# Tone mapping

Digital Visual Effects

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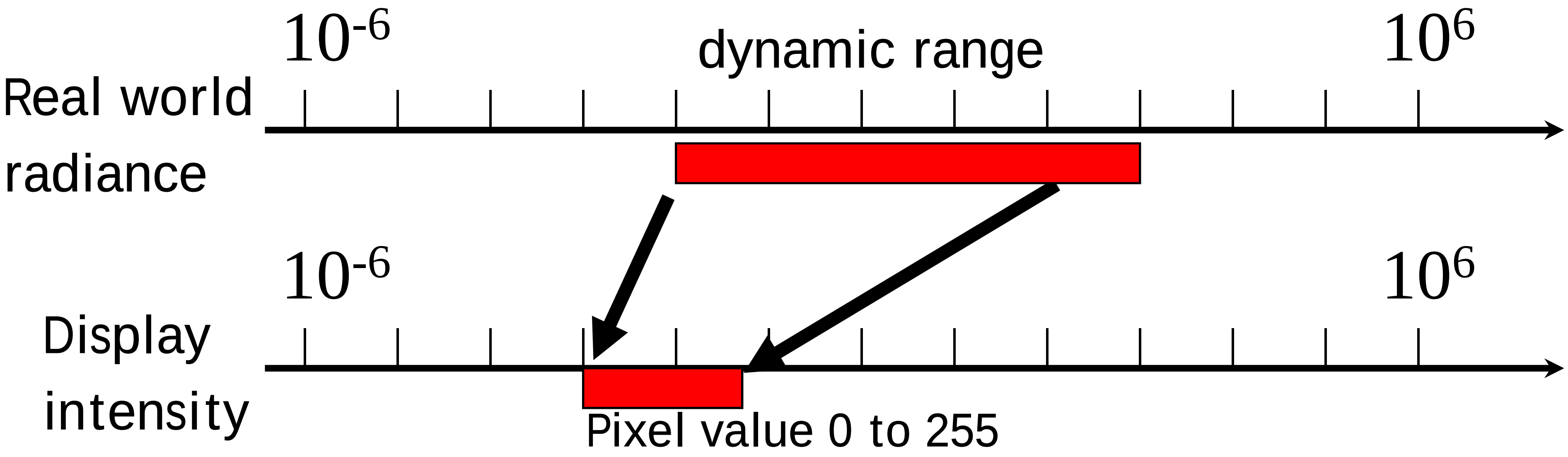
*with slides by Fredo Durand, Lin-Yu Tseng, and Alexei Efros*

# Tone mapping

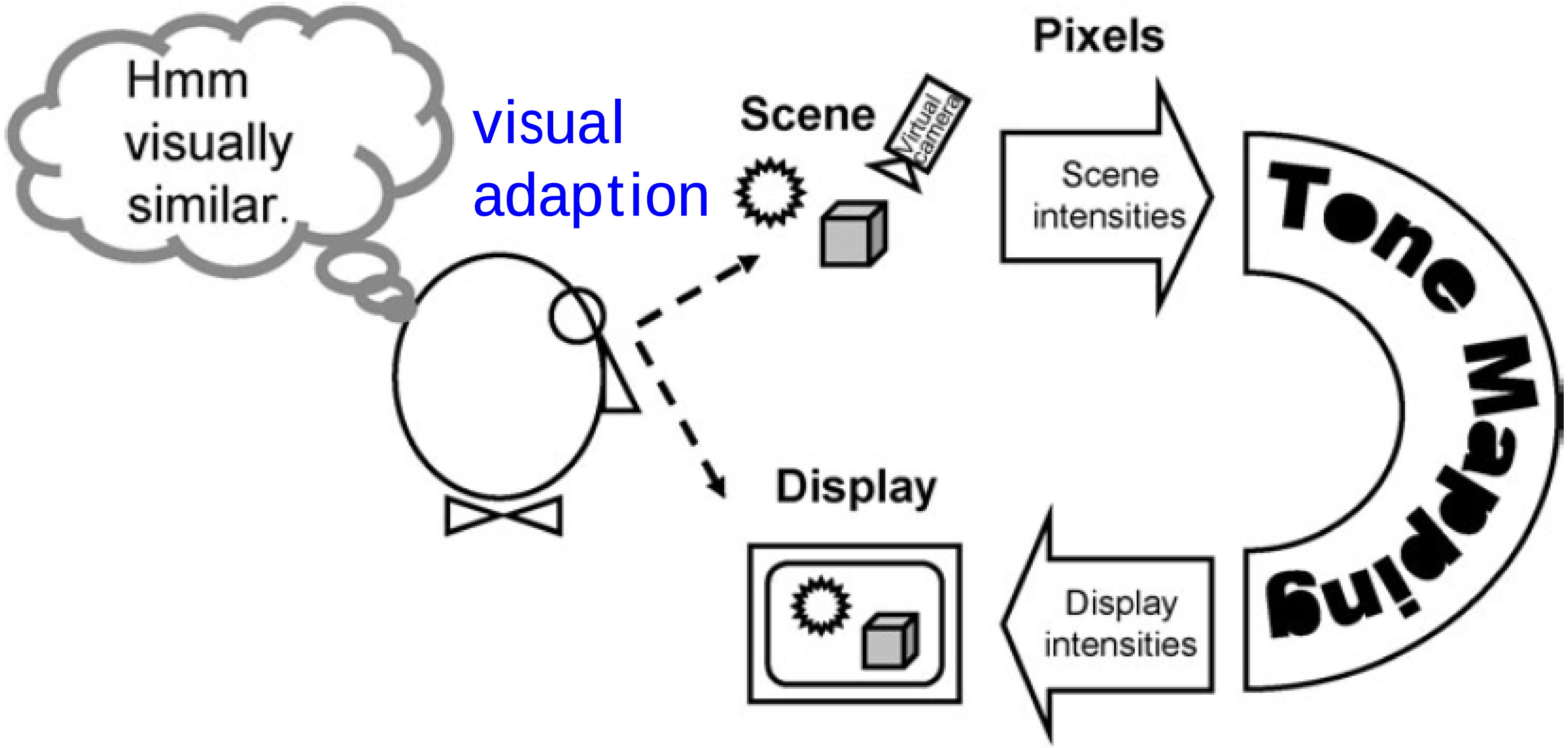
- How should we map scene luminances (up to 1:100,000) to display luminances (only around 1:100) to produce a satisfactory image?

  Linear scaling?, thresholding?



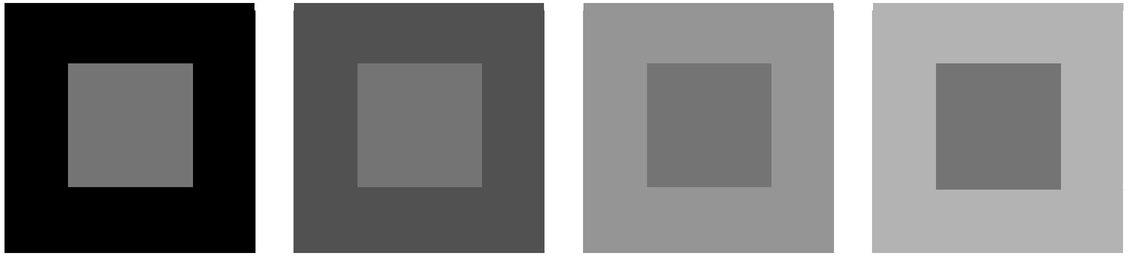

CRT has 300:1 dynamic range

# 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.

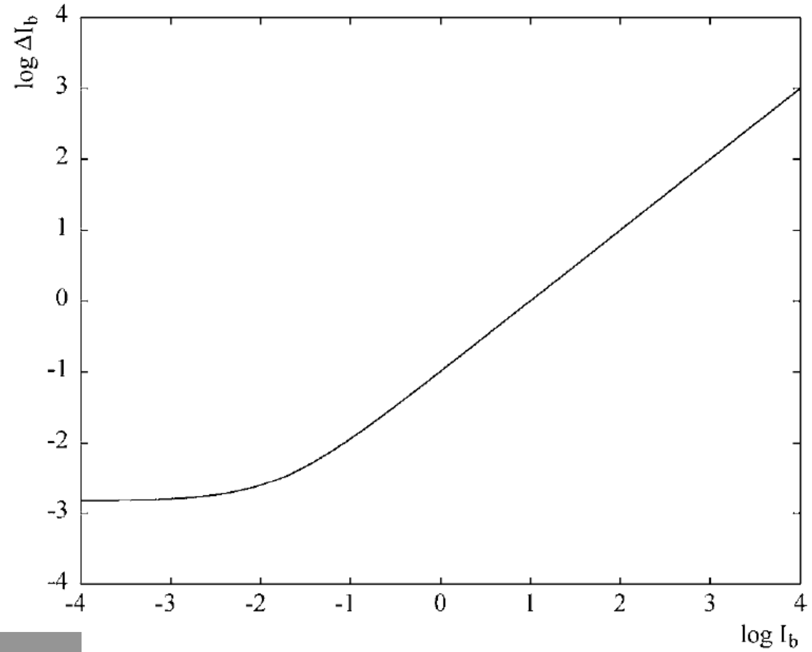
# We are more sensitive to contrast

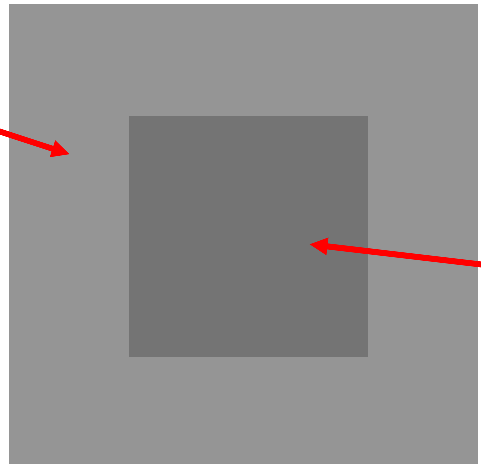
- Weber's law

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

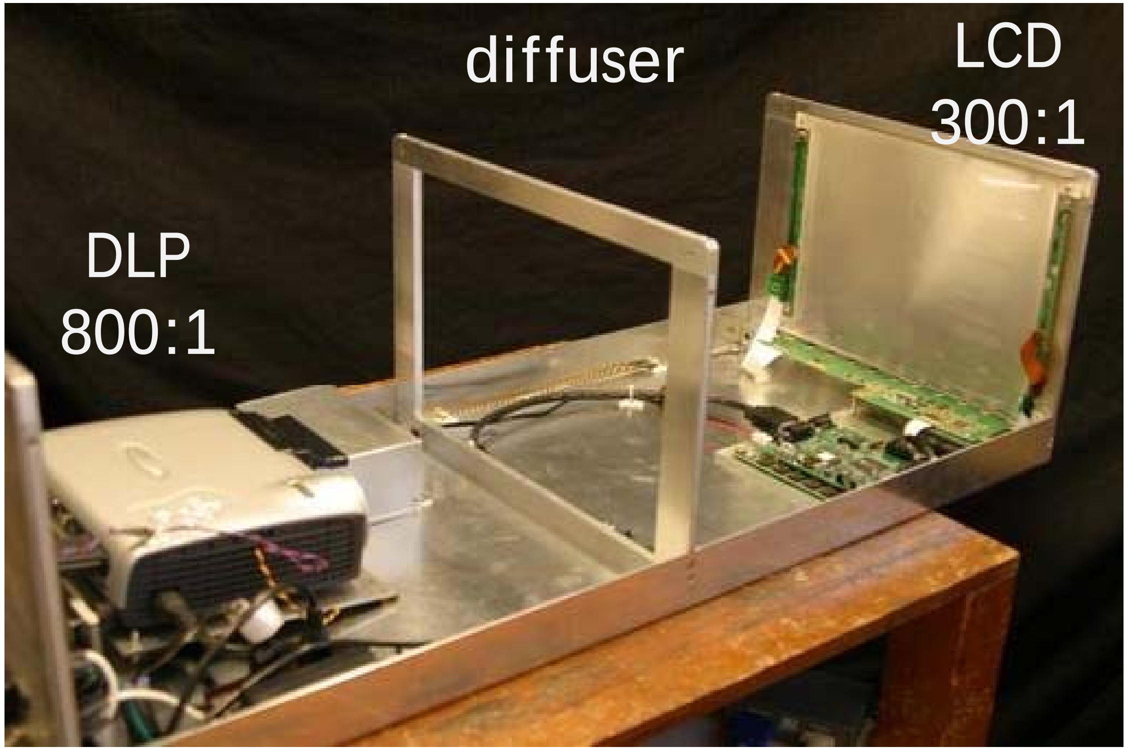
- For color images

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

- 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

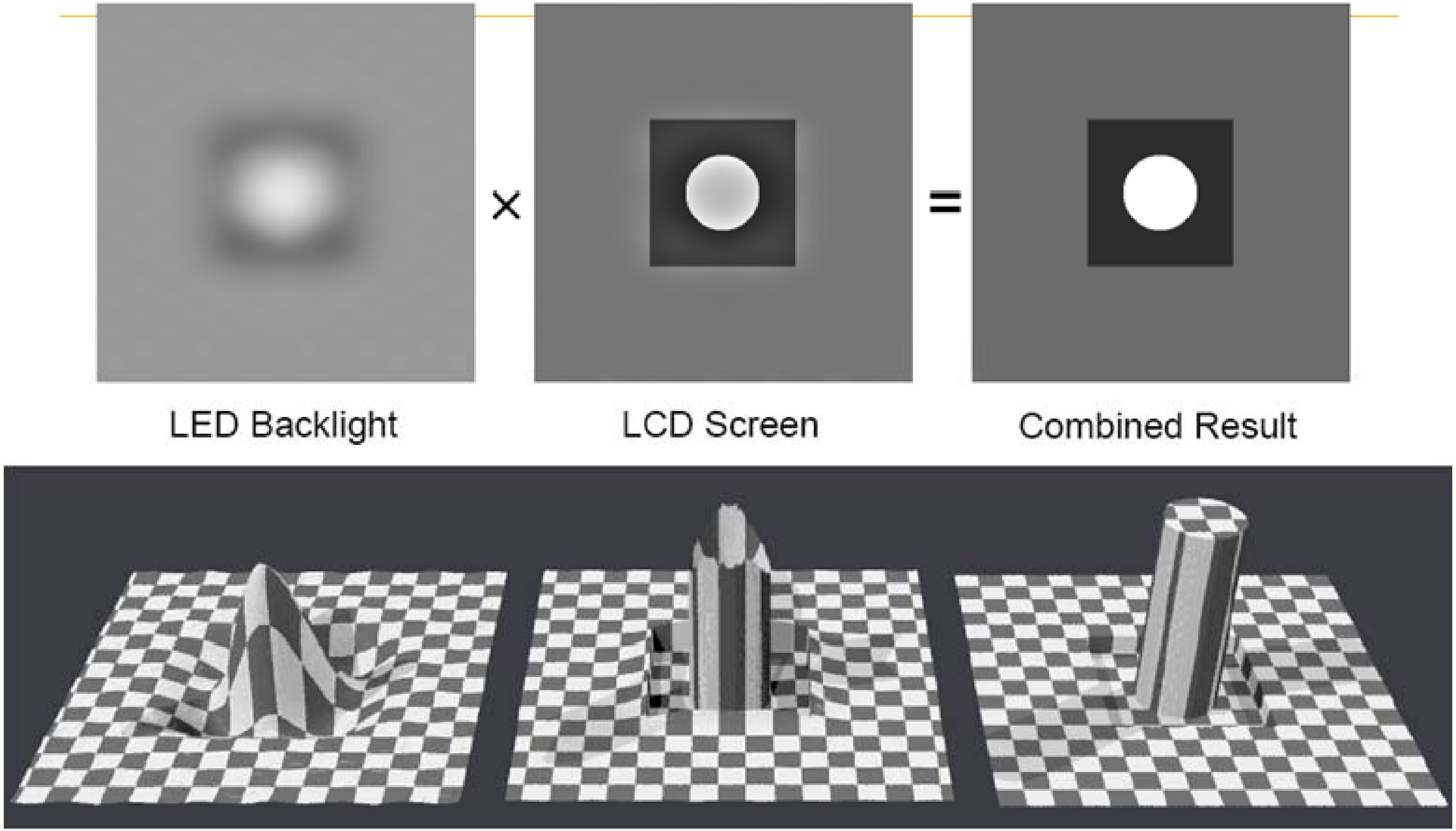
HDR display system, Sunnybrook Technology, SIGGRAPH2004

