CPSC 4040/6040 Computer Graphics Images

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Lecture 15
Tone Mapping

Oct. 8, 2015

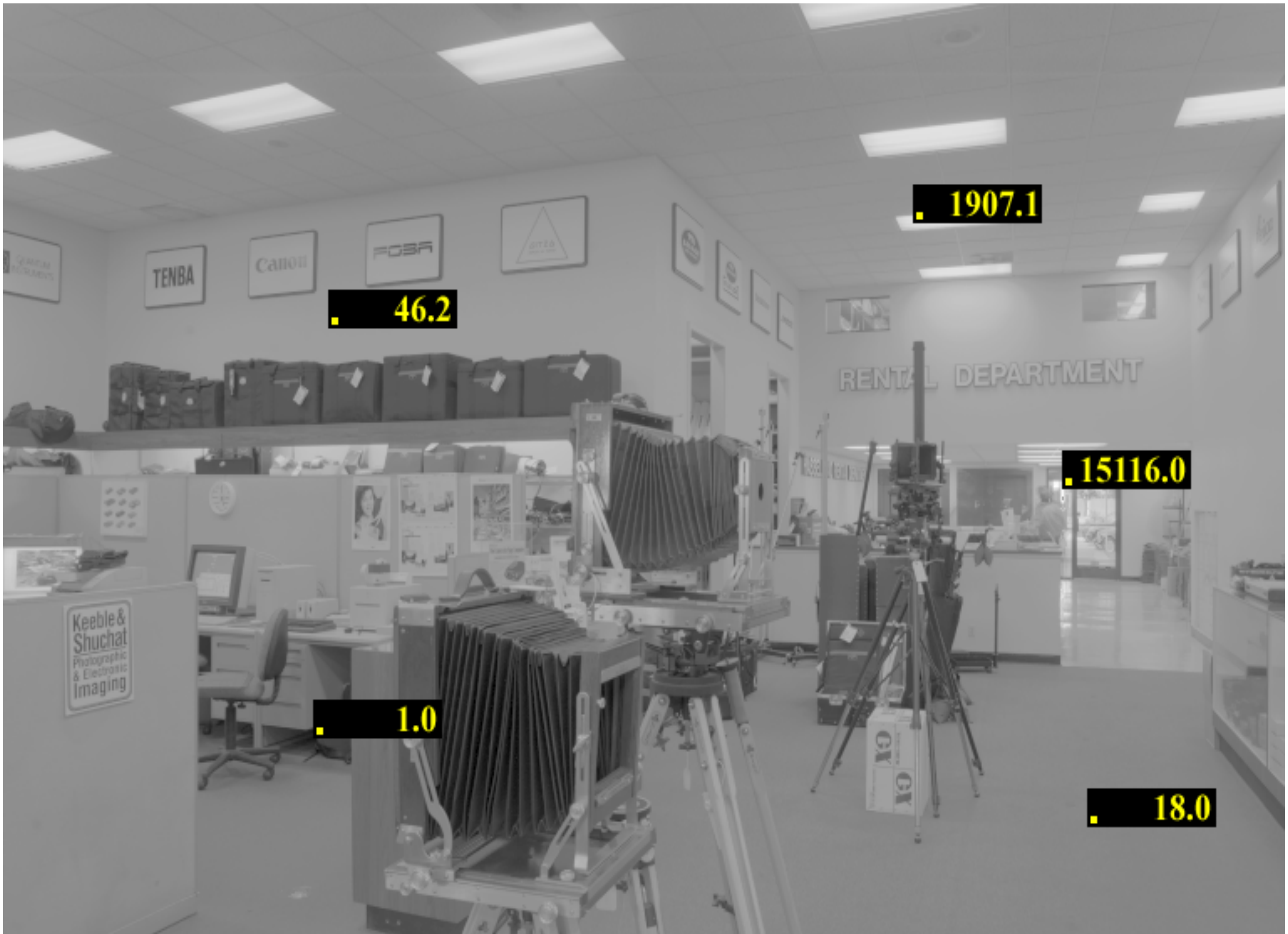
Slide Credits:
Frédo Durand
Alexei Efros

Agenda

- PA04 questions?
- Final Project Proposals — coming up after Fall Break

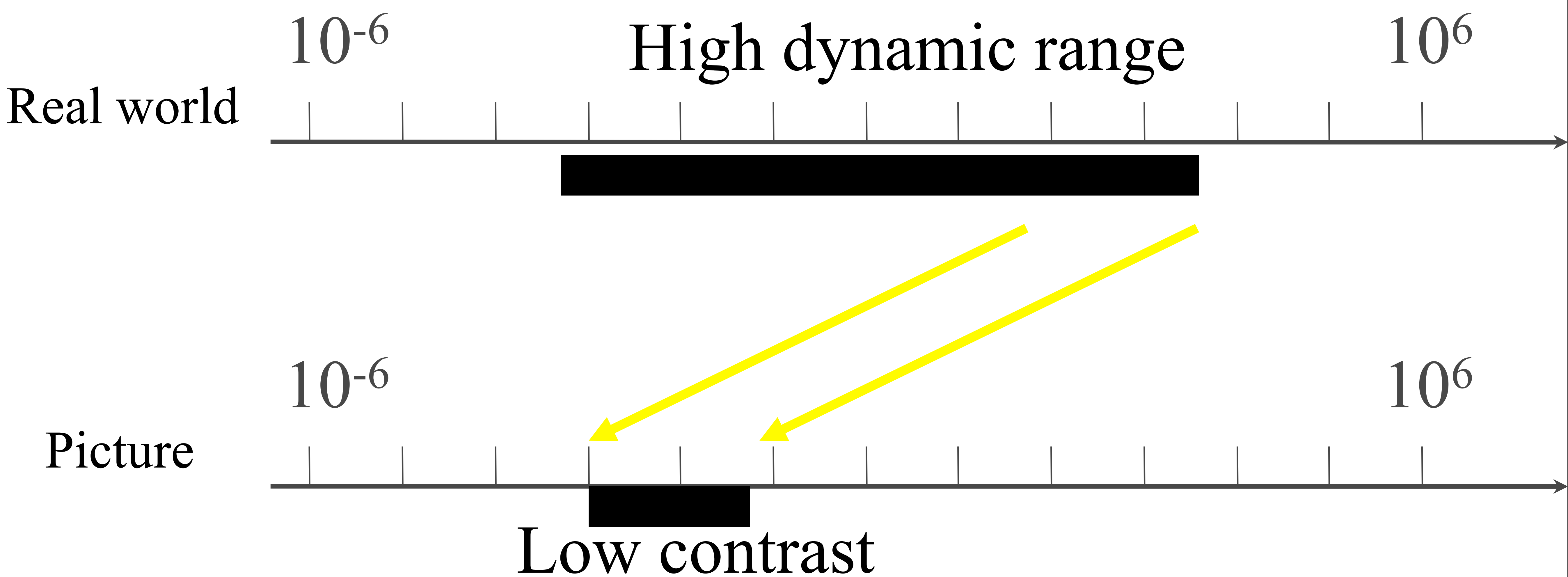
Last Time

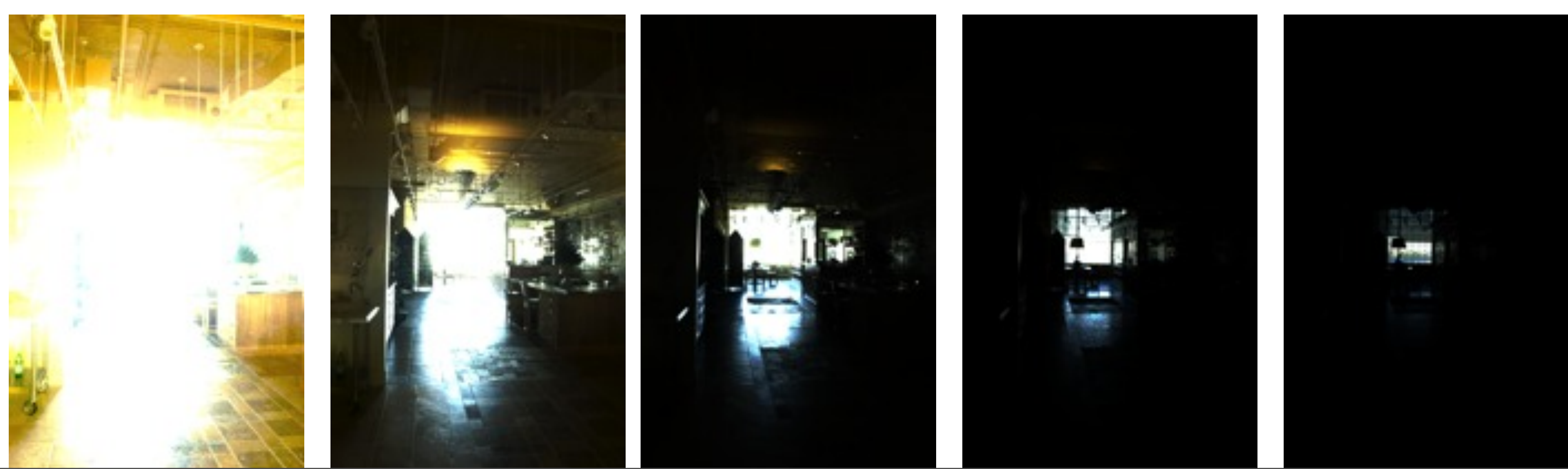
The World is a High Dynamic Range (HDR)



Multiple exposure photography

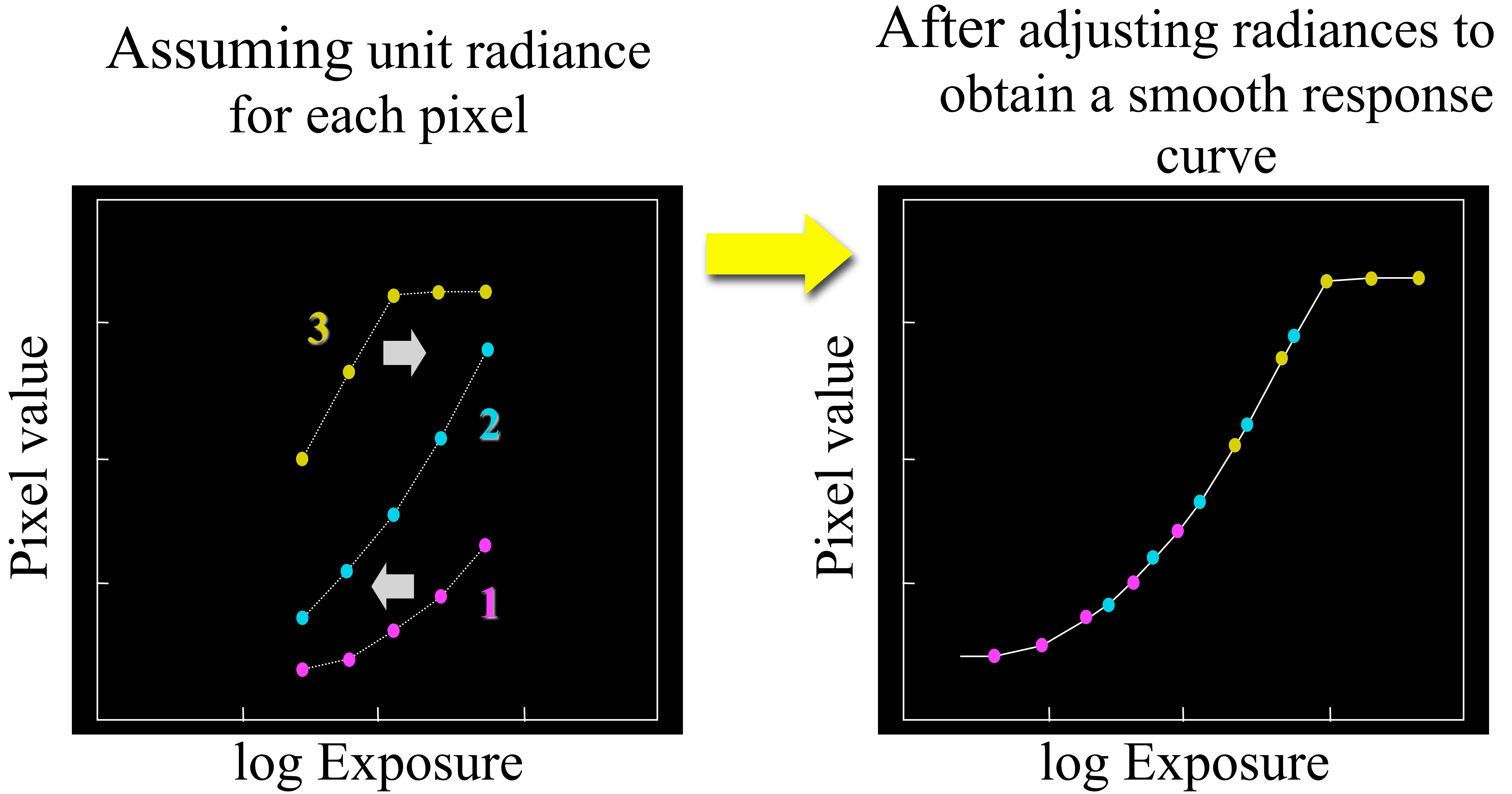
- **Sequentially measure all segments of the range**





Response Curve

- Radiance is unknown, fit to find a smooth curve



HDR File Formats

Overview of HDR Encoding

- RGBE/XYZE
  - 24 bits/pixels as usual, plus 8 bit of common exponent
  - Introduced by Greg Ward for Radiance (light simulation)
  - Enormous dynamic range
- OpenEXR
  - By Industrial Light + Magic, also standard in graphics hardware
  - 16bit per channel (48 bits per pixel) 10 mantissa, sign, 5 exponent
  - Fine quantization (because 10 bit mantissa), only 9.6 orders of magnitude
- Others: 48-/96-bit TIFF, 32-bit LogLuv TIFF, PPM Extension (32-bit/channel), JPEG200 Extension (can be lossy)

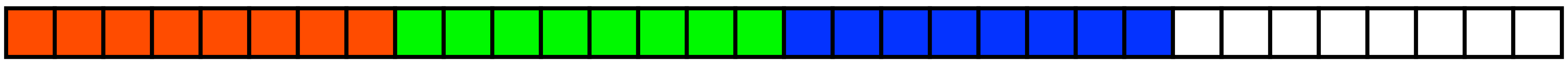
Summary (Greg Ward): http://www.anyhere.com/gward/hdrenc/hdr_encodings.html

Radiance RGBE and XYZE

- Simple format with free source code
- 8 bits each for 3 mantissas and 1 exponent
- 76 orders of magnitude in 1% steps
- Run-length encoding (20% avg. compression)
- RGBE format does not cover visible gamut
- Dynamic range at expense of accuracy
- Color quantization not perceptually uniform

Radiance RGBE Format (.pic, .hdr)

32 bits/pixel



Red Green Blue Exponent

(145, 215, 87, 149) =

(145, 215, 87) * 2^(149-128) =

1190000 1760000 713000

(145, 215, 87, 103) =

(145, 215, 87) * 2^(103-128) =

0.00000432 0.00000641 0.00000259

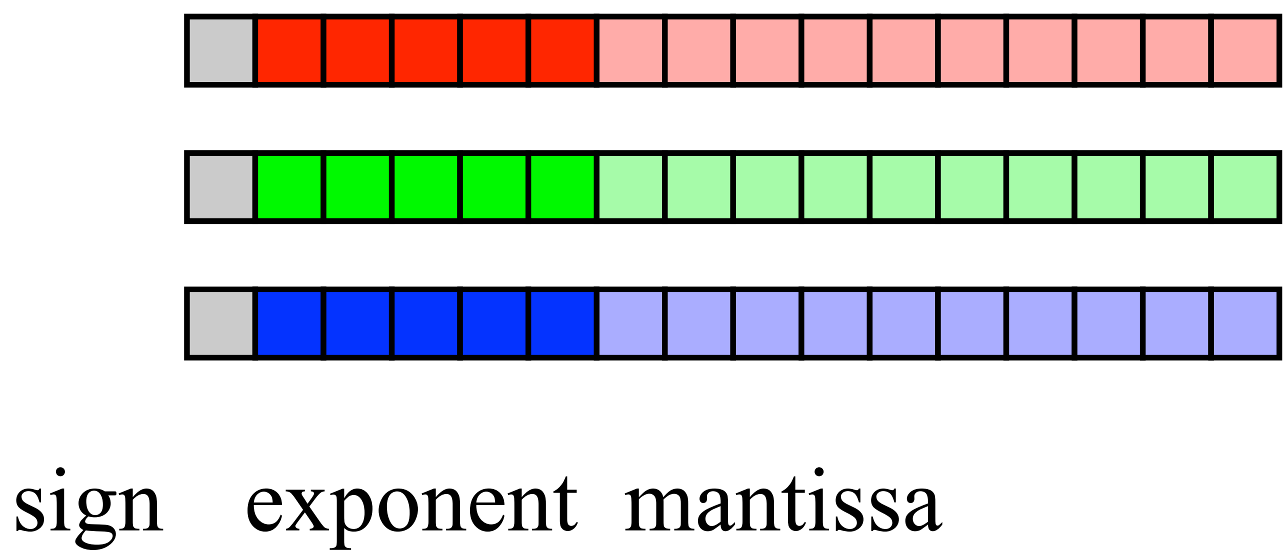
Ward, Greg. "Real Pixels," in Graphics Gems IV, edited by James Arvo, Academic Press, 1994

ILM OpenEXR Format

- 16-bit/primary floating point (sign,1; exponent, 5; mantissa, 10)
- 9.6 orders of magnitude in 0.1% steps
- Additional order of magnitude near black
- Wavelet compression of about 40%
- Negative colors and full gamut RGB
- Alpha and multichannel support
- Open Source I/O library released Fall 2002
- Slower to read and write

ILM's OpenEXR (.exr)

- 6 bytes per pixel, 2 for each channel, compressed

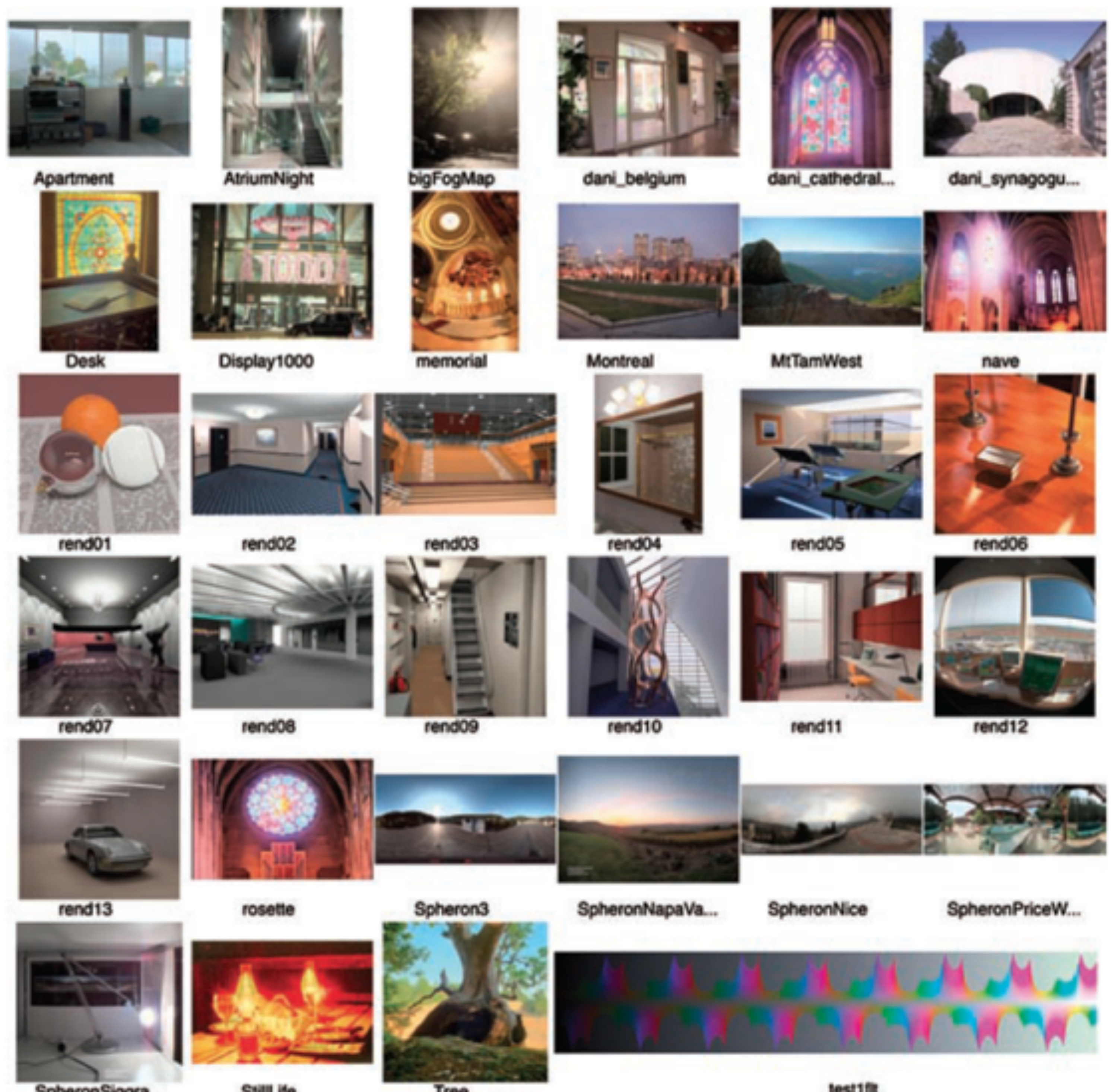


- Several lossless compression options, 2:1 typical
- Compatible with the “half” datatype in NVidia's Cg
- Supported natively on GeForce FX and Quadro FX

