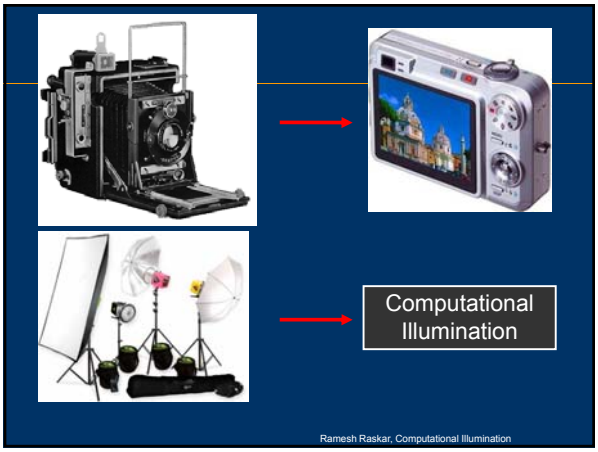
Computational Illumination

Computational Illumination

SIGGRAPH 2006 Course

Course WebPage :
http://www.merl.com/people/raskar/photo/

Ramesh Raskar
Mitsubishi Electric Research Labs



Edgerton 1930's

Not Special Cameras but Special Lighting

Edgerton 1930's

Stroboscope
(Electronic Flash)

Multi-flash
Sequential Photography

Computational Illumination:

- Presence or Absence, Duration, Brightness
  - Flash/No-flash
- Light color/wavelength
- Light position
  - Multi-flash for depth edges
  - Programmable dome (image re-lighting and matting)
- Spatial Modulation
  - Dual Photography

Ramesh Raskar, Computational Illumination

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Denoising Challenging Images

Available light:

+ nice lighting

- noise/blurriness
- color

Flash:

+ details
+ color

- flat/artificial

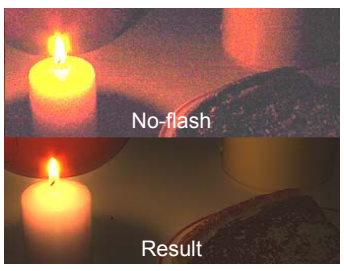
Elmar Eisemann and Frédo Durand , Flash Photography Enhancement via Intrinsic Relighting

Georg Petschnigg, Maneesh Agrawala, Hugues Hoppe, Richard Szeliski, Michael Cohen, Kentaro Toyama. Digital Photography with Flash and No-Flash Image Pairs

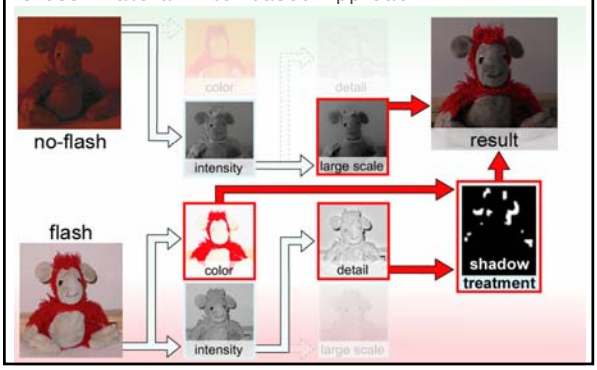
Denoise no-flash image using flash image

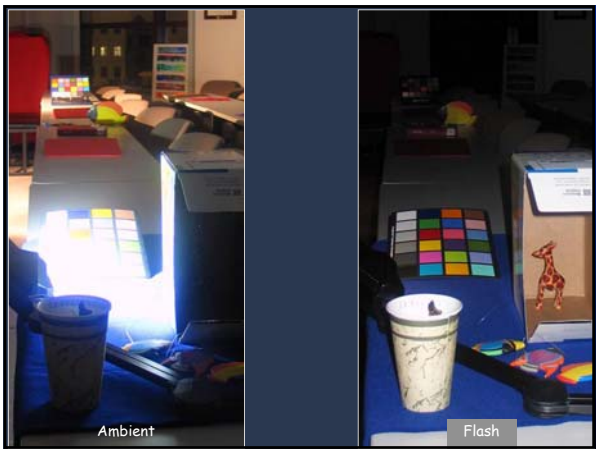
Transfer detail from flash image to no-flash image

+ original lighting
+ details/sharpness
+ color



Cross-Bilateral Filter based Approach

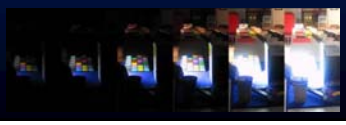


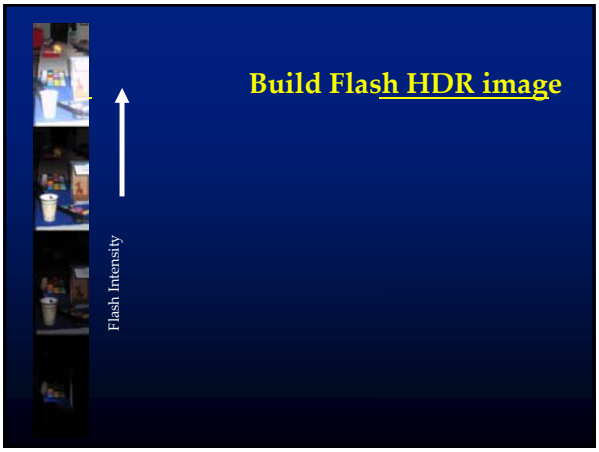


Build Exposure HDR image

- Multiple images with different exposure
  - Debevec & Malik, Siggraph 97
  - Nayar & Mitsunaga, CVPR 00

Increasing Exposure





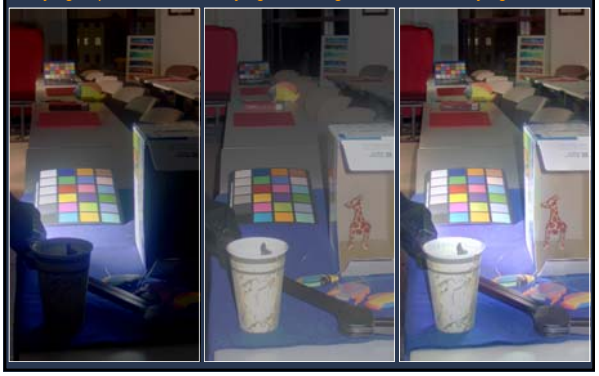
Build Flash HDR image

Build Flash-Exposure HDR image

Agrawal, Raskar, Nayar, Li
Siggraph05

Capturing HDR Image

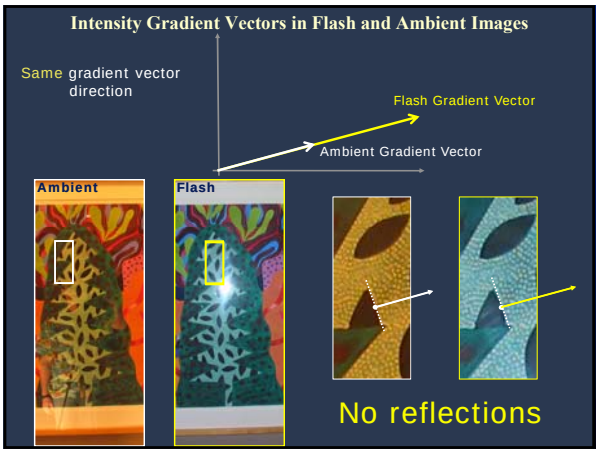
Varying Exposure time | Varying Flash brightness | Varying both

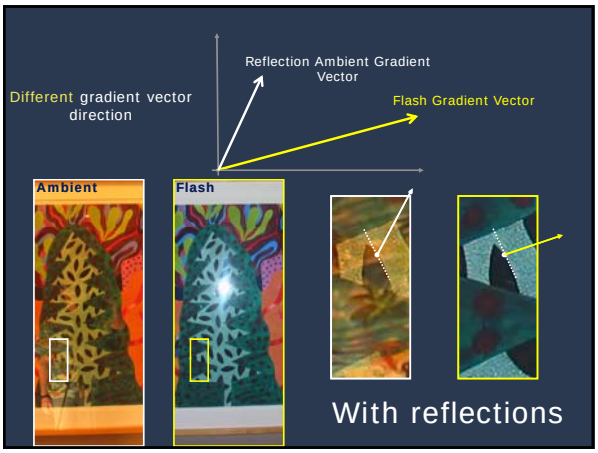


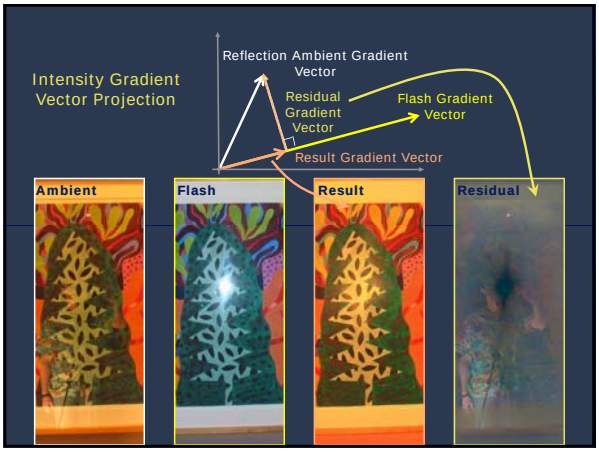
Flash and Ambient Images

[Agrawal, Raskar, Nayar, Li Siggraph05]

