High Dynamic Range Imaging

Multimedia Techniques & Applications

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(this slides are borrowed from Prof. Yung-Yu Chuang)

1

High Dynamic Range (HDR) Imaging

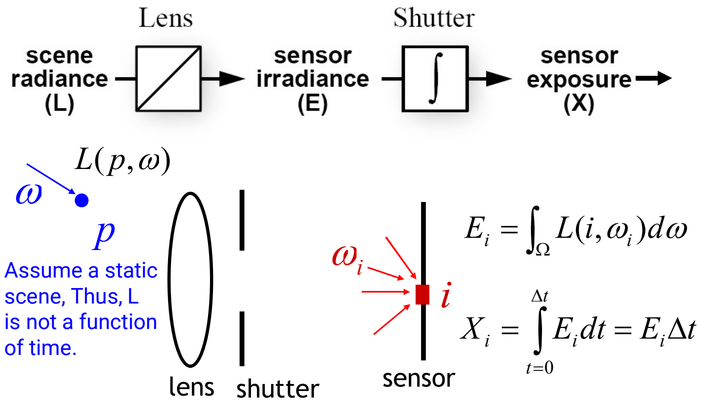
2

Why do We Need HDR

- Camera is an imperfect device for measuring the radiance distribution of a scene because it cannot capture the full spectral content and dynamic range
- Limitations in sensor design prevent cameras from capturing all information passed by lens

3

Camera Pipeline

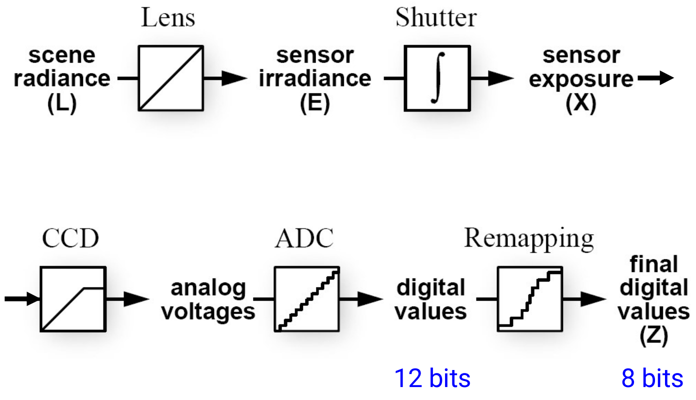


$$E_i = \int_\Omega L(i, \omega_i) d\omega$$

$$X_i = \int_{t=0}^{\Delta t} E_i dt = E_i \Delta t$$

4

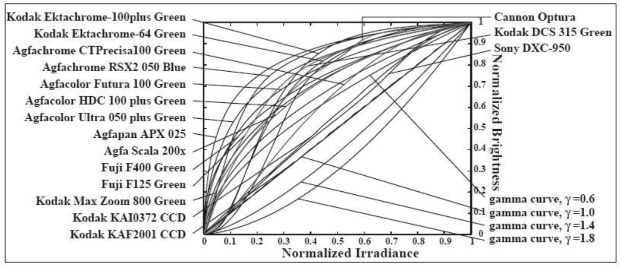
Camera Pipeline (cont.)



5

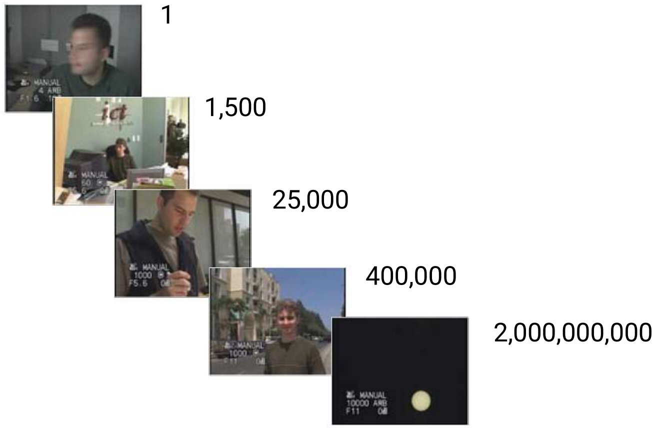
Real-world Response Functions

- In general, the response function is not provided by camera makers who consider it part of their proprietary product differentiation
- In addition, they are beyond the standard gamma curves