- Available at http://www.openexr.net/

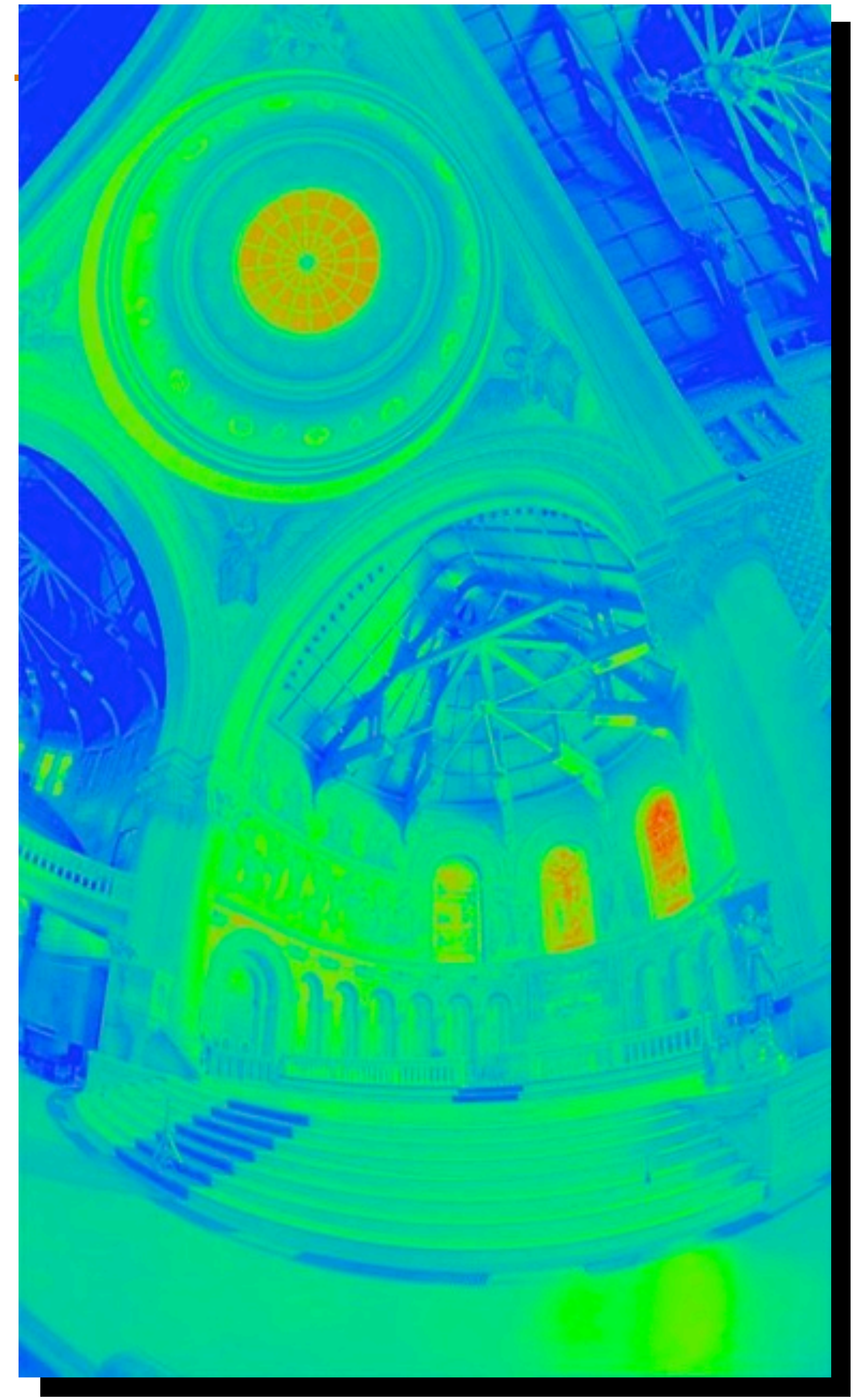
HDR File Performance Compared

See http://www.anyhere.com/gward/hdrenc/hdr_encodings.html



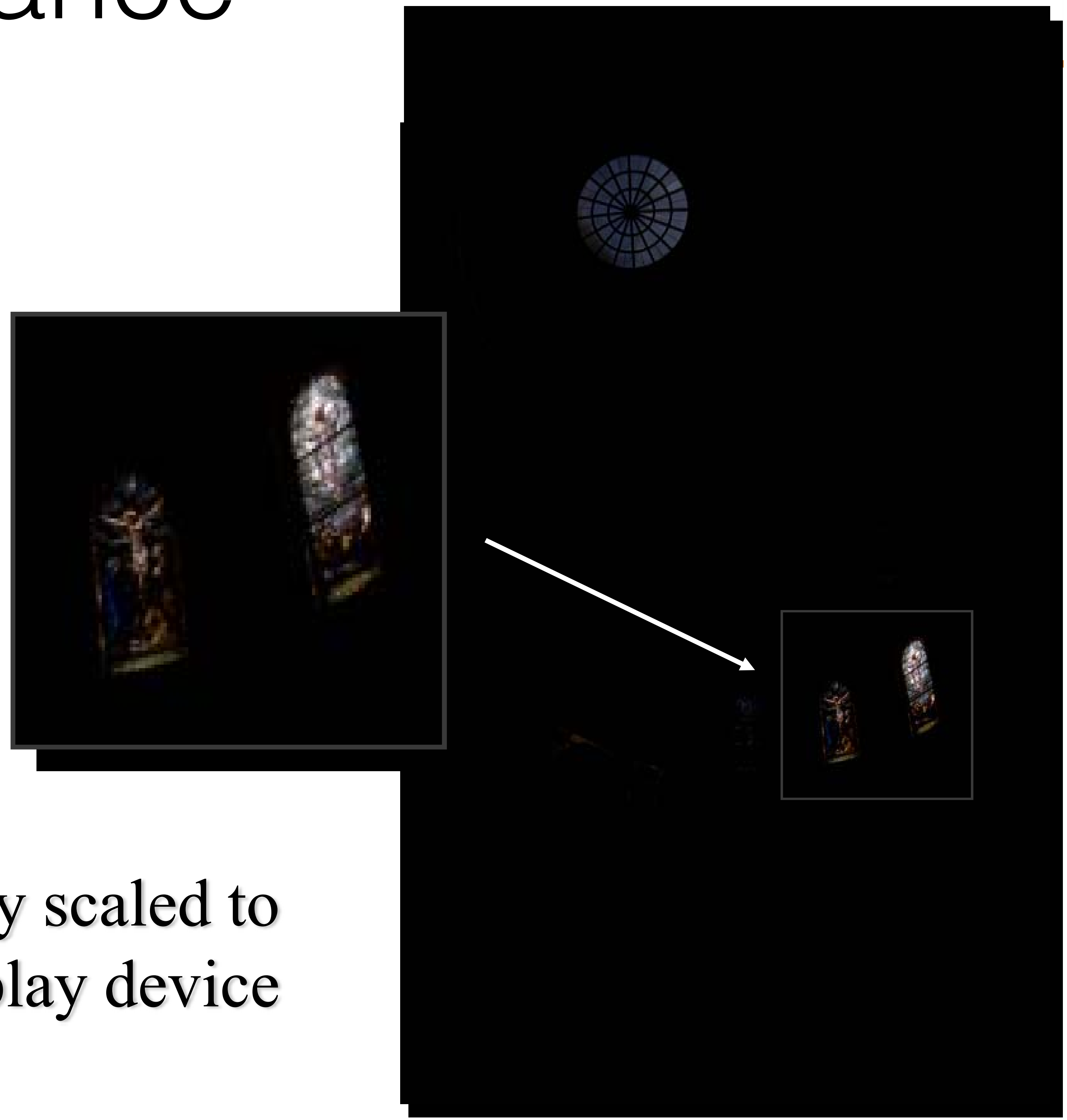
Tone Mapping Overview

The Radiance Map



The Radiance Map

Linear mapping to display is insufficient!

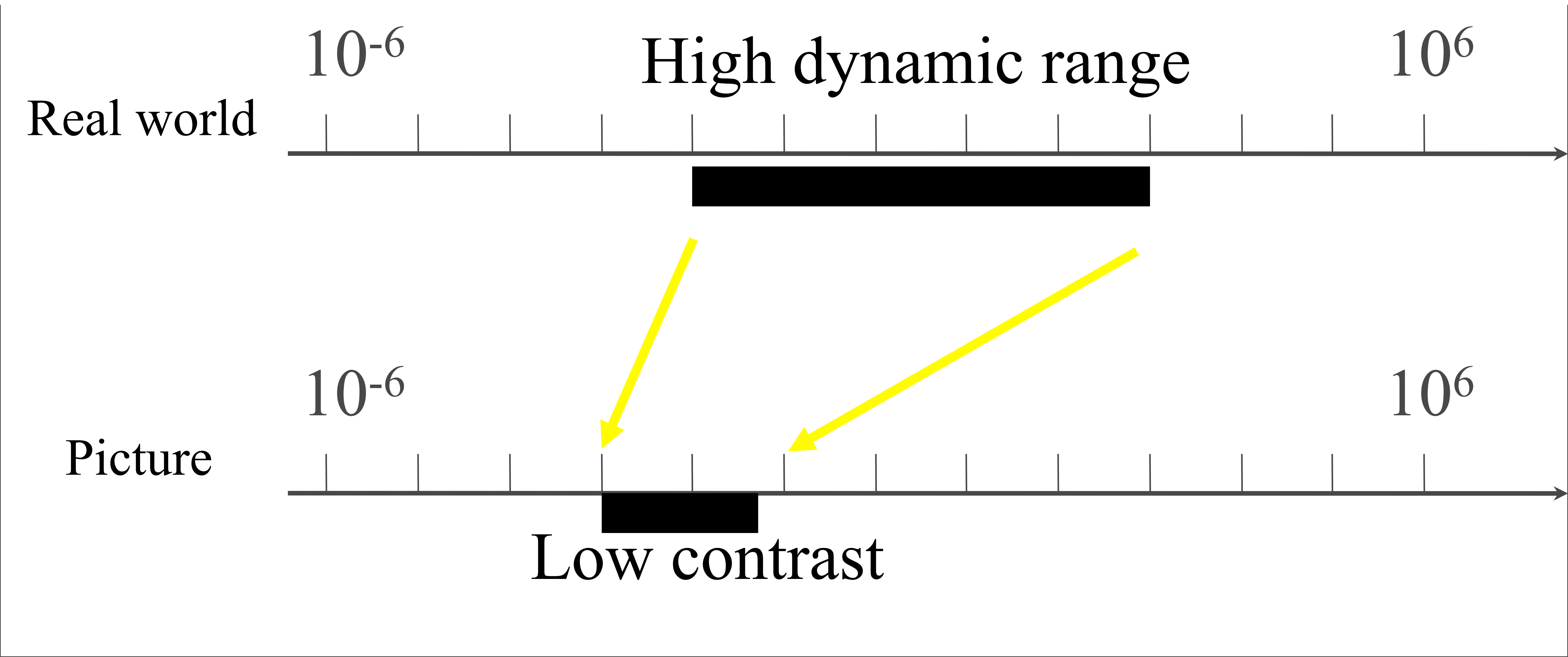


Linearly scaled to display device

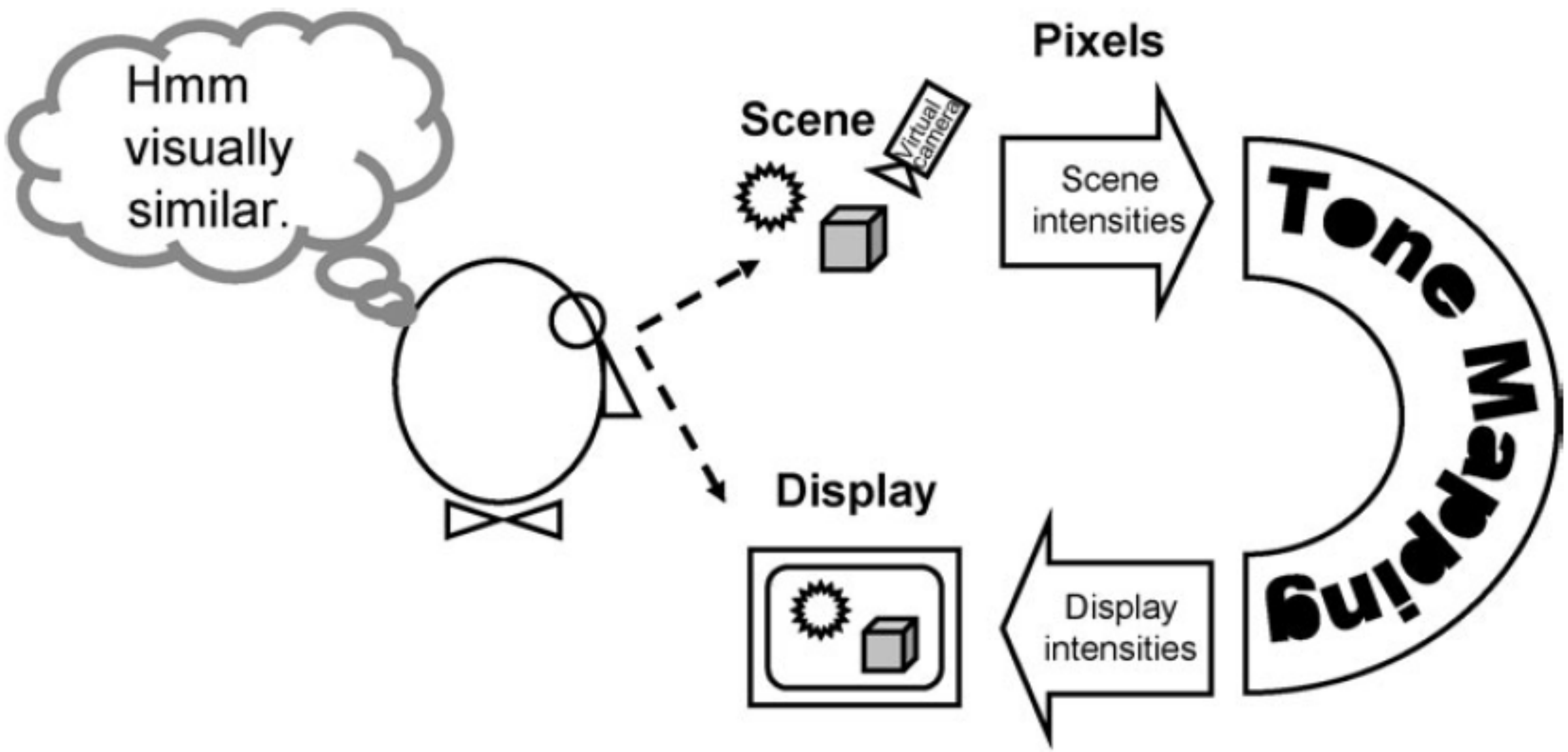
Figure 4-23: *Tonemapping plays an essential role in real-time rendering. It defines the look and enhances the cinematic appearance of high-end games like* Uncharted 3 *by Naughty Dog.*

Tone Mapping

- Problem: How should we map scene radiances (up to 1:100,000) to display radiances (only around 1:100) to produce a satisfactory image?
- Goal: match limited contrast of the display medium while preserving details



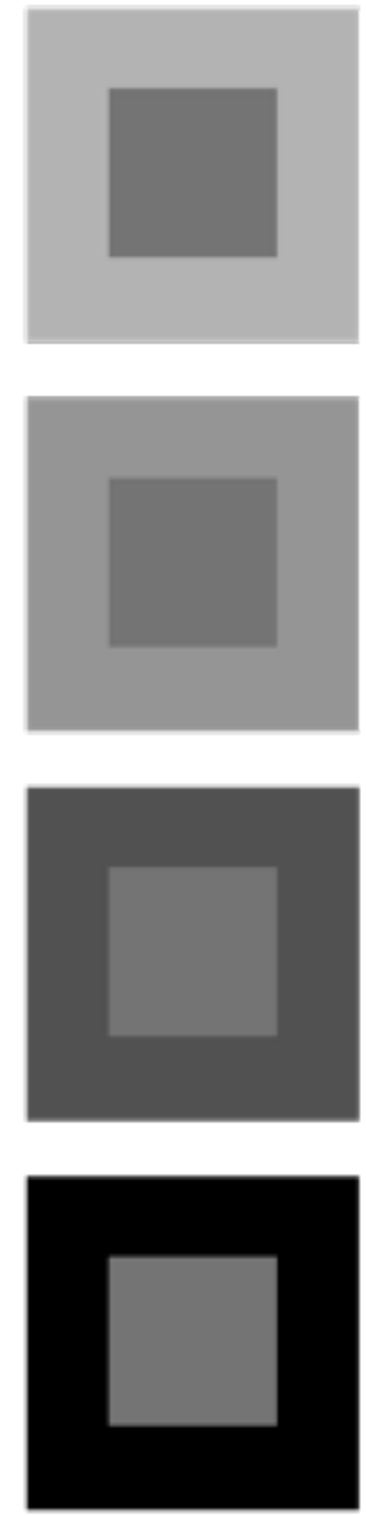
Visual Matching



- We do not need to reproduce the true radiance as long as it gives us a visual match.

Recall: Eyes and Dynamic Range

- We're sensitive to contrast (multiplicative)
  - A ratio of 1:2 is perceived as the same contrast as a ratio of 100 to 200
  - Use the log domain as much as possible
- Eyes are not photometers
  - Dynamic adaptation (very local in retina)
  - Different sensitivity to spatial frequencies



Headlights are ON in both photos

Weber's Law

Just Noticeable Difference (JND)

Base intensity

$$\frac{\Delta I}{I} = K_w$$

Weber fraction (**constant!**)

- We can detect ~0.5% changes in intensity
  - The perceived minimum increment is the **just noticeable difference**
- True for luminance as well as other things (length, weight, sound, etc.)
- Takeaway: The amount of difference that we can detect is relative to the context between the two things, not an absolute quantity
  - If you change the context, you change the increment

Figure 4-21: *Atmospheric haze is easily wiped away with tonemapping techniques. Recovering all these details from the murky shadows is exactly where local TMOs excel.*

Christian Bloch - The HDRI Handbook 2.0

Common Artifacts to Avoid

- Tone Reversal: large image areas have swapped brightness
- Noise boost: noise emphasized in regions which were smooth
- Oversaturation: increasing color beyond what is natural
- Halos: bright glows around dark edges
- Flattening: over compressing the dynamic range into something less than the display can do
- Webbing: Division of the image into cells based on natural lines

Tone Reversal　Noise Boost　Oversaturation　Halos　Flattening　Webbing

Christian Bloch - The HDRI Handbook 2.0

Simple Approaches to Tone Mapping

Can we just scale? Maybe!

