# Computational Photography

COS 526: Advanced Computer Graphics

PRINCETON UNIVERSITY

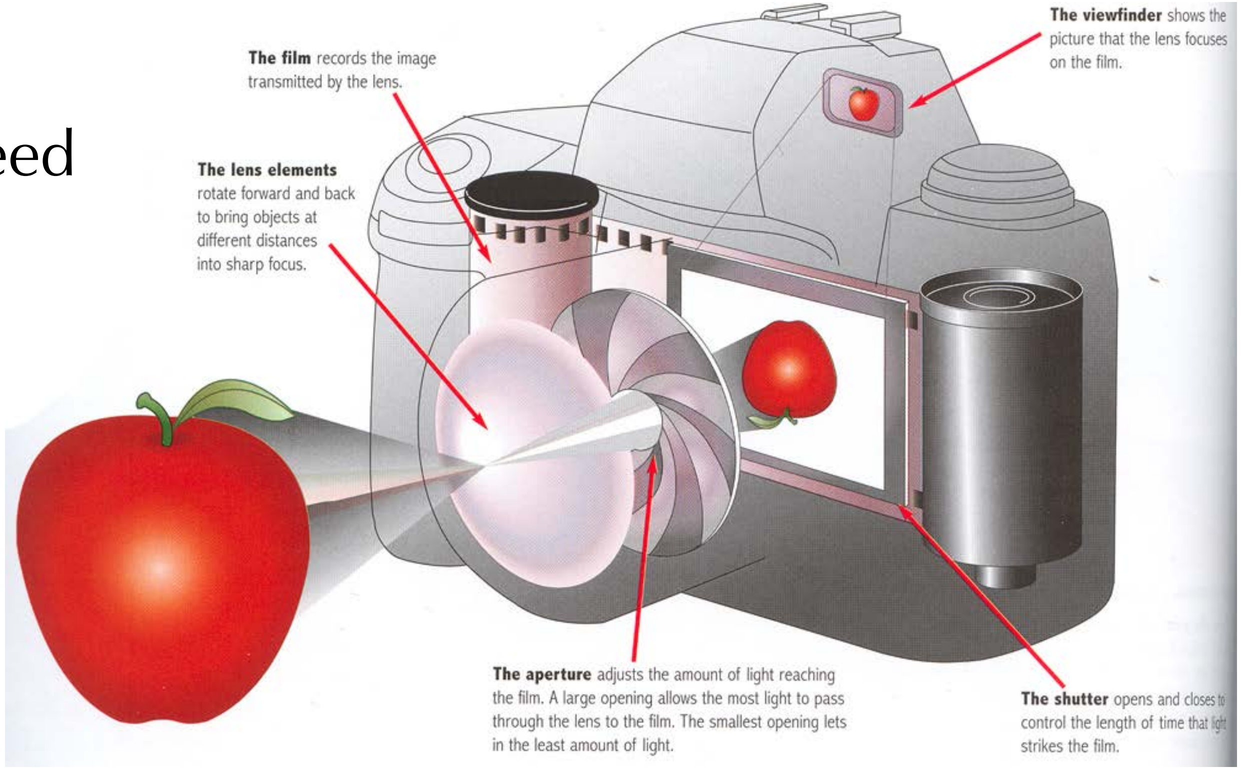
Slide credits: Funkhouser, Finkelstein, Durand, Debevec, Efros, Gunturk

# What is Computational Photography?

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

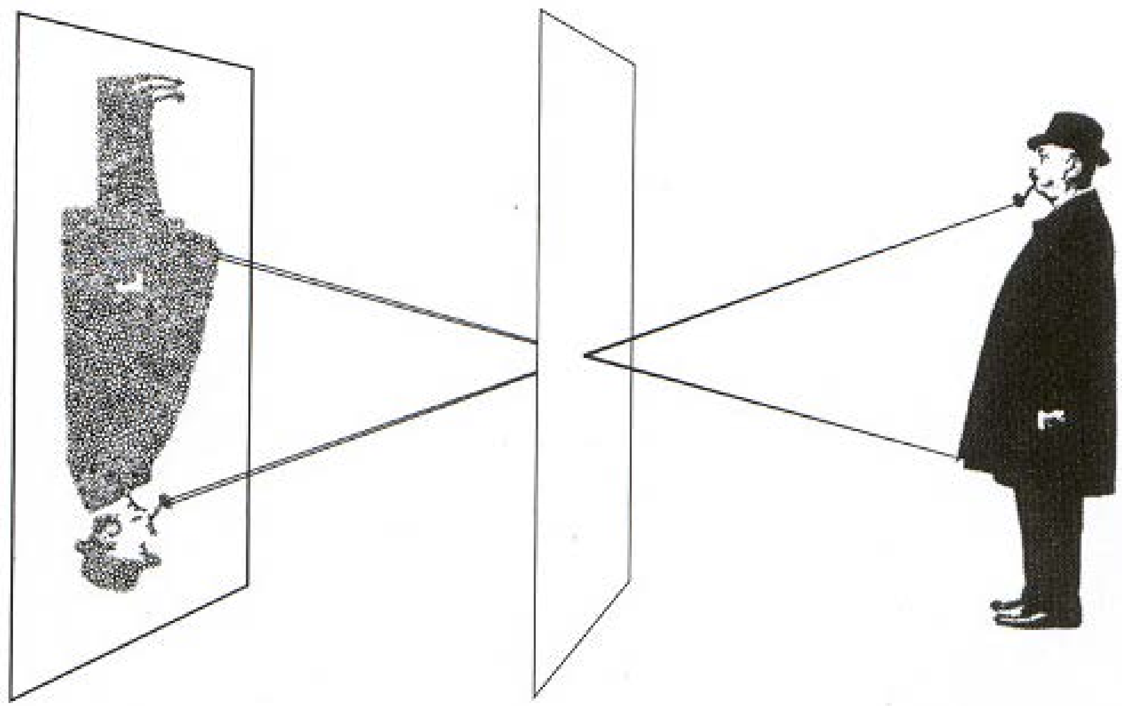
# Traditional Photography

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



# Traditional Photography

- Pin-hole camera:

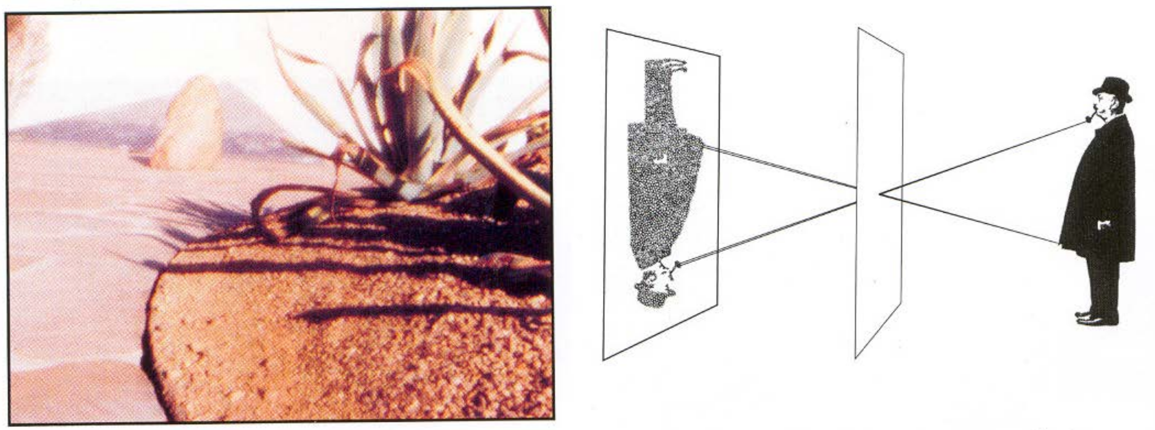


From Photography, London et al.

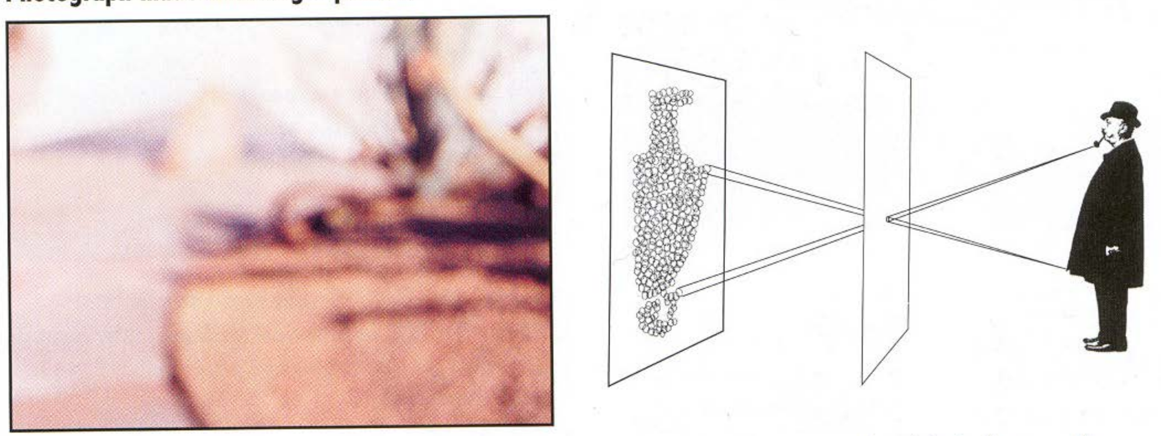
# Traditional Photography

- Pin-hole size?

**Photograph made with small pinhole**



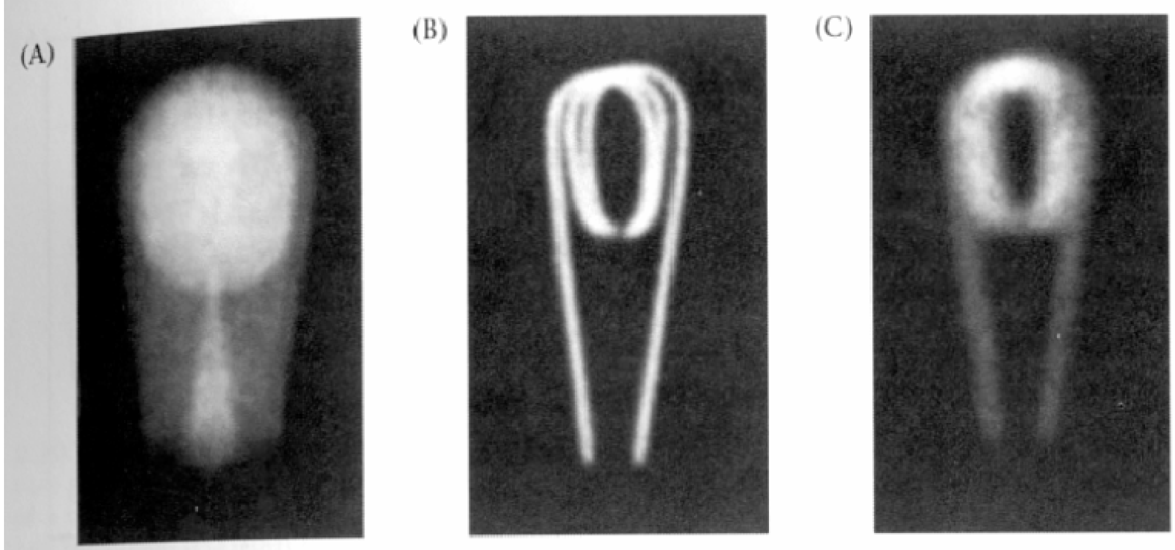
**Photograph made with larger pinhole**



From Photography, London et al.