6

The World is High Dynamic Range



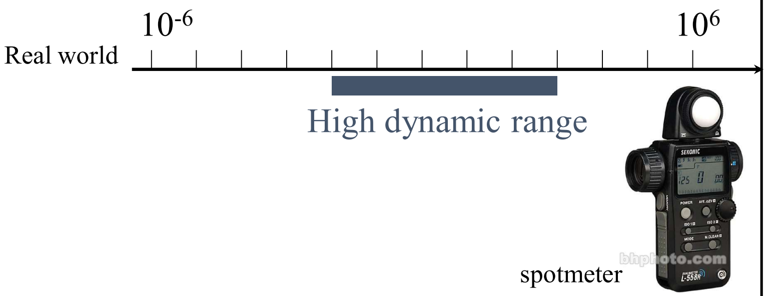
7

The World is High Dynamic Range (cont.)

8

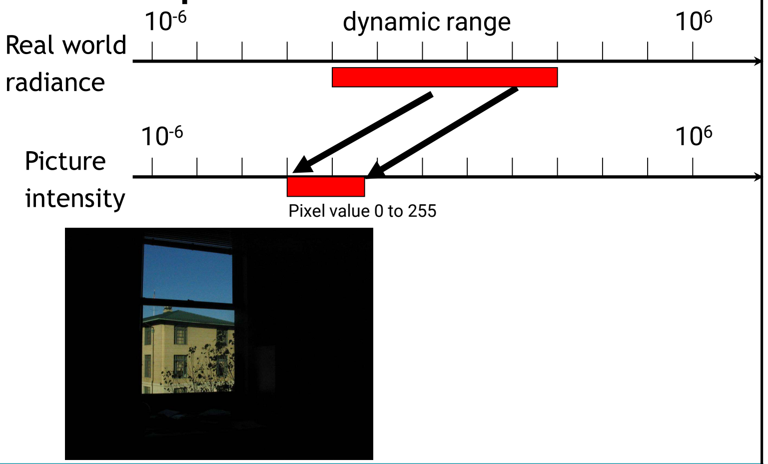
Real-world Dynamic Range

- Eye can adapt from ~ 10^{-6} to 10^{6} cd/m^2
- Often 1:100,000 in a scene
- Typical 1:50, max 1:500 for pictures



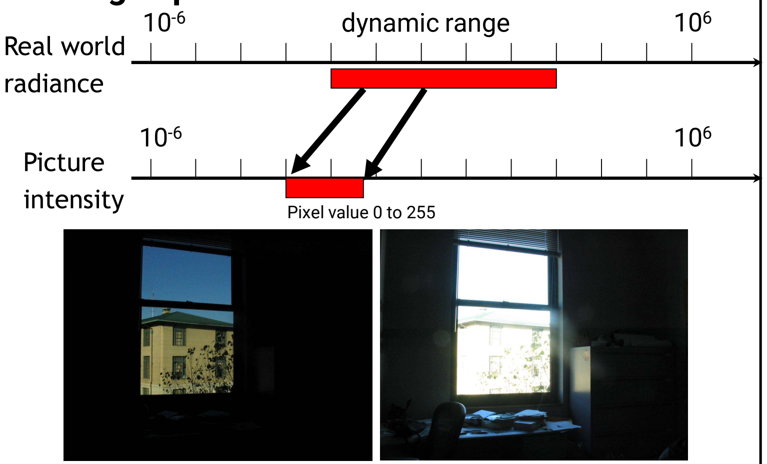
9

Short Exposure



10

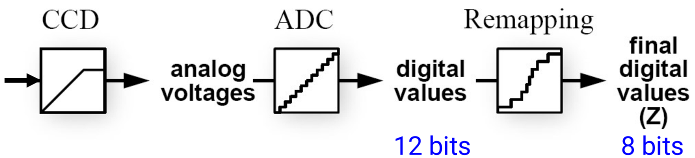
Long Exposure



11

Camera is Not a Photometer

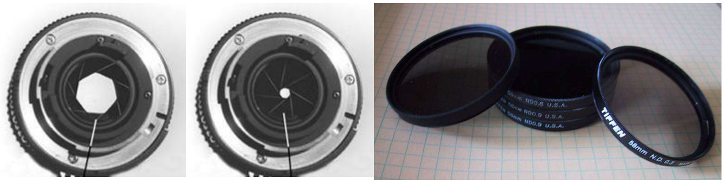
- **Limited dynamic range**
  - Perhaps use multiple exposures?
- **Unknown, nonlinear response**
  - Not possible to convert pixel values to radiance
- **Solution**
  - Recover response curve from multiple exposures, then reconstruct the radiance map



