Tone mapping

Digital Visual Effects
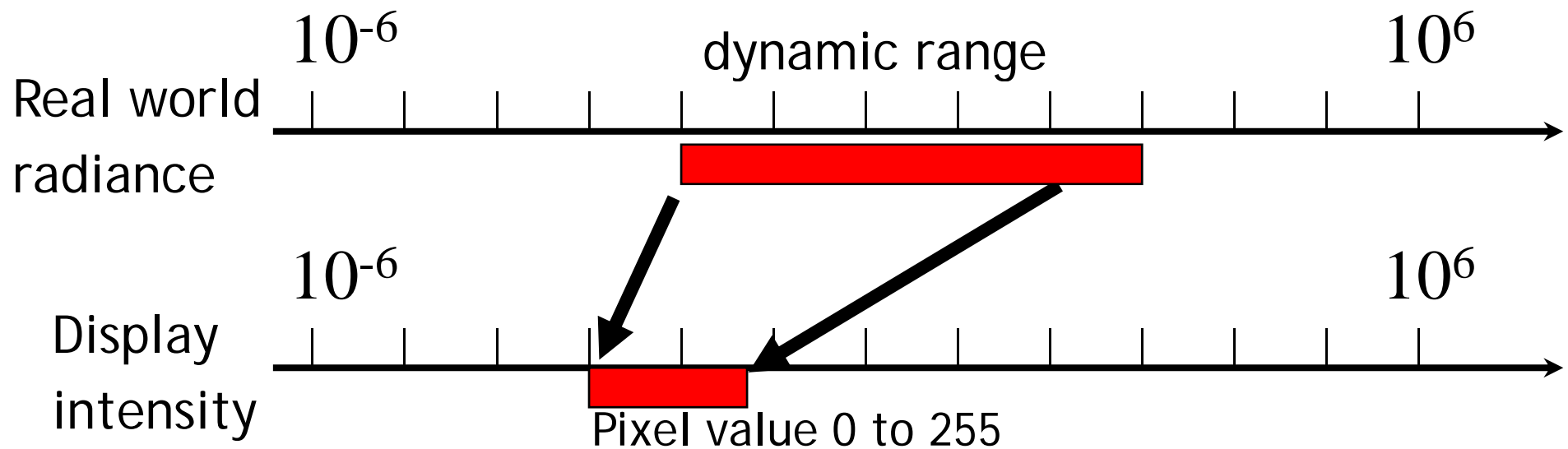*Yung-Yu Chuang*

with slides by Fredo Durand, and Alexei Efros
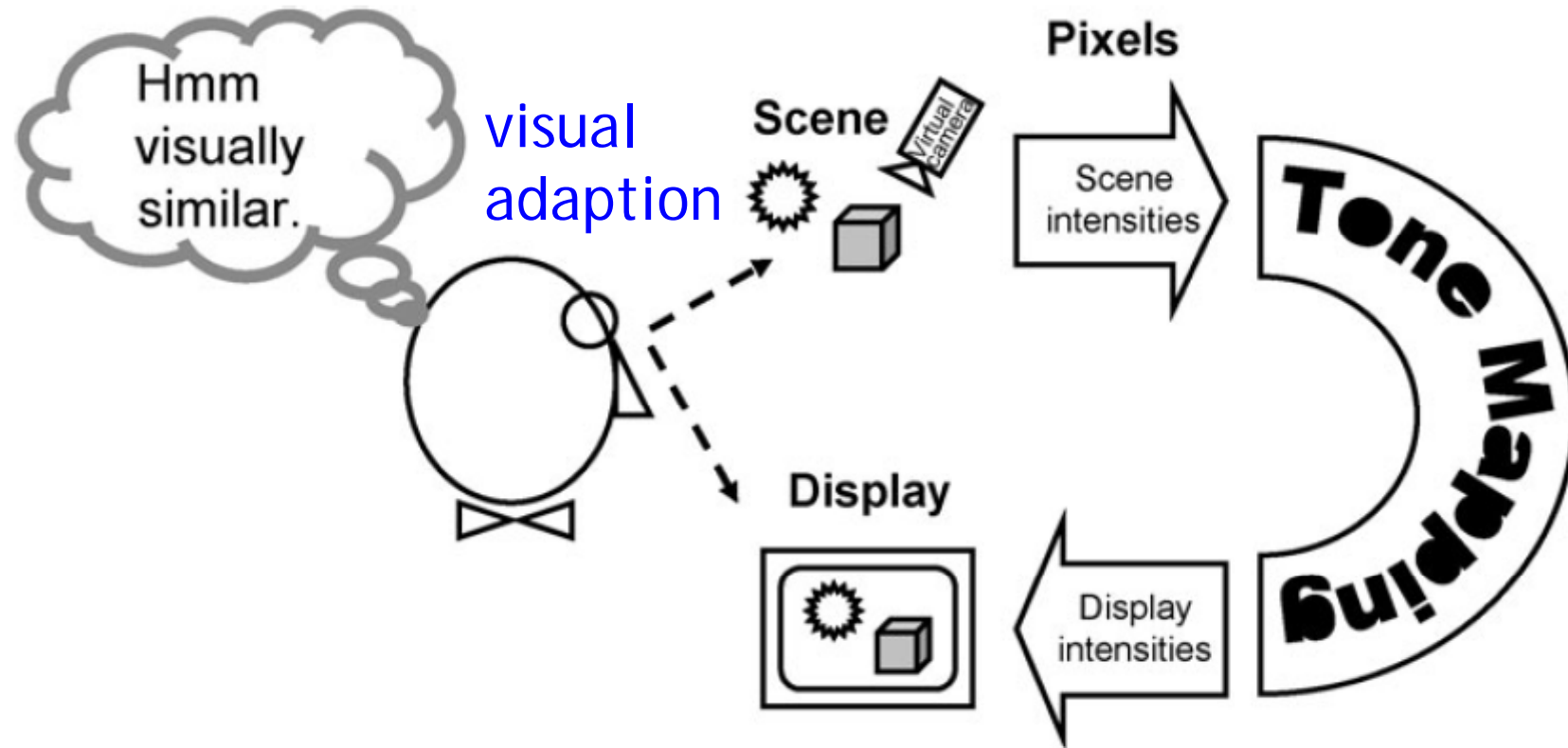
Tone mapping

- How should we map scene luminances (up to 1:100,000) to display luminances (only around 1:100) to produce a satisfactory image?

  Linear scaling?, thresholding?

CRT has 300:1 dynamic range

The ultimate goal is a visual match

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

Eye is not a photometer!

- Dynamic range along the visual pathway is only around 32:1.
- The key is adaptation

Eye is not a photometer!

Are the headlights different in two images? Physically, they are the same, but perceptually different.
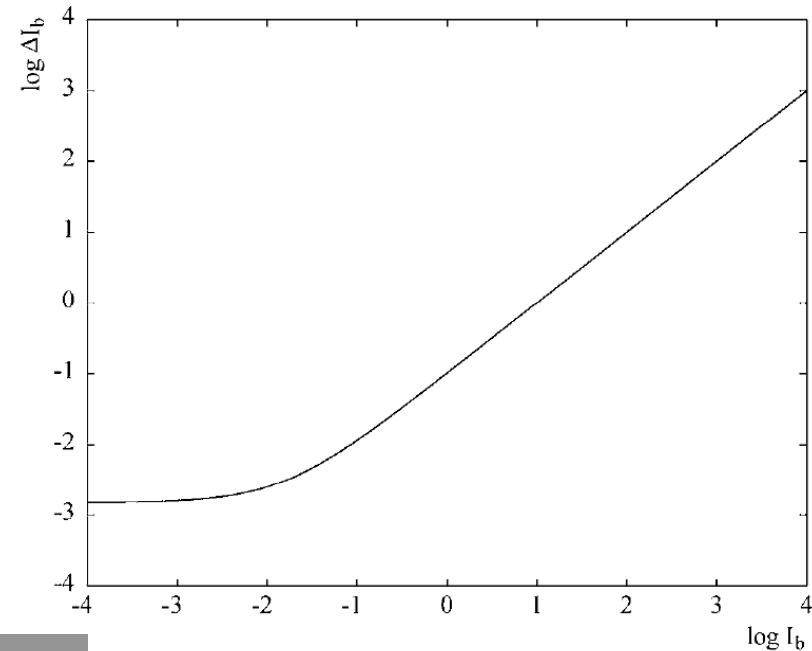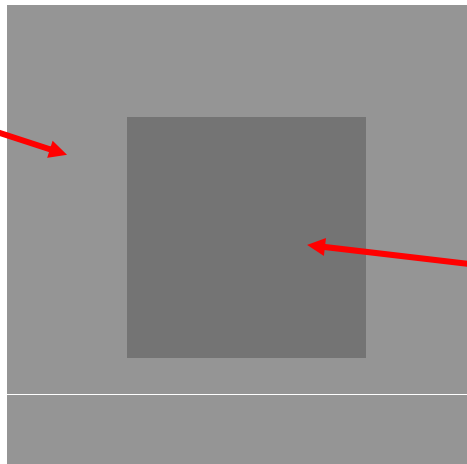
We are more sensitive to contrast

- Weber's law

Just-noticeable
Difference (JND)

$$\frac{\Delta I_b}{I_b} \sim 1\%$$

background
intensity

flash

How humans deal with dynamic range

- We're more sensitive to contrast (multiplicative)
  - A ratio of 1:2 is perceived as the same contrast as a ratio of 100 to 200
  - Makes sense because illumination has a multiplicative effect
  - Use the log domain as much as possible
- Dynamic adaptation (very local in retina)
  - Pupil (not so important)
  - Neural
  - Chemical
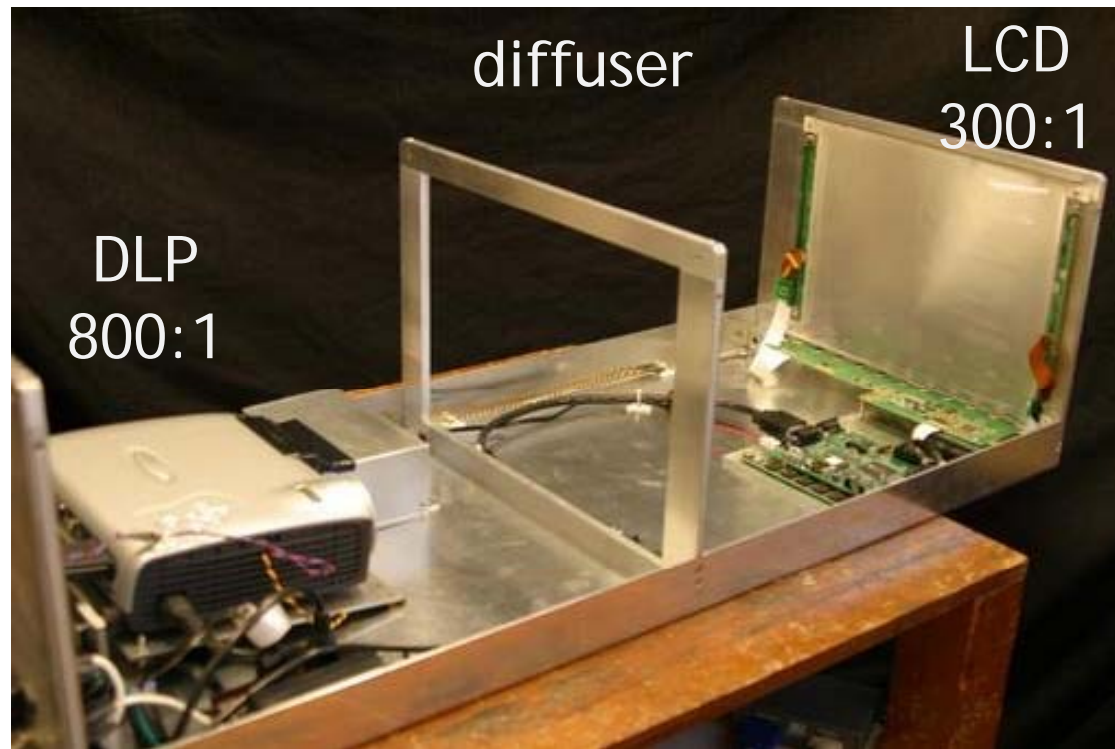- Different sensitivity to spatial frequencies

Preliminaries

- For color images

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

- Log domain is usually preferred.

HDR Display

- Once we have HDR images (either captured or synthesized), how can we display them on normal displays?
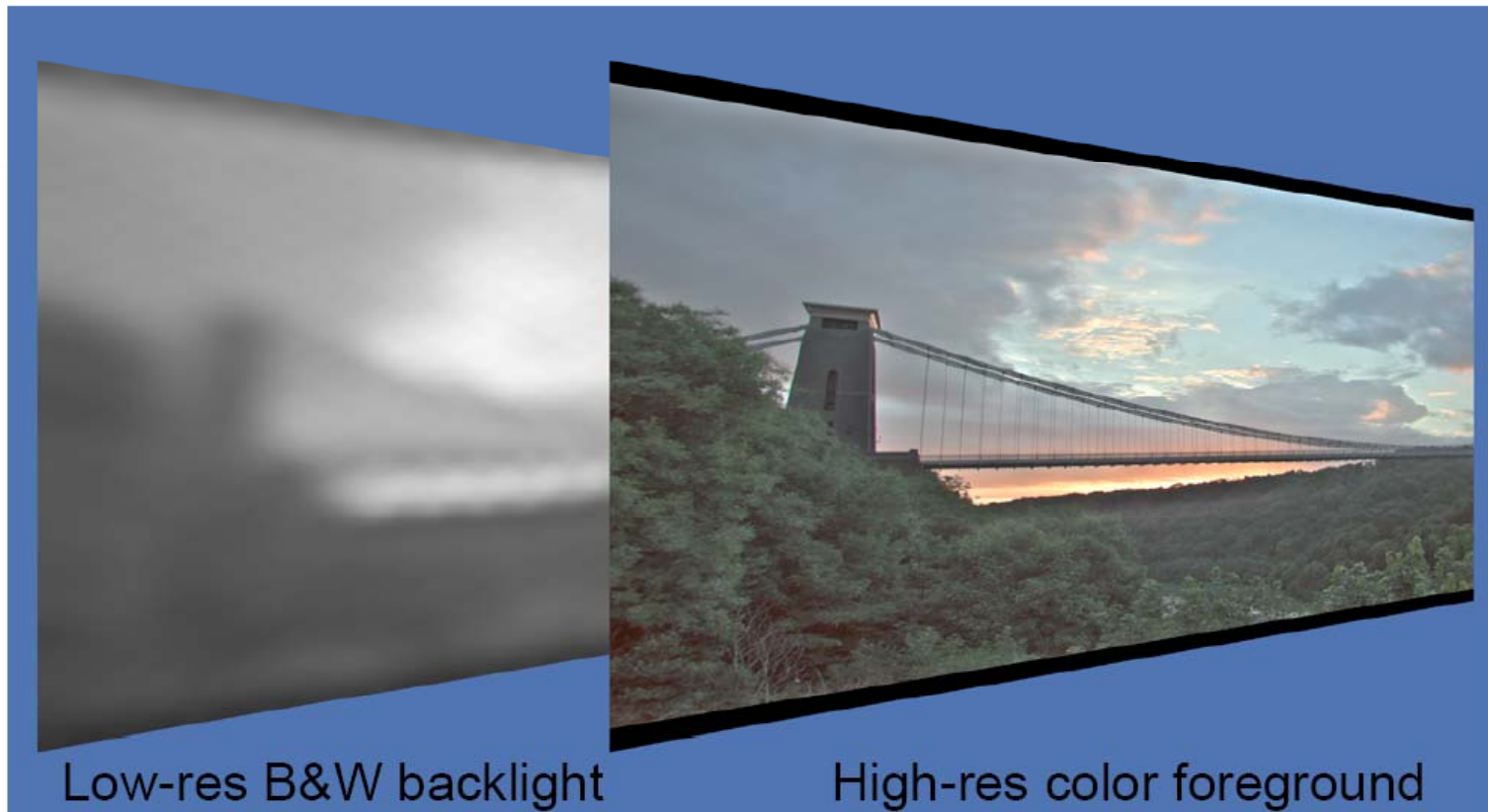

Theoretically, 240,000:1.

