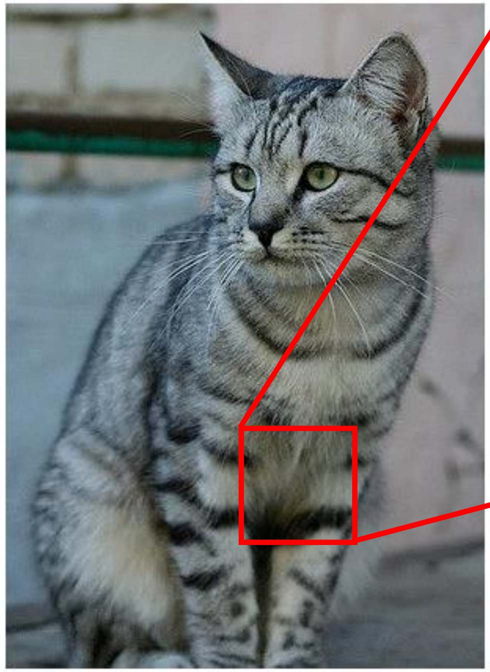
3. Radiometric Calibration & HDR

The Physical Meaning of Pixel Values



105	112	108	111	104	99	106	99	96	103	112	119	104	97	93	87
91	98	102	106	104	79	98	103	99	105	123	136	110	105	94	85
76	85	90	105	128	105	87	96	95	99	115	112	106	103	99	85
99	81	81	93	120	131	127	100	95	98	102	99	96	93	101	94
106	91	61	64	69	91	88	85	101	107	109	98	75	84	96	95
114	108	85	55	55	69	64	54	64	87	112	129	98	74	84	[illegible]
133	137	147	103	65	81	80	65	52	54	74	84	102	93	85	82
128	137	144	140	109	95	86	70	62	65	63	63	60	73	86	101
125	133	148	137	119	121	117	94	65	79	80	65	54	64	72	98
127	125	131	147	133	127	126	131	111	96	89	75	61	64	72	84
115	114	109	123	150	148	131	118	113	109	100	92	74	65	72	78
89	93	90	97	108	147	131	118	113	114	113	109	106	95	77	80
63	77	86	81	77	79	102	123	117	115	[illegible]	125	125	130	115	87
62	65	82	89	78	71	80	101	124	126	119	101	107	114	131	119
63	65	75	88	89	71	62	81	120	138	135	105	81	98	110	[illegible]
87	65	71	87	106	95	69	45	76	130	126	107	92	94	105	112
118	97	82	86	117	123	116	66	$\boxed{42}$	51	[illegible]	93	89	95	102	107
164	146	112	80	82	120	124	104	76	48	45	66	88	101	102	109
157	170	157	120	93	86	114	132	112	97	69	55	70	82	99	94
130	128	134	161	139	100	109	118	121	134	114	87	65	53	69	86
128	112	96	117	150	144	120	115	104	107	102	93	87	81	72	79
123	107	96	86	83	112	153	149	122	109	104	75	80	107	112	99
122	121	102	80	82	86	94	117	145	148	153	102	58	78	92	107
122	164	148	103	71	56	78	83	93	103	119	139	102	61	69	84

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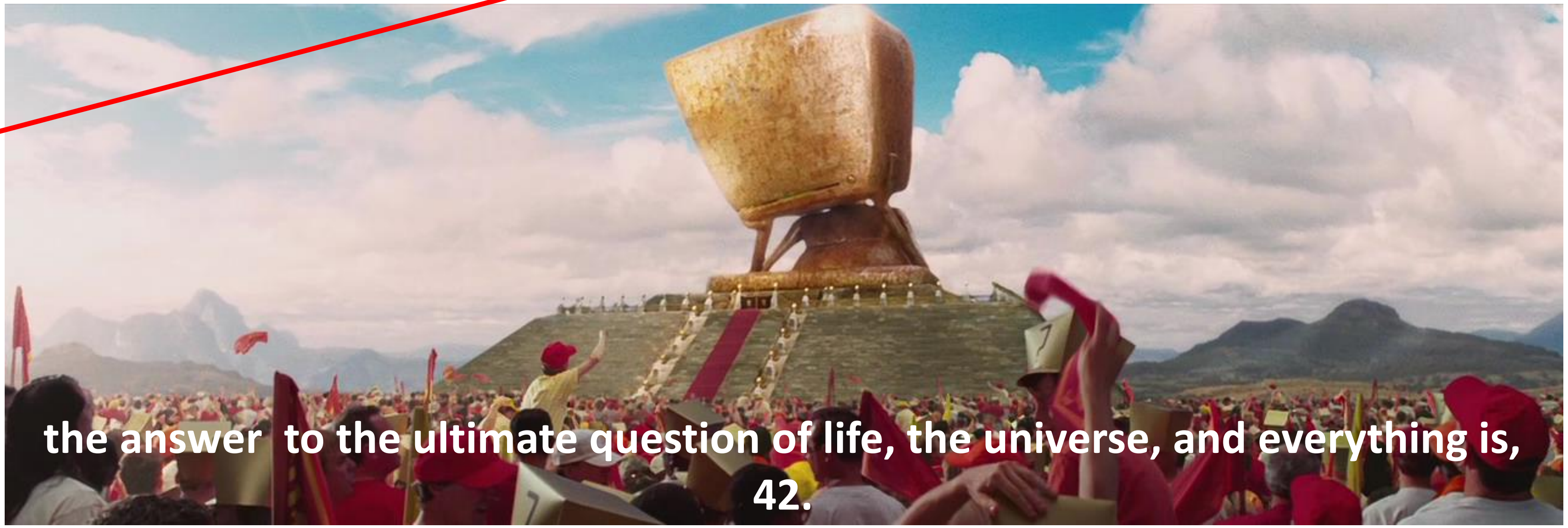
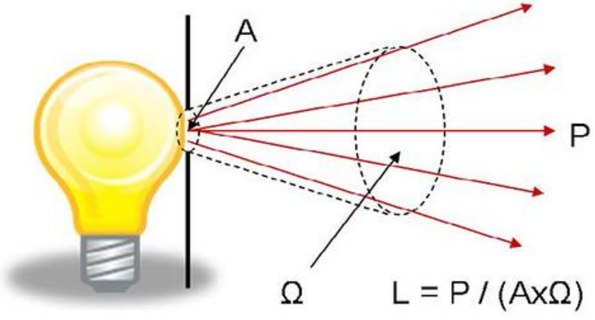
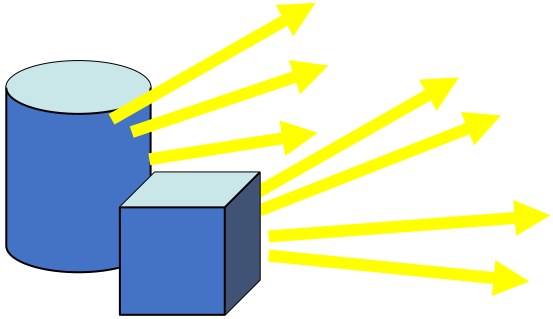


a hitchhiker's guide to the galaxy

Preliminary Terms

- Radiance



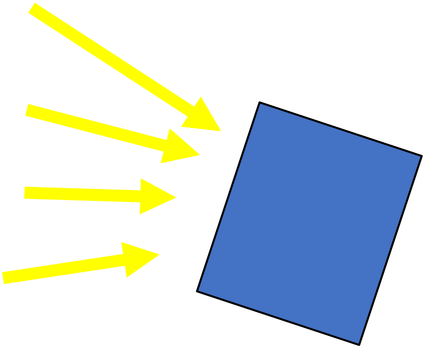


Light emitting (or reflecting) from a surface.

Only a light source would emit light, most things reflect light.

Radiance is measure in watts per steradian per square meter

- Irradiance



Amount of light falling onto a surface.

Irradiance is measured as watts per square meter

Note, that radiance and irradiance are fundamentally different.