# Traditional Photography

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

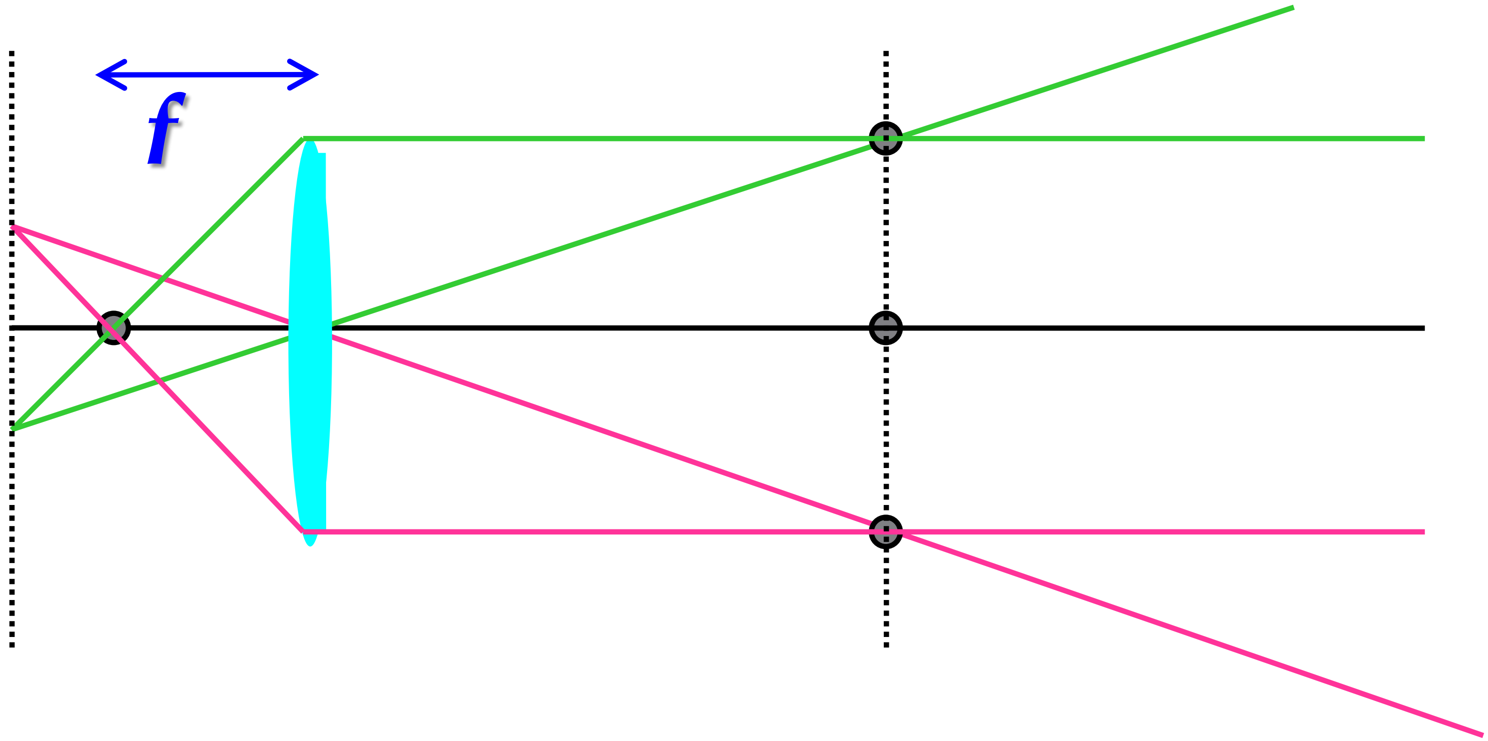



**2.18 DIFFRACTION LIMITS THE QUALITY OF PINHOLE OPTICS.** These three images of a bulb filament were made using pinholes with decreasing size. (A) When the pinhole is relatively large, the image rays are not properly converged, and the image is blurred. (B) Reducing the size of the pinhole improves the focus. (C) Reducing the size of the pinhole further worsens the focus, due to diffraction. From Ruechardt, 1958.

[Wandell]

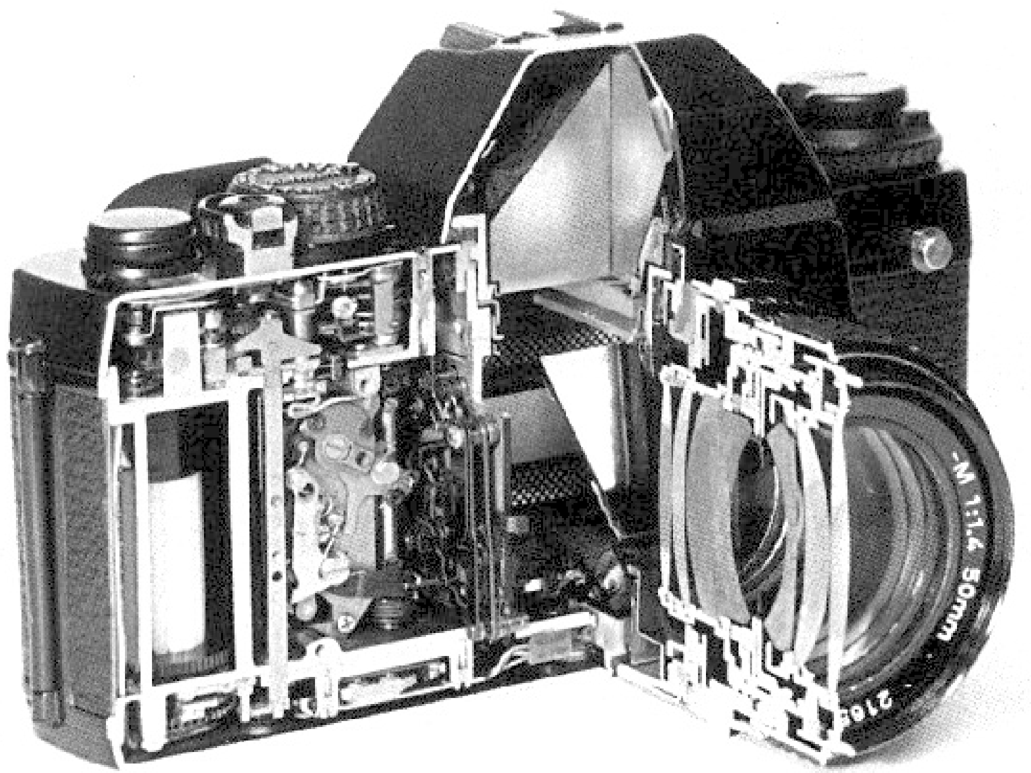
# Traditional Photography

- Lenses



# Traditional Photography

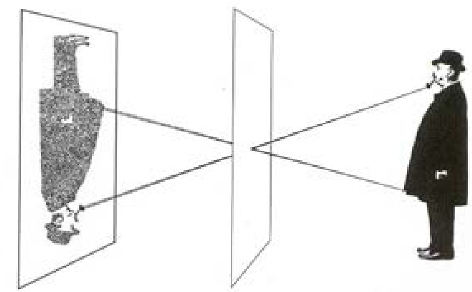
- Lens *systems* use many lenses to overcome limitations of single lenses



# Traditional Photography

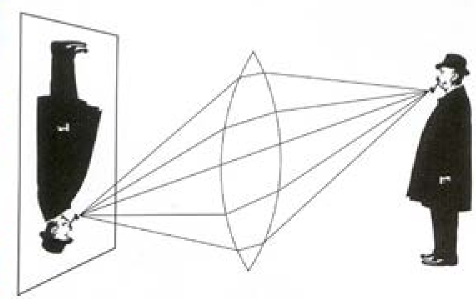
- Lenses
  - + More light
  - + Sharp …
  - - at one depth

**Photograph made with small pinhole**



***To make this picture, the lens of a camera was replaced with a thin metal disk pierced by a tiny pinhole,*** *equivalent in size to an aperture of f/182. Only a few rays of light from each point on the subject got through the tiny opening, producing a soft but acceptably clear photograph. Because of the small size of the pinhole, the exposure had to be 6 sec long.*

**Photograph made with lens**



***This time, using a simple convex lens with an f/16 aperture,*** *the scene appeared sharper than the one taken with the smaller pinhole, and the exposure time was much shorter, only 1/100 sec.*

*The lens opening was much bigger than the pinhole, letting in far more light, but it focused the rays from each point on the subject precisely so that they were sharp on the film.*

From Photography, London et al.

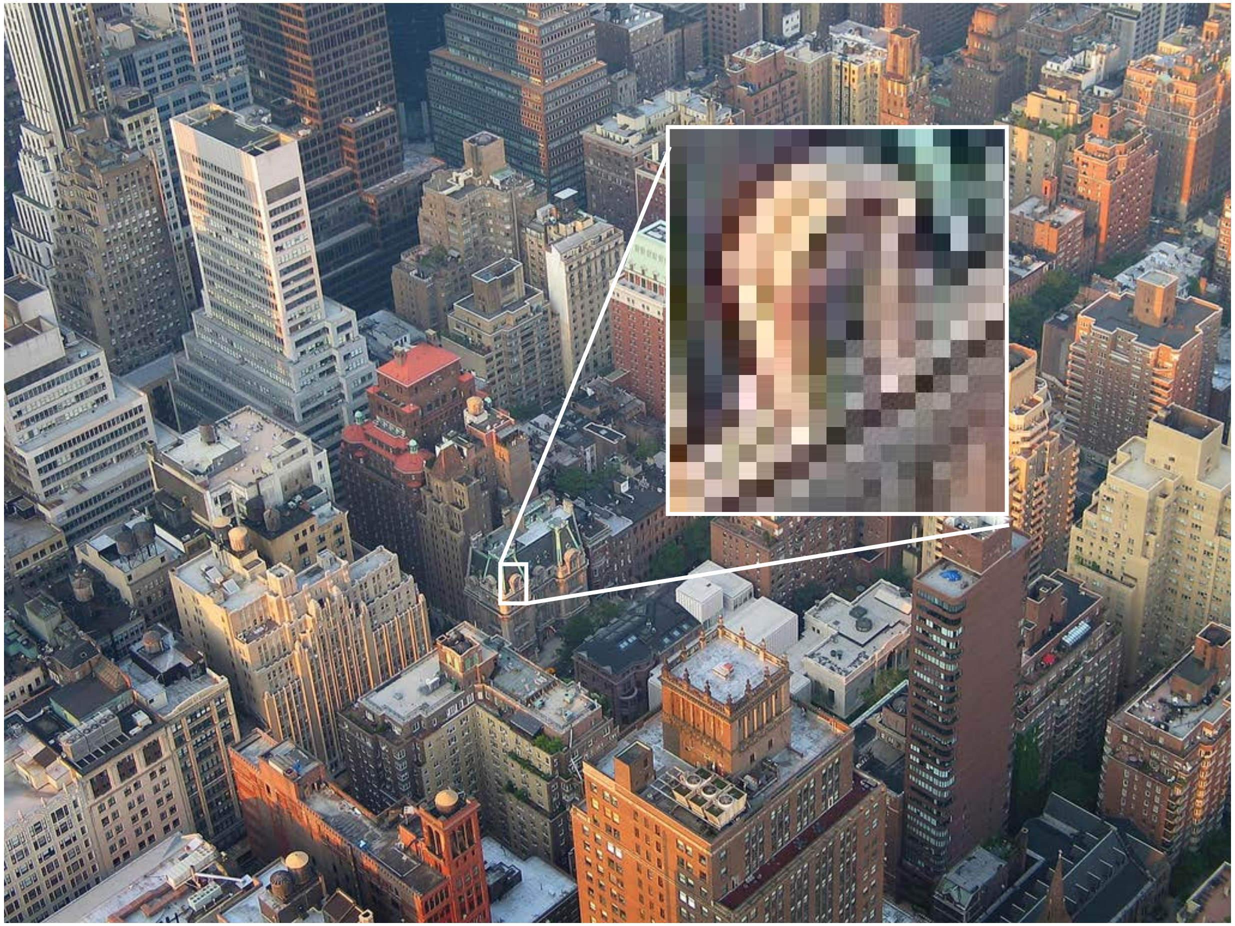
# Limitations of traditional photography

