Exposure and high dynamic range imaging
Course announcements

• Homework 1 is out.
  - Due September 13\textsuperscript{th}.
  - Make sure to sign up for a camera if you need one.
  - Drop by Yannis’ office to pick up cameras any time.

• Any remaining waitlisting issues?
Overview of today’s lecture

• Exposure control.
• Light metering.
• Our devices do not match the world.
• High dynamic range imaging.
• Radiometric calibration.
• Other aspects of HDR imaging.
• Tonemapping.
• A few thoughts on HDR imaging and tonemapping.
Many of these slides were inspired or adapted from:

- James Hays (Georgia Tech).
- Fredo Durand (MIT).
- Gordon Wetzstein (Stanford).
- Marc Levoy (Stanford, Google).
- Sylvain Paris (Adobe).
- Sam Hasinoff (Google).
Exposure control
What is exposure?

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

Exposure = Gain $\times$ Irradiance $\times$ Time

- Irradiance is controlled by the aperture.
- Time is controlled by the shutter speed.
- Gain is controlled by the ISO.
Exposure controls brightness of image
Exposure controls brightness of image
Shutter speed

Controls the **length of time** that shutter remains open.

![Diagram showing shutter speed](image)

- **Incoming light**
  - **Shutter**
  - **Sensor**

*Closed shutter*
Shutter speed

Controls the **length of time** that shutter remains open.
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

Exposure

Aperture

Shutter

ISO
Aperture

controls area of lens that receives light

focal plane
Aperture

controls area of lens that receives light

focal plane
Aperture

- unit: f-number $N = \frac{f}{D}$
Aperture size
Circle of Confusion

\[ c = M \cdot D \cdot \frac{|S - S_1|}{S} \]

aperture also determines the size of circle of confusion for out of focus objects

\[ M = \frac{f}{S_1 - f} \]

focal plane: \( S_1 \)

circle of confusion: \( c \)
Circle of confusion

Aperture also controls size of circle of confusion for out of focus objects

Take off your glasses and squint.
Depth of field

Range of depths for which the circle of confusion is “acceptable”
Circle of Confusion

\[ c = M \cdot D \cdot \frac{|S - S_1|}{S} \]

Canon 5D Mark III:  f=50mm, f/2.8 (N=2.8),
    focused at 5m, pixel size=7.5um
Depth of field
Depth of field

Sharp depth of field ("bokeh") is often desirable.

Which of the two images was captured with the larger aperture?
Depth of field

Sharp depth of field ("bokeh") is often desirable.
Depth of field

Form of bokeh is determined by shape of aperture
Lens “speed”

A “fast” lens is one that has a very large \( \max \) aperture.

- We can use the paraxial approximation to estimate a limit on F-number equal to:

\[
N = \frac{1}{\frac{2}{\sin \theta}}
\]

- Lowest possible \( N \) in air is \( f / 0.5 \).
Fastest lenses commercially available

In consumer photography, fastest lenses are f/0.9 – f/0.95.

Leica Noctilux 50mm f/0.95 (Price tag: > $10,000)

Fast lenses tend to be bulky and expensive.
Fastest lens made?

Zeiss 50 mm f / 0.7 Planar lens

- Originally developed for NASA’s Apollo missions.
- Stanley Kubrick somehow got to use the lens to shoot movies under only candlelight.
Fastest lens made?

Zeiss 50 mm f / 0.7 Planar lens

- Originally developed for NASA’s Apollo missions.
- Stanley Kubrick somehow got to use the lens to shoot movies under only candlelight.
How can you simulate bokeh?
How can you 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
The (in-camera) image processing pipeline

The sequence of image processing operations applied by the camera’s image signal processor (ISP) to convert a RAW image into a “conventional” image.
Analog front-end

**Analog amplifier (gain):**
- Gets voltage in range needed by A/D converter.
- Accommodates ISO settings.
- Accounts for vignetting.

**Analog-to-digital converter (ADC):**
- Depending on sensor, output has 10-16 bits.
- Most often (?) 12 bits.

**Look-up table (LUT):**
- Corrects non-linearities in sensor’s response function (within proper exposure).
- Corrects defective pixels.
Side-effects of increasing ISO

Image becomes very grainy because noise is amplified.
ISO is not an acronym.