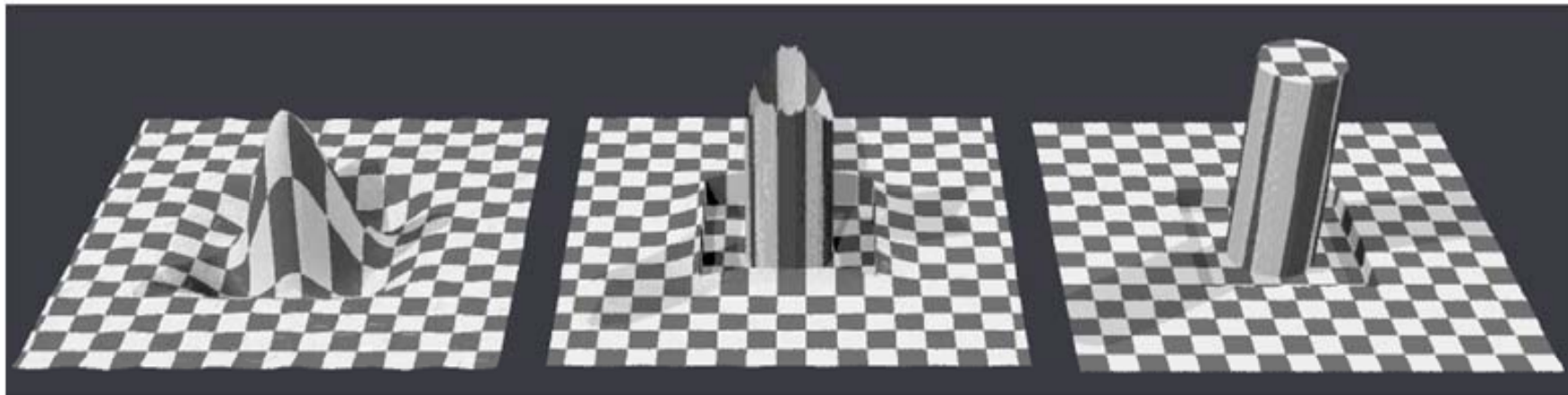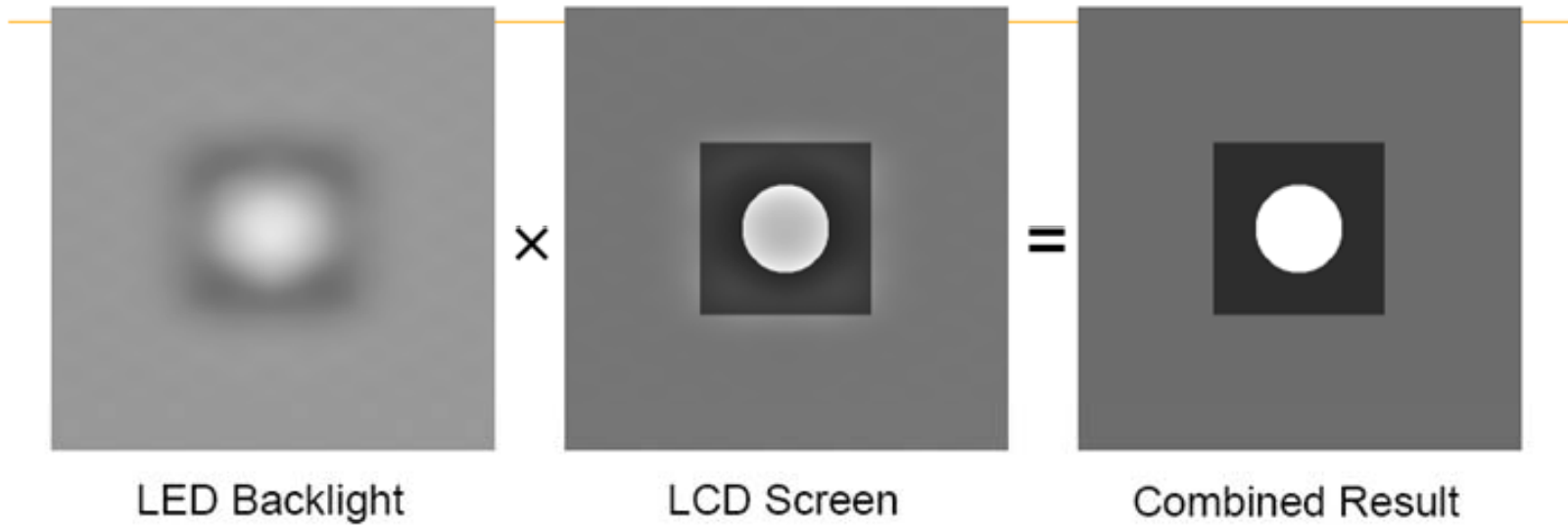Due to imperfect optical depth, 54,000:1 measured

HDR display system, Sunnybrook Technology, SIGGRAPH2004

Sunnybrook HDR display

- Use Bright Source + Two 8-bit Modulators
  - Transmission multiplies together
  - Over 10,000:1 dynamic range possible

Low-res B&W backlight　　　　High-res color foreground

Slide from the 2005 Siggraph course on HDR

How it works

LED Backlight × LCD Screen = Combined Result

Brightside HDR display

World's First Extreme Dynamic Range Display

37"

200000:1

Acquired by Dolby

Tone mapping operators

- Spatial (global/local)
- Frequency domain
- Gradient domain

- 3 papers from SIGGRAPH 2002
  - Photographic Tone Reproduction for Digital Images
  - Fast Bilateral Filtering for the Display of High-Dynamic-Range Images
  - Gradient Domain High Dynamic Range Compression

Photographic Tone Reproduction for Digital Images
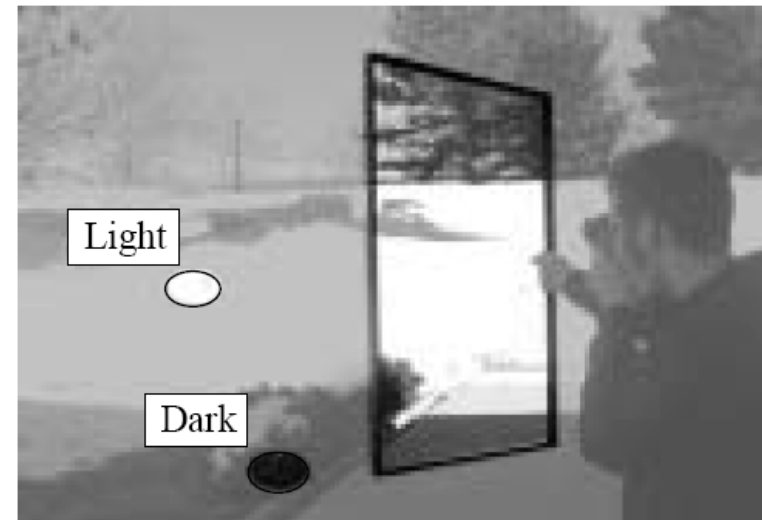
Erik Reinhard   Mike Stark

Peter Shirley   Jim Ferwerda

SIGGRAPH 2002

Photographic tone reproduction

- Proposed by Reinhard et. al. in SIGGRAPH 2002
- Motivated by traditional practice, zone system by Ansel Adams and dodging and burning
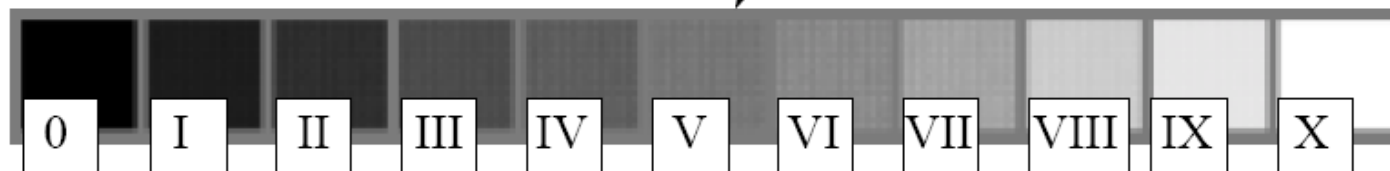- It contains both global and local operators

Zone system

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

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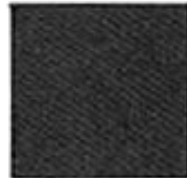

Source: Ansel Adams

The Zones

The Zones

0 Solid black; the same as the film rebate

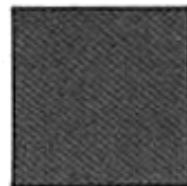**I** Nearly black; just different from Zone 0
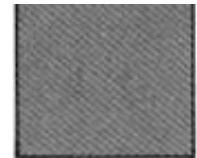
II The first hint of texture

III Textured shadow; the first recognizable shadow detail

IV Average shadow value on Caucasian skin, foliage and buildings
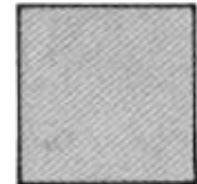
V Middle grey: the pivot value; light foliage, dark skin

VI Caucasian skin, textured light grey; shadow on snow

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

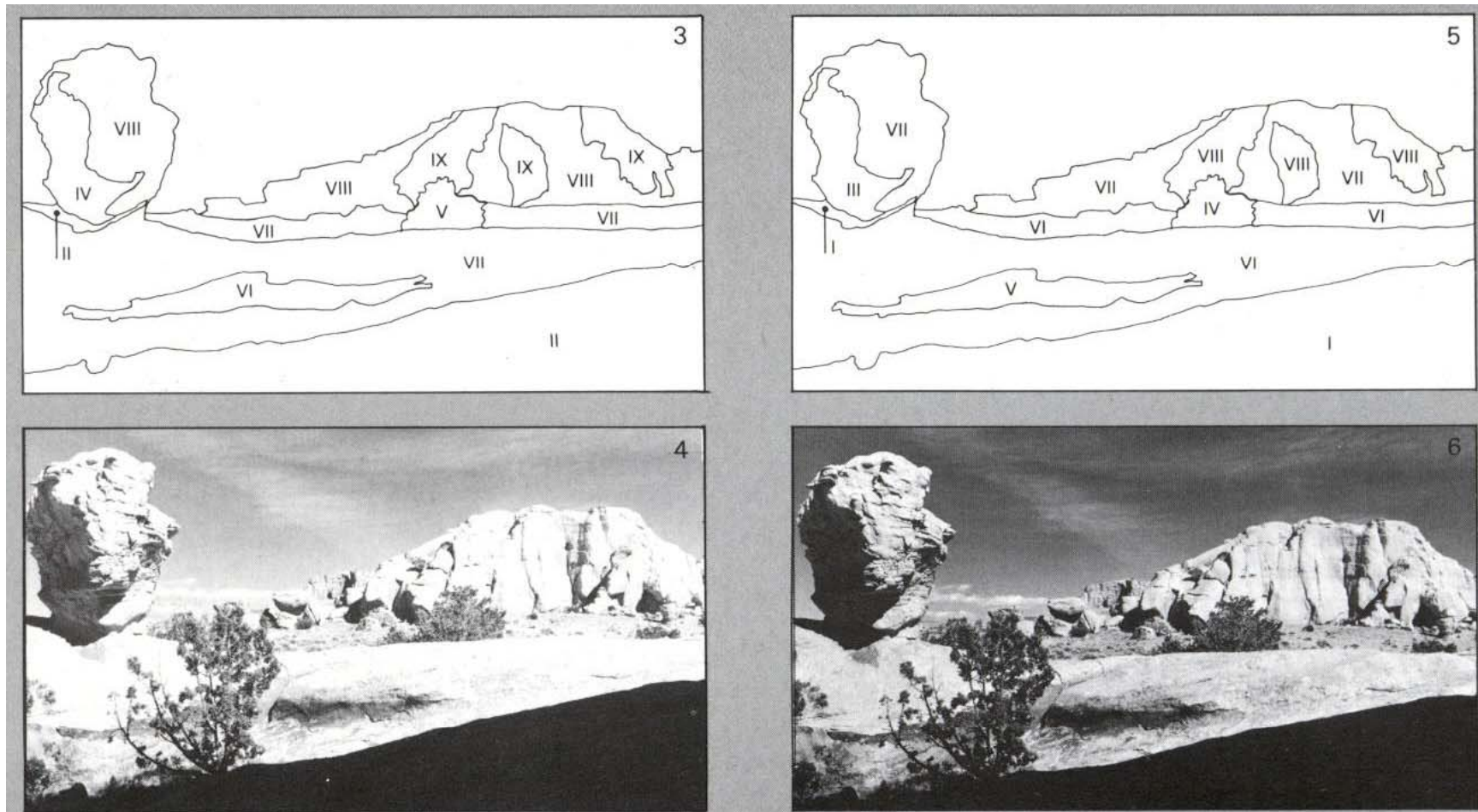**VIII** Highest zone with any texture
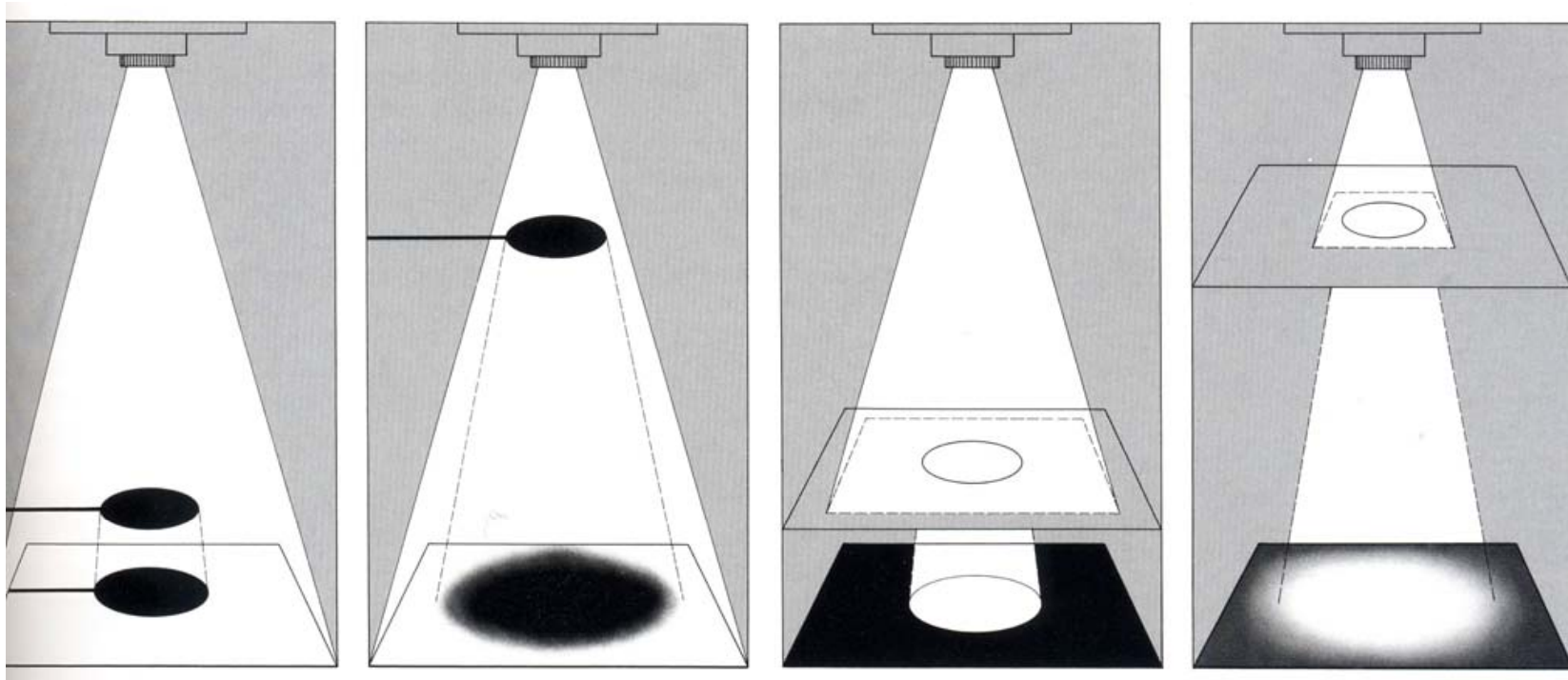
IX Pure untextured white