- Single depth of focus

Slide by Lazebnik

# Limitations of traditional photography

- Limited resolution



Slide by Lazebnik

# Limitations of traditional photography

- Bad color / no color

Slide by Lazebnik

# Limitations of traditional photography

- Limited dynamic range

Slide by Lazebnik

# Limitations of traditional photography

- Single viewpoint

NFL

# Limitations of traditional photography

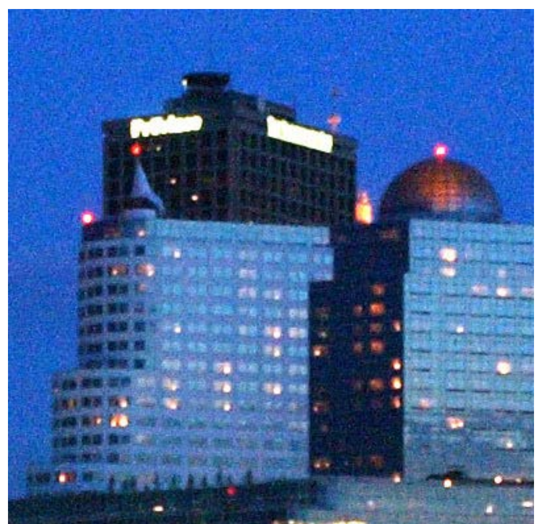
- Static scene

Slide by Lazebnik

# Limitations of traditional photography

- Blur, camera shake, noise, damage






# Limitations of traditional photography

- Unfortunate expressions

Slide by Lazebnik

# Limitations of traditional photography

- Unwanted objects

Slide by Lazebnik

# Computational Photography

**Computer Graphics**

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

**Computational Photography**

Realism
Manipulation
Ease of capture

**Photography**

- hard to manipulate objects/viewpoint

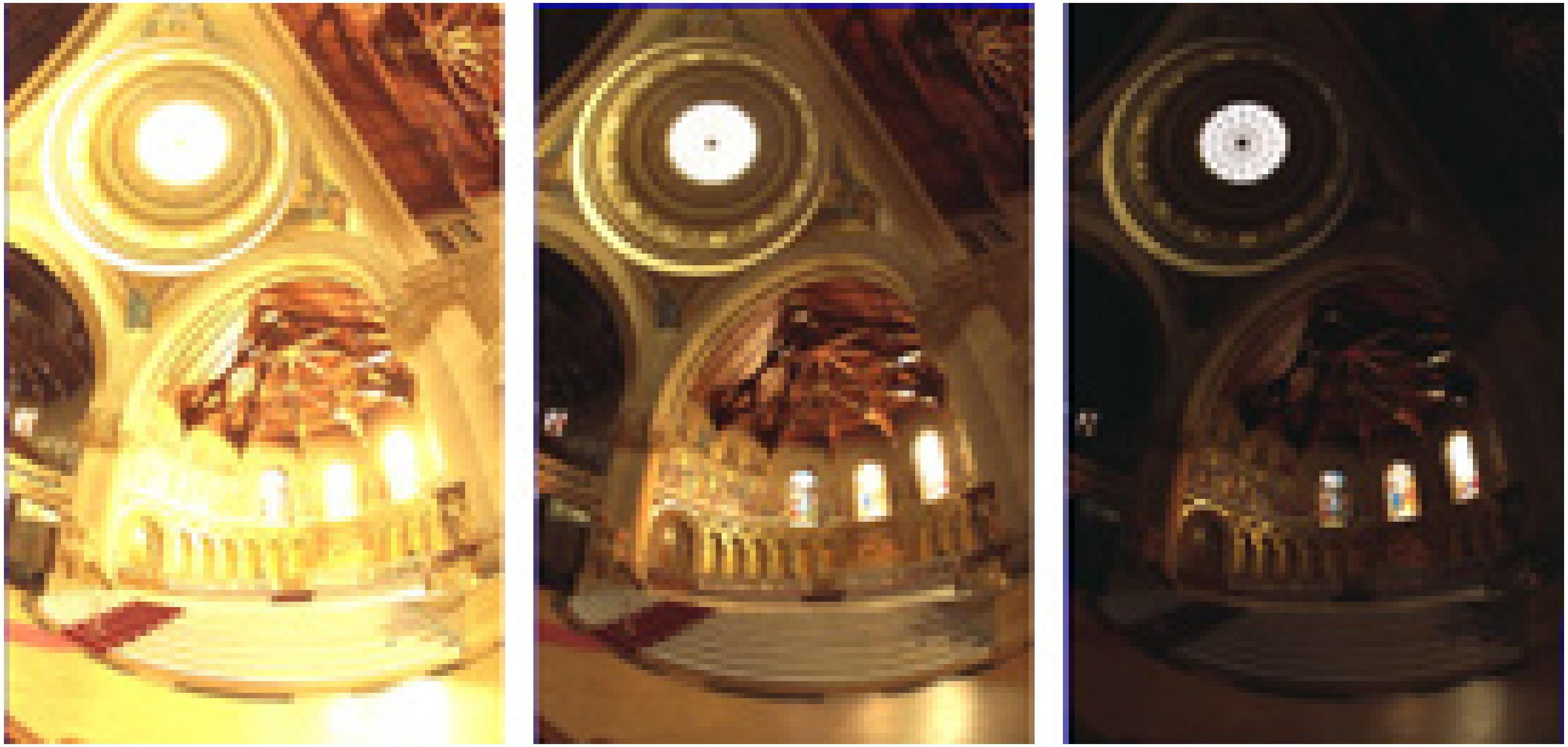
+ easy to acquire

+ instantly realistic

Slide by Efros

# Computational Photography

- Example: high-dynamic range



Debevec

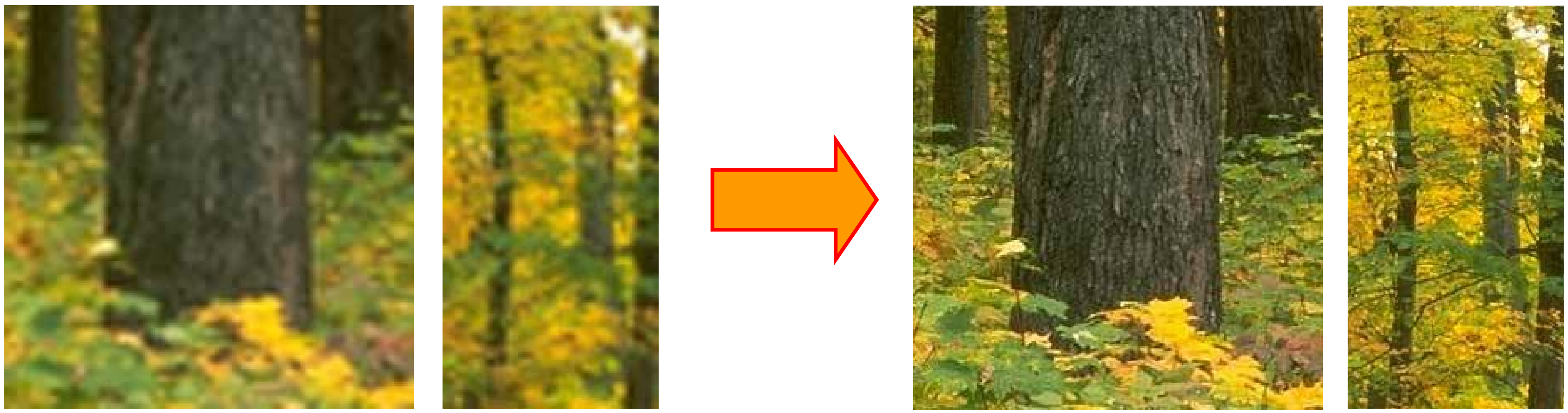
# Computational Photography

- Example: deblurring

Fergus