12

Varying Exposure

- Way to change exposure
  - Shutter speed
  - Aperture



13

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

14

Varying Shutter Speed

15

HDRI Capturing from Multiple Exposures

- Capture images with multiple exposures
- Image alignment (even if you use tripod, it is suggested to run alignment)
- Response curve recovery
- Ghost / flare removal

16

Image Alignment

- We will introduce a fast and easy-to-implement method for this task, called **Median Threshold Bitmap (MTB)** alignment technique
- Consider only **integral translations**. It is enough empirically
- The inputs are *N* grayscale images (you can either use the green channel or convert them into grayscale by *Y=(54R+183G+19B)/256*)
- **MTB is a binary image formed by thresholding the input image using the median of intensities**

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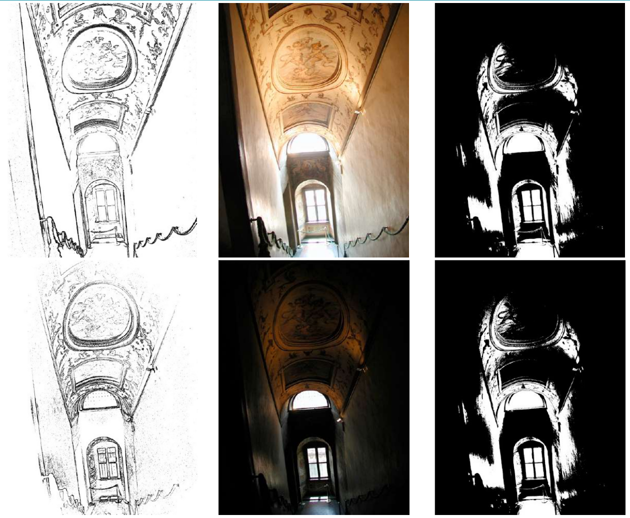

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Why is MTB Better Than Gradient?

- Edge-detection filters are dependent on image exposures
- Taking the difference of two edge bitmaps would not give a good indication of where the edges are misaligned

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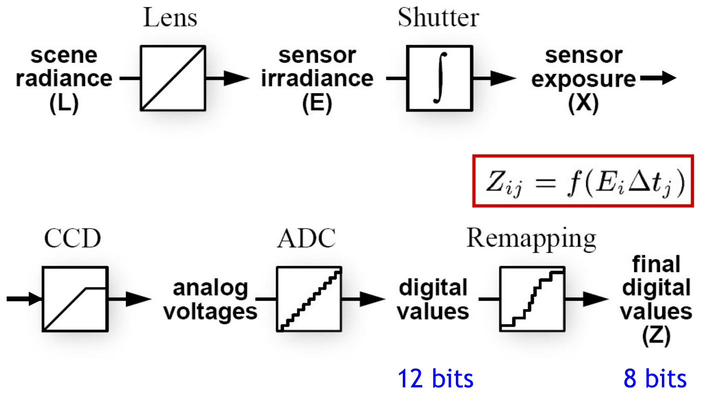
Results of MTB

- Success rate = 84%. 10% failure due to rotation. 3% for excessive motion and 3% for too much high-frequency content.

Recover Response Curve

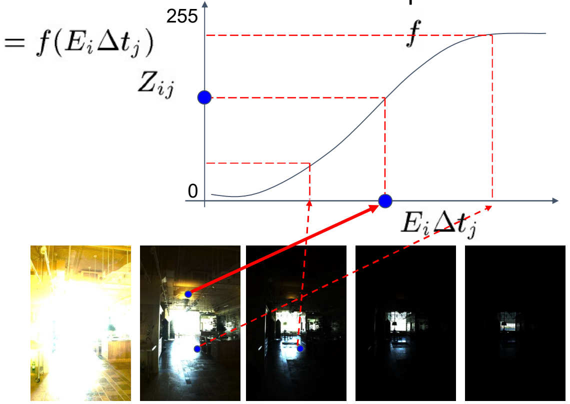


21

Recover Response Curve (cont.)