Ambient | Flash | Result | Reflection Layer







Ramesh Raskar, Computational Illumination

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Dark Flash Photography

Dilip Krishnan and Rob Fergus

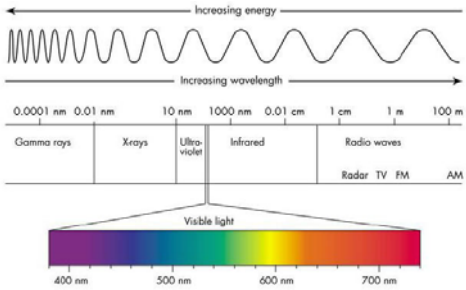
Dept. of Computer Science,
Courant Institute,
New York University

Dark Flash Photography

- Dark flash is ~200 times dimmer than conventional

Dark flash image | Ambient image | Reconstruction | Ground truth

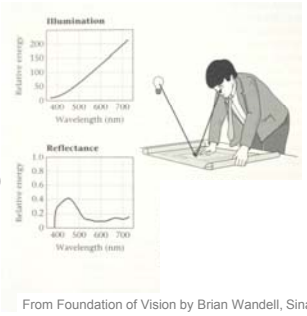
Electromagnetic Spectrum



Spectral Image Formation

I(λ)

R(λ)



From Foundation of Vision by Brian Wandell, Sinauer Associates, 1995

Spectral Image Formation

$$p_c = \int I(\lambda) S_c(\lambda) R(\lambda)\ d\lambda$$

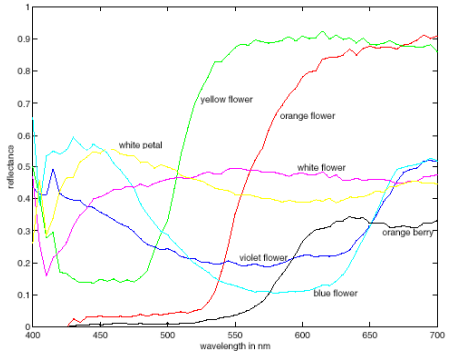
I(λ) - Illumination Spectrum

$S_c(\lambda)$ - Spectral sensitivity of channel c
Properties of illumination/sensor

R(λ) - Surface reflectance/transmission
Property of the scene

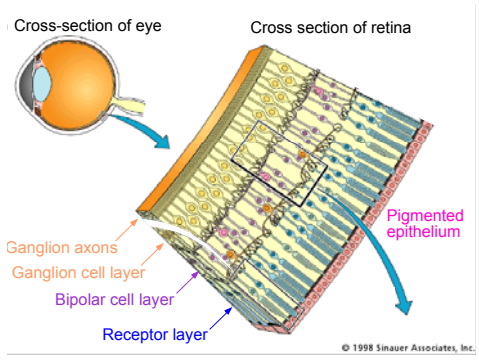
Pixel value / Perceived color depends on all 3 terms

Some Reflectance Spectra R(λ)



Forsyth, 2002

The Retina



Two Types of Light Sensitive Receptors

Cones

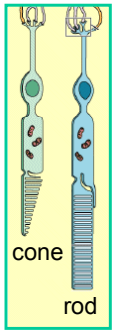
cone-shaped
color vision

less sensitive
Photopic -- operate in high light

Rods

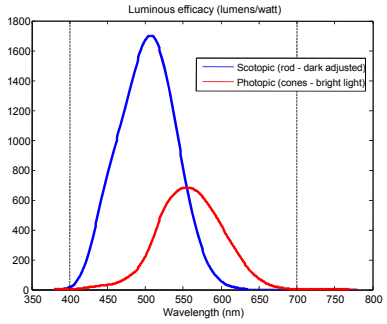
rod-shaped
gray-scale vision

highly sensitive
Scotopic -- operate in low light



Human Spectral Sensitivity Function

$S_{human}(\lambda)$

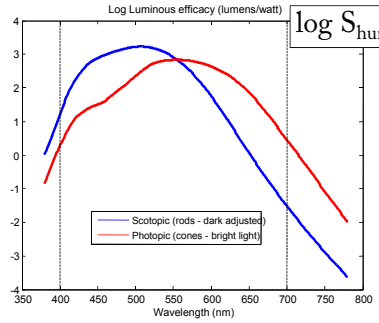


Vos 1978

Log Human Spectral Sensitivity Function

$\log S_{human}(\lambda)$

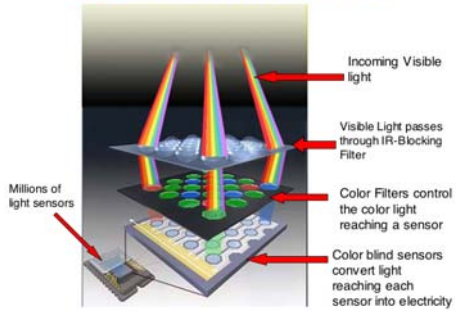
Steep fall off outside 400-700nm range



Vos 1978

DSLR Camera Sensor

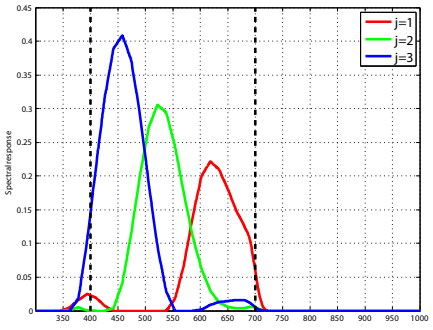
RGB Inside the Camera



http://www.photoaxe.com/wp-content/uploads/2007/04/camera-sensor.jpg

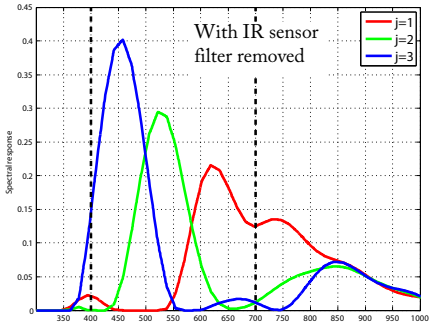
Camera Spectral Sensitivity Function

$S_{camera}(\lambda)$



Camera Spectral Sensitivity Function

$S_{camera}(\lambda)$



Camera Spectral Sensitivity Function

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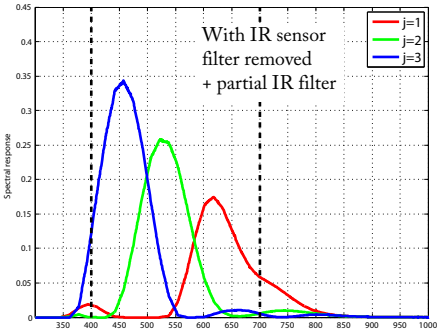
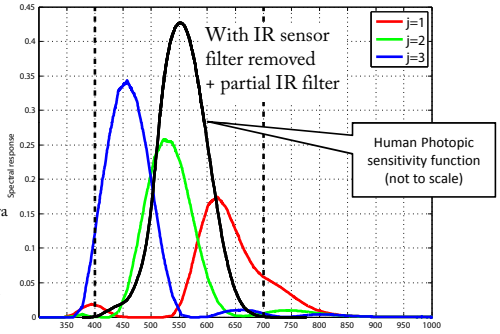
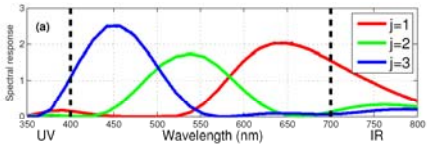


Camera Spectral Sensitivity Function

$S_{camera}(\lambda)$

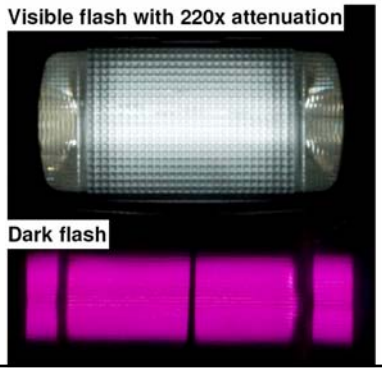


The camera has a broader spectral range than our eye!



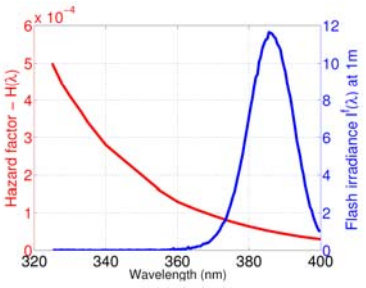
$S_j(\lambda)$ Spectral sensitivity of channel j

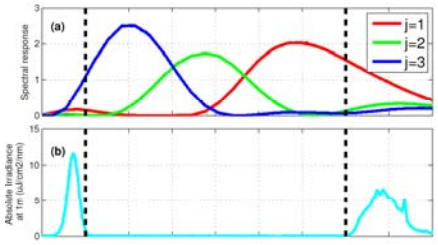
How invisible is the flash?



How Safe is the flash?