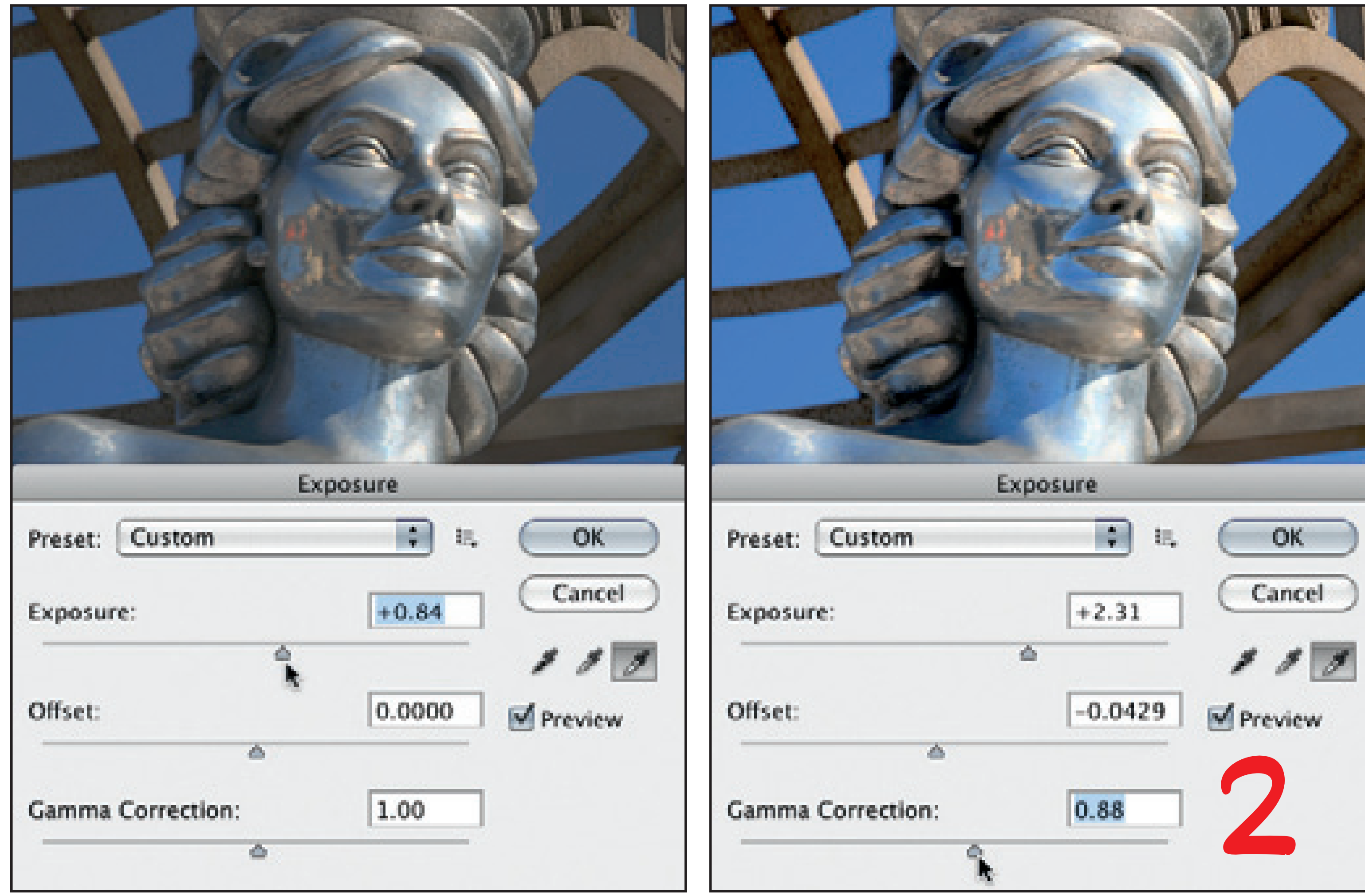
- For a color image, try to convert the input (world) luminance Lw to a target display luminance Ld
- This type of scaling works (sometimes). In particular, it works best in the log and/or exponential domains (because of Weber's law)

$$\begin{bmatrix} R_d \\ G_d \\ B_d \end{bmatrix} = \begin{bmatrix} L_d \dfrac{R_w}{L_w} \\ L_d \dfrac{G_w}{L_w} \\ L_d \dfrac{B_w}{L_w} \end{bmatrix}$$

Recall: Gain, Bias, and Gamma

$$C_{out} = (\boldsymbol{\alpha} C_{in} + \boldsymbol{\beta})^{\gamma}$$

- $\boldsymbol{\alpha}$ is known as gain (exposure)
- $\boldsymbol{\beta}$ is known as bias (offset)
- γ maps us to a non-linear curve (gamma correction)



Photoshop has this functionality

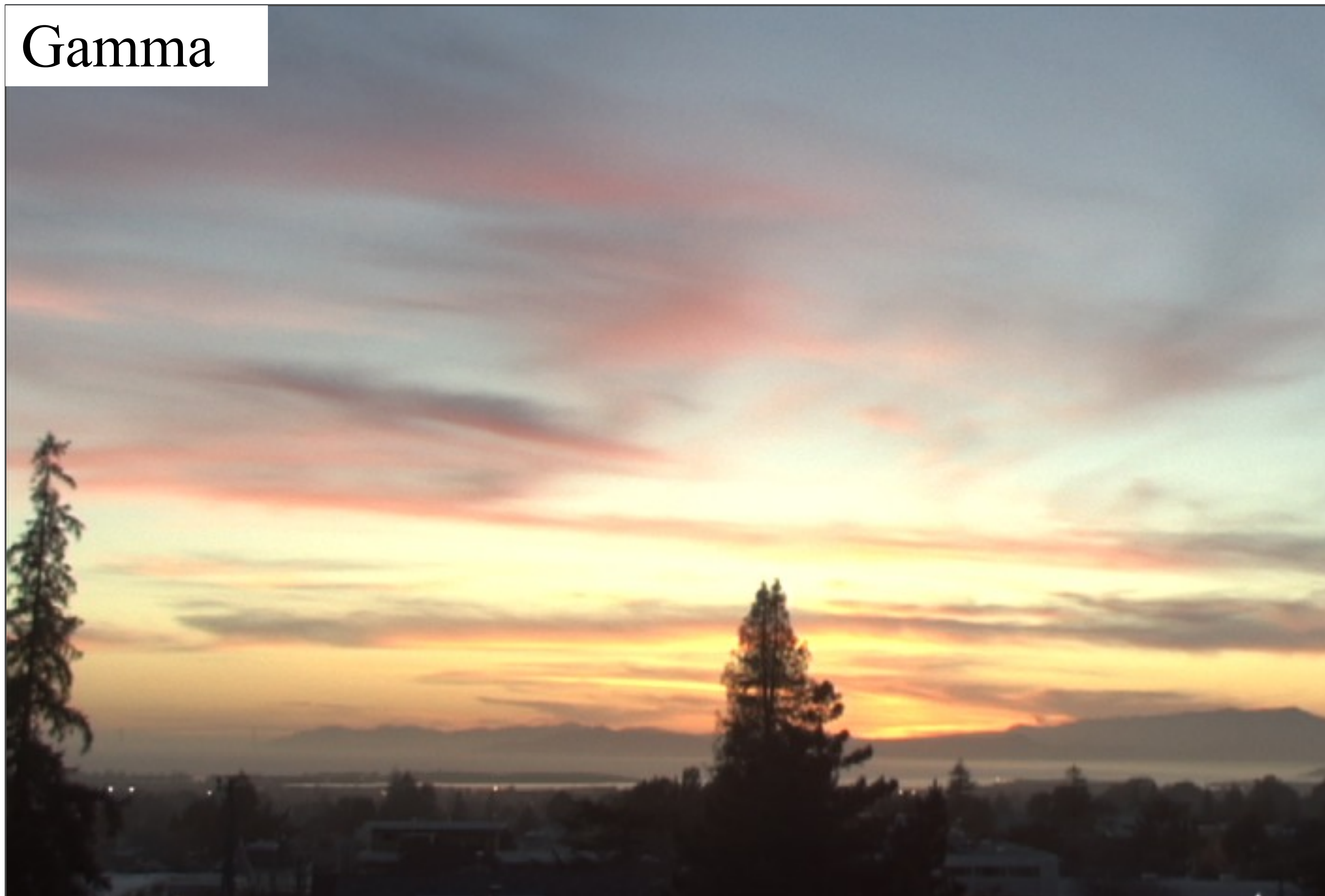
Christian Bloch - The HDRI Handbook 2.0

Normalization

- Typical scene has 1:10,000 contrast, display has 1:100
- Simplest reduction destroys midtones

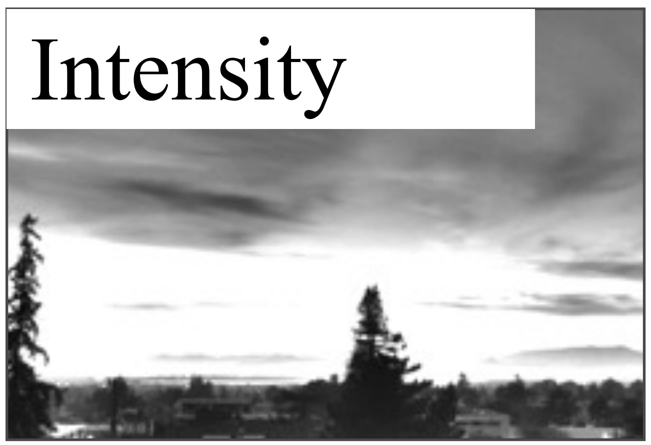
Gamma Compression

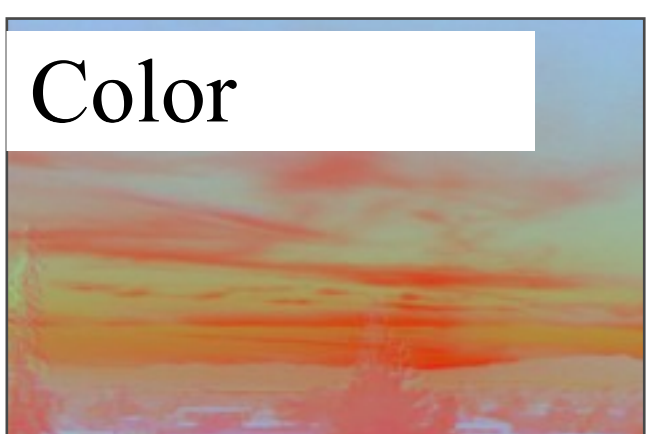
- $C_{out} = C_{in}^{\gamma}$, where $0 < \gamma < 1$ applied to each R,G,B channel
- Colors are washed out, why?

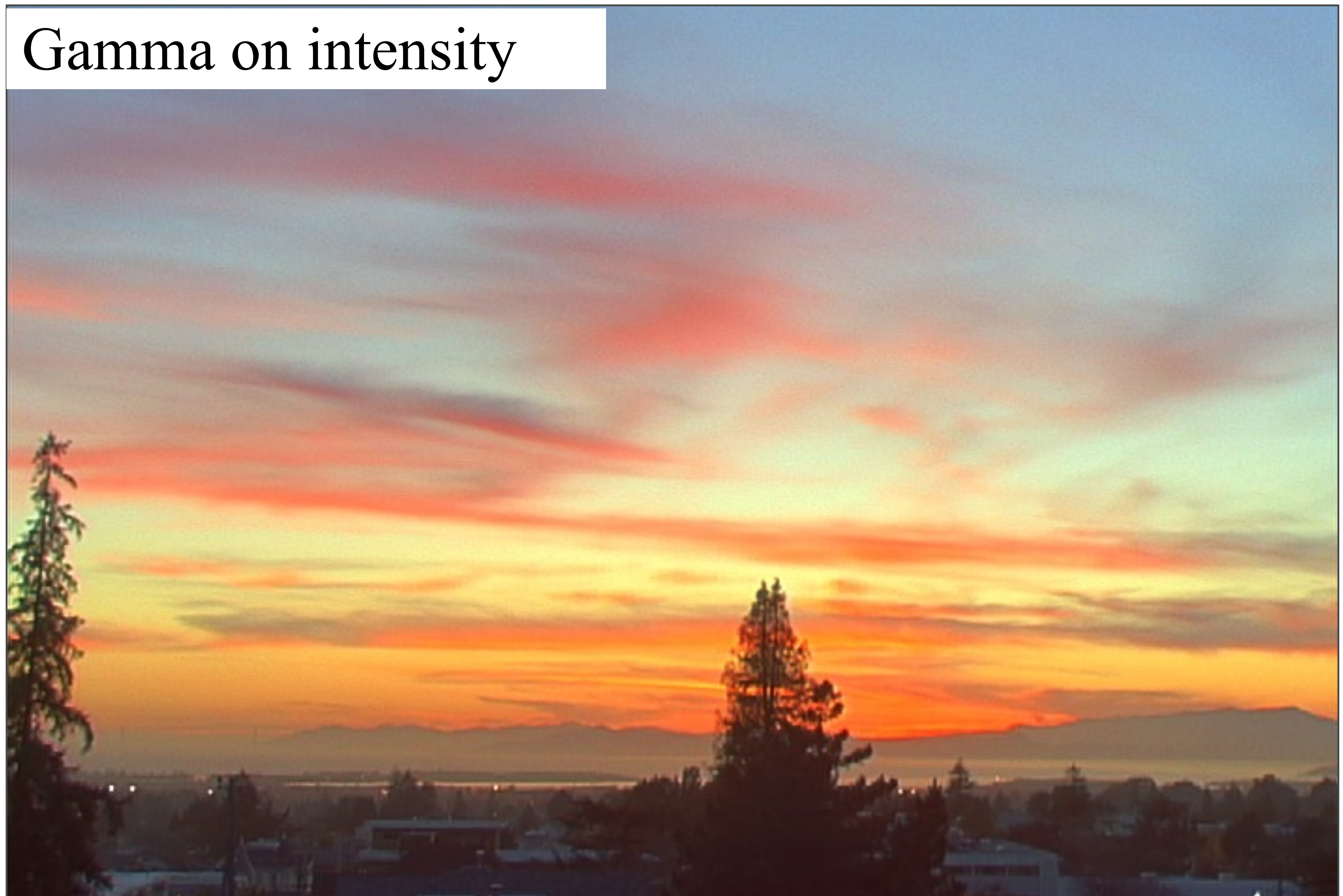


Gamma Compression on Intensity

- Colors ok, but details in intensity are blurry

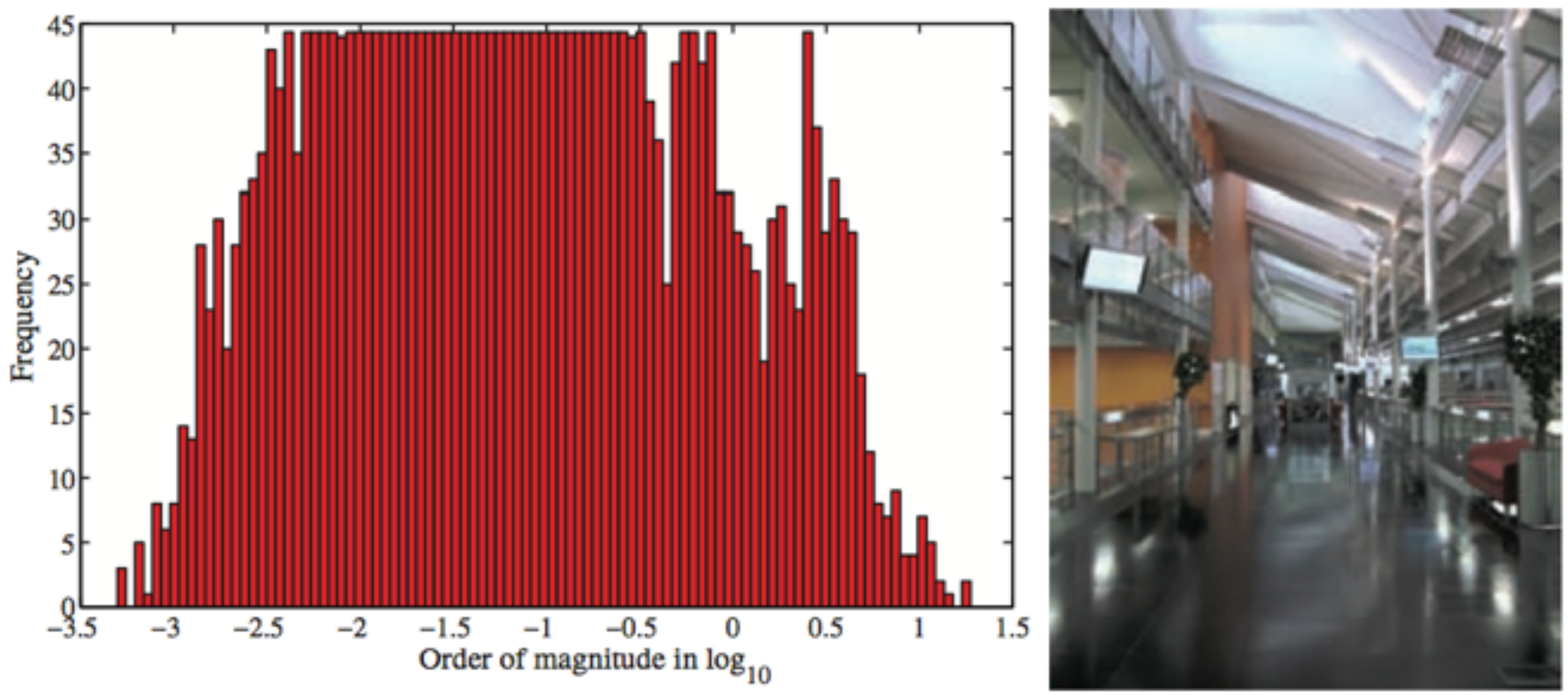






Histogram Equalization

- Questions to answer: how many bins?
- Better to equalize the log of intensity



(a) (b)

Figure 3.7. An example of the Histogram adjustment by Larson et al. [110] to the IDL HDR image. (a) The histogram of the HDR image. (b) The tone mapped image.

Using Local Operators

Photographic Tone Reproduction for Digital Images

Erik Reinhard, University of Utah
Michael Stark, University of Utah
Peter Shirley, University of Utah
James Ferwerda, Cornell University

Abstract

A classic photographic task is the mapping of the potentially high dynamic range of real world luminances to the low dynamic range of the photographic print. This tone reproduction problem is also faced by computer graphics practitioners who map digital images to a low dynamic range print or screen. The work presented in this paper leverages the time-tested techniques of photographic practice to develop a new tone reproduction operator. In particular, we use and extend the techniques developed by Ansel Adams to deal with digital images. The resulting algorithm is simple and produces good results for a wide variety of images.

CR Categories: I.4.10 [Computing Methodologies]: Image Processing and Computer Vision—Image Representation

Keywords: Tone reproduction, dynamic range, Zone System.