# Computational Photography

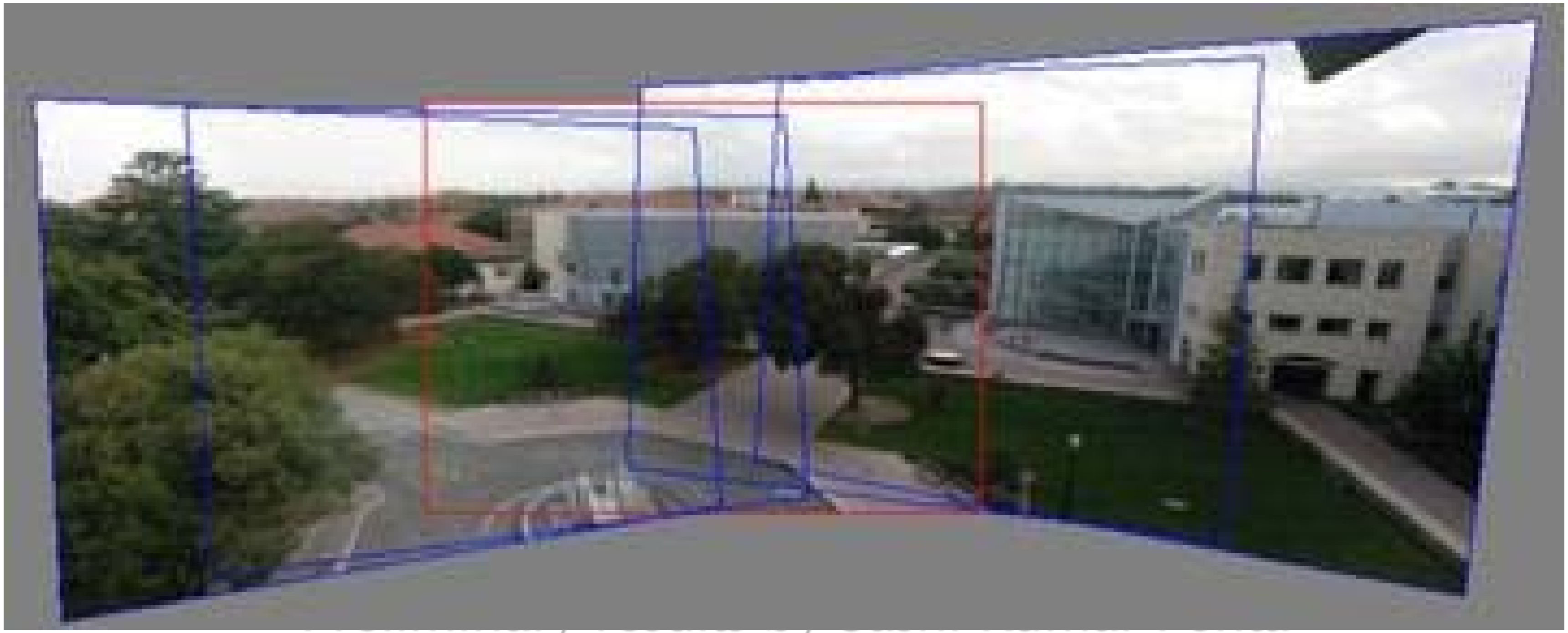
- Example: super-resolution



Hertzmann

# Computational Photography

- Example: creating panoramas



# Computational Photography

- Example: gigapixel images

Kopf

# Computational Photography

- Example: color harmonization

Cohen-Or

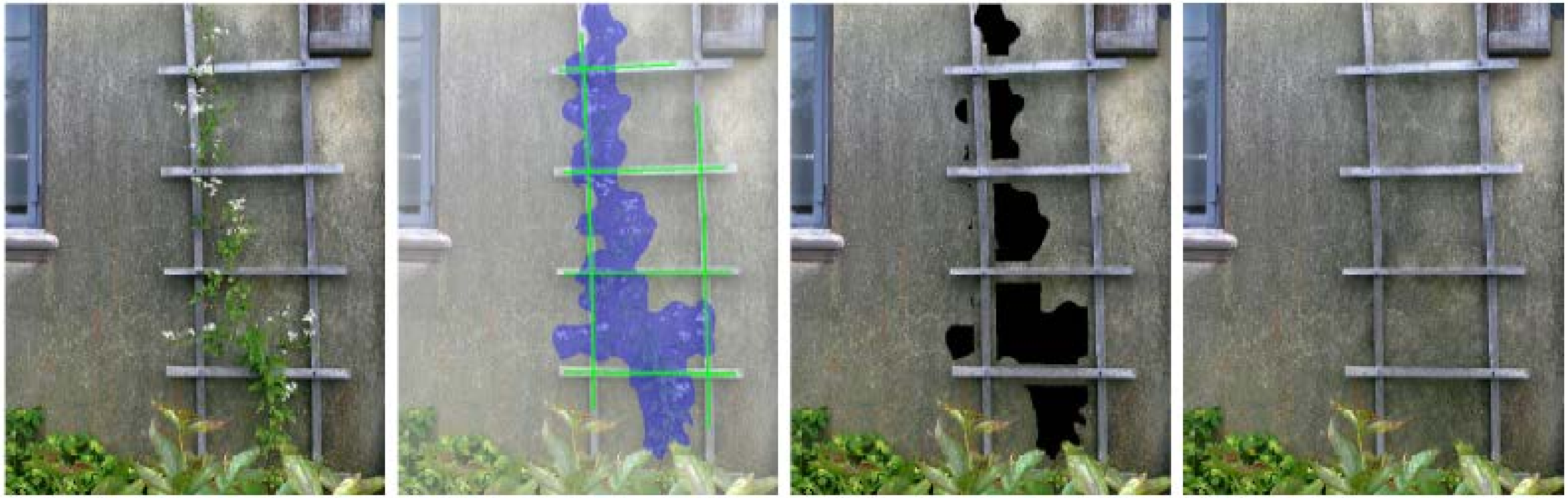
# Computational Photography

- Example: background replacement

(a) input (b) result 1 result 2

# Computational Photography

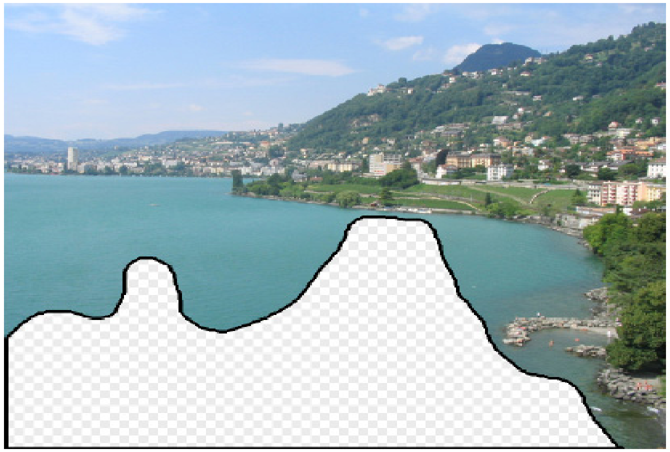
- Example: image completion

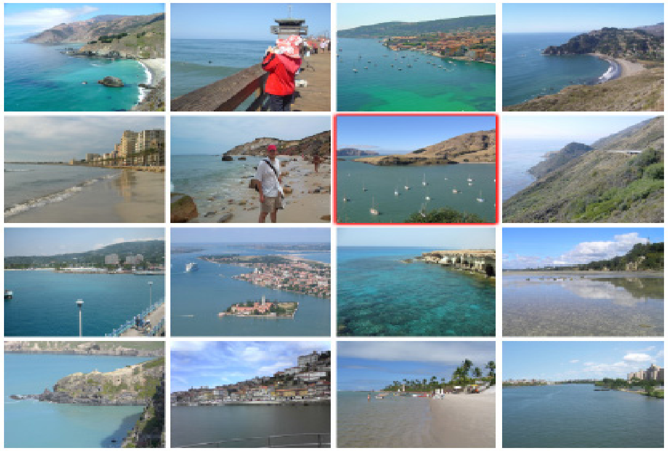


Sun

# Computational Photography

- Example: image completion





Efros

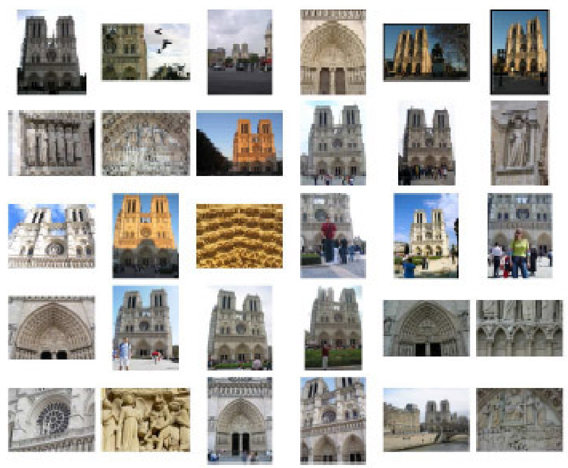
# Computational Photography

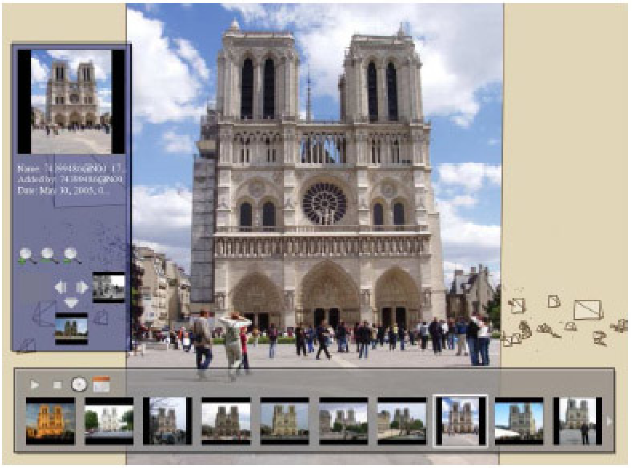
- Example: tour into the picture

Horry

# Computational Photography

- Example: photo tourism

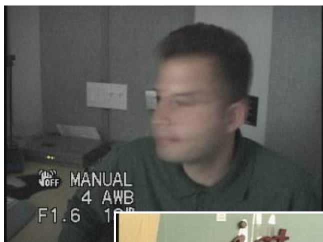




Snavely

# High Dynamic Range Imaging

# Dynamic Range




1


1500


25,000

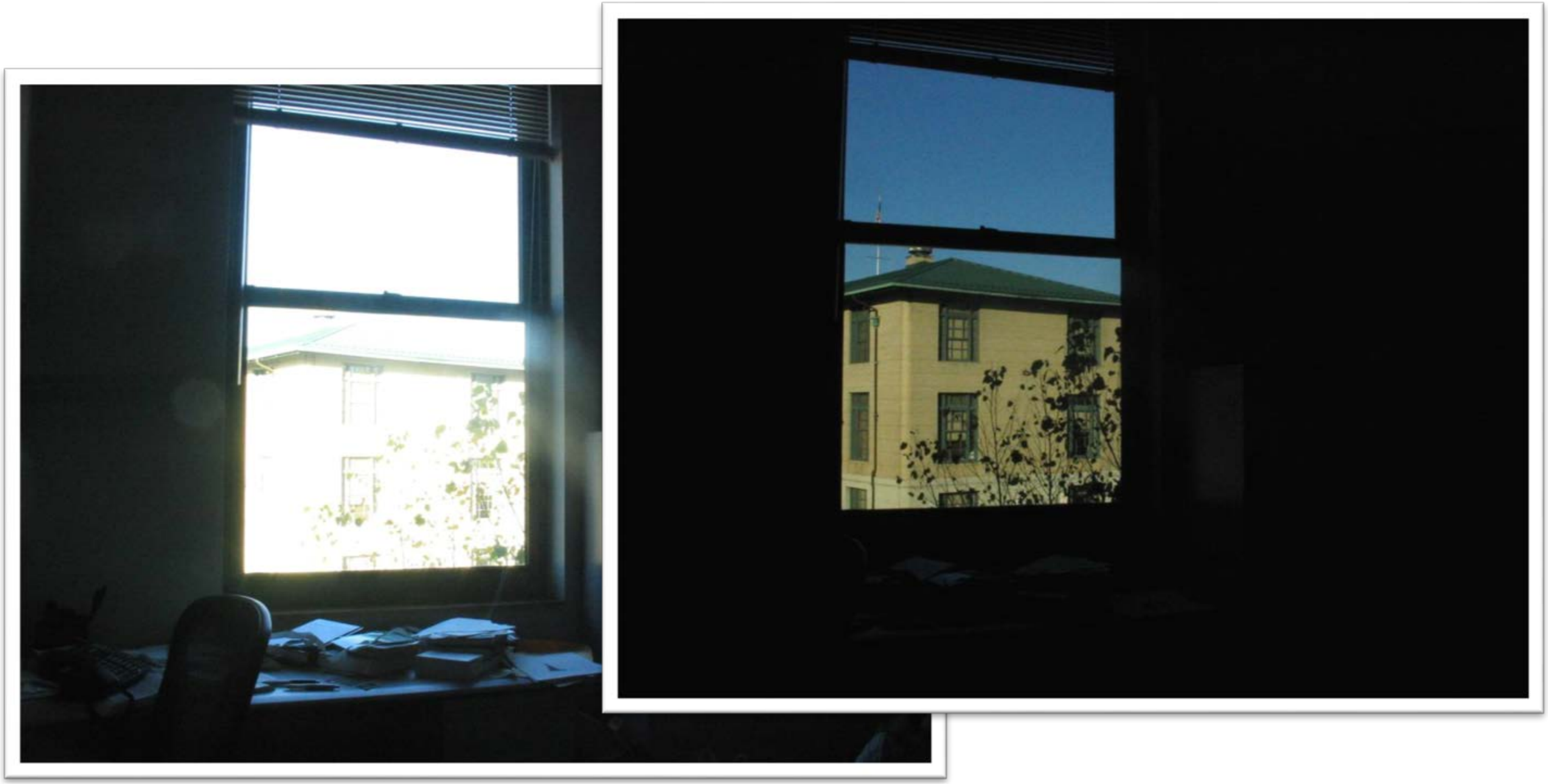

400,000


2,000,000,000

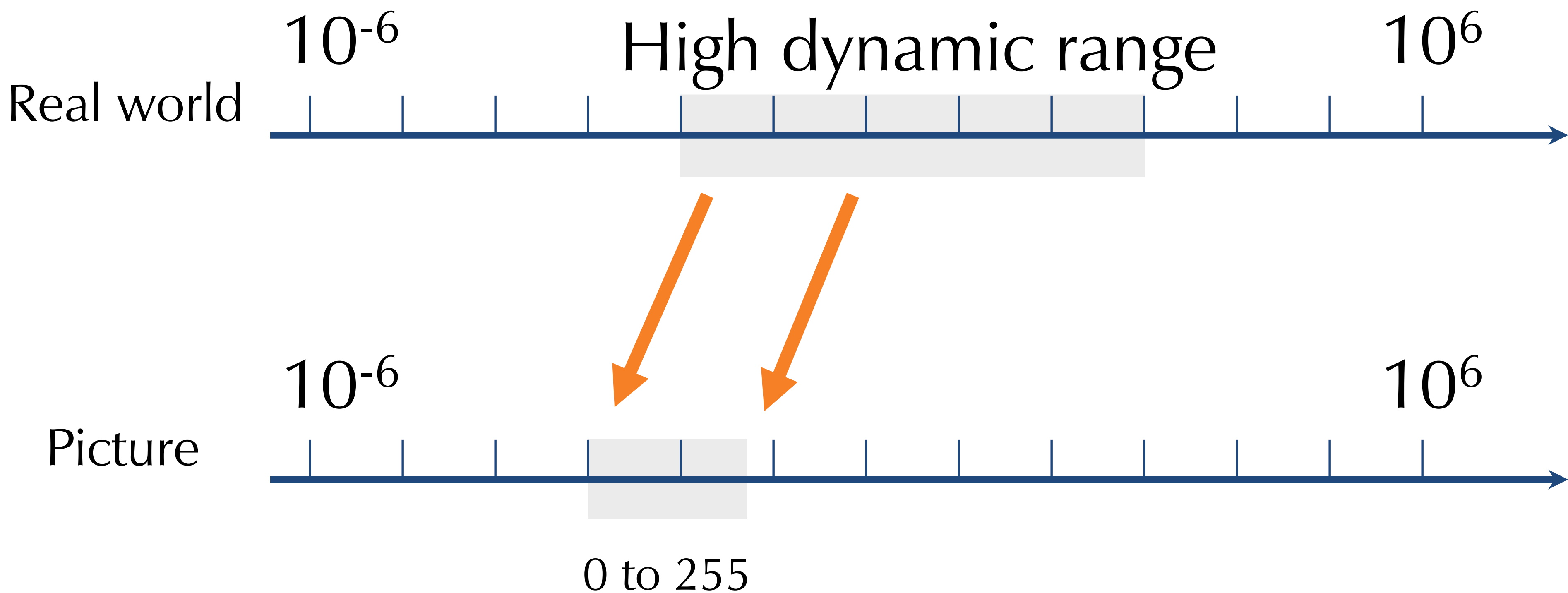
The real world is
high dynamic range.

# Problem

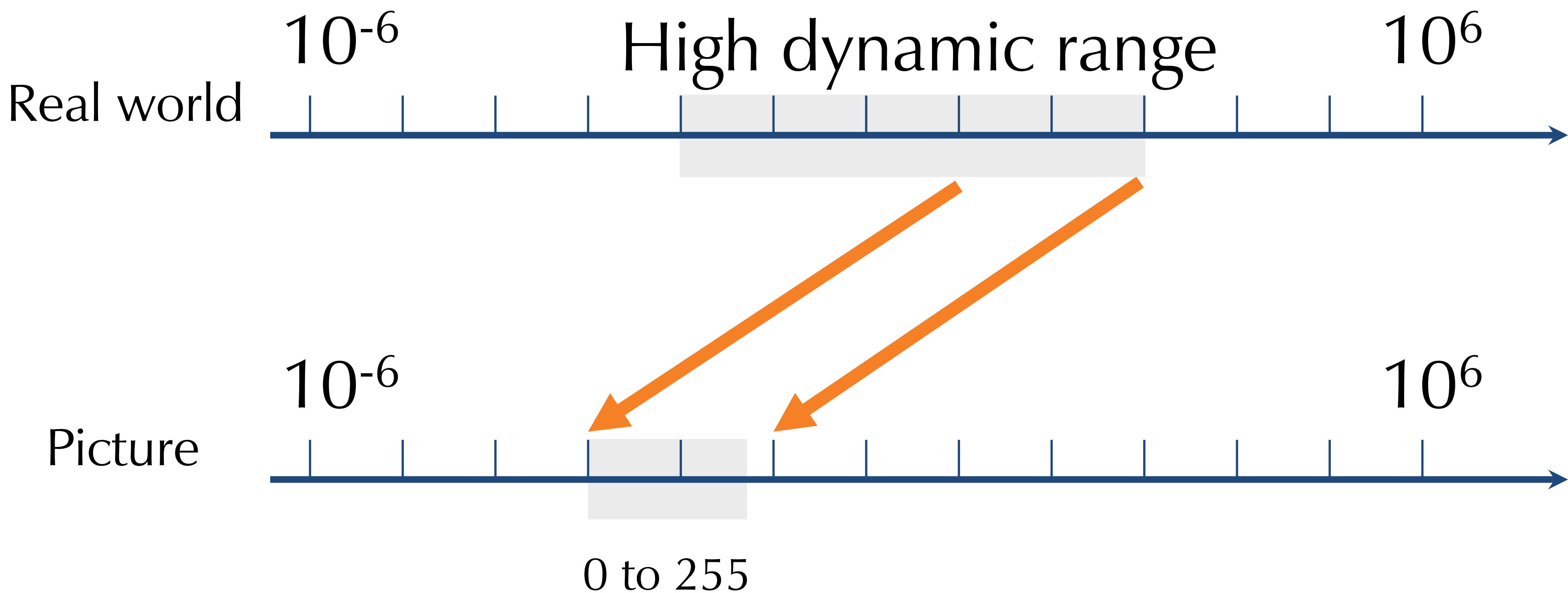
- Cameras cannot capture the full dynamic range of the world