- It refers to the International Organization for Standardization.
- ISO comes from the Greek word ἰσος, which means equal.
- It is pronounced (roughly) *eye-zo*, and should not be spelled out.
Camera modes

Aperture priority ("A"): you set aperture, camera sets everything else.
• Pros: Direct depth of field control.
• Cons: Can require impossible shutter speed (e.g. with f/1.4 for a bright scene).

Shutter speed priority ("S"): you set shutter speed, camera sets everything else.
• Pros: Direct motion blur control.
• Cons: Can require impossible aperture (e.g. when requesting a 1/1000 speed for a dark scene)

Automatic ("AUTO"): camera sets everything.
• Pros: Very fast, requires no experience.
• Cons: No control.

Manual ("M"): you set everything.
• Pros: Full control.
• Cons: Very slow, requires a lot of experience.
Camera modes

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• Cons: Very slow, requires a lot of experience.
Light metering
Light metering in modern cameras

- SLR cameras use a separate low-resolution sensor that is placed at the focusing screen.

- Mirrorless cameras use measurements directly from the main sensor.
Light metering in modern cameras

- Measurements are averaged to produce a single intensity estimate, which is assumed to correspond to a scene of 18% reflectance (the “key”).

- Exposure is set so that this average is exposed at the middle of the sensor’s dynamic range.

- Averaging can be done in many ways:
  1. Center-weighed.
  2. Spot.
  3. Scene-specific preset (portrait, landscape, horizon).
Metering challenges: low resolution

Low-resolution can make it difficult to correctly meter the scene and set exposure.

• In which of these scenes is it OK to let the brightest pixels be overexposed?
Metering challenges: low resolution

Low-resolution can make it difficult to correctly meter the scene and set exposure.

- In which of these scenes is it OK to let the brightest pixels be overexposed?
Our devices do not match the world
The world has a high dynamic range

1

1500

25,000

2,000,000,000

400,000
The world has a high dynamic range

adaptation range of our eyes

common real-world scenes
(Digital) sensors also have a low dynamic range

adaptation range of our eyes

common real-world scenes

sensor
(Digital) images have an even lower dynamic range compared to common real-world scenes. The adaptation range of our eyes is much wider, spanning from $10^{-6}$ to $10^6$, whereas digital images typically capture a much smaller range of exposures.
(Digital) images have an even lower dynamic range than the adaptation range of our eyes.

- High exposure
- Common real-world scenes
- Adaptation range of our eyes

The diagram illustrates the dynamic range of digital images and the human visual system's adaptation range.
(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?

About 50x brighter

pure black

pure white
(Digital) images have an even lower dynamic range than the adaptation range of our eyes in common real-world scenes.
(Digital) images have an even lower dynamic range than common real-world scenes and the adaptation range of our eyes.
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 include in the 8-14 bits available to our device?
2. Tonemapping – which parts of the world do we display in the 4-10 bits available to our device?
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

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), need to touch camera (shake)
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

- 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?

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
The image processing pipeline

The sequence of image processing operations applied by the camera’s image signal processor (ISP) to convert a RAW image into a “conventional” image.

RAW image (mosaiced, linear, 12-bit) → analog front-end

- denoising
- CFA demosaicing
- white balance
- compression

final RGB image (non-linear, 8-bit)
The image processing pipeline

The sequence of image processing operations applied by the camera’s image signal processor (ISP) to convert a RAW image into a “conventional” image.

- denoising
- CFA demosaicing
- white balance
- tone reproduction
- compression
- final RGB image (non-linear, 8-bit)
RAW images have a linear response curve

Colorchecker: Great tool for radiometric and color calibration.

Patches at bottom row have reflectance that increases linearly.
Over/under exposure

in highlights we are limited by clipping

in shadows we are limited by noise
RAW (linear) image formation model

Real scene radiance for image pixel \((x, y)\): \(L(x, y)\)

Exposure time:

\[ t_5 \quad t_4 \quad t_3 \quad t_2 \quad t_1 \]

What is an expression for the image \(I_{\text{linear}}(x, y)\) as a function of \(L(x, y)\)?
RAW (linear) image formation model

Real scene radiance for image pixel \((x, y)\): \(L(x, y)\)

Exposure time:

\(t_5\) \hspace{1cm} \(t_4\) \hspace{1cm} \(t_3\) \hspace{1cm} \(t_2\) \hspace{1cm} \(t_1\)

What is an expression for the image \(I_{\text{linear}}(x, y)\) as a function of \(L(x, y)\)?

