Announcements

- HW3 due Wednesday 5/10
- HW4 is out
- Project proposal due in 1 month!

- See website for all office hours/problem session dates
Motivation
Exposure control
What is exposure?

Roughly speaking, the “brightness” of a captured image given a fixed scene.

Exposure = Gain x Flux x Time

• Flux is controlled by the aperture.
• Time is controlled by the shutter speed.
• Gain is controlled by the ISO.
Exposure controls brightness of image

Exposure

Aperture

Shutter

ISO
Exposure controls brightness of image
Shutter speed

Controls the length of time that shutter remains open.

incoming light

shutter

sensor

closed shutter
Shutter speed

Controls the length of time that shutter remains open.

incoming light

shutter

sensor

open shutter
Nikon D3s
Shutter speed

Controls the period of time that shutter remains open.

What happens to the image as we increase shutter speed?
Side-effects of shutter speed

Moving scene elements appear blurry.

How can we “simulate” decreasing the shutter speed?
Motion deblurring

Shah et al. High-quality Motion Deblurring from a Single Image, SIGGRAPH 2008
Exposure controls brightness of image
Aperture size

Controls area of lens that lets light pass through.

Also determines circle of confusion.
Aperture size

Controls area of lens that lets light pass through.

Also determines circle of confusion.
Aperture size

Most lenses have apertures of variable size.
• The size of the aperture is expressed as the “f-number”: The bigger this number, the smaller the aperture.

You can see the aperture by removing the lens and looking inside it.
Side-effects of aperture size

Depth of field decreases as aperture size increases.

- Having a very sharp depth of field is known as “bokeh”.

![Image of depth of field effect](image-url)
How can we simulate bokeh?
How can we simulate bokeh?

Infer per-pixel depth, then blur with depth-dependent kernel.

- Example: Google camera “lens blur” feature
Exposure controls brightness of image

Exposure

Aperture

Shutter

ISO
Side-effects of increasing ISO

Image becomes very grainy because noise is amplified.
Note about the name ISO

ISO is not an acronym.

• It refers to the International Organization for Standardization.
• ISO comes from the Greek word ἴσος, which means equal.
• It is pronounced (roughly) eye-zo, and should not be spelled out.
Our devices do not match the world
The world has a high dynamic range
The world has a high dynamic range
(Digital) sensors also have a low dynamic range compared to the adaptation range of our eyes.

Sensor: $10^{-6}$ to $10^6$

Common real-world scenes: $10^{-6}$ to $10^6$

Adaptation range of our eyes: $10^{-6}$ to $10^6$
(Digital) images have an even lower dynamic range than the adaptation range of our eyes. Common real-world scenes are within the dynamic range of our eyes, but digital images can represent a much wider range, with high exposure allowing for images to capture a wider range of light levels.
(Digital) images have an even lower dynamic range.

- Low exposure
- Common real-world scenes
- Adaptation range of our eyes
(Digital) images have an even lower dynamic range

Any guesses about the dynamic range of a standard 0-255 image?

pure black  pure white
(Digital) images have an even lower dynamic range.

Any guesses about the dynamic range of a standard 0-255 image?

- pure black
- pure white

about 50x brighter
Our devices do not match the real world

- 10:1 photographic print (higher for glossy paper)
- 20:1 artist's paints
- 200:1 slide film
- 500:1 negative film
- 1000:1 LCD display
- 2000:1 digital SLR (at 12 bits)
- 100000:1 real world

Two challenges:

1. HDR imaging – which parts of the world do we measure in the 8-14 bits available to our sensor?
2. Tonemapping – which parts of the world do we show in the 4-10 bits available to our display?
Our devices do not match the real world

- 10:1 photographic print (higher for glossy paper)
- 20:1 artist's paints
- 200:1 slide film
- 500:1 negative film
- 1000:1 LCD display
- 2000:1 digital SLR (at 12 bits)
- 100000:1 real world

HDR imaging and tonemapping are distinct techniques with different goals

Two challenges:

1. HDR imaging – which parts of the world do we measure in the 8-14 bits available to our sensor?
2. Tonemapping – which parts of the world do we show in the 4-10 bits available to our display?
High dynamic range imaging
Key idea