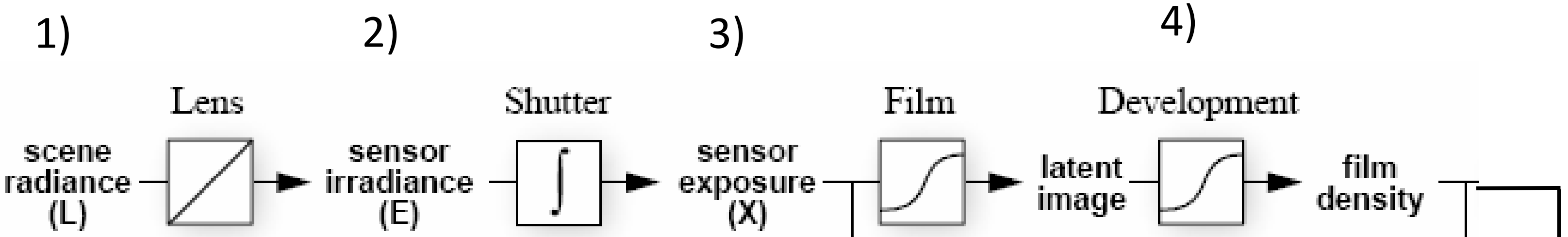
Scene Radiance

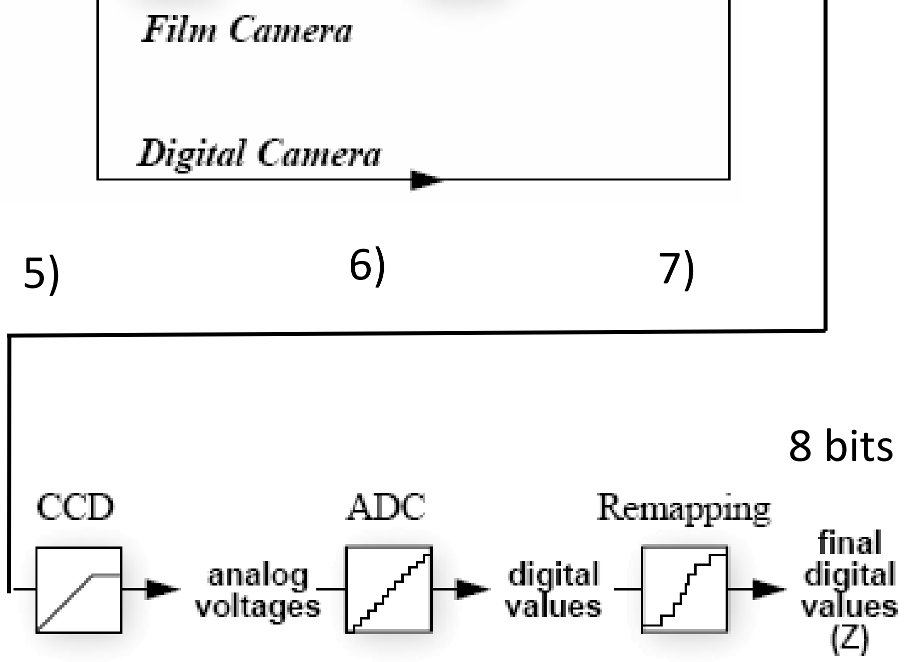
- Amount of radiance in a 3D scene varies greatly

Each point is a different radiance reading

From Radiance to Pixel Values

Many steps from the scene to the final pixel value ‘z’.

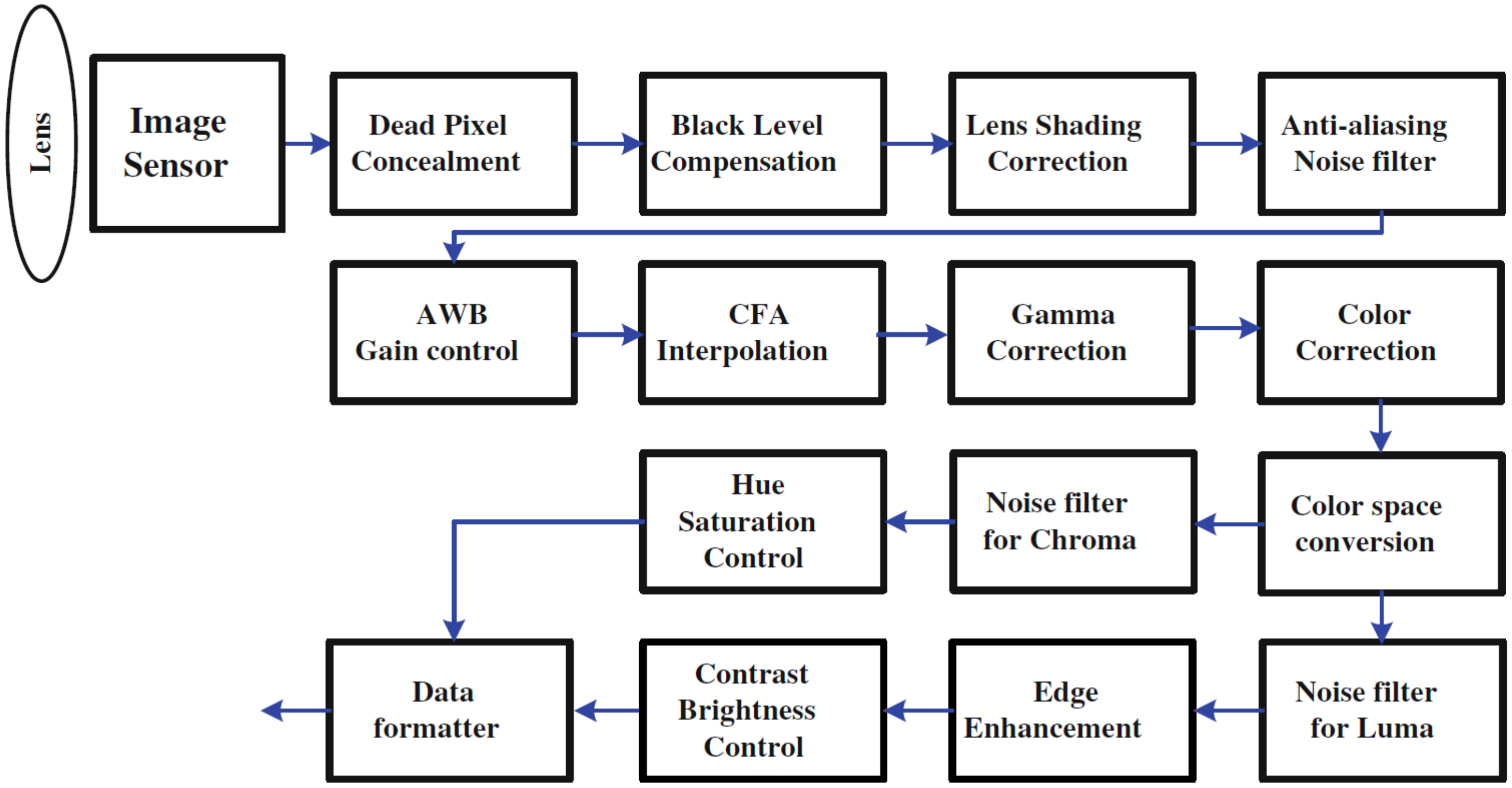




1. Scene generates radiance L
2. This can be attenuated through a lens, then hits the imaging devices sensor (now we call it irradiance, E)
3. E is exposed for Δt seconds. The product (E • Δt) is the exposure
4. Film has a response curve to E • Δt. This response is often not linear; The development process may also not be linear.
5. If we are using a digital camera, the CCD response is linear!
6. However, this response is quantized
7. And typically (almost always) “6” is remapped through a non-curve to behave like film, so even though the CCD is linear, we get back a non-linear response!

many steps in the re-mapping

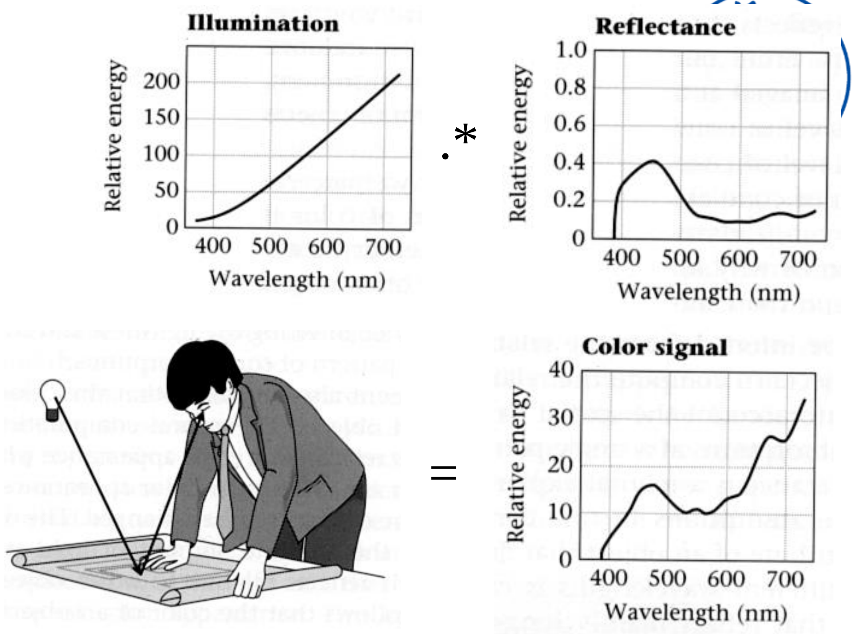
- This is called the Image Signal Processor (ISP) in a camera
- A typical pipeline:



Theory and Applications of Smart Cameras, Kyung C-M, Springer 2016

sample: auto white balance

- The light source affects the color of the scene objects
- Human eyes can correct this color bias
- Auto-white-balance
  - Identify the illuminant color
  - Neutralize the color of the illuminant
    (often by scaling the R, G, B values respectively)