- Eye is most sensitive part of the body
- Threshold Limit Values [TLV] specify safe limits





$S_j(\lambda)$ Spectral sensitivity of channel j

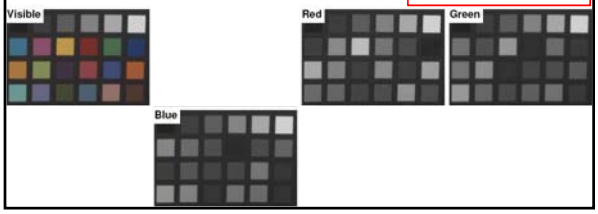
$I(\lambda)$ Flash spectrum

Recording Five Different Spectral Bands

- Need two images
  - Temporal multiplexing
- With UV/IR flash image:
  - "Blue" channel records UV
  - "Red" channel records IR

Assumptions

1. Little ambient UV and IR light
2. UV/IR flash dominates ambient visible light

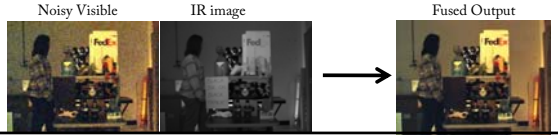


Flash/No-flash photography

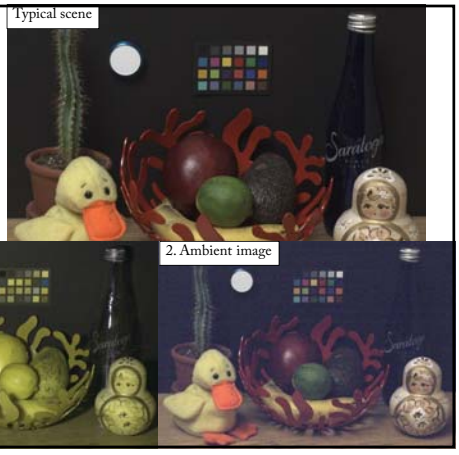
- Visible flash & ambient (no flash) image
- Petsnigg et al. SIGGRAPH 2004
- Eisemann & Durand SIGGRAPH 2004
- Cross/Joint-bilateral filter combines images

Related Work

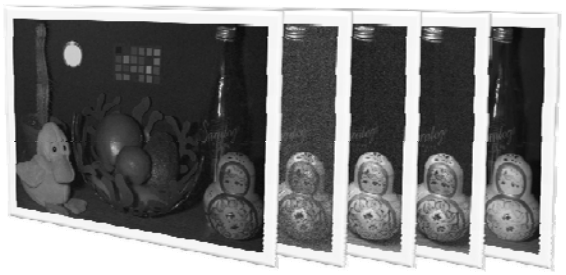
- Relighting faces with IR (Wang et al. Eurographics '08)
  |
- Multispectral Video Fusion
  - Bennett, Mason and McMillan IEEE TIP '07
  - Twin cameras: IR/Visible
  - Temporal smoothing
  - Cross-bilateral filter



Our Approach



Spatio-Spectral Volume



Wavelength : UV Blue Green Red IR

Clean → Noisy ← Clean

Spatial-Spectral Model

1. Likelihood: $\left[\text{Reconstruction} - \text{Ambient} \right]^2$ — Keeps intensities of reconstruction close to ambient

$\left| \nabla \text{Gradients of Reconstruction} \right|^{\alpha}$, $\alpha \le 1$ — Keeps gradients of reconstruction sparse

$\left| \nabla \text{Gradients of Reconstruction} - \nabla \text{Gradients of IR flash} \right|^{\alpha}$ — Keeps **difference of gradients** between reconstruction and IR flash sparse

(Also for UV flash)

Spatial-Spectral Model

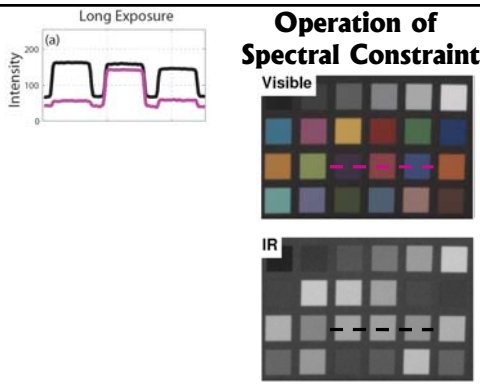
1. Likelihood: $\left[\text{Reconstruction} - \text{Ambient} \right]^2$ — Keeps intensities of reconstruction close to ambient

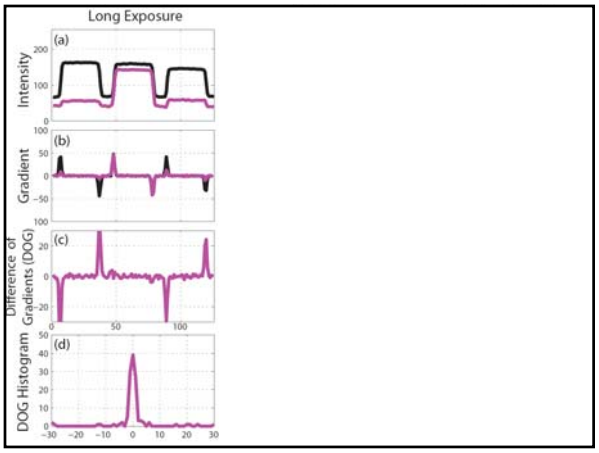
2. Spatial prior: $\left| \text{Gradients of Reconstruction} \right|^{\alpha}$, $\alpha \le 1$ — Keeps gradients of reconstruction sparse

3. Spectral constraint: $\left| \text{Gradients of Reconstruction} - \text{Gradients of IR flash} \right|^{\alpha}$ — Keeps **difference of gradients** between reconstruction and IR flash sparse

(Also for UV flash)

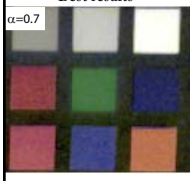
Operation of Spectral Constraint





Effect of Varying α in Spectral Term

Best results



Non-convex optimization

Slow: ~20mins for 1.4 megapixel image

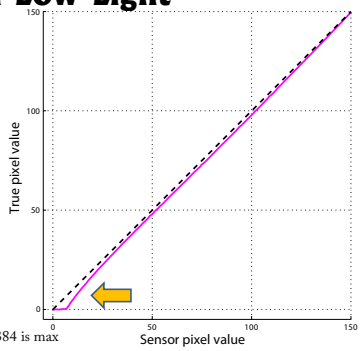
Models actual distributio

Overall Scheme

- Pre-processing
  - White balance
  - Masking of shadows in dark flash image
- Optimization of spatial-spectral model
  - Each channel in reconstruction estimated separately
- Post-processing
  - Removal of color cast
  - Gamma correction

Sensor Non-Linearity in Low Light

- Due to noise processes in sensor
- Introduces color cast if channels have different levels



N.B. Using 14-bit images, i.e. 16384 is max

Color Cast Correction

- Use noise curve

- Only form of color correction used
- Further correction color possible e.g. leveraging face detector

Experiments

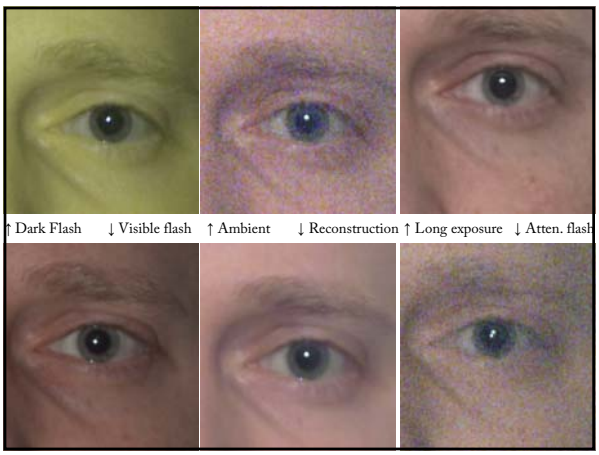
- People & General scenes
  - Wide range of materials
- Explore different levels of ambient lighting
- Comparison to other approaches
- All scenes captured with a tripod, $\alpha = 0.7$

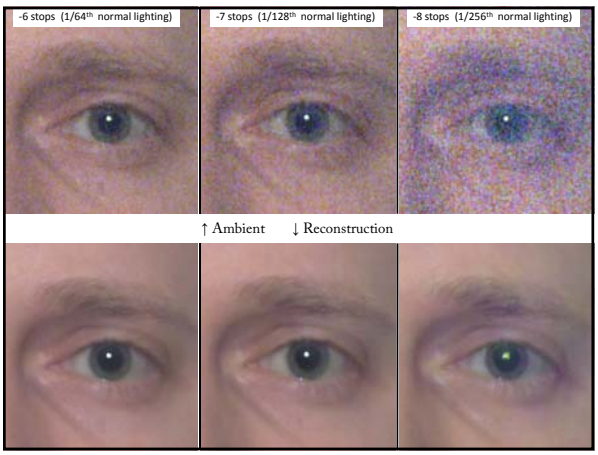

UV/IR flash

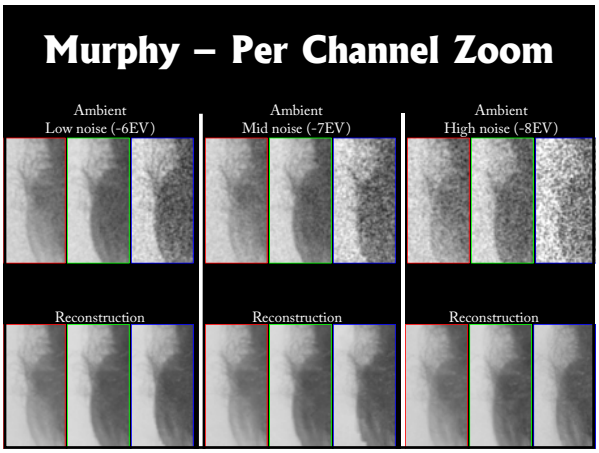

Ambient illumination
Medium noise
-7 stops
(1/128th of normal illumination)