# Long Exposure

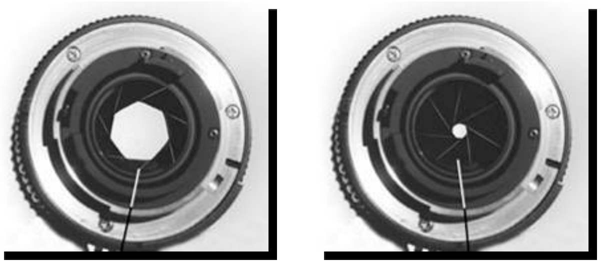


# Short Exposure



# Ways to Vary Exposure

- Shutter Speed (*)
- F/stop (aperture, iris)



- Neutral Density (ND) Filters

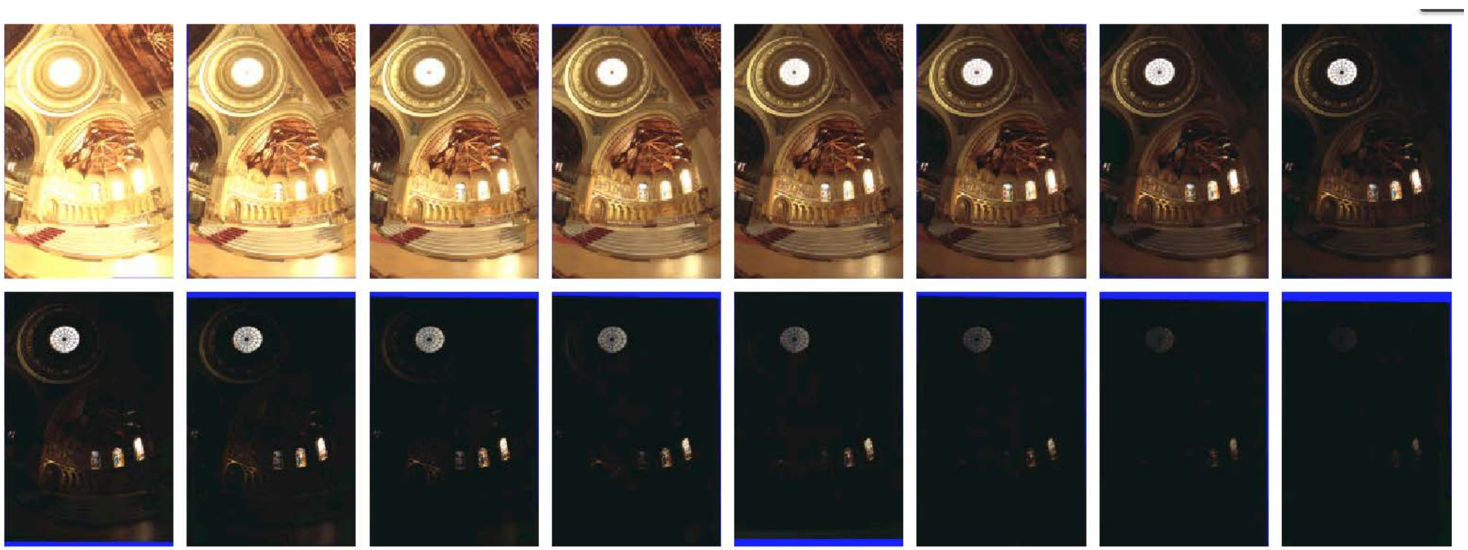
# Varying Shutter Speed

- 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)

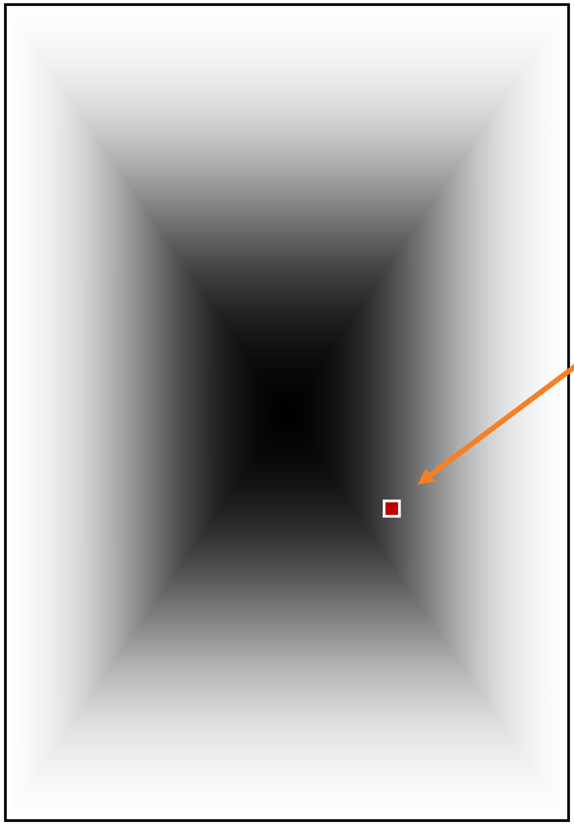
# General Approach

- Build model of imaging system

  (radiance → pixel values)
- Invert model

  (pixel values → radiance)

# Imaging System?

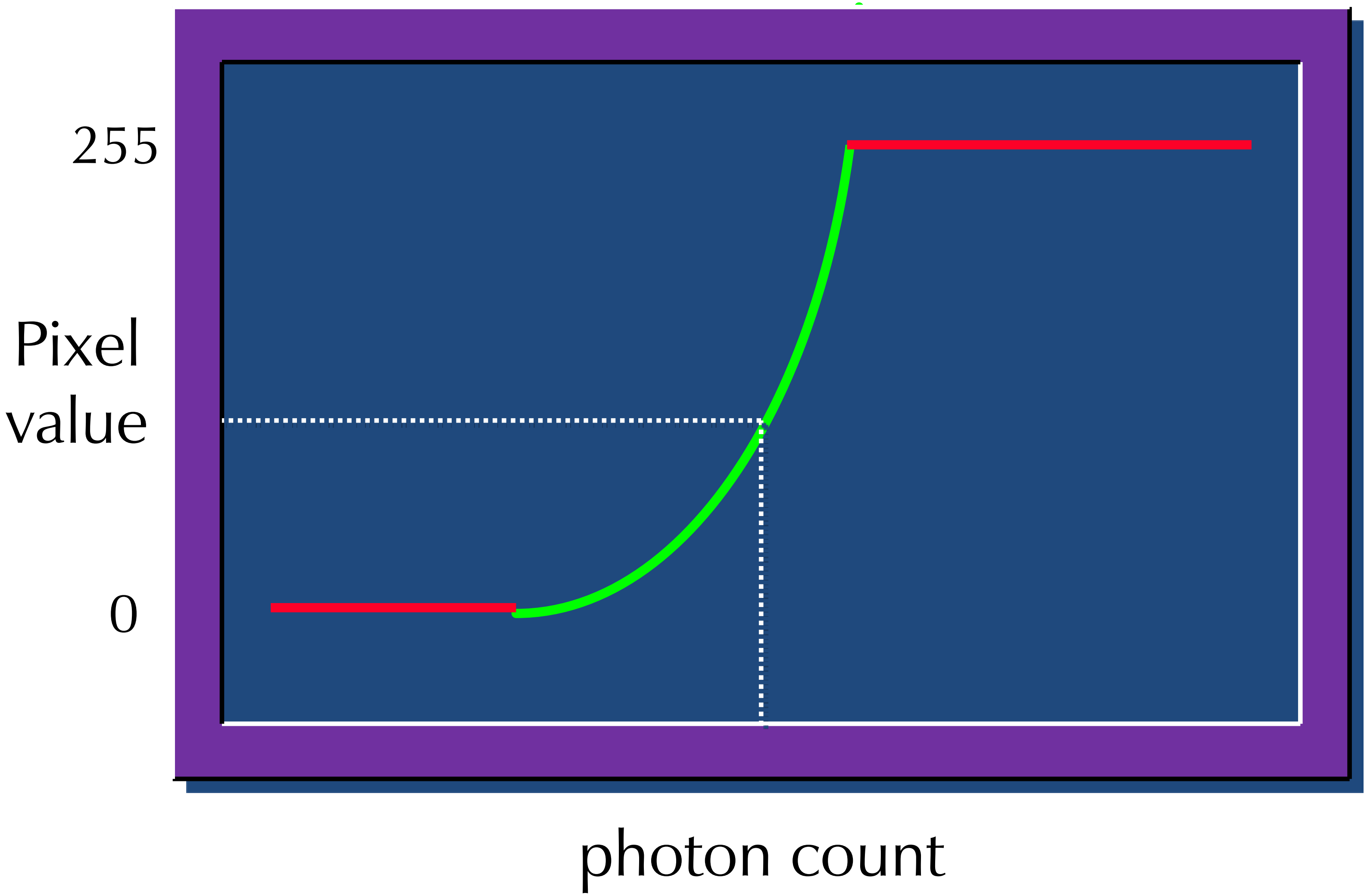


Image

pixel (312, 284) = 42

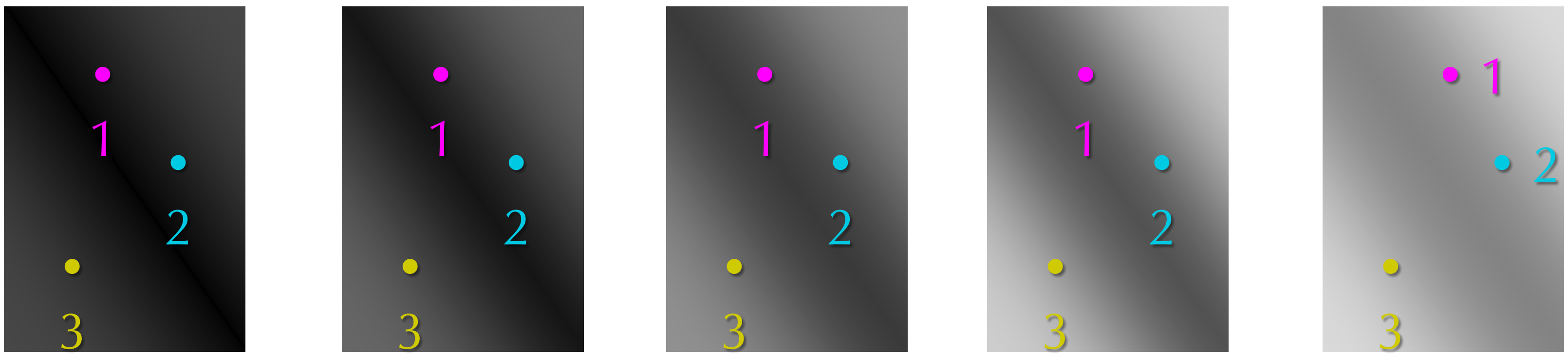
What does 42 mean?

# Imaging System Response Function



# Recovering the Response Curve

Image series




$\Delta t =$ 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)

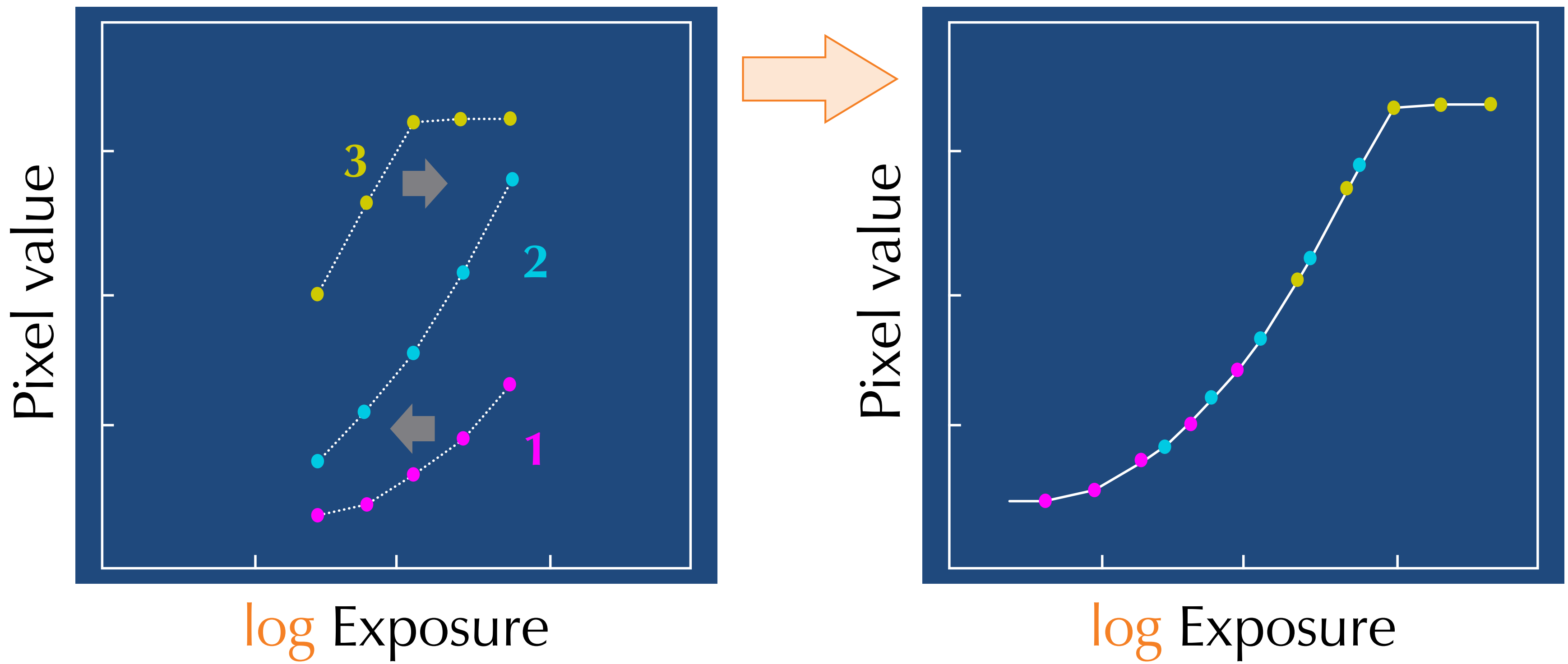
$$\text{Exposure} = \text{Radiance} \cdot \Delta t$$