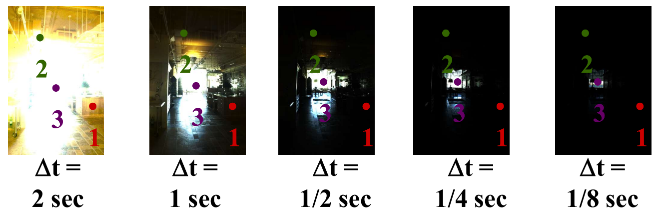
- We want to obtain the inverse of the response curve

$$Z_{ij} = f(E_i \Delta t_j)$$

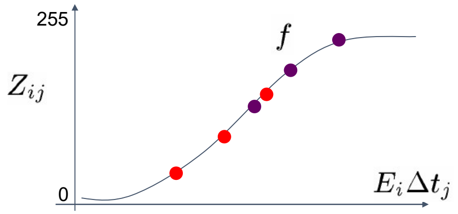


22

Recover Response Curve (cont.)

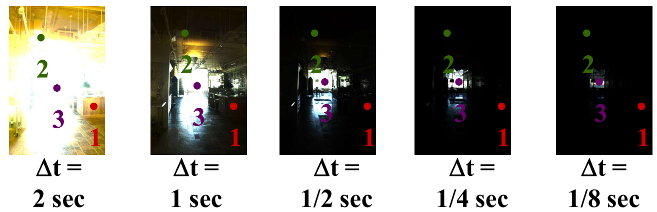


$$Z_{ij} = f(E_i \Delta t_j)$$

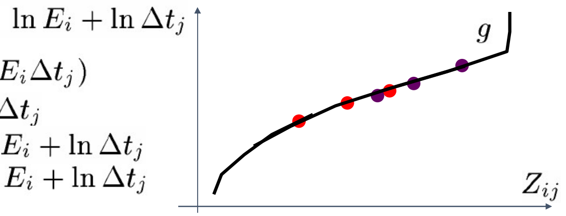


23

Recover Response Curve (cont.)

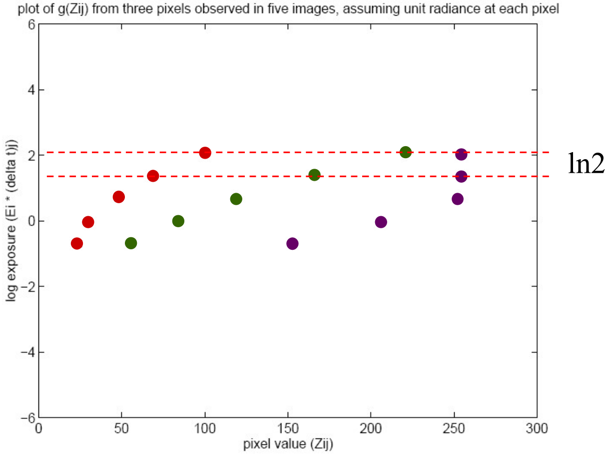


$$Z_{ij} = f(E_i \Delta t_j)$$
$$X_{ij} = E_i \Delta t_j$$
$$\ln X_{ij} = \ln E_i + \ln \Delta t_j$$
$$g(Z_{ij}) = \ln E_i + \ln \Delta t_j$$



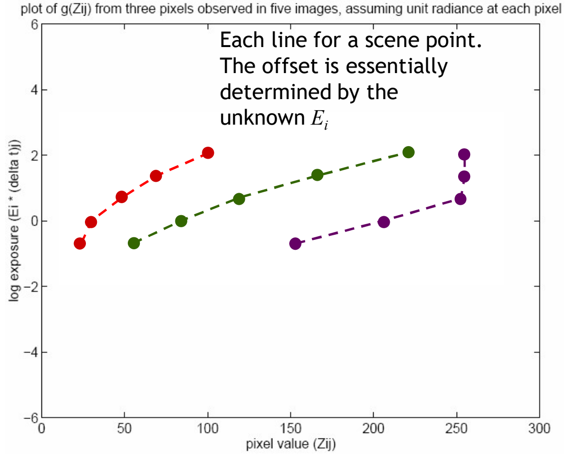
24

Idea behind the Math



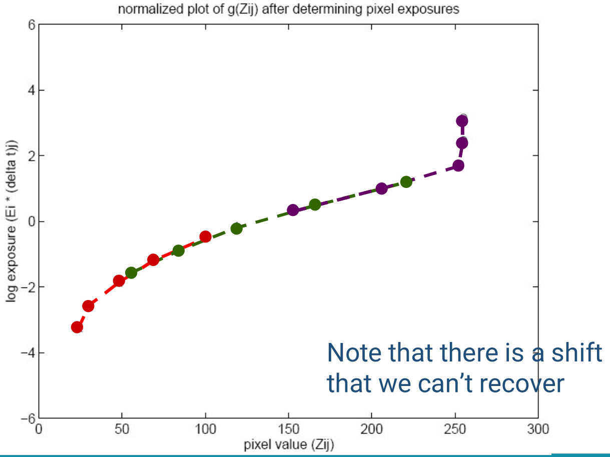
25

Idea behind the Math (cont.)