1 Introduction

The range of light we experience in the real world is vast, spanning approximately ten orders of absolute range from star-lit scenes to sun-lit snow, and over four orders of dynamic range from shadows to highlights in a single scene. However, the range of light we can reproduce on our print and screen display devices spans at best about two orders of absolute dynamic range. This discrepancy leads to the *tone reproduction* problem: how should we map measured/simulated scene luminances to display luminances and produce a satisfactory image?

courtesy of Cornell Program of Computer Graphics

Ansel Adams

The Zone System

- Formalism to talk about exposure, density
- Zone = intensity range, in powers of two
- In the scene, on the negative, on the print

Ansel Adams

The Zones

The Zones

0 Solid black; the same as the film rebate

I Nearly black; just different from Zone 0

II The first hint of texture

III Textured shadow; the first recognizable shadow detail

IV Average shadow value on Caucasian skin, foliage and buildings

V Middle grey: the pivot value; light foliage, dark skin

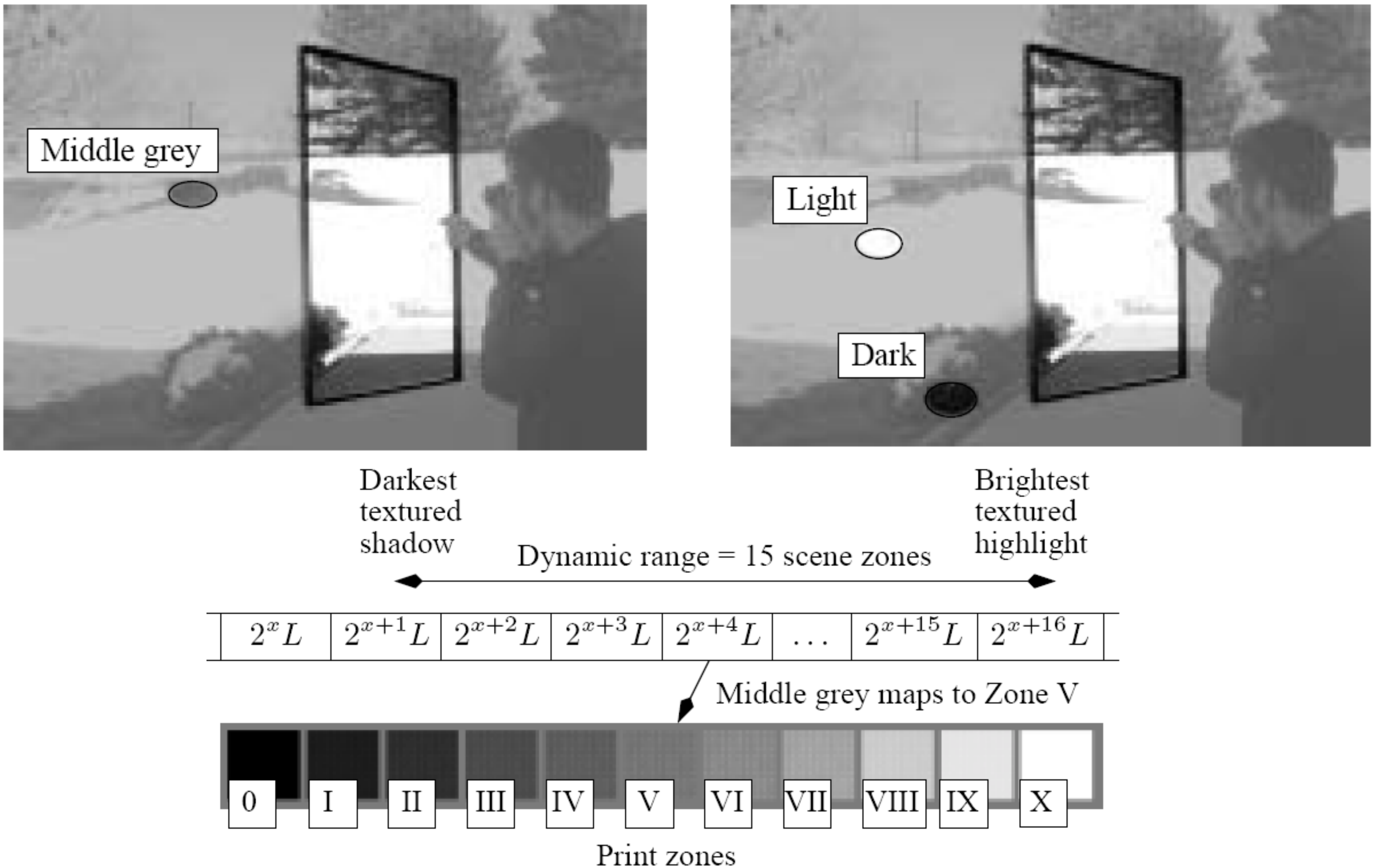
VI Caucasian skin, textured light grey; shadow on snow

VII Light skin; bright areas with texture, such as snow in low sunlight

VIII Highest zone with any texture

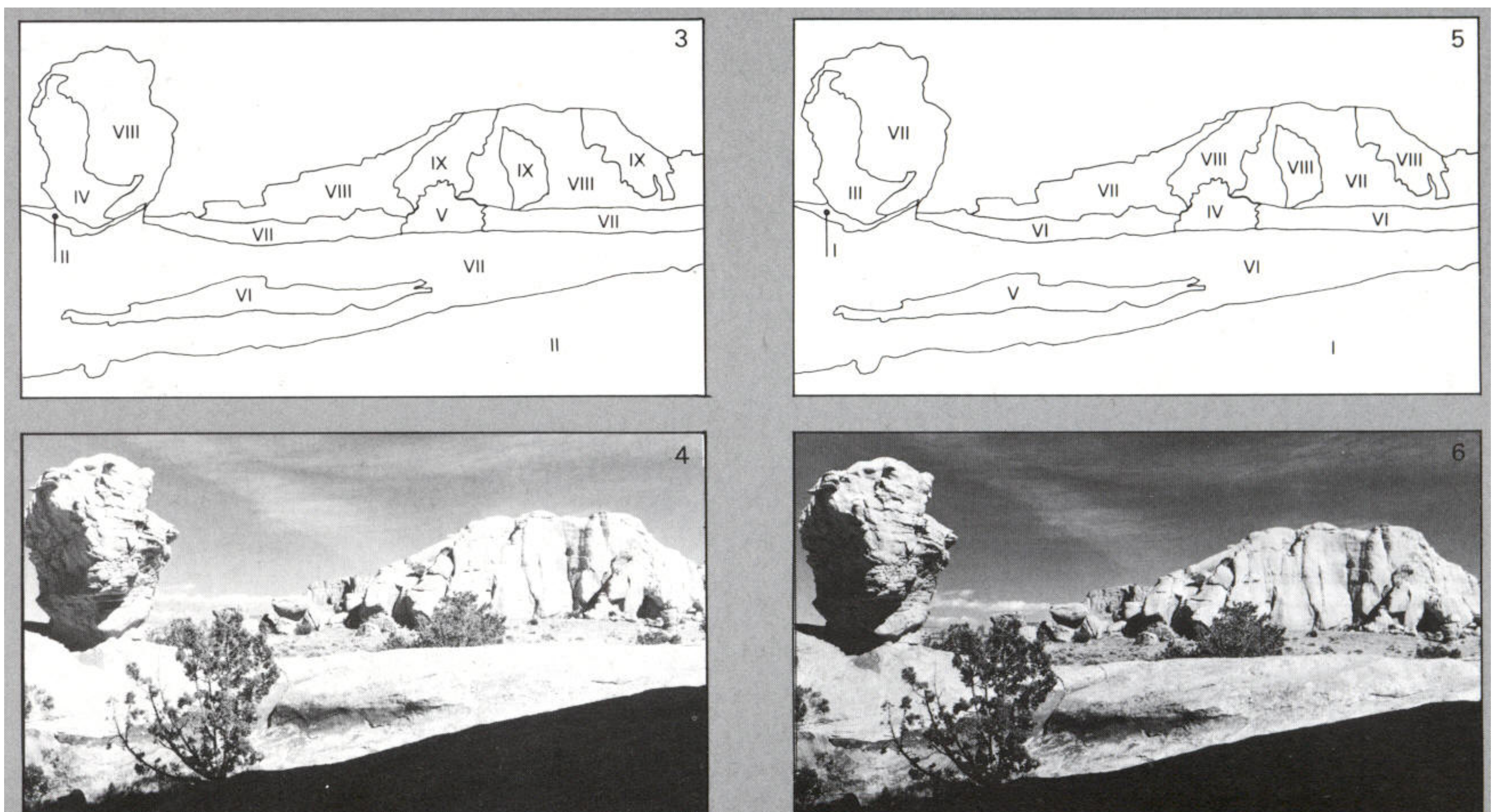
IX Pure untextured white

Zone System


Middle grey
Light
Dark
Darkest textured shadow
Brightest textured highlight
Dynamic range = 15 scene zones
$2^x L$
$2^{x+1} L$
$2^{x+2} L$
$2^{x+3} L$
$2^{x+4} L$
...
$2^{x+15} L$
$2^{x+16} L$
Middle grey maps to Zone V
0
I
II
III
IV
V
VI
VII
VIII
IX
X
Print zones

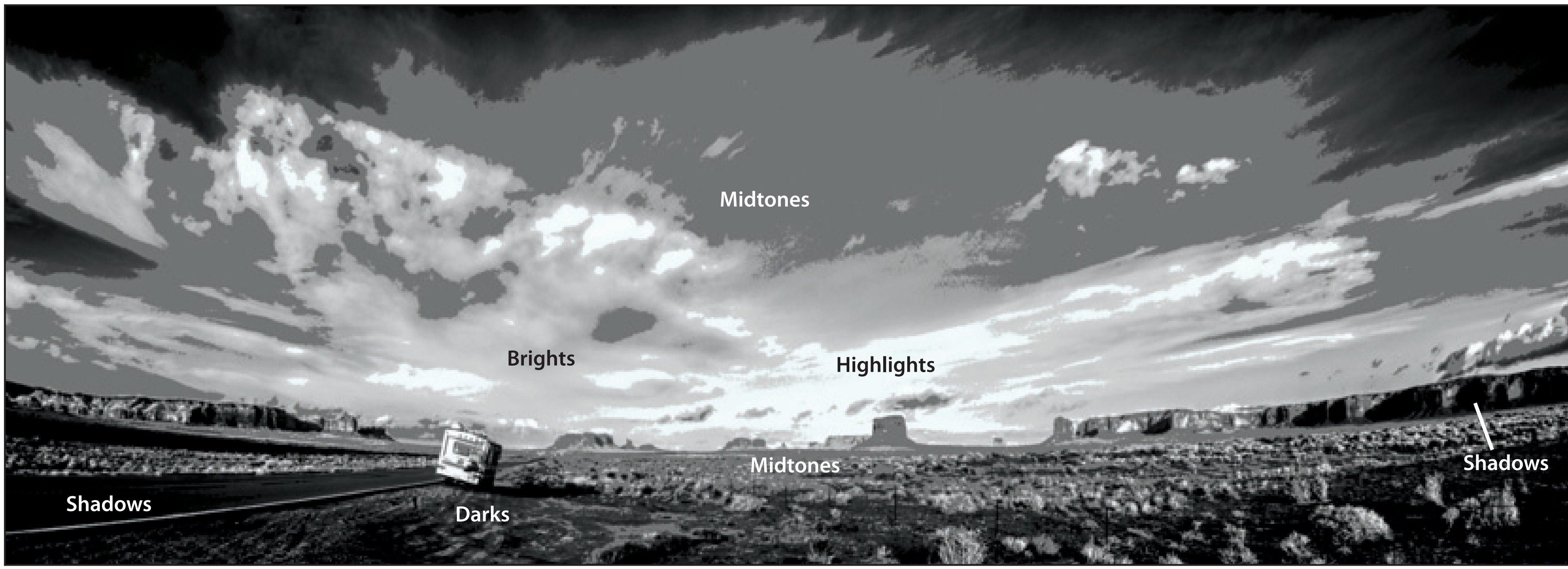
The Zone System

- You decide to put part of the system in a given zone
- Decision: exposure, development, print



Zones Example

Figure 4-32:
Zone chart of the assignments for this image.



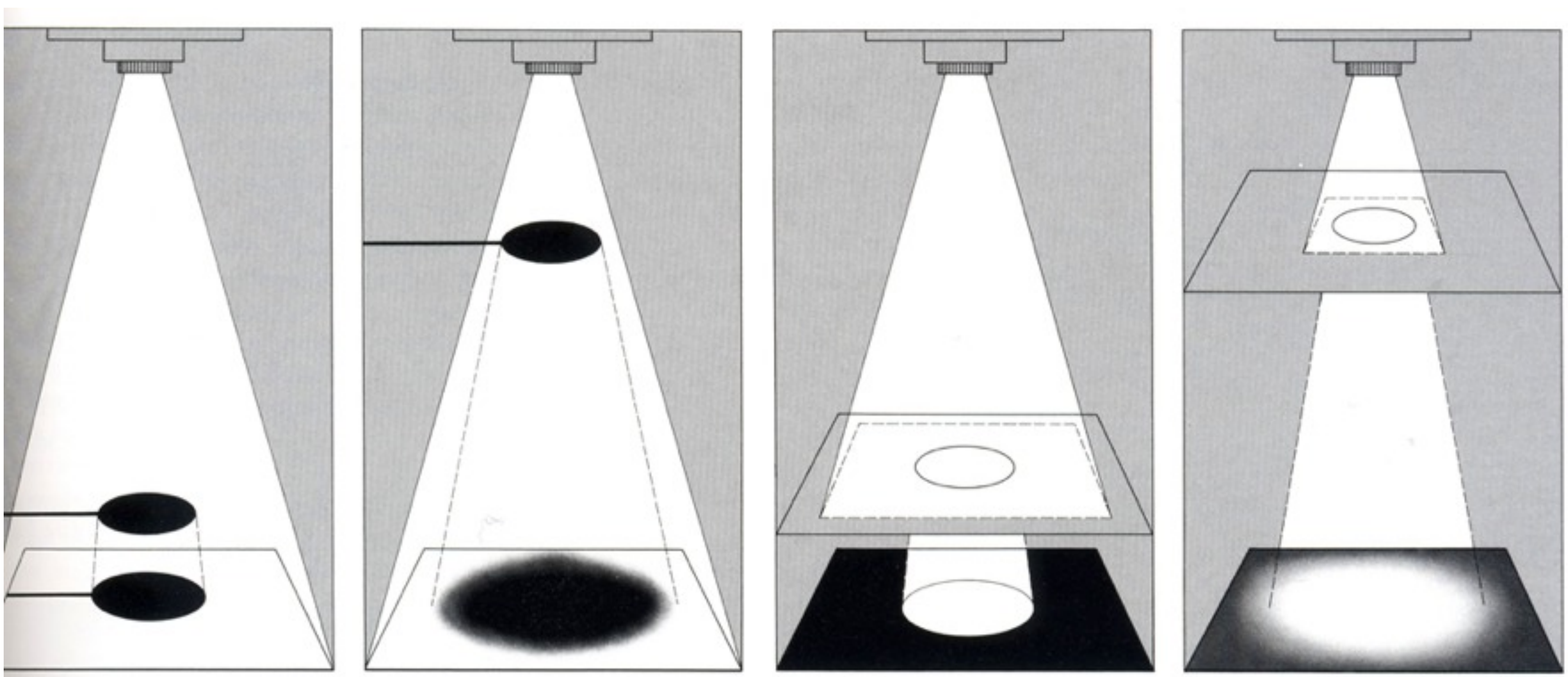
Dodging and Burning

Limited dynamic range can be good!

- W. Eugene Smith photo of Albert Schweitzer. 5 days to print!
- Things can be related because the intensity is more similar
- Balance, composition

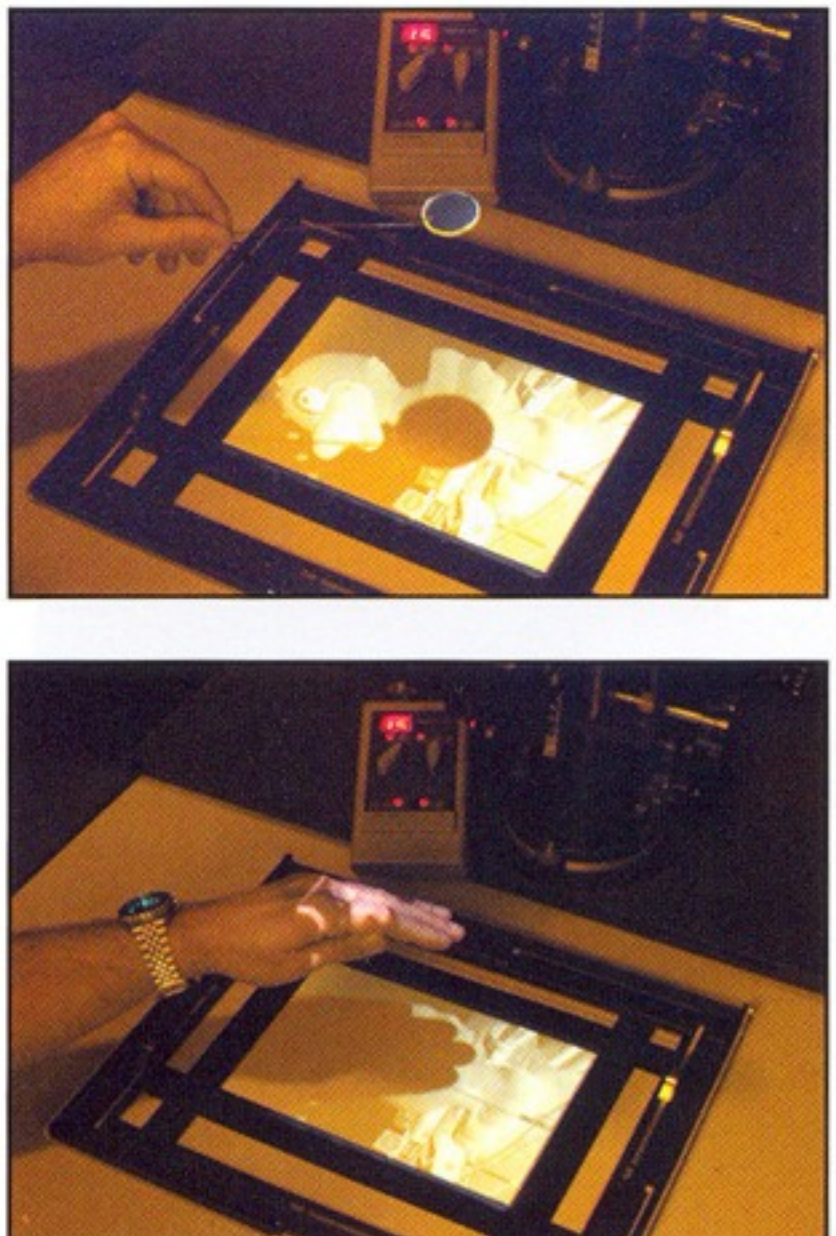
Dodging and burning

- During the print process, selectively hide parts of the print during exposure
- Dodging (left) block light from regions to make darker
- Burning (right) overexpose regions to make brighter

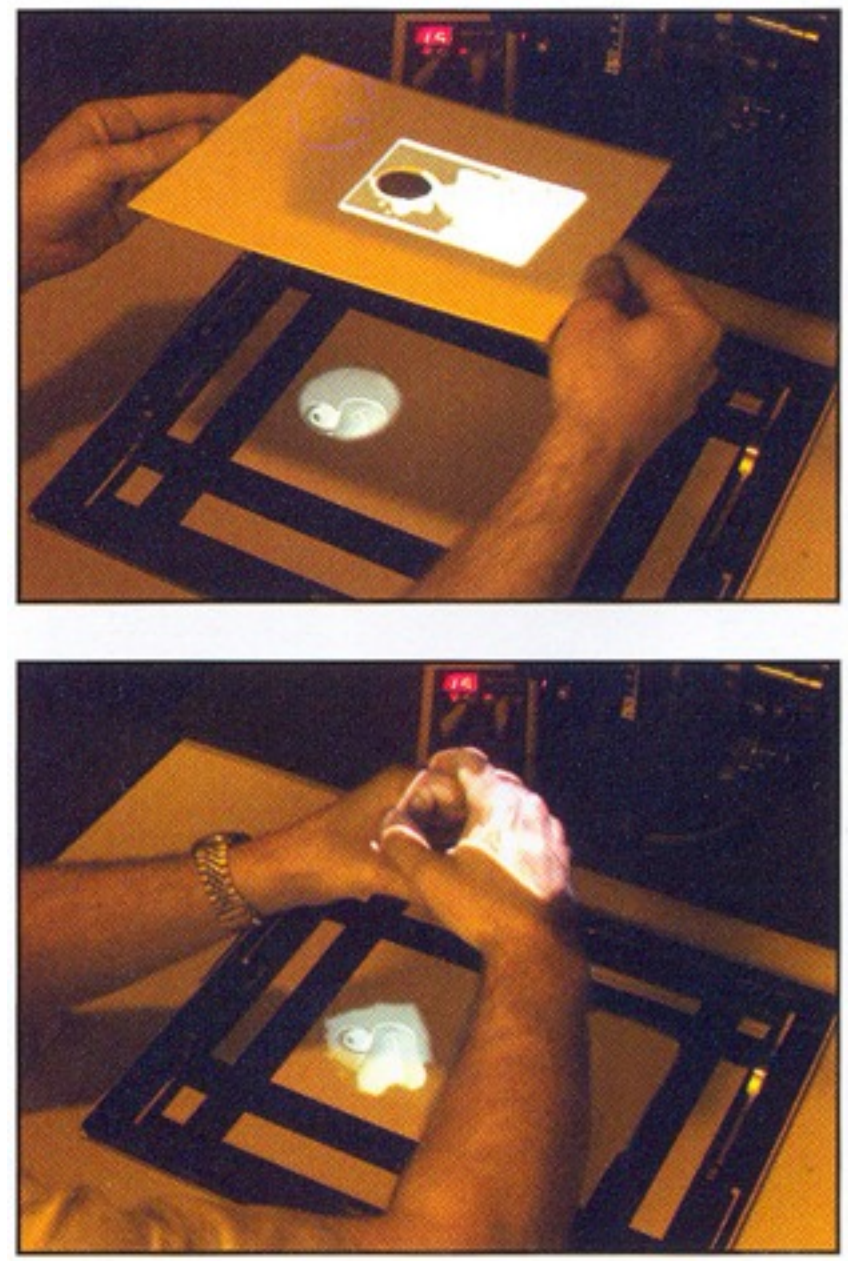


From The Master Printing Course, Rudman

Dodging and Burning



Dodging *holds back light during the basic printing exposure to lighten an area.*



Burning *adds light after the basic exposure to darken an area.*

From Photography by London et al.