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

# 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:

$$\log Radiance_i + \log \Delta t_j = g(Z_{ij})$$

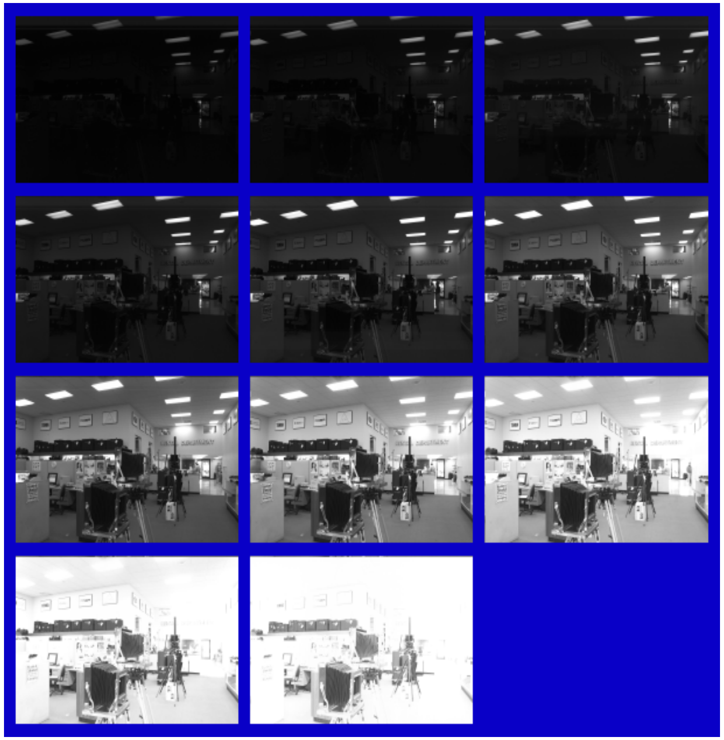
- Solve the overdetermined linear system via least squares:

$$\sum_{i=1}^{N} \sum_{j=1}^{P} \left(\log Radiance_i + \log \Delta t_j - g(Z_{ij})\right)^2 + \lambda \sum_{z=Z_{min}}^{Z_{max}} g''(z)^2$$

