Low-level digital imaging

• Fredo Durand, MIT EECS & CSAIL
Low-level digital imaging

Frédo Durand
MIT - EECS
• DISCUSS high res vs low res sensor (no penalty for photon, bad for read)
• DISCUSS THE USE OF HIGH ISO TO GET LESS NOISE!
Today: low-level digital imaging

- White balance
- Dynamic range
- From photon to pixels & noise
- Gamma encoding
- Traditional photography & dynamic range

Next time: multiple-exposure high-dynamic range imaging & tone mapping
WHITE BALANCE
White balance & Chromatic adaptation

• Different illuminants have different color temperature

• Our eyes adapt to this: Chromatic adaptation
  – We actually adapt better in brighter scenes
  – This is why candlelit scenes still look yellow
White balance problem

- When watching a picture on screen or print, we adapt to the illuminant of the room, not that of the scene in the picture
- The eye cares more about objects’ intrinsic color, not the color of the light leaving the objects
- We need to discount the color of the light source

*Same object, different illuminants*
White balance & Film

- Different types of film for fluorescent, tungsten, daylight
- Need to change film!

- Electronic & Digital imaging are more flexible
Von Kries adaptation

- Multiply each channel by a gain factor
  - $R' = R \times k_r$
  - $G' = G \times k_g$
  - $B' = B \times k_b$

http://www.cambridgeincolour.com/tutorials/white-balance.htm
Von Kries adaptation

• Multiply each channel by a gain factor
• Note that the light source could have a more complex effect
  – Arbitrary 3x3 matrix
  – More complex spectrum transformation

http://www.cambridgeincolour.com/tutorials/white-balance.htm
White balance challenge

• How do we find the scaling factors for r, g, and b?
Best way to do white balance

• Grey card:
• Take a picture of a neutral object (white or gray)
• Deduce the weight of each channel
• If the object is recoded as \( r_w, g_w, b_w \) use weights \( k/r_w, k/g_w, k/b_w \) where \( k \) controls the exposure
Lightroom demo

• Most photo editing software lets you click on a neutral object to achieve white balance
  • In “Levels” in Photoshop
  • In “basic” in Lightroom
  • In Adjustments in Aperture
• You also often have presets such as daylight, tungsten
Party name tags

• Provide excellent white references!
Without grey cards

- We need to “guess” which pixels correspond to white objects
Grey world assumption

- Assume average color in the image is grey
- Use weights proportional to
  \[
  \frac{1}{\int_{image} r'}, \frac{1}{\int_{image} g'}, \frac{1}{\int_{image} b}
  \]
- Usually assumes 18% grey to set exposure
Brightest pixel assumption

• Highlights usually have the color of the light source
  – At least for dielectric materials
• White balance by using the brightest pixels
  – Plus potentially a bunch of heuristics
  – In particular use a pixel that is not saturated/clipped
Refs

• Recent work on color constancy
  – http://gvi.seas.harvard.edu/paper/color-subspaces-photometric-invariants

• Still an open problem!
Questions?

from xkcd

Thursday, February 10, 2011
DYNAMIC RANGE
Light, exposure and dynamic range

- Exposure: how bright is the scene overall?
- Dynamic range: contrast in the scene

- Bottom-line problem:
- Display/print have limited contrast
Example:

- Photo with a Canon G3
- Jovan is too dark
- Sky is too bright
Real world dynamic range

- Eye can adapt from $\sim 10^{-6}$ to $10^6$ cd/m$^2$
- Often 1 : 100,000 in a scene

High dynamic range

spotmeter
The world is high dynamic range

- Slide from Paul Debevec
Picture dynamic range: Guess!