Dodging and burning

- Downside: Must be done for every single print

Straight print

After dodging and burning

Dodging & Burning is Difficult

A *The straight work print without additional burning-in.*

B *This print shows the result of trying to mask off the foreground by using a moving card. An even more obvious light band will appear in the sky if the card is not kept moving.*

C *In order to remove the light band in fig B, the mask has been lowered. This, however, has caused parts of the horizon to become black.*

D *The halo effect, here deliberately exaggerated, resulted from dodging the stones during the second exposure while burning-in the sky.*

E *It is very difficult to cut a dodging card with precision, especially for a relatively small print like this. As a result, parts of the sky at the horizon are white, although careful spotting can disguise this problem when it is small. But parts of the mid-grey hill tops have gone jet black, which is less easy to rectify.*

Source: Rudman

Digital Zoning

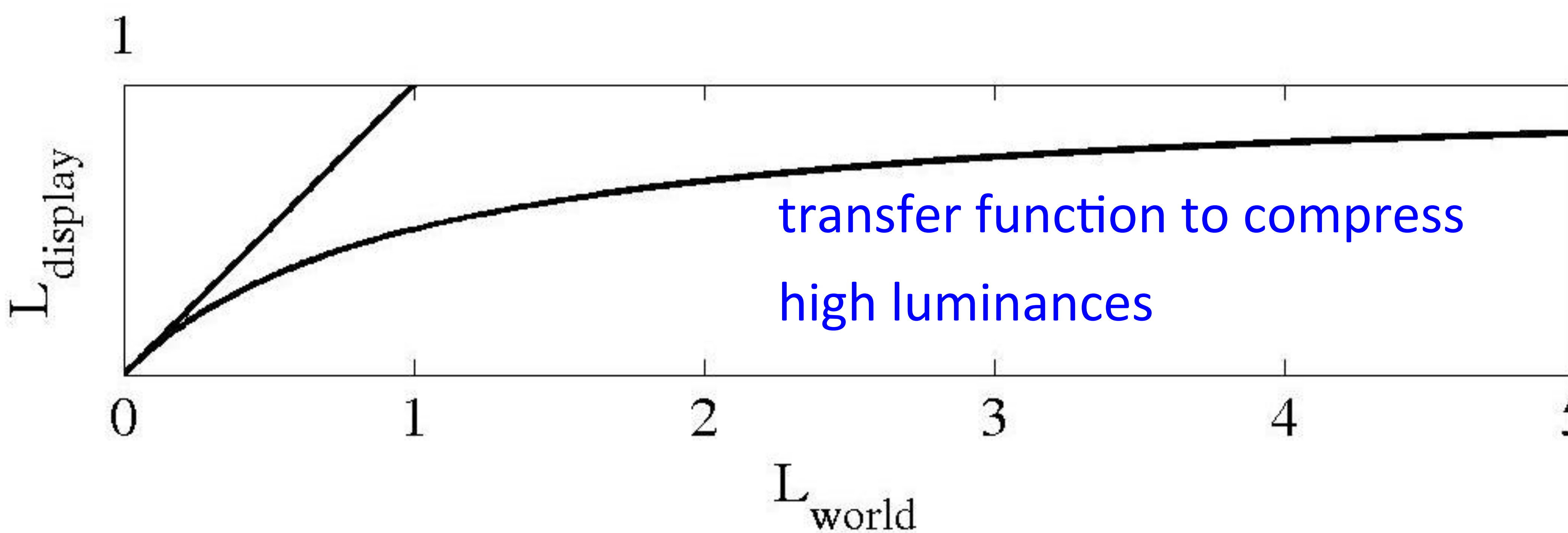
Global operator

$$\bar{L}_w = \exp\left(\frac{1}{N}\sum_{x,y}\log(\delta + L_w(x,y))\right)$$

Approximation of scene's key (how light or dark it is). Map to 18% of display range for average-key scene

User-specified; high key or low key

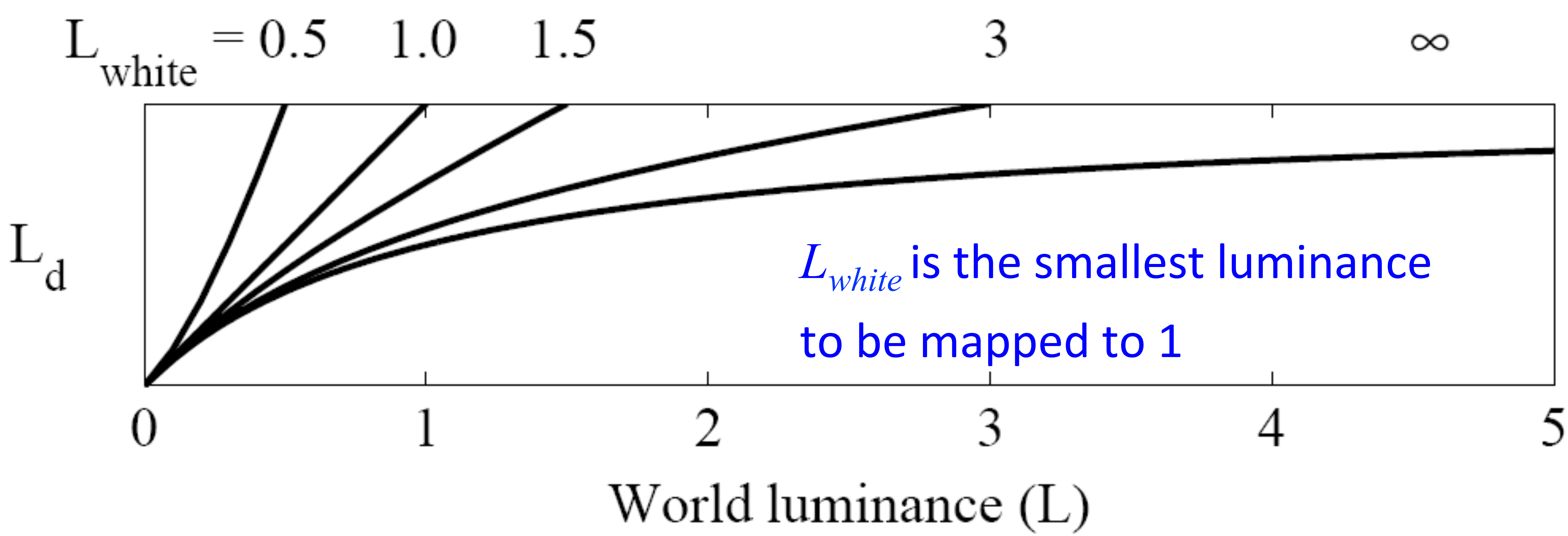
$$L_m(x,y) = \frac{a}{\bar{L}_w} L_w(x,y) \qquad L_d(x,y) = \frac{L_m(x,y)}{1 + L_m(x,y)}$$



Global operator

It seldom reaches 1 since the input image does not have infinitely large luminance values.

$$L_d(x,y) = \frac{L_m(x,y)\left(1 + \frac{L_m(x,y)}{L_{white}^2(x,y)}\right)}{1 + L_m(x,y)}$$



low key (0.18)

high key (0.5)

Dodging and burning (local operators)

- Area receiving a different exposure is often bounded by sharp contrast
- Find largest surrounding area without any sharp contrast

$$L_s^{blur}(x,y) = L_m(x,y) \otimes G_s(x,y)$$

$$V_s(x,y) = \frac{L_s^{blur}(x,y) - L_{s+1}^{blur}(x,y)}{2^{\phi}\, a / s^2 + L_s^{blur}}$$

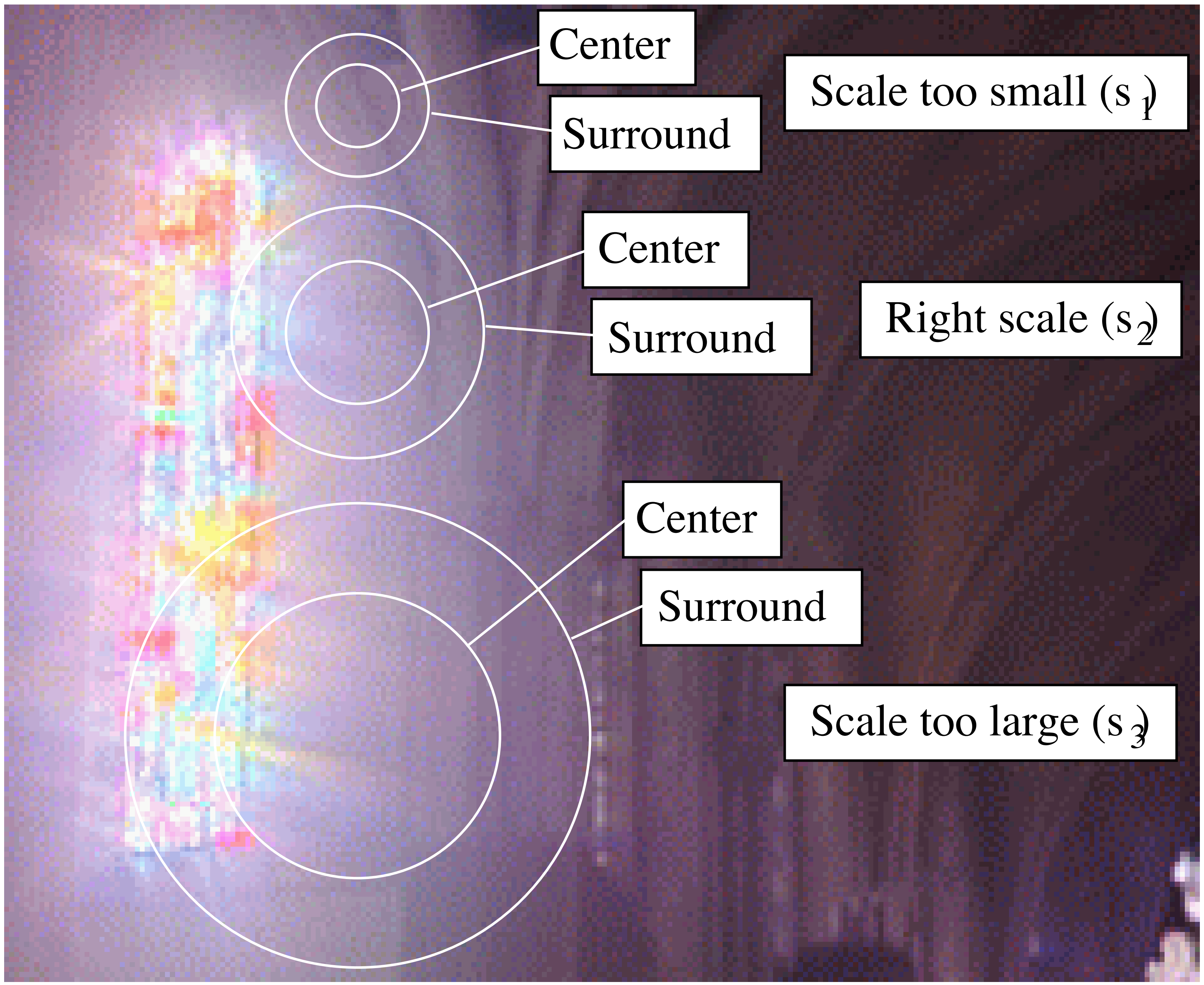
$$s_{\max} : \left| V_{s_{\max}}(\mathrm{x}, \mathrm{y}) \right| < \varepsilon$$

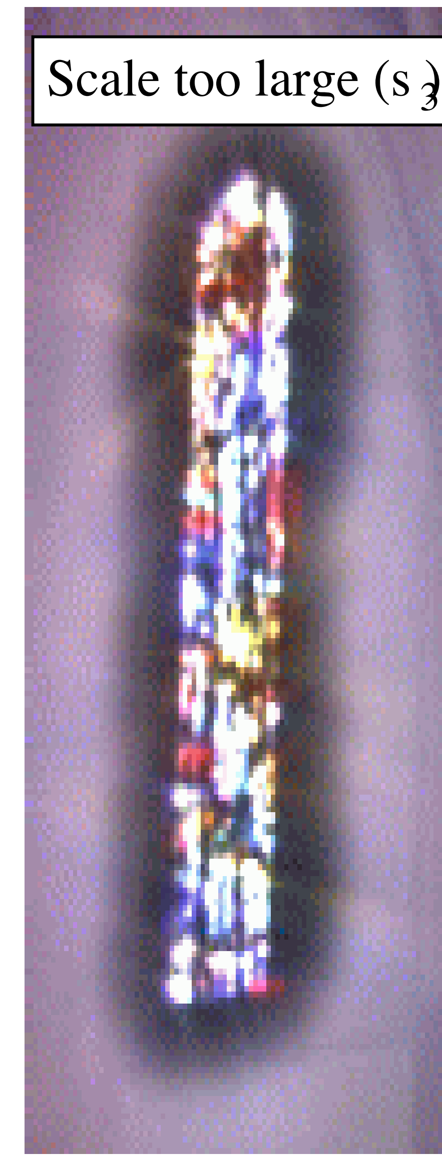
Dodging and burning (local operators)

$$L_d(x, y) = \frac{L_m(x, y)}{1 + L_{s_{\max}}^{blur}(x, y)}$$

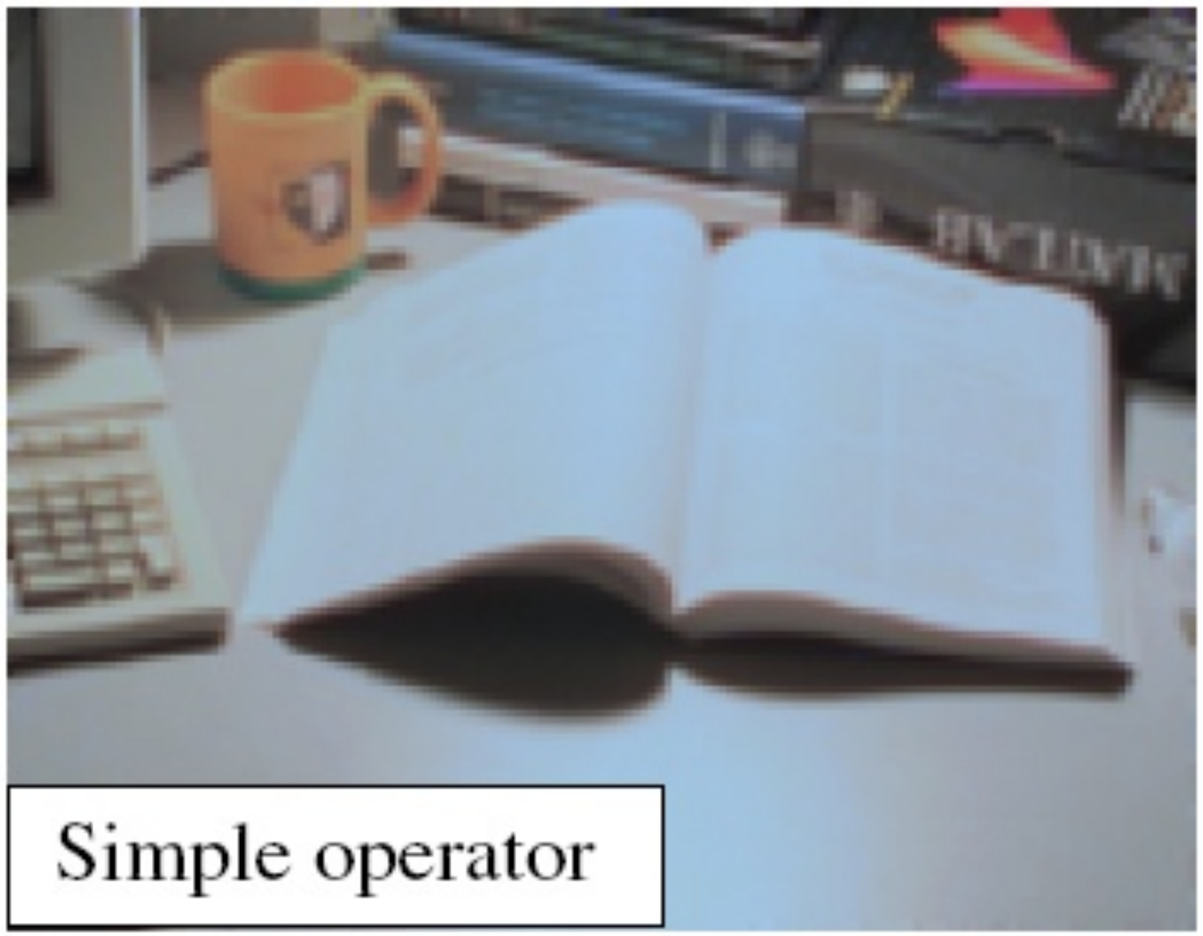
- A darker pixel (smaller than the blurred average of its surrounding area) is divided by a larger number and become darker (dodging)
- A brighter pixel (larger than the blurred average of its surrounding area) is divided by a smaller number and become brighter (burning)
- Both increase the contrast

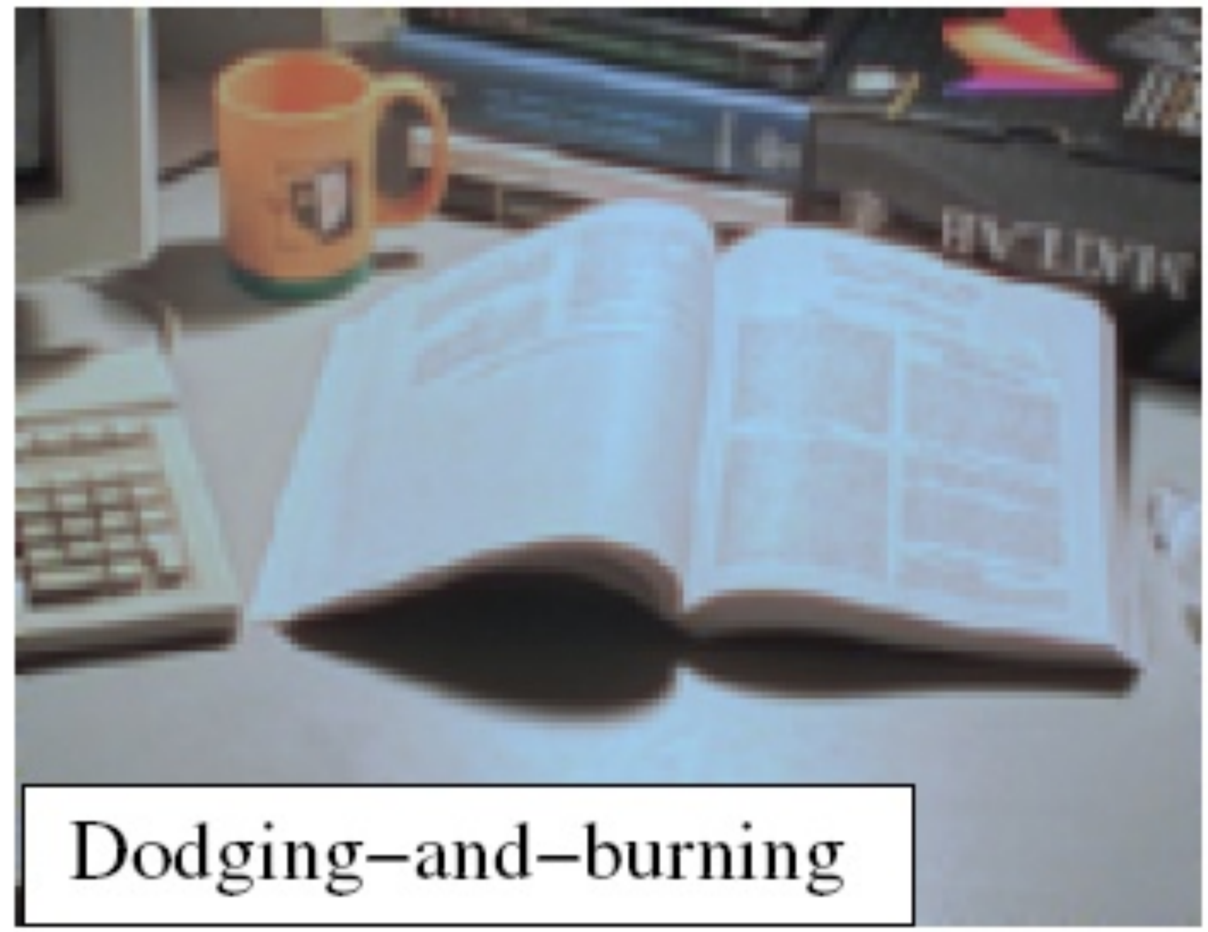
Scale Selection





Dodging and burning





Bilateral Filtering

(slides from Frédo Durand)

Fast Bilateral Filtering
for the Display of High-Dynamic-Range Images

Frédo Durand and Julie Dorsey
Laboratory for Computer Science, Massachusetts Institute of Technology

Abstract

We present a new technique for the display of high-dynamic-range images, which reduces the contrast while preserving detail. It is based on a two-scale decomposition of the image into a base layer, encoding large-scale variations, and a detail layer. Only the base layer has its contrast reduced, thereby preserving detail. The base layer is obtained using an edge-preserving filter called the *bilateral filter*. This is a non-linear filter, where the weight of each pixel is computed using a Gaussian in the spatial domain multiplied by an influence function in the intensity domain that decreases the weight of pixels with large intensity differences. We express bilateral filtering in the framework of robust statistics and show how it relates to anisotropic diffusion. We then accelerate bilateral filtering by using a piecewise-linear approximation in the intensity domain and appropriate subsampling. This results in a speed-up of two orders of magnitude. The method is fast and requires no parameter setting.