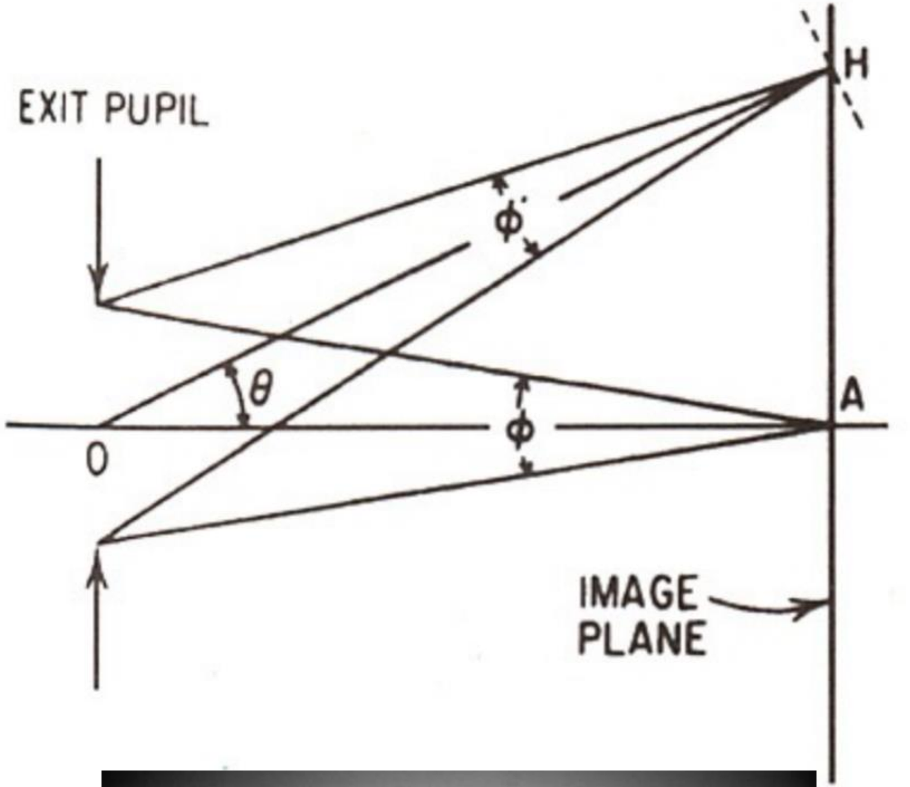


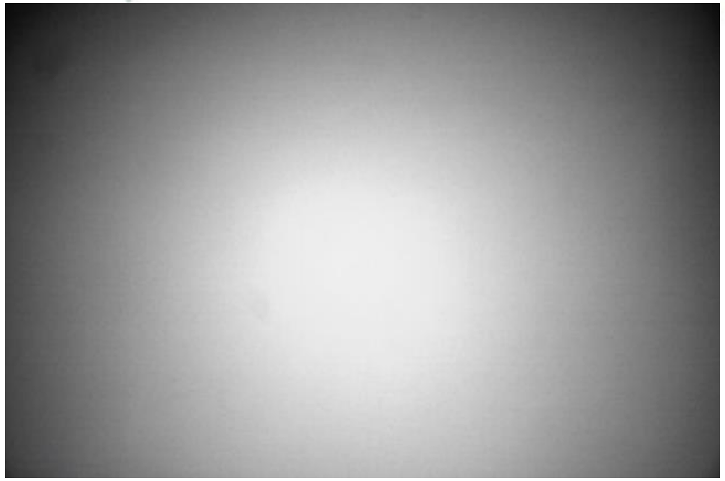
$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} s_r & & \\ & s_g & \\ & & s_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

(source: www.cambridgeincolour.com)

sample: vignetting

- Irradiance is proportional to
  - projected area of aperture as seen from pixel
  - projected area of pixel as seen from aperture
  - distance^2 from aperture to pixel
- Combining all these
  - each ~ a factor of cos θ
  - light drops as $\cos^4\theta$
- Calibrating
  - take a photo of a uniformly white object
  - the picture shows the attenuation, divide the pixel values by it





sample: noise reduction

- Most image details occur repeatedly
- Image self-similarity can be used to eliminate noise

- Each color indicates a group of squares which are almost indistinguishable
- Average the squares of the same color to denoise

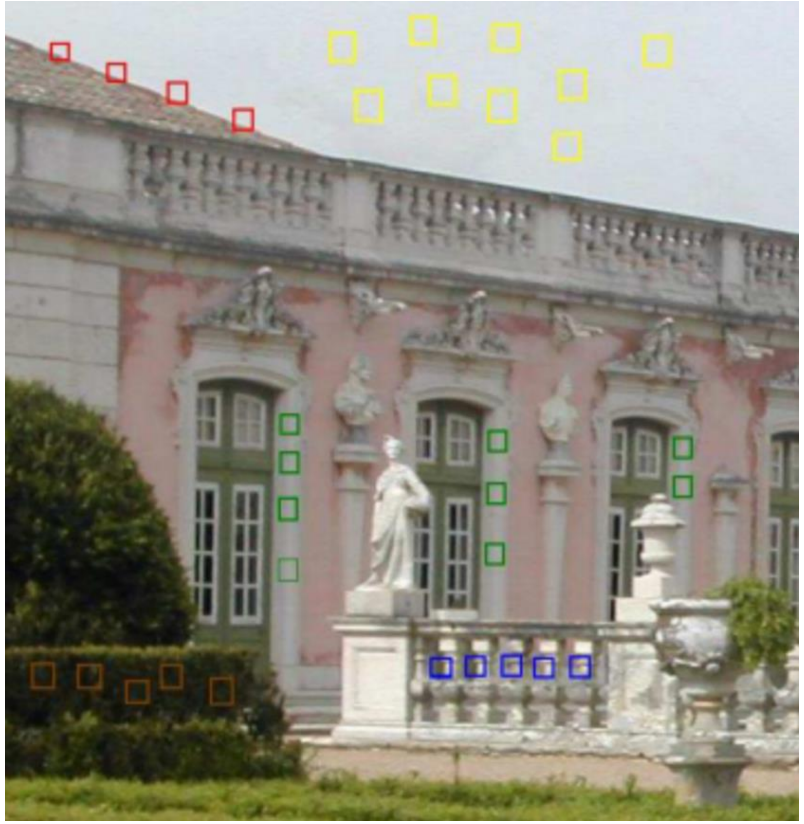
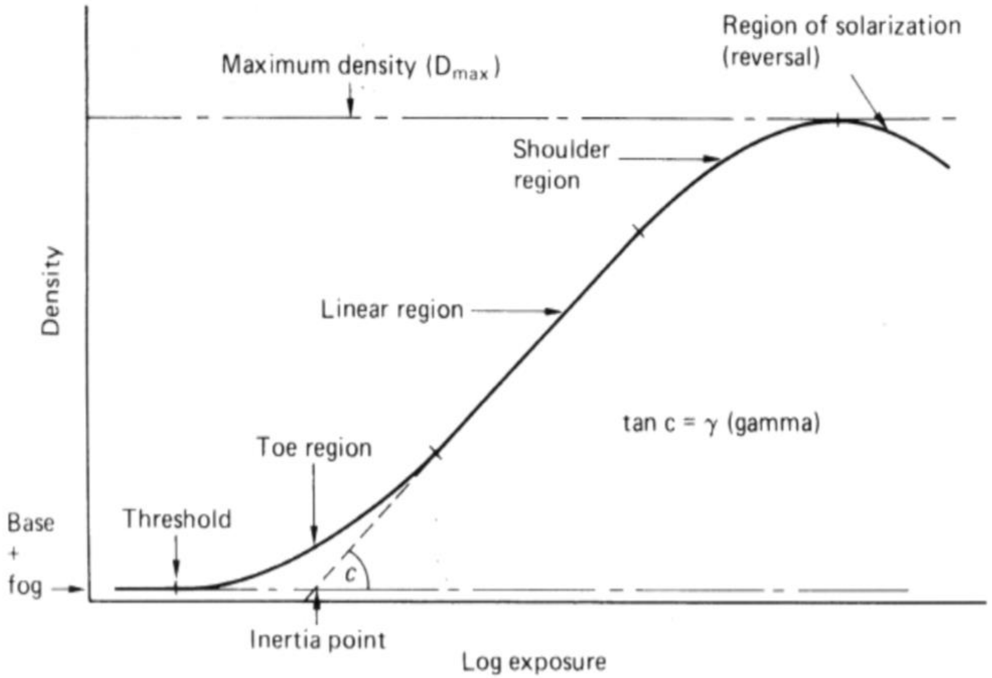