# Sunnybrook HDR display

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


Slide from the 2005 Siggraph course on HDR

# How it works




Slide from the 2005 Siggraph course on HDR

# Brightside HDR display


37”

200000:1

Acquired by Dolby

# Tone mapping operators

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

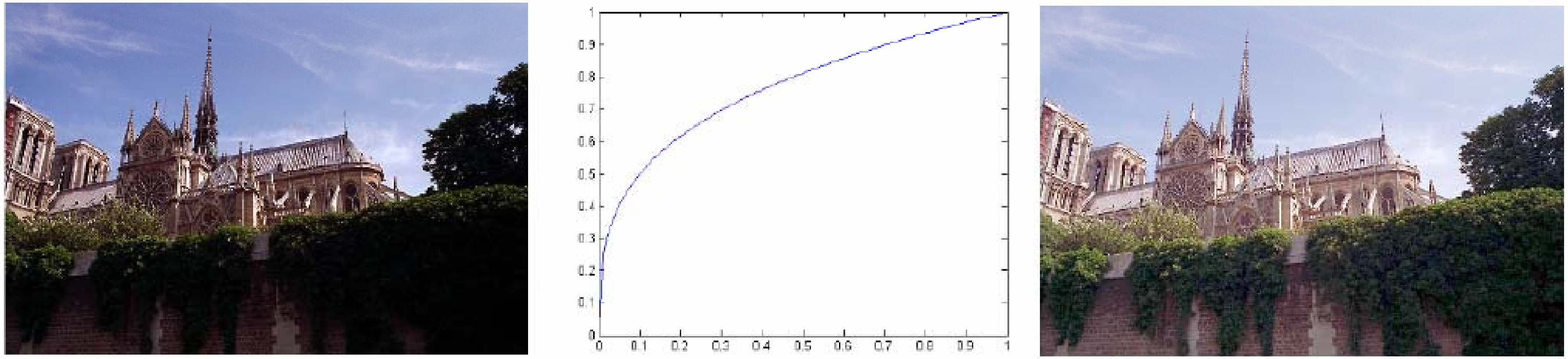
- 3 papers from SIGGRAPH 2002
  - Photographic Tone Reproduction for Digital Images
  - Fast Bilateral Filtering for the Display of High-Dynamic-Range Images
  - Gradient Domain High Dynamic Range Compression

# Photographic Tone Reproduction for Digital Images

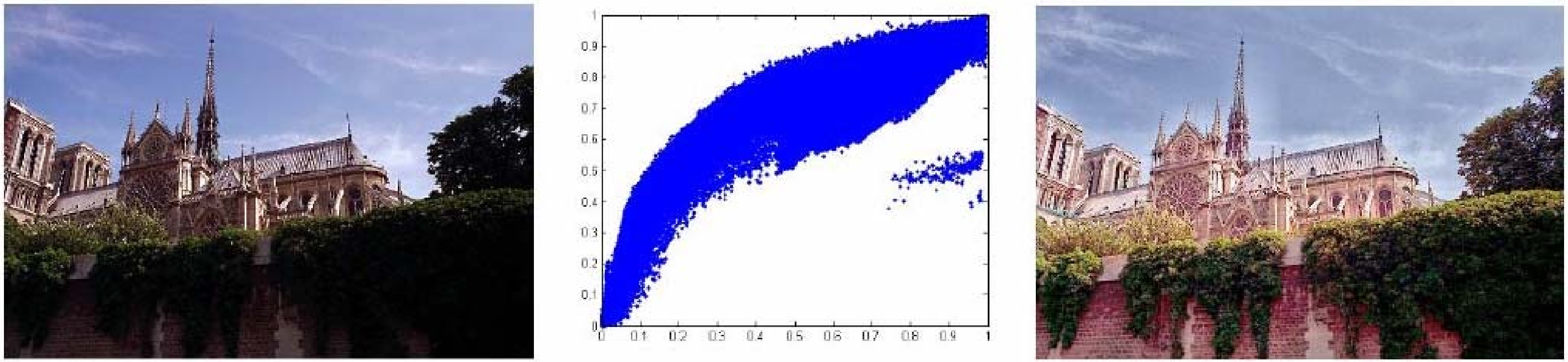
Erik Reinhard Mike Stark
Peter Shirley Jim Ferwerda

SIGGRAPH 2002

# Global v.s. local




Example : Gamma Compression

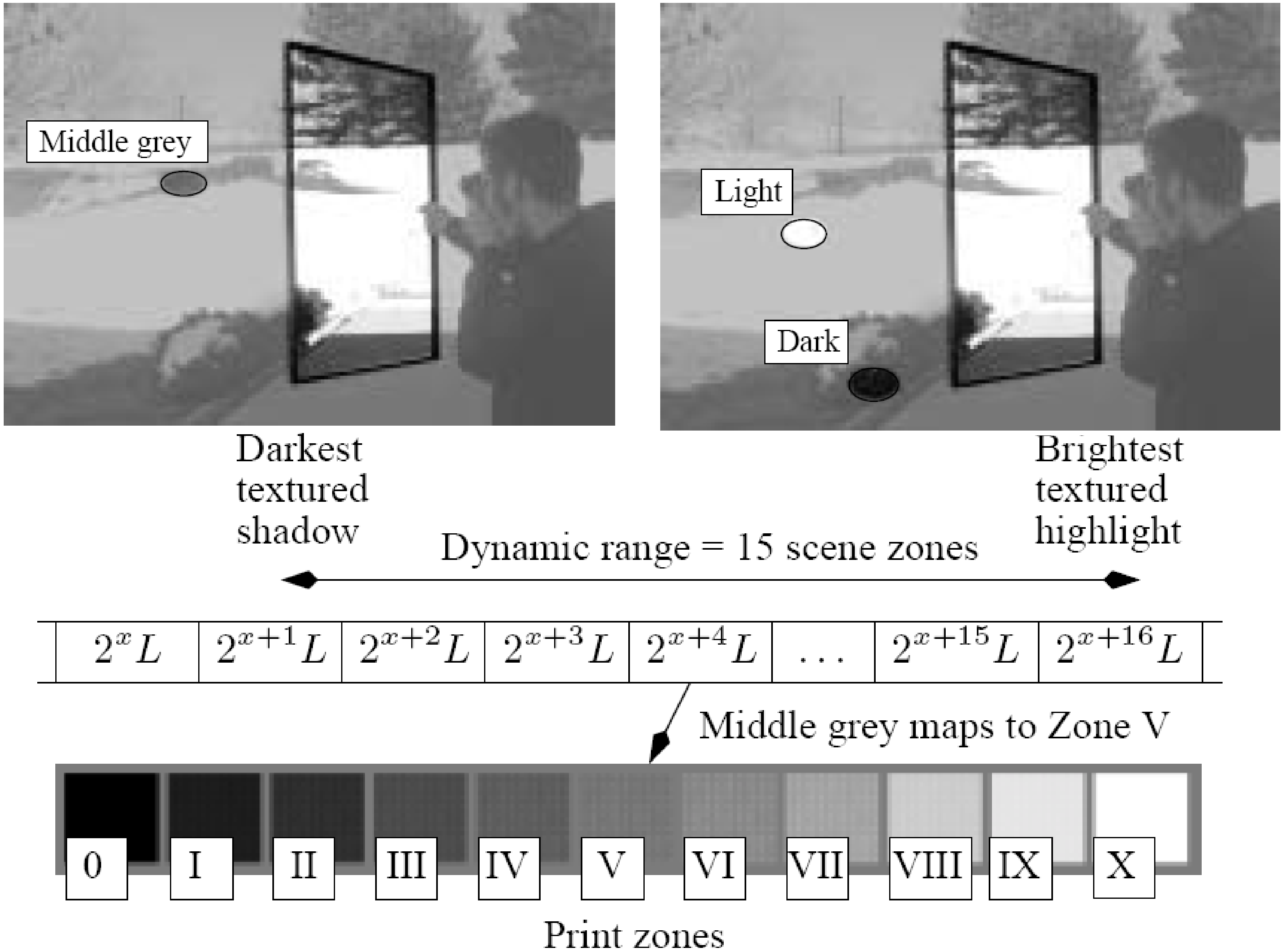



Example : Adaptive Histogram Equalization

# 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

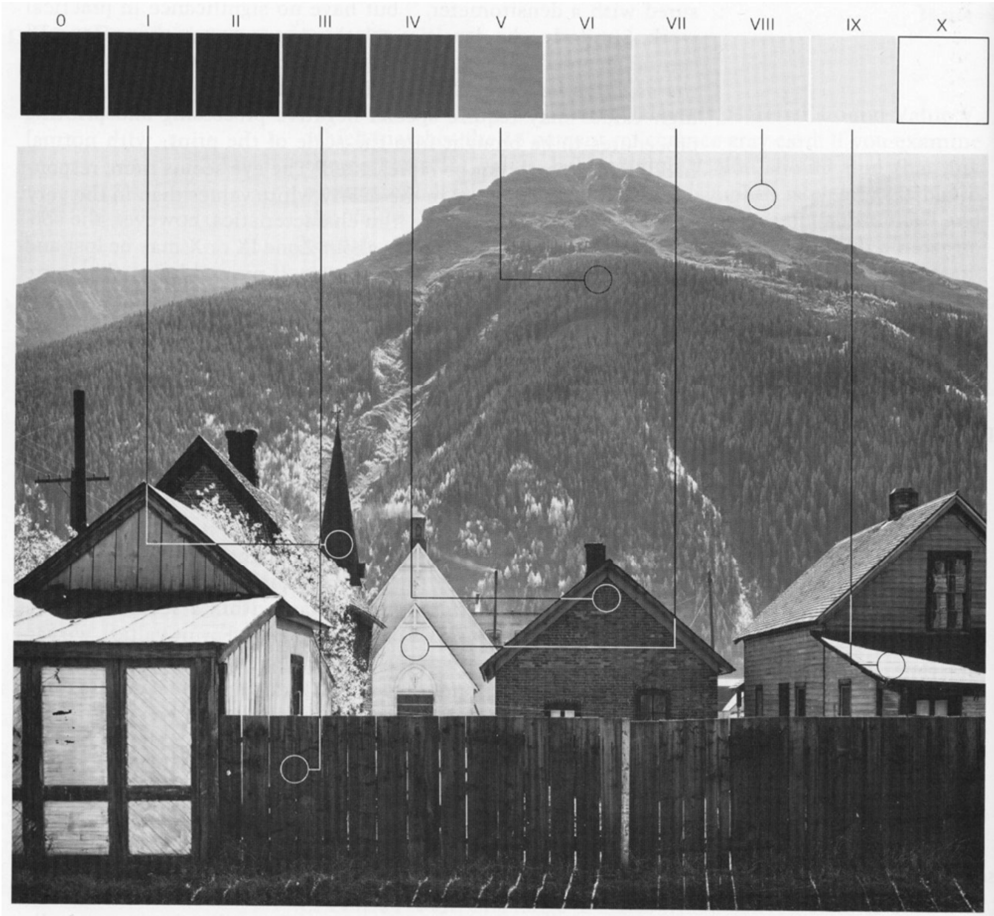
# Zone system



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

- 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

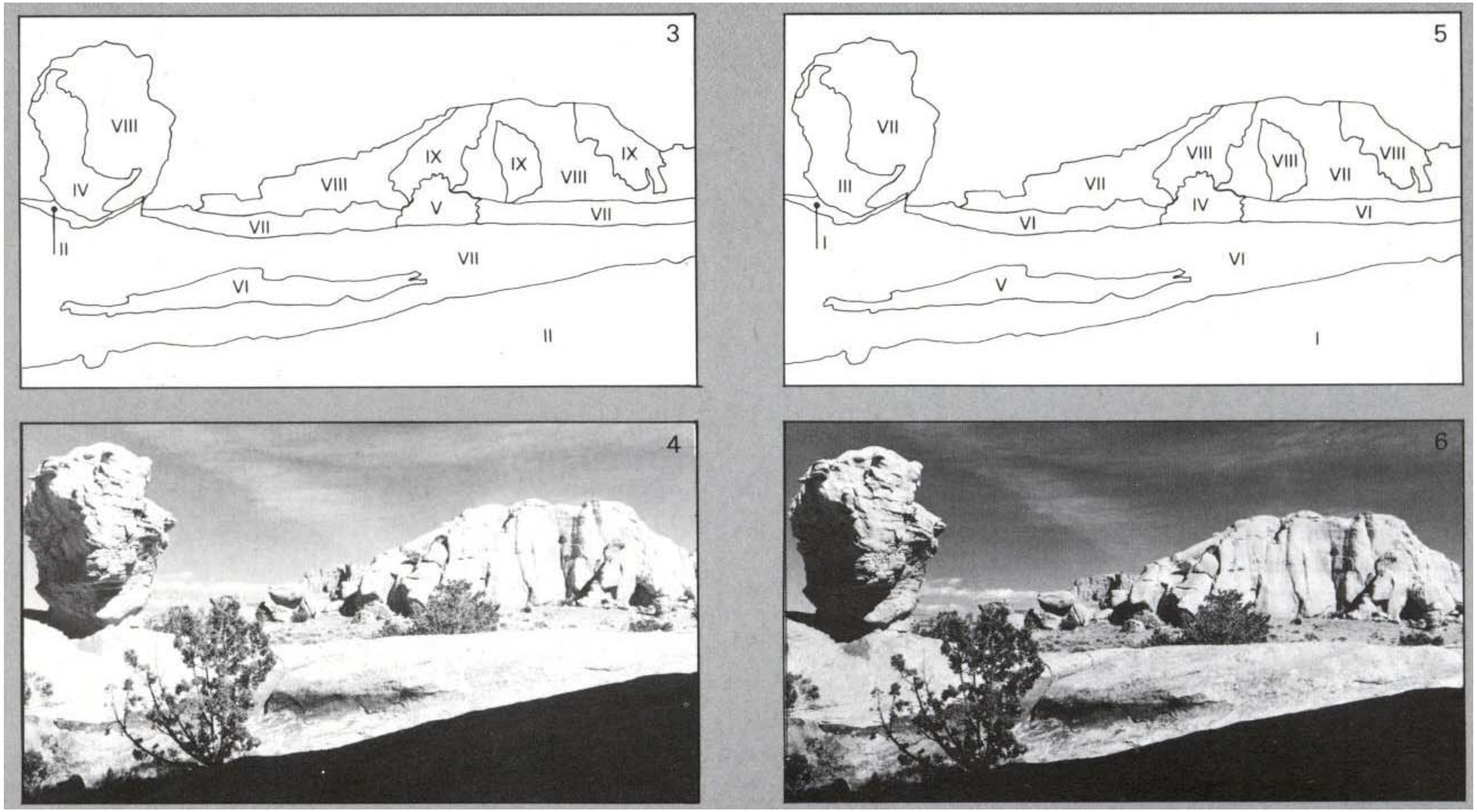
**VII** Light skin; bright areas with texture, such as snow in low sunlight