The Zone system

- You decide to put part of the system in a given zone
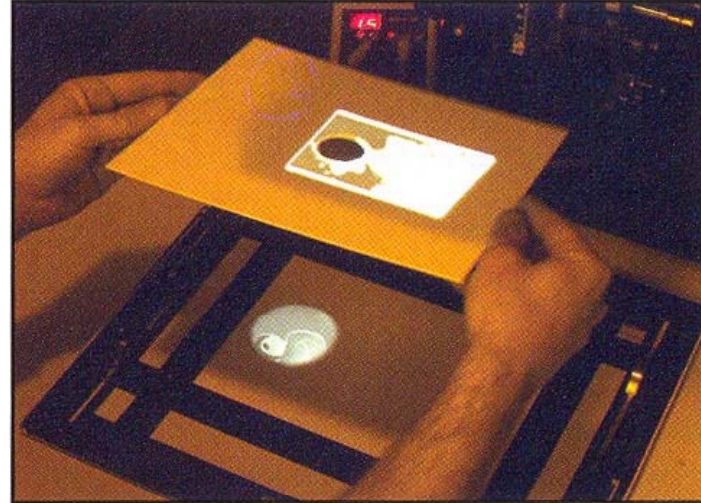
Dodging and burning

- During the print
- Hide part of the print during exposure
  - Makes it brighter

Dodging and burning
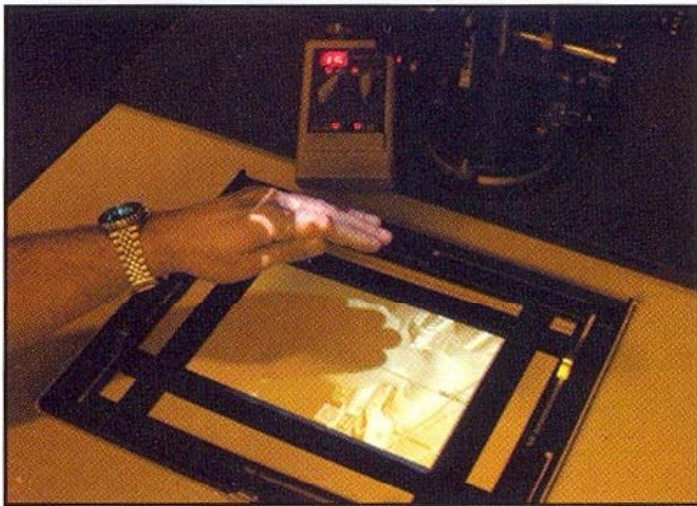
dodging

burning

From Photography by London et al.

Dodging and burning

- Must be done for every single print!
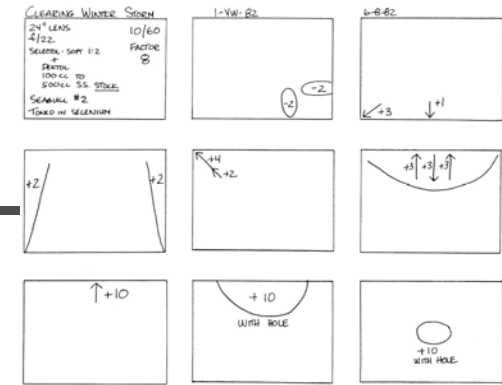
Straight print

After dodging and burning

Global operator

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

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

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

transfer function to compress high luminances

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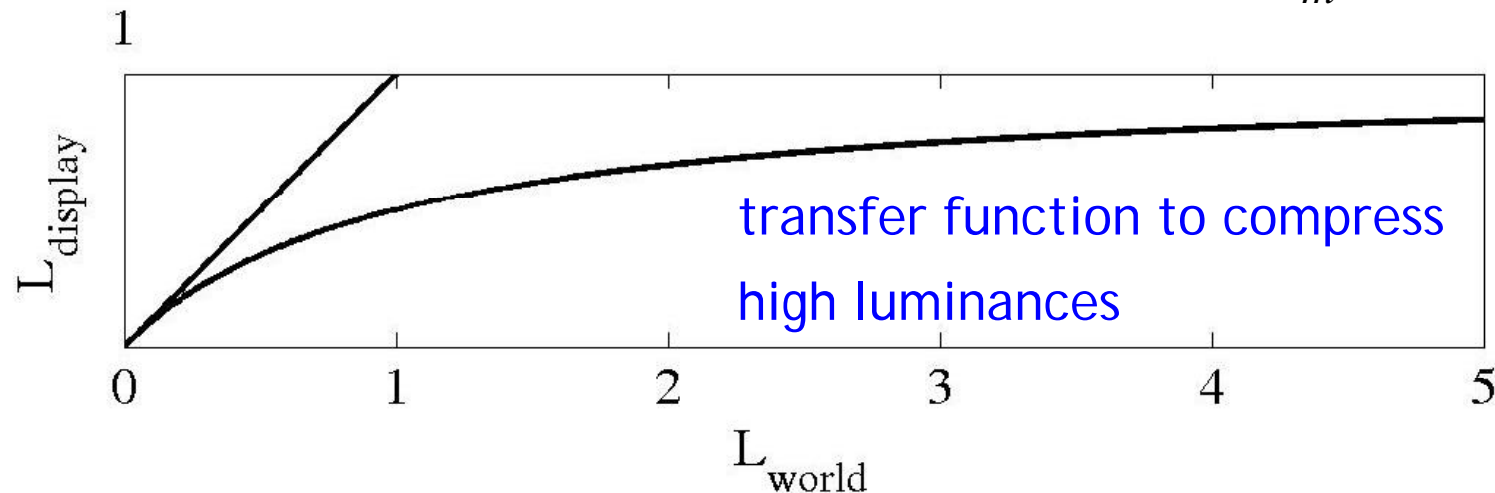
It seldom reaches 1 since the input image does not have infinitely large luminance values.

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

L_{white} is the smallest luminance to be mapped to 1
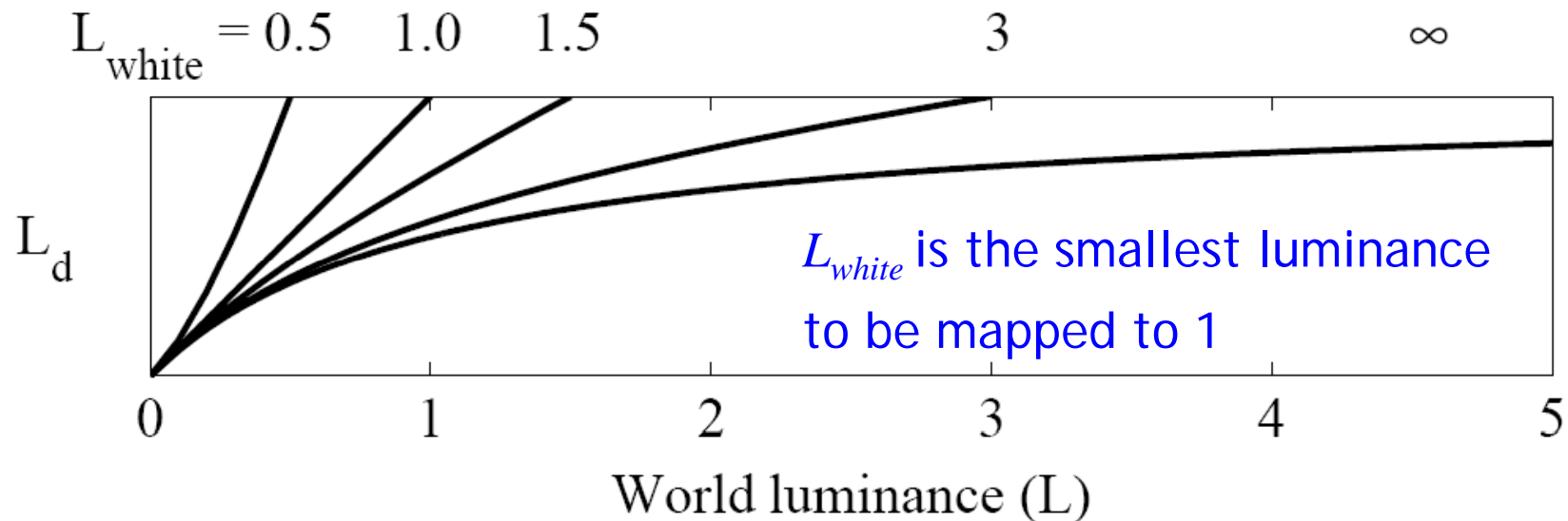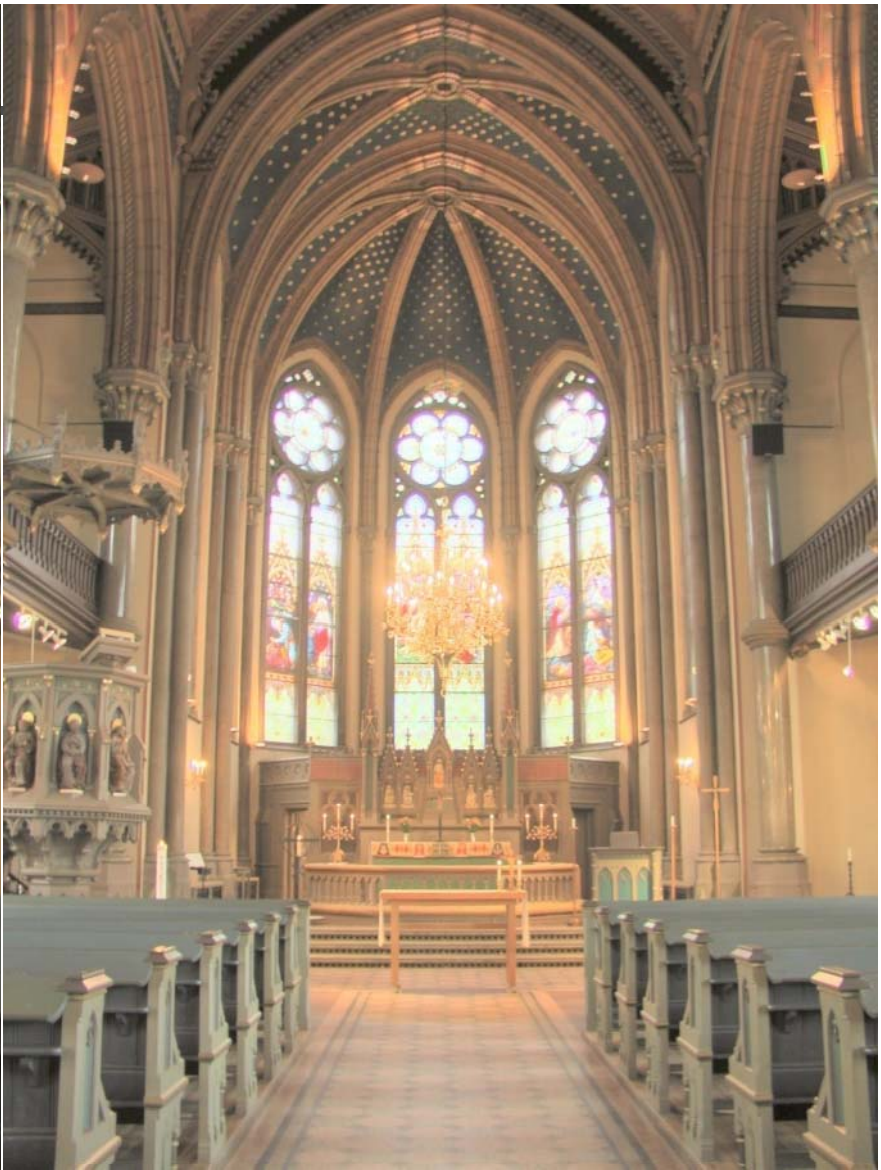
low key (0.18)   high key (0.5)

