

# Great Ideas in Computational Photography

HDR Imaging, Tone Mapping, Coded Apertures & Imaging

EE367/CS448I: Computational Imaging

[stanford.edu/class/ee367](http://stanford.edu/class/ee367)

Lecture 6

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# Computational Photography on your Phone

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







exposure sequence





# Motivation

wikipedia



HDR  
contrast  
reduction  
(scaling)



# 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

4.25 $\mu$ m



12,000e<sup>-</sup>

6.5 $\mu$ m



45,000e<sup>-</sup>  
(~3.8X more e<sup>-</sup>)

11 $\mu$ m



80,000e<sup>-</sup>  
(~6.3X more e<sup>-</sup>)

## Terminology:

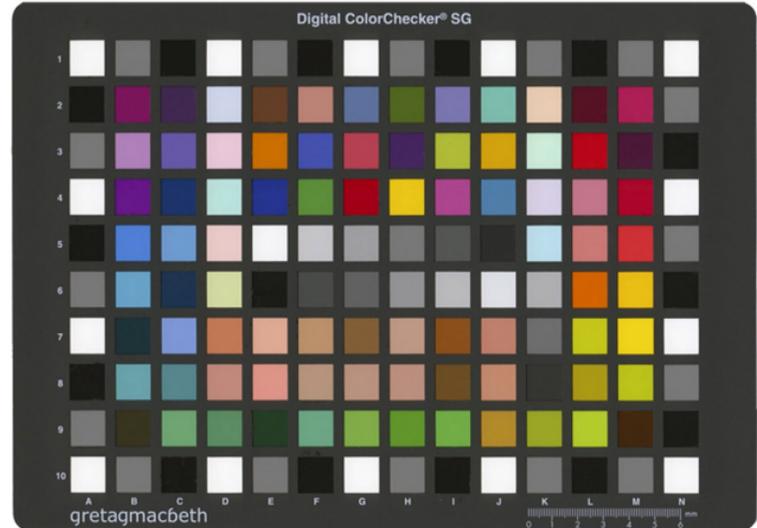
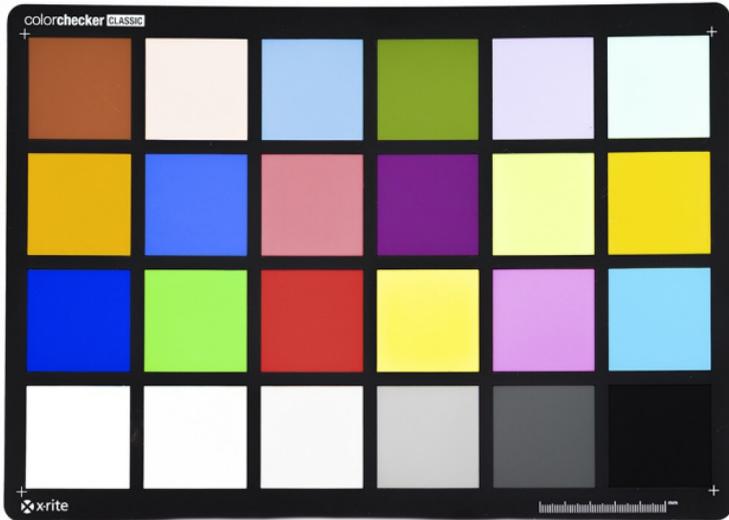
- dynamic range: ratio between brightest and darkest value
- quantization (i.e., precision) within that range is equally important  
→ from 8 bits (256 values) to 32 bits floating point

# 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)

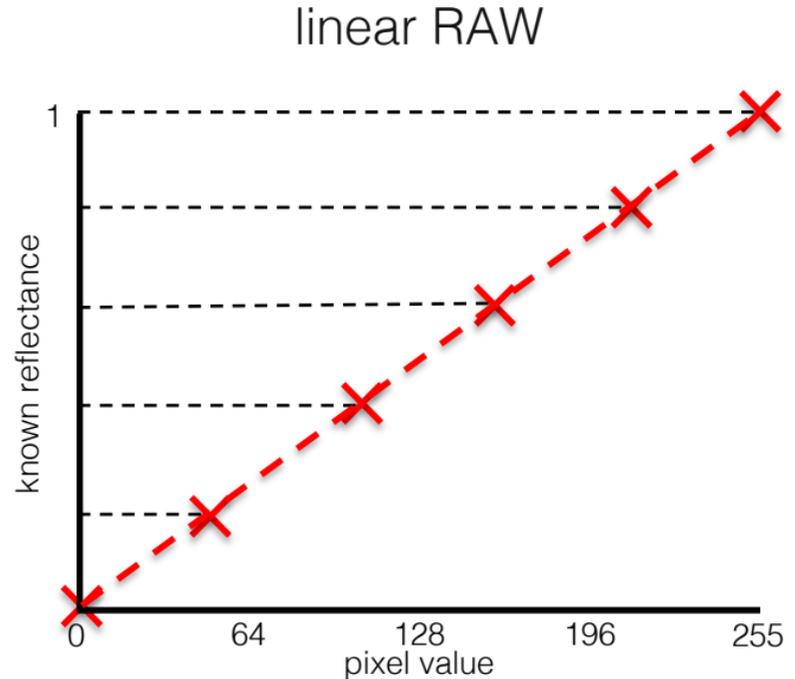
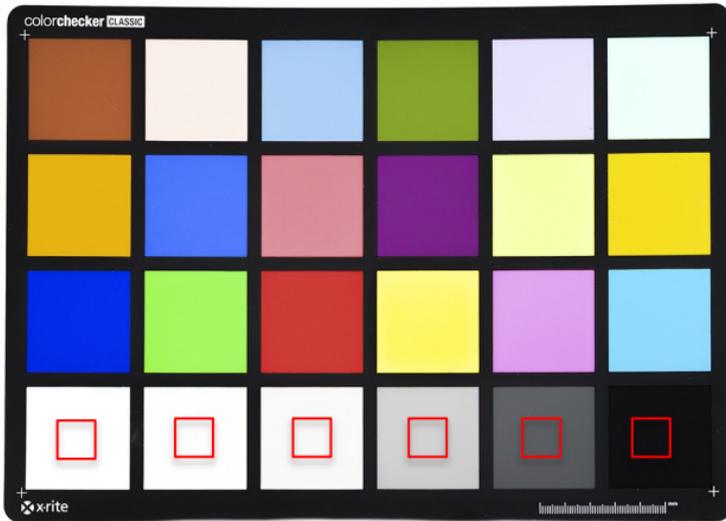
# HDRI – Estimating the Response Curve

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



# HDRI – Estimating the Response Curve

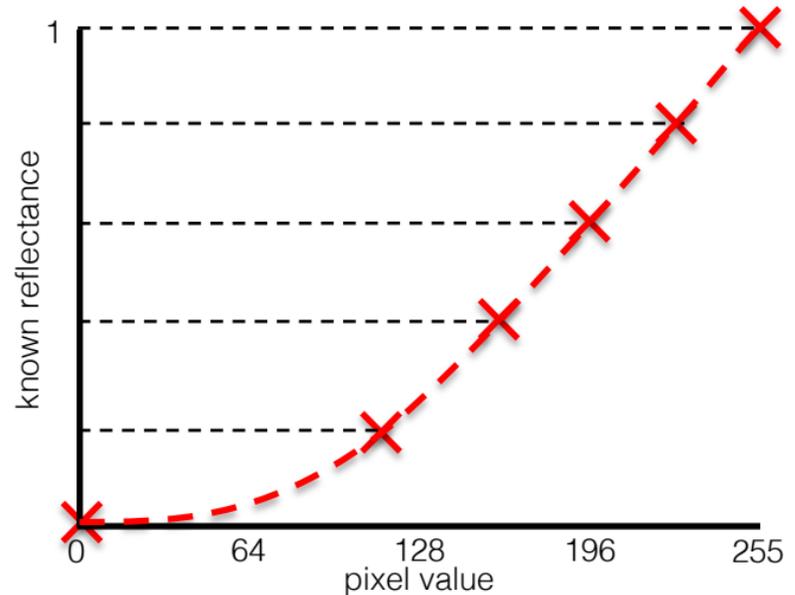
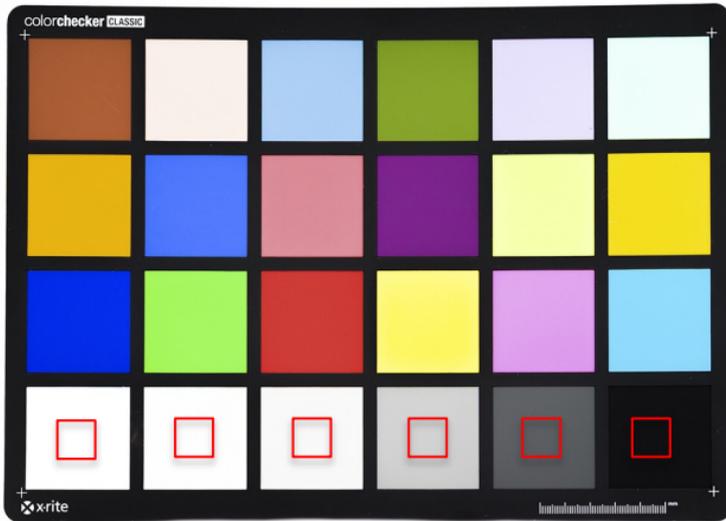
- not required when working with linear RAW images
- easiest option: use calibration chart