**VIII** Highest zone with any texture

**IX** Pure untextured white

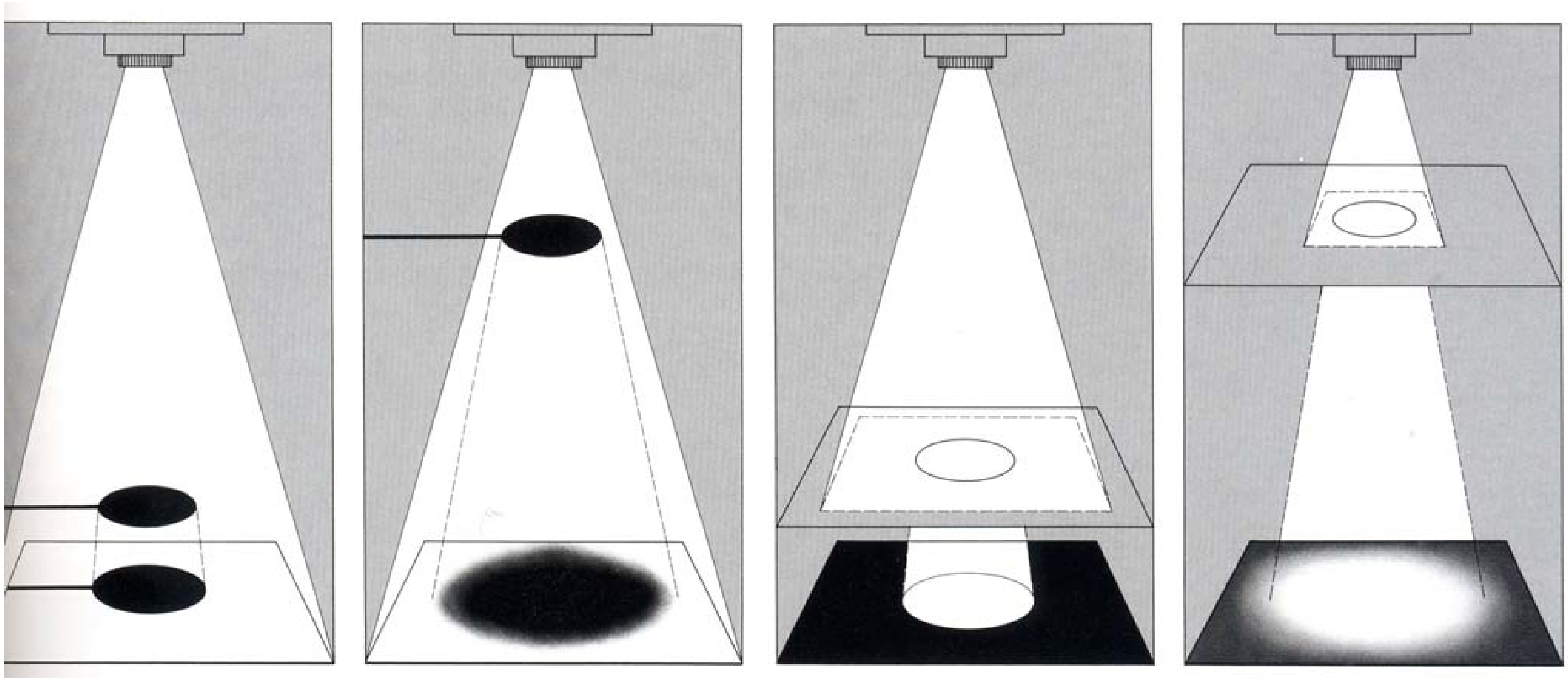
# The Zone system

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



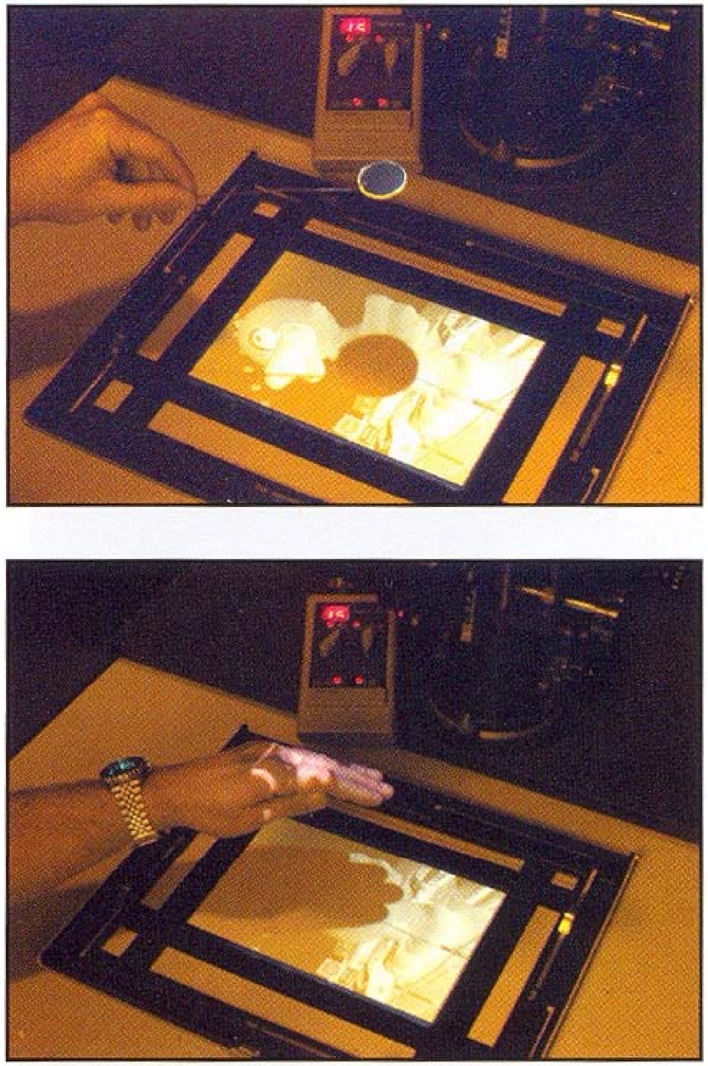
# Dodging and burning

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

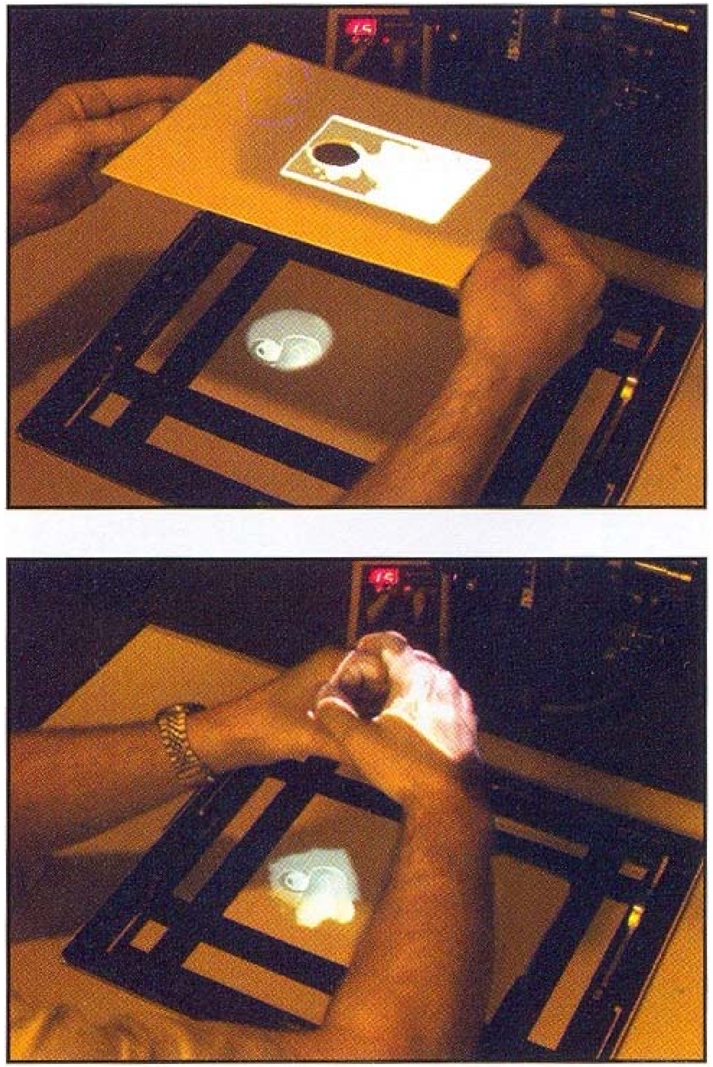


From The Master Printing Course, Rudman

# Dodging and burning



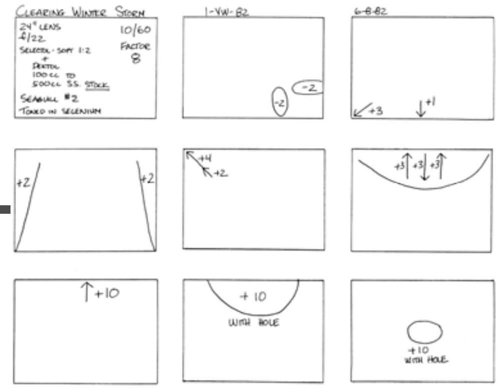
dodging



burning

From Photography by London et al.

# Dodging and burning




- Must be done for every single print!

Straight print

After dodging and burning

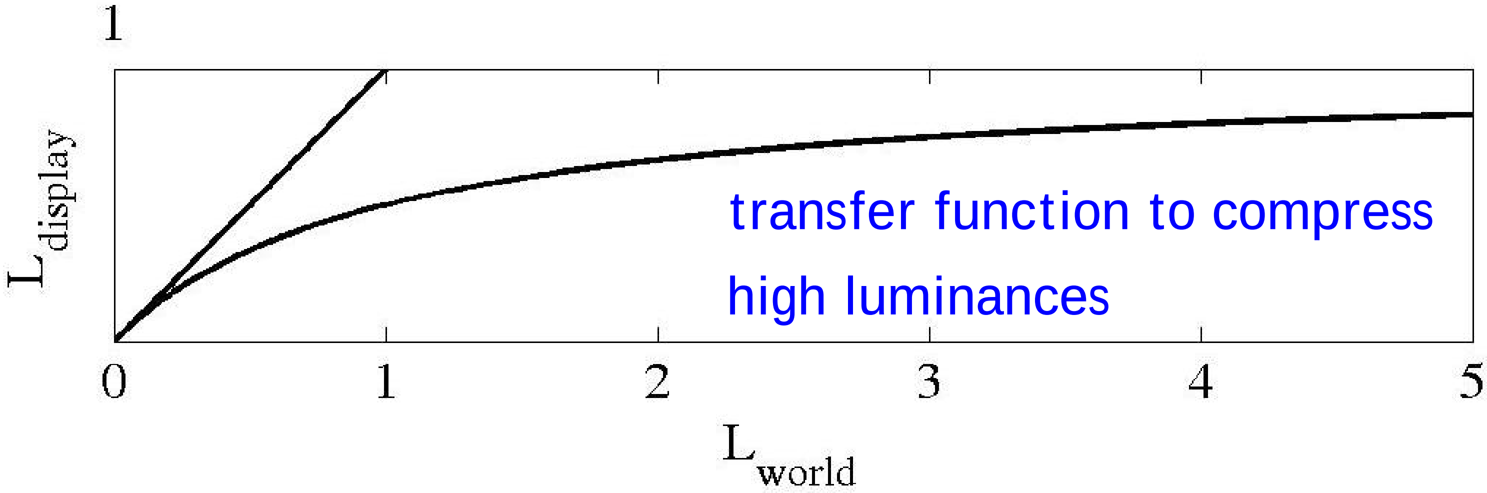
# Global operator

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

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

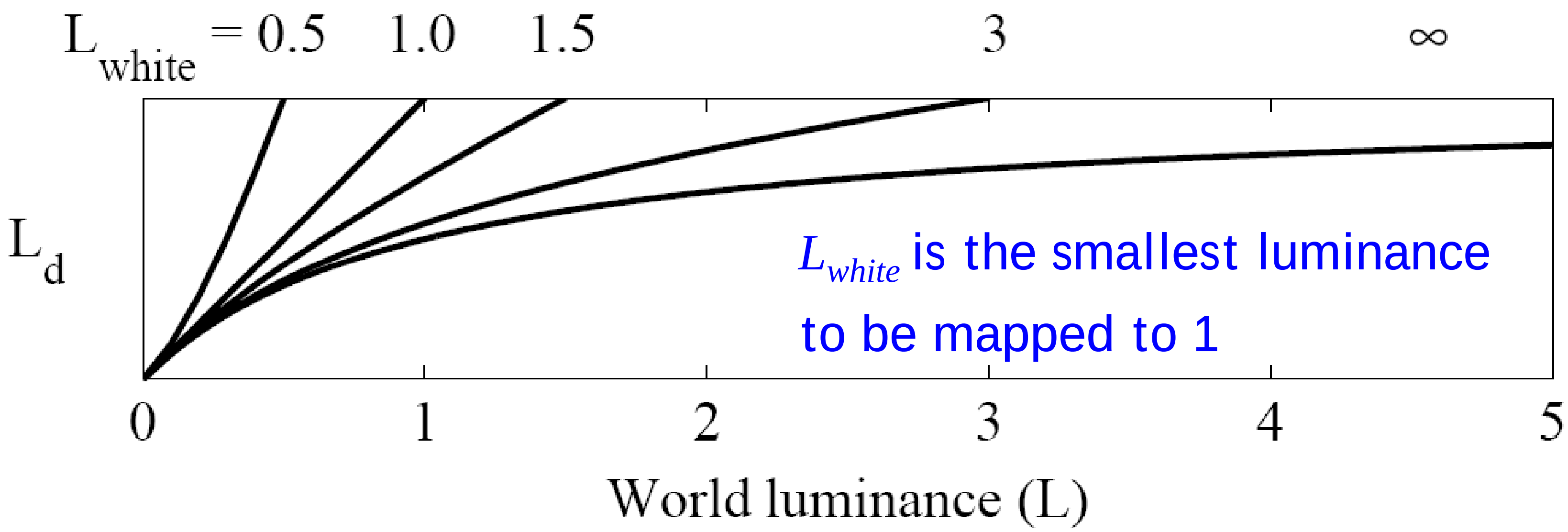
$$L_m(x,y) = \frac{a}{\bar{L}_w} L_w(x,y) \qquad L_d(x,y) = \frac{L_m(x,y)}{1 + L_m(x,y)}$$