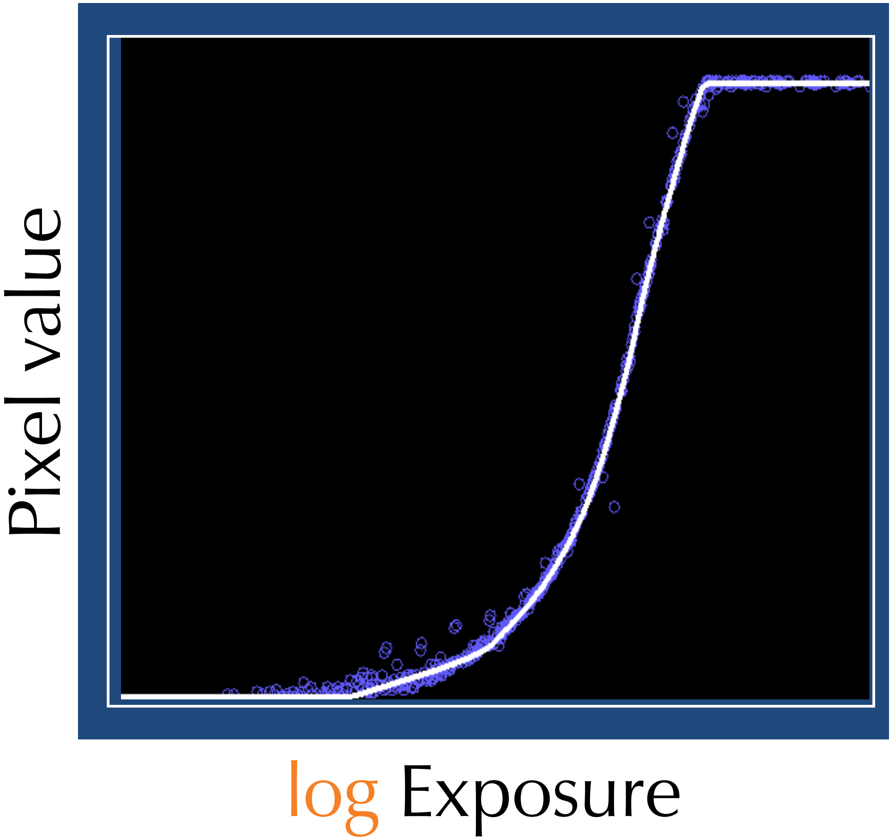
fitting term smoothness term

# Results: Digital Camera

Kodak DCS460
1/30 to 30 sec



Recovered response
curve

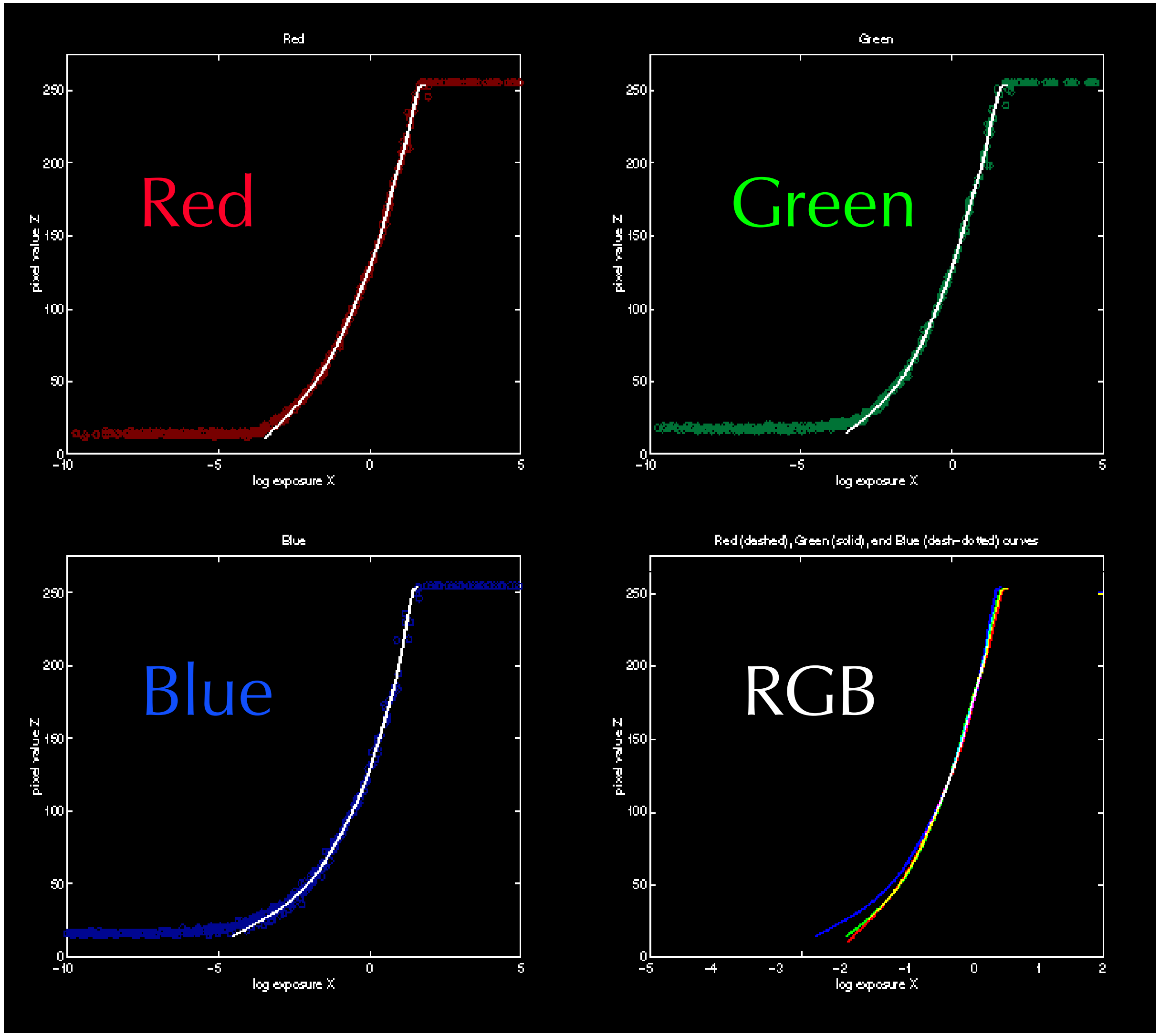


# Reconstructed Radiance Map

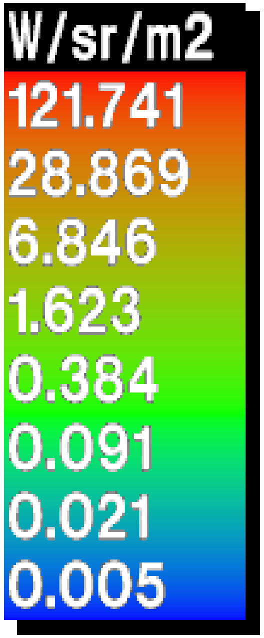
# Results: Color Film

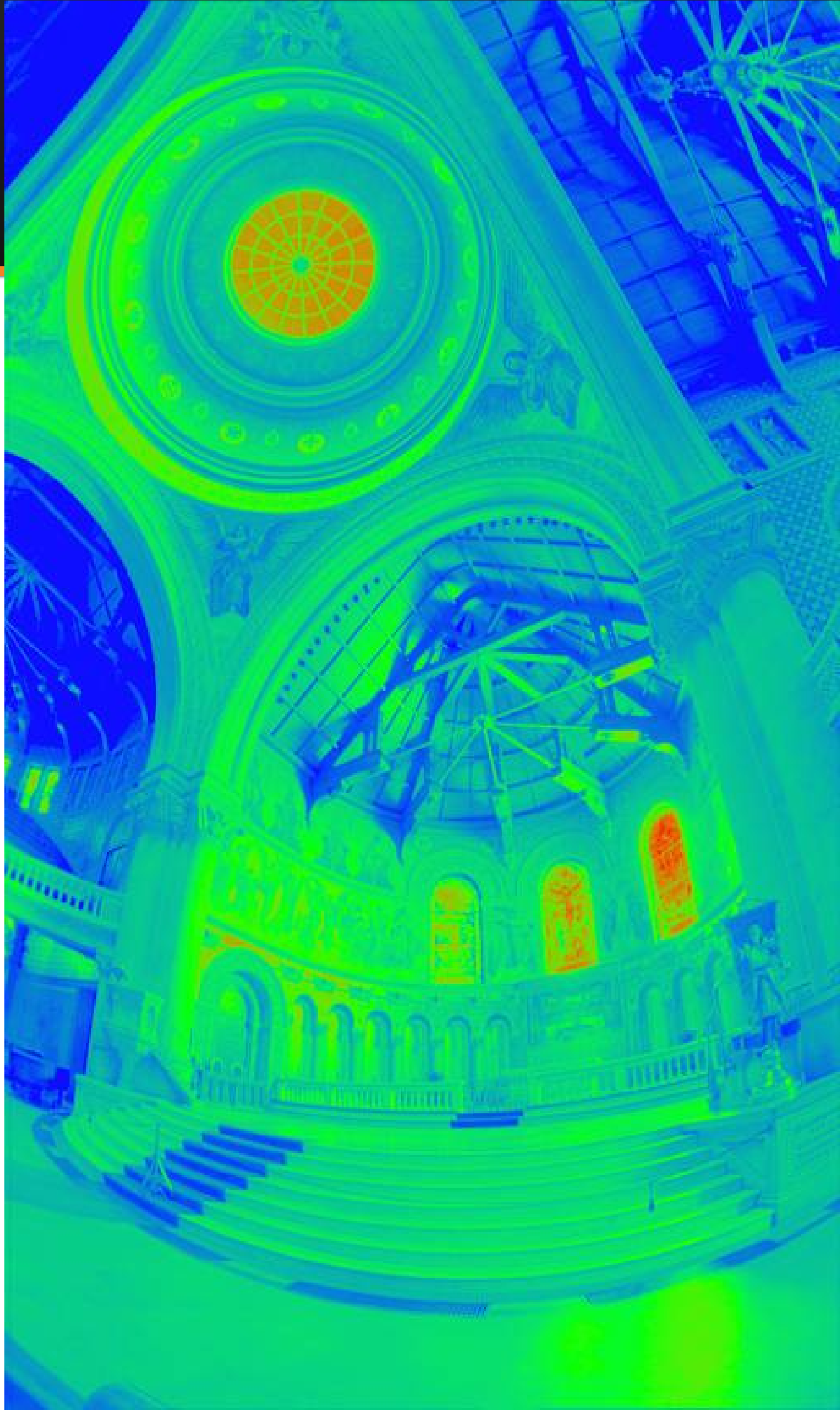
- Kodak Gold ASA 100, PhotoCD

# Recovered Response Curves



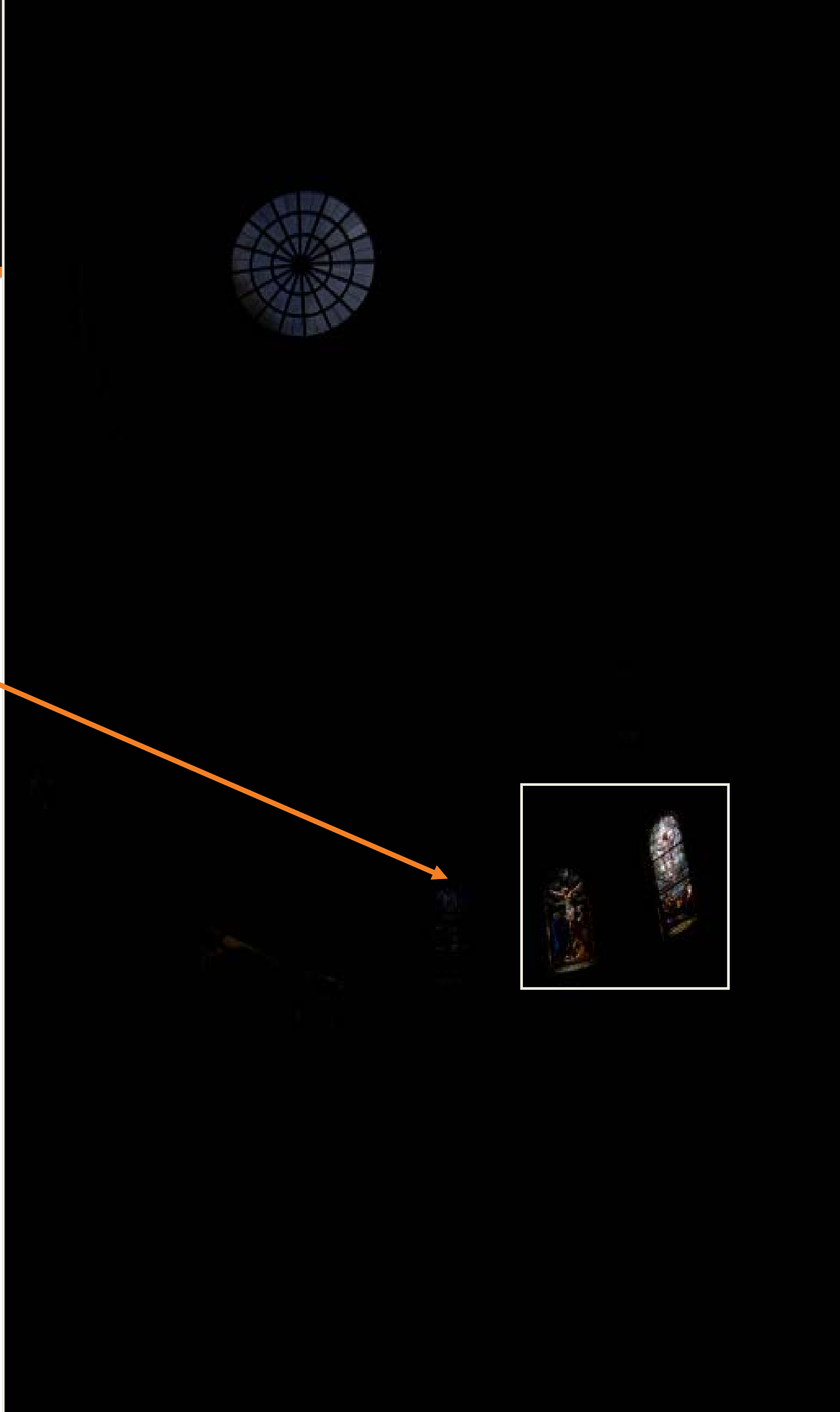
# The Radiance Map



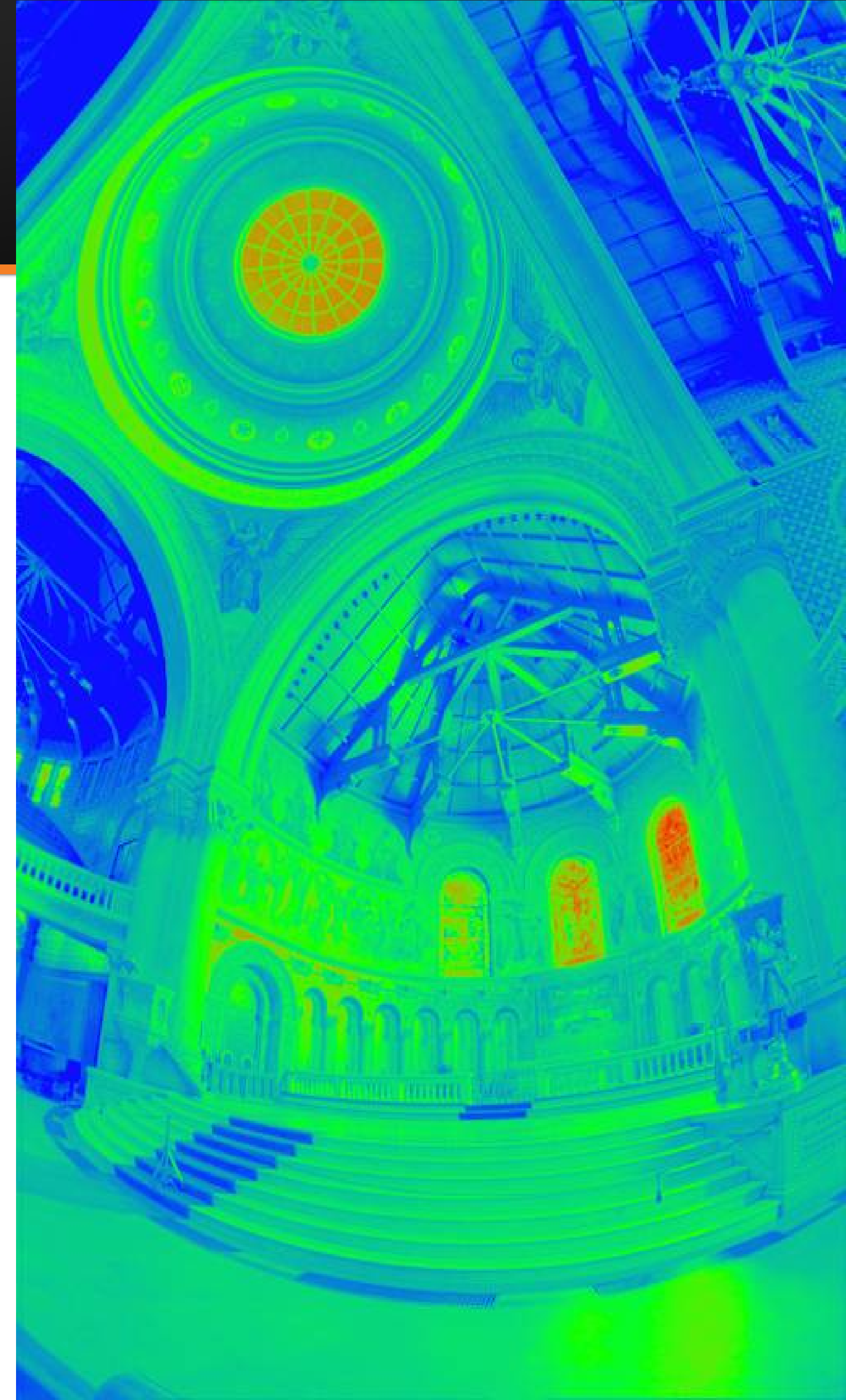



# The Radiance Map

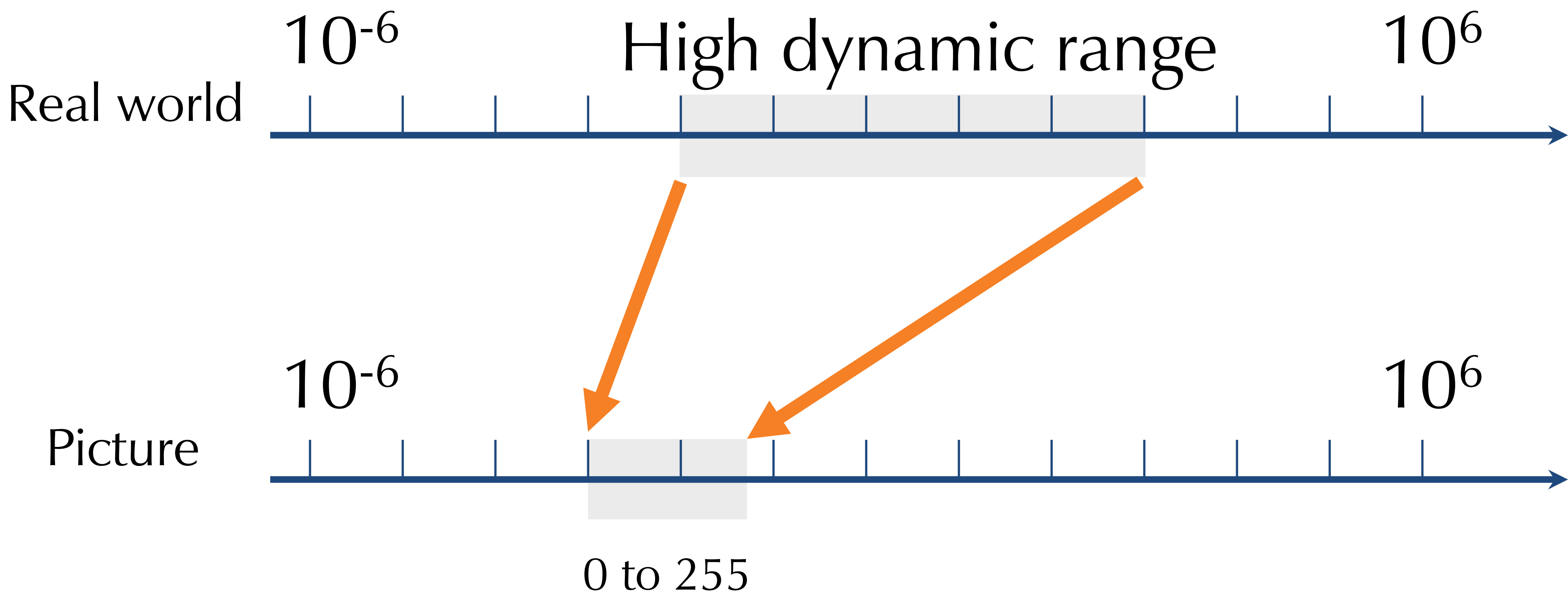
Linearly scaled to display device



# Now What?

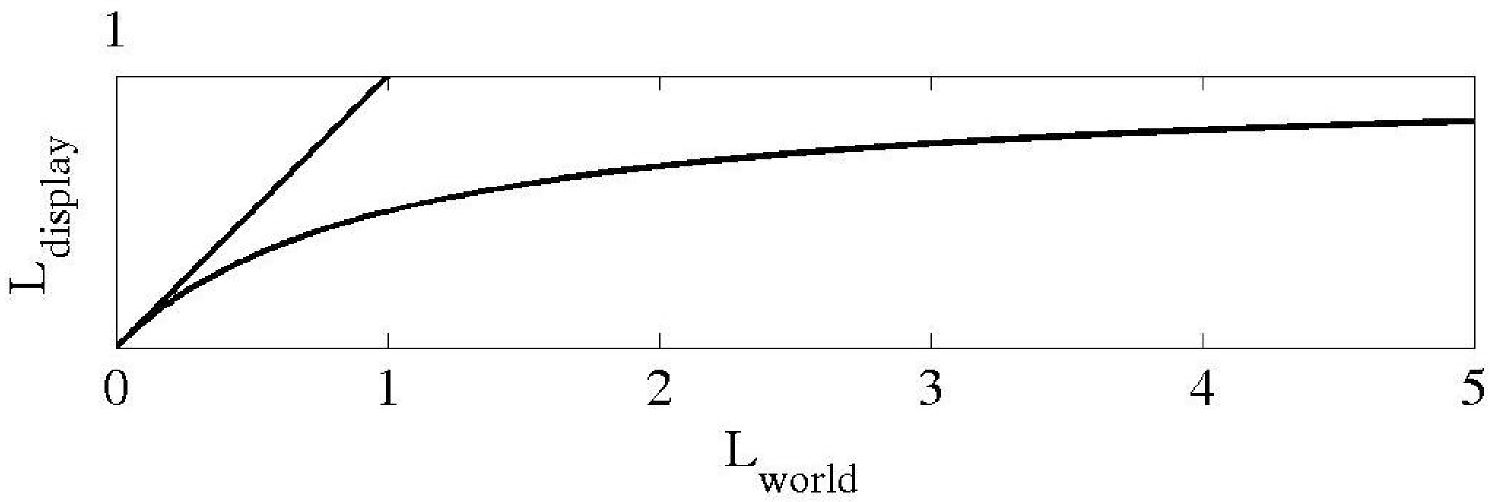