1. Exposure bracketing: Capture multiple LDR images at different exposures

2. Merging: Combine them into a single HDR image
Key idea

1. Exposure bracketing: Capture multiple LDR images at different exposures

2. Merging: Combine them into a single HDR image
Ways to vary exposure

1. Shutter speed

2. F-stop (aperture, iris)

3. ISO

4. Neutral density (ND) filters

Pros and cons of each for HDR?
Ways to vary exposure

1. Shutter speed
   - Range: about 30 sec to 1/4000 sec (6 orders of magnitude)
   - Pros: repeatable, linear
   - Cons: noise and motion blur for long exposure
Ways to vary exposure

1. Shutter speed
   - Range: about 30 sec to 1/4000 sec (6 orders of magnitude)
   - Pros: repeatable, linear
   - Cons: noise and motion blur for long exposure

2. F-stop (aperture, iris)
   - Range: about f/0.98 to f/22 (3 orders of magnitude)
   - Pros: fully optical, no noise
   - Cons: changes depth of field
Ways to vary exposure

1. Shutter speed
   – Range: about 30 sec to 1/4000 sec (6 orders of magnitude)
   – Pros: repeatable, linear
   – Cons: noise and motion blur for long exposure

2. F-stop (aperture, iris)
   – Range: about f/0.98 to f/22 (3 orders of magnitude)
   – Pros: fully optical, no noise
   – Cons: changes depth of field

3. ISO
   – Range: about 100 to 1600 (1.5 orders of magnitude)
   – Pros: no movement at all
   – Cons: noise
Ways to vary exposure

1. Shutter speed
   - Range: about 30 sec to 1/4000 sec (6 orders of magnitude)
   - Pros: repeatable, linear
   - Cons: noise and motion blur for long exposure

2. F-stop (aperture, iris)
   - Range: about f/0.98 to f/22 (3 orders of magnitude)
   - Pros: fully optical, no noise
   - Cons: changes depth of field

3. ISO
   - Range: about 100 to 1600 (1.5 orders of magnitude)
   - Pros: no movement at all
   - Cons: noise

4. Neutral density (ND) filters
   - Range: up to 6 densities (6 orders of magnitude)
   - Pros: works with strobe/flash
   - Cons: not perfectly neutral (color shift), extra glass (interreflections, aberrations)
Exposure bracketing with shutter speed

Note: shutter times usually obey a power series – each “stop” is a factor of 2

\[
\frac{1}{4}, \frac{1}{8}, \frac{1}{15}, \frac{1}{30}, \frac{1}{60}, \frac{1}{125}, \frac{1}{250}, \frac{1}{500}, \frac{1}{1000} \text{ sec}
\]

usually really is

\[
\frac{1}{4}, \frac{1}{8}, \frac{1}{16}, \frac{1}{32}, \frac{1}{64}, \frac{1}{128}, \frac{1}{256}, \frac{1}{512}, \frac{1}{1024} \text{ sec}
\]
Exposure bracketing with shutter speed

Note: shutter times usually obey a power series – each “stop” is a factor of 2

1/4, 1/8, 1/15, 1/30, 1/60, 1/125, 1/250, 1/500, 1/1000 sec
usually really is
1/4, 1/8, 1/16, 1/32, 1/64, 1/128, 1/256, 1/512, 1/1024 sec

Questions:
1. How many exposures?
2. What exposures?
Exposure bracketing with shutter speed

Note: shutter times usually obey a power series – each “stop” is a factor of 2

\[
\frac{1}{4}, \frac{1}{8}, \frac{1}{15}, \frac{1}{30}, \frac{1}{60}, \frac{1}{125}, \frac{1}{250}, \frac{1}{500}, \frac{1}{1000} \text{ sec}
\]

usually really is

\[
\frac{1}{4}, \frac{1}{8}, \frac{1}{16}, \frac{1}{32}, \frac{1}{64}, \frac{1}{128}, \frac{1}{256}, \frac{1}{512}, \frac{1}{1024} \text{ sec}
\]

Questions:

1. How many exposures?
2. What exposures?

Answer: Depends on the scene, but a good default is 5 exposures, the metered exposure and +/- 2 stops around that.
Key idea

1. Exposure bracketing: Capture multiple LDR images at different exposures

2. Merging: Combine them into a single HDR image
Over/under exposure

In highlights we are limited by clipping.