26

Idea behind the Math (cont.)



27

Basic Idea

- Design an objective function
- Optimize it

28

Math for Recovering the Response Curve

$$Z_{ij} = f(E_i \Delta t_j)$$

f is monotonic, it is invertible

$$\ln f^{-1}(Z_{ij}) = \ln E_i + \ln \Delta t_j$$

let us define function $g = \ln f^{-1}$

$$g(Z_{ij}) = \ln E_i + \ln \Delta t_j$$

minimize the following

$$\mathcal{O} = \sum_{i=1}^{N} \sum_{j=1}^{P} [g(Z_{ij}) - \ln E_i - \ln \Delta t_j]^2 + \lambda \sum_{z=Z_{min}+1}^{Z_{max}-1} g''(z)^2$$

$$g''(z) = g(z-1) - 2g(z) + g(z+1)$$

Recover Response Curve (cont.)

- Add a hat weighting function

$$w(z) = \begin{cases} z - Z_{min} & \text{for } z \le \frac{1}{2}(Z_{min} + Z_{max}) \\ Z_{max} - z & \text{for } z > \frac{1}{2}(Z_{min} + Z_{max}) \end{cases}$$

- The objective function becomes

$$\mathcal{O} = \sum_{i=1}^{N} \sum_{j=1}^{P} \{w(Z_{ij}) [g(Z_{ij}) - \ln E_i - \ln \Delta t_j]\}^2 +$$

$$\lambda \sum_{z=Z_{min}+1}^{Z_{max}-1} [w(z) g''(z)]^2$$

Recover Response Curve (cont.)

- We want $N(P-1) > (Z_{max} - Z_{min})$
  If P = 11, N ~ 25 (typically 50 is used)
- We prefer that selected pixels are well distributed and sampled from constant regions
- It is an overdetermined system of linear equations and can be solved using SVD

Matlab Code

```
%
% gsolve.m - Solve for imaging system response function
%
% Given a set of pixel values observed for several pixels in several
% images with different exposure times, this function returns the
% imaging system's response function g as well as the log film irradiance
% values for the observed pixels.
%
% Assumes:
%
%  Zmin = 0
%  Zmax = 255
%
% Arguments:
%
%  Z(i,j) is the pixel values of pixel location number i in image j
%  B(j)   is the log delta t, or log shutter speed, for image j
%  l      is lamdba, the constant that determines the amount of smoothness
%  w(z)   is the weighting function value for pixel value z
%
% Returns:
%
%  g(z)   is the log exposure corresponding to pixel value z
%  lE(i)  is the log film irradiance at pixel location i
%
```

```
function [g,lE]=gsolve(Z,B,l,w)

n = 256;
A = zeros(size(Z,1)*size(Z,2)+n+1,n+size(Z,1));
b = zeros(size(A,1),1);

k = 1;            %% Include the data-fitting equations
for i=1:size(Z,1)
  for j=1:size(Z,2)
    wij = w(Z(i,j)+1);
    A(k,Z(i,j)+1) = wij; A(k,n+i) = -wij; b(k,1) = wij * B(i,j);
    k=k+1;
  end
end

A(k,129) = 1;       %% Fix the curve by setting its middle value to 0
k=k+1;

for i=1:n-2         %% Include the smoothness equations
  A(k,i)=l*w(i+1); A(k,i+1)=-2*l*w(i+1); A(k,i+2)=l*w(i+1);
  k=k+1;
end

x = A\b;            %% Solve the system using SVD

g = x(1:n);
lE = x(n+1:size(x,1));
```

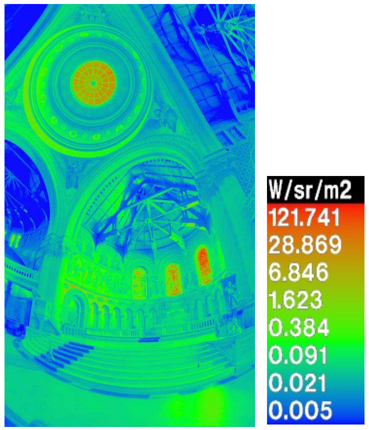

Constructing HDR Radiance Map

$$\ln E_i = g(Z_{ij}) - \ln \Delta t_j$$

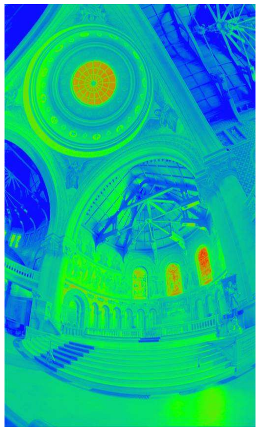
combine pixels to reduce noise and obtain a more reliable estimation

$$\ln E_i = \frac{\sum_{j=1}^{P} w(Z_{ij})(g(Z_{ij}) - \ln \Delta t_j)}{\sum_{j=1}^{P} w(Z_{ij})}$$