Dodging and burning (local operators)

- Area receiving a different exposure is often bounded by sharp contrast

- Find largest surrounding area without any sharp contrast

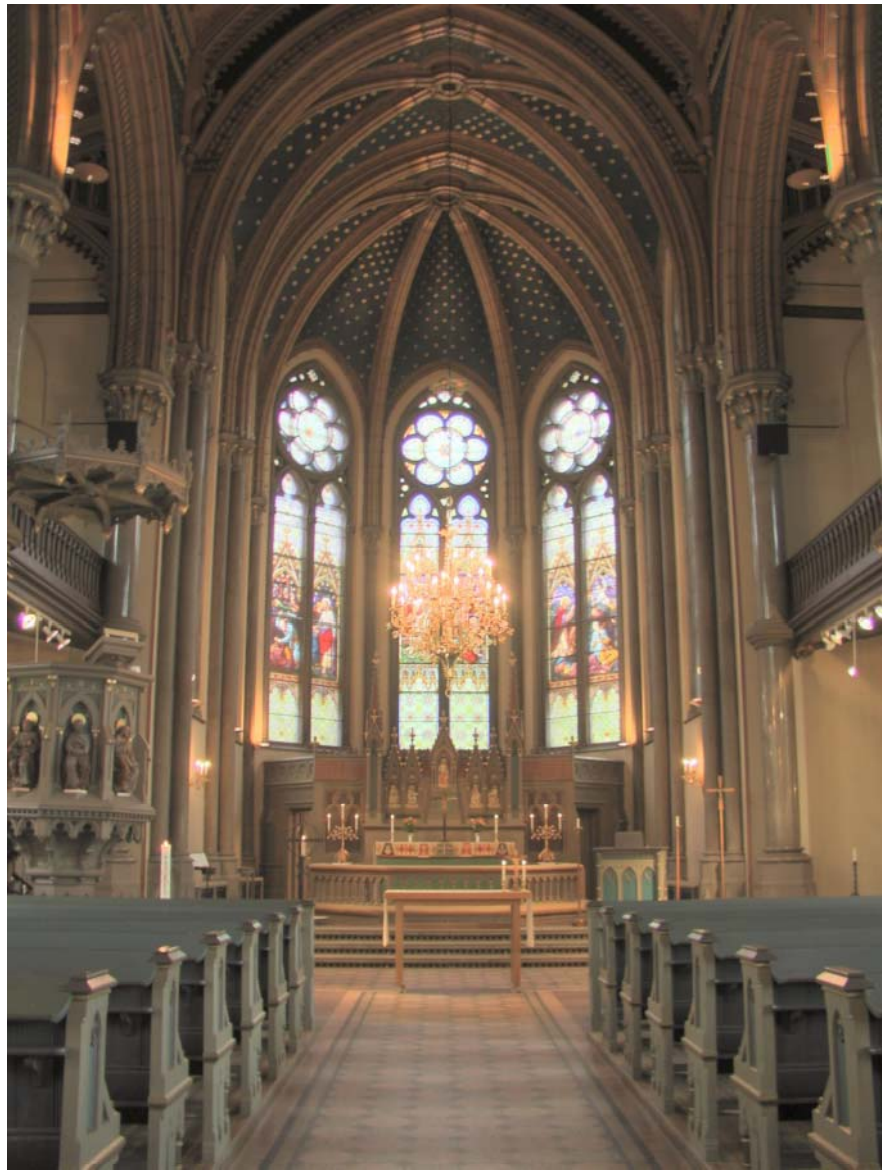$$L_s^{blur}(x, y) = L_m(x, y) \otimes G_s(x, y)$$

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

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

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

Dodging and burning

Simple operator

Dodging–and–burning
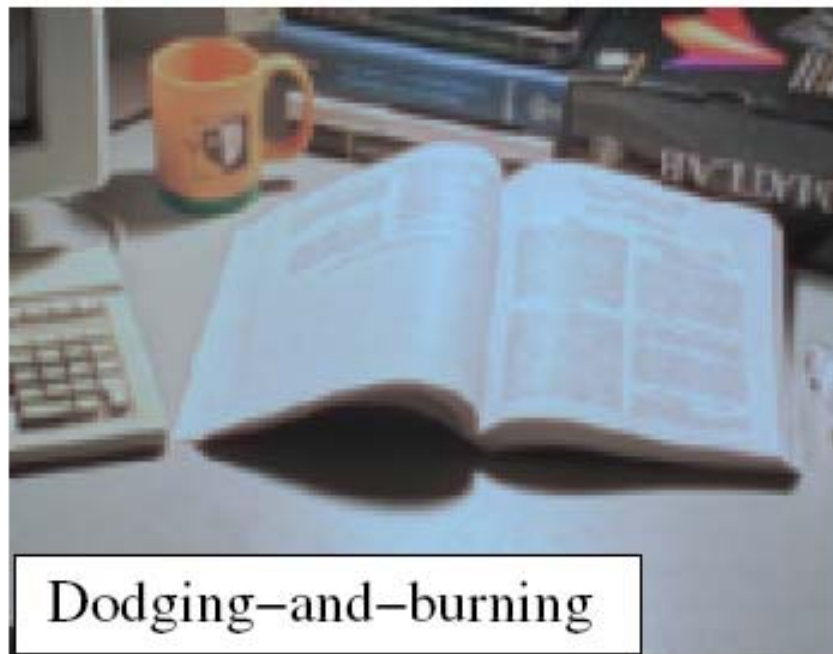
Frequency domain

- First proposed by Oppenheim in 1968!
- Under simplified assumptions,

image = illuminance * reflectance

low-frequency   high-frequency
attenuate more   attenuate less

Oppenheim

- Taking the logarithm to form density image
- Perform FFT on the density image
- Apply frequency-dependent attenuation filter

$$s(f) = (1-c) + c\frac{kf}{1+kf}$$

- Perform inverse FFT
- Take exponential to form the final image

Fast Bilateral Filtering for the Display of High-Dynamic-Range Images
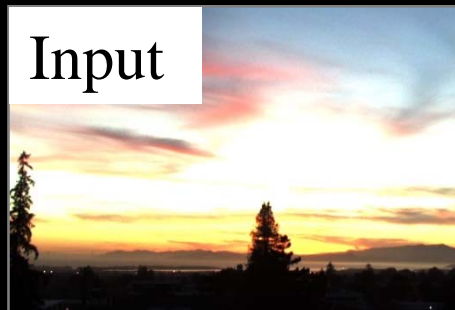
Frédo Durand & Julie Dorsey

SIGGRAPH 2002

A typical photo

- Sun is overexposed
- Foreground is underexposed

Gamma compression

- $X \rightarrow X^{\gamma}$

- Colors are washed-out

Input

Gamma

Gamma compression on intensity

- Colors are OK, but details (intensity high-frequency) are blurred
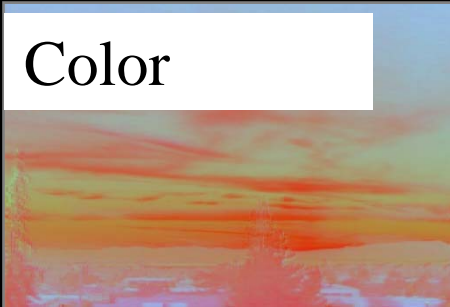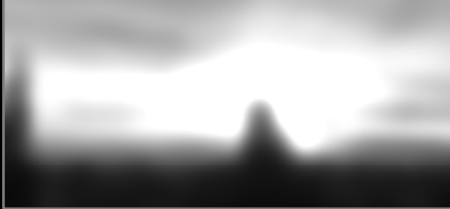

Intensity

Gamma on intensity

Color

Chiu et al. 1993

- Reduce contrast of low-frequencies
- Keep high frequencies

Low-freq.

High-freq.

Color

Reduce low frequency

The halo nightmare

- For strong edges
- Because they contain high frequency
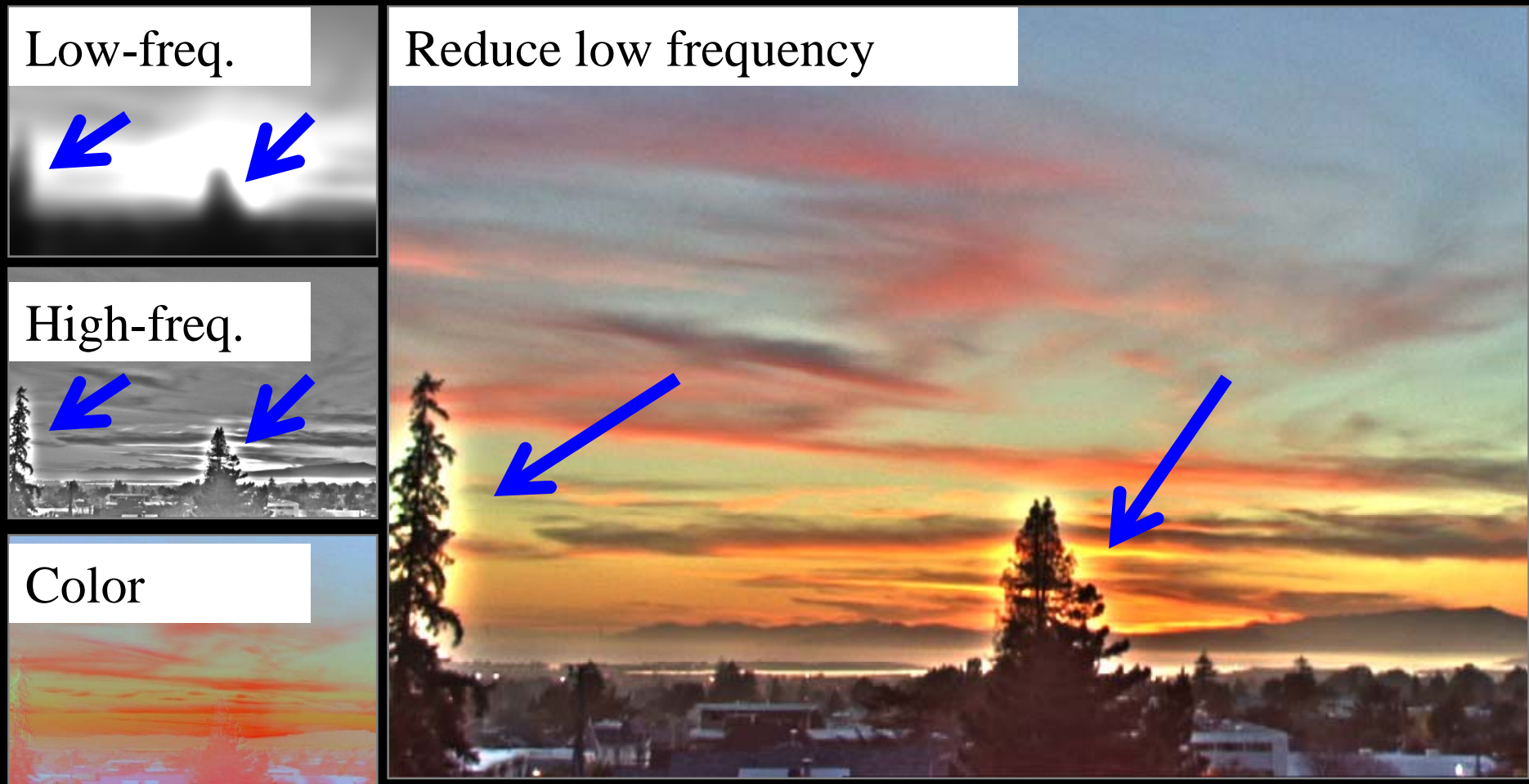
Durand and Dorsey