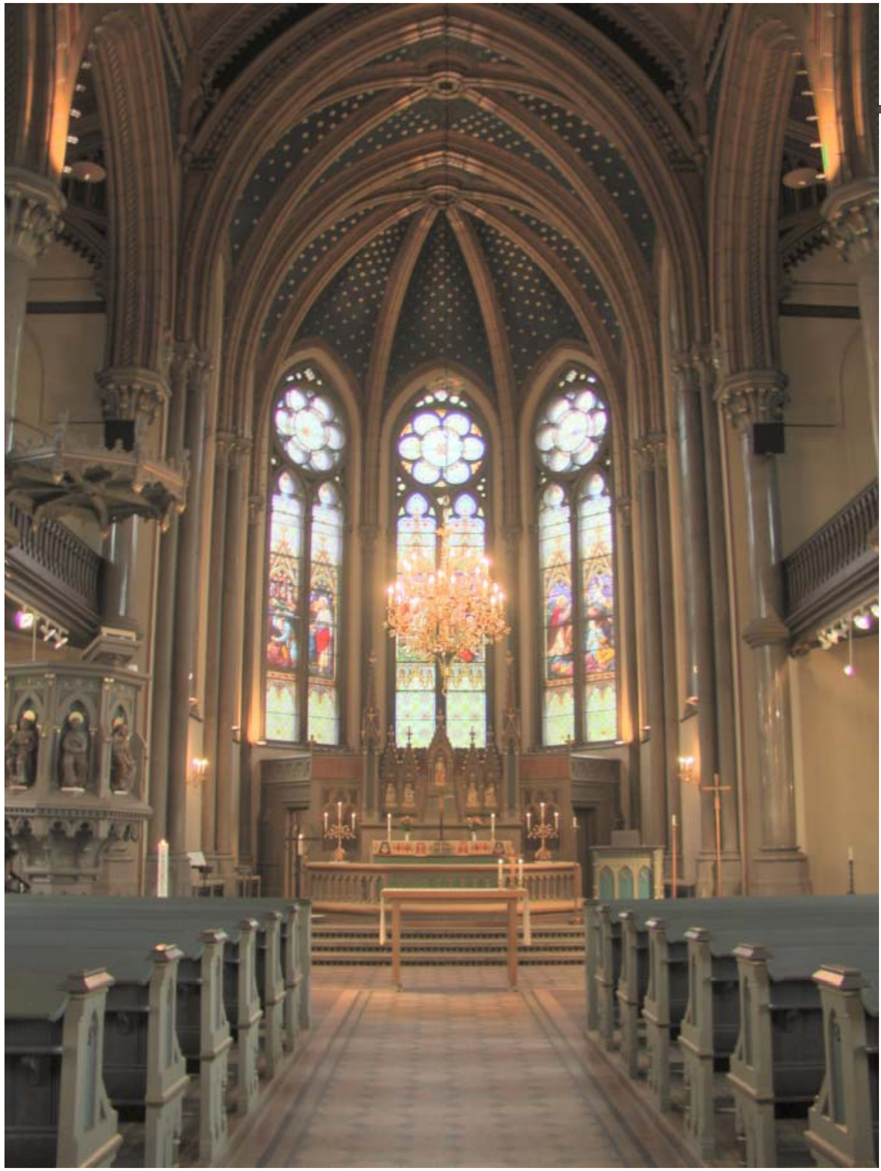


# Global operator

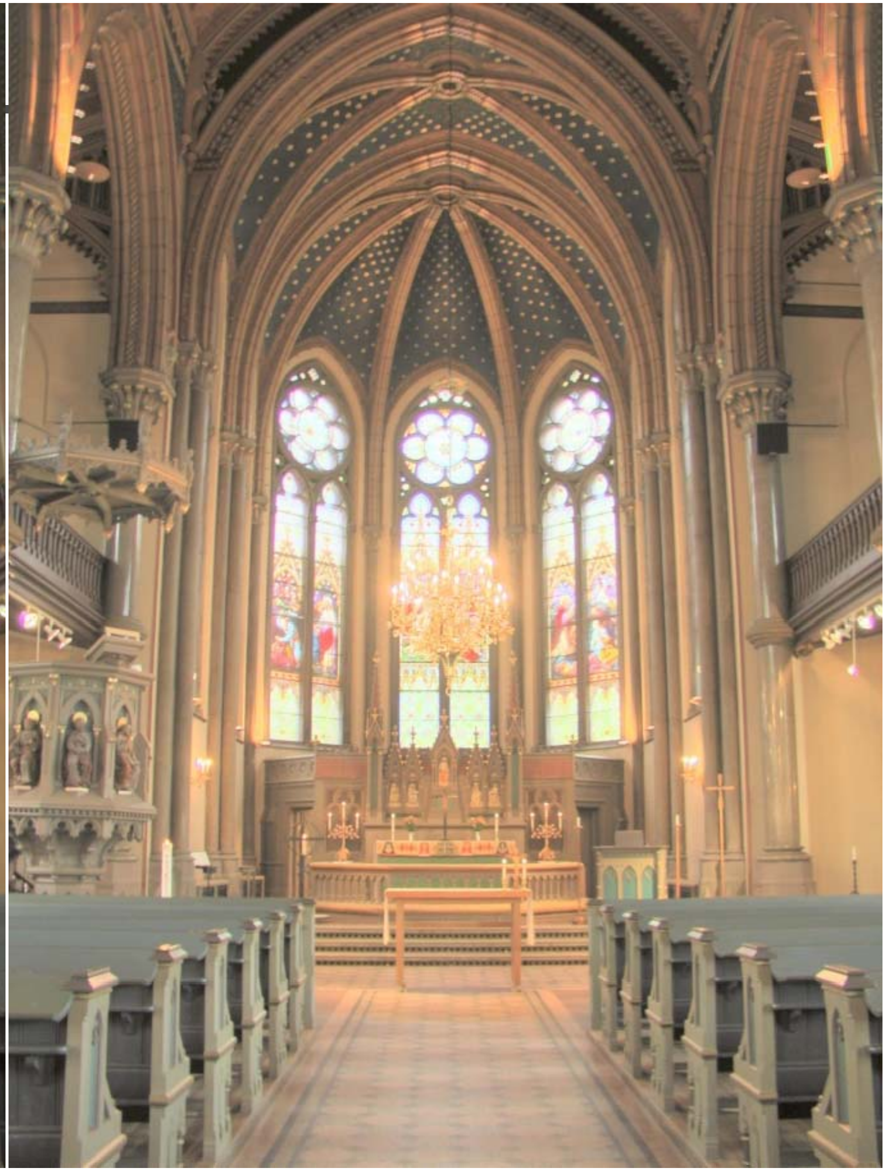
It seldom reaches 1 since the input image does not have infinitely large luminance values.

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





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

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

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

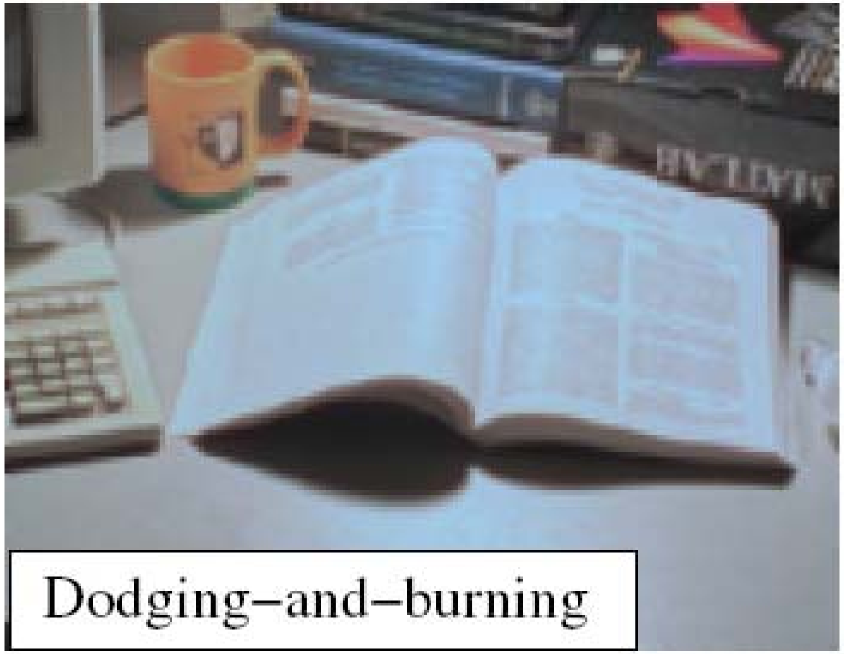
$$s_{\max} : \left| V_{s_{\max}}(\mathrm{x}, \mathrm{y}) \right| < \varepsilon$$

# 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

# Dodging and burning

# Frequency domain

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

image = illuminance * reflectance

low-frequency attenuate more (illuminance)

high-frequency attenuate less (reflectance)

# 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

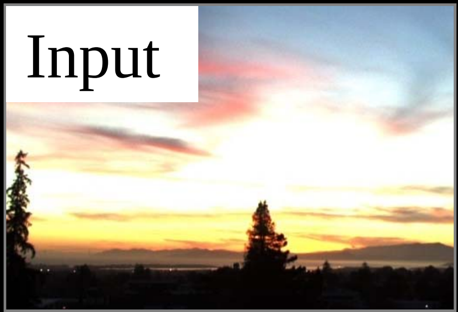
SIGGRAPH 2002

# A typical photo

- Sun is overexposed
- Foreground is underexposed

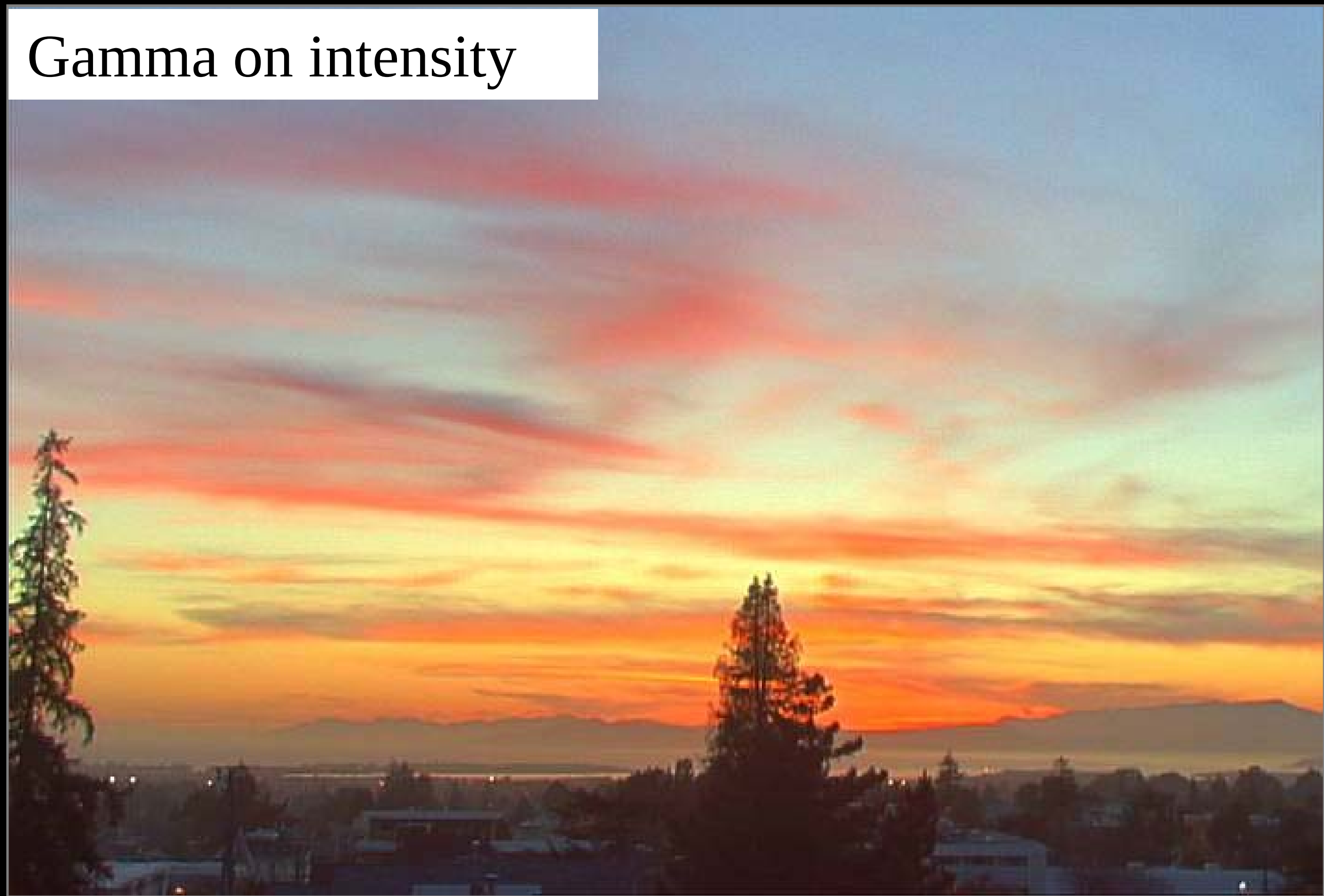
# Gamma compression

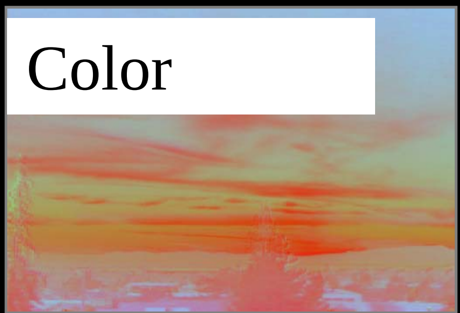
- $X \rightarrow X^{\gamma}$
- Colors are washed-out