# HDRI – Estimating the Response Curve

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

e.g. JPEG



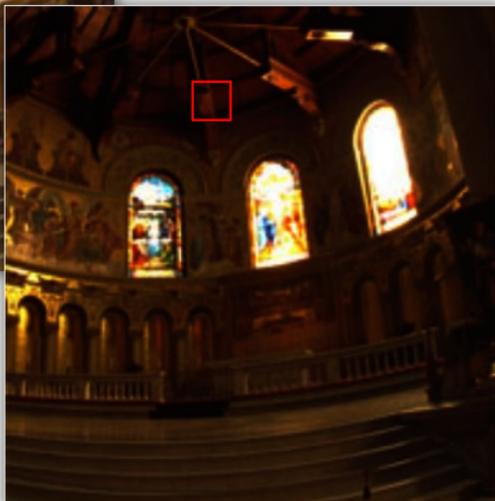
# HDRI – Linearizing LDR Exposures

- capture exposure, apply lookup table

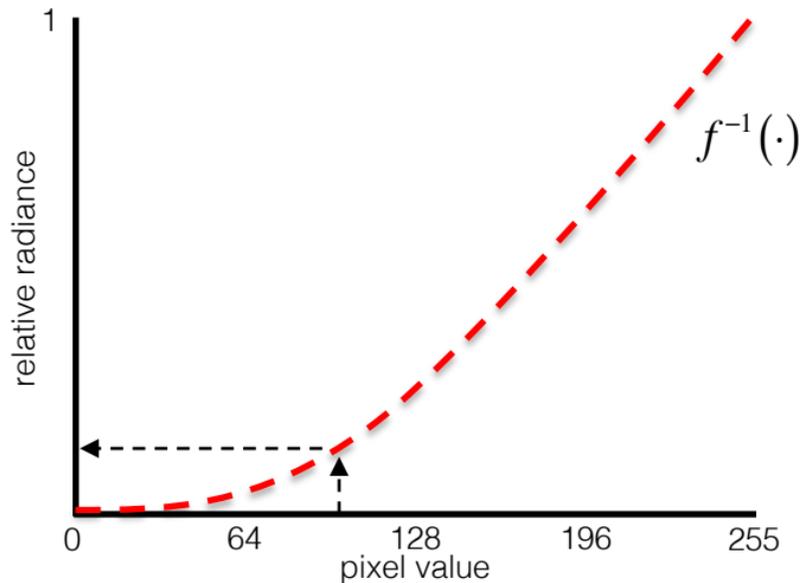


$I$

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

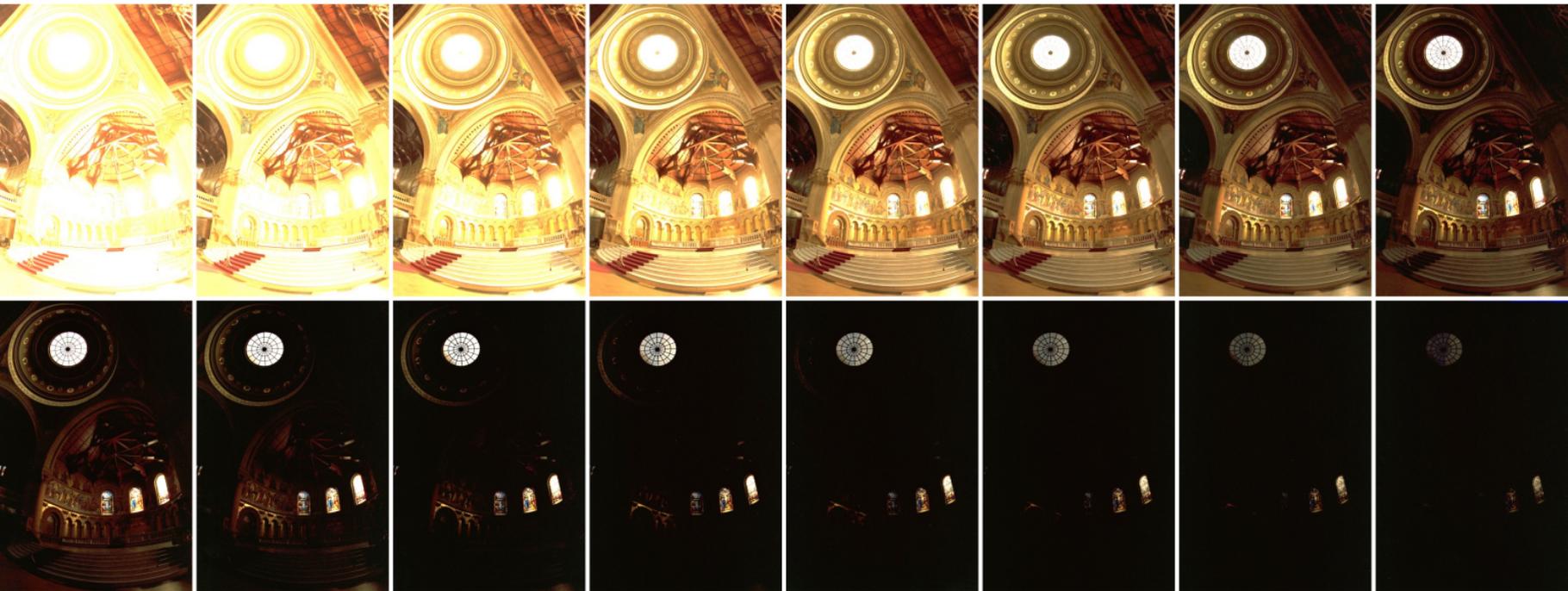


e.g. JPEG



# HDRI – Merging LDR Exposures

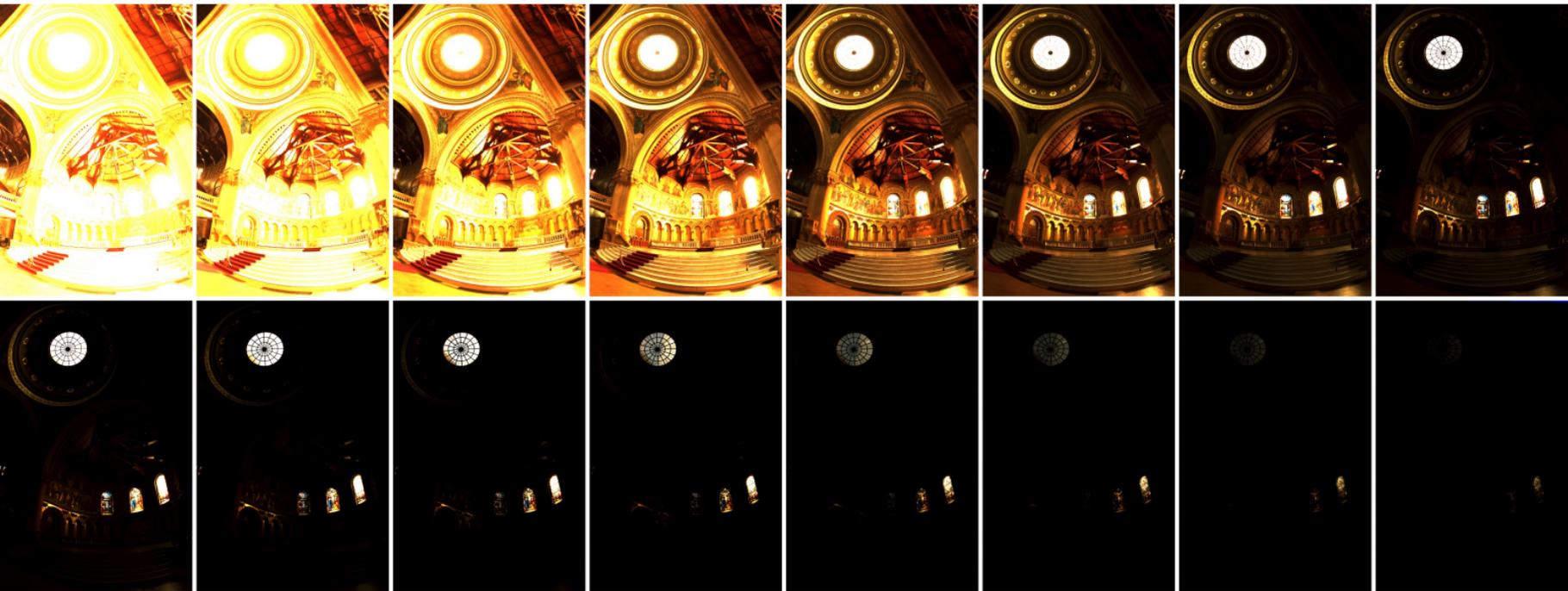
- start with LDR image sequence  $I_i$  (only exposure time  $t_i$  changes)
- individual exposure is:  $I_i = f(t_i, X)$ ,  $f$  is camera response function



# HDRI – Merging LDR Exposures

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

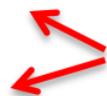
e.g., gamma function  $f(I) = I^{1/\gamma} \rightarrow f^{-1}(I) = I^\gamma$



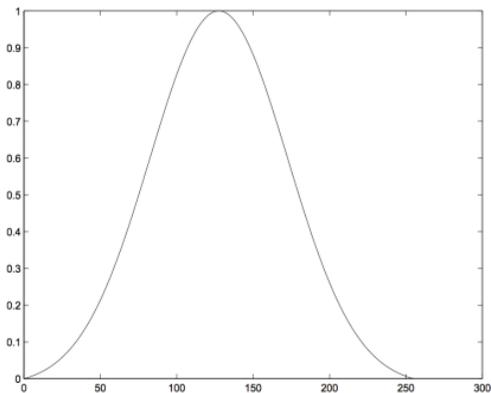
# HDRI – Merging LDR Exposures

- compute a weight (confidence) that a pixel is well-exposed  
→ (close to) saturated pixel = not confident, pixel in center of dynamic range = confident!