In shadows we are limited by noise.
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!

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

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

\[ w_{ij} = \exp \left( -4 \frac{(I_{\text{lin},ij} - 0.5)^2}{0.5^2} \right) \]
HDRI – Merging LDR Exposures

- define least-squares objective function in log-space → perceptually linear:
  \[
  \text{minimize}_{x} \quad O = \sum_{i} w_{i} \left( \log(I_{\text{lin}_{i}}) - \log(t_{i}X) \right)^2
  \]

- equate gradient to zero:
  \[
  \frac{\partial O}{\partial \log(X)} = -2 \sum_{i} w_{i} \left( \log(I_{\text{lin}_{i}}) - \log(t_{i}) - \log(X) \right) = 0
  \]

- gives:
  \[
  \hat{X} = \exp\left( \frac{\sum_{i} w_{i} \left( \log(I_{\text{lin}_{i}}) - \log(t_{i}) \right)}{\sum_{i} w_{i}} \right)
  \]
HDRI – Merging LDR Exposures

• define least-squares objective function in log-space \(\rightarrow\) perceptually linear:

\[
\text{minimize}_X \quad O = \sum_i w_i \left( \log(I_{lin_i}) - \log(t_i X) \right)^2
\]

• equate gradient to zero:

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

• gives:

\[
\hat{X} = \exp \left( \frac{\sum_i w_i \left( \log(I_{lin_i}) - \log(t_i) \right)}{\sum_i w_i} \right)
\]
What if I cannot use raw?
Radiometric calibration
Radiometric calibration

The process of measuring the camera’s response curve. Can be done in three ways:

• Take images of scenes with different flux while keeping exposure the same.
• Takes images under different exposures while keeping flux the same.
• Takes images of scenes with different flux and under different exposures.
Same camera exposure, varying scene flux

Colorchecker: Great tool for radiometric and color calibration.

Patches at bottom row have log-reflectance that increases linearly.

Different values correspond to patches of increasing reflected flux.

e.g. JPEG
**Same scene flux, varying camera exposure**

*White balance card:* Great tool for white balancing and radiometric calibration.

All points on (the white part of) the target have the same reflectance.

**Different values correspond to images taken under increasing camera exposure.**

**Graph:***

- Known exposure vs. pixel value
- Known exposures are plotted against the corresponding pixel values, showing a clear increase in pixel values with increasing known exposures.
Varying both scene flux and camera exposure

You can do this using the LDR exposure stack itself.

Different scene flux, same camera exposure

Same scene flux, different camera exposure
Non-linear image formation model

Real scene flux for image pixel \((x,y)\): \(\Phi(x, y)\)
Exposure time: \(t_i\)

\[
l_{\text{linear}}(x,y) = \text{clip}[ t_i \cdot \Phi(x,y) + \text{noise} ]
\]

\[
l_{\text{non-linear}}(x,y) = f[ l_{\text{linear}}(x,y) ]
\]

How would you merge the non-linear images into an HDR one?
Non-linear image formation model

Real scene flux for image pixel \((x, y)\): \(\Phi(x, y)\)
Exposure time: \(t_i\)

\[ I_{\text{linear}}(x,y) = \text{clip}[t_i \cdot \Phi(x,y) + \text{noise}] \]
\[ I_{\text{non-linear}}(x,y) = f[I_{\text{linear}}(x,y)] \]

\[ I_{\text{est}}(x,y) = f^{-1}[I_{\text{non-linear}}(x,y)] \]

Use inverse transform to estimate linear image, then proceed as before
Linearization

\[ I_{\text{non-linear}}(x, y) = f[I_{\text{linear}}(x, y)] \]

\[ I_{\text{est}}(x, y) = f^{-1}[I_{\text{non-linear}}(x, y)] \]
Merging non-linear exposure stacks

1. Calibrate response curve

2. Linearize images

For each pixel:

3. Find “valid” images

4. Weight valid pixel values appropriately

5. Form a new pixel value as the weighted average of valid pixel values

Same steps as in the RAW case.
What if I cannot measure the response curve?
You may find information in the image itself

If you cannot do calibration, take a look at the image’s EXIF data (if available).