CR Categories: I.3.3 [Computer Graphics]: Picture/image generation—Display algorithms; I.4.1 [Image Processing and Computer Vision]: Enhancement—Digitization and image capture

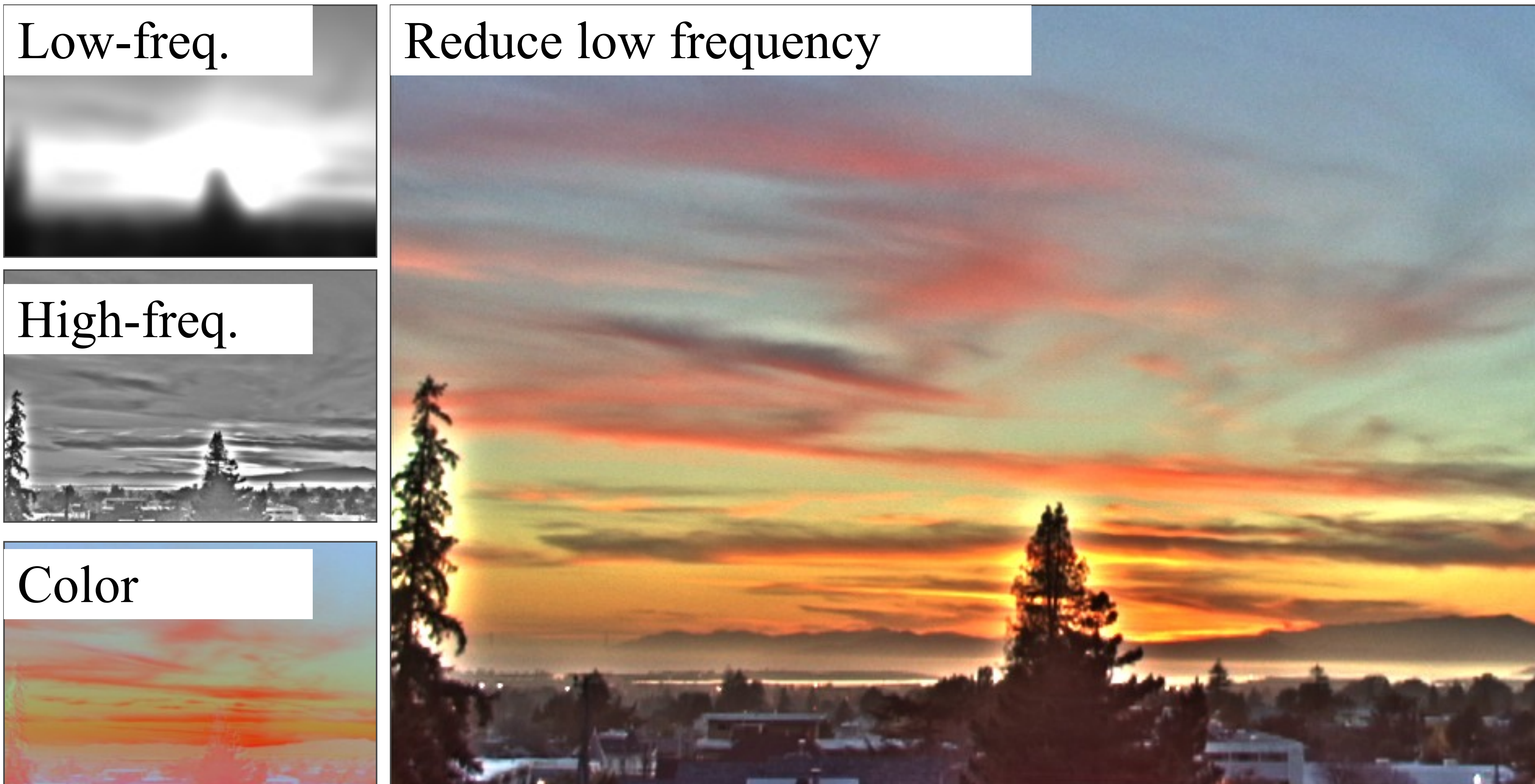
Keywords: image processing, tone mapping, contrast reduction, edge-preserving filtering,weird maths

1 Introduction

Figure 1: High-dynamic-range photography. No single global exposure can preserve both the colors of the sky and the details of the landscape, as shown on the rightmost images. In contrast, our spatially-varying display operator (large image) can bring out all details of the scene. Total clock time for this 700x480 image is 1.4 seconds on a 700Mhz PentiumIII. Radiance map courtesy of Paul Debevec, USC. [Debevec and Malik 1997]

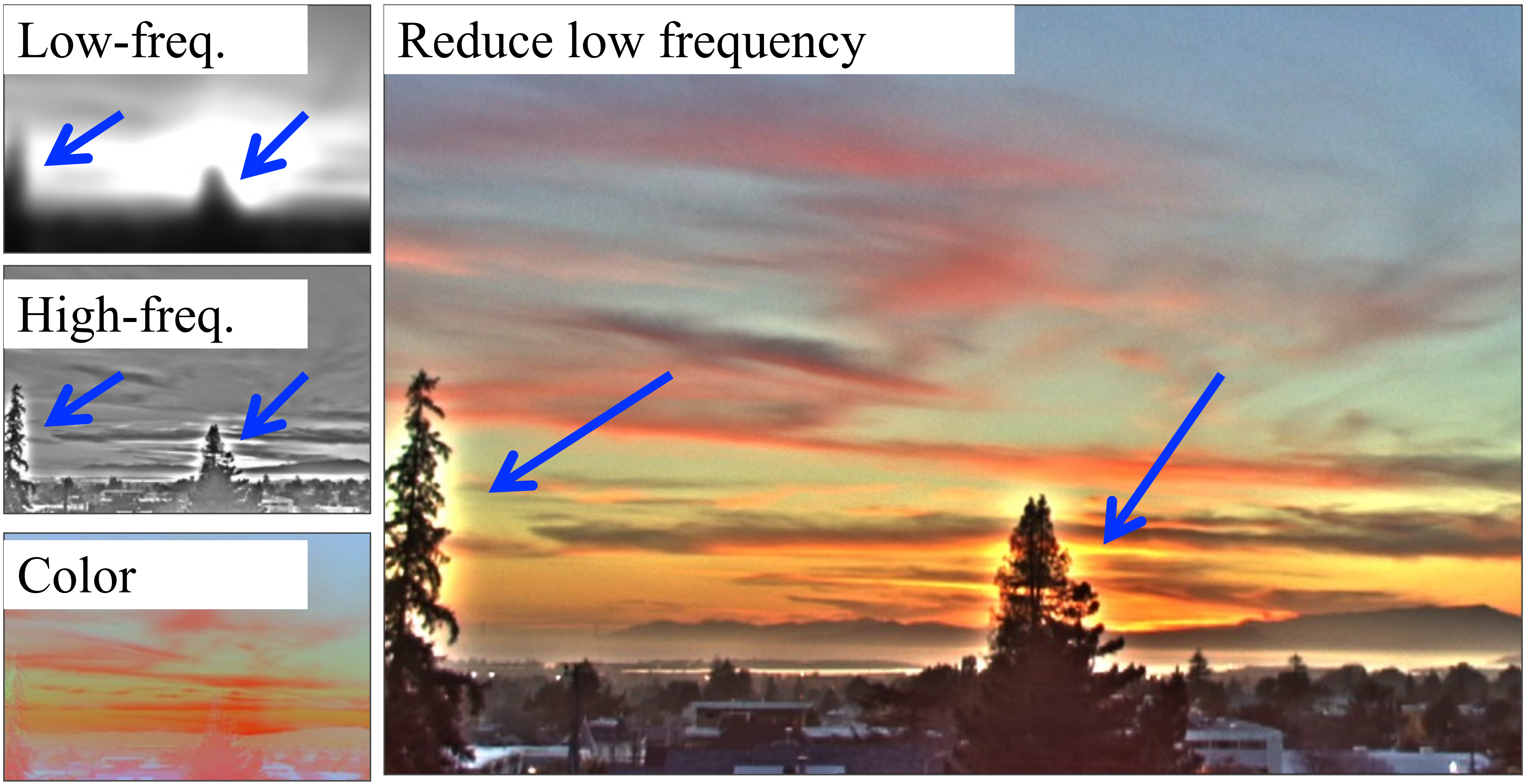
Oppenheim 1968, Chiu et al. 1993

- Reduce contrast of low-frequencies
- Keep mid and high frequencies



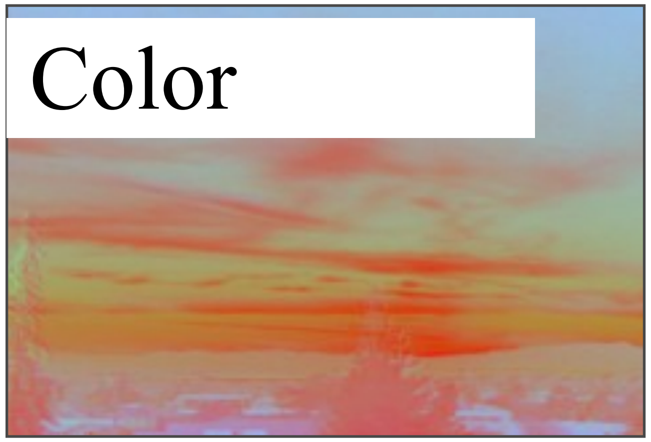
The halo nightmare

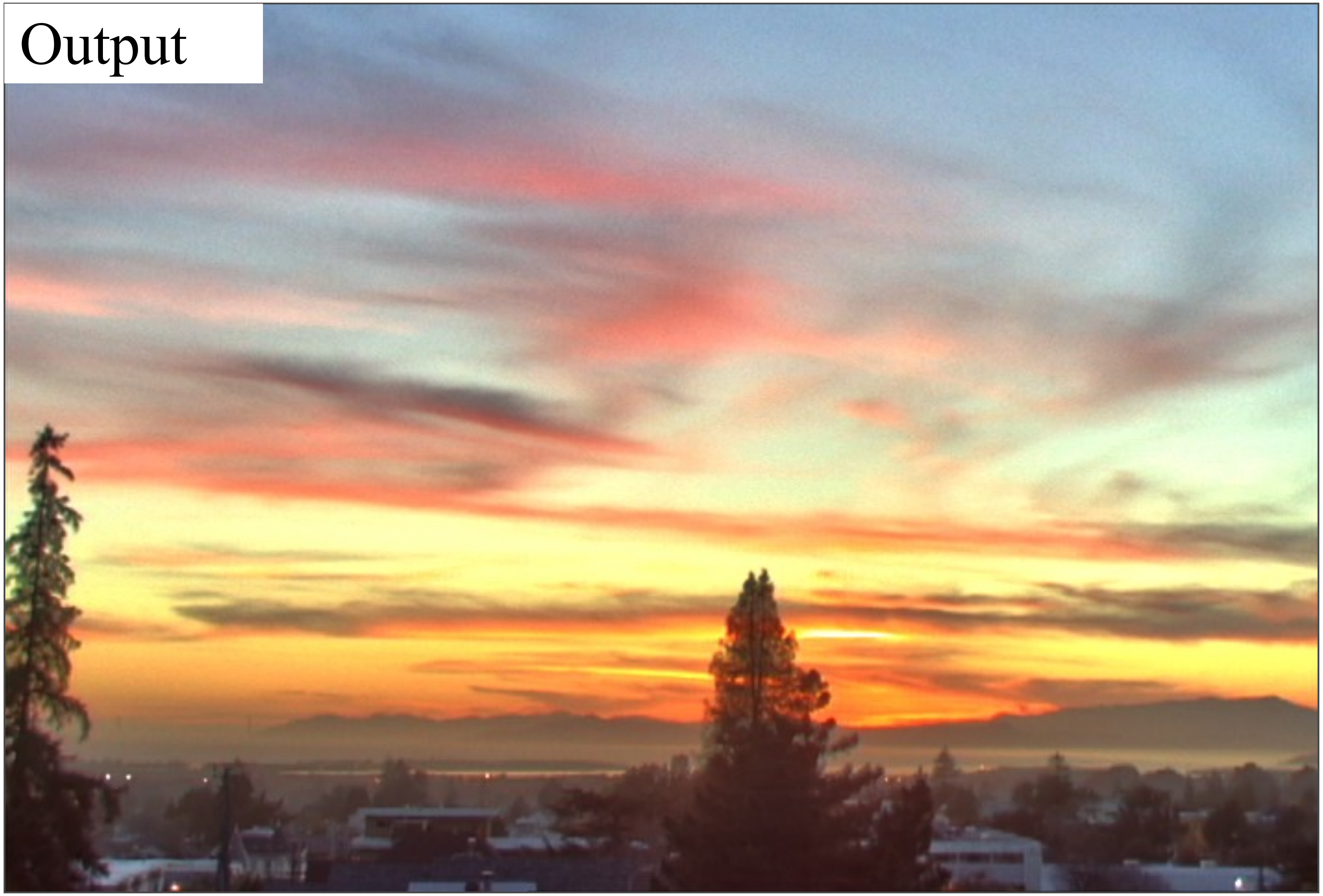
- For strong edges
- Because they contain high frequency