Reconstruction
Medium noise
-7 stops
(1/128th of normal illumination)


Visible flash


↑ Dark Flash
↓ Visible flash
↑ Ambient
↓ Reconstruction
↑ Long exposure
↓ Atten. flash

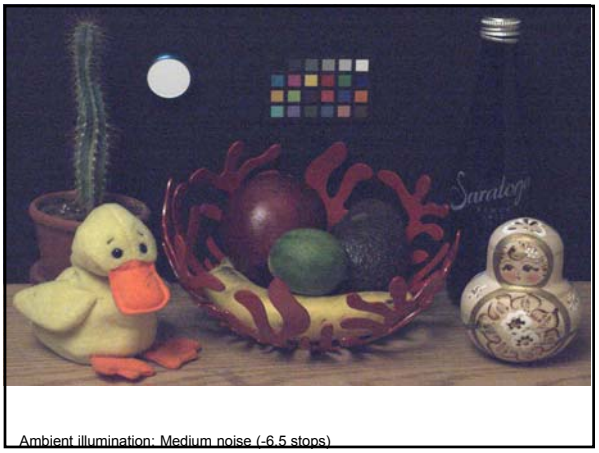

-6 stops (1/64th normal lighting)
-7 stops (1/128th normal lighting)
-8 stops (1/256th normal lighting)
↑ Ambient
↓ Reconstruction



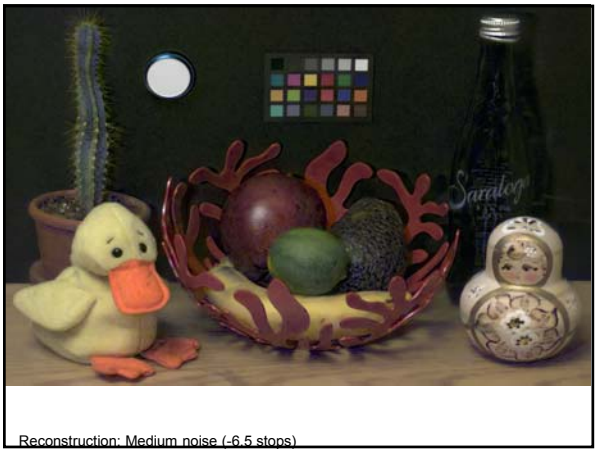
Long exposure reference shot

Visible flash

UV/IR flash



Ambient illumination: Medium noise (-6.5 stops)

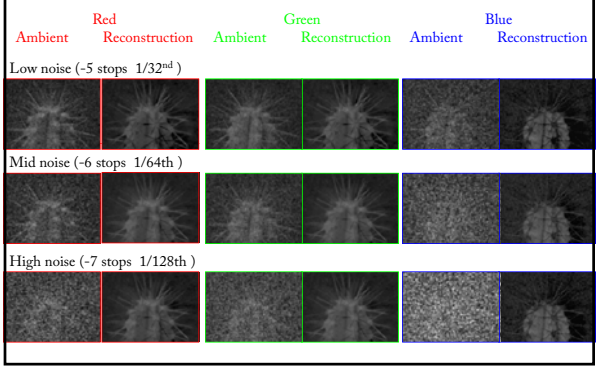


Reconstruction: Medium noise (-6.5 stops)

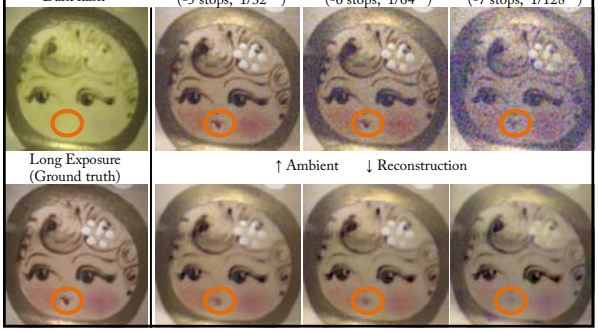
Long exposure reference shot

Visible flash

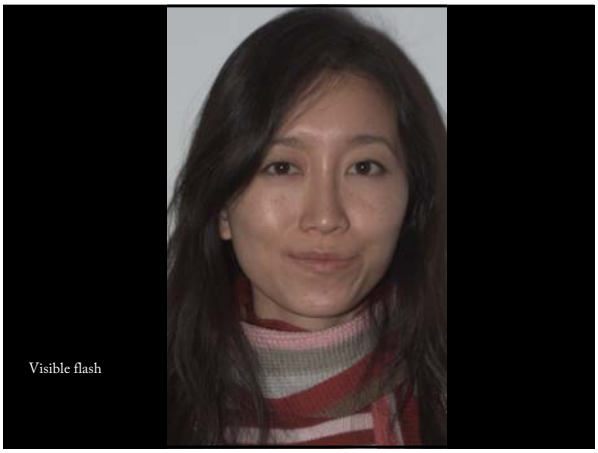
Doll image, Per Channel Close-up



Doll image - Close-up



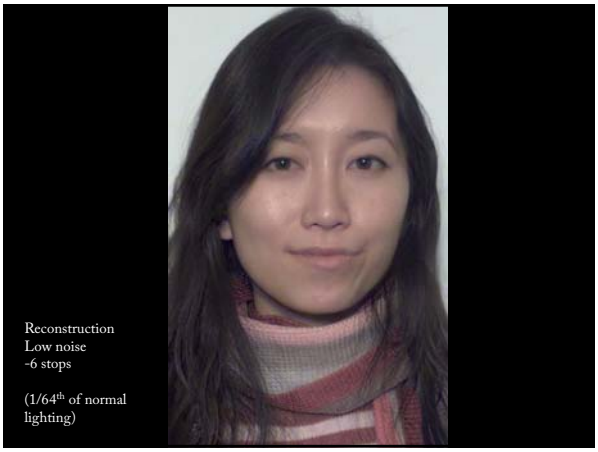
Long exposure reference

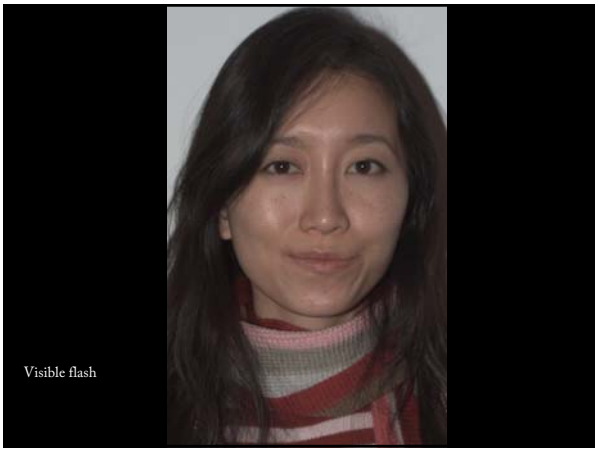


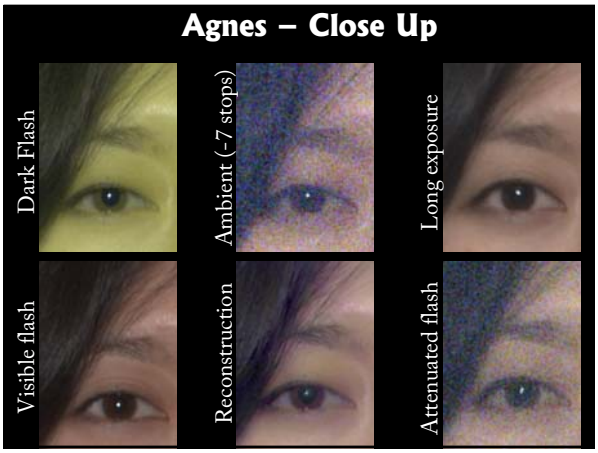
Visible flash

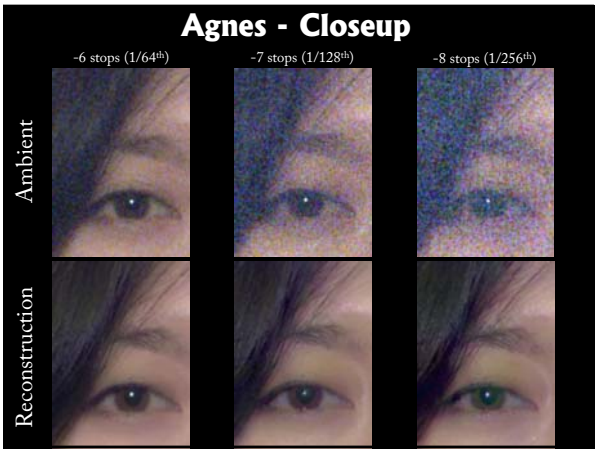

UV/IR flash


Ambient illumination
Low noise
-6 stops
(1/64th of normal lighting)


Reconstruction
Low noise
-6 stops
(1/64th of normal lighting)

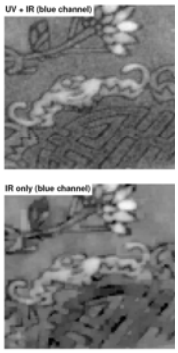

Visible flash


Agnes – Close Up
Dark Flash
Ambient (-7 stops)
Long exposure
Visible flash
Reconstruction
Attenuated flash


Agnes - Closeup
-6 stops (1/64th)
-7 stops (1/128th)
-8 stops (1/256th)
Ambient
Reconstruction

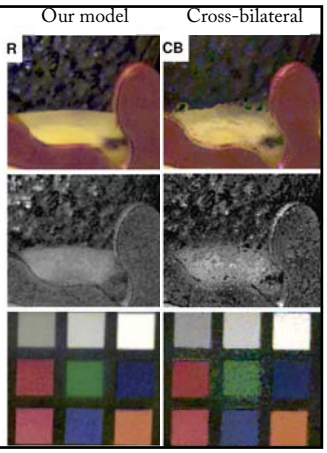
Are both IR and UV Flash Channels Needed?