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



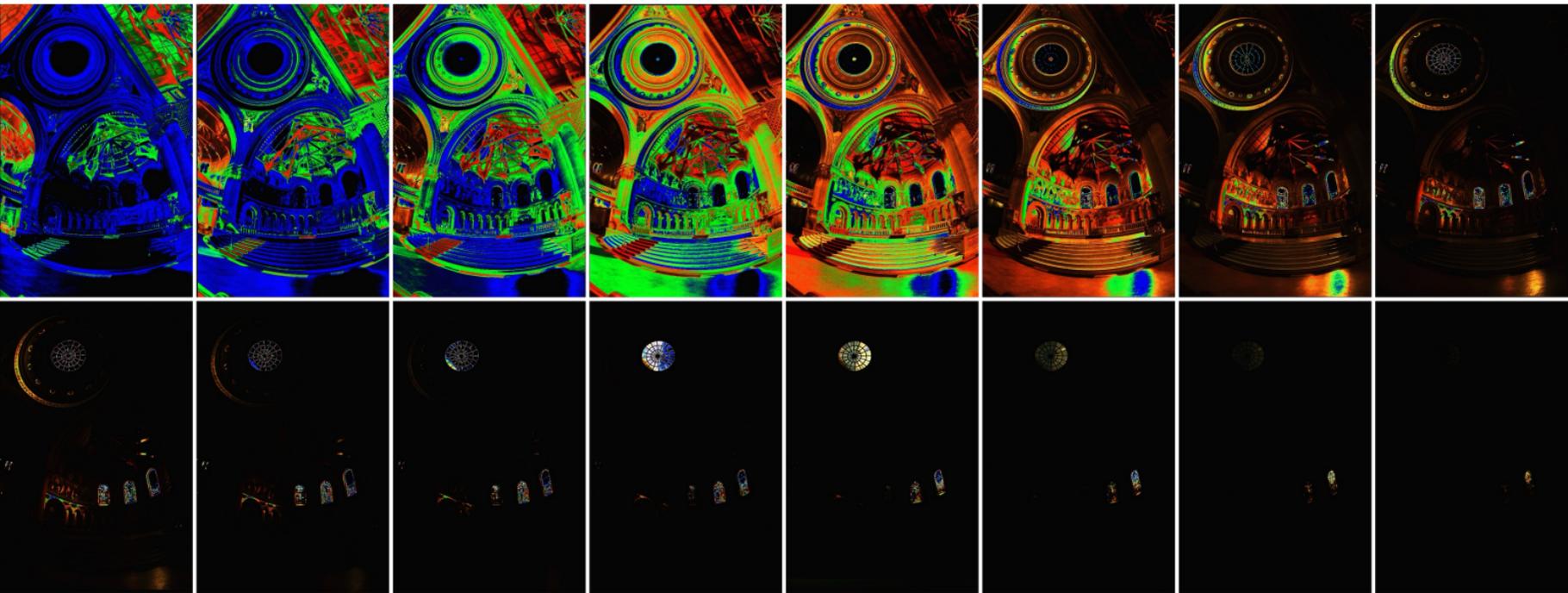
or mean pixel value,  
e.g. 127.5 if I in [0, 255]



# HDRI – Merging LDR Exposures

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

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



# HDRI – Merging LDR Exposures

- define least-squares objective function in log-space  $\rightarrow$  perceptually

linear: 
$$\underset{X}{\text{minimize}} \quad \mathcal{O} = \sum_i w_i \left( \log(I_{lin_i}) - \log(t_i X) \right)^2$$

- equate gradient to zero:

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

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

# HDRI – Merging LDR Exposures

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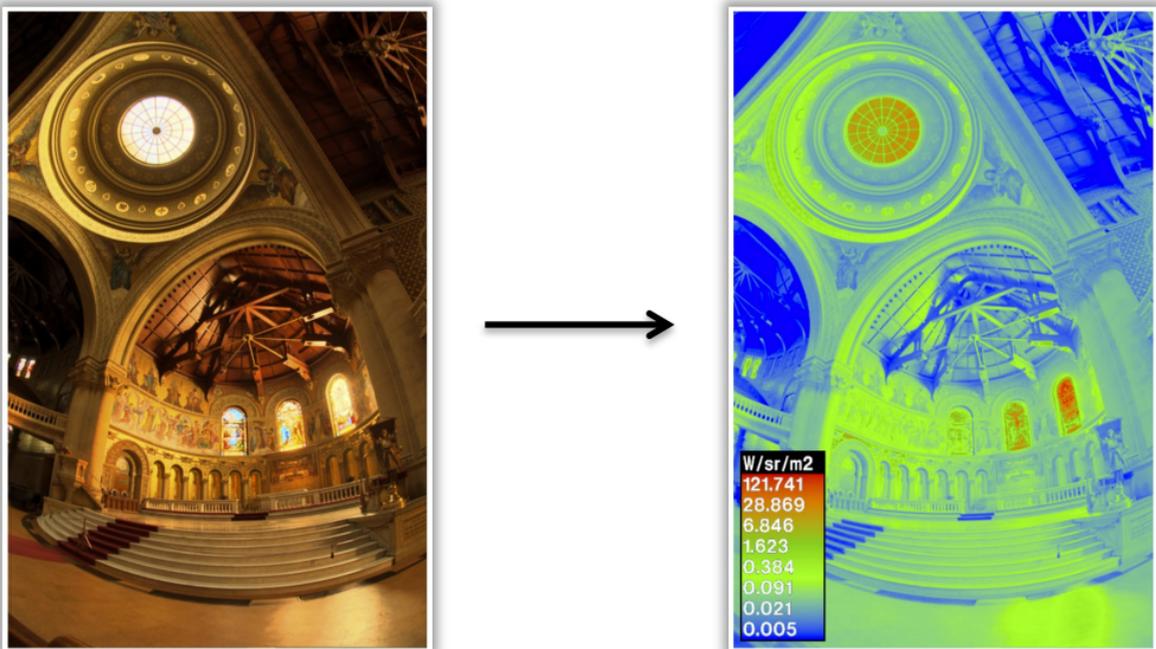
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- gives:

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# HDRI – Relative v Absolute Radiance