# Gamma compression on intensity

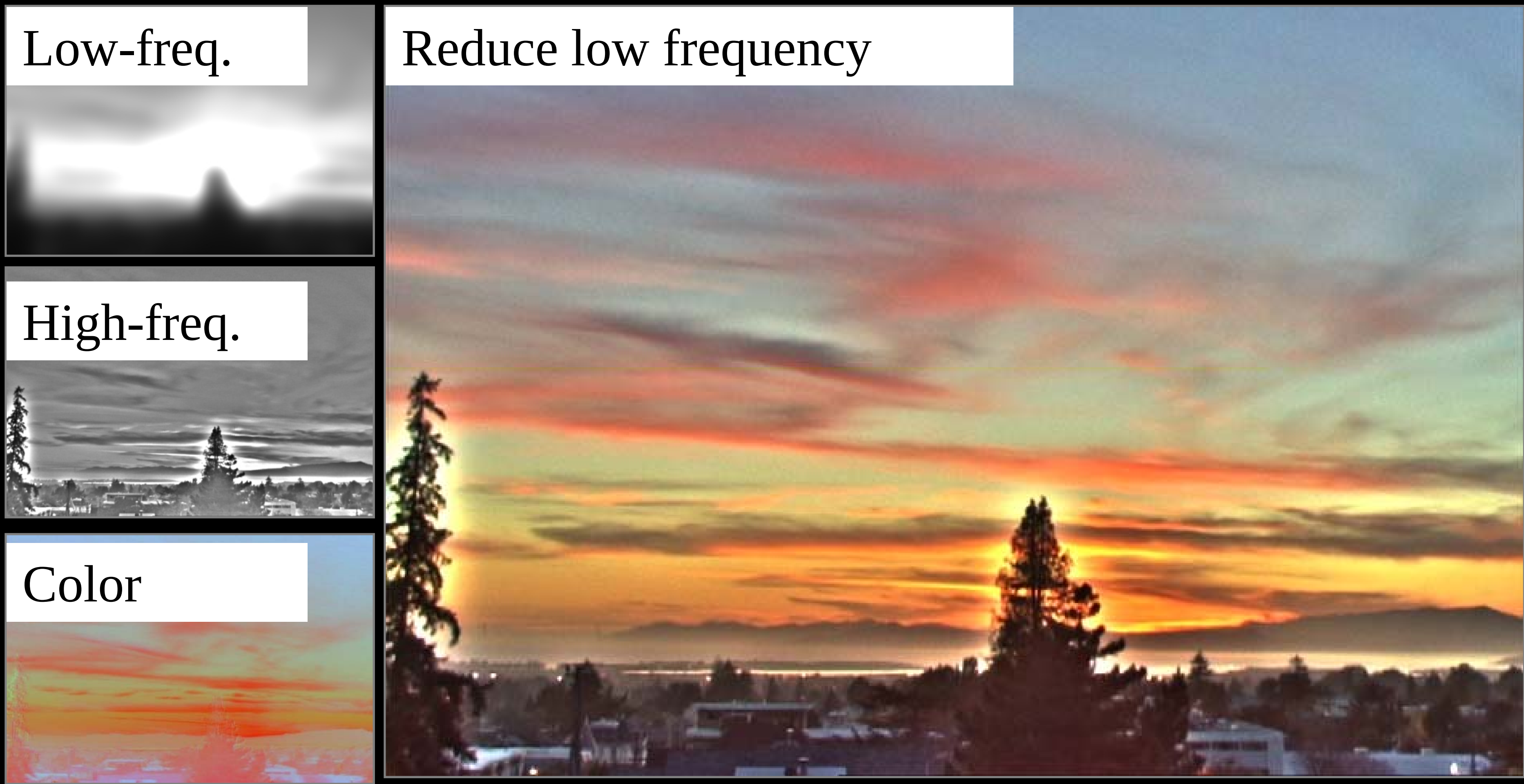
- Colors are OK, but details (intensity high-frequency) are blurred

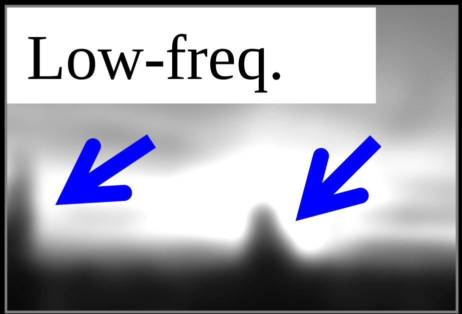
# Chiu et al. 1993

- Reduce contrast of low-frequencies
- Keep high frequencies

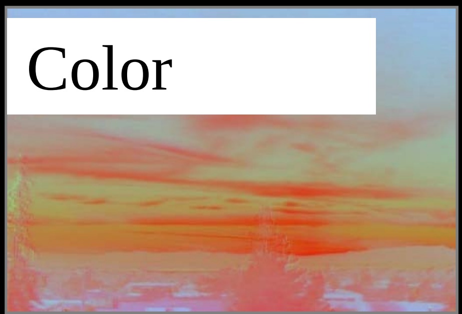


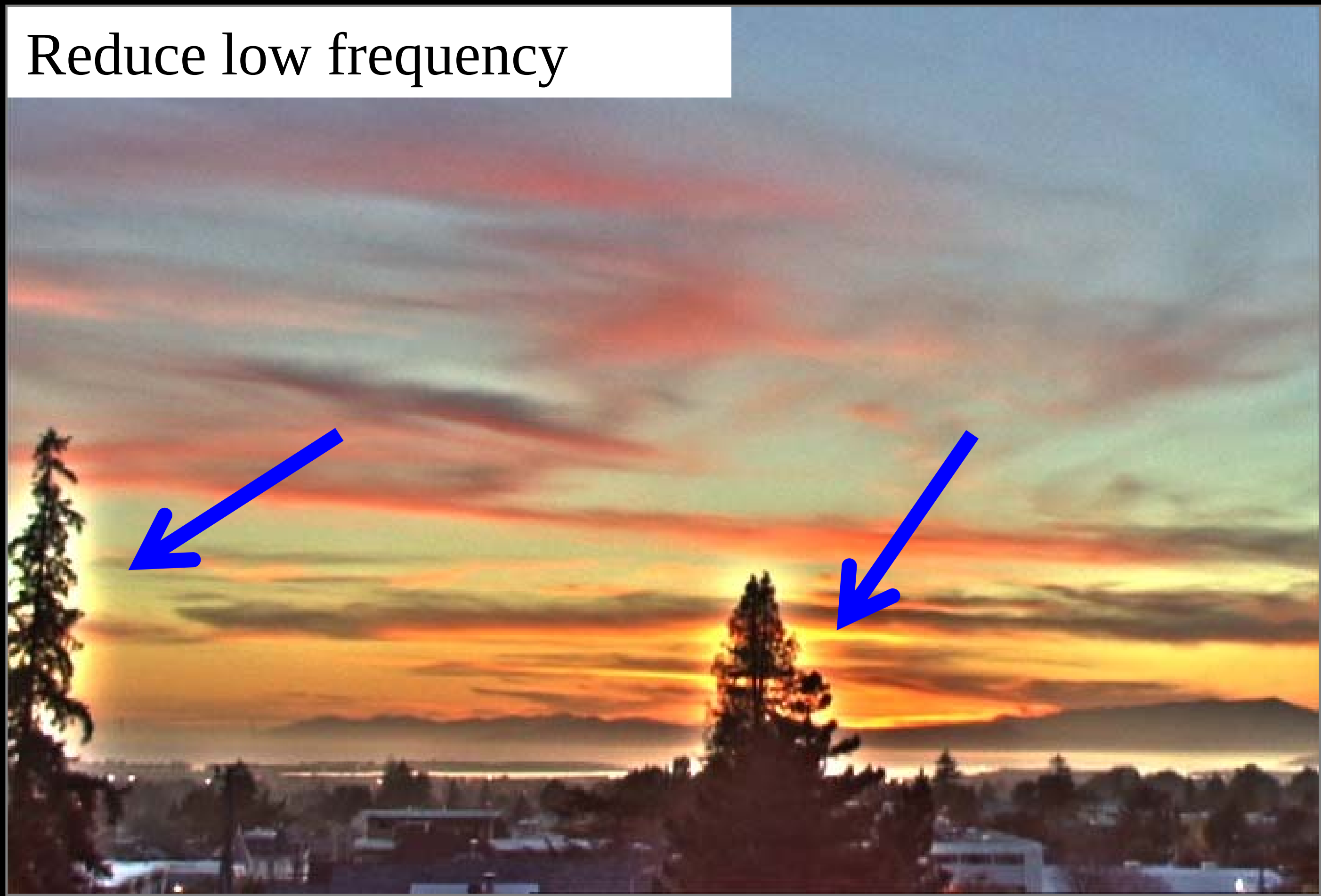
# The halo nightmare

- For strong edges
- Because they contain high frequency



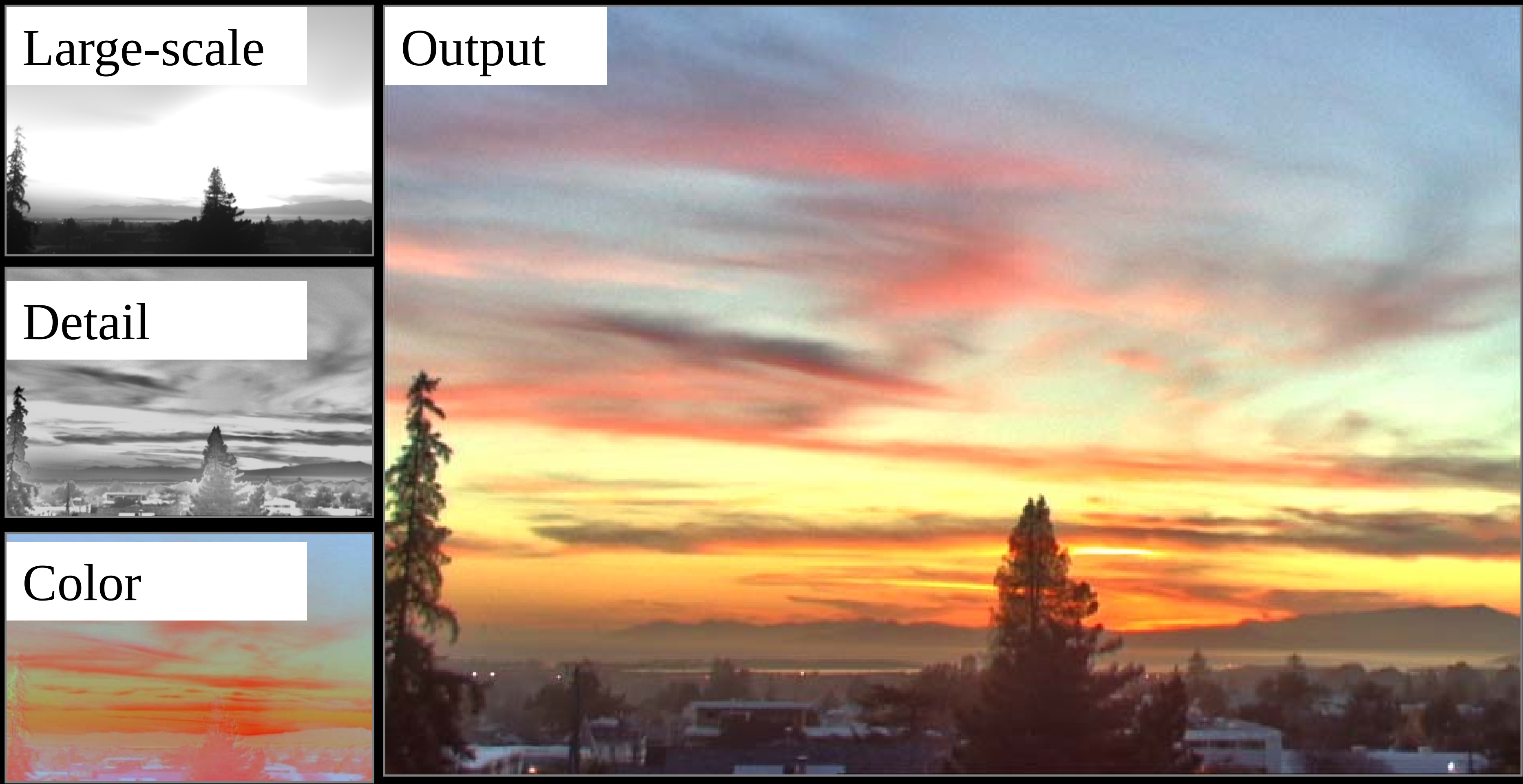




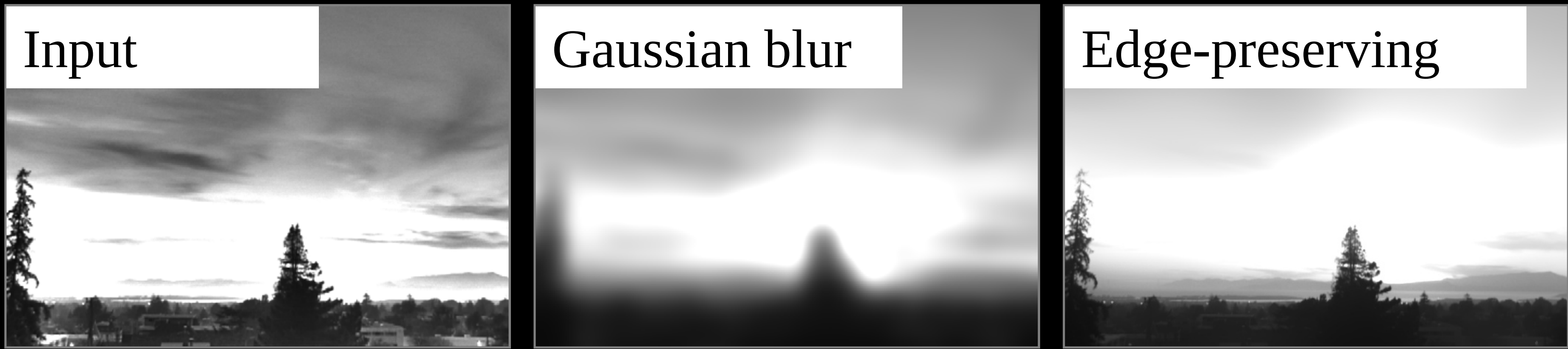
# Durand and Dorsey

- Do not blur across edges
- Non-linear filtering



# Edge-preserving filtering

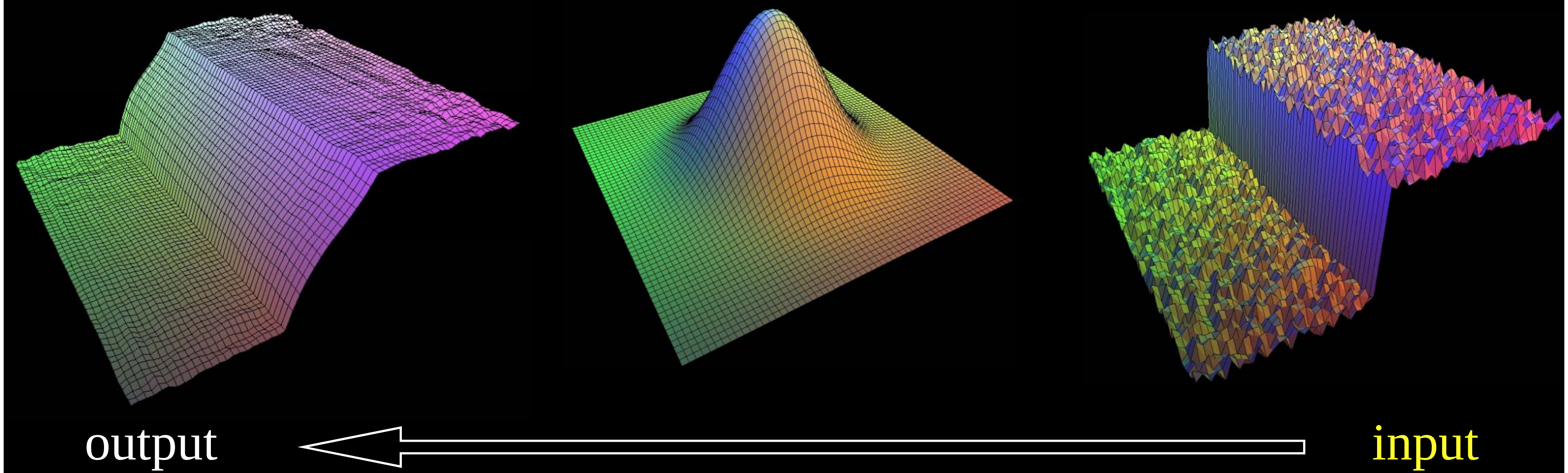
- Blur, but not across edges




- Anisotropic diffusion [Perona & Malik 90]
  - Blurring as heat flow
  - LCIS [Tumblin & Turk]
- Bilateral filtering [Tomasi & Manduci, 98]