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

How would you merge these images into an HDR one?
Merging RAW (linear) exposure stacks

For each pixel:

1. Find “valid” images
2. Weight valid pixel values appropriately
3. Form a new pixel value as the weighted average of valid pixel values

How would you implement steps 1-2?
Merging RAW (linear) exposure stacks

For each pixel:

1. Find “valid” images

2. Weight valid pixel values appropriately

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

(noise) 0.05 < pixel < 0.95 (clipping)
Merging RAW (linear) exposure stacks

For each pixel:

1. Find “valid” images

2. Weight valid pixel values appropriately

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

\[
\text{pixel value} / t_i
\]

(noise) \(0.05 < \text{pixel} < 0.95\) (clipping)
Merging result (after tonemapping)
What if I cannot use raw?
Radiometric calibration
The image processing pipeline

- Can you foresee any problem when we switch from RAW to rendered images?
The image processing pipeline

- Can you foresee any problem when we switch from RAW to rendered images?
- How do we deal with the nonlinearities?
Radiometric calibration

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

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

**Colorchecker**: Great tool for radiometric and color calibration.

Patches at bottom row have reflectance that increases linearly.

Different values correspond to patches of increasing reflected irradiance.
Same scene irradiance, varying camera exposure

**Colorchecker**: 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.

e.g. JPEG
Varying both scene irradiance and camera exposure

You can do this using the LDR exposure stack itself

• More information in Homework 2
Non-linear image formation model

Real scene radiance for image pixel \((x,y)\): \(L(x, y)\)
Exposure time: \(t_i\)

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

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

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

Real scene radiance for image pixel \((x,y)\): \(L(x, y)\)

Exposure time: \(t_i\)

\[
\begin{align*}
I_{\text{linear}}(x,y) &= \text{clip}\left[ t_i \cdot L(x,y) + \text{noise} \right] \\
I_{\text{non-linear}}(x,y) &= f[I_{\text{linear}}(x,y)] \\
I_{\text{est}}(x,y) &= f^{-1}[I_{\text{non-linear}}(x,y)]
\end{align*}
\]

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 facets of HDR imaging
Relative vs absolute radiance

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

HDR image (relative radiance)  →  spotmeter (absolute radiance at one point)  →  absolute radiance 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 (later lecture)
Another way to create HDR images

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

• Their outputs are very often HDR images
Tonemapping
How do we display our HDR images?

adaptation range of our eyes

10^{-6} - 10^{6}

display

HDR image

common real-world scenes

10^{-6} - 10^{6}
Linear scaling

Scale image so that maximum value equals 1

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 $\rightarrow$ asymptote to 1
- Leave dark areas alone $\rightarrow$ slope = 1 near 0

$$I_{\text{display}} = \frac{I_{\text{HDR}}}{1 + I_{\text{HDR}}}$$

(exact formula more complicated)

- Photographic because designed to approximate film zone system.
- Perceptually motivated, as it approximates our eye’s response curve.
What is the zone system?

- Technique formulated by Ansel Adams for film development.
- Still used with digital photography.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Pure black</td>
</tr>
<tr>
<td>I</td>
<td>Near black, with slight tonality but no texture</td>
</tr>
<tr>
<td>II</td>
<td>Textured black; the darkest part of the image in which slight detail is recorded</td>
</tr>
<tr>
<td>III</td>
<td>Average dark materials and low values showing adequate texture</td>
</tr>
<tr>
<td>IV</td>
<td>Average dark foliage, dark stone, or landscape shadows</td>
</tr>
<tr>
<td>V</td>
<td>Middle gray: clear north sky; dark skin, average weathered wood</td>
</tr>
<tr>
<td>VI</td>
<td>Average Caucasian skin; light stone; shadows on snow in sunlit landscapes</td>
</tr>
<tr>
<td>VII</td>
<td>Very light skin; shadows in snow with acute side lighting</td>
</tr>
<tr>
<td>VIII</td>
<td>Lightest tone with texture: textured snow</td>
</tr>
<tr>
<td>IX</td>
<td>Slight tone without texture; glaring snow</td>
</tr>
<tr>
<td>X</td>
<td>Pure white: light sources and specular reflections</td>
</tr>
</tbody>
</table>
Examples
Examples

photographic tonemapping

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

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).