Often contains information about tone reproduction curve and color space.
The exact tone reproduction curve depends on the camera.
• Often well approximated as \( L^\gamma \), for different values of the power \( \gamma \) ("gamma").
• A good default is \( \gamma = 1 / 2.2 \).

If nothing else, take the square of your image to approximately remove effect of tone reproduction curve.
Other aspects of HDR imaging
Relative vs absolute flux

Final fused HDR image gives flux only up to a global scale
• If we know exact flux at one point, we can convert relative HDR image to absolute flux map
Basic HDR approach

1. Capture multiple LDR images at different exposures
2. Merge them into a single HDR image

Any problems with this approach?
Basic HDR approach

1. Capture multiple LDR images at different exposures

2. Merge them into a single HDR image

Problem: Very sensitive to movement

- Scene must be completely static
- Camera must not move

Most modern automatic HDR solutions include an alignment step before merging exposures
How do we store HDR images?

- Most standard image formats store integer 8-bit images
- Some image formats store integer 12-bit or 16-bit images
- HDR images are floating point 32-bit or 64-bit images
How do we store HDR images?

Use specialized image formats for HDR images

- portable float map (.pfm)
  - very simple to implement

- Radiance format (.hdr)
  - supported by Matlab

- OpenEXR format (.exr)
  - multiple extra features
Another type of HDR images

Light probes: place a chrome sphere in the scene and capture an HDR image

- Used to measure real-world illumination environments ("environment maps")

Application: image-based relighting
Another way to create HDR images

Physics-based renderers simulate flux maps (relative or absolute)

• Their outputs are very often HDR images
Our devices do not match the real world

- 10:1 photographic print (higher for glossy paper)
- 20:1 artist's paints
- 200:1 slide film
- 500:1 negative film
- 1000:1 LCD display
- 2000:1 digital SLR (at 12 bits)
- 100000:1 real world

HDR imaging and tonemapping are distinct techniques with different goals

Two challenges:

1. HDR imaging – which parts of the world do we measure in the 8-14 bits available to our sensor?
2. Tonemapping – which parts of the world do we show in the 4-10 bits available to our display?
Tonemapping
How do we display our HDR images?

10^-6

10^-6

10^-6

adaptation range of our eyes

display

HDR image

common real-world scenes
Linear scaling

Scale image so that maximum value equals 1.

HDR image looks underexposed because of the display’s limited dynamic range, but is not actually underexposed.
Linear scaling

Scale image so that 10% value equals 1.

HDR image looks saturated because of the display’s limited dynamic range, but is not actually saturated.

Can you think of something better?
Photographic tonemapping

Apply the same non-linear scaling to all pixels in the image so that:
• Bring everything within range → asymptote to 1
• Leave dark areas alone → slope = 1 near 0

\[ I_{\text{display}} = \frac{I_{\text{HDR}}}{1 + I_{\text{HDR}}} \]

(exact formula more complicated)

• Perceptually motivated, as it approximates our eye’s response curve.
Examples

photographic tonemapping
linear scaling (map 10% to 1)
linear scaling (map 100% to 1)
Compare with LDR images

photographic tonemapping  high exposure  low exposure
Dealing with color

If we tonemap all channels the same, colors are washed out

Can you think of a way to deal with this?
Intensity-only tonemapping

tonemap intensity (e.g., luminance $Y$ in $xyY$)

leave color the same (e.g., $xy$ in $xyY$)

How would you implement this?
Comparison

Color now OK, but some details are washed out due to loss of contrast

Can you think of a way to deal with this?
Low-frequency intensity-only tonemapping

- tonemap low-frequency intensity component
- leave high-frequency intensity component the same
- leave color the same

How would you implement this?
Comparison

We got nice color and contrast, but now we’ve run into the halo plague

Can you think of a way to deal with this?
Edge-aware filtering and tonemapping

Separate base and detail using edge-preserving filtering (e.g., bilateral filtering).
Comparison

We fixed the halos without losing contrast
Gradient-domain processing and tonemapping

Compute gradients, scale and merge them, then integrate (solve Poisson problem).
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]
Comparison (which one do you like better?)