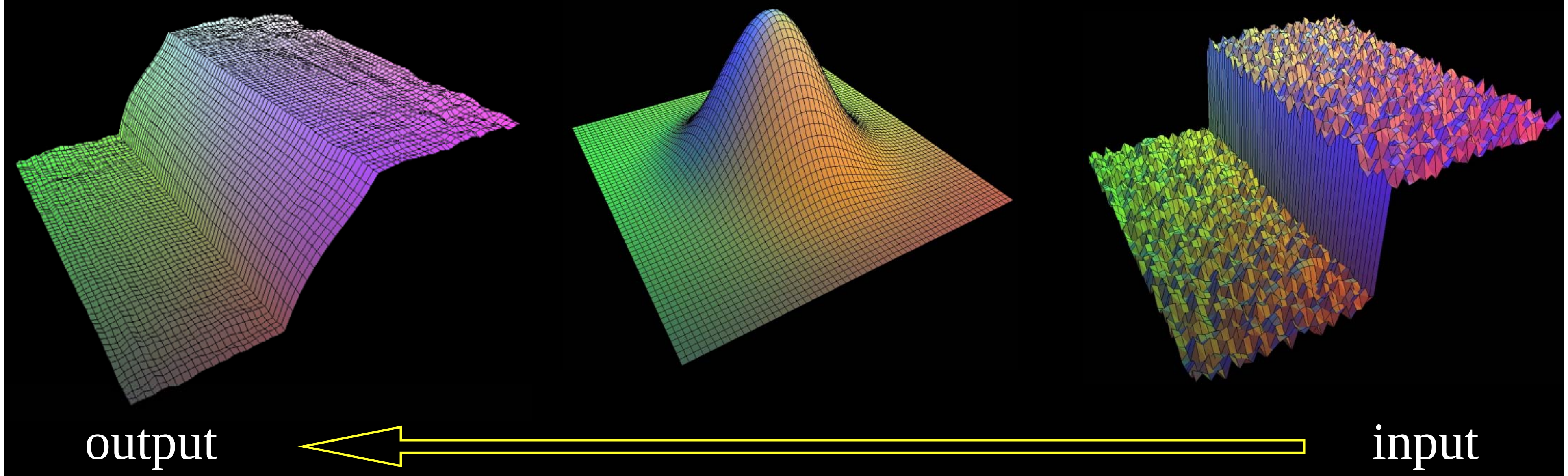
# Start with Gaussian filtering

- Here, input is a step function + noise



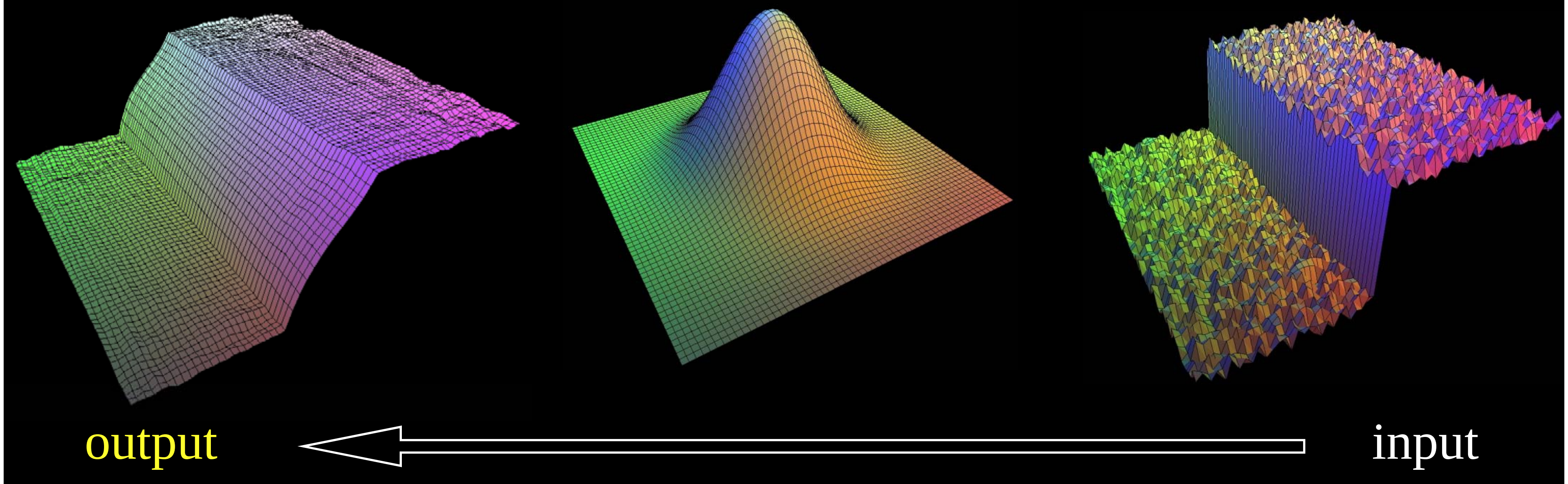
# Start with Gaussian filtering

- Spatial Gaussian f

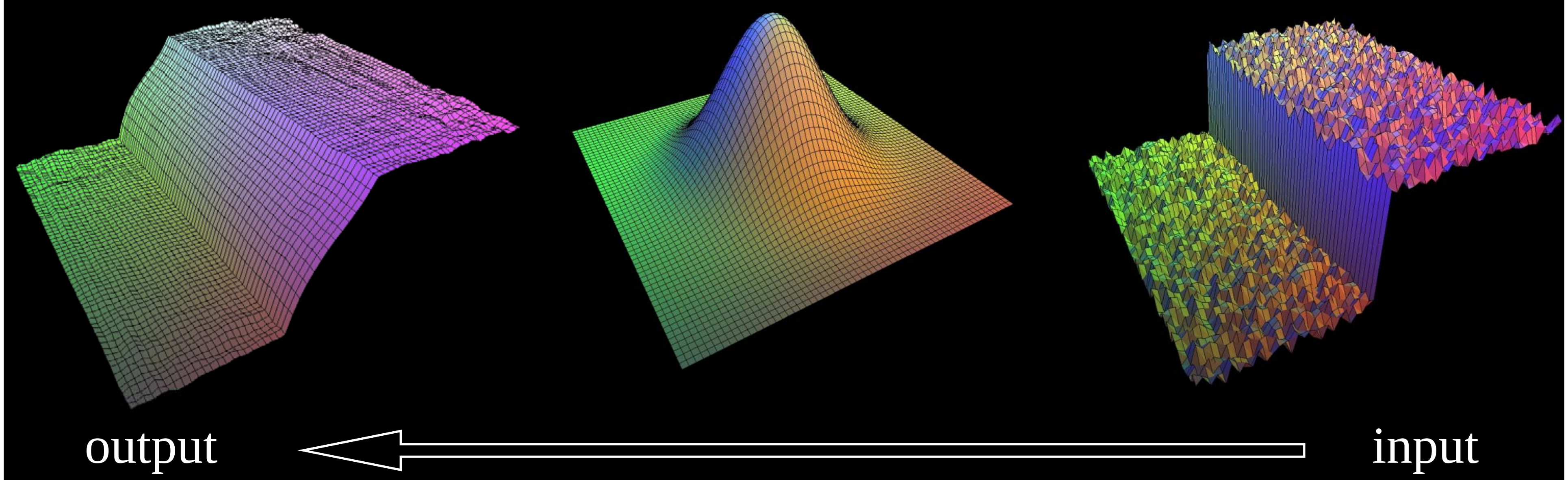


# Start with Gaussian filtering

- Output is blurred

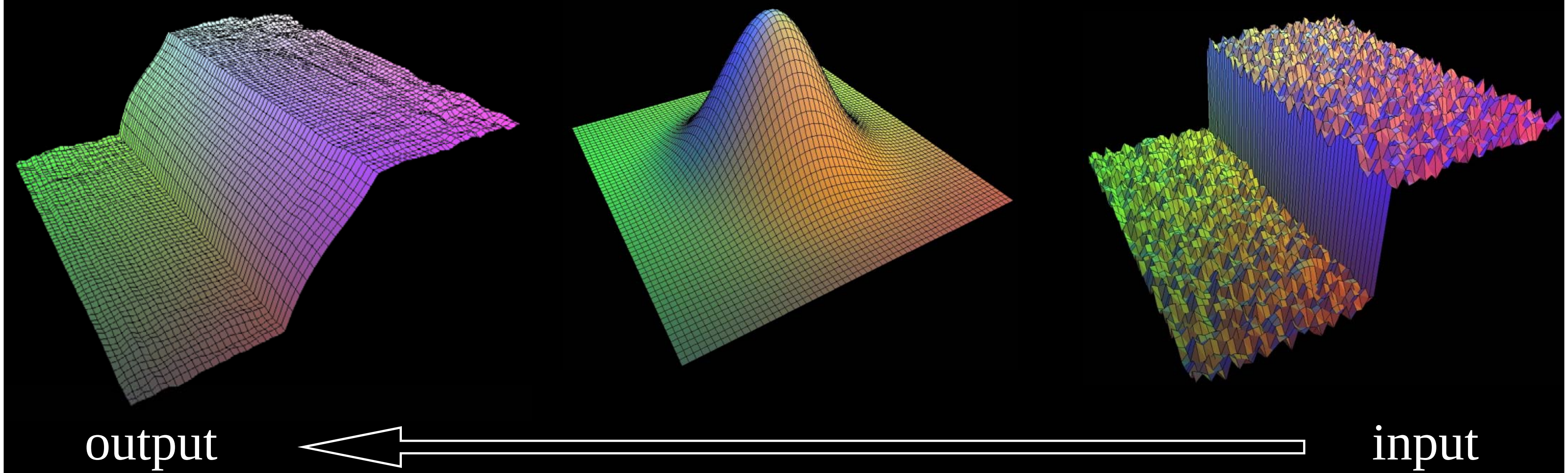


# Gaussian filter as weighted average



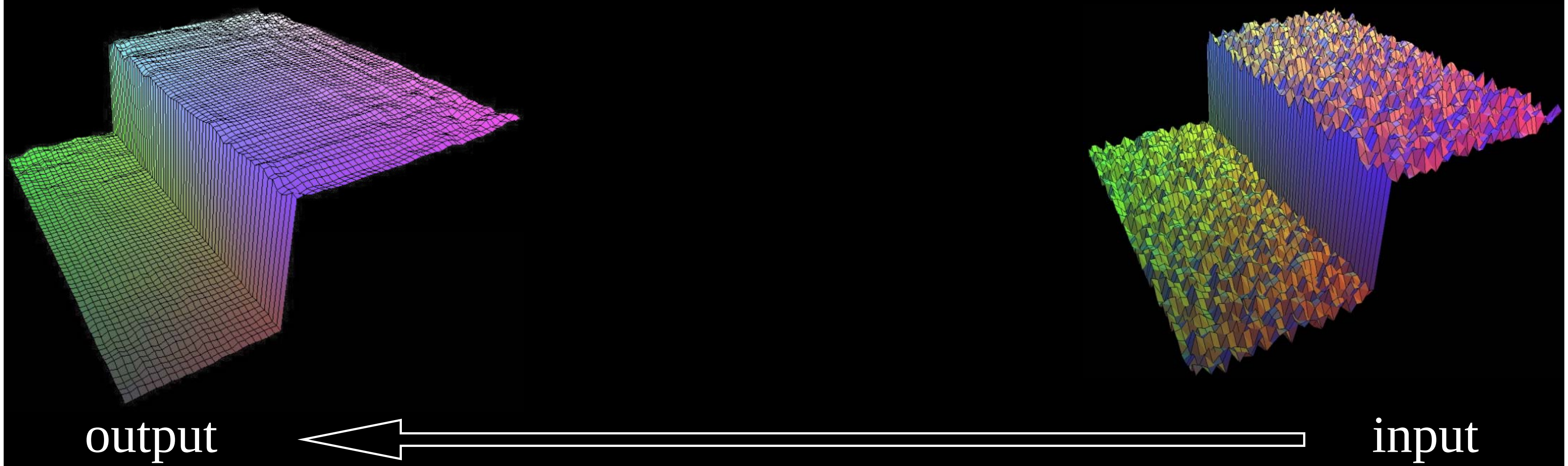
# The problem of edges

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



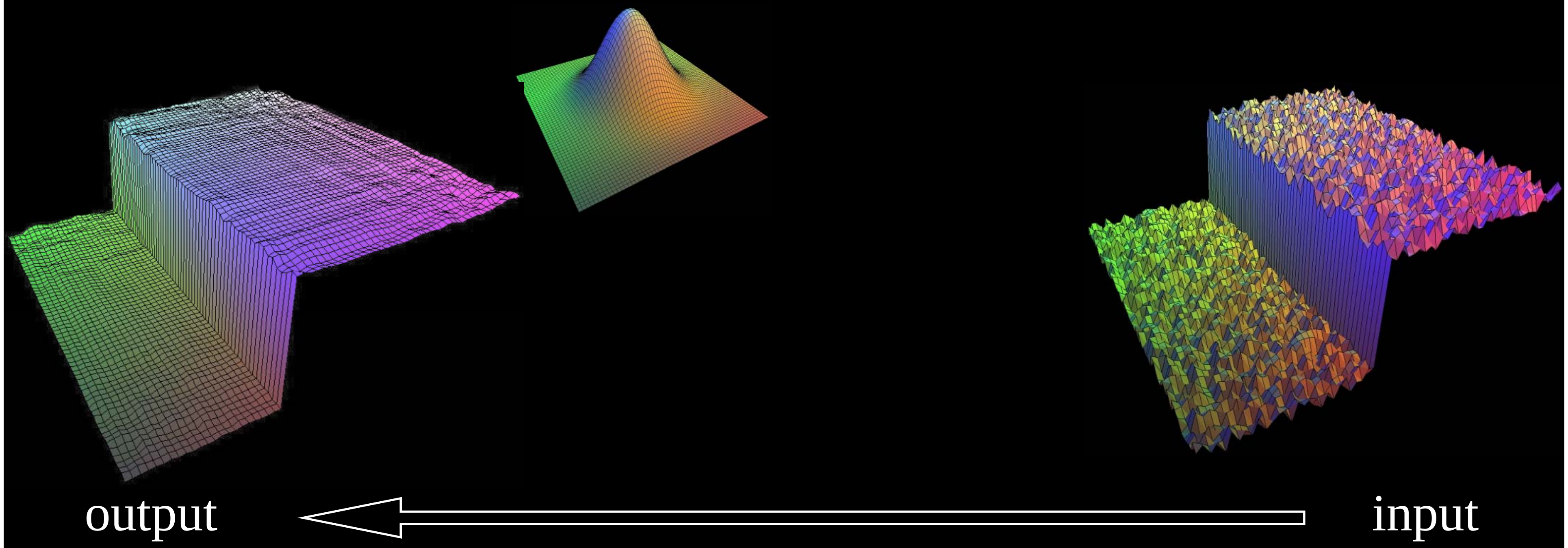
# Principle of Bilateral filtering

- [Tomasi and Manduchi 1998]