More in later lecture.
Comparison

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

Compute gradients, scale and merge them, then integrate (solve Poisson problem).

- More in later lecture.
Gradient-domain processing and tonemapping
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
Tonemapping for a single image

Modern DSLR sensors capture about 3 stops of dynamic range.
• Tonemap single RAW file instead of using camera’s default rendering.
Tonemapping for a single image

Modern DSLR sensors capture about 3 stops of dynamic range.

- Tonemap single RAW file instead of using camera’s default rendering.

Careful not to “tonemap” noise.
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.

Technically, HDR imaging is simply 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.

In consumer photography, HDR photography includes step 4 (tonemapping).
Another note about terminology

Tonemapping is just another form of tone reproduction.
• Many ISPs implement the tonemapping algorithms we discussed for tone reproduction.
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.
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 pipeline (left), mid-side and near-first photography pipeline (right) coping on the same cell phone camera. In the low-light setting (about 0.7 lux), the conventional camera pipeline produces a noisy result. Refocusing the image (middle) yields heavy spatial sharpening, which results in less detail and an unpleasantly bloomed appearance. Perpixel noise in the image increases the signal-to-noise ratio, making excess spatial sharpening unnecessary. We encourage the reader to view in wide on pipeline events in low-light and high dynamic range scenes, for an example of the latter see figure 3G; it is computationally efficient and reliably artifact-free, as it can be deployed on a mobile camera and used as a substitute for the conventional pipeline in almost all circumstances. For readability, the figure has been made uniformly brighter than the original photographs.)

Abstract
Cell phone cameras have small sensors, which limits the number of photons that are captured. Scaling to today’s ranges in low-light. They also have small pixel sizes, which limits the number of dynamic range that can be captured. Leading to limited dynamic range. We describe a computational photography pipeline that captures, aligns, and composites three frames to reduce noise and enhance dynamic range. Our system has several key features that help make a robust and efficient. First, we use an automated exposure, instead of capturing multiple exposure using cameras for constant exposure, which means that the frames are saved in a robust manner. Second, we select from the captured frames, which allows us to capture the entire light range of the scene. Third, we select the best pixels, which allows us to capture the entire light range of the scene. Fourth, daytime shots with high dynamic range may also be processed with this framework. In particular, it is possible to compress the entire range of exposure without losing information.

1 Introduction
The main technical approach is to perform photographs in low light. Indoor and outdoor scenes, the same as a single exposure produces a single exposure. The main challenge is to reduce noise and increase spatial resolution. We provide a framework for this purpose. Our framework is based on a computational model that captures the entire range of exposure without losing information. This framework is based on a computational model that captures the entire range of exposure without losing information. The framework is based on a computational model that captures the entire range of exposure without losing information. The framework is based on a computational model that captures the entire range of exposure without losing information.
Basic reading:

- Szeliski textbook, Sections 10.1, 10.2.
  
  The two classical papers on radiometric calibration and HDR imaging, which more or less started HDR imaging research in computer vision and graphics.
  
  The photographic tonemapping paper, including a very nice discussion of the zone system for film.

Additional reading:

  
  A very comprehensive book about everything relating to HDR imaging and tonemapping.
  
  The paper on tonemapping using bilateral filtering.
  
  The paper on tonemapping using gradient-domain processing.
  
  The original HDR light probe paper.
  
  The paper describing Google’s HDR+.
  
  The paper that introduced (among other things) the .hdr image format for HDR images. The website has a very detailed discussion of HDR image formats.
  
  Two standard papers on motion deblurring for dealing with long shutter speeds.
  
  The paper that introduced the lens blur algorithm.
  
  One of many, many papers trying to do a perceptual evaluation of different tonemapping algorithms.
  
  A set of slides by Marc Levoy on the challenges of HDR imaging and modern approaches for addressing them.