Image and movie denoising by nonlocal means, Buades, Coll, Morel, IJCV 2006

From Radiance to Pixel Values

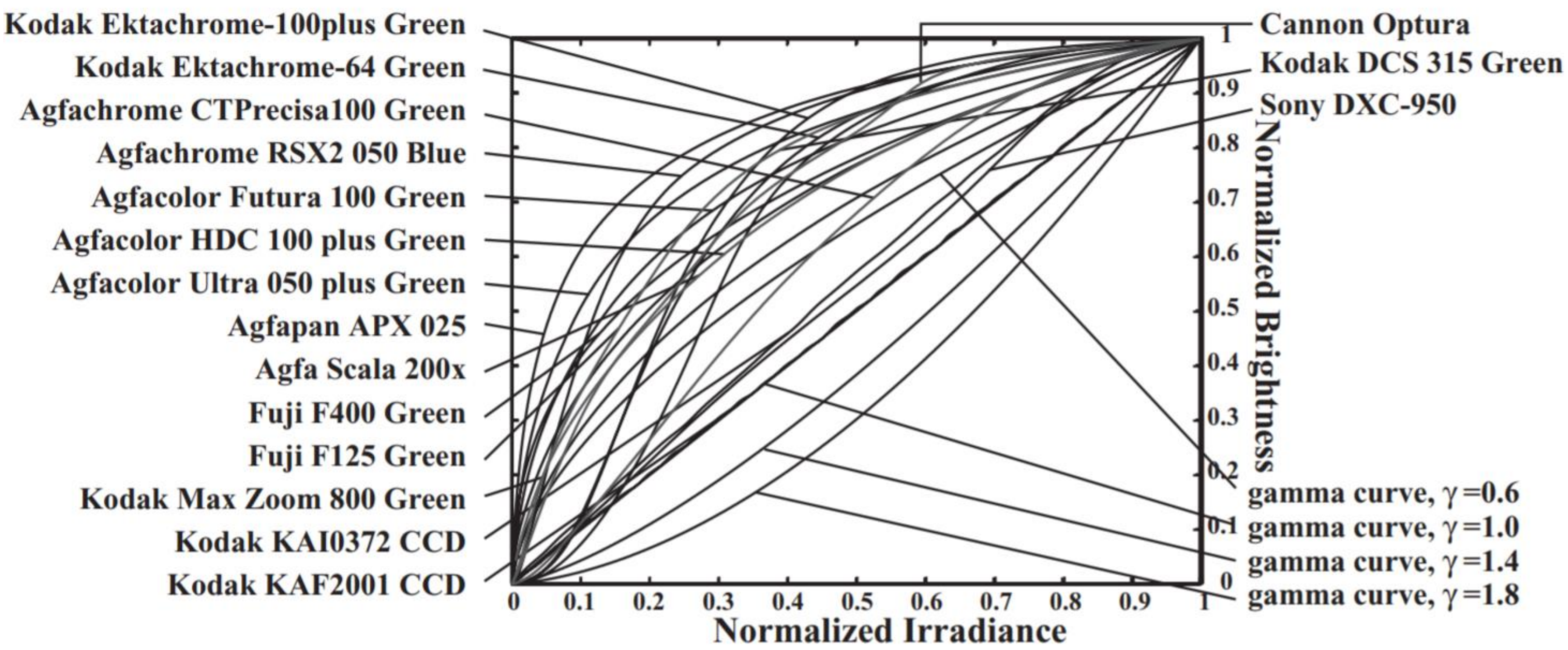
- Film response curve
  - Toe region: the chemical process is just starting
  - Middle: mostly linear, if some amount of light turned half of the crystals to silver, the same amount more turns half of the rest
  - Shoulder region: close to saturation



The 'geography' of the characteristic curve of a negative material

From Radiance to Pixel Values

- Digital camera response curve
  - Modern cameras might have scene dependent processing, or even spatially variant processing
  - Making the curve impossible to calibrate or inverse! (let's ignore it for today)



Questions?

Radiometric Calibration

- Cameras have non-linear responses in terms of exposure $(E \bullet \Delta t)$
- Radiometric calibration amounts to recover the response function as:

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

Here Z_{ij} is the final pixel value (from 0-255) at pixel i,
E_i is the irradiance at i,
Δt_j is the shutter speed

Thus: $E_i \bullet \Delta t_j$ is the exposure of light on pixel i

Why Radiometric Calibration?

- Application 1: radiometric image analysis
  - Reflectance capture (Chapter 4)
  - Photometric stereo (Chapter 4)
  - Shape-from-shading

- Application 2: HDR (High Dynamic Range) imaging (today)
  - To capture both dark and bright areas in an image

Conventional Tricks for HDR

- Use fill-in flash lights to reduce contrast

Vue à travers une fenêtre

Les scènes comportant une vue extérieure prise dans un intérieur sont très difficiles à réaliser. Dans ce cas, la mesure pour la zone lumineuse de la fenêtre 1 (sur le schéma ci-dessous) donne un résultat acceptable,

dessous à droite) pas plus satisfaisante pour l'extérieur que pour l'intérieur. La solution adoptée consiste à éclairer l'intérieur avec un flash diffusé 4, pour faire venir des détails à l'intérieur tout en conservant une vue détaillée de l'extérieur. La distance du flash a été calculée comme indiqué ci-dessous.

Exposure for outside

Exposure for inside

Average exposure

Using fill-in flash

Conventional Tricks for HDR

- Use neutral density filters to reduce contrast

No filter: sky is too bright

Vertical neutral density gradient

Steps of HDR Imaging (& Radiometric Calibration)

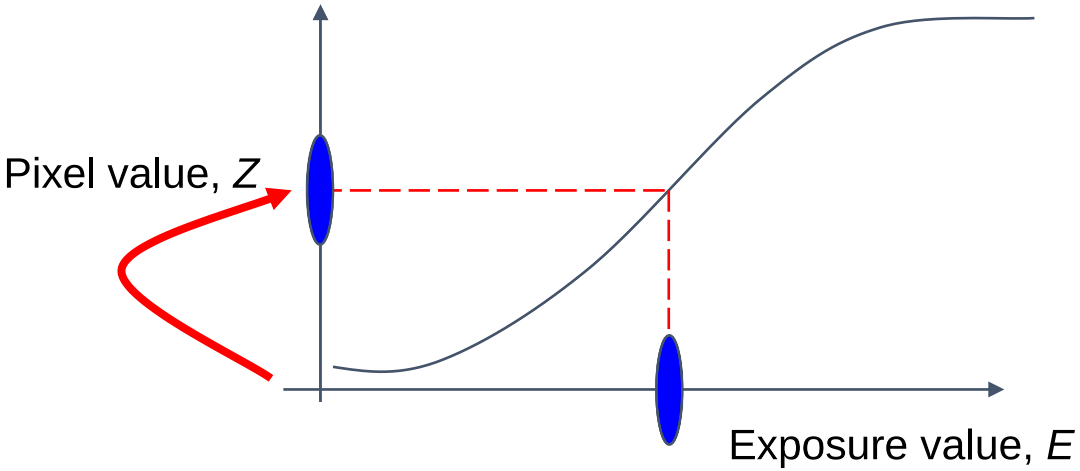
- Step 1: Capture Images with different exposure (e.g. by varying the shutter speeds)

Assume scene is static, camera is static, and lighting is static, so all images are in register

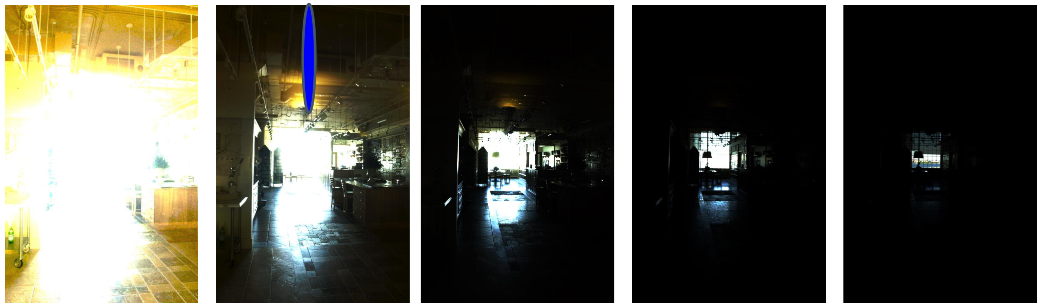
Steps of HDR Imaging (& Radiometric Calibration)

- Step 2: Recover the camera response curve and the HDR image

The response curve transfers a pixel value to an exposure value (essentially # of photons)



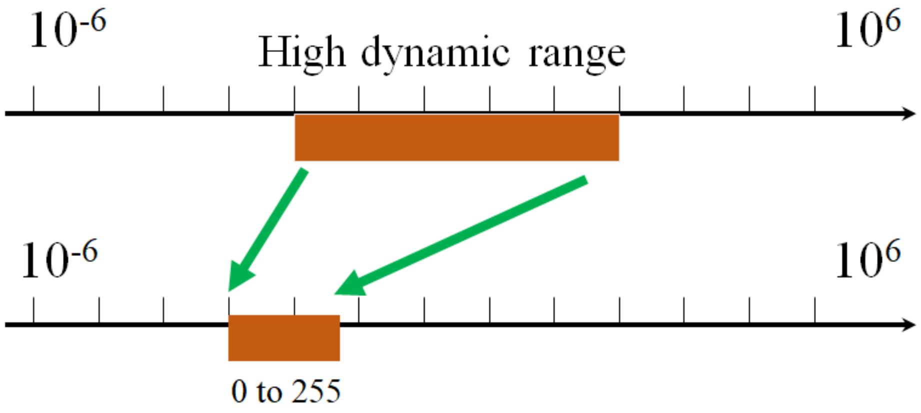
For each pixel in each image convert the pixel value (an integer within [0,255]) to scene exposure value

