Computational Photography

COS 526: Advanced Computer Graphics

Slide credits: Funkhouser, Finkelstein, Durand, Debevec, Efros, Gunturk
What is Computational Photography?

- The use of computational techniques to overcome the limitations of traditional photography
Traditional Photography

- Camera controls:
  - Viewpoint
  - Lens
  - Shutter speed
  - Aperture
  - Sensor
Traditional Photography

• Pin-hole camera:
Traditional Photography

- Pin-hole size?
Traditional Photography

• Pin-hole size?
  – Smaller produces sharper image (up to limits of diffraction)
  – Larger lets in more light

2.18 Diffraction limits the quality of pinhole optics. These three images of a bulb filament were made using pinholes with decreasing size. (A) When the pinhole is relatively large, the image rays are not properly converged, and the image is blurred. (B) Reducing the size of the pinhole improves the focus. (C) Reducing the size of the pinhole further worsens the focus, due to diffraction. From Ruechaedt, 1958.
Traditional Photography

- Lenses

![Diagram of a lens system showing focal length (f)]
Traditional Photography

- Lens systems use many lenses to overcome limitations of single lenses
Traditional Photography

- Lenses
  + More light
  + Sharp ...
  - at one depth

From Photography, London et al.
Limitations of traditional photography

- Single depth of focus
Limitations of traditional photography

- Limited resolution
Limitations of traditional photography

- Bad color / no color
Limitations of traditional photography

- Limited dynamic range
Limitations of traditional photography

- Single viewpoint
Limitations of traditional photography

- Static scene
Limitations of traditional photography

- Blur, camera shake, noise, damage
Limitations of traditional photography

- Unfortunate expressions
Limitations of traditional photography

- Unwanted objects
Computational Photography

Computer Graphics

- + easy to manipulate objects/viewpoint
- - hard to acquire/create
- - hard to make realistic

Photography

- - hard to manipulate objects/viewpoint
- + easy to acquire
- + instantly realistic

Realism
Manipulation
Ease of capture

Slide by Efros
Computational Photography

- Example: high-dynamic range
Computational Photography

- Example: deblurring
Computational Photography

- Example: super-resolution
Computational Photography

- Example: creating panoramas
Computational Photography

- Example: gigapixel images
Computational Photography

• Example: color harmonization
Computational Photography

- Example: background replacement
Computational Photography

- Example: image completion
Computational Photography

- Example: image completion
Computational Photography

- Example: tour into the picture

Horry
Computational Photography

- Example: photo tourism
High Dynamic Range Imaging
Dynamic Range

The real world is high dynamic range.
Problem

- Cameras cannot capture the full dynamic range of the world
Long Exposure

Real world

10^{-6}  |  High dynamic range |  10^6

Picture

10^{-6}  |  0 to 255

10^6
Short Exposure

Real world

$10^{-6}$

High dynamic range

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

Picture

$10^{-6}$

0 to 255

$10^6$
Ways to Vary Exposure

- Shutter Speed (*)
- F/stop (aperture, iris)
- Neutral Density (ND) Filters
Varying Shutter Speed

• Ranges:  Canon D30: 30 to 1/4,000 sec.
  Sony VX2000: 1/4 to 1/10,000 sec.

• Pros:
  – Directly varies the exposure
  – Usually accurate and repeatable

• Issues:
  – Noise in long exposures
Varying Shutter Speed

- Shutter times approximately obey a power series:
  1/4, 1/8, 1/15, 1/30, 1/60, 1/125, 1/250, 1/500, 1/1000 sec
Varying Shutter Speed
High Dynamic Range Imaging

- Infer radiance of scene from multiple images with varying exposure (photometric calibration)
General Approach

- Build model of imaging system
  (radiance $\rightarrow$ pixel values)
- Invert model
  (pixel values $\rightarrow$ radiance)
What does 42 mean?

Pixel (312, 284) = 42

Image
Imaging System Response Function

![Graph showing the relationship between photon count and pixel value. The graph has a y-axis labeled 'Pixel value' with values ranging from 0 to 255, and an x-axis labeled 'photon count'. The graph shows a curve that starts at 0 on the pixel value axis and rises sharply to 255 as the photon count increases.]
Recovering the Response Curve

Image series

Pixel Value $Z = f(\text{Exposure})$

Exposure = Radiance $\cdot$ $\Delta t$

$log$ Exposure = $log$ Radiance + $log$ $\Delta t$
Recovering the Response Curve

Assuming unit radiance for each pixel

After adjusting radiances to obtain a smooth response curve
Recovering the Response Curve

- Let $g(z)$ be the discrete inverse response function.
- For each pixel site $i$ in each image $j$, want:
  $$\log \text{Radiance}_i + \log \Delta t_j = g(Z_{ij})$$
- Solve the overdetermined linear system via least squares:
  $$\sum_{i=1}^{N} \sum_{j=1}^{P} \left( \log \text{Radiance}_i + \log \Delta t_j - g(Z_{ij}) \right)^2 + \lambda \sum_{z=Z_{\text{min}}}^{Z_{\text{max}}} g''(z)^2$$

  - fitting term
  - smoothness term
Results: Digital Camera

Kodak DCS460
1/30 to 30 sec

Recovered response curve

Pixel value

log Exposure
Reconstructed Radiance Map
Results: Color Film

- Kodak Gold ASA 100, PhotoCD
Recovered Response Curves

Red

Green

Blue

RGB
The Radiance Map

Linearly scaled to display device
Now What?
Tone Mapping: HDR Content on LDR Devices

Real world

High dynamic range

Picture

0 to 255
Reinhart et al

\[ L_{\text{display}} = \frac{L_{\text{world}}}{1 + L_{\text{world}}} \]
Reinhart et al. Results
Reinhart et al Comparison

Reinhart Operator

Darkest 0.1% scaled to display device
Fattal et al (in 1D)

2500:1

7.5:1

log

exp

derivative

integrate

attenuate
Fattal et al Comparison

Gradient-space
[Fattal et al.]

Bilateral
[Durand et al.]

Photographic
[Reinhard et al.]
Fattal et al Comparison

Gradient-space [Fattal et al.]

Bilateral [Durand et al.]

Photographic [Reinhard et al.]
HDR Tone Mapping Example