- Do not blur across edges
- Non-linear filtering

Large-scale

Detail

Color

Output
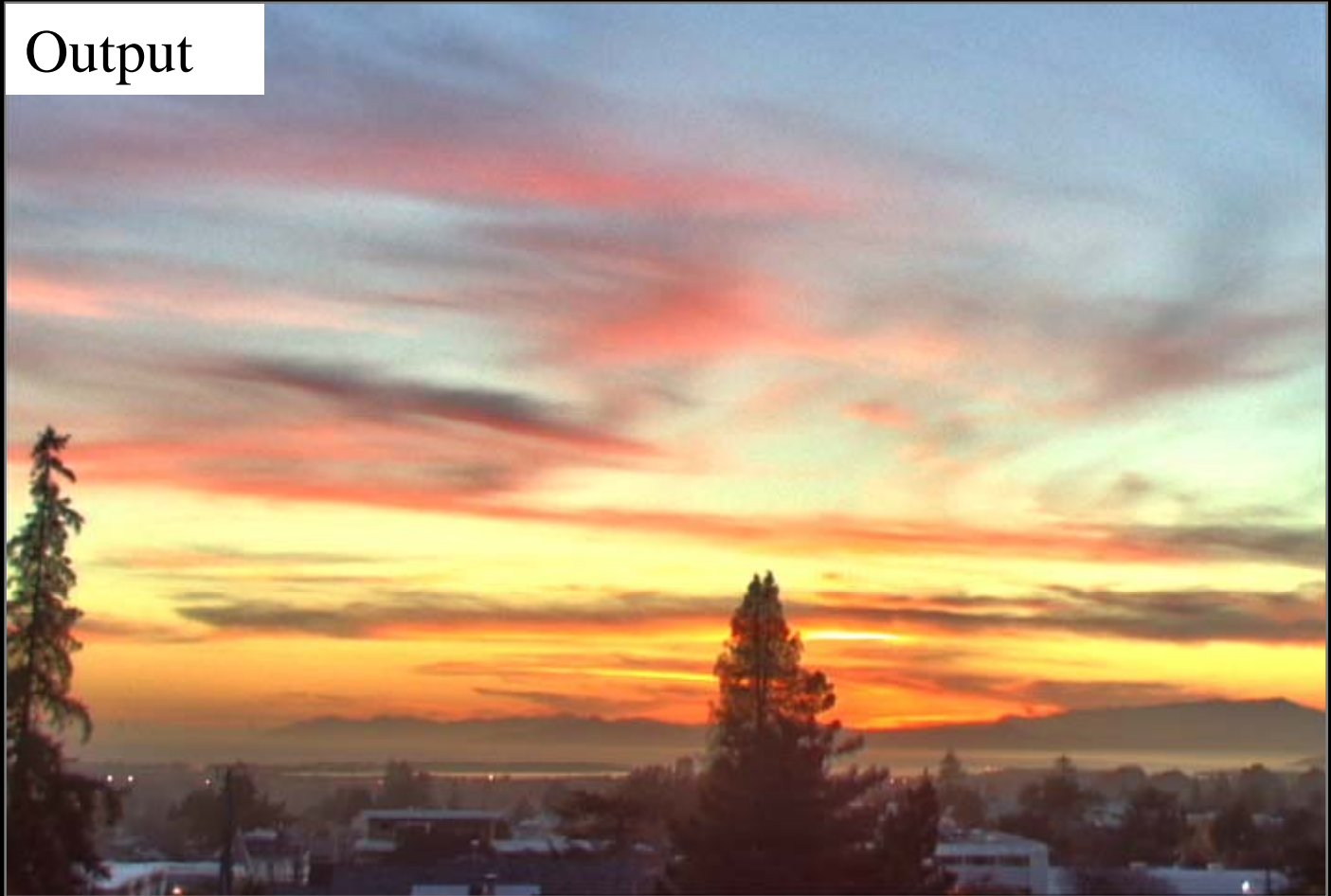
Edge-preserving filtering

- Blur, but not across edges

Input | Gaussian blur | Edge-preserving
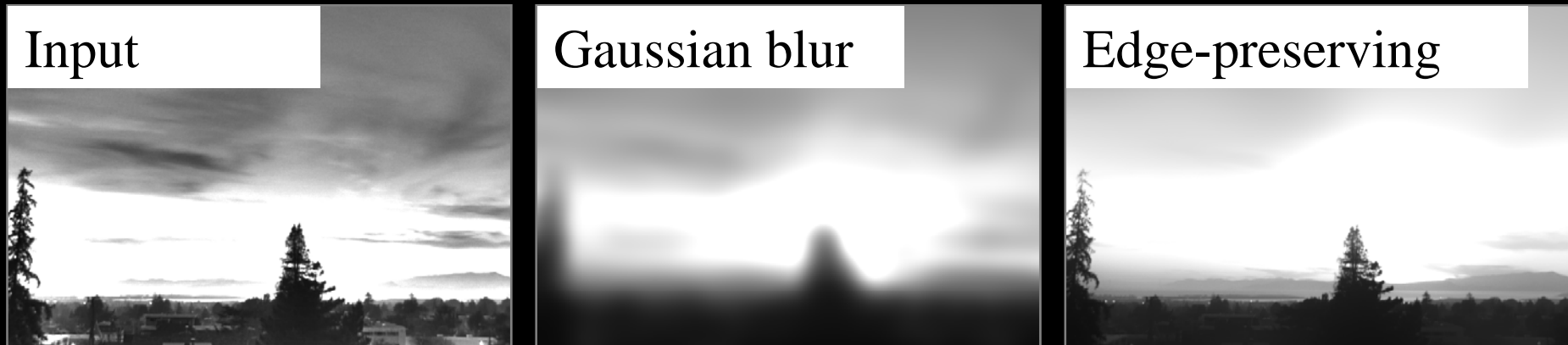
- Anisotropic diffusion [Perona & Malik 90]
  - Blurring as heat flow
  - LCIS [Tumblin & Turk]
- Bilateral filtering [Tomasi & Manduci, 98]

Start with Gaussian filtering

- Here, input is a step function + noise

output ⟵ input
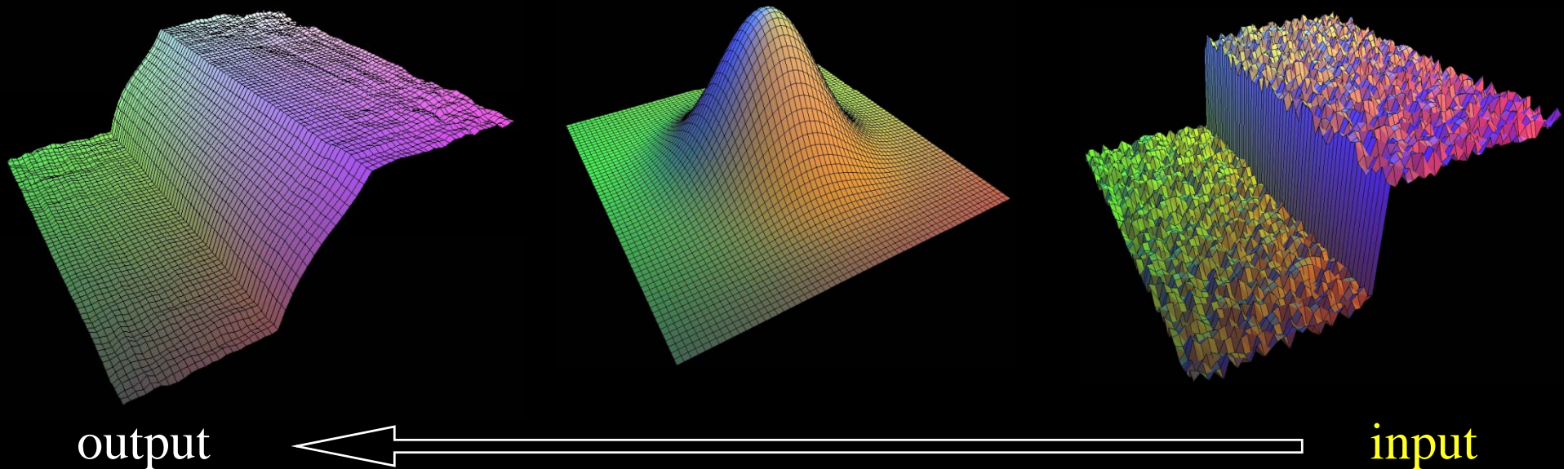
Start with Gaussian filtering

- Spatial Gaussian f

output ⟵ input
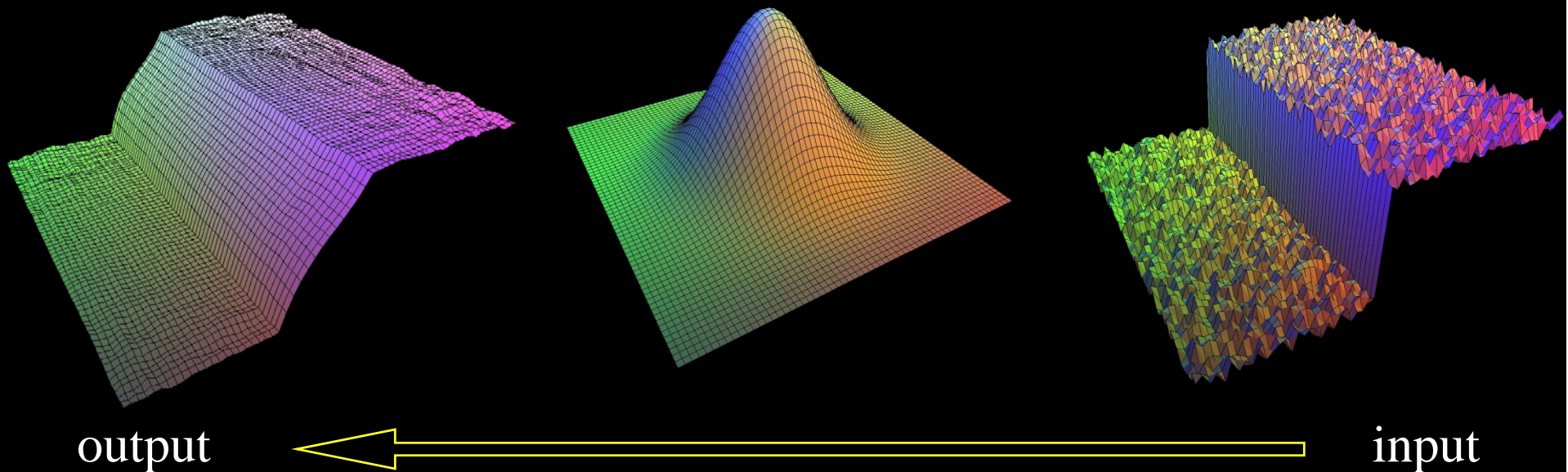
Start with Gaussian filtering

- Output is blurred

output $\longleftarrow$ input
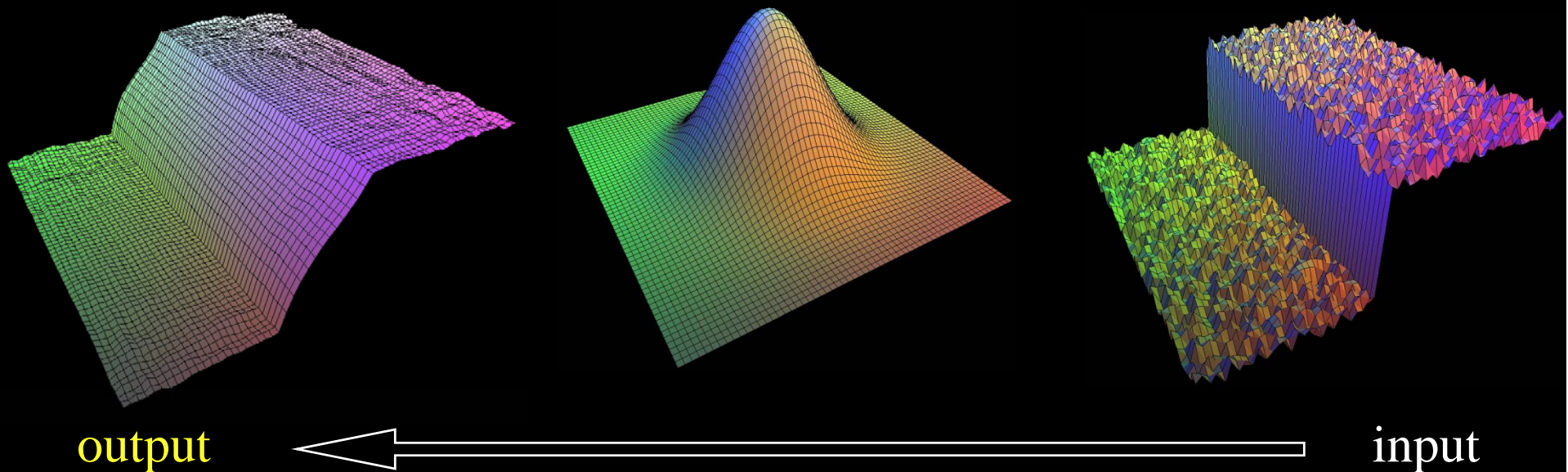
Gaussian filter as weighted average

output ⟸ input
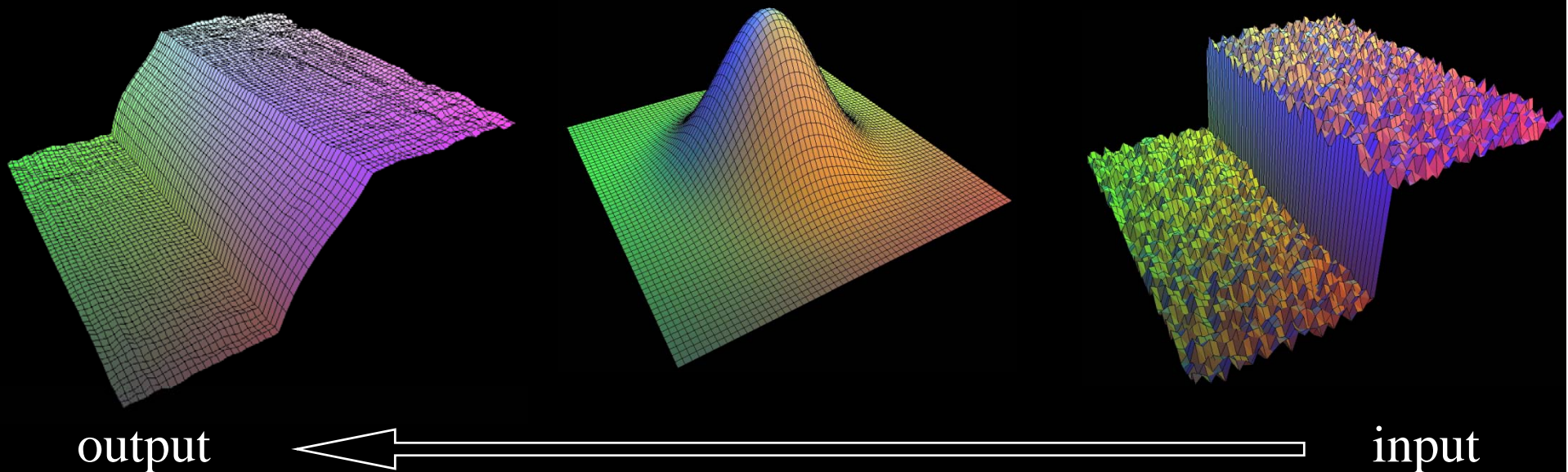
The problem of edges

- Here,   "pollutes" our estimate J(x)
- It is too different

output ⟸⟸⟸ input
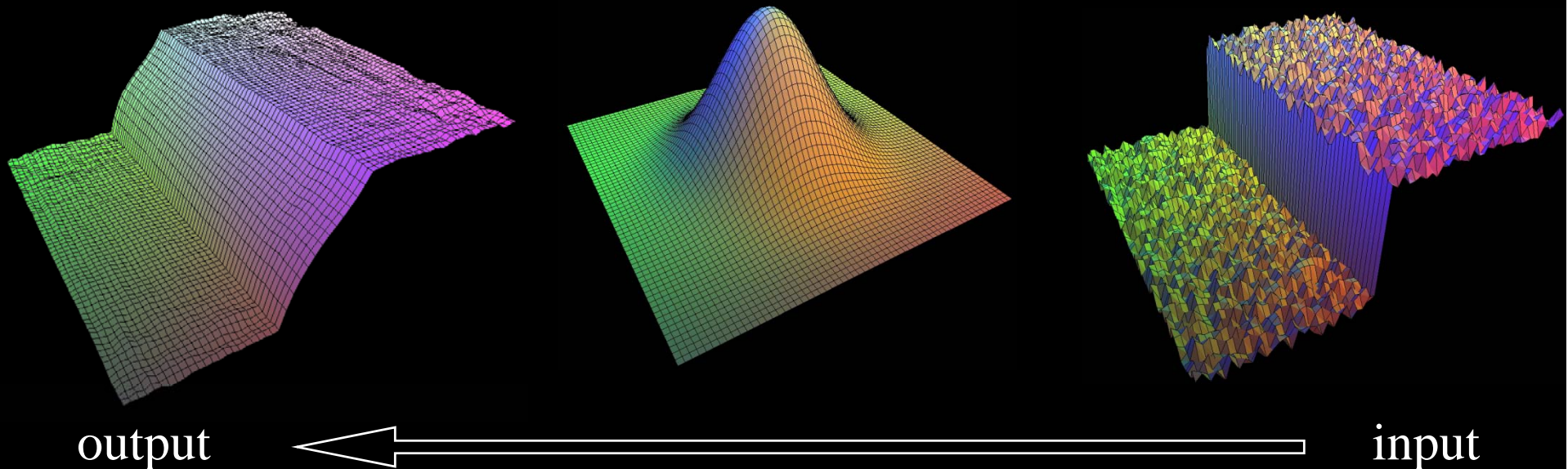
Principle of Bilateral filtering