- photographic
- bilateral filtering
- gradient-domain
Comparison (which one do you like better?)

photographic  bilateral filtering  gradient-domain
Comparison (which one do you like better?)

There is no ground-truth: which one looks better is entirely subjective

photographic  bilateral filtering  gradient-domain
Some notes about HDR imaging and tonemapping
A note about terminology

“High-dynamic-range imaging” is used to refer to a lot of different things:

1. Using single RAW images.
2. Performing radiometric calibration.
3. Merging an exposure stack.
4. Tonemapping an image (linear or non-linear, HDR or LDR).
5. Some or all of the above.
A note about terminology

“High-dynamic-range imaging” is used to refer to a lot of different things:

1. Using single RAW images.
2. Performing radiometric calibration.
3. Merging an exposure stack.
4. Tonemapping an image (linear or non-linear, HDR or LDR).
5. Some or all of the above.

Technically, HDR imaging and tonemapping are distinct processes:

- HDR imaging is the process of creating a radiometrically linear image, free of overexposure and underexposure artifacts. This is achieved using some combination of 1-3, depending on the imaging scenario.
- Tonemapping (step 4) process of mapping the intensity values in an image (linear or non-linear, HDR or LDR) to the range of tones available in a display.
A note about terminology

“High-dynamic-range imaging” is used to refer to a lot of different things:

1. Using single RAW images.
2. Performing radiometric calibration.
3. Merging an exposure stack.
4. Tonemapping an image (linear or non-linear, HDR or LDR).
5. Some or all of the above.

Technically, HDR imaging and tonemapping are distinct processes:

- HDR imaging is the process of creating a radiometrically linear image, free of overexposure and underexposure artifacts. This is achieved using some combination of 1-3, depending on the imaging scenario.
- Tonemapping (step 4) process of mapping the intensity values in an image (linear or non-linear, HDR or LDR) to the range of tones available in a display.

But:

- In consumer photography, “HDR photography” is often used to refer to both HDR imaging (steps 1-3) and tonemapping (step 4).
A note of caution

• HDR photography can produce very visually compelling results.
A note of caution

• HDR photography can produce very visually compelling results.

• It is also a very routinely abused technique, resulting in awful results.
A note of caution

- HDR photography can produce very visually compelling results.
- It is also a very routinely abused technique, resulting in awful results.
- The problem typically is tonemapping, not HDR imaging itself.
A note about HDR today

• Most cameras (even phone cameras) have automatic HDR modes/apps.

• Popular-enough feature that phone manufacturers are actively competing about which one has the best HDR.

• The technology behind some of those apps (e.g., Google’s HDR+) is published in SIGGRAPH and SIGGRAPH Asia conferences.

Figure 1: A comparison of a conventional camera (left), an ultra-wide lens (middle), and a smartphone’s (right) magnification on the same cellphone camera. In this low-light setting (about 0.7 lux), the conventional camera is prone to underexposure (left). By blurring the image (middle) reduces noise and spatial distortion, which results in less detail and an unpleasantly flat appearance. Enlarging a blur of images increases the signal-to-noise ratio, ending apparent spatial distortion automatically. The camera is then zoomed. While our smartphone (right) in low-light and high-dynamic range scenes (as exemplified by the latter in figure 1), it is commercial (with the advantage of artifact-free, as the camera is a mobile camera and used as a substitute for the conventional camera to about all circumstances. For capability, the figure has been made uniformly brighter than the original photographs.

Abstract

Cell phone cameras have small apertures, which limits the number of photons they can gather, leading to noisy images in low-light. They also have small sensor pixels, which limits the number of photons each pixel can collect. These factors lead to poor image quality, especially in low-light conditions. To address this, many smartphone manufacturers have developed computational photography (CPhot) techniques that capture, align, and merge frames to improve image quality and increase dynamic range. Our system has several key features: it can operate in a robust and efficient manner, it can capture frames of constant exposure, it can align multiple exposures, and it can capture high dynamic range (HDR) images (figure 1). The result of using HDR is clear and provides high image quality. We demonstrate this by merging multiple images and accurately merging multiple exposures.