Our approach

- **Do not blur across edges**
- **Non-linear filtering**

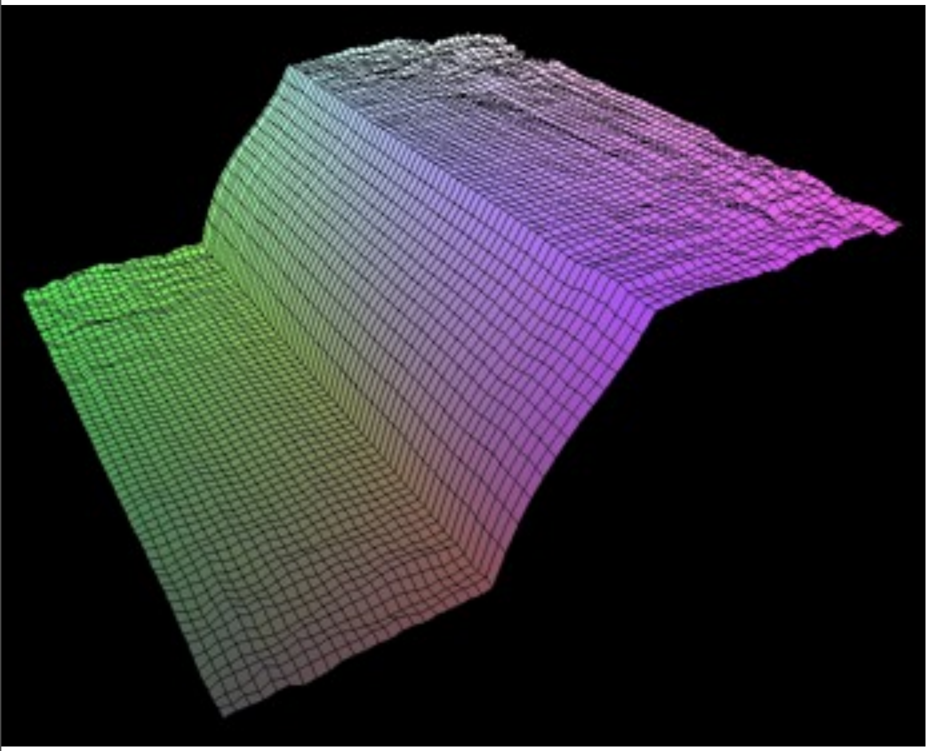


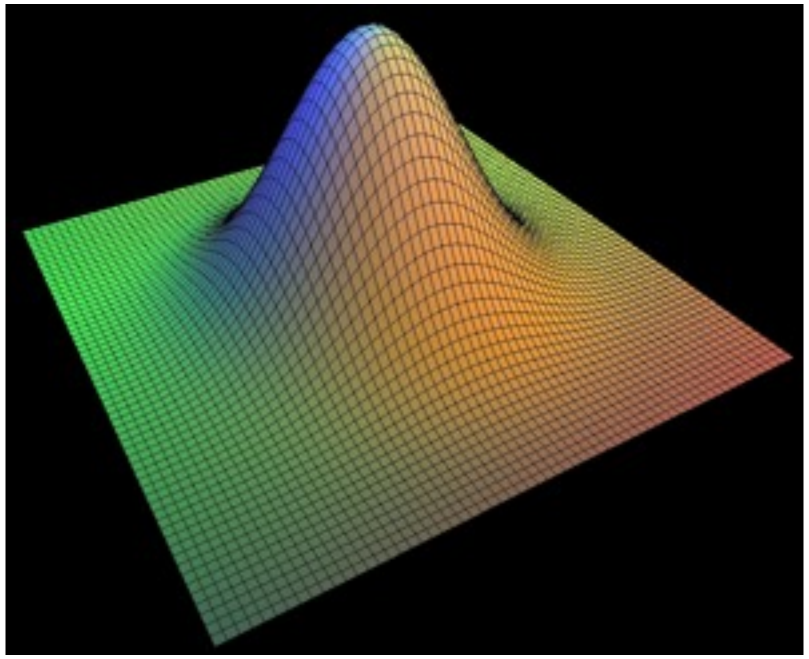


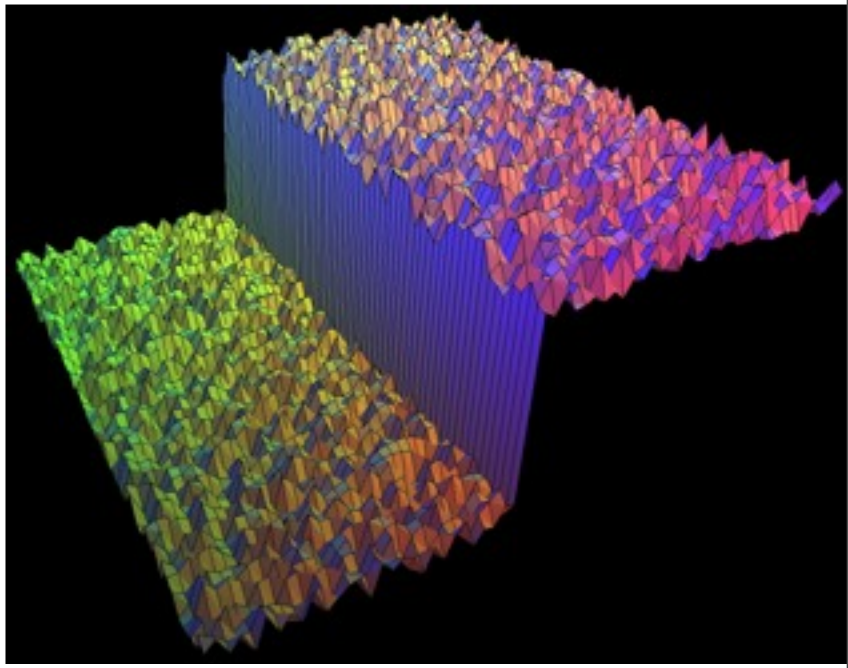
Start with Gaussian filtering

- **Here, input is a step function + noise**

$$J = f \otimes I$$







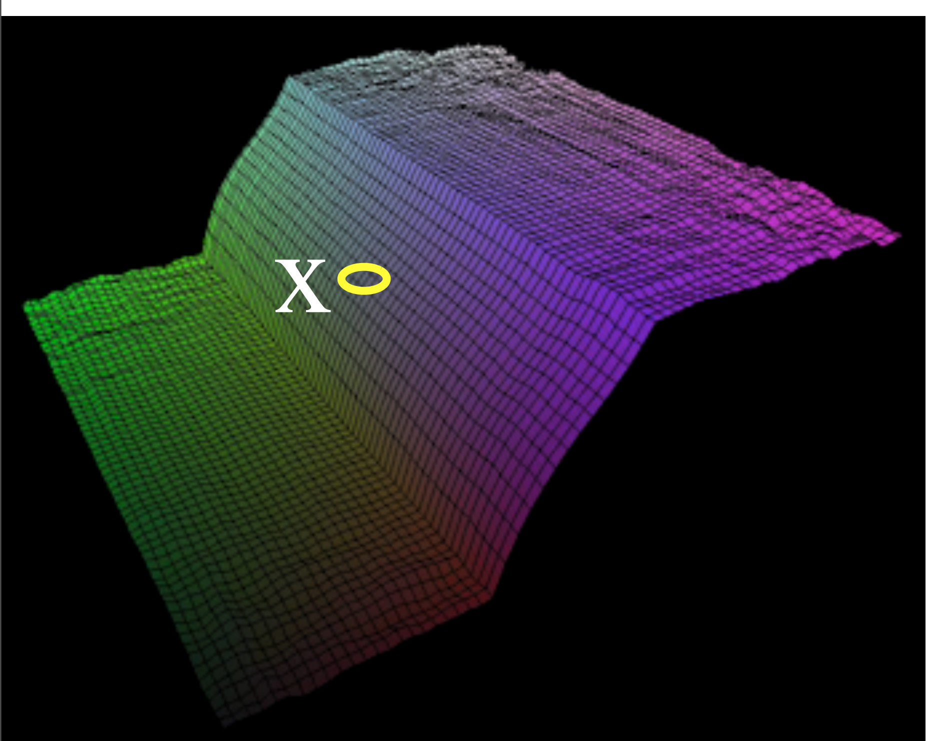
output

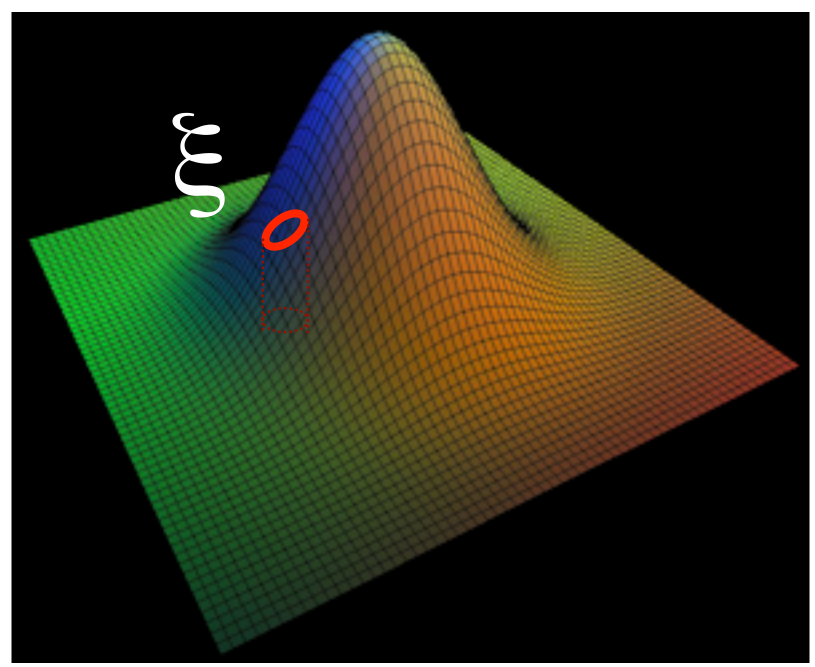
input

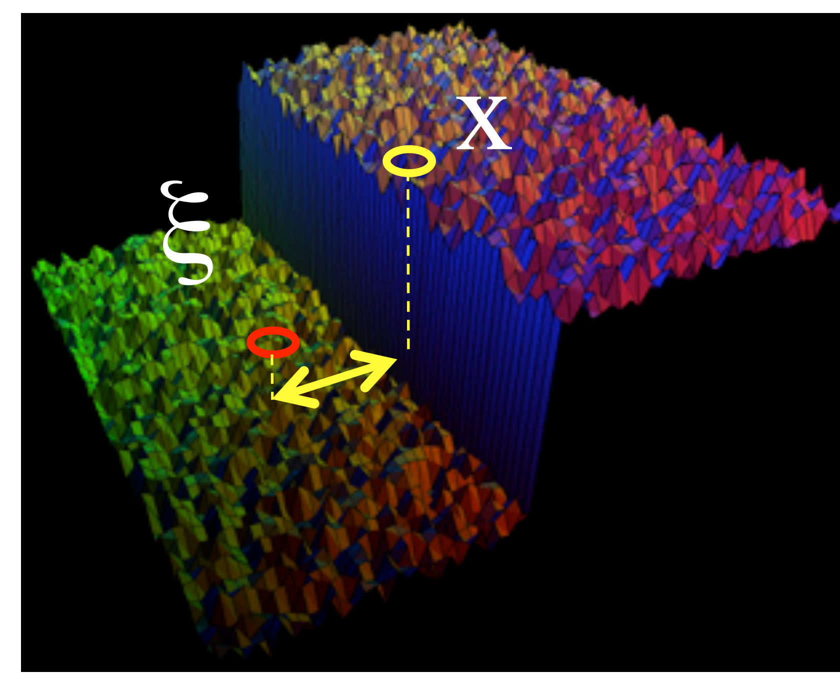
Gaussian filter as weighted average

- **Weight of ξ depends on distance to x**

$$J(x) = \sum_{\xi} \quad f(x,\xi) \quad I(\xi)$$





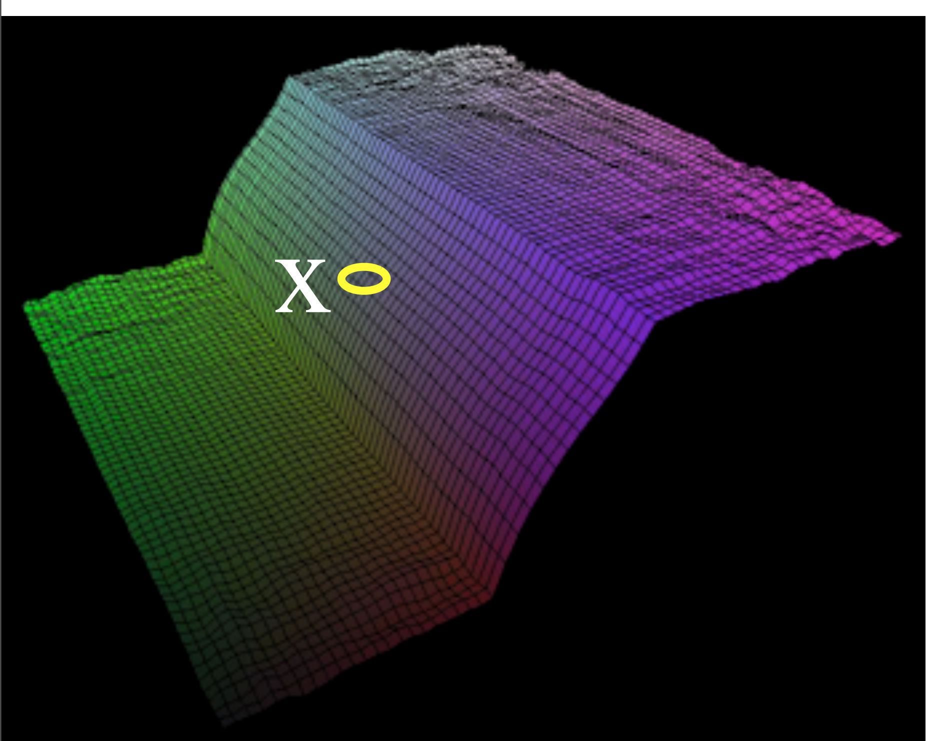


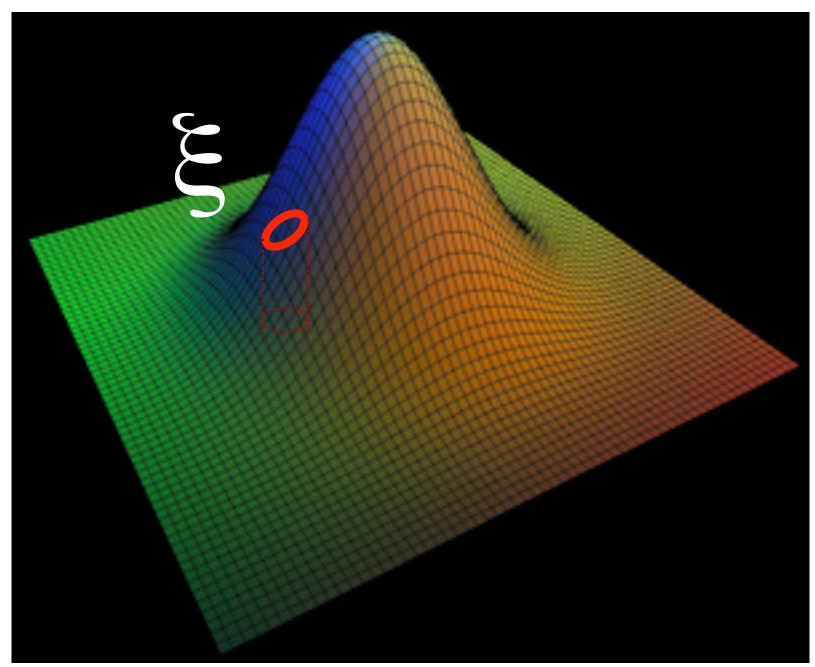
output ⟸ input

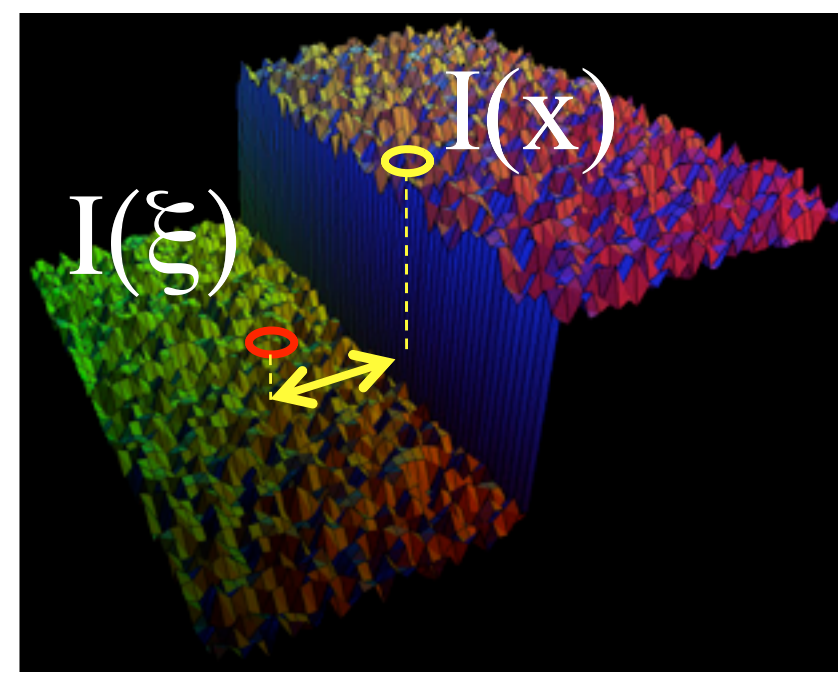
The problem of edges

- Here, $I(\xi)$ "pollutes" our estimate J(x)
- It is too different

$$J(x) = \sum_{\xi} f(x,\xi) \quad I(\xi)$$







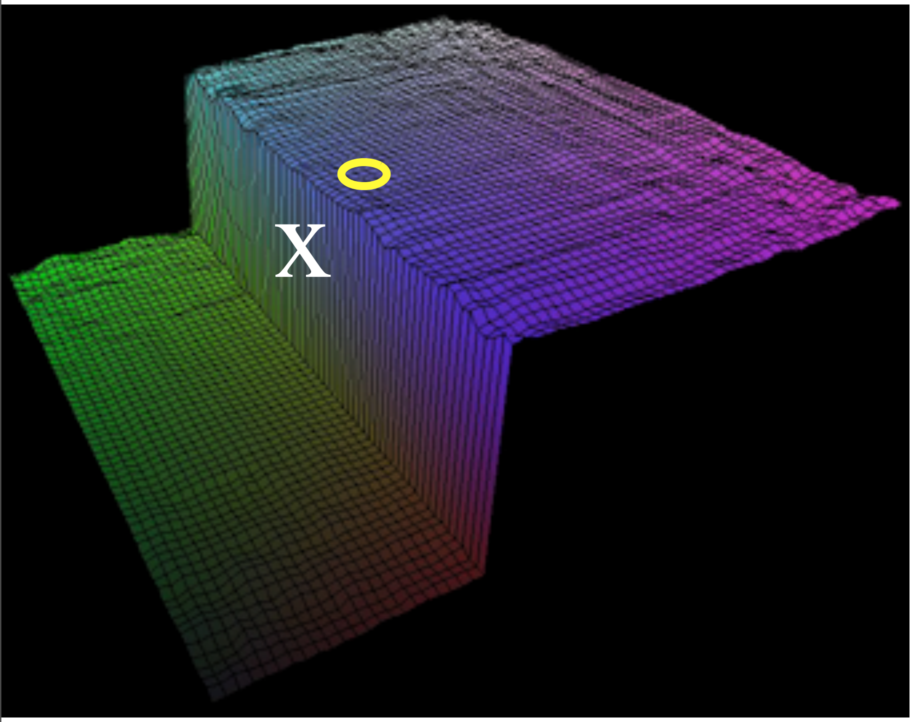
output ← input

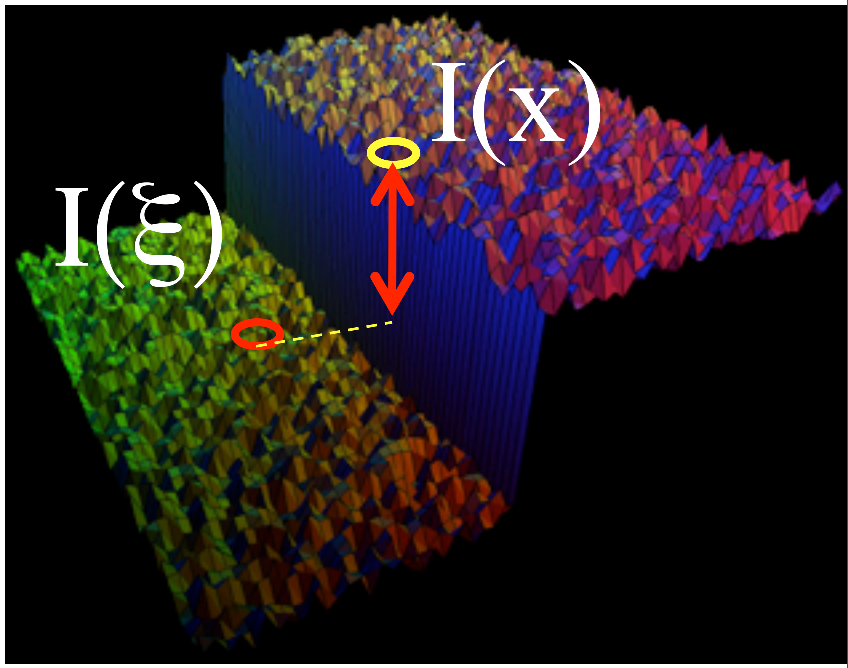
Principle of Bilateral filtering

[Tomasi and Manduchi 1998]

- **Penalty g on the intensity difference**

$$J(x) = \frac{1}{k(x)} \sum_{\xi} f(x,\xi) \quad g(I(\xi) - I(x)) \quad I(\xi)$$





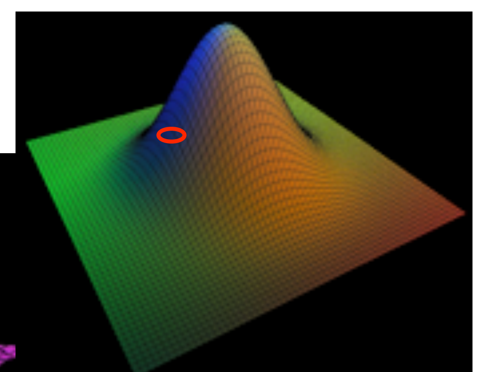
output ⟸ input

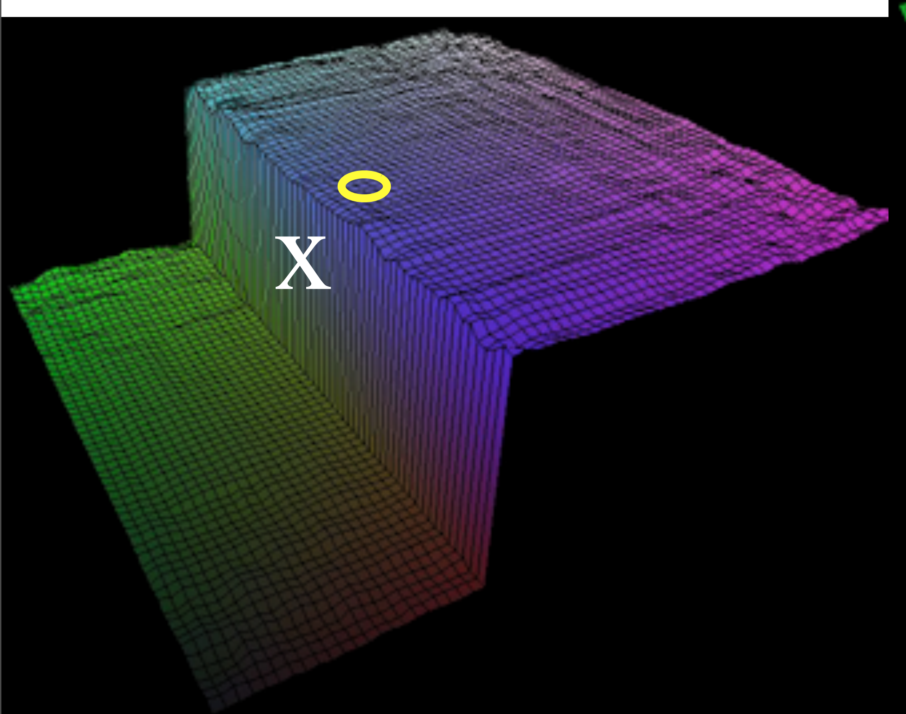
Bilateral filtering

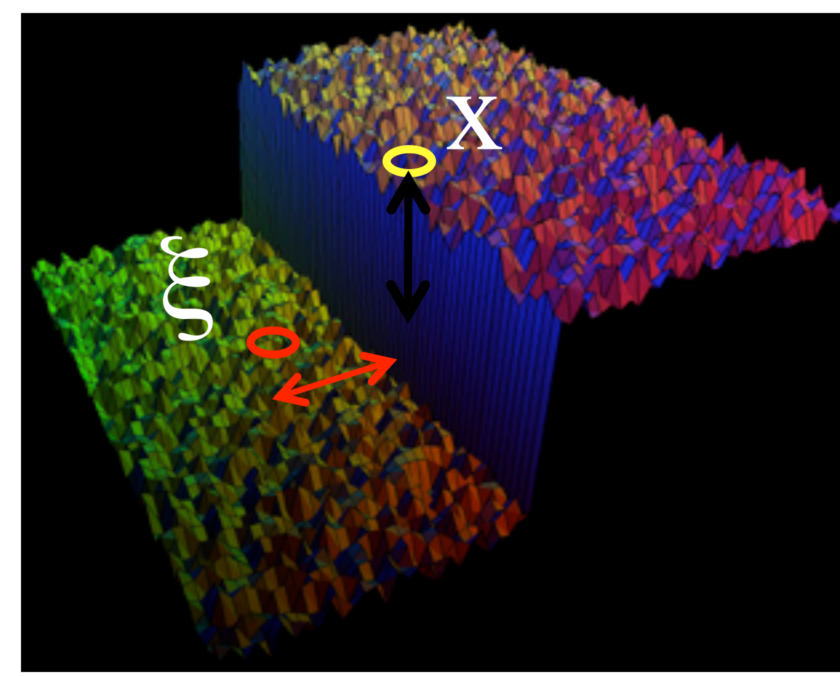
[Tomasi and Manduchi 1998]

