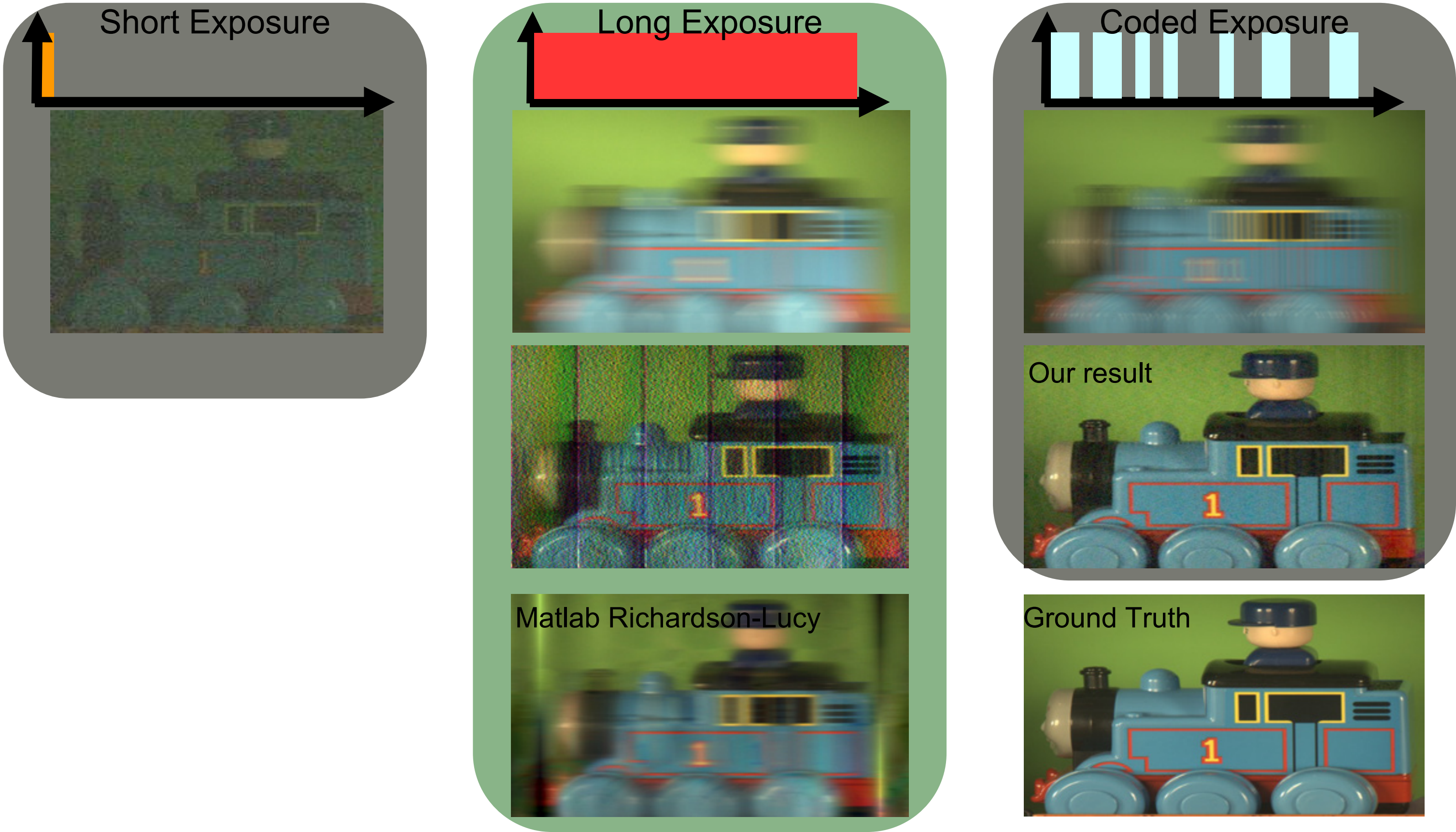
Convolution

Traditional Camera: Box Filter

Flutter Shutter: Coded Filter

[Raskar et al. 2006]




Short Exposure
Long Exposure
Coded Exposure
Our result
Matlab Richardson-Lucy
Ground Truth

[Raskar et al. 2006]

License Plate Retrieval

[Raskar et al. 2006]

License Plate Retrieval

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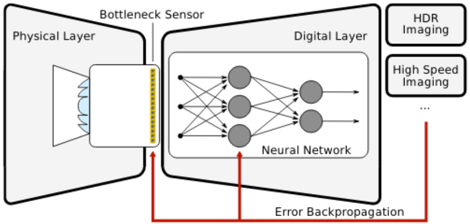
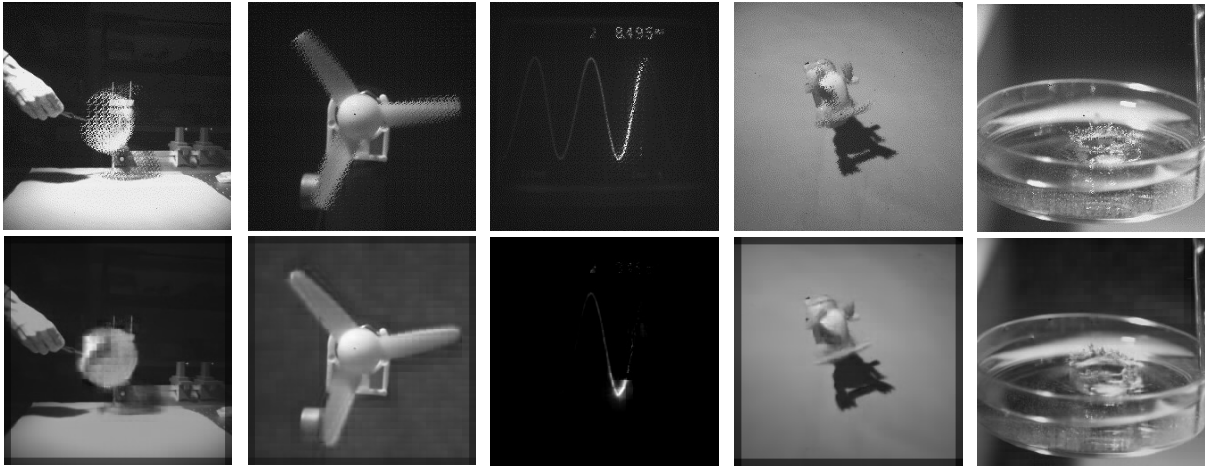
Coded Imaging with Neural Sensors



Coded Measurements

Reconstructions



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