- [Tomasi and Manduchi 1998]

- Penalty g on the intensity difference

output ⟸⟸⟸⟸⟸⟸⟸⟸⟸⟸⟸⟸⟸⟸⟸ input

Bilateral filtering

- [Tomasi and Manduchi 1998]

- Spatial Gaussian f

output ⟸ input
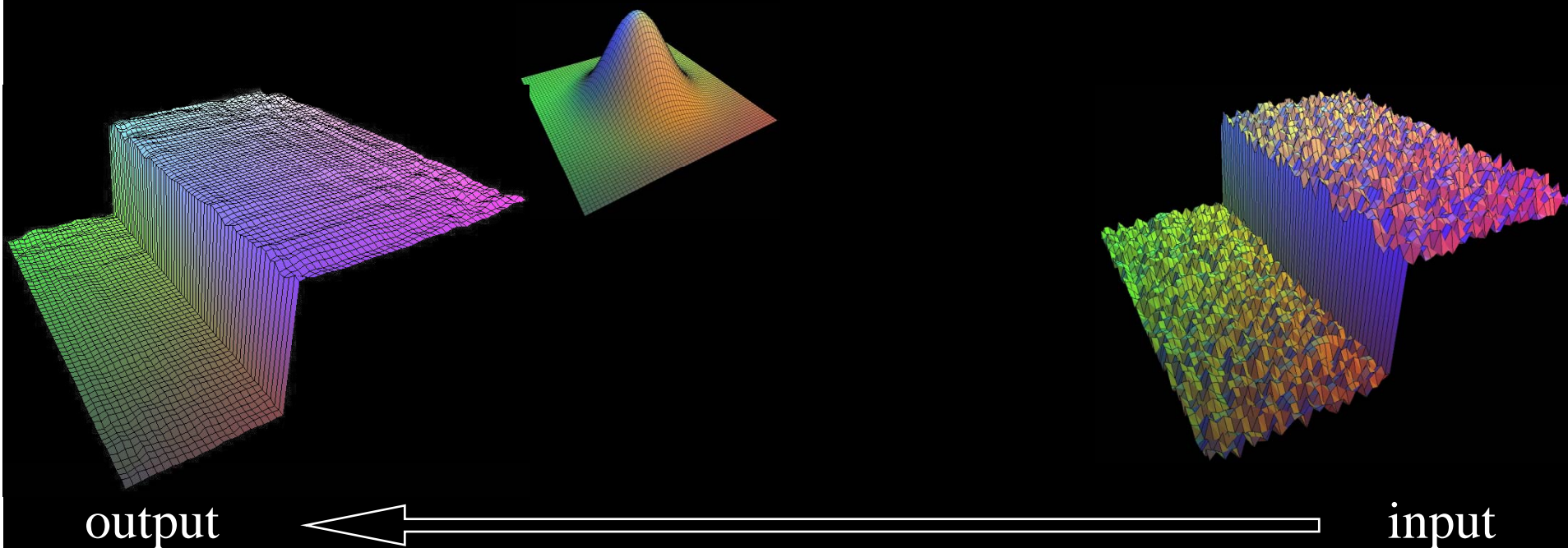
Bilateral filtering

- [Tomasi and Manduchi 1998]

- Spatial Gaussian f

- Gaussian g on the intensity difference
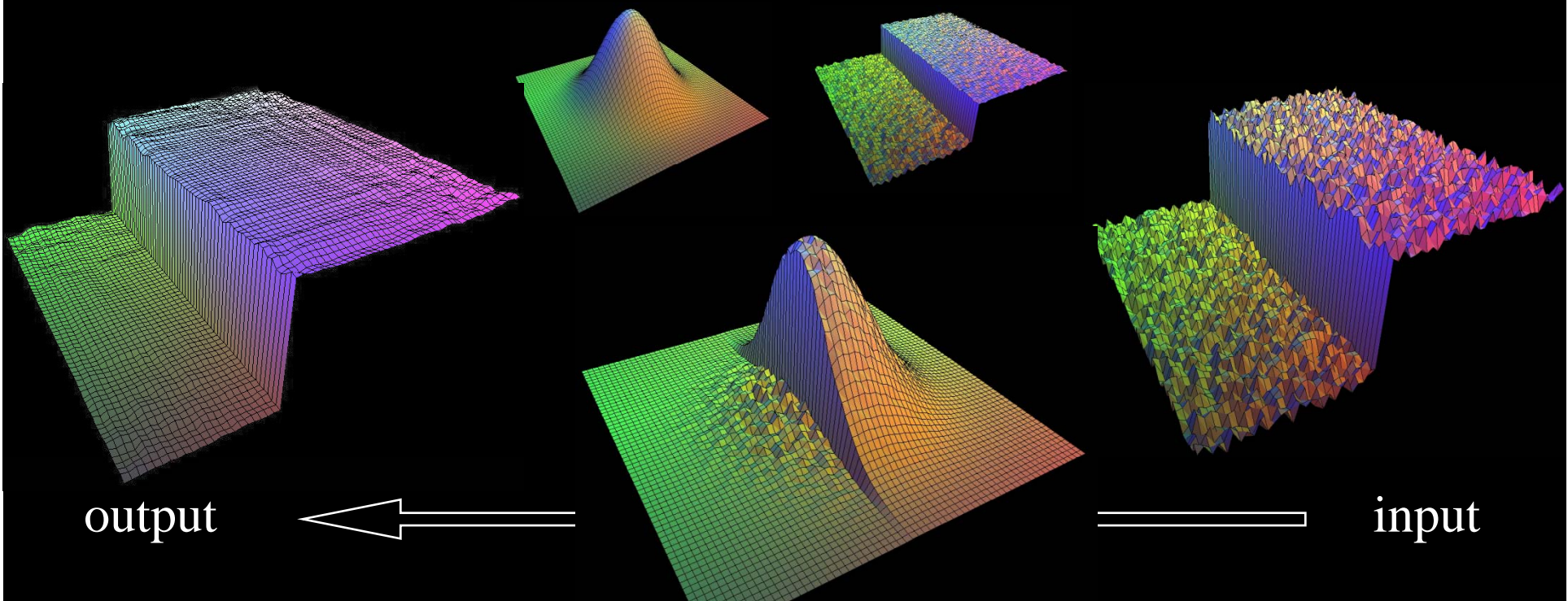
output ⟸   input

Normalization factor

- [Tomasi and Manduchi 1998]

- $k(x)=$
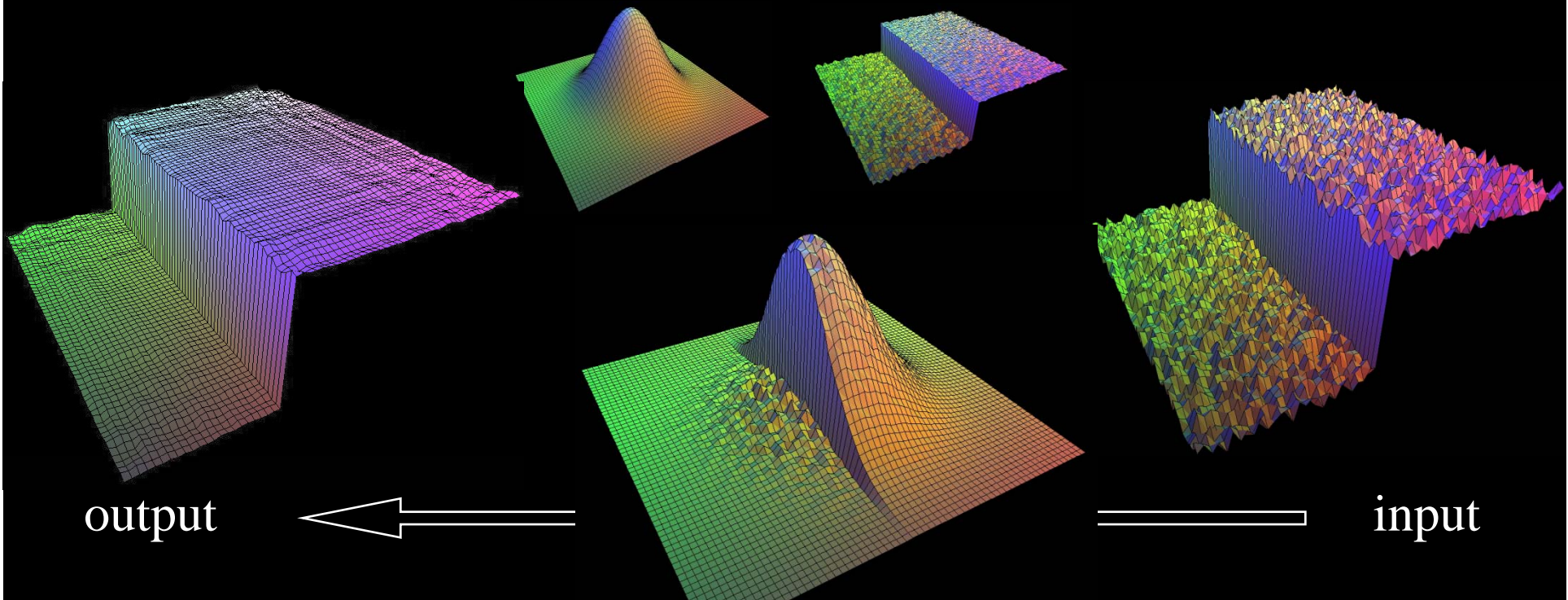
output ⟸ input

Bilateral filtering is non-linear

- [Tomasi and Manduchi 1998]
- The weights are different for each output pixel

output ⟸ input
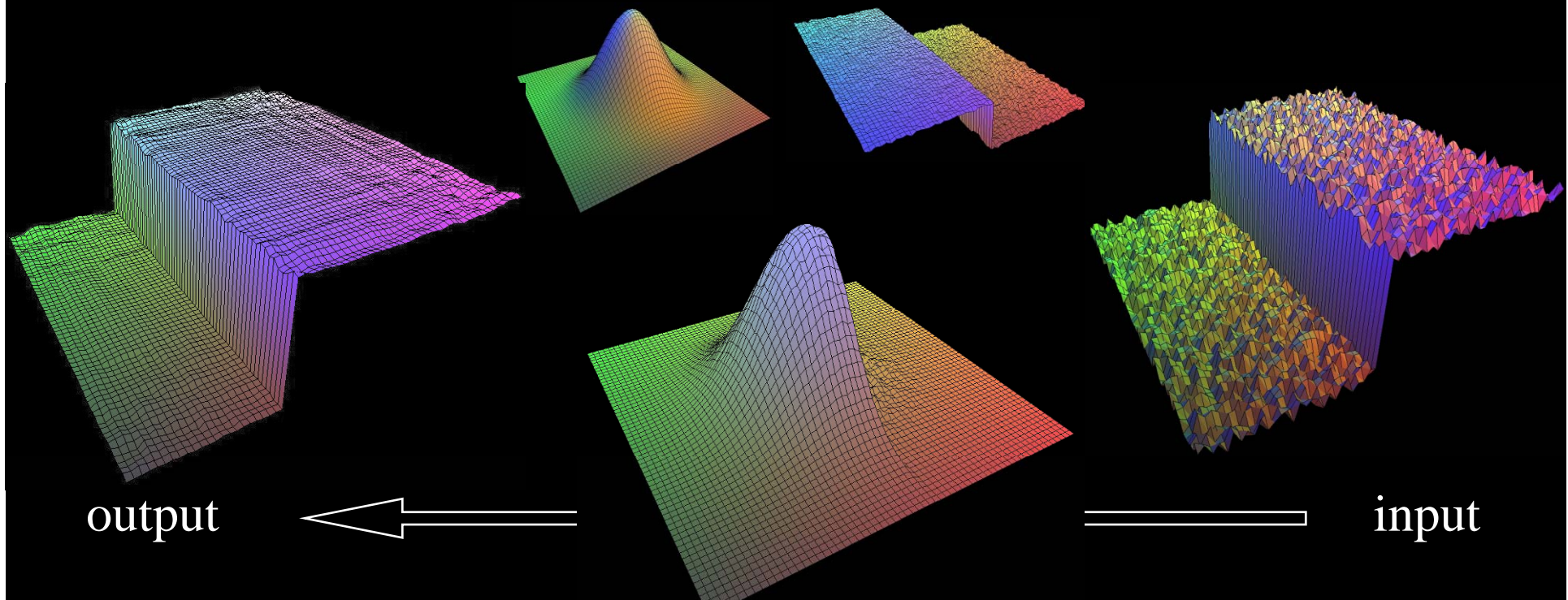
Contrast reduction
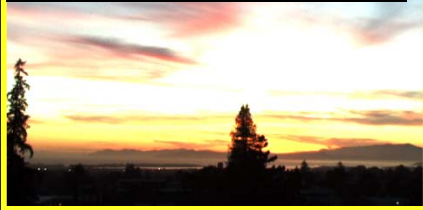
Input HDR image

Contrast
too high!

Contrast reduction

Input HDR image

Intensity

Color

Contrast reduction

Input HDR image

Intensity

Large scale

Fast
Bilateral
Filter

Color

Contrast reduction

Input HDR image

Intensity

Color

Fast
Bilateral
Filter

Large scale

Detail

Contrast reduction

Input HDR image

Intensity

Color

Fast
Bilateral
Filter

Large scale

Detail

Scale in log domain

Reduce
contrast

Large scale

Contrast reduction

Input HDR image

Intensity

Color

Fast
Bilateral
Filter

Large scale

Detail

Reduce
contrast

Preserve!