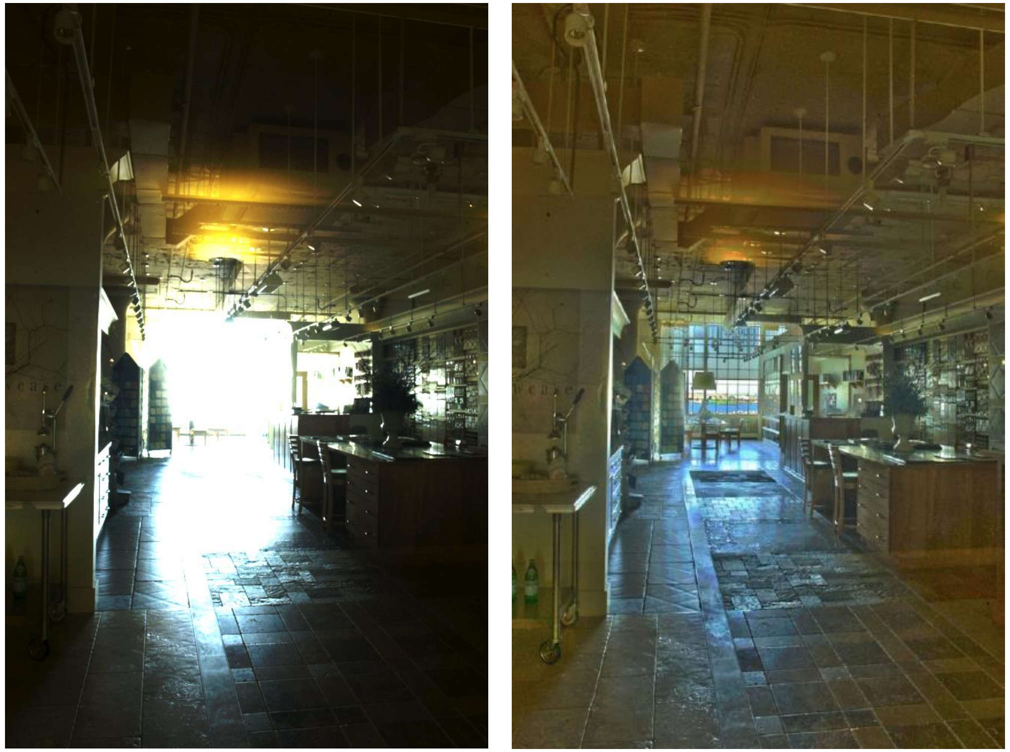


Average exposure values from different images to denoise

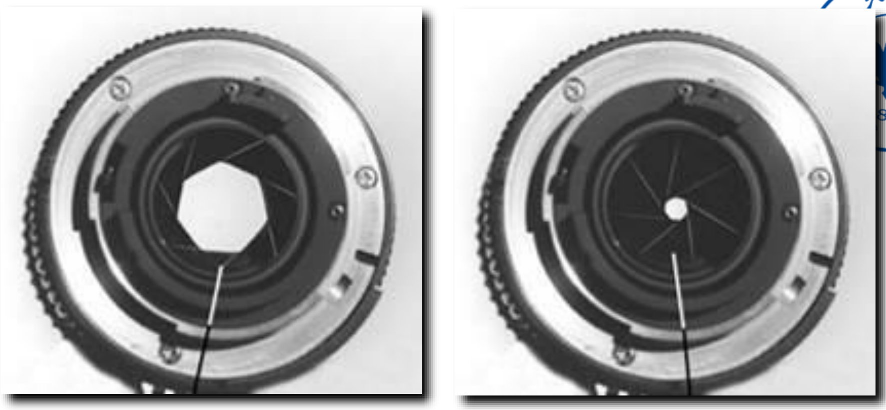
Steps of HDR Imaging (& Radiometric Calibration)

- Step 3: remap the exposure value back to integers within [0,255]
  - →Because displays and printers only support that format
  - →To reduce the dynamic range, but preserve all the details





How to Change Exposure



- Ways to change exposure
  - Shutter speed
  - Aperture
  - Natural density filters
- Exposure times usually obey a power series – each “stop” is a factor of 2
- Camera settings say:

¼, 1/8, 1/15, 1/30, 1/60, 1/125, 1/250, 1/500, 1/1000 sec

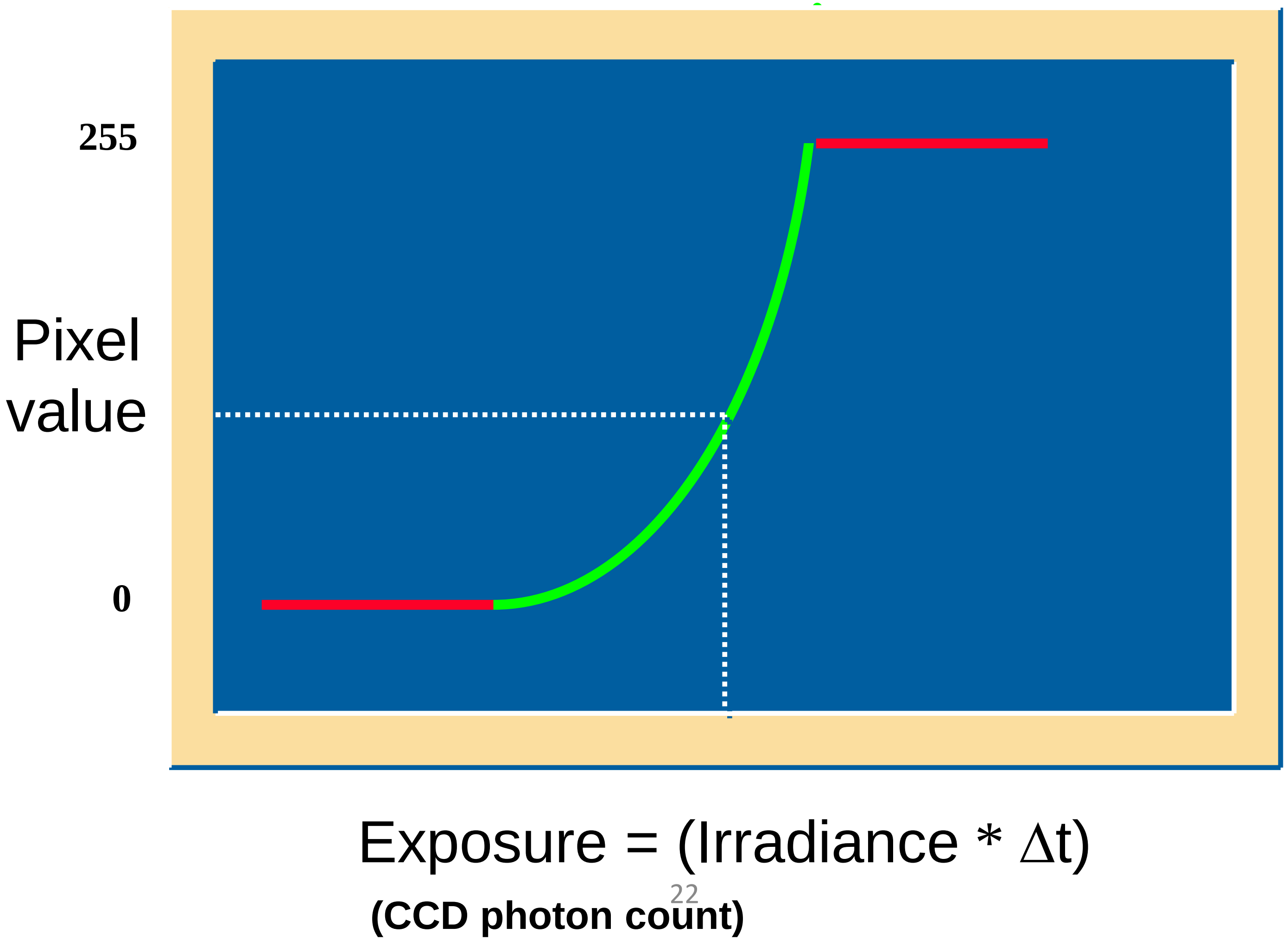
In reality is:

¼, 1/8, 1/16, 1/32, 1/64, 1/128, 1/256, 1/512, 1/1024 sec

Questions?