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



# 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



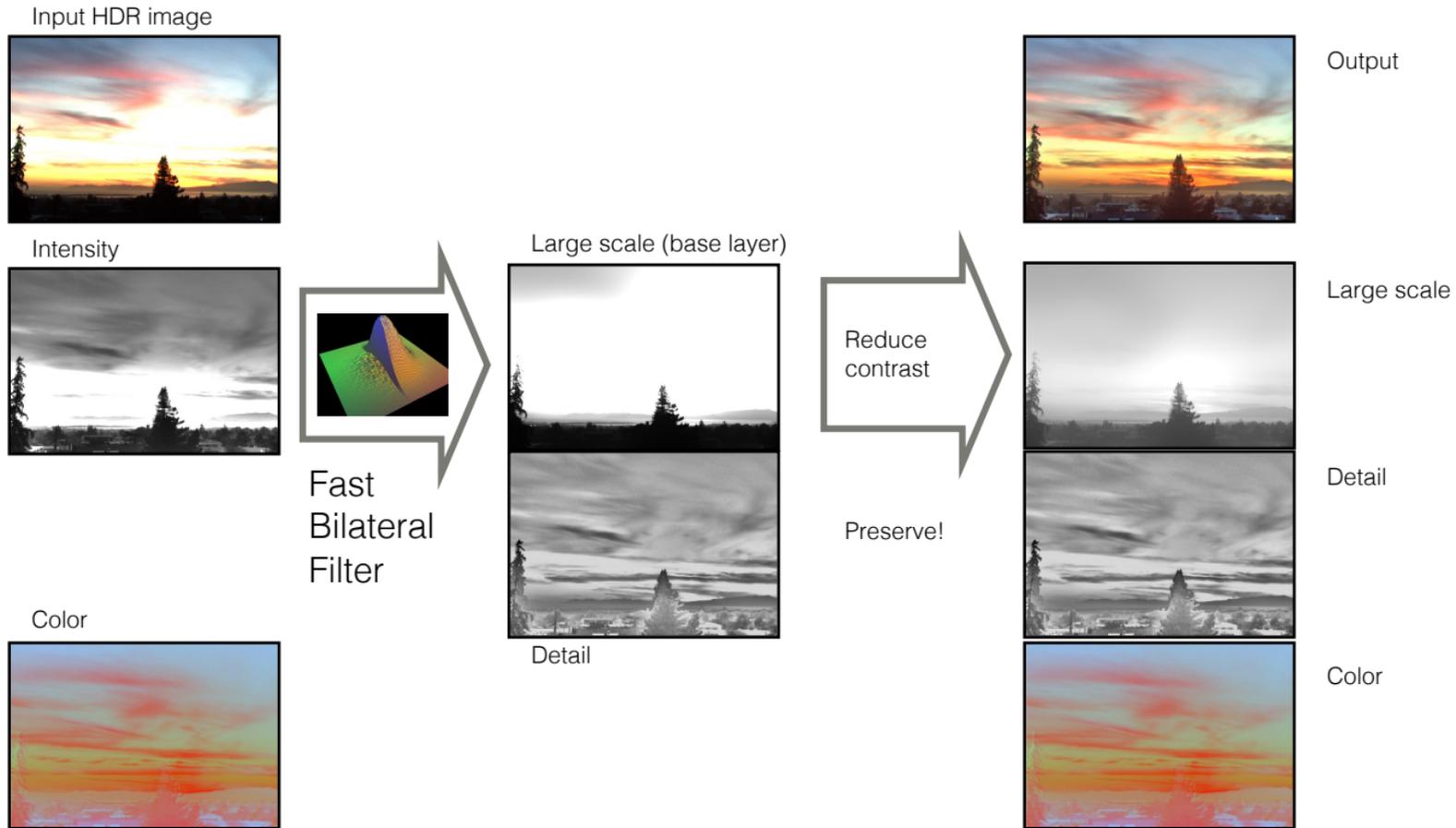
# Tone Mapping w/ Simple Gamma



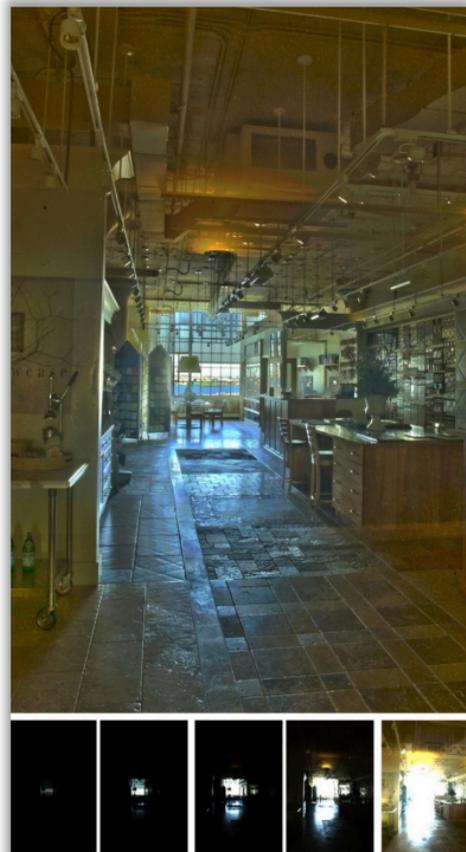
- gamma in intensity only
- intensity details lost



# Tone Mapping w/ Bilateral Filter

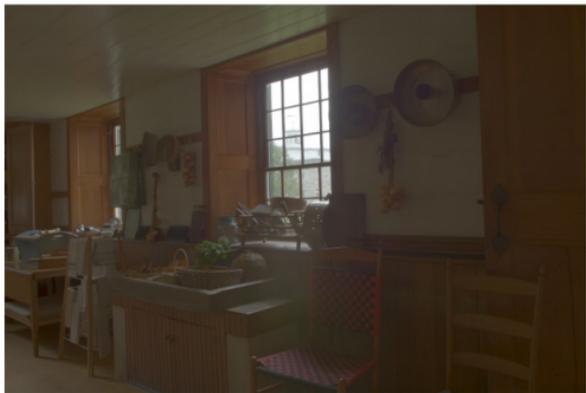


# Tone Mapping w/ Bilateral Filter



# 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)



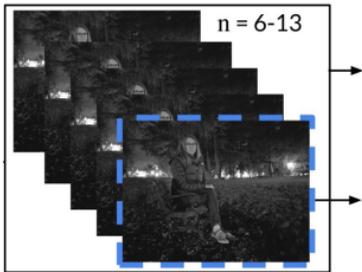
(b) our pyramid-based tone mapping, set to preserve details without increasing them



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

# 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

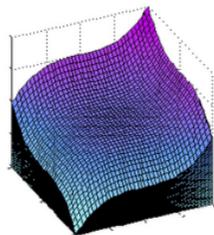
# Camera Aperture Revisited

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

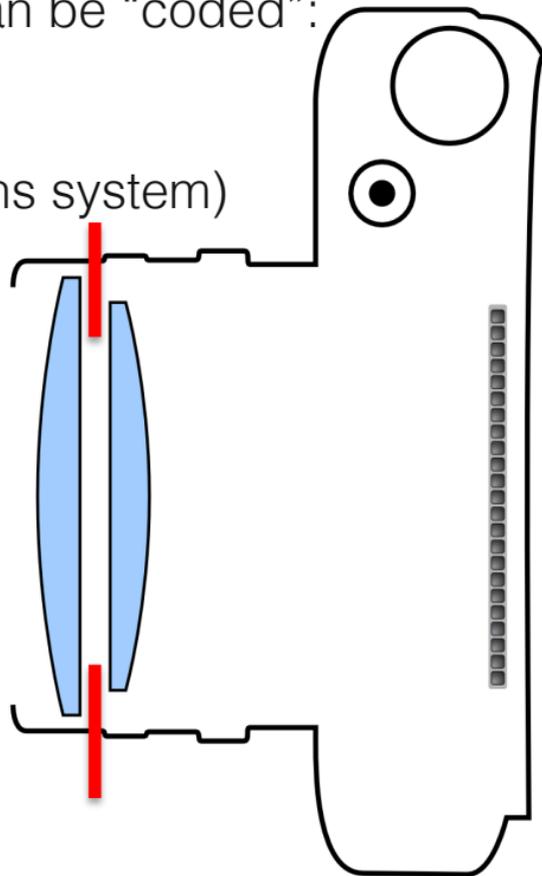
1. aperture stop – attenuating pattern
2. refractive elements (lens or compound lens system)



1. attenuating coded aperture

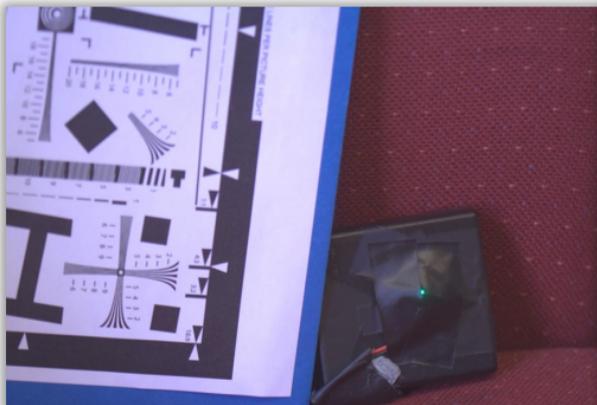
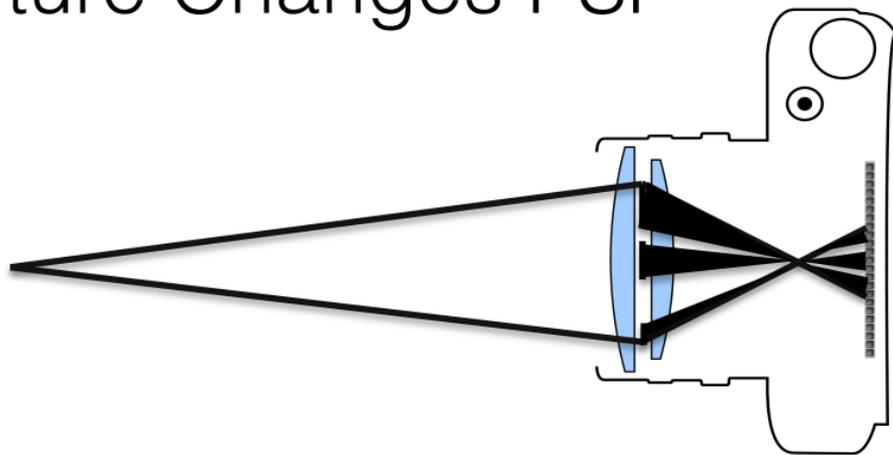


2. refractive or diffractive coded aperture or lens system

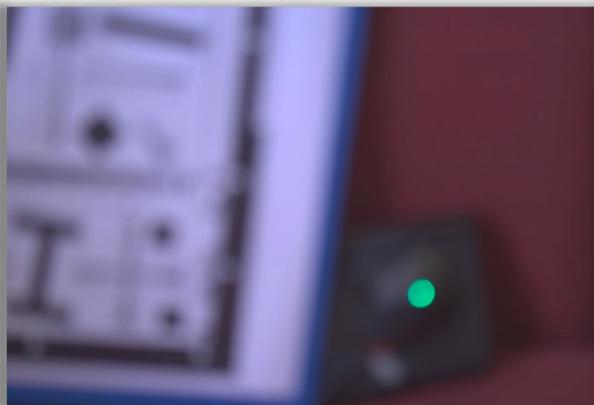


# Coded Aperture Changes PSF

[Veeraraghavan et al. 2007]



in-focus photo



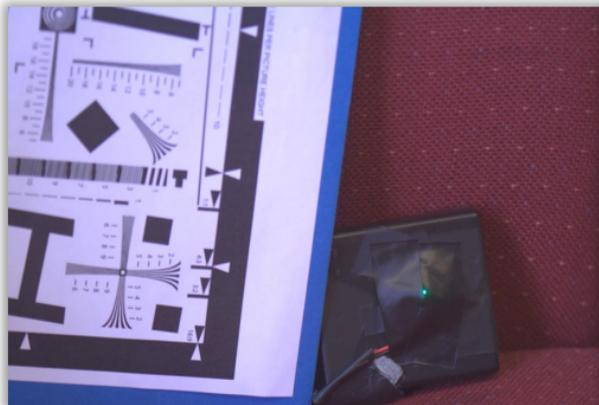
out-of-focus, circular aperture



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 ...

