Exposure and high dynamic range imaging
Course announcements

• Homework assignment 2 is out.
  - Due September 29th.
  - Bonus component worth an extra half homework assignment.

• Computational photography talk on Monday at 1:30 pm: Paul Debevec.
  - See Slack for details.
Overview of today’s lecture

• Leftover from previous 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.
Slide credits

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 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

Aperture

Exposure

Shutter

ISO
Exposure controls brightness of image
Shutter speed

Controls the \textit{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
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.

- in-focus object distance $S$
- focal length $f$
- actual object distance $O$
- sensor distance $S'$
Aperture size

Controls area of lens that lets light pass through.

Also determines circle of confusion.

in-focus object distance $S$  focal length $f$

actual object distance $O$  sensor distance $S’$
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”.
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
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.

- RAW image (mosaiced, linear, 12-bit)
- analog front-end
- white balance
- demosaicing
- CFA
denoising
- color transforms
- tone reproduction
- compression
- final RGB image (non-linear, 8-bit)
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.
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.
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.

• Pros: Full control.
• Cons: Very slow, requires a lot of experience.
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.
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 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.
The world has a high dynamic range

adaptation range of our eyes

common real-world scenes

$10^{-6}$ $10^6$
(Digital) sensors also have a low dynamic range.
(Digital) images have an even lower dynamic range compared to common real-world scenes. The adaptation range of our eyes spans from $10^{-6}$ to $10^6$, while digital images are typically limited to $10^{-6}$ to $10^6$ exposure levels.
(Digital) images have an even lower dynamic range than common real-world scenes. The adaptation range of our eyes spans from $10^{-6}$ to $10^6$, while images often capture scenes with a much narrower range, around $10^{-6}$ to $10^6$, indicating a lower dynamic range compared to the human eye's.
(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
(Digital) images have an even lower dynamic range.
(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 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

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?

HDR imaging compensates for sensor limitations

Tonemapping compensates for display limitations

HDR imaging and tonemapping are distinct techniques with different goals
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.
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 images have a linear response curve

Colorchecker: Great tool for radiometric and color calibration.

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

when not over/under exposed
Over/under exposure

- In highlights we are limited by clipping.
- In shadows we are limited by noise.
RAW (linear) image formation model

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

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 flux for image pixel (x, y): \( \Phi(x, y) \)

Exposure time:

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

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

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

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

\[
\text{noise: } 0.05 < \text{pixel} < 0.95 \quad \text{(clipping)}
\]

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

RAW image (mosaiced, linear, 12-bit) → analog front-end → final RGB image (non-linear, 8-bit)

- denoising
- CFA demosaicing
- white balance
- color transforms
- tone reproduction
- compression
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 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.

*Example: 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.
Varying both scene flux and camera exposure

You can do this using the LDR exposure stack itself.

- More information in homework assignment 2.
Non-linear image formation model

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

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

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

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: \(t_i\)

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

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

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

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.

(noise) 0.05 < pixel < 0.95 (clipping)
(pixel value) / t_i
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.
Tone reproduction curves

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

HDR image (relative flux)  →  spotmeter (absolute flux at one point)  →  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 (later lecture)
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

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?

HDR imaging and tonemapping are distinct techniques with different goals.

HDR imaging compensates for sensor limitations.

Tonemapping compensates for display limitations.
Tonemapping
How do we display our HDR images?

adaptation range of our eyes

10^{-6}                 10^{6}

display

10^{-6}                 10^{6}

HDR image

10^{-6}                 10^{6}

common real-world scenes

adaptation range of our eyes
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

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

(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

- 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).

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.
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.

result from image processing pipeline (basic tone reproduction)
tonemapping using bilateral filtering (I think)
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
Our devices do not match the real world

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HDR imaging and tonemapping are distinct techniques with different goals.

HDR imaging compensates for sensor limitations.

Tonemapping compensates for display limitations.
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).
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.
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.

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**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 available at each pixel. To circumvent this problem, a common technique is to apply a high dynamic range (HDR) technique to images captured with a small sensor. This is done by using a combination of several techniques, including capturing multiple images at different exposures, combining them using an algorithm, and outputting a final image.

In this work, we present a new method for capturing HDR images on mobile devices. Our method is based on the idea of capturing a sequence of images at different exposures and combining them to create a final HDR image. We show that this method is effective in a variety of lighting conditions and can produce images with higher dynamic range than previous methods.

**Keywords**: computational photography, high dynamic range

**1 Introduction**

The use of digital and handheld devices in our daily lives has led to a significant increase in the amount of data we generate and process. This has led to the development of new technologies that can help us better understand and make sense of this data. One such technology is high dynamic range (HDR) imaging, which is a technique used to capture images with a wider range of luminance than is possible with traditional cameras. HDR images can be used to create panoramic images, 3D models, and other applications that require a high dynamic range.
References

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.