Real world

pure black $10^{-6}$ pure white

10$^6$

Picture

$10^{-6}$

10$^6$
Picture dynamic range

- Typically 1:20 or 1:50
  - Black is ~50x darker than white

- Max 1:500

Real world

![Image showing dynamic range comparison between real world and picture. The real world has a dynamic range of 10^{-6} to 10^6, while the picture has a lower contrast range with 10^{-6} to 10^6. The diagram visually represents the difference in contrast.]
Problem 1: record the information

- The range of illumination levels that we encounter is 10 to 12 orders of magnitudes.
- Negatives/sensors can record 2 to 3 orders of magnitude.

\[
\begin{align*}
10^{-6} & \quad \text{Real scenes} \quad 10^6 \\
10^0 & \quad 10^3 \\
\end{align*}
\]

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The future: HDR Cameras

- HDR sensors using CMOS
  - Use a log response curve
  - e.g. SMaL,
- Assorted pixels
  - Fuji
  - Nayar et al.
- Per-pixel exposure
  - Filter
  - Integration time
- Multiple cameras using beam splitters
- Other computational photography tricks
HDR cameras

- http://www.hdrc.com/home.htm
- http://www.smalcamera.com/technology.html
- http://www.pixim.com/
- http://www.ptgrey.com/
- http://www.siliconimaging.com/
The Present

• In the meantime, we are stuck with limited dynamic range sensors
• Next lecture: multiple-exposure photography to increase dynamic range.
Problem 2: Display the information

- Match limited contrast of the medium
- Preserve details

Real world

10^{-6} \quad \text{High dynamic range} \quad 10^6

Picture

10^{-6} \quad \text{Low contrast} \quad 10^6
The Future: Dolby HDR display

• see http://investor.dolby.com/releasedetail.cfm?ReleaseID=363298

• Use Bright Source + Two 8-bit Modulators
  – Transmission multiplies together
  – Over 10,000:1 dynamic range possible

Slide from the 2005 Siggraph course on HDR
The present

• In the meantime, most display technologies (print, projector, monitors) have limited dynamic range
• We need to compress the dynamic range of the picture
  – Today we’ll discuss traditional photography solutions
  – Next time, computational solutions
Questions?
HUMANS & DYNAMIC RANGE
How humans deal with dynamic range

• We're sensitive to contrast (multiplicative)
  – A ratio of 1:2 is perceived as the same contrast as a ratio of 100 to 200
  – Makes sense because illumination has a multiplicative effect
  – Example:
    • grey patch that reflects 50% of light over a dark background that reflects 10%.
    • The contrast is the same no matter what the light intensity: 1 to 5

⇒ For image processing, use the log domain as much as possible
How humans deal with dynamic range

- Dynamic adaptation (very local in retina)
  - Pupil (not so important)
  - Neural
  - Chemical
Sensitivity to different frequencies

- Low sensitivity to low frequencies
- Importance of medium to high frequencies
- Most methods to deal with dynamic range reduce the contrast of low frequencies
- But keep the color

Figure 1-18. Spatial contrast sensitivity functions for luminance and chromatic contrast.
Important: image processing

• Multiplying image by constant makes it brighter (aka. change density)
• Because contrast = ratio
• How do we change contrast then?

Exponent $x \Rightarrow x^y$,

– e.g. square root reduces contrast
– Note: an exponent will also change the average brightness. Can be compensated to keep the midtones.
Matlab demo

- >> I=imadjust(double(imread('colo.jpg'))/255.0, [], [], 2.2);
  >> figure; imshow(imadjust(I, [], [], 1/2.2));
  >> figure; imshow(imadjust(I*2, [], [], 1/2.2));
  >> figure; imshow(imadjust(I*3, [], [], 1/2.2));
  >> figure; imshow(imadjust(I*0.3, [], [], 1/2.2));
  >> figure; imshow(imadjust(I.^1.5, [], [], 1/2.2));
  >> figure; imshow(imadjust(I.^1.5/0.3^0.5, [], [], 1/2.2));
  >> figure; imshow(imadjust(I.^0.5/0.3^-0.5, [], [], 1/2.2));

  Ignore the imadjust for now. Its here for gamma encoding/decoding so that we can work on linear values

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Matlab demo

- Original I
- I*3
- I*0.3

- \( \text{I} \cdot 1.5 \)
- \( \text{I} \cdot 1.5 / 0.3^{0.5} \)
- \( \text{I} \cdot 0.5 / 0.3^{-0.5} \)

- Note: Photoshop does smarter things to preserve highlights/shadows

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Photography version

/blackness

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From Photography by London et al.