# Coded (Aperture) Imaging

Applications of *Coded Aperture Imaging*:

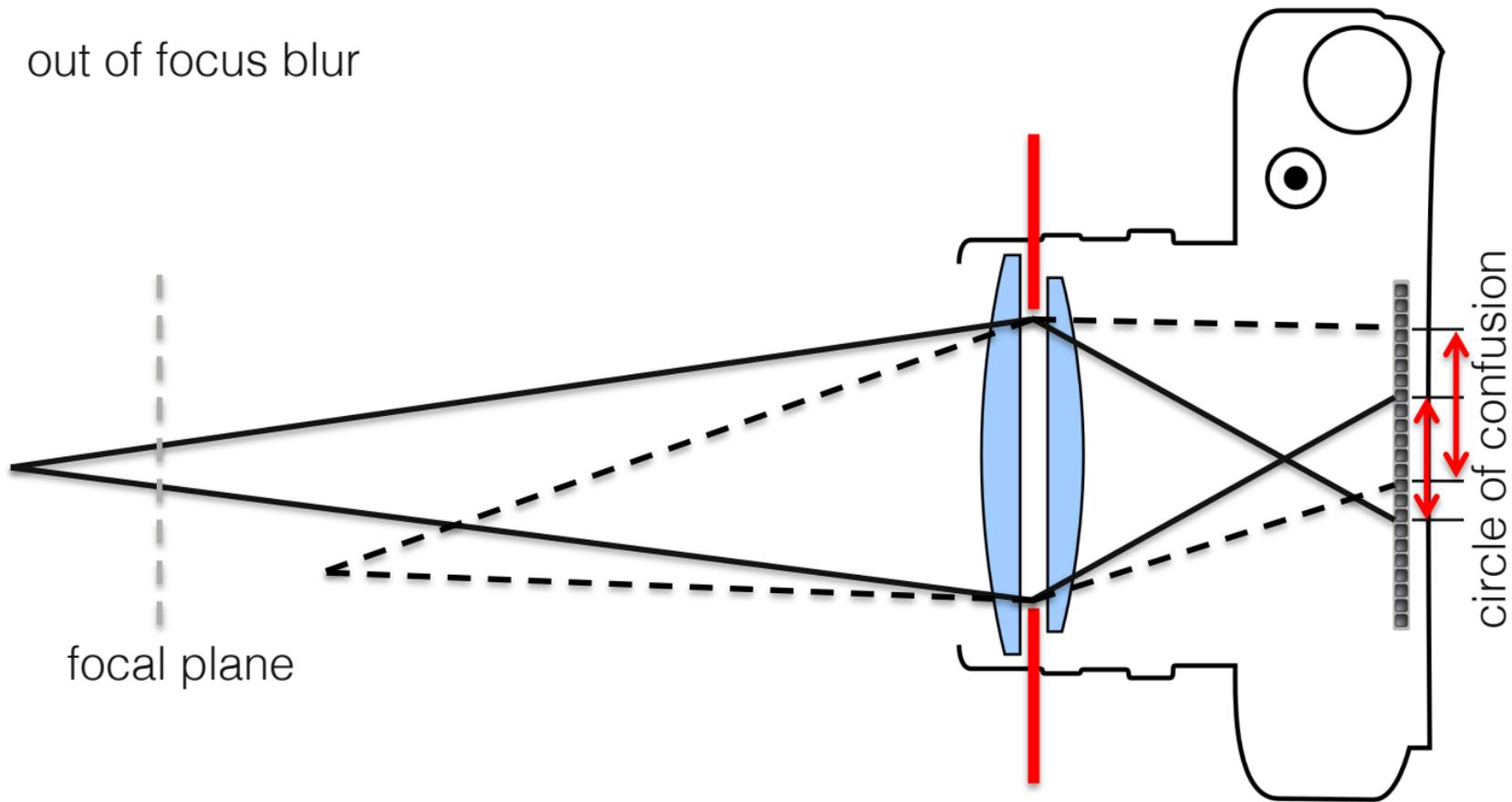
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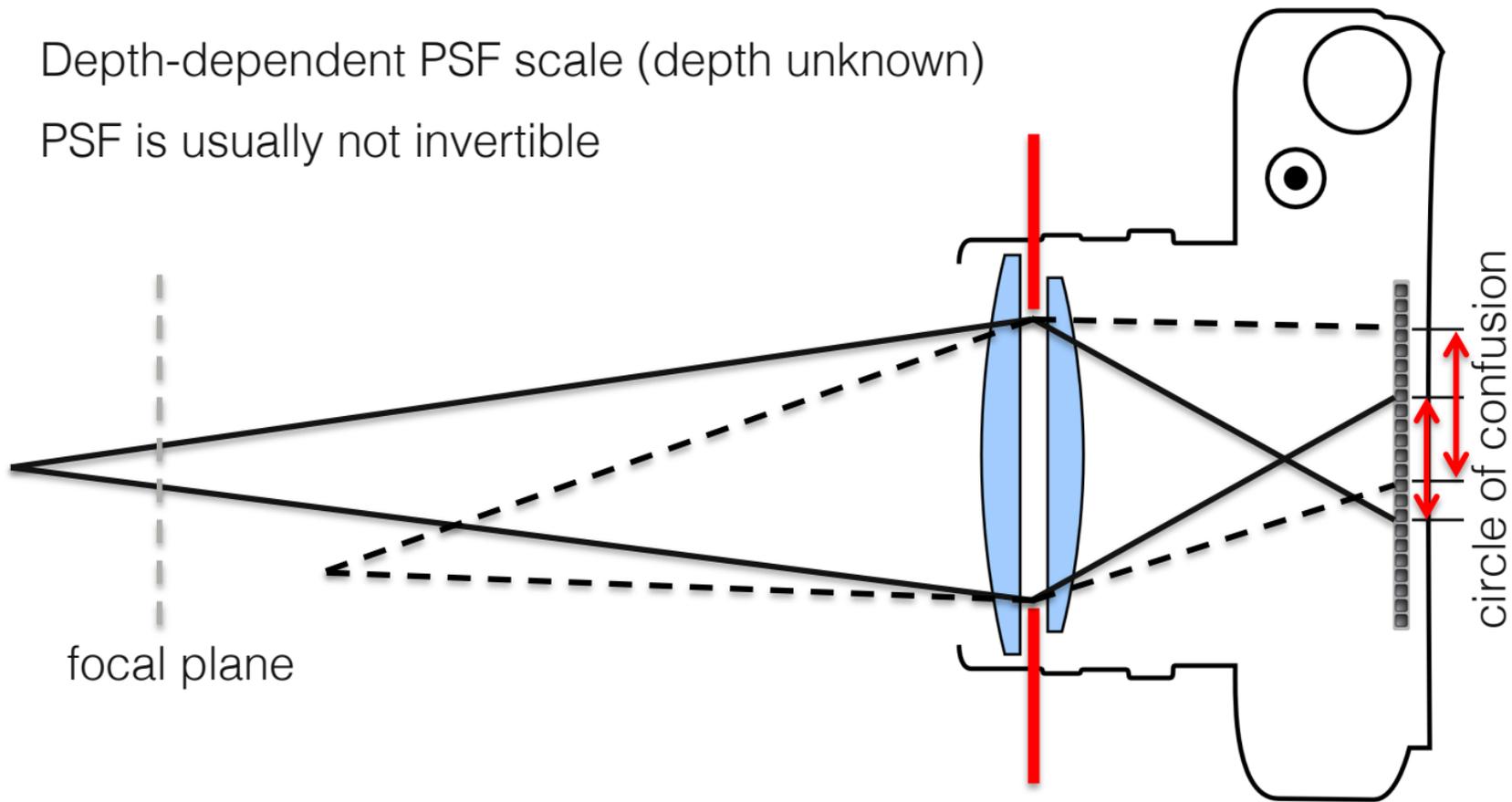
# What makes Defocus Deblurring Hard?

- 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

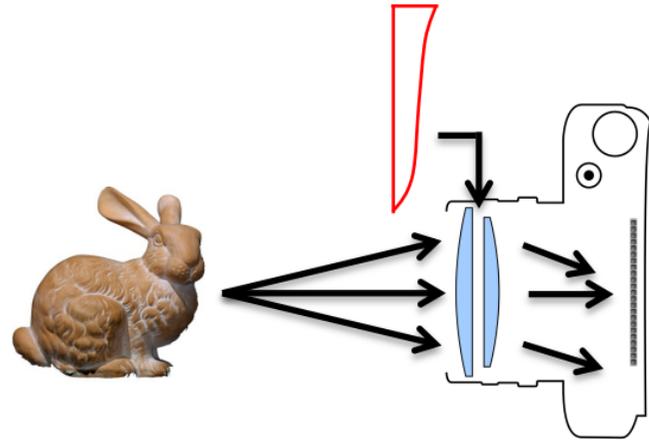
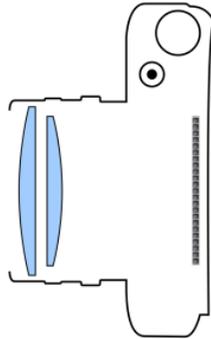
1. Problem: depth-dependent PSF scale (depth unknown)
  - engineer PSF to be depth invariant
  - resulting shift-invariant deconvolution is much easier!
2. Problem: circular / Airy PSF is usually not invertible: ill-posed problem
  - engineer PSF to be broadband (flat Fourier magnitudes)
  - resulting inverse problem becomes well-posed

# Extended Depth of Field

- Two general approaches for engineering depth-invariant PSFs:

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

2. change optics  
(e.g., wavefront coding)



# Extended Depth of Field – Focal Sweep

[Nagahara et al. 2008]

conventional photo  
(small DOF)



captured focal sweep  
always blurry!



conventional photo  
(large DOF, noisy)



EDOF image

# 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)

# Coded (Aperture) Imaging

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- Extended depth of field
- Monocular depth estimation

Applications of *Coded Imaging* in General:

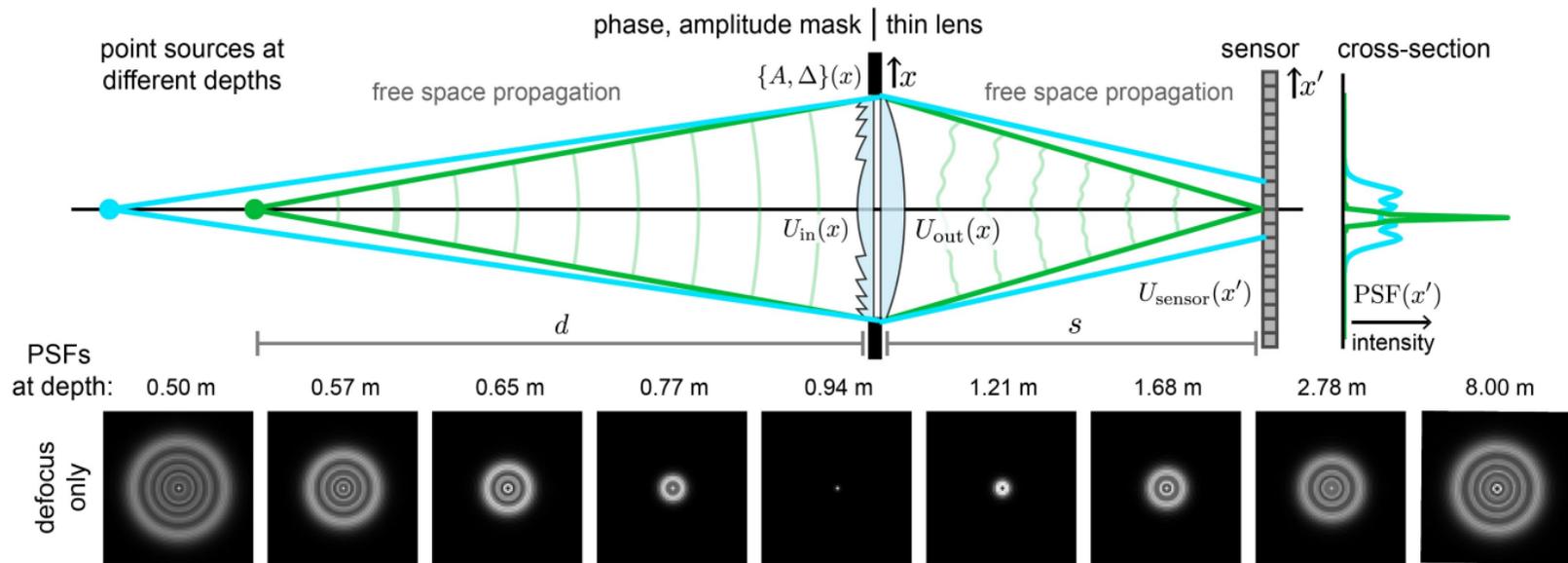
- Motion deblurring
- High-speed, hyperspectral, light field, single-pixel imaging ...

# Monocular Depth Estimation

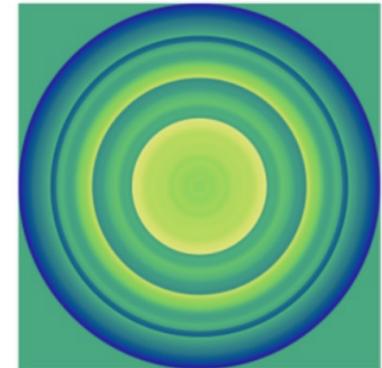


- Problem: 3D/depth cameras are hard
- Solution: a single image contains a lot of depth cues – learn to use them for depth estimation (like humans)

# Coded Apertures for Depth Estimation



# Coded Apertures for Depth Estimation



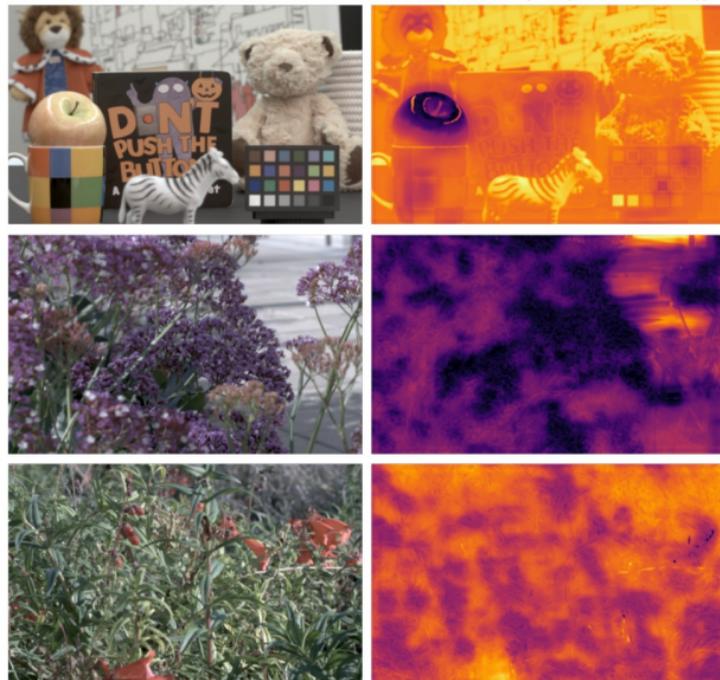
0.0 μm 2.1 μm

# 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)

Conventional

Estimated Depth (conventional)

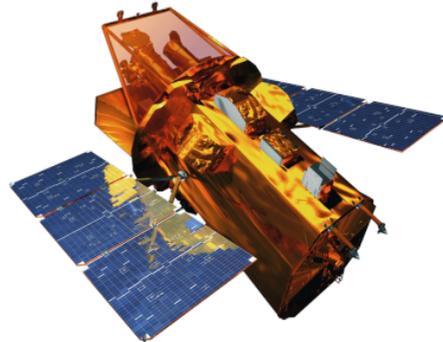
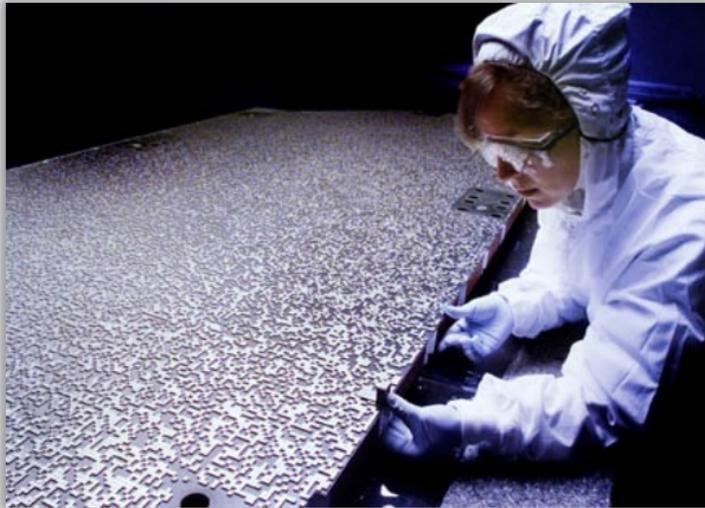


# Coded Apertures in Astronomy

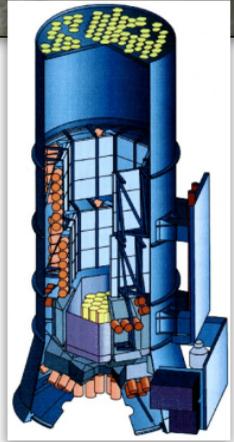
- some wavelengths are difficult to focus
- no “lenses” available
- coded apertures for x-rays and gamma rays



ESA SPI / INTEGRAL

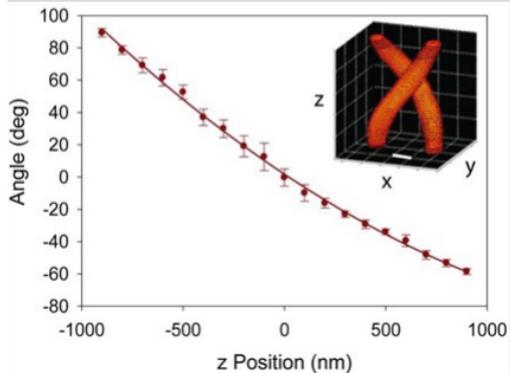
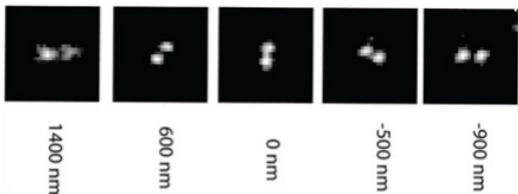


NASA Swift



# Coded Apertures in Microscopy

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



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

# Coded (Aperture) Imaging

Applications of *Coded Aperture Imaging*:

- Extended depth of field
- Monocular depth estimation

Applications of *Coded Imaging* in General:

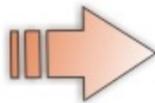
- Motion deblurring
- High-speed, hyperspectral, light field, single-pixel imaging ...