Large scale

Detail

Contrast reduction

Input HDR image

Output

Intensity

Fast
Bilateral
Filter

Large scale

Detail

Reduce
contrast

Preserve!
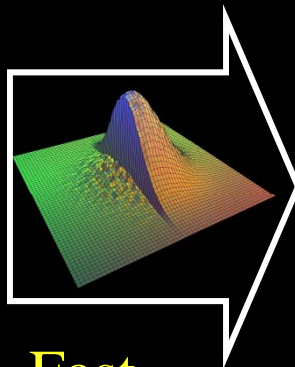
Large scale

Detail

Color

Color
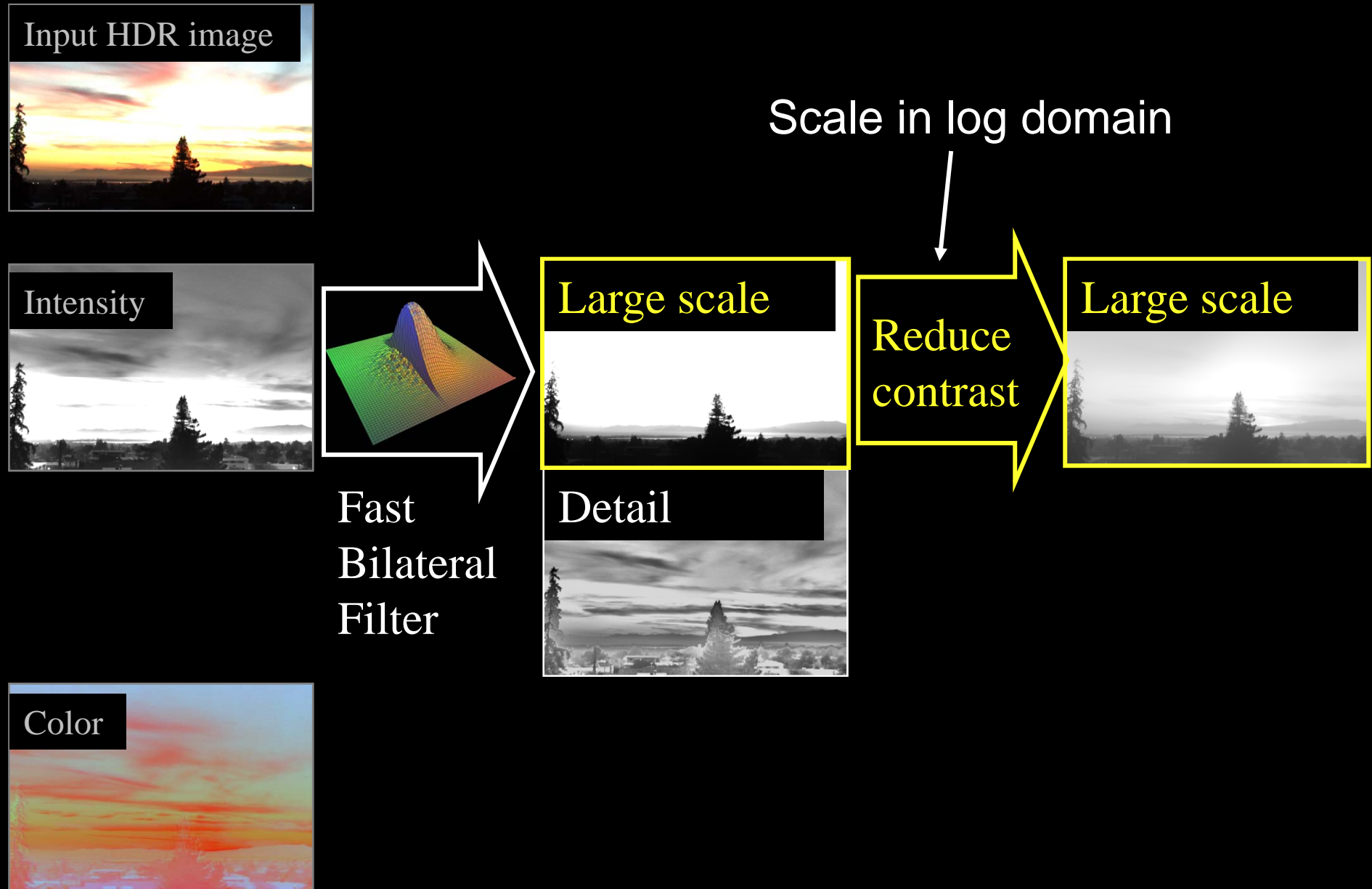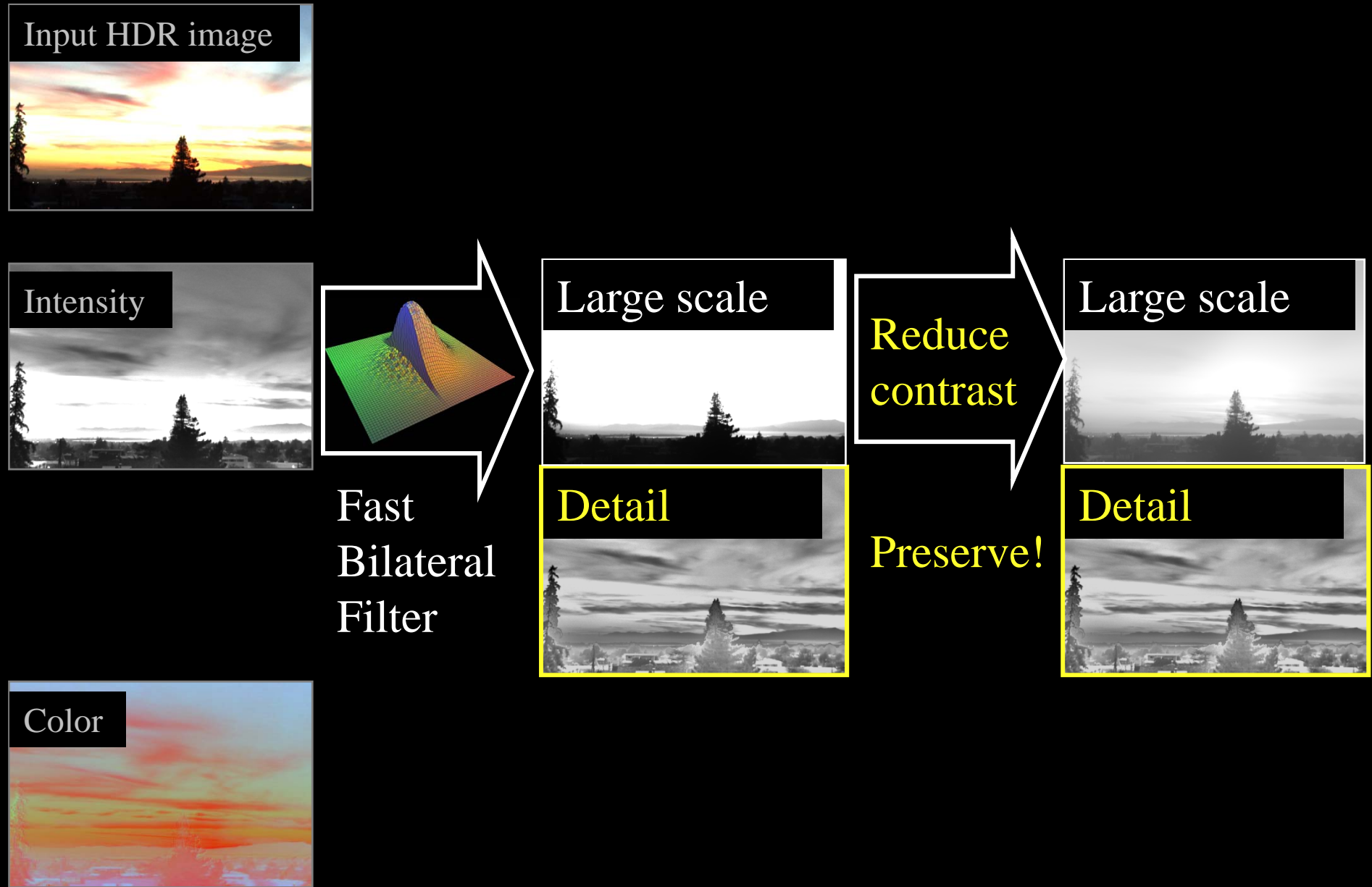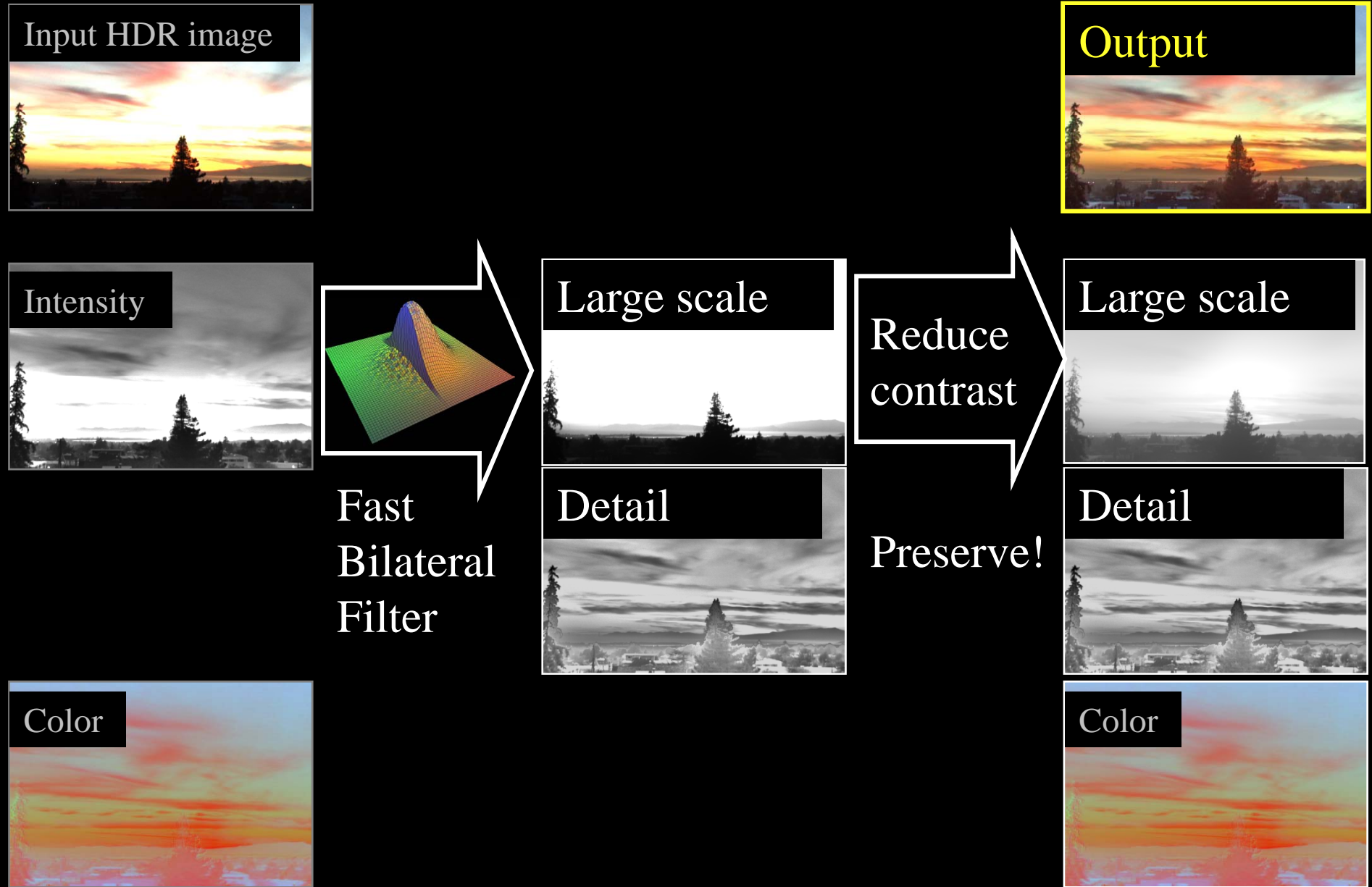
Bilateral filter is slow!

- Compared to Gaussian filtering, it is much slower because the kernel is not fixed.

- Durand and Dorsey proposed an approximate approach to speed up

- Paris and Durand proposed an even-faster approach in ECCV 2006. We will cover this one when talking about computational photogrphy.
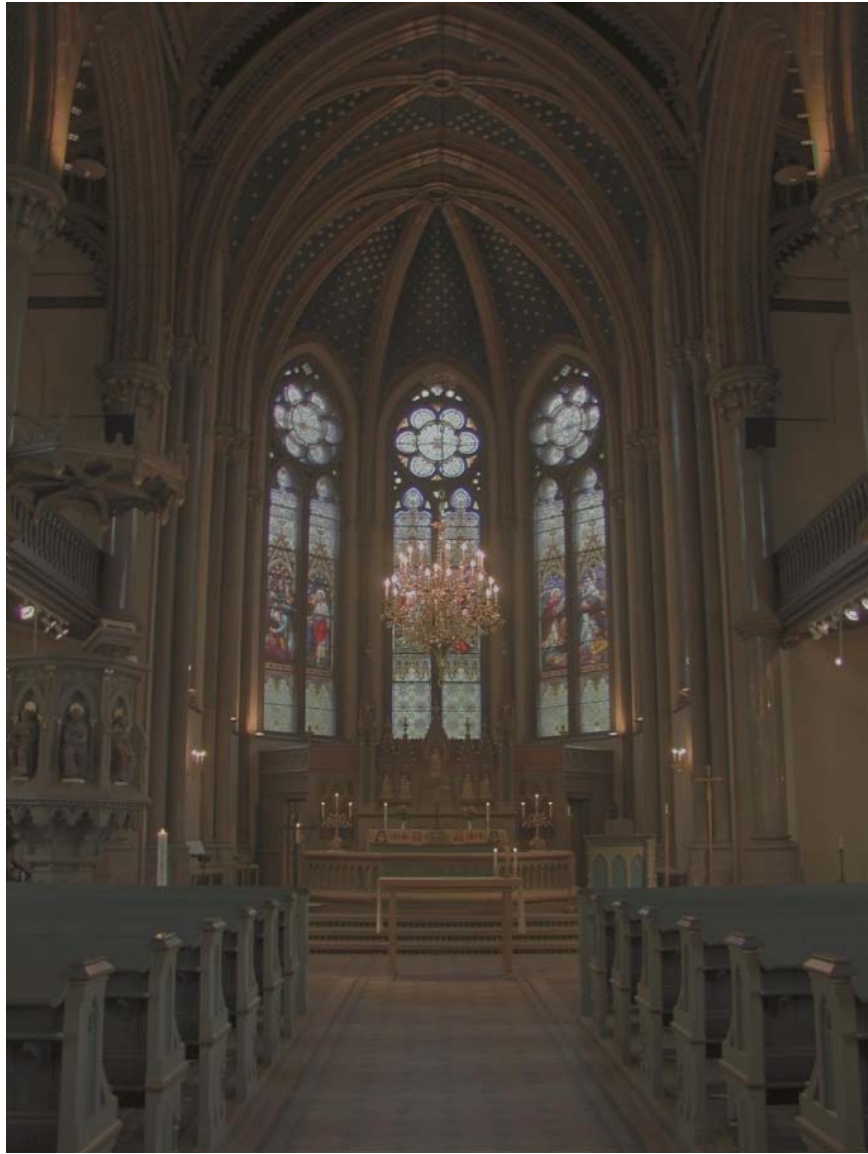
Oppenheim   bilateral

Gradient Domain High Dynamic Range Compression

Raanan Fattal   Dani Lischinski   Michael Werman

SIGGRAPH 2002

Log domain

- Logorithm is a crude approximation to the perceived brightness
- Gradients in log domain correspond to ratios (local contrast) in the luminance domain