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Questions?
What limits camera dynamic range

- Saturation for bright pixels
- Noise for dark pixels
Noise!

Digital pipeline

• Photosites transform photons into charge (electrons)
  – The sensor itself is linear
• Gets amplified (depending on ISO setting)
• Then goes through analog to digital converter
  – up to 14 bits/channel these days

Stop here when shooting RAW

• Then demosaicing, denoising, white balance, a response curve, gamma encoding are applied
• Quantized and recorded as 8-bit JPEG
Pipeline & noise

• This is a conceptual diagram, don’t take it too literally
  – e.g. the AD converter is a serious source of noise, but usually electronic noise, not quantization artifacts

• Orders of magnitude:
  – # of photons per photosite: 10,000-100,000
  – Electronic noise 5-30 electrons per photosite
ISO amplifies

• e.g. going from ISO 100 to ISO 400 amplifies by 4
• both noise & signal
• usually use high ISO when signal is low
• => worse signal/noise ratio
ISO


Canon 400D

ISO 100

ISO 1600
• But, for a given signal level, and a given desired image brightness,
- But, for a given signal level, and a given desired image brightness, two alternatives
  - use low ISO and brighten digitally
  - use high ISO to get brightness directly
- The latter gives less noise because you don’t amplify post-gain noise
ISO recap

- ISO is a simple gain
- amplifies noise as well

- But when the signal is low, it’s better to amplify as early as possible (ISO rather than digitally)
- Ideally, you make sure the signal is high by use a slower exposure or larger aperture
Questions?
Main noise sources

- **Quantum (aka Schott/shot/Poisson/photon) noise**
  - Statistical fluctuation of # photons

- **Additive electronic noise**
  - read noise: before amplification
    => worsens with higher ISO
  - after amplification (at ADC level in particular)
    => same for all ISO

---

**Diagram:**
- **Photons** → **Sensor** → **Gain (ISO)** → **A/D** → **Digital image**
  - **additive noise**
  - **quantization**
Main noise sources

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    => same for all ISO

- **Misc.**
  - thermal (mostly for long exposure)
  - various fixed pattern issues
Photon noise

• Say the average flux of Photons over the sensor is, 100 photons during the exposure time
  – With random fluctuation, we might get 96, or maybe 101, maybe 105.

• Extreme case: the average flux is 0.5 photons during the exposure:
  – We might get 0 or 1

• The amount of fluctuation grows with the average rate, but not as fast: square root.
  – absolute noise increases with intensity
  – relative noise decreases
Photon noise (simulation)

- Going from left to right, the mean number of photons per pixel over the whole image is (top row) 0.001, 0.01, 0.1 (middle row) 1.0, 10.0, 100.0

Great ref on noise

- [http://theory.uchicago.edu/~ejm/pix/20d/tests/noise/index.html](http://theory.uchicago.edu/~ejm/pix/20d/tests/noise/index.html)
- Noise, Dynamic Range and Bit Depth in Digital SLRs
- by Emil Martinec © 2008
Sensor size varies a lot and influences noise.
Well capacity & pixel size

• Well capacity: max number of electro per photosite
• Bigger pixel is better:
  – reduce Photon noise
  – increase electronic signal, need less gain

Recap: Main noise sources

- **Quantum (aka Schott/shot/Poisson/photon) noise**
  - $\sqrt{\text{#photons}}$
  - dominates for brighter pixels

- **Additive electronic noise**
  - read noise: before amplification
    - worsens with higher ISO
  - after amplification (at ADC level in particular)
    - same for all ISO
  - usually dominates for dark pixels

- **Misc.**
  - thermal (mostly for long exposure)
  - various fixed pattern issues
Different regimes

• For bright pixels (in fact, most pixels), photon noise dominates
• For dark pixels: electronic noise dominates

• For low ISO, post-gain noise dominates
• For high ISO, pre-gain noise dominates