# 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

# Motion Deblurring w/ Flutter Shutter

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



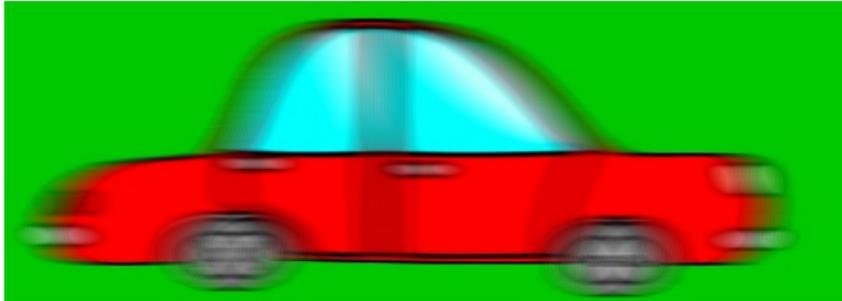
Input Photo



Deblurred Result

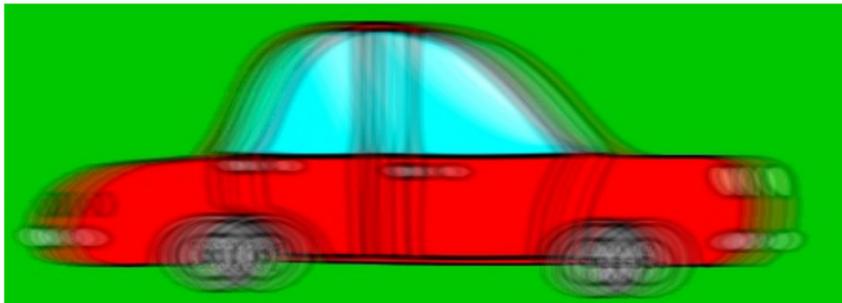
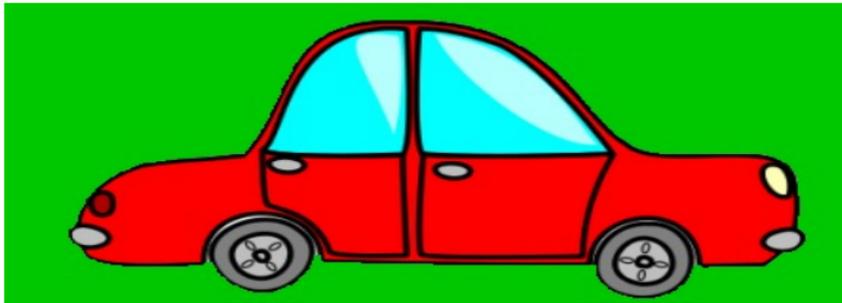


Traditional Camera:  
Shutter is OPEN



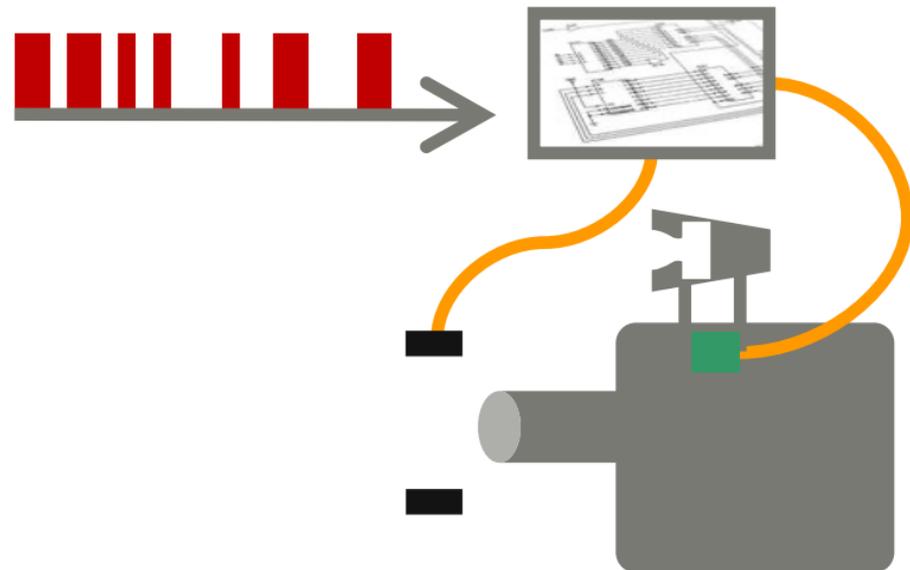


Flutter Shutter Camera:  
Shutter is OPEN &  
CLOSED

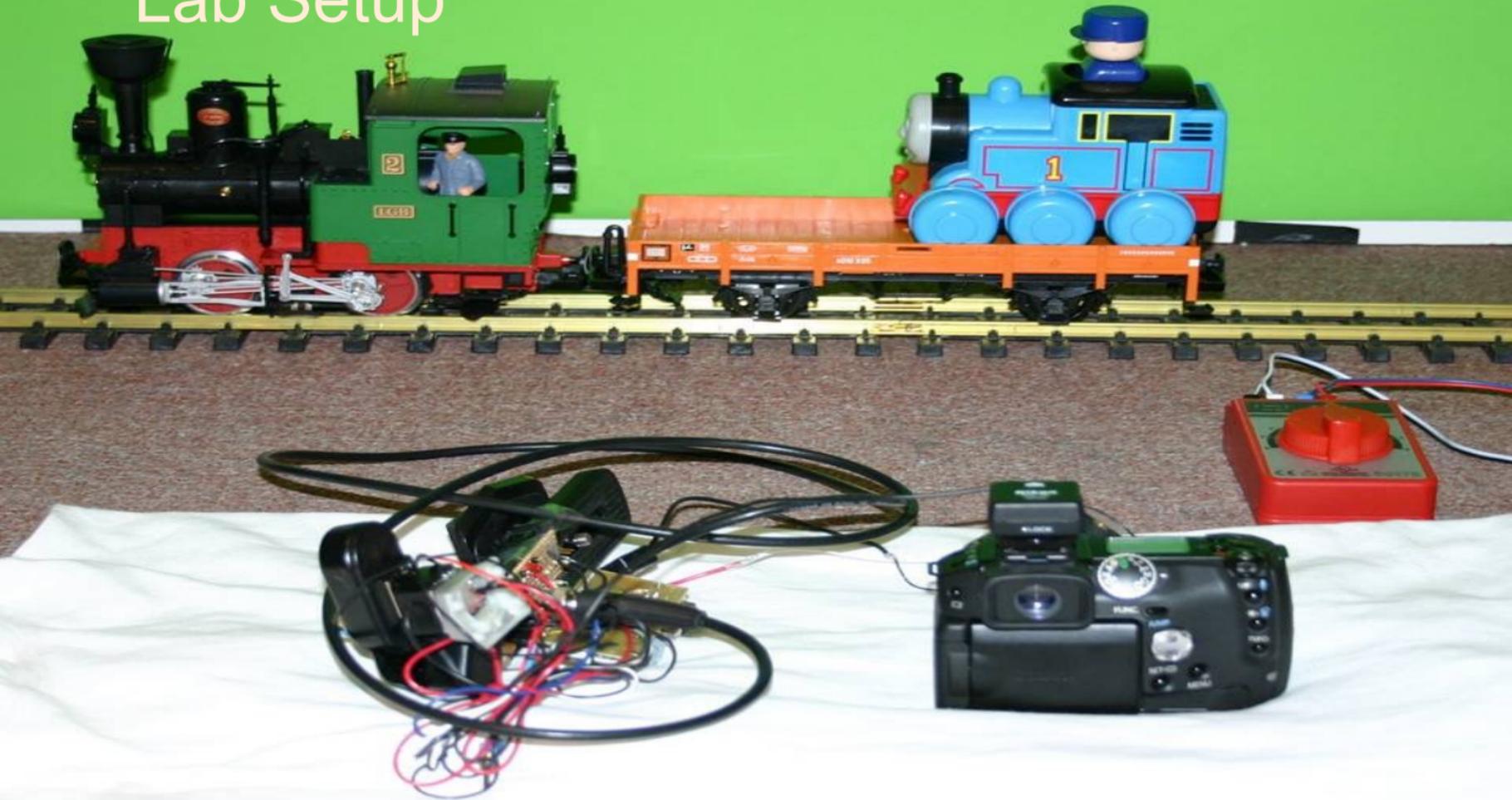


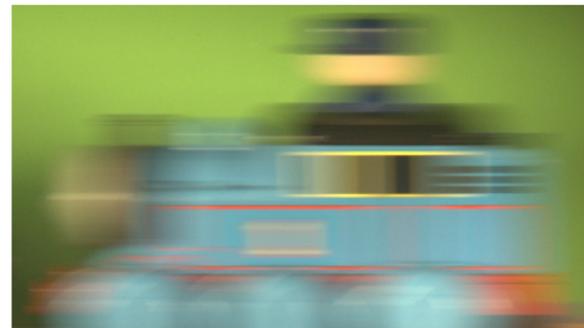
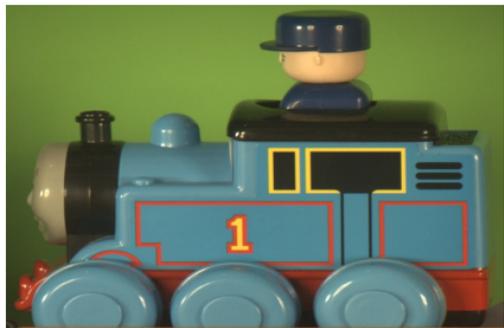
Inspired by Harold "Doc" Edgerton