Effect of removing UV flash component

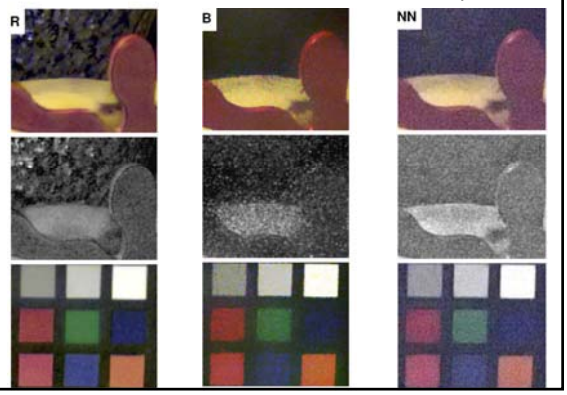


Comparison to Cross-Bilateral Filtering

- Cross bilateral filtering is method used in flash/no-flash papers (Petsnigg et al. , Eiseman & Durand Siggraph 2004)
- Also known as joint bilateral filtering
- Has L2-like constraint between color channels
  - Similar to $\alpha = 2$



Comparison to Denoising Methods



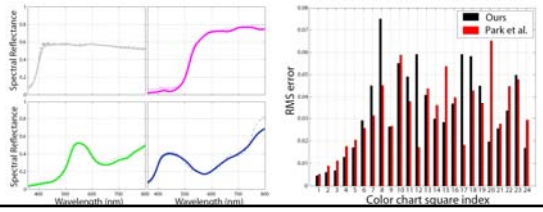
Other Applications

1. Spectroscopy
   (Hardware)
2. Color channel denoising
   (Software)

1. Spectroscopy

- Reconstruct R(λ) using two images:
  1. With dark flash
  2. With visible-only flash

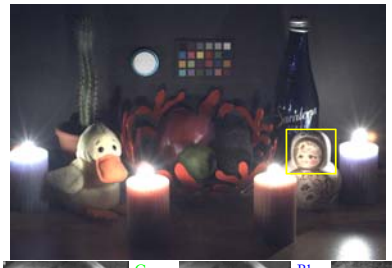
  Model R(λ) using 6-dim PCA projections
- Comparison to Park et al. ICCV '07 on Macbeth color chart squares

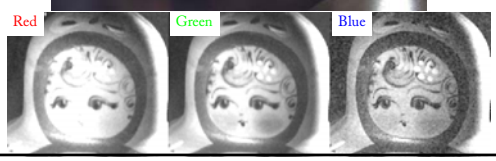


2. Color Channel Denoising

Candle-lit scene, after white balancing

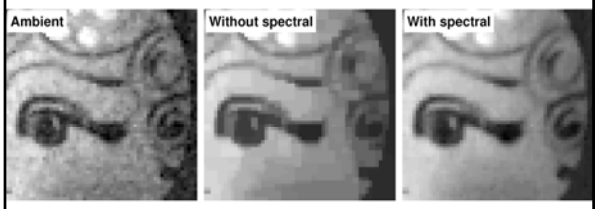
Captured by unmodified camera





2. Color Channel Denoising

- Denoise blue channel
- Spectral terms use red and green channels as constraint on blue



- Technique can be applied to images captured with a standard camera

Off-the-shelf Hardware

Standard Nikon 50mm f/1.8 lens (~$80) + MaxMax CC3 filter (~$50)

Hoya U360 filter glass (~$200)

Fuji IS Pro (~$3000)
Comes without IR filter sensor

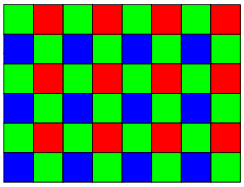
Nikon SB-14 flash (~$200)

Improving the Hardware

- Can use LEDs for flash
  - Narrow spectral width
  - Good for cell phones (low power, compact)
- Need to two separate images is awkward
  - Some cameras have sensors with double image buffer, e.g. Fuji finePix Z10d

Single Shot Dark Flash Photography

Standard Bayer
3 channels



Summary

- Dark flash system that can capture images in low light conditions without dazzling subjects
- Spatial-spectral model with novel spectral constraints
- Future work:
  - Better color correction
  - Improve hardware to require only a single shot

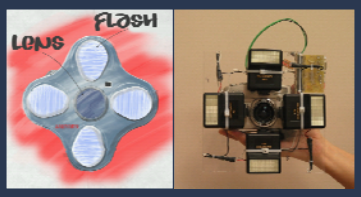
Acknowledgements

- Fredo Durand, Yann LeCun, Anat Levin, Olga Sorkine, Dennis Zorin
- Subjects: Agnes Chen, Murphy Stein
- MaxMax.com for camera hardware

Computational Illumination:

- Presence or Absence, Duration, Brightness
  - Flash/No-flash
- Light color/wavelength
- Light position
  - Multi-flash for depth edges
  - Programmable dome (image re-lighting and matting)
- Spatial Modulation
  - Dual Photography

Non-photorealistic Camera: Depth Edge Detection and Stylized Rendering using Multi-Flash Imaging



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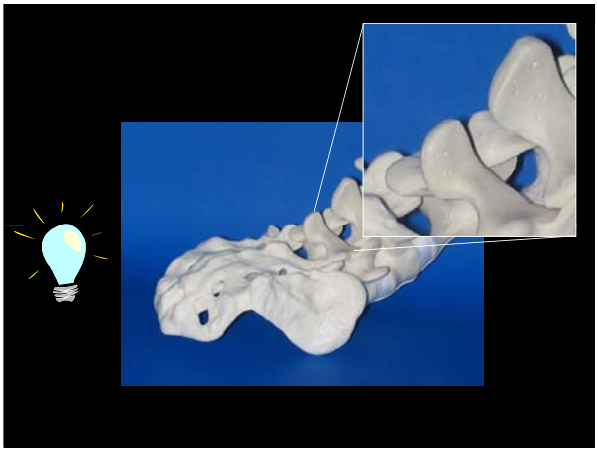
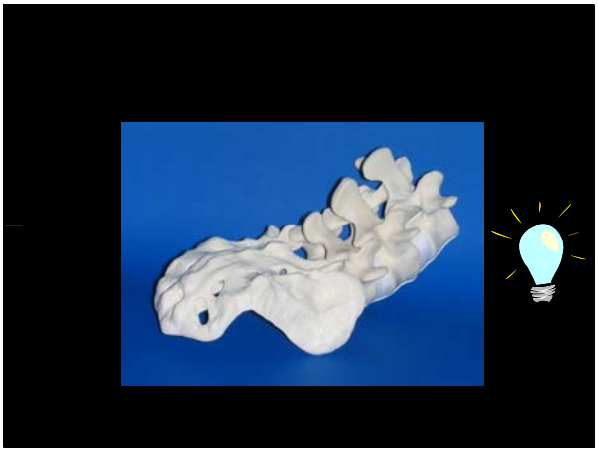
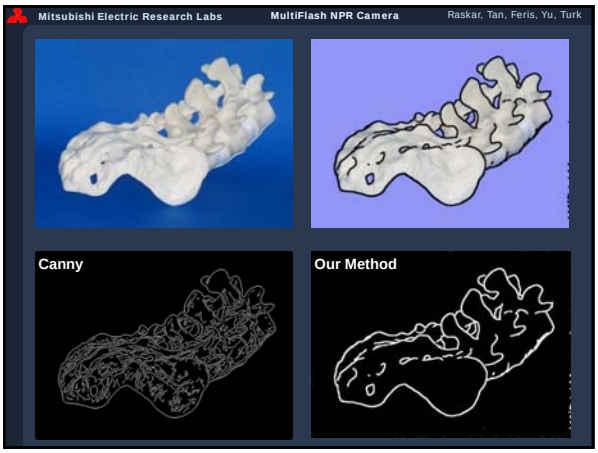
Jingyi Yu, Matthew Turk
Mitsubishi Electric Research Labs (MERL), Cambridge, MA
U of California at Santa Barbara
U of North Carolina at Chapel Hill