• For long exposures, thermal noise kicks in
Factors that influence noise

- Pixel pitch (8 microns: good, 2 microns: bad)
- Area of the photosite actually photosensitive
- Microlens that focus light on that photosensitive area
- Quality of electronics
  - Analog to Digital converter, power supply
- Temperature
  - CCDs for Astronomy are cooled
Sensors and dynamic range

• On the bright value side, once well capacity is exceeded, the sensor saturates

• On the dark side, signal-noise ratio limits you: at some point, noise is above signal

• Note: quantization is NOT the limiting factor. Instead, the well capacity and noise are.
  – 14 bits does not necessarily mean more dynamic range than 12 bits
Questions
Recap: Digital photography pipeline

• Photosites transform photons into charge (electrons)
• Gets amplified (depending on ISO setting)
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Stop here when shooting RAW

• Demosaicing
• Denoising
• Color space conversion (from sensor to sRGB)
• White balance
• Response curve, color enhancement
• Gamma encoding
• Quantized and recorded as JPEG
  – DCT, quantization based on CSF, entropy coding

Well, some cameras apply some processing such as denoising to the RAW data
Recap: Digital photography pipeline

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Response curve of D-SLR

- straight for mid-tones
- toe and shoulder preserve more dynamic range around dark and bright areas, at the cost of reduced contrast

http://www.dpreview.com/reviews/canoneos5d/page22.asp
• Following slide not used in lecture but useful cultural background
GAMMA ENCODING
The infamous gamma curve

• A gamma curve $x \rightarrow x^{\gamma}$ is used for many reasons:
  – CRT response
  – Color quantization
  – Perceptual effect

• Sometimes with $\gamma > 1$, sometimes $\gamma < 1$

• These issues are often oversimplified/confused, including in prominent textbooks
  – i.e. they are explained wrong
Color quantization gamma

• The human visual system is more sensitive to ratios: is a grey twice as bright as another one?
• If we use linear encoding, we have tons of information between 128 and 255, but very little between 1 and 2!
• Ideal encoding?
  Log
• Problems with log?
  Gets crazy around zero
Solution: gamma
Color quantization gamma

- The human visual system is more sensitive to ratios: is a grey twice as bright as another one?
- If we use linear encoding, we have tons of information between 128 and 255, but very little between 1 and 2!
- This is why a non-linear gamma remapping of about 2.0 is applied before encoding
- True also of analog imaging to optimize signal-noise ratio
Gamma encoding

- From Greg Ward
- only 6 bits for emphasis
IMPORTANT MESSAGE

• Digital images are usually gamma encoded
  – often $\gamma=2.2$ (but 1.8 for Profoto RGB)
• To get linear values, you must decode
  – apply $x \rightarrow x^\gamma$

• That’s why I had $^1/2.2$ in my matlab demo
• Crucial when you rely on linearity
  – e.g. deblurring, matting, lighting/texture separation
Film have a gamma too!

- Control dynamic range, contrast mapping

Gamma in terms of density and log exposure

From The Manual of Photography, Jacobson et al.
Another gamma: Cathode Ray Tube

- The relationship between voltage and CRT light intensity is non linear
- Can be approximated by an exponent 2.5
- Must be inverted to get linear response
- Nice coincidence that it’s close to 2.2
  - But justs a coincidence

From Ponton’s FAQ
http://www.poynton.com/
Another gamma: Stevens effect

• Perceived contrast increases with luminance
At the end of the day

- At the camera or encoding level, apply a gamma of around 1/2.2
- The CRT applies a gamma of 2.5
- The residual exponent 2.2/2.5 boosts the colors/contrast to compensate for the dark environment

- See
  http://www.poynton.com/GammaFAQ.html
  http://www.poynton.com/notes/color/GammaFQA.html
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TRADITIONAL PHOTOGRAPHY
Limited dynamic range can be good!