# Tone Mapping: HDR Content on LDR Devices



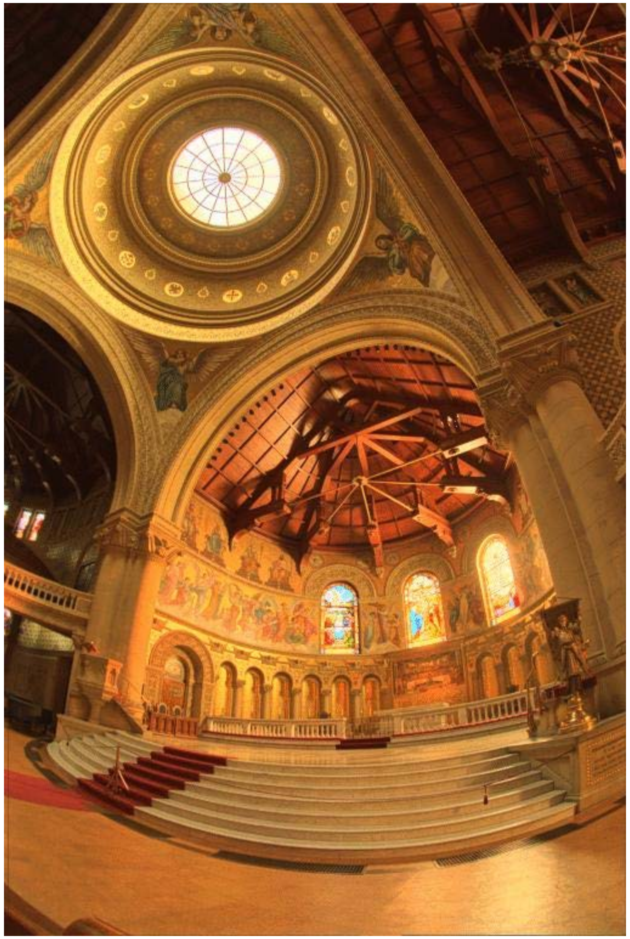
# Reinhart et al

$$L_{display} = \frac{L_{world}}{1 + L_{world}}$$

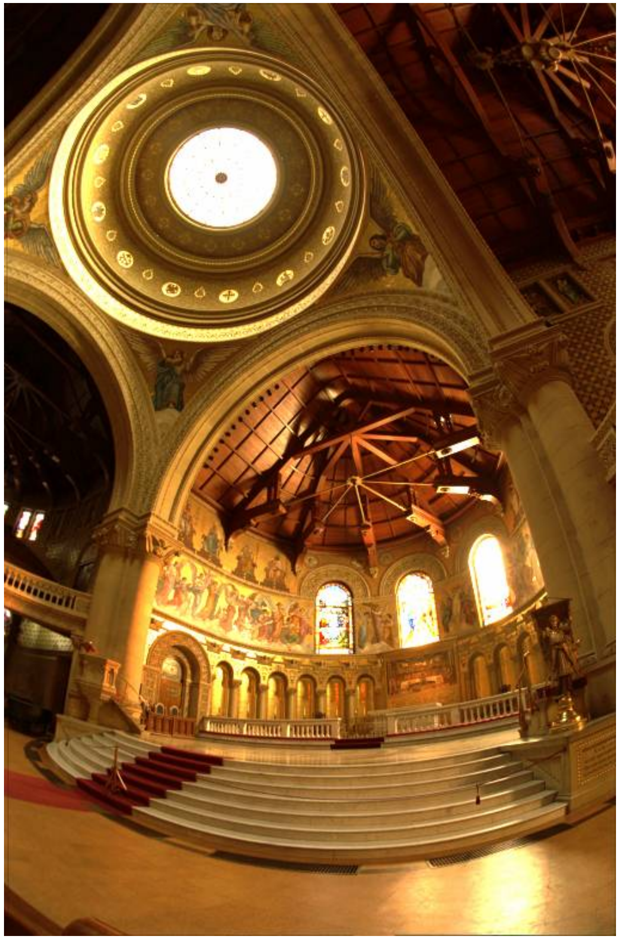


# Reinhart et al Results

# Reinhart et al Comparison

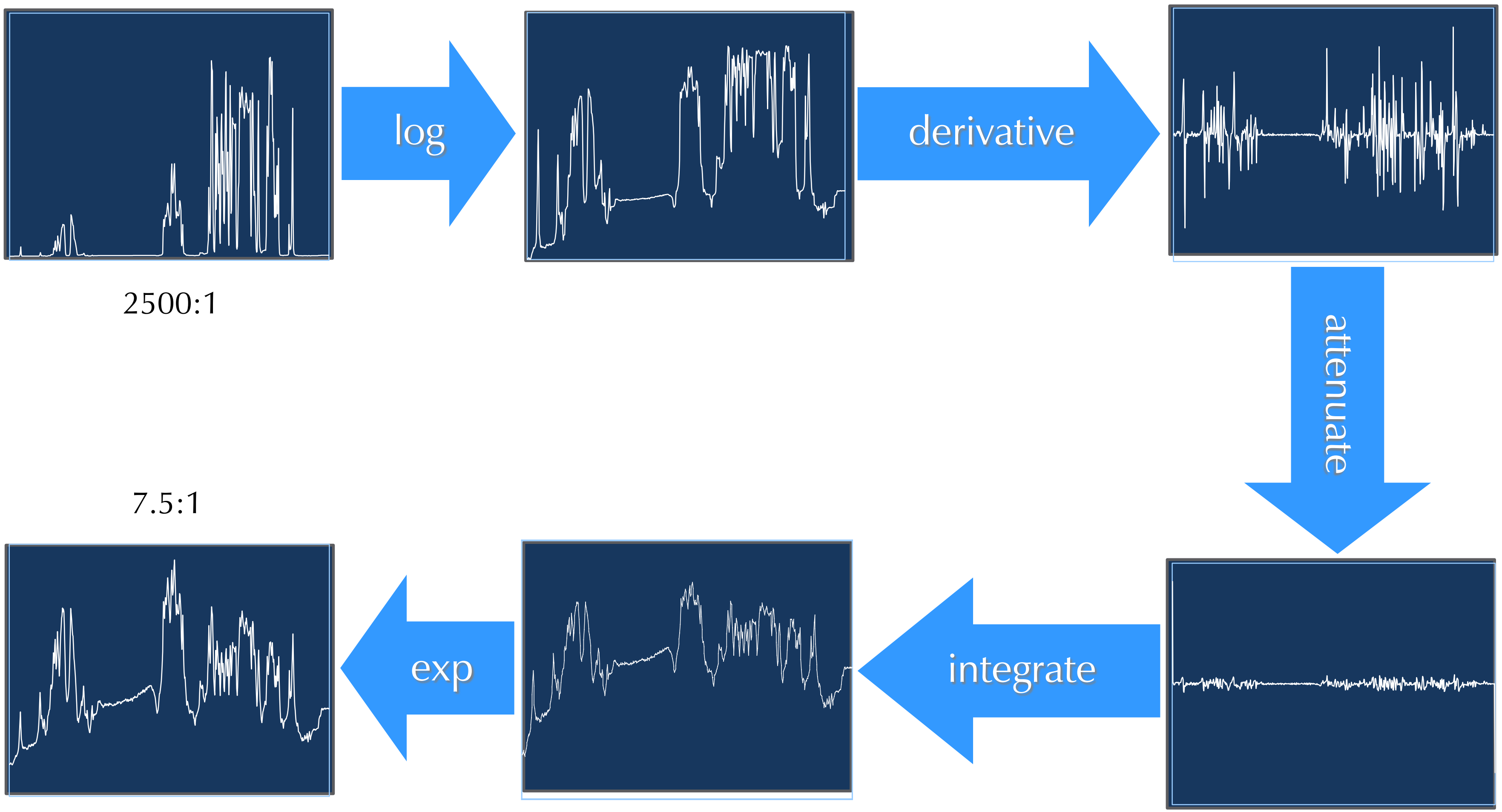


Reinhart Operator



Darkest 0.1% scaled to display device

# Fattal et al (in 1D)

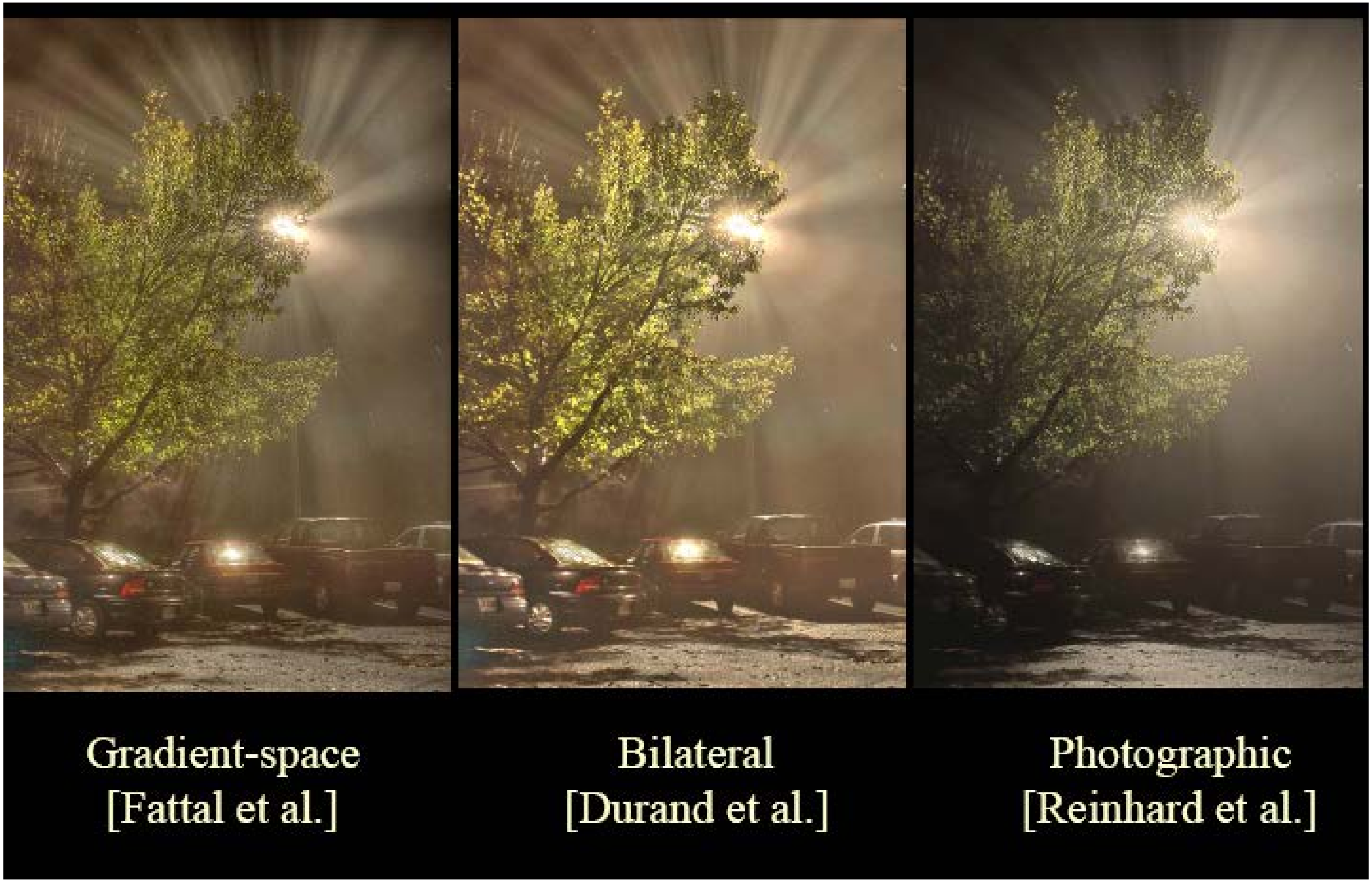


# Fattal et al Comparison

Gradient-space [Fattal et al.] | Bilateral [Durand et al.] | Photographic [Reinhard et al.]

Durand & Dorsey

# Fattal et al Comparison



# HDR Tone Mapping Example