- **Spatial Gaussian f**

$$J(x) = \frac{1}{k(x)} \sum_{\xi} f(x,\xi)\, g(I(\xi) - I(x)) \quad I(\xi)$$







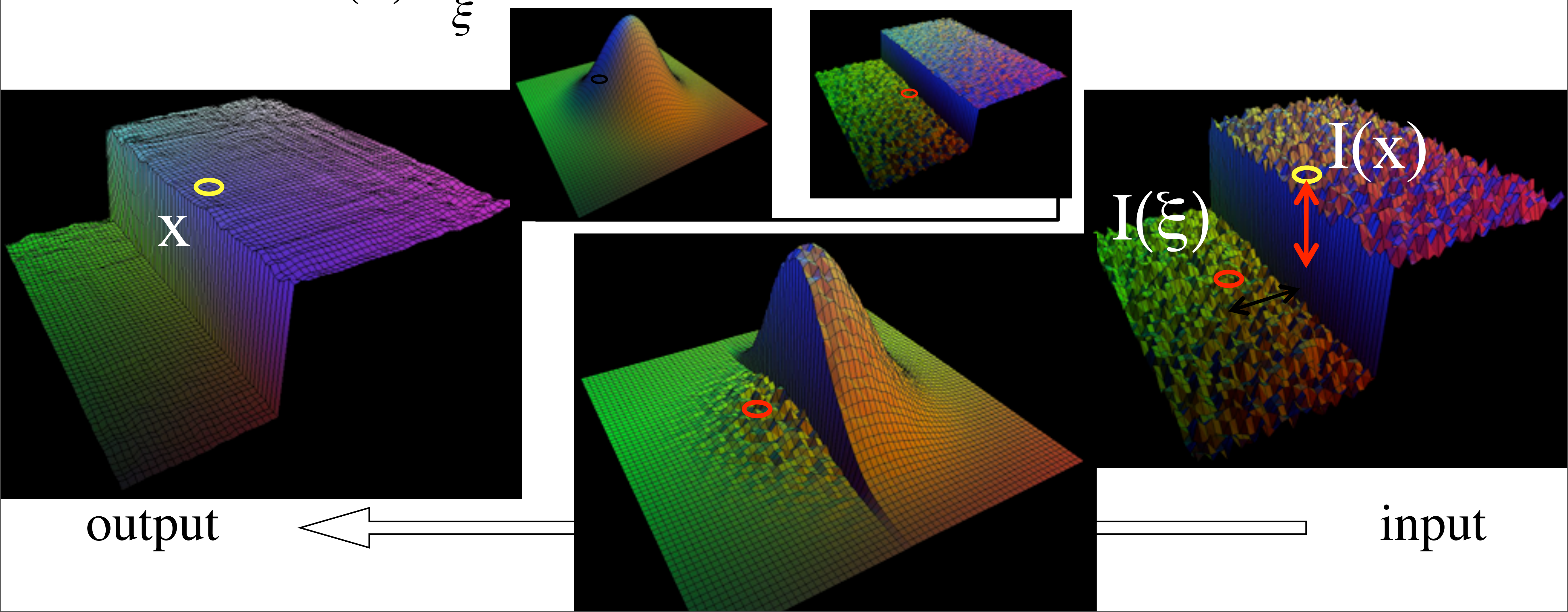
output input

Bilateral filtering

[Tomasi and Manduchi 1998]

- Spatial Gaussian f
- Gaussian g on the intensity difference

$$J(x) = \frac{1}{k(x)} \sum_{\xi} f(x,\xi)\, g(I(\xi) - I(x))\, I(\xi)$$

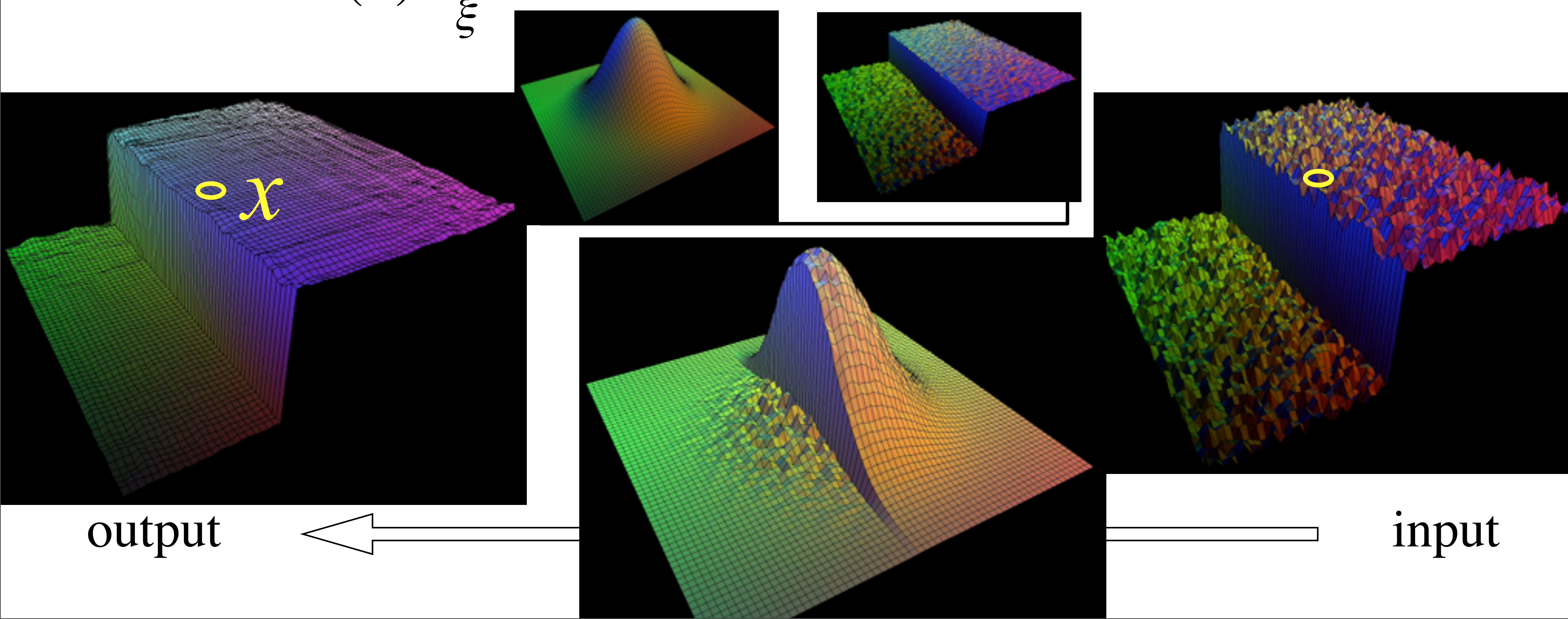


Normalization factor

[Tomasi and Manduchi 1998]

- **k(x)=** $\sum_{\xi} f(x,\xi) \quad g(I(\xi)-I(x))$

$$J(x) = \frac{1}{k(x)} \sum_{\xi} f(x,\xi) \quad g(I(\xi)-I(x)) \quad I(\xi)$$

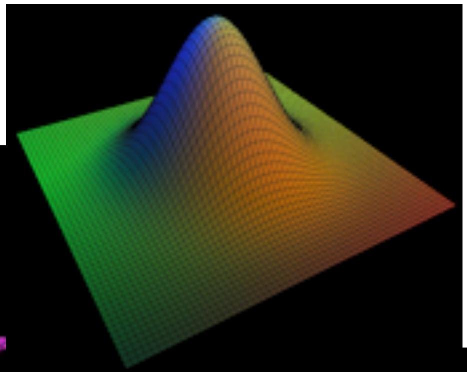


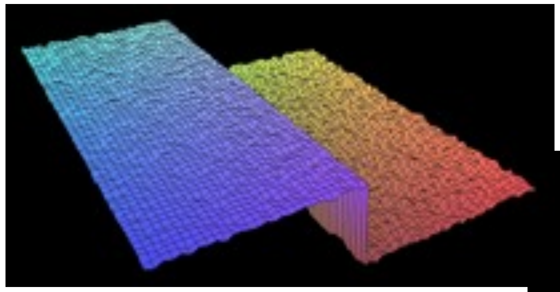
Bilateral filtering is non-linear

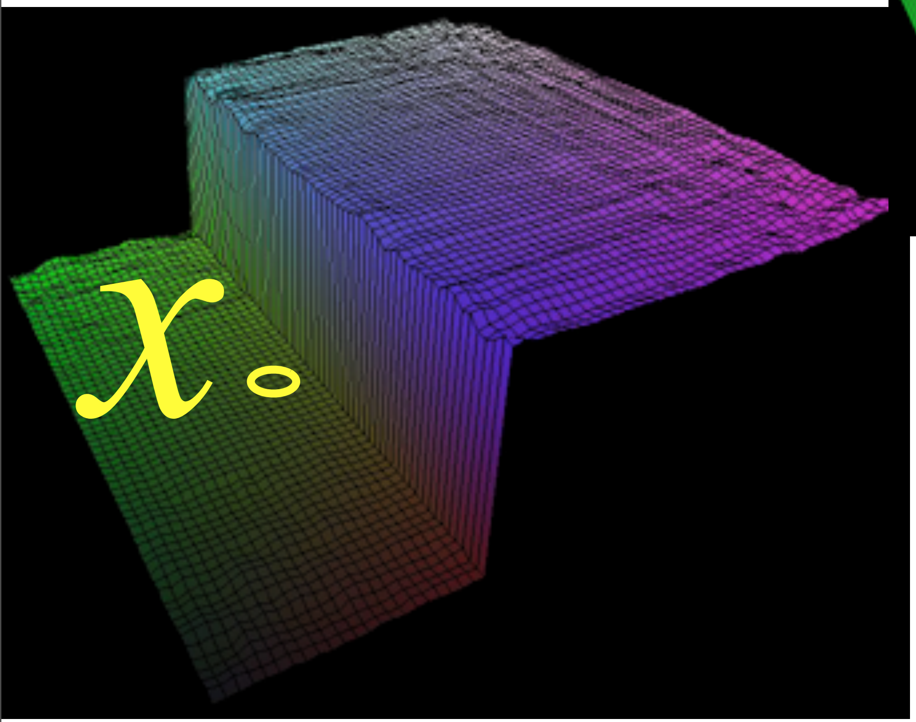
[Tomasi and Manduchi 1998]

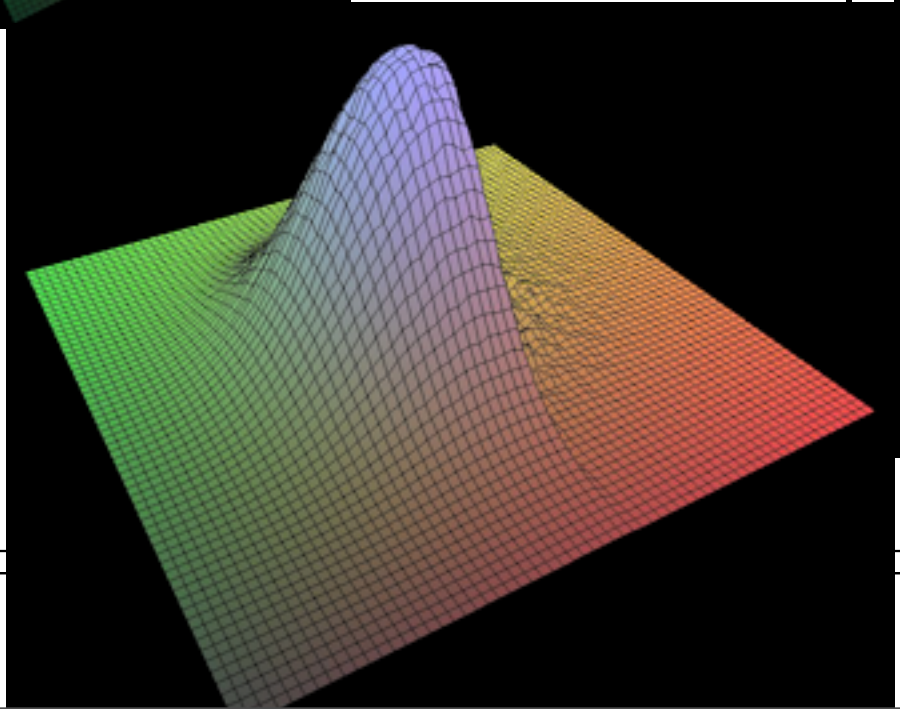
- The weights are different for each output pixel

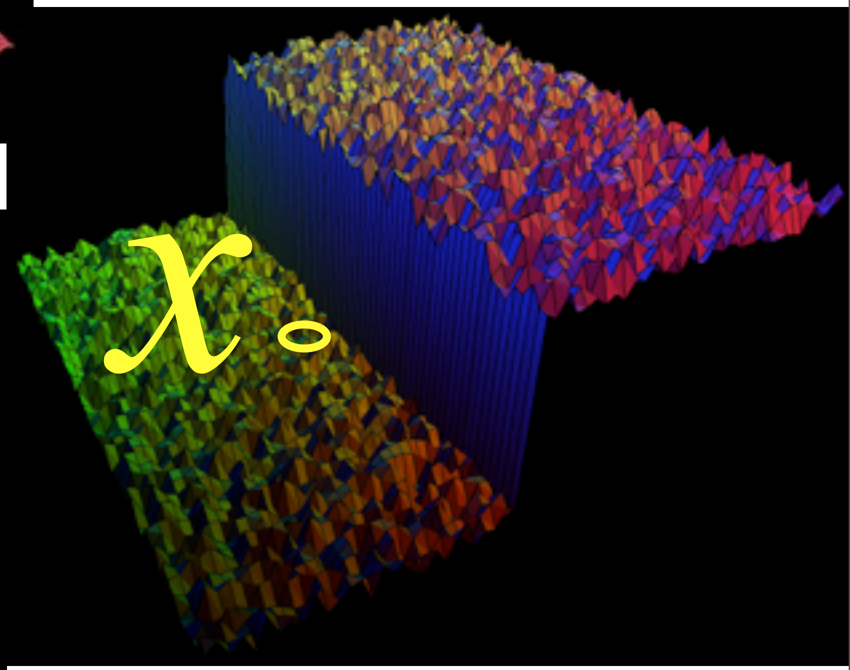
$$J(x) = \frac{1}{k(x)} \sum_{\xi} f(x,\xi) \quad g(I(\xi) - I(x)) \quad I(\xi)$$









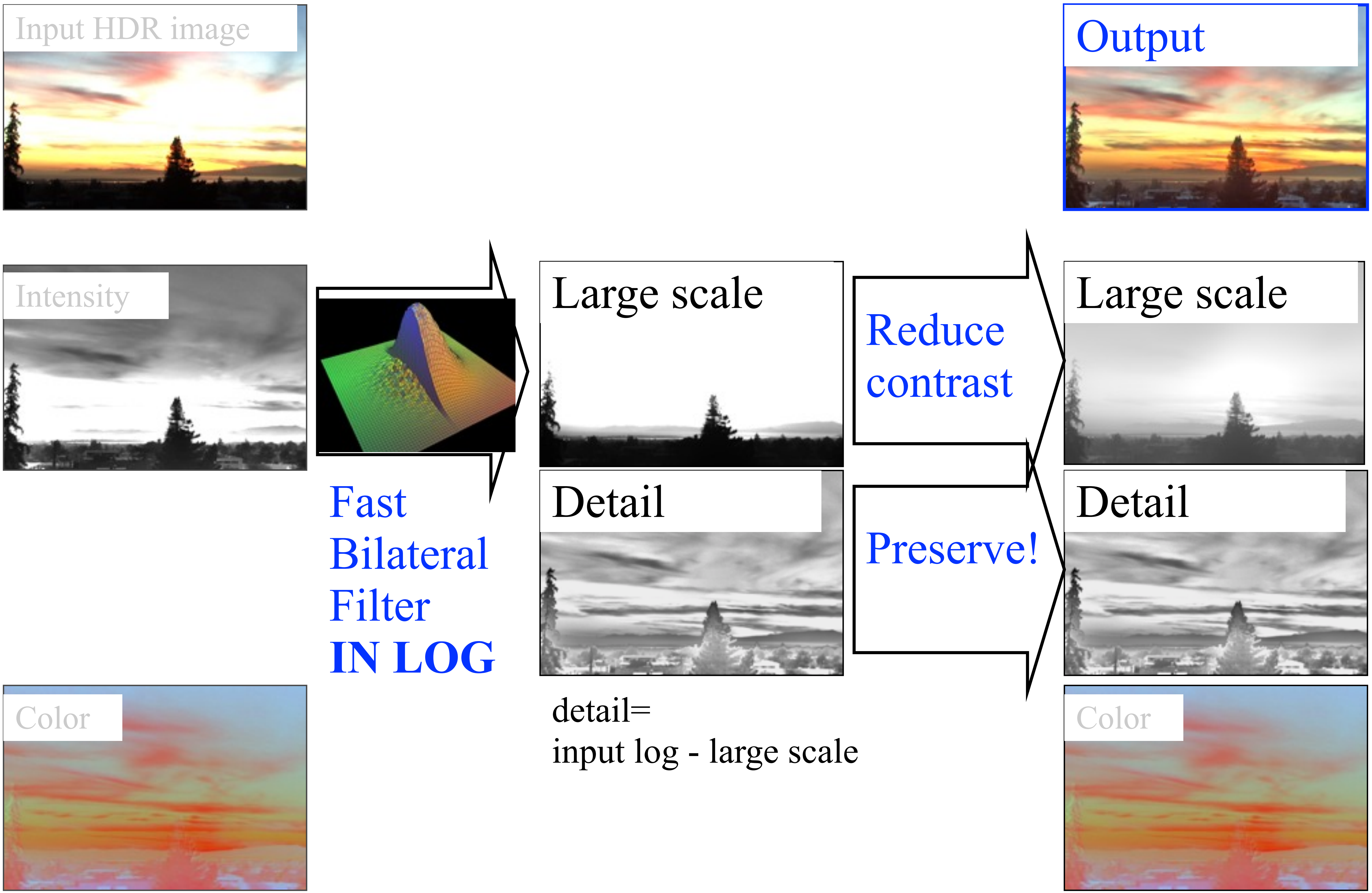


output input

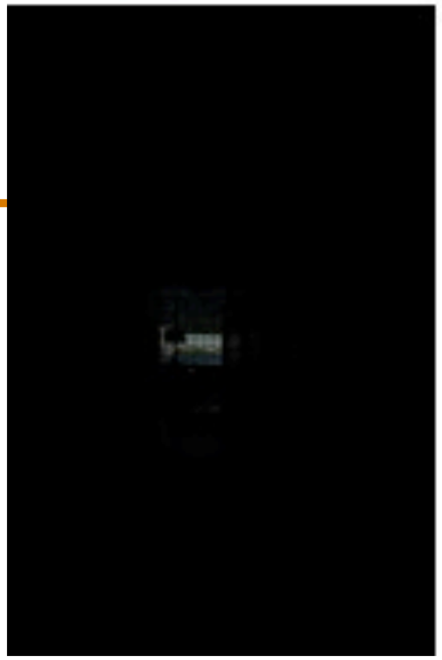
Log domain

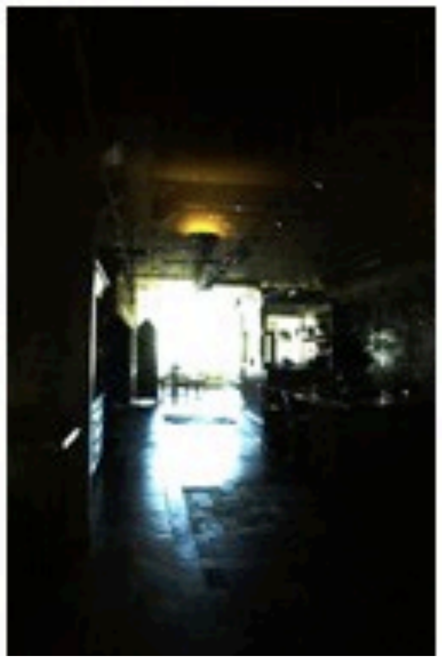
- Very important to work in the log domain
- Recall: humans are sensitive to multiplicative contrast
- With log domain, our notion of “strong edge” always corresponds to the same contrast

Recap



Input HDR image
Output
Intensity
Large scale
Reduce contrast
Large scale
Fast Bilateral Filter IN LOG
Detail
Preserve!
Detail
detail=
input log - large scale
Color
Color



Lec16 Required Reading

- None. Instead, begin thinking about project proposals.