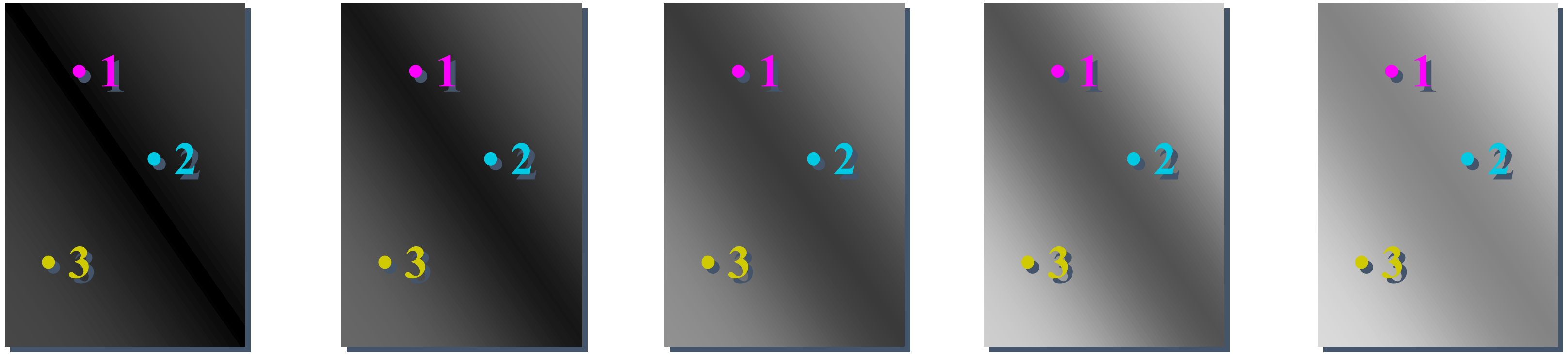
Camera Response Calibration

- The non-linear mapping between exposure and pixel values.



The Algorithm

Input Images



$\Delta t =$ 1/64 sec | $\Delta t =$ 1/16 sec | $\Delta t =$ 1/4 sec | $\Delta t =$ 1 sec | $\Delta t =$ 4 sec

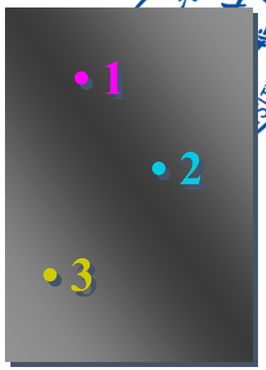
Pixel Value Z = f (Exposure)

Exposure: irradiance $\cdot\ \Delta t$ = # of photons (per pixel)

$$\log \text{Exposure} = \log \text{Irradiance} + \log \Delta t$$

$$g(Z) = \log f^{-1}(Z) = \log \text{Irradiance} + \log \Delta t$$

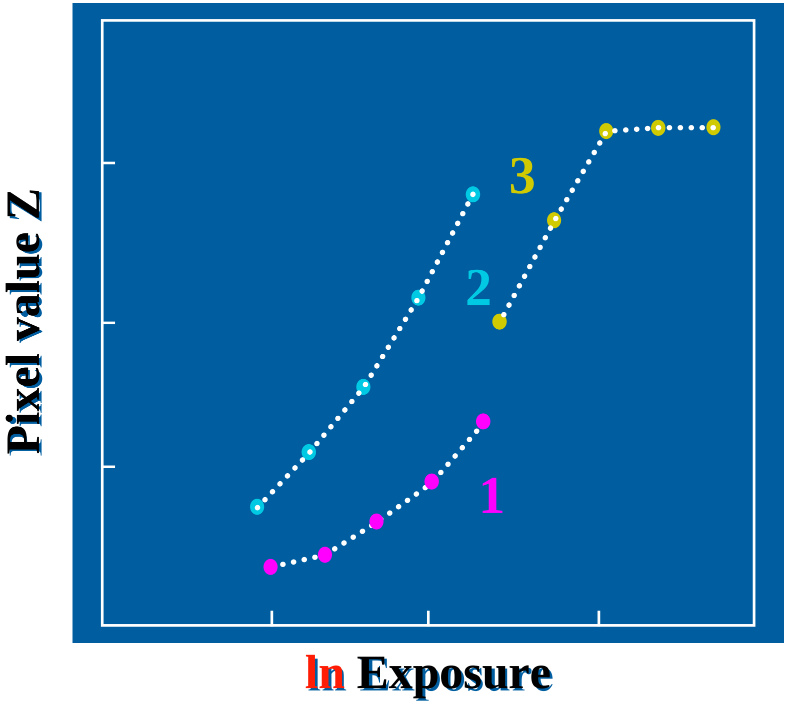
The Algorithm



- Plot the observations from a single pixel

$$g(Z) = \log \text{Exposure} = \log \text{Irradiance} + \log \Delta t$$

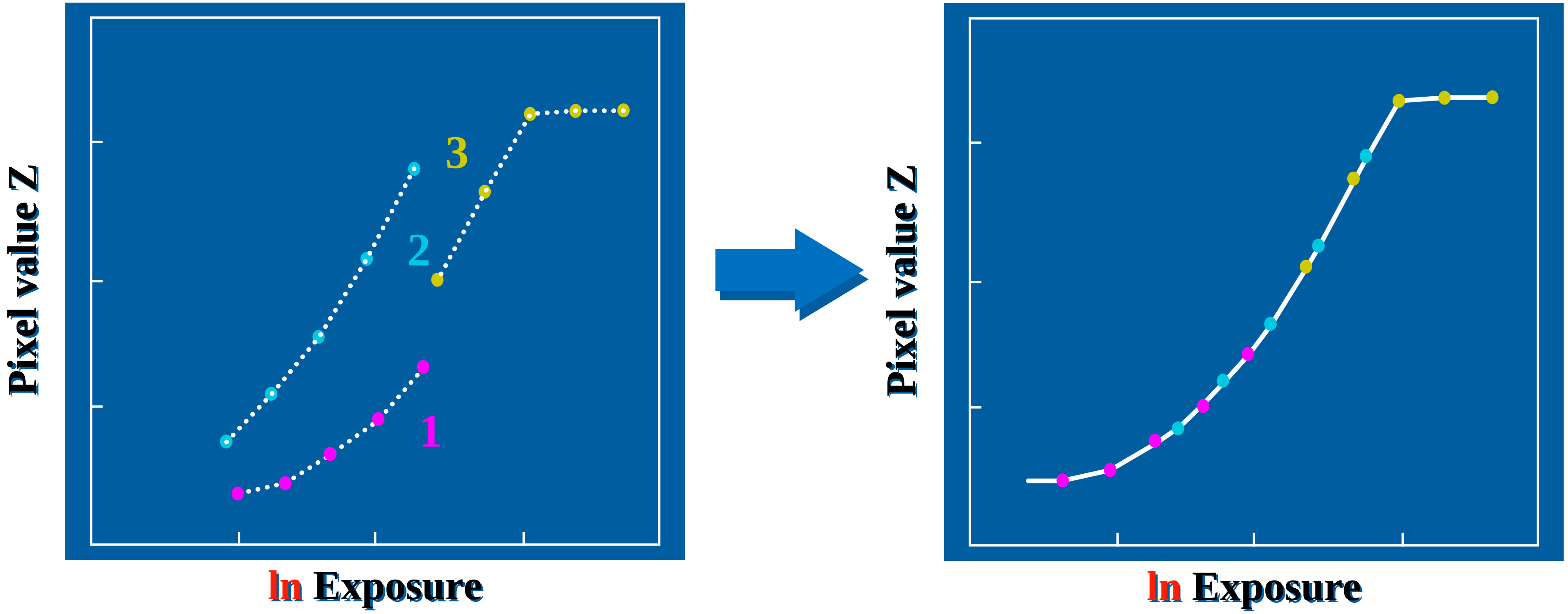
- Obtain a log-curve in the "Pixel Value – Exposure" space
- A different pixel generate a different curve



The horizontal offset of each curve is the unknown irradiance E_i at each pixel i

The Algorithm

- We can estimate the irradiance of all pixels to align these pieces to a smooth curve



The Math

- For each pixel site i in each image j, want

$$\ln E_i + \ln \Delta t_j - g(Z_{ij}) = 0$$

  - # of unknowns: N + 256 (N is the # of pixels)

    $g(Z)$ is determined by $g(0), g(1), \dots\ g(255)$
  - # of equations: NK (K is the # of images)
- Minimize the following

$$\underbrace{\sum_{i=1}^{N}\sum_{j=1}^{P}\left[\ln E_i + \ln \Delta t_j - g(Z_{ij})\right]^2}_{\text{fitting term}} + \lambda \sum_{z=Z_{min}}^{Z_{max}} \underbrace{\left[g(z) - \frac{\mathrm{g}(\mathrm{z}+1) + \mathrm{g}(\mathrm{z}-1)}{2}\right]^2}_{\text{smoothness term}}$$

$$g''(z) = 0$$

- The solution can be only up to a scale, add a constraint

$$g(128) = 0$$

How to Optimize?