- Penalty g on the intensity difference



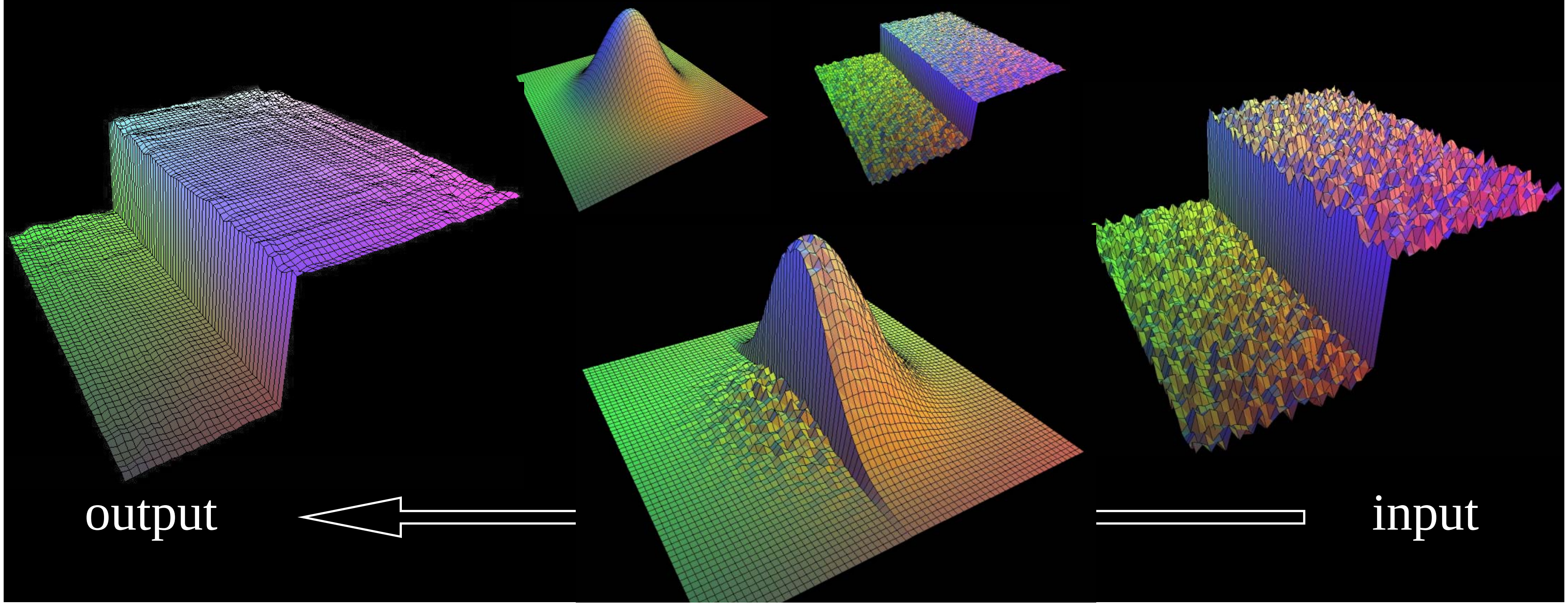
# Bilateral filtering

- [Tomasi and Manduchi 1998]
- Spatial Gaussian f



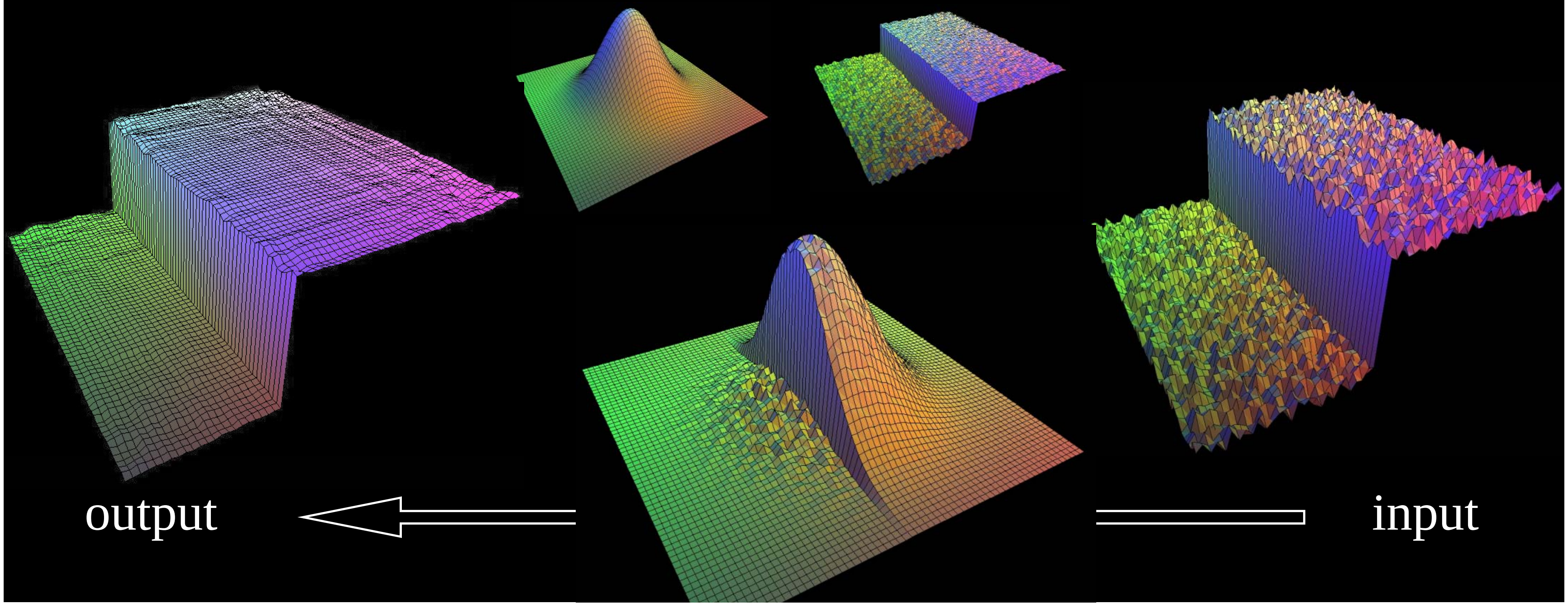
# Bilateral filtering

- [Tomasi and Manduchi 1998]
- Spatial Gaussian f
- Gaussian g on the intensity difference



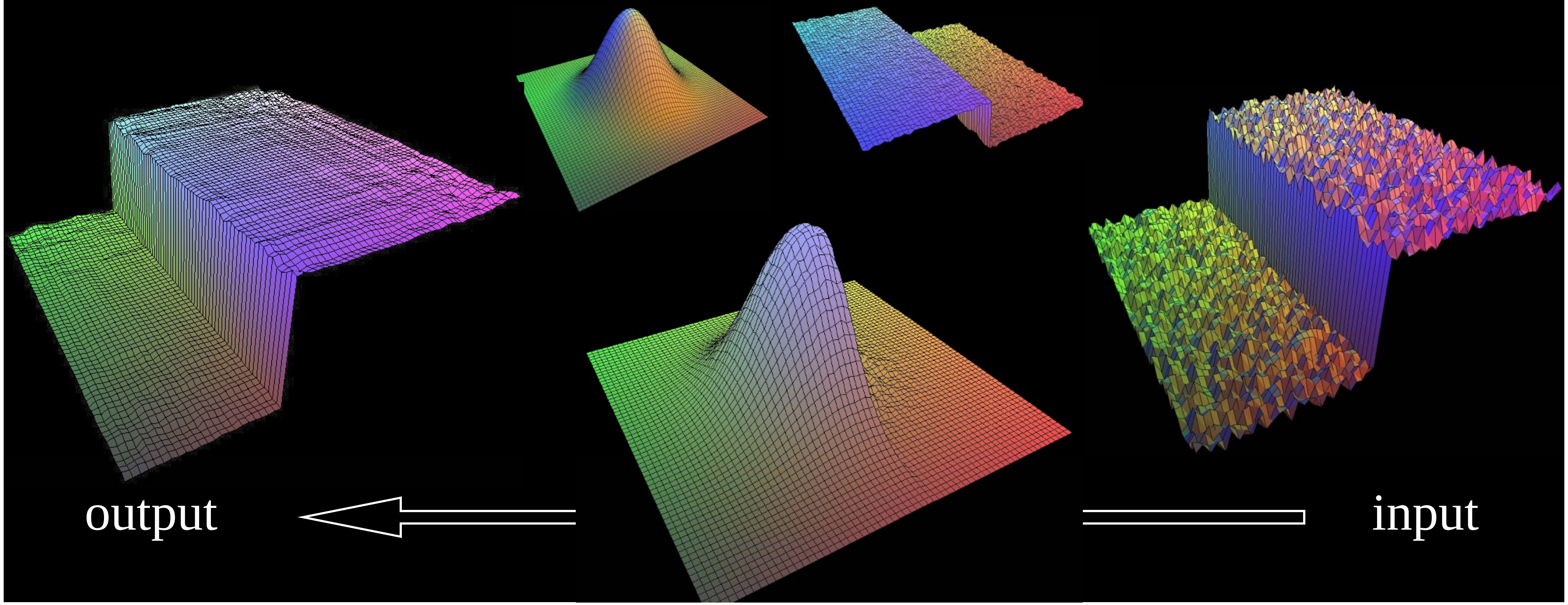
# Normalization factor

- [Tomasi and Manduchi 1998]
- k(x)=



# Bilateral filtering is non-linear

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



# Contrast reduction

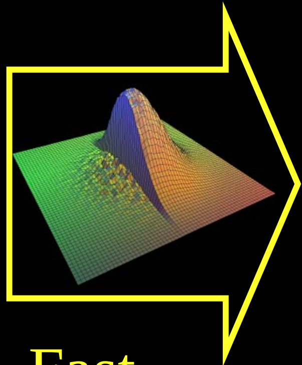

Contrast
too high!