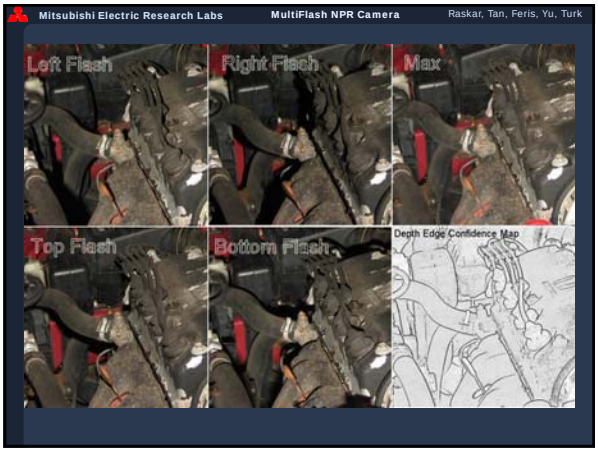


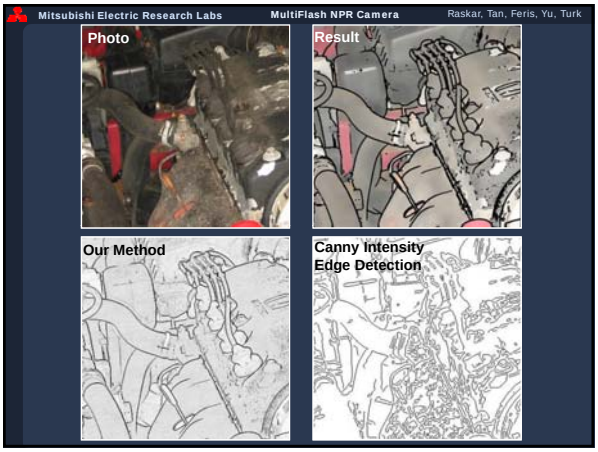


Depth Discontinuities

Internal and external
Shape boundaries, Occluding contour, Silhouettes





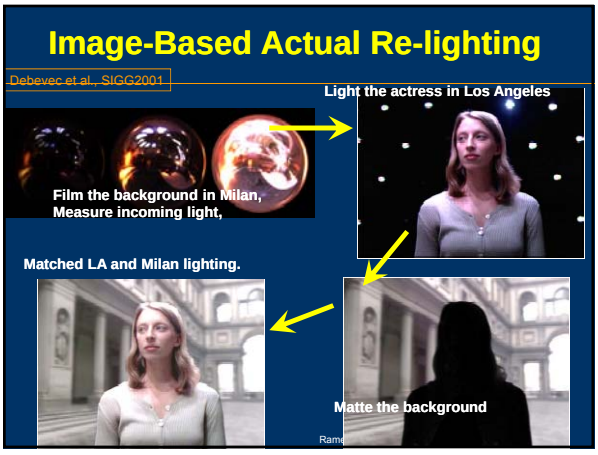


Debevec et al. 2002: 'Light Stage 3'

Ramesh Raskar, Computational Illumination

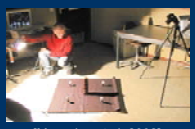
Image-Based Actual Re-lighting

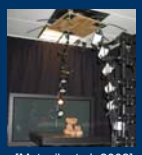
Debevec et al., SIGG2001



A 4-D Light Source


[Debevec et al. 2000]


[Masselus et al. 2002]


[Matusik et al. 2002]


[Debevec et al. 2002]


[Masselus et al. 2003]


[Malzbender et al. 2002]

Ramesh Raskar, Computational Illumination

Computational Illumination:

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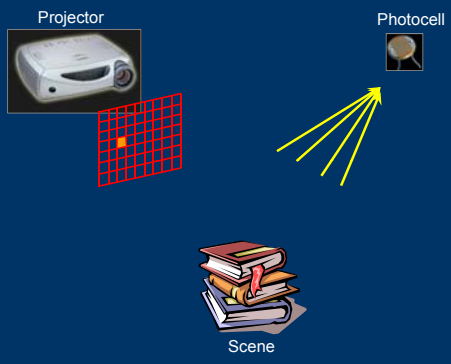
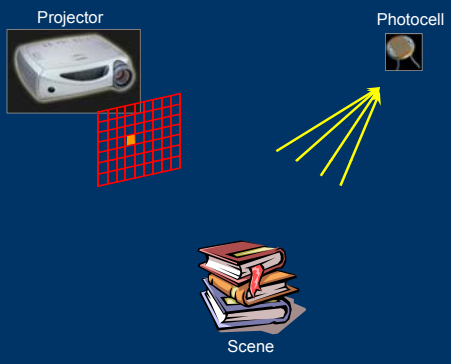
  - Flash/No-flash
- Light color/wavelength
- Light position
  - Multi-flash for depth edges
  - Programmable dome (image re-lighting and matting)
- Spatial Modulation
  - Dual Photography

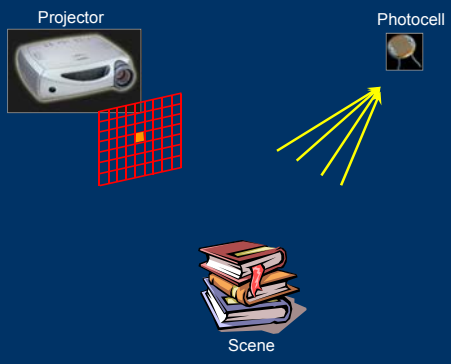
Dual Photography



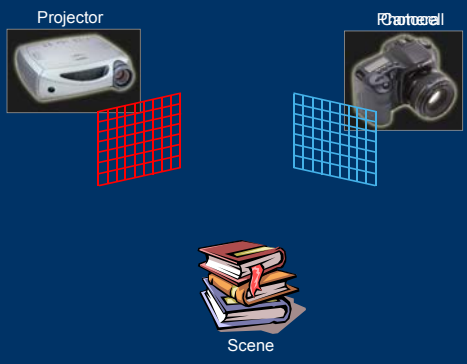
Dual Photography



Dual Photography

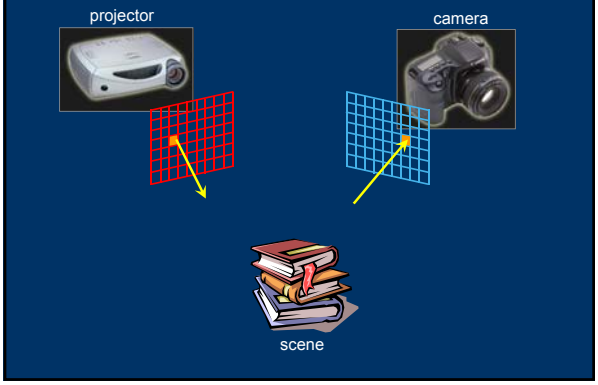


Dual Photography



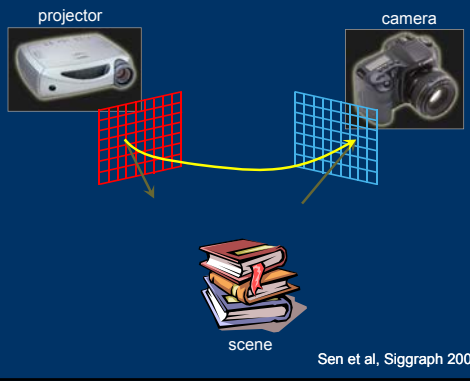
The 4D transport matrix:

Contribution of each projector pixel to each camera pixel



The 4D transport matrix:

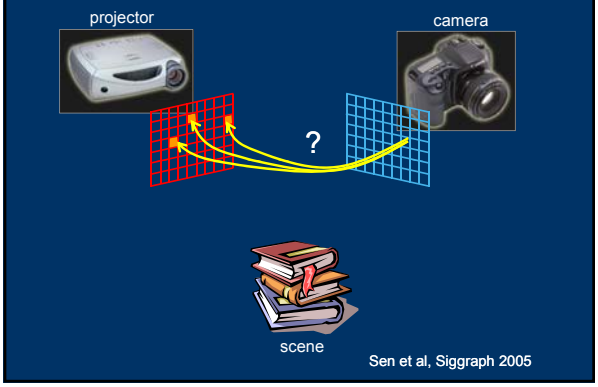
Contribution of each projector pixel to each camera pixel



Sen et al, Siggraph 2005

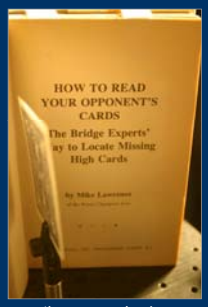
The 4D transport matrix:

Which projector pixel contribute to each camera pixel

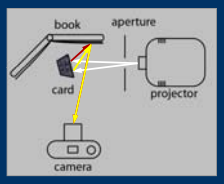


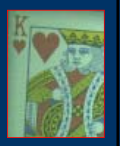
Sen et al, Siggraph 2005

Dual photography from diffuse reflections

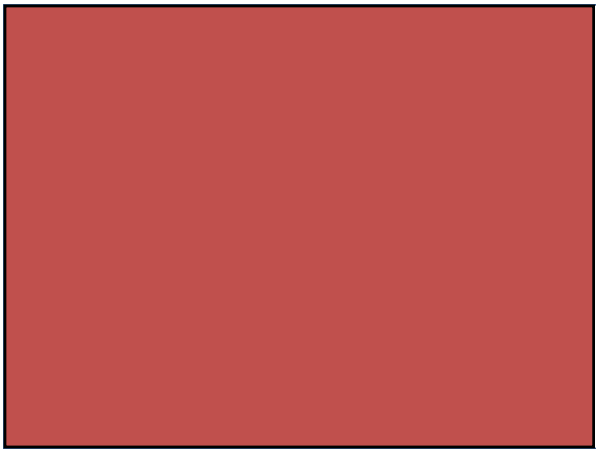


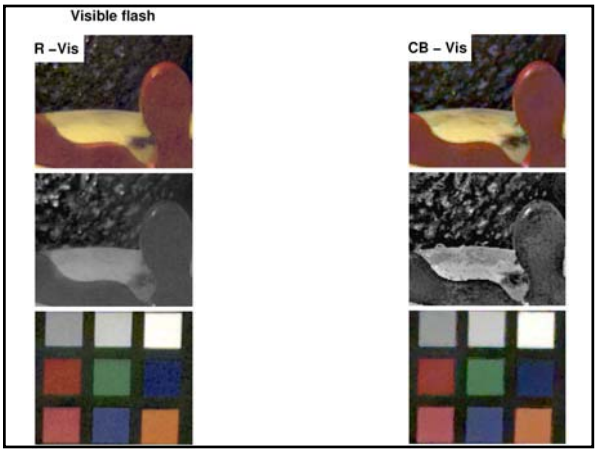
the camera's view



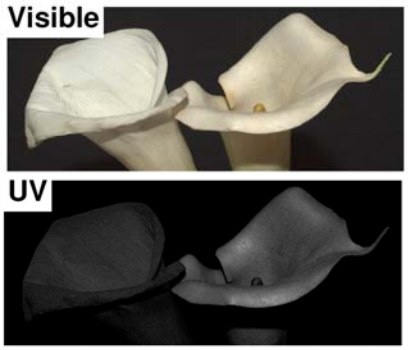


Sen et al, Siggraph 2005



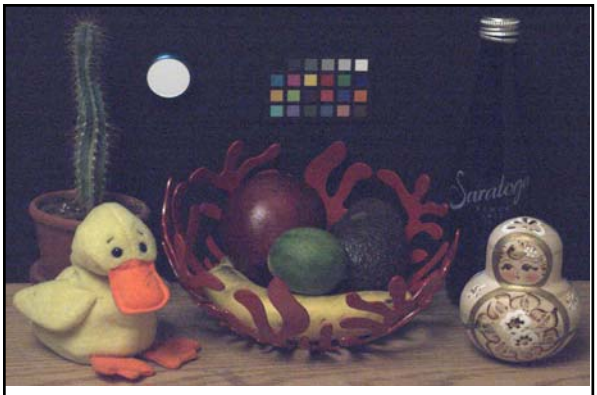


Metamer identification



Reconstruction: Medium noise (-6.5 stops, with only UV flash)

Reconstruction: Medium noise (-6.5 stops, with only IR flash)



Ambient illumination: Medium noise (-6.5 stops)

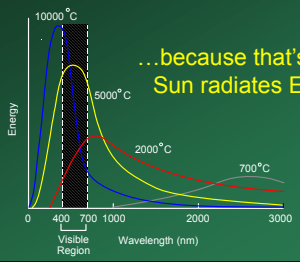
Unsure what this is

Brief overview of Color

Visible Light

Plank's law for Blackbody radiation
Surface of the sun: ~5800K

Why do we see light of these wavelengths?

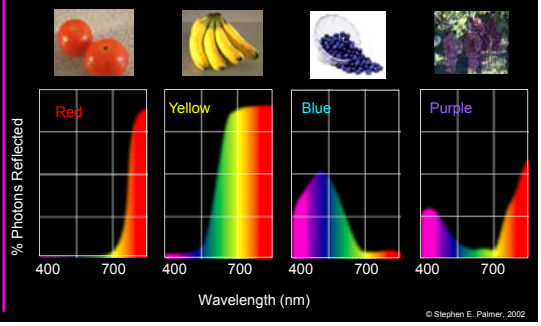


…because that's where the Sun radiates EM energy

© Stephen E. Palmer, 2002

The Physics of Light

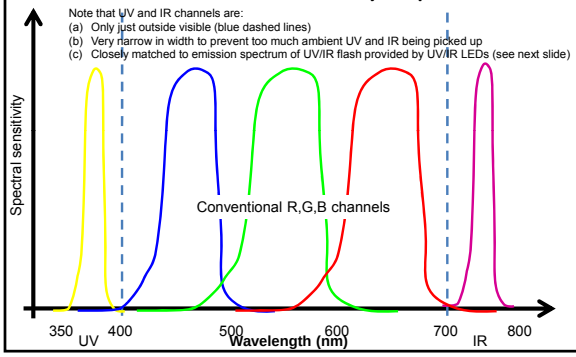
Some examples of the reflectance spectra of surfaces



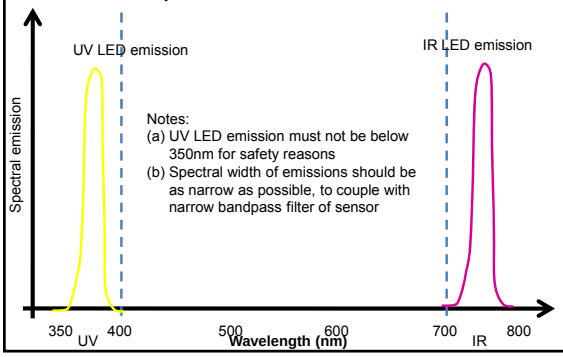
© Stephen E. Palmer, 2002

Simulation of spectral sensitivities of 5 channel dark flash Bayer pattern

Note that UV and IR channels are:
(a) Only just outside visible (blue dashed lines)
(b) Very narrow in width to prevent too much ambient UV and IR being picked up
(c) Closely matched to emission spectrum of UV/IR flash provided by UV/IR LEDs (see next slide)

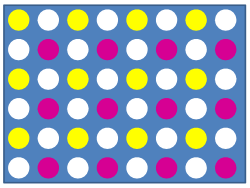


Simulation of emission spectrum of dark flash

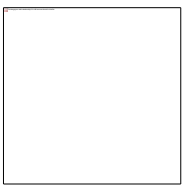


Dark flash design for cellphone/camera

- Array of White LEDs, UV LEDs (shown in yellow) and IR LEDs (shown in magenta)
- White LEDs provided standard visible flash
- UV/IR LEDs provide dark flash
- LEDs are cheap/compact



Ultra-Violet photography



http://www.naturfotograf.com/uvstart.html

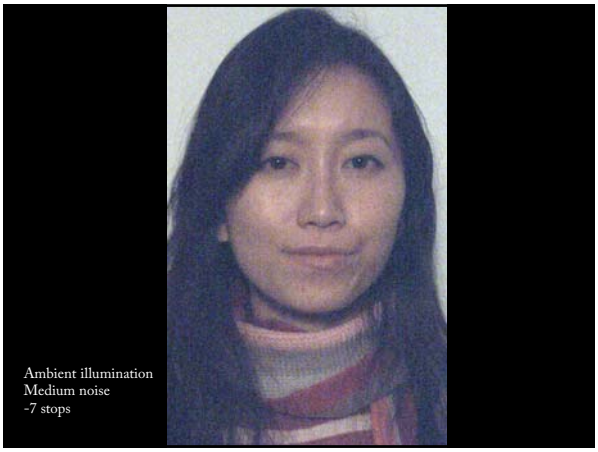
***Potentilla anserina* © Bjørn Rørslett/NN 2001**

Infra-Red Photography

Normal Visible light

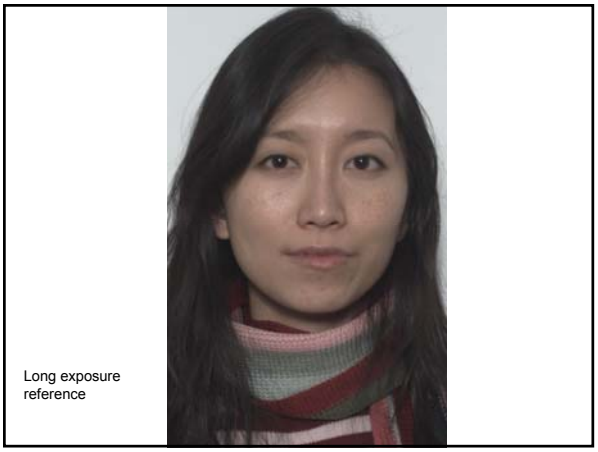
Infra Red (only >715nm)

Photos from MaxMax.com



Ambient illumination
Medium noise
-7 stops

Reconstruction
Medium noise
-7 stops



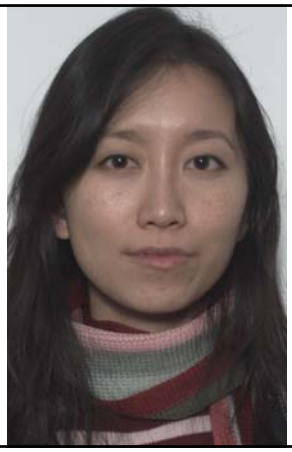
Long exposure
reference

Ambient illumination
High noise
-8 stops

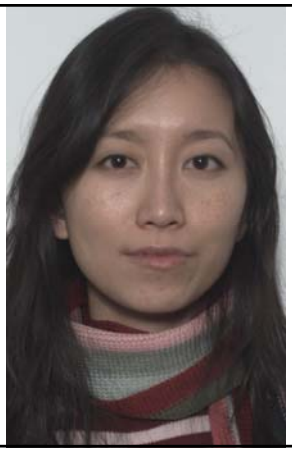
Reconstruction
High noise
-8 stops

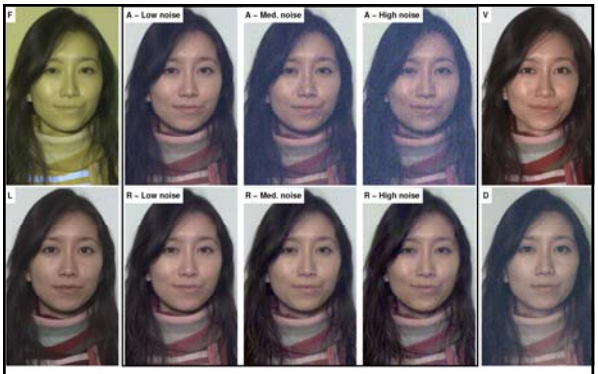
Low power
Visible flash

Long exposure
reference



Long exposure
reference





Ambient illumination: Low noise (-5.5 stops)