Reconstructed Radiance Map



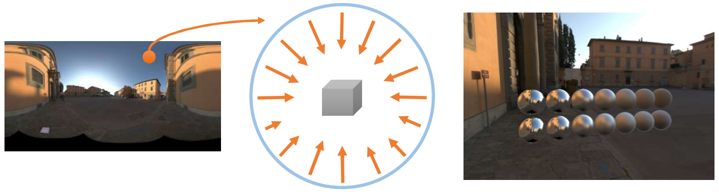
Reconstructed Radiance Map (cont.)



- What is this for?
  - Human perception
  - Vision / graphics applications

Recap: Environment Lighting

- Environment light illuminates the scene from a **virtual sphere at infinite distance**
- The spherical energy distribution is usually represented with longitude-latitude images
- Also called **image-based lighting (IBL)**



37

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Recap: Environment Lighting

- Widely used in digital visual effects and film production

38

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Automatic Ghost Removal

before

after

39

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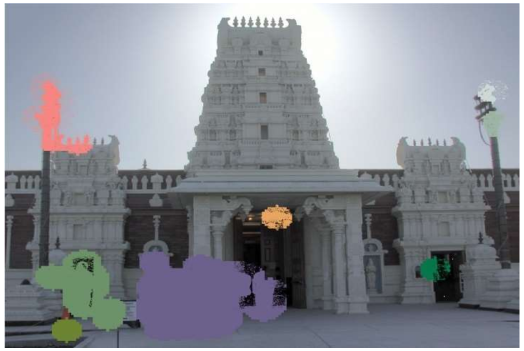
Weighted Variance

- Moving objects and high-contrast edges render high variance

40

Weighted Variance

- Moving objects and high-contrast edges render high variance



41

Result of Ghost Removal

42

Ghost Removal by Patch-based HDR

Input LDR sources   Reconstructed LDR images   Final tonemapped HDR result

43

More Examples (I)

44

More Examples (I)

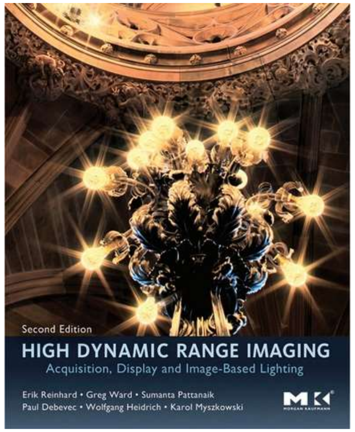
More Examples (II)

More Examples (II)

HDR Becomes Common Practices

- Many cameras has bracket exposure modes
- For example, since iPhone 4, iPhone has HDR option
  - But it could be more exposure blending rather than true HDR

References



References

- Paul E. Debevec, Jitendra Malik, Recovering High Dynamic Range Radiance Maps from Photographs, SIGGRAPH 1997.
- Tomoo Mitsunaga, Shree Nayar, Radiometric Self Calibration, CVPR 1999.
- Mark Robertson, Sean Borman, Robert Stevenson, Estimation-Theoretic Approach to Dynamic Range Enhancement using Multiple Exposures, Journal of Electronic Imaging 2003.
- Michael Grossberg, Shree Nayar, Determining the Camera Response from Images: What Is Knowable, PAMI 2003.
- Michael Grossberg, Shree Nayar, Modeling the Space of Camera Response Functions, PAMI 2004.
- Srinivasa Narasimhan, Shree Nayar, Enhancing Resolution Along Multiple Imaging Dimensions Using Assorted Pixels, PAMI 2005.
- G. Krawczyk, M. Goesele, H.-P. Seidel, Photometric Calibration of High Dynamic Range Cameras, MPI Research Report 2005.
- G. Ward, Fast Robust Image Registration for Compositing High Dynamic Range Photographs from Hand-held Exposures, jgt 2003.