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

1. Set partial derivatives to zero

$$\min \sum_{i=1}^{N} (\mathbf{a_i x} - \mathbf{b_i})^2 \rightarrow \text{linear equations of} \begin{bmatrix} \mathbf{a_1} \\ \mathbf{a_2} \\ \vdots \\ \mathbf{a_N} \end{bmatrix} \mathbf{x} = \begin{bmatrix} \mathbf{b_1} \\ \mathbf{b_2} \\ \vdots \\ \mathbf{b_N} \end{bmatrix}$$

2. Solve the linear equation (over-determined, i.e. more equations than unknowns)

$$\underset{\substack{m\times n \\ m>n}}{\mathbf{A}}\mathbf{x} = \mathbf{b} \quad \Longrightarrow \quad \underset{n\times n}{\mathbf{A}^T\mathbf{A}}\mathbf{x} = \mathbf{A}^T\mathbf{b}$$

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
%
```

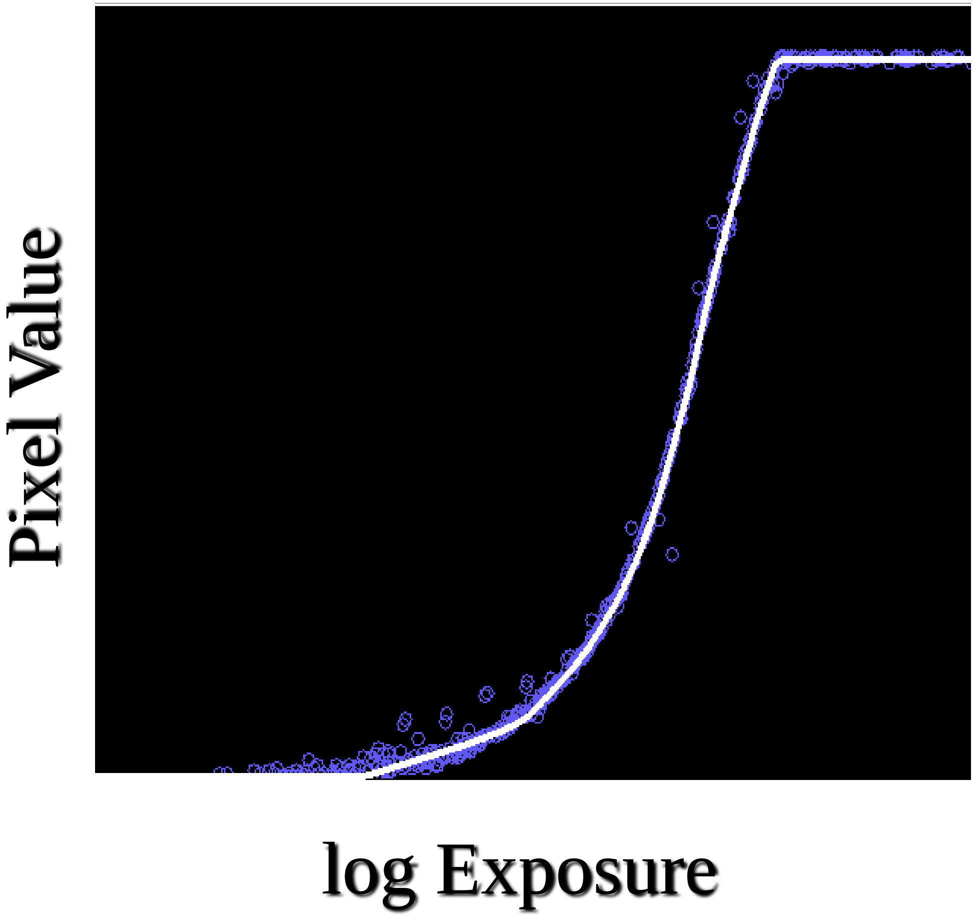
Matlab code