1 Introduction

The main technical impediment to higher performance is the lack of light. In order to improve performance, scenes can be broken up into separate image or a high dynamic range image. It is also not an easy proposition to find a solution to this problem, especially in low-light conditions. For this reason, we have developed an algorithm that can be used to improve the performance of this system. The algorithm is based on a hybrid algorithm that is designed to capture and merge the frames into a single image. Our implementation is built into the Samsung Galaxy S7, which provides a high-definition camera and access to the system, and is written in the Smartphone Hardware Language (SHL). It runs on a 64-bit system on a smartphone (not a 1.2GHz single-core processor), requires no user intervention, and ships on several smartphones from Google.

Keywords: computational photography, high-dynamic range, mobile imaging
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 changes shape of PSF

New PSF preserves high frequencies
• More content available to help us determine correct depth
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*:

- Extended depth of field
- Monocular depth estimation

Applications of *Coded Imaging* in General:

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

- Captured focal sweep always blurry!
- Conventional photo (small DOF)
- EDOF image
- Conventional photo (large DOF, noisy)
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!
Wavefront coding

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

[Godard et al., 2017]
Coded Apertures for Depth Estimation

Point sources at different depths propagate through a phase/amplitude mask and a thin lens, with free space propagation before and after the lens. The sensor captures the output of the system. PSFs at various depths are shown, with a focus on how they change with depth.

[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

NASA Swift

ESA SPI / INTEGRAL
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

[Shan et al. 2008]
Motion Deblurring w/ Flutter Shutter

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

[Raskar et al. 2006]
Traditional Camera:
Shutter is OPEN
Flutter Shutter Camera:

Shutter is OPEN & CLOSED
Blurring = Convolution

sinc function

Fourier magnitudes

Traditional Camera: Box Filter

[Raskar et al. 2006]
Flutter Shutter: Coded Filter

Preserves High Frequencies!!!

Spatial convolution

[Raskar et al. 2006]

Fourier magnitudes

Flutter Shutter: Coded Filter
License Plate Retrieval

[Raskar et al. 2006]
License Plate Retrieval

[Raskar et al. 2006]
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 $x(t) = at^2$

- 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
Some results

static camera input  parabolic camera input  deconvolution output
Some results

static camera input

output after deconvolution
Why does it fail in this case?
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 Imaging with Neural Sensors

[Bottleneck Sensor]

Physical Layer

Digital Layer

Neural Network

HDR Imaging

High Speed Imaging

Error Backpropagation

Reconstructions

Coded Measurements

[Martel et al., 2020]
Next time: image processing with neural networks
References and Further Reading

HDR
-Debevec, Malik, “Recovering High Dynamic Range Radiance Maps from Photographs”, SIGGRAPH 1997

Tone Mapping

Burst Photography/Denoising
- Hasinoff, Sharlet, Geiss, Adams, Barron, Kainz, Chen, Levoy “Burst photography for high dynamic range and low-light imaging on mobile cameras”, SIGGRAPH Asia 2016
- Liba et al., “Handheld Mobile Photography in Very Low Light”, ACM SIGGRAPH Asia 2019

Extended Depth of Field
- Levin, Hasinoff, Green, Durand, Freeman, “4D Frequency Analysis of Computational Cameras for Depth of Field Extension”, ACM SIGGRAPH 2009
- O. Cossairt, S. Nayar “Spectral Focal Sweep for Extending Depth of Field”, ICCP 2010

Depth Estimation
- C. Godard, O. Aodha, G. Bostrow, “Unsupervised Monocular Depth Estimation with Left-Right Consistency”, CVPR 2017

Motion Deblurring
- Bando, Holtzman, Raskar, “Near-Invariant Blur for Depth and 2D Motion via Time-Varying Light Field Analysis”, ACM Trans. Graph. 2013

Other