# Contrast reduction



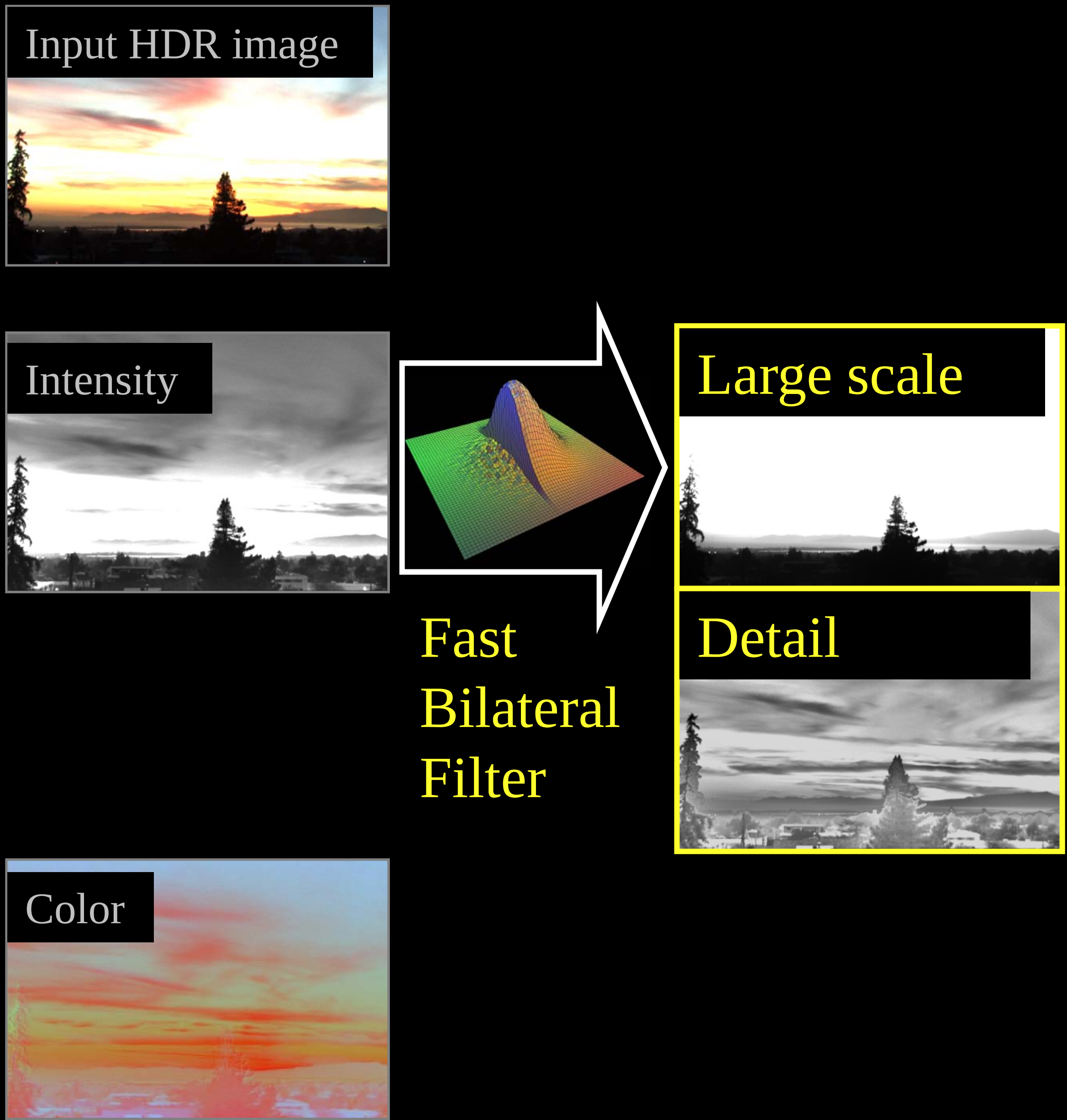
# Contrast reduction



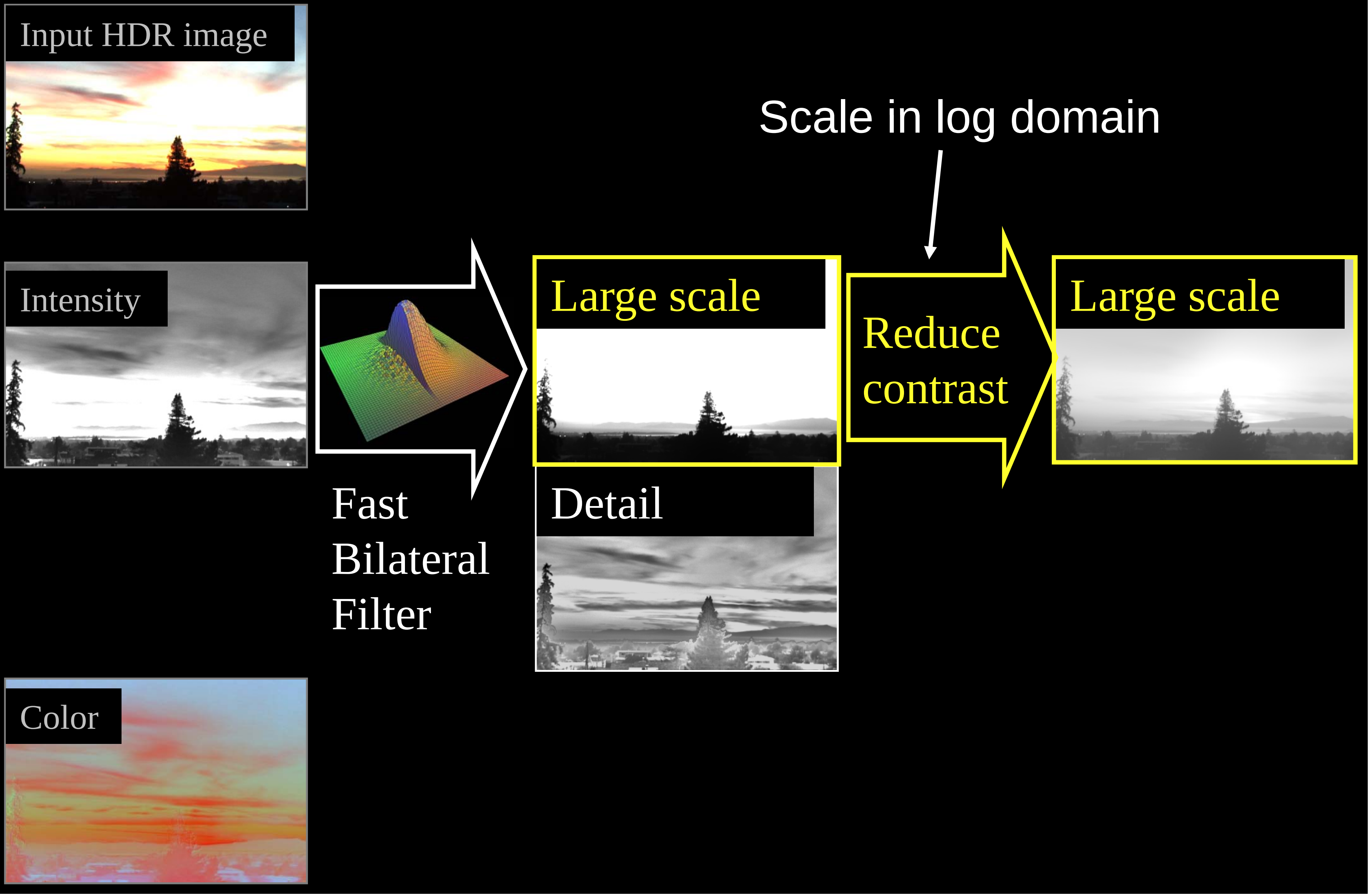


Fast
Bilateral
Filter

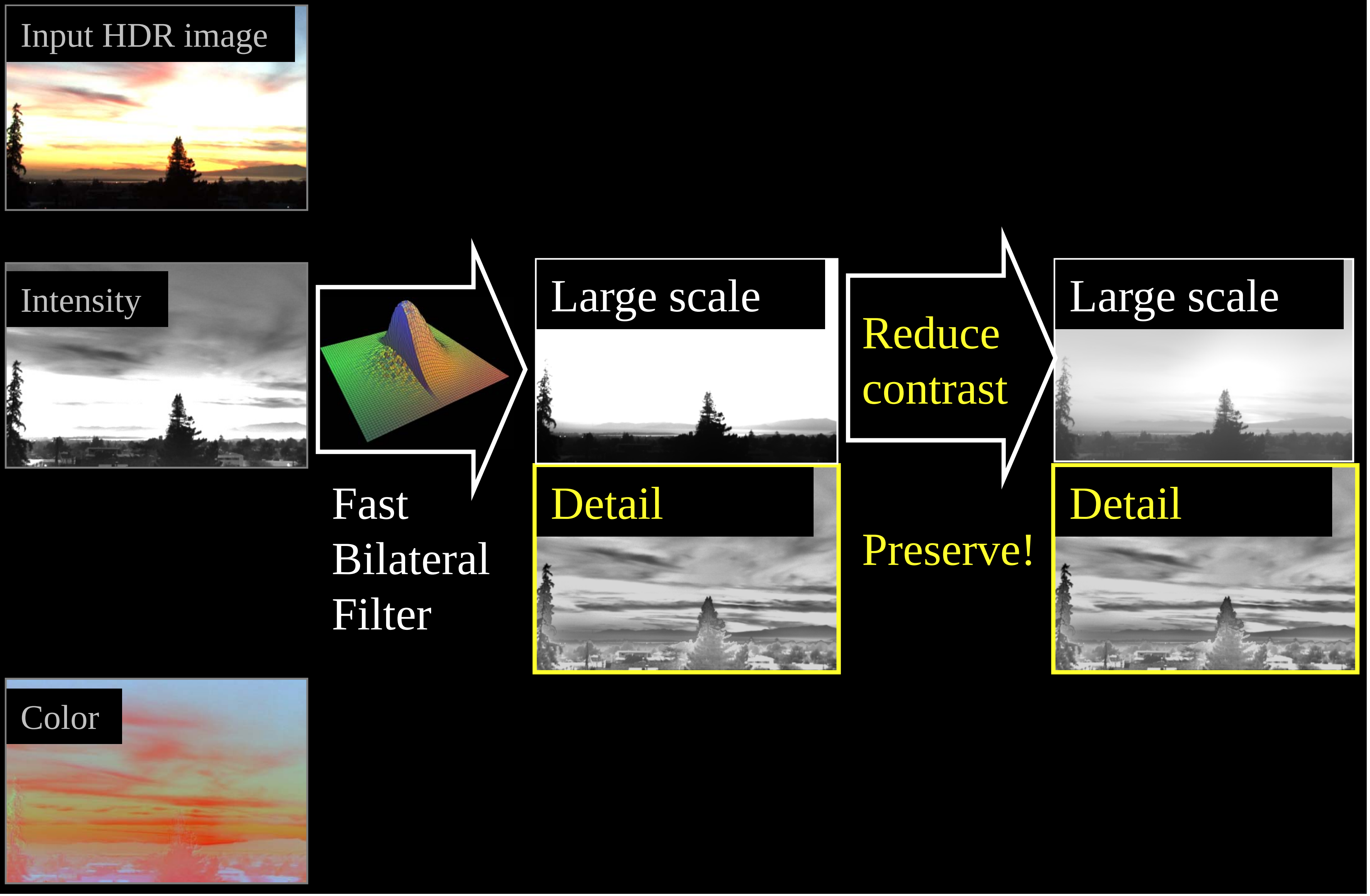

# Contrast reduction



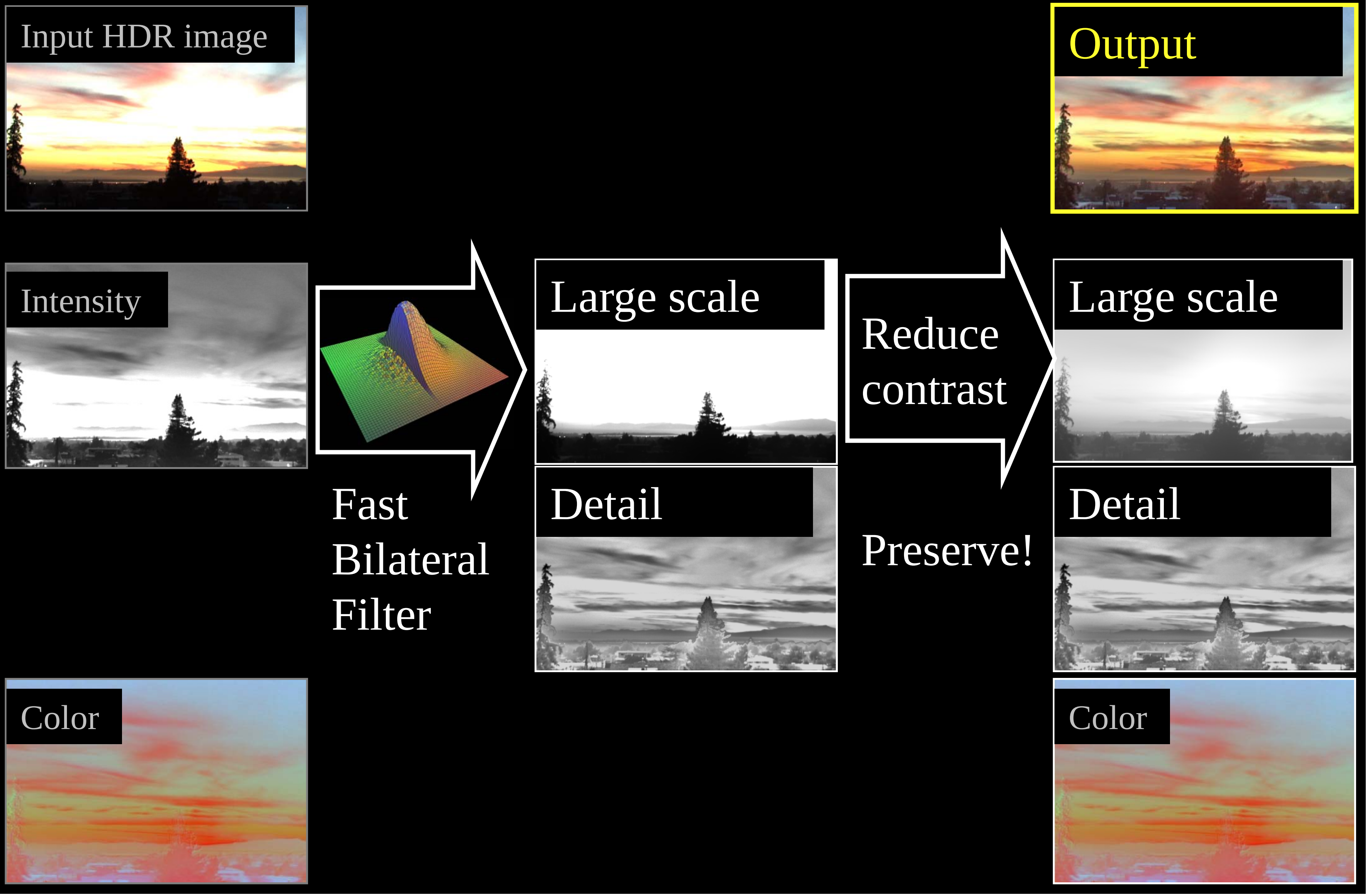
# Contrast reduction



# Contrast reduction

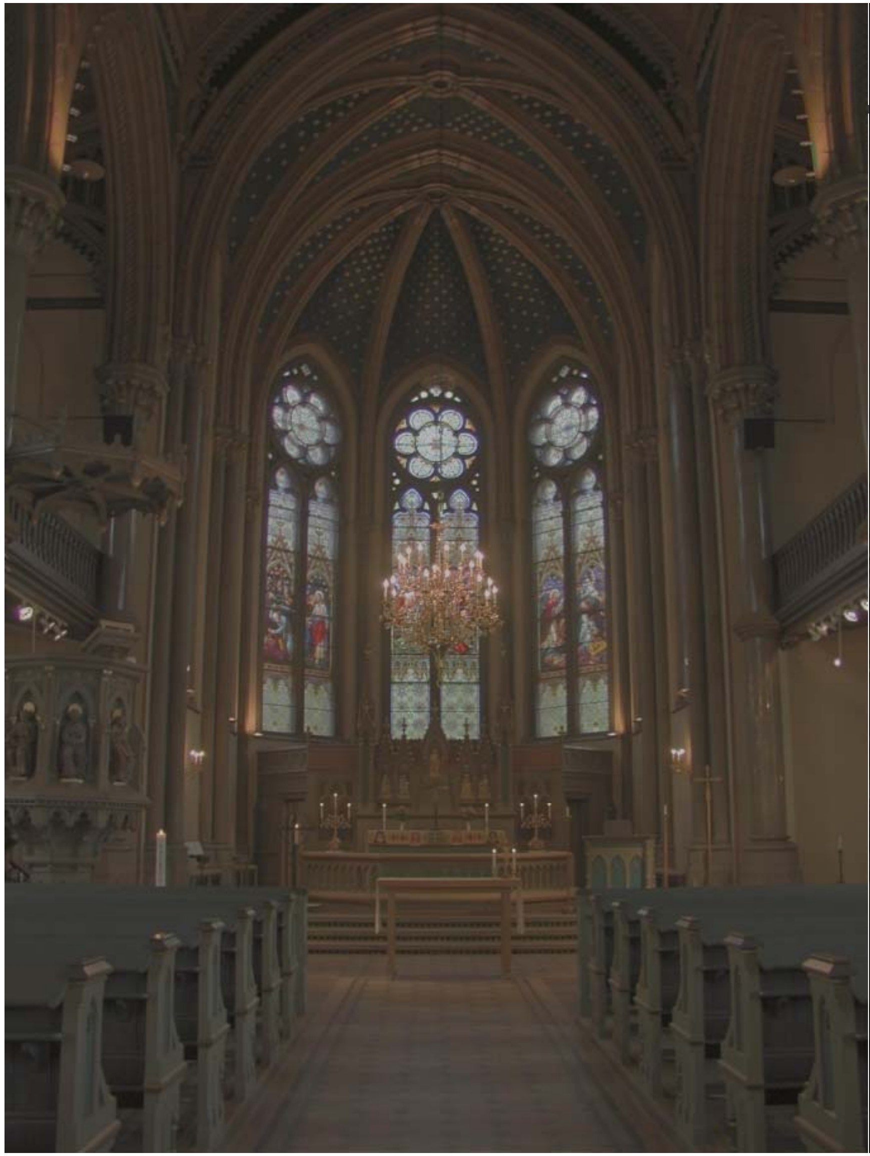


# Contrast reduction