- W. Eugene Smith photo of Albert Schweitzer
- 5 days to print!
- Things can be related because the intensity is more similar
- Balance, composition
Negative and response curve

- Negatives typically afford 3 orders of magnitude
- More than printing paper
- Shoulder region provides a little more dynamic range (but less precision there)
Questions?
Response curve manipulation

• **Traditional photography**
  – Chemicals and duration of development
  – Paper grade ($\gamma$)
  – Flashing the paper before printing
  – Various chemicals on paper
  – Note: you have one curve for negative, one for paper
    Usually they have inverse gamma (but not strictly, enables contrast control)

• **Digital**
  – Curve tool
Photoshop curves

• Specify an arbitrary remapping curve
• Especially useful for black and white
Examples of curves

• Brighten
• Darken
• Contrast
Figure 15.8  Effect of development time on characteristic curve of current sensitive materials

From The Manual of Photography, Jacobson et al.
Reduced development

Normal development  Contraction (short development)

Source: Ansel Adams
Two solutions

One development solution
Two development solution: the dark areas are the same, but bright areas are different

Source: Ansel Adams
Pre-exposure

- Briefly expose negative to a uniform light
- Raises the values of everything (in particular puts dark values above the low-contrast toe of response curve)

Source: Ansel Adams

Without pre-exposure  With pre-exposure

Source: Ansel Adams
Questions?
Lighting

• E.g. 3-point lighting
  – Reduce dynamic range
  – Emphasize silhouettes
! 3D cues

• Goals of lighting:
  – Manage dynamic range
  – Reveal shape, layout, material
  – Tell story
Portrait lighting

Main light
Fill-in light
Accent light
Background light
Fill-in flash
Questions?
Filtering: black and white

- Red/orange/yellow filters darken the sky

Source: Ansel Adams

No filter  With red filter

Source: Ansel Adams
Graduated neutral density

No filter: sky is too bright

Vertical neutral density gradient
Graduated ND & landscape

- Art Wolfe: In the late evening light, I composed this image using a graduated neutral-density filter to bring the overall exposure into alignment, thus preserving the detail in the clouds in the sky and the reflections on the water.

http://www.artwolfe.com/
Graduated ND & landscape

- Art Wolfe: Here I had to use a combination of filters and settings that greatly reduced my chance of success. I used my zoom to bring in Denali and the moose. A polarizing filter brought out the rich colors of the tundra and darkening the sky and a graduated, neutral-density filter to bring the entire scene into the same exposure.

http://www.artwolfe.com/
Questions?
Dodging and burning

• During the print
• Hide part of the print during exposure
  – Makes it brighter

From The Master Printing Course, Rudman
Dodging and burning

*Dodging* holds back light during the basic printing exposure to lighten an area.

*Burning* adds light after the basic exposure to darken an area.

From Photography by London et al.
Dodging and burning

- Must be done for every single print!

Straight print

After dodging and burning

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Dodging and burning

Source: Ansel Adams
Dodging & burning is difficult!

Source: Rudman

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Questions?

- Gordon Parks
Digital dodge-burn and graduated ND

• **Use adjustment layer and gradient tool**
  – Use curve adjustment layer
  – Modulate its effect using the layer mask

• **Just paint in black**
  – On a separate layer
  – With a low opacity

• **Multiple exposure photography**
  – Use a tripod
  – “Bracket” your exposure
  – Stack exposures as layers in Photoshop
  – Use layer masks to select which region comes from which exposure
Questions?
Refs

http://www.hdrsoft.com/resources/dri.html
http://www.clarkvision.com/imagedetail/dynamicrange2/
http://www.debevec.org/HDRI2004/
http://www.luminous-landscape.com/tutorials/hdr.shtml
http://www.anyhere.com/gward/hdrenc/
http://www.openexr.com/
http://gl.ict.usc.edu/HDRShop/
http://www.anyhere.com/
Ref on sensor performance

- http://www.dxomark.com/
Questions?
Exception: Sunnybrook HDR display

- Use Bright Source + Two 8-bit Modulators
  - Transmission multiplies together
  - Over 10,000:1 dynamic range possible

Low-res B&W backlight  High-res color foreground
• http://www.dolby.com/promo/hdr/technology.html