Reconstruction: Low noise (-5.5 stops)

Long exposure reference shot

Long exposure reference shot

Ambient illumination: High noise (-7.5 stops)

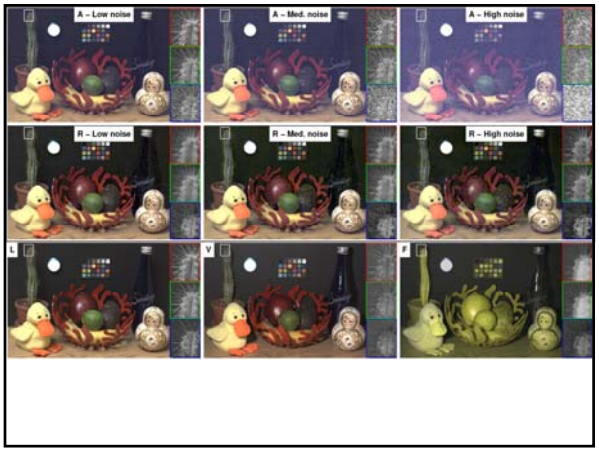
Reconstruction: High noise (-7.5 stops)

Long exposure reference shot

Reconstruction: Medium noise using cross-bilateral filter

Reconstruction: L2 spectral term

Reconstruction: Medium noise (-6.5 stops) with Noise Ninja denoising software



Ambient Illumination: Low noise (5.5 stops underexposed)

Reconstruction: Low noise (-5.5 stops)

Visible flash

Ambient Illumination: High noise (7.5 stops underexposed)

Reconstruction: High noise (7.5 stops)

Visible flash

Ambient illumination
Low noise
-6 stops

Reconstruction
Low noise
-6 stops

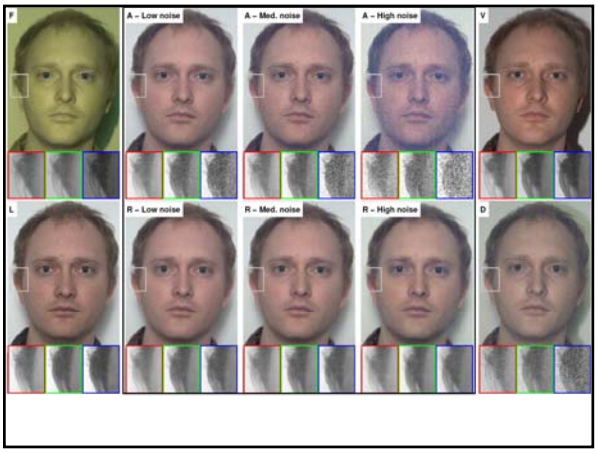
Long exposure
Reference

Ambient illumination
High noise
-8 stops

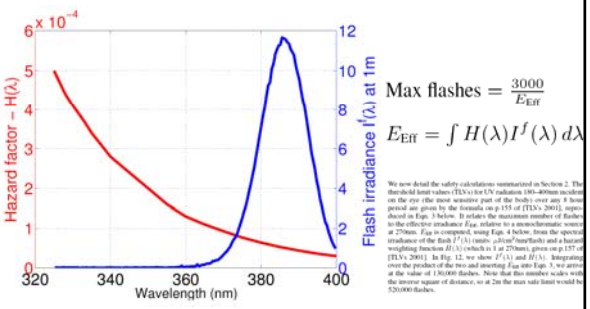
Reconstruction
High noise
-8 stops

Visible flash

Low power
visible flash



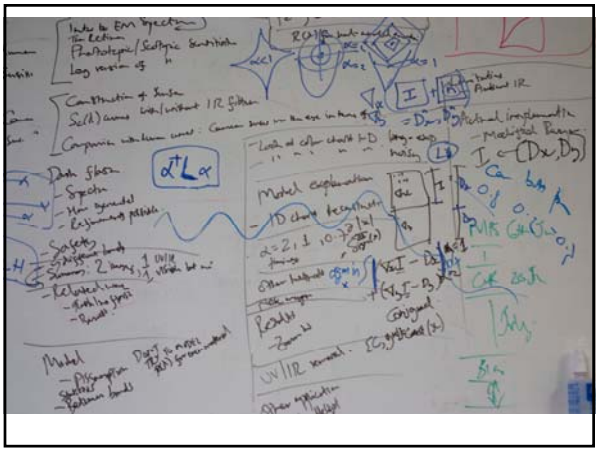
UV Safety



Max flashes $= \frac{3000}{E_{\text{Eff}}}$

$E_{\text{Eff}} = \int H(\lambda) I^f(\lambda)\, d\lambda$

We now detail the safety calculations summarized in Section 2. The threshold limit values (TLVs) for UV radiation (180–400nm incident on the eye (the most sensitive part of the body) over any 8 hour period are given by the formula on p.155 of [TLVs 2001], reproduced in Eqn. 3 below. It relates the maximum number of flashes to the effective irradiance E_{Eff}, relative to a monochromatic source at 270nm. E_{Eff} is computed, using Eqn. 4 below, from the spectral irradiance of the flash $I^f(\lambda)$ (units: μJ/cm^2/nm/flash) and a hazard weighting function $H(\lambda)$ (which is 1 at 270nm), given on p.157 of [TLVs 2001]. In Fig. 12, we show $I^f(\lambda)$ and $H(\lambda)$. Integrating over the product of the two and inserting E_{Eff} into Eqn. 3, we arrive at the value of 130,000 flashes. Note that this number scales with the inverse square of distance, so at 2m the max safe limit would be 520,000 flashes.



Cost function

- Alpha = 0.7 – sparse norm

$$\underset{R_j}{\operatorname{argmin}} \sum_p \Big[\underbrace{\mu_j\, m(p)(R_j(p) - A_j(p))^2}_{\text{Likelihood}} + \underbrace{\kappa\, m(p)|\nabla R_j(p)|^\alpha}_{\text{Spatial}} + \underbrace{|\nabla R_j(p) - \nabla F_1(p)|^\alpha}_{\text{IR Spectral}} + \underbrace{|\nabla R_j(p) - \nabla F_3(p)|^\alpha}_{\text{UV Spectral}} \Big]$$

Reference Long exposure shot

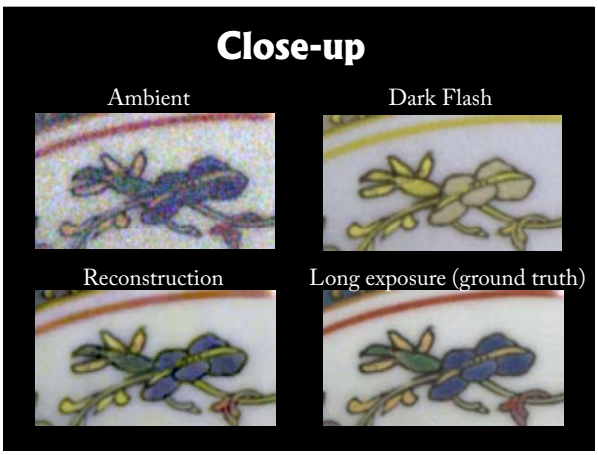
Visible flash

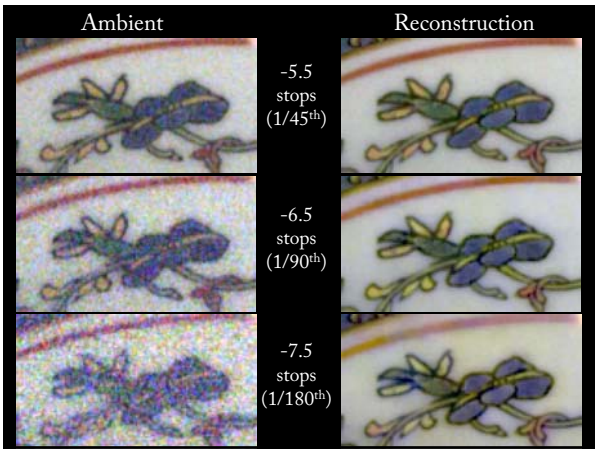
UV/IR flash

Ambient Illumination: Medium noise (-6.5 stops)

Reconstruction: Medium noise (-6.5 stops)

Reference Long exposure shot




Ambient
Reconstruction
-5.5 stops (1/45th)
-6.5 stops (1/90th)
-7.5 stops (1/180th)