# Lab Setup

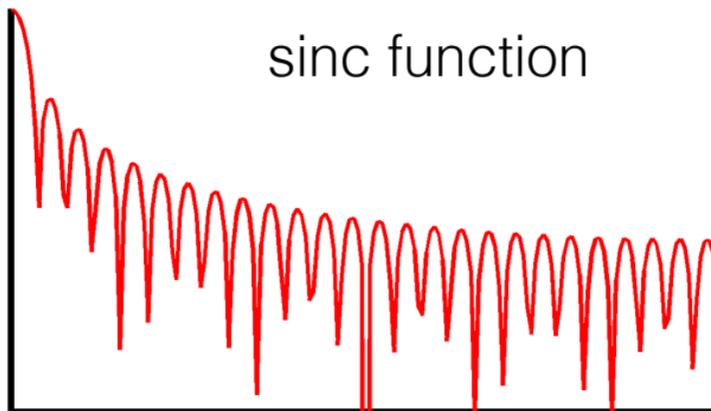




spatial convolution



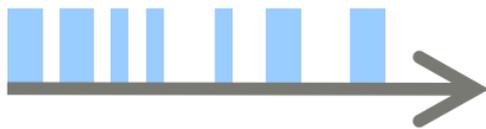
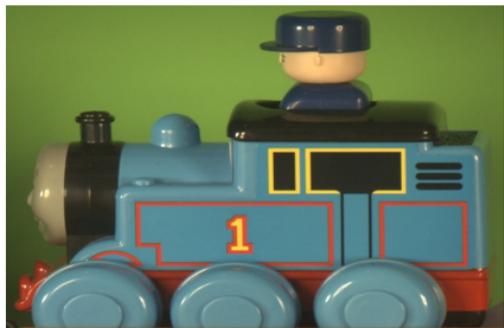
sinc function



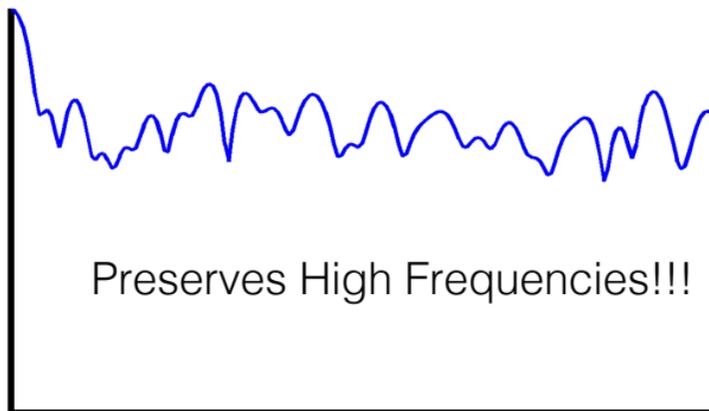
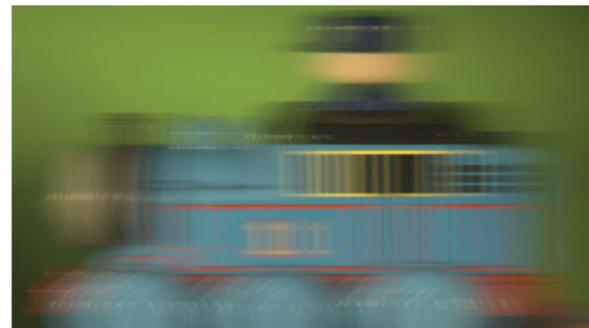
Fourier magnitudes

Blurring  
=  
Convolution

Traditional Camera: Box Filter



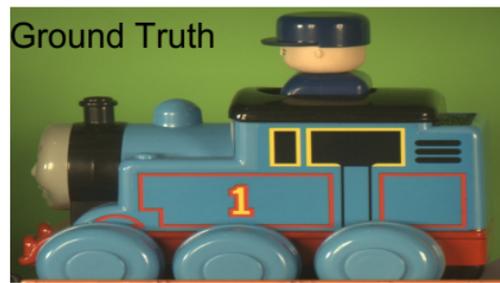
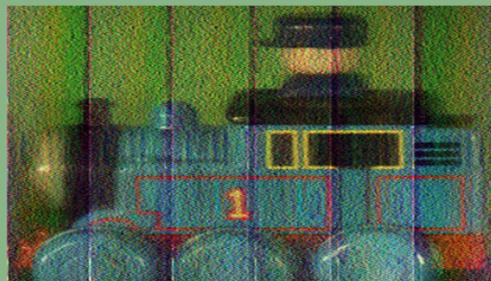
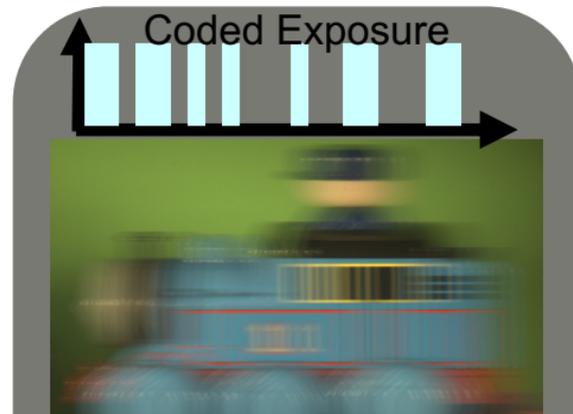
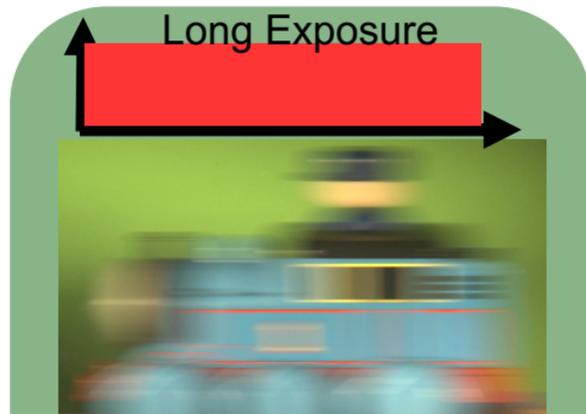
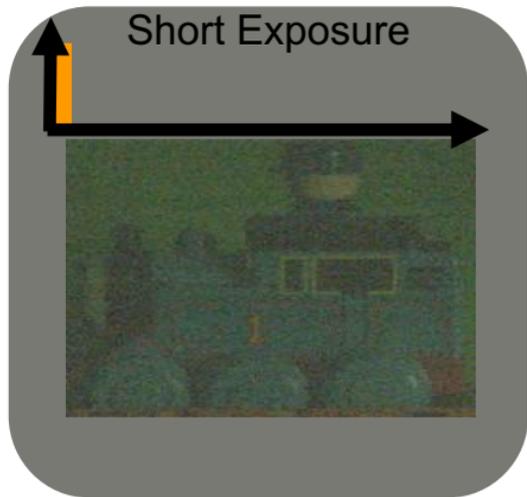
spatial convolution



Preserves High Frequencies!!!

Fourier magnitudes

Flutter Shutter: Coded Filter





License Plate Retrieval



License Plate Retrieval

# Coded (Aperture) Imaging

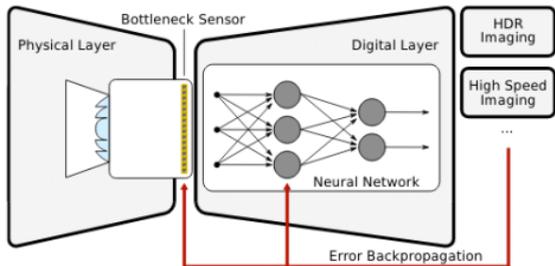
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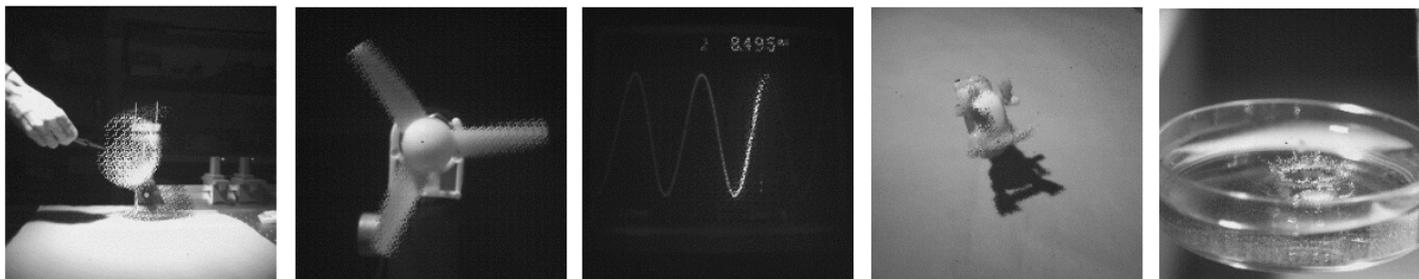
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- Motion deblurring
- High-speed, hyperspectral, light field, single-pixel imaging ...

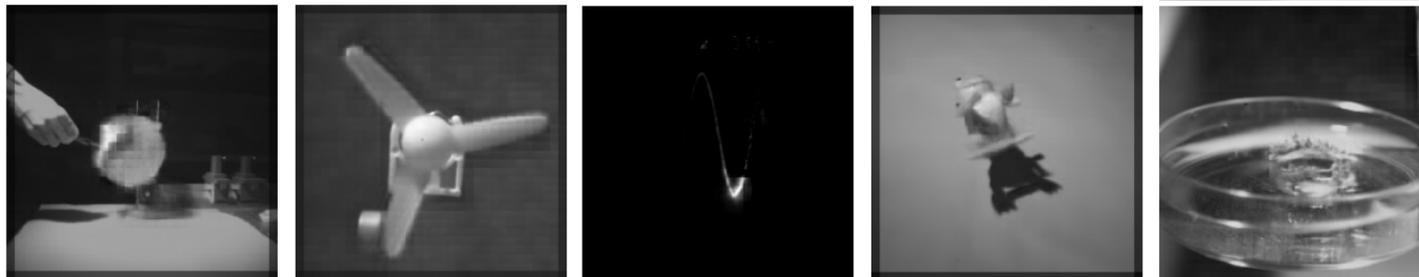
# Coded Imaging with Neural Sensors



Coded Measurements



Reconstructions



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