```
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));
```

Results: Camera Response Function

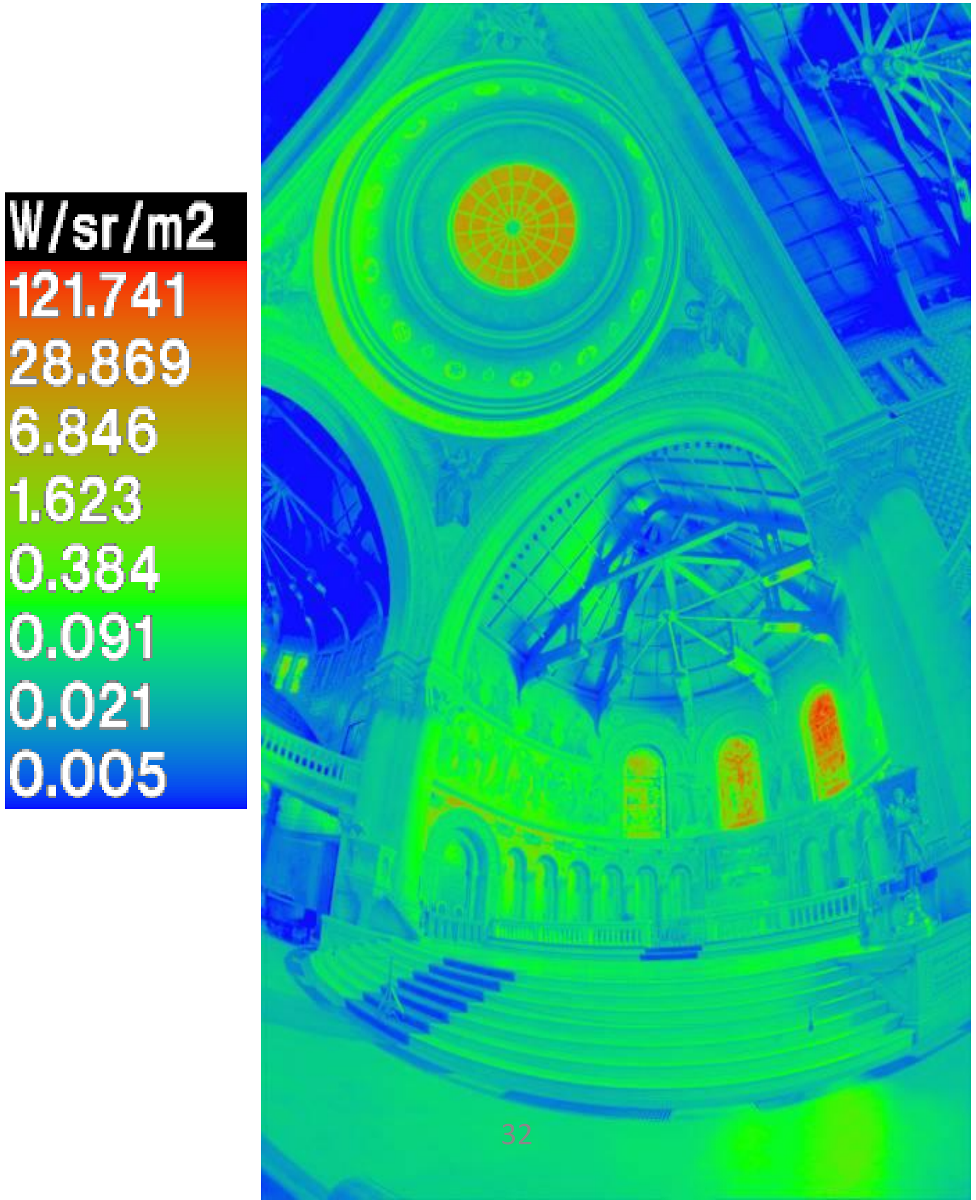
Kodak DCS460 (1/30 to 30 sec)

Recovered response curve



Example: Input Images

Example: Recovered Radiance Map



Irradiance map, sometimes also called radiance map

…

Ignoring the vignetting effect, irradiance is proportional to the scene radiance

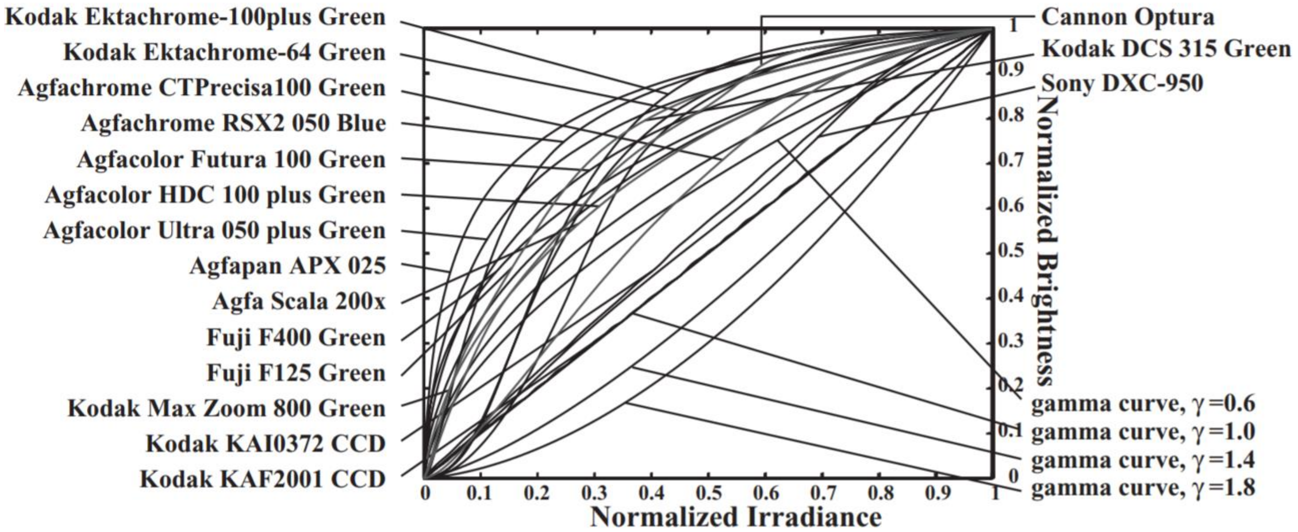
Questions?

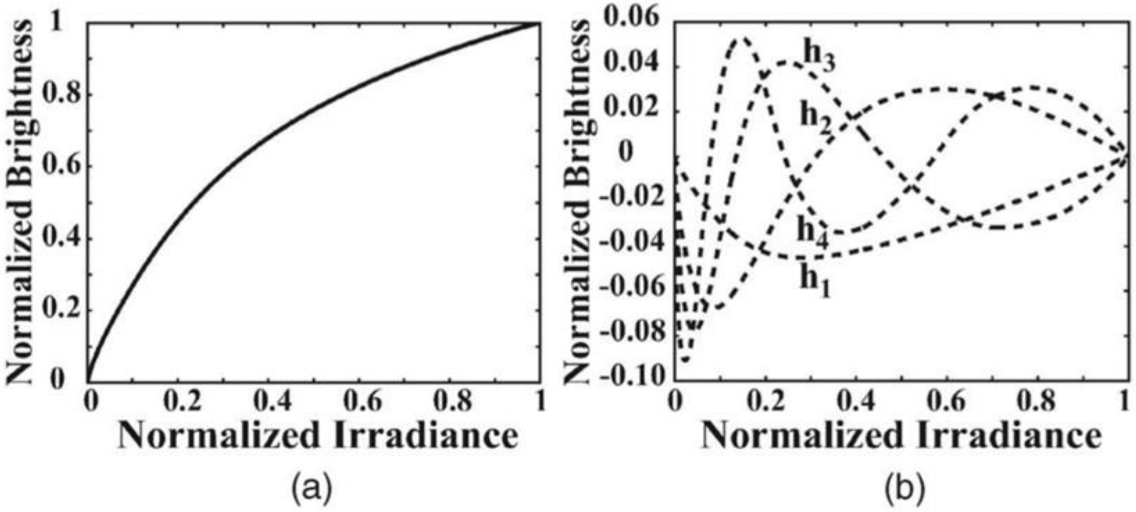
Modeling the Space of Camera Response Functions

Michael D. Grossberg, *Member*, *IEEE Computer Society*, and Shree K. Nayar

PAMI 2004

Empirical Model of Response Functions





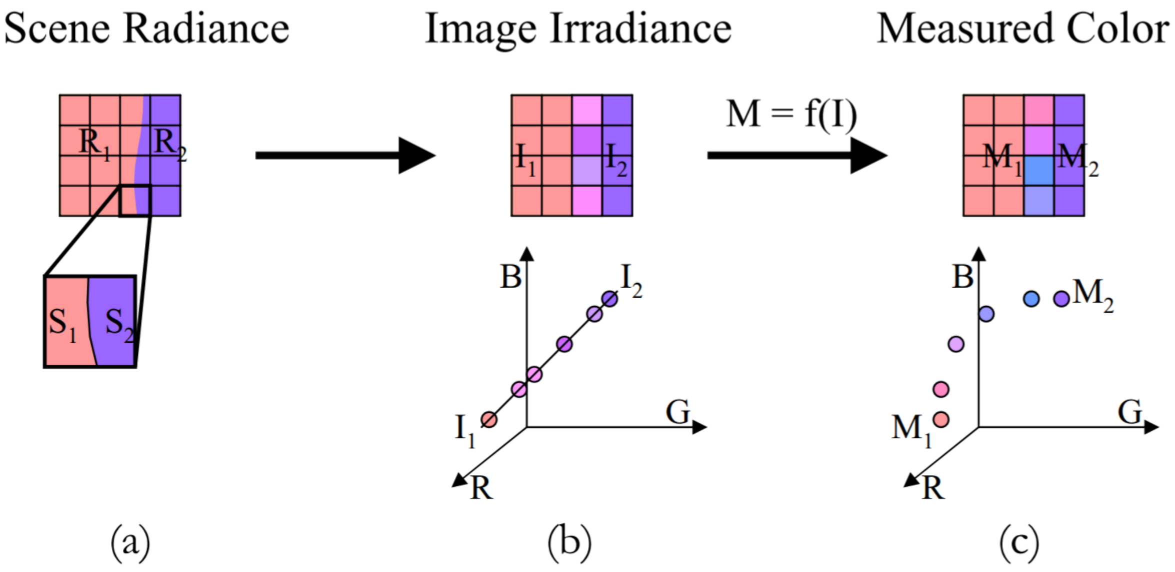
- Measure response functions of many real cameras
- PCA to obtain a linear parametric model of the response function
- Further enforce monotonicity

Radiometric Calibration from a Single Image

Stephen Lin[†] Jinwei Gu[‡] Shuntaro Yamazaki[§] Heung-Yeung Shum[†]

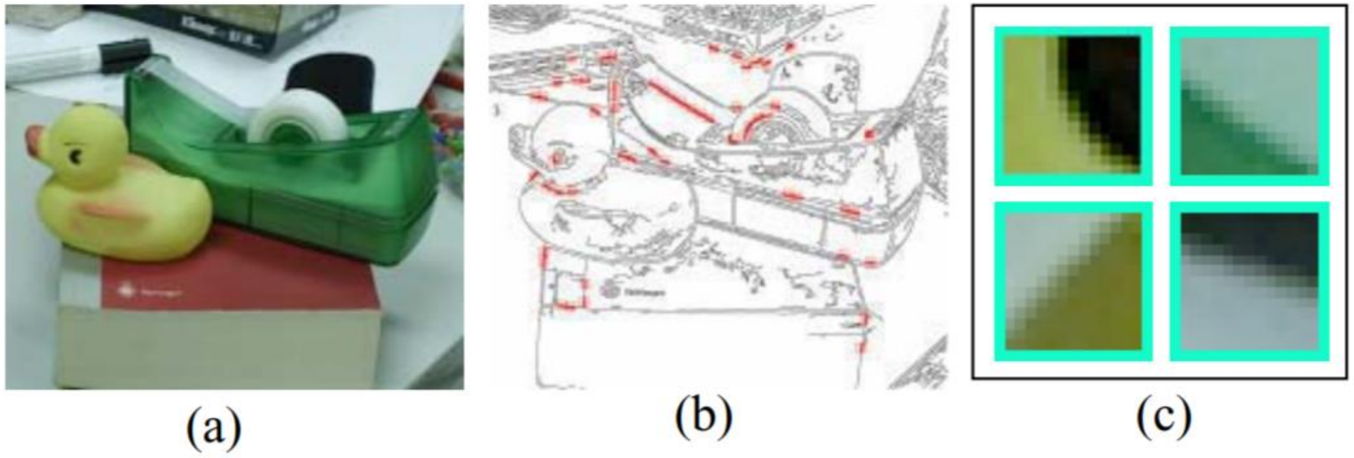
CVPR 2004

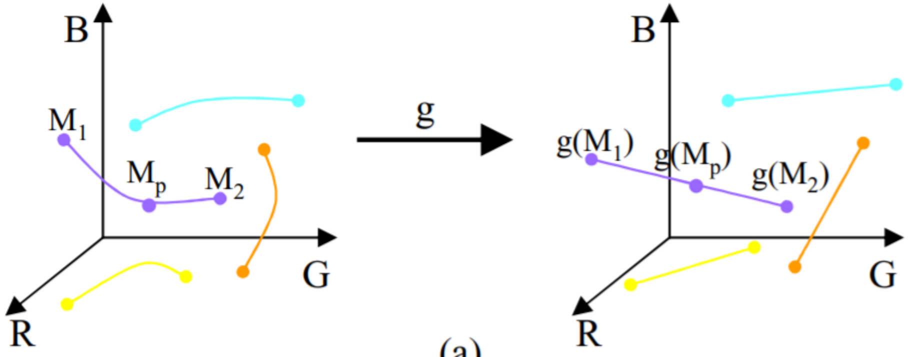
Edge Color Distributions



- Pixels on edge blend two colors
- They should lie on a line connecting the two colors
- Due to nonlinear camera response, these blended pixels form a curve
- So we can find the (inverse of) camera response curve by making these curves straight lines

Camera Linearization





- Automatically choose edges in an image
- Measure the nonlinearity at these edges
- Use the PCA response function model from Grossberg and Nayar
- Find the best parameter to minimize the nonlinearity

Questions?