The method in 1D
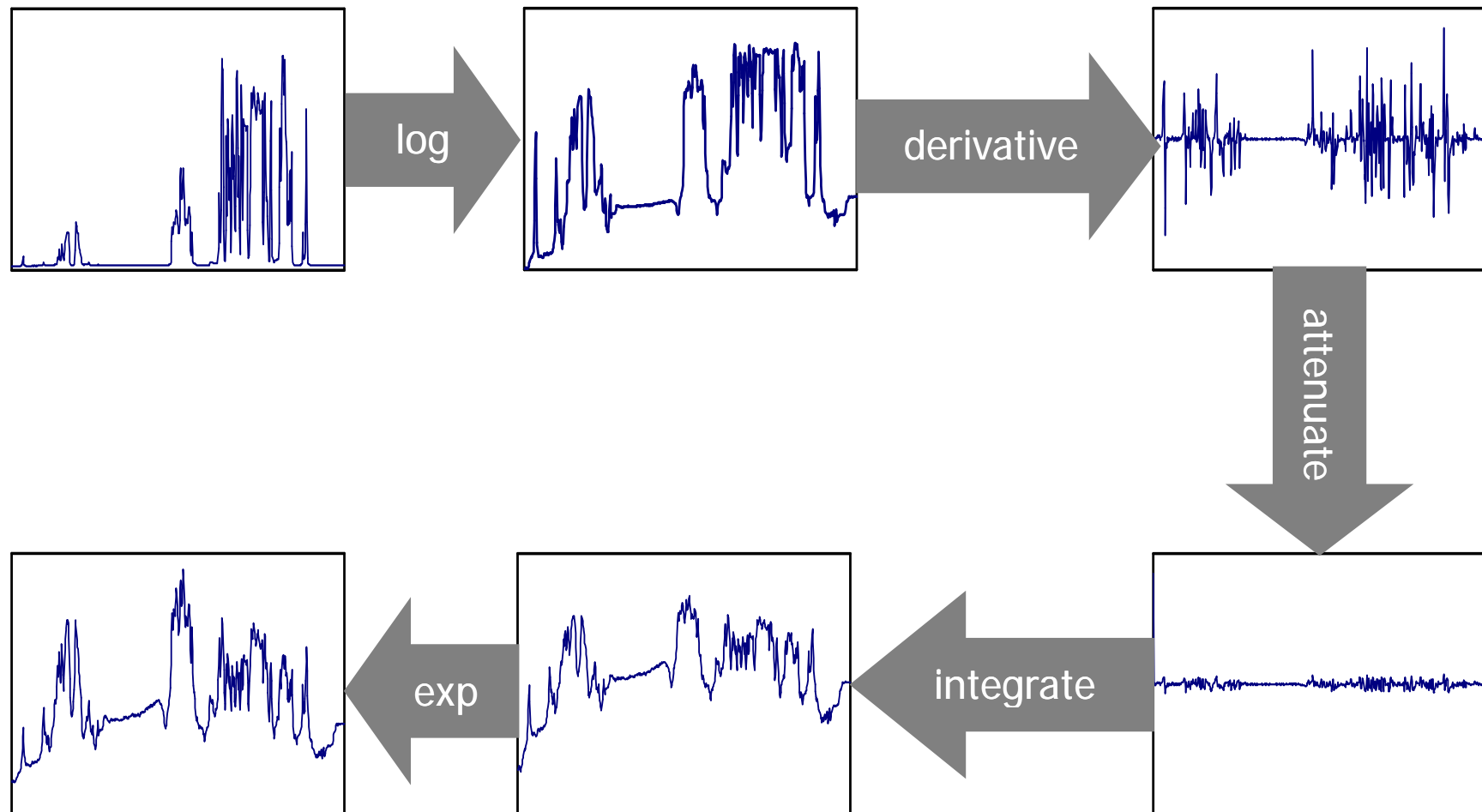
The method in 2D

- Given: a log-luminance image $H(x,y)$

- Compute an *attenuation map* $\Phi\big(\|\nabla H\|\big)$

- Compute an attenuated gradient field G:

$$G(x, y) = \nabla H(x, y) \cdot \Phi\big(\|\nabla H\|\big)$$

- Problem: G may not be integrable!

Solution

- Look for image I with gradient closest to G in the least squares sense.
- I minimizes the integral: $\iint F(\nabla I, G)\, dx dy$

$$F(\nabla I, G) = \|\nabla I - G\|^2 = \left(\frac{\partial I}{\partial x} - G_x \right)^2 + \left(\frac{\partial I}{\partial y} - G_y \right)^2$$

$$\Longrightarrow \quad \frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} = \frac{\partial G_x}{\partial x} + \frac{\partial G_y}{\partial y} \quad \text{Poisson equation}$$

Solve $\dfrac{\partial^2 I}{\partial x^2} + \dfrac{\partial^2 I}{\partial y^2} = \dfrac{\partial G_x}{\partial x} + \dfrac{\partial G_y}{\partial y}$

$$G_x(x, y) - G_x(x-1, y) + G_y(x, y) - G_y(x, y-1)$$

$$I(x+1, y) + I(x-1, y) + I(x, y+1) + I(x, y-1) - 4I(x, y)$$

$$\begin{bmatrix} \;.. 1 \;... \quad 1 \text{-}4 \; 1 \;... \quad 1 \;.. \end{bmatrix} \begin{bmatrix} \mathbf{I} \end{bmatrix} = \begin{bmatrix} \; \end{bmatrix}$$

Solving Poisson equation

- No analytical solution
- Multigrid method
- Conjugate gradient method

Attenuation

- Any dramatic change in luminance results in large luminance gradient at some scale
- Edges exist in multiple scales. Thus, we have to detect and attenuate them at multiple scales
- Construct a Gaussian pyramid H_i

Attenuation

$$\varphi_k(x, y) = \left(\frac{\|\nabla H_k(x, y)\|}{\alpha} \right)^{\beta - 1} \quad \beta \sim 0.8$$

$$\alpha = 0.1\overline{\nabla H}$$
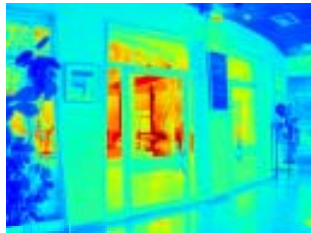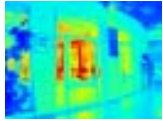
log(Luminance)　　　gradient magnitude　　　attenuation map

Multiscale gradient attenuation
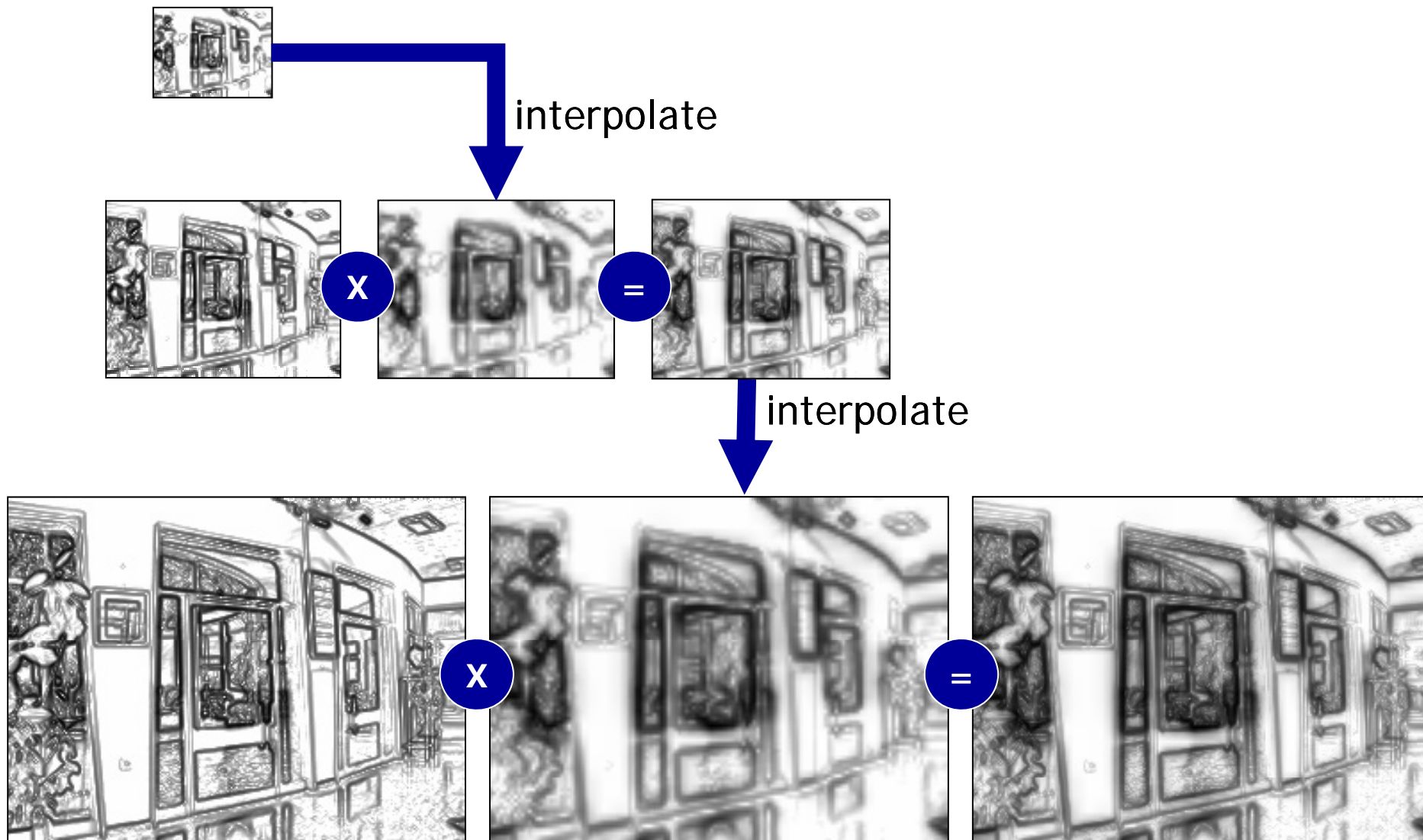
Final gradient attenuation map

Performance

- Measured on 1.8 GHz Pentium 4:

    - 512 x 384: 1.1 sec
    - 1024 x 768: 4.5 sec
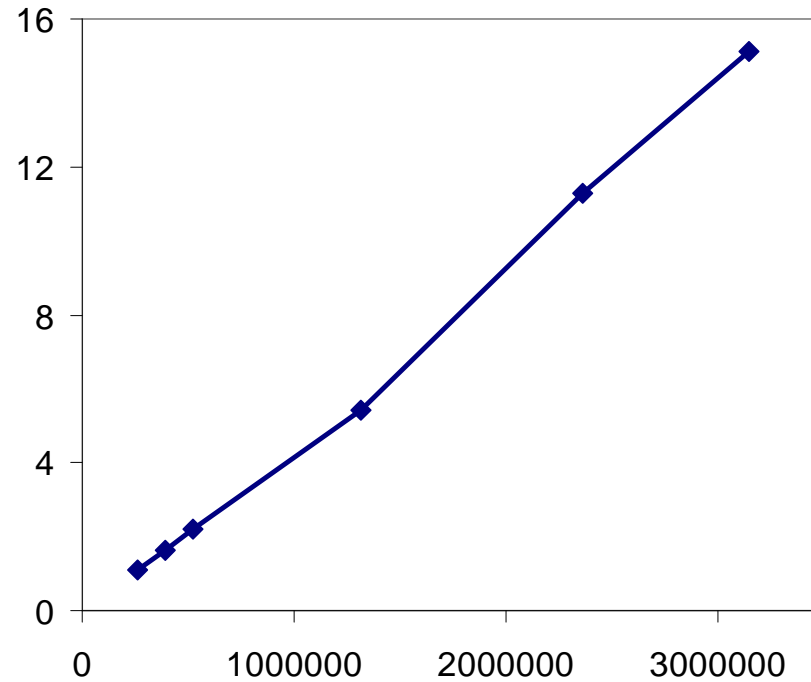
- Can be accelerated using processor-optimized libraries.

Informal comparison

Gradient domain
[Fattal et al.]

Bilateral
[Durand et al.]

Photographic
[Reinhard et al.]

Informal comparison

Gradient domain
[Fattal et al.]

Bilateral
[Durand et al.]

Photographic
[Reinhard et al.]

Informal comparison

Gradient domain
[Fattal et al.]

Bilateral
[Durand et al.]

Photographic
[Reinhard et al.]

Evaluation of Tone Mapping Operators using a High Dynamic Range Display

Patrick Ledda   Alan Chalmers

Tom Troscinko   Helge Seetzen

SIGGRAPH 2005

Six operators

- H: histogram adjustment
- B: bilateral filter
- P: photographic reproduction
- I: iCAM
- L: logarithm mapping
- A: local eye adaption

23 scenes

Scene 1

Scene 2

Scene 3

Scene 4

Scene 5

Scene 6

Scene 7

Scene 8

Scene 9

Scene 10

Scene 11

Scene 12

Scene 13

Scene 14

Scene 15

Experiment setting

tonemapping result

HDR display

tonemapping result

Preference matrix

- Ranking is easier than rating.
- 15 pairs for each person to compare. A total of 345 pairs per subject.

	tmo_1	tmo_2	tmo_3	tmo_4	tmo_5	tmo_6	Score
tmo_1	-	1	0	0	1	1	3
tmo_2	0	-	0	1	1	0	2
tmo_3	1	1	-	1	1	1	5
tmo_4	1	0	0	-	0	0	1
tmo_5	0	0	0	1	-	1	2
tmo_6	0	1	0	1	0	-	2

preference matrix (tmo2->tmo4, tom2 is better than tmo4)

Statistical measurements

- Statistical measurements are used to evaluate:
  - Agreement: whether most agree on the ranking between two tone mapping operators.
  - Consistency: no cycle in ranking. If all are confused in ranking some pairs, it means they are hard to compare. If someone is inconsistent alone, his ranking could be droped.

Overall similarity

- Scene 8

	P	H	B	L	I	A	Total
P	-	24	46	42	10	32	154
H	24	-	44	32	8	12	120
B	2	4	-	8	2	4	20
L	6	16	40	-	4	12	78
I	38	40	46	44	-	38	206
A	16	36	44	36	10	-	142

Summary

Overall Similarity: Color

I	P	H	A	L	B
3712	3402	2994	2852	1902	1696

Bright Detail

I	A	P	H	B	L
823	688	569	549	474	347

Dark Detail

P	A	I	L	H	B
815	793	583	491	485	283

Not settled yet!

- Some other experiment said bilateral are better than others.

- For your reference, photographic reproduction performs well in both reports.

- There are parameters to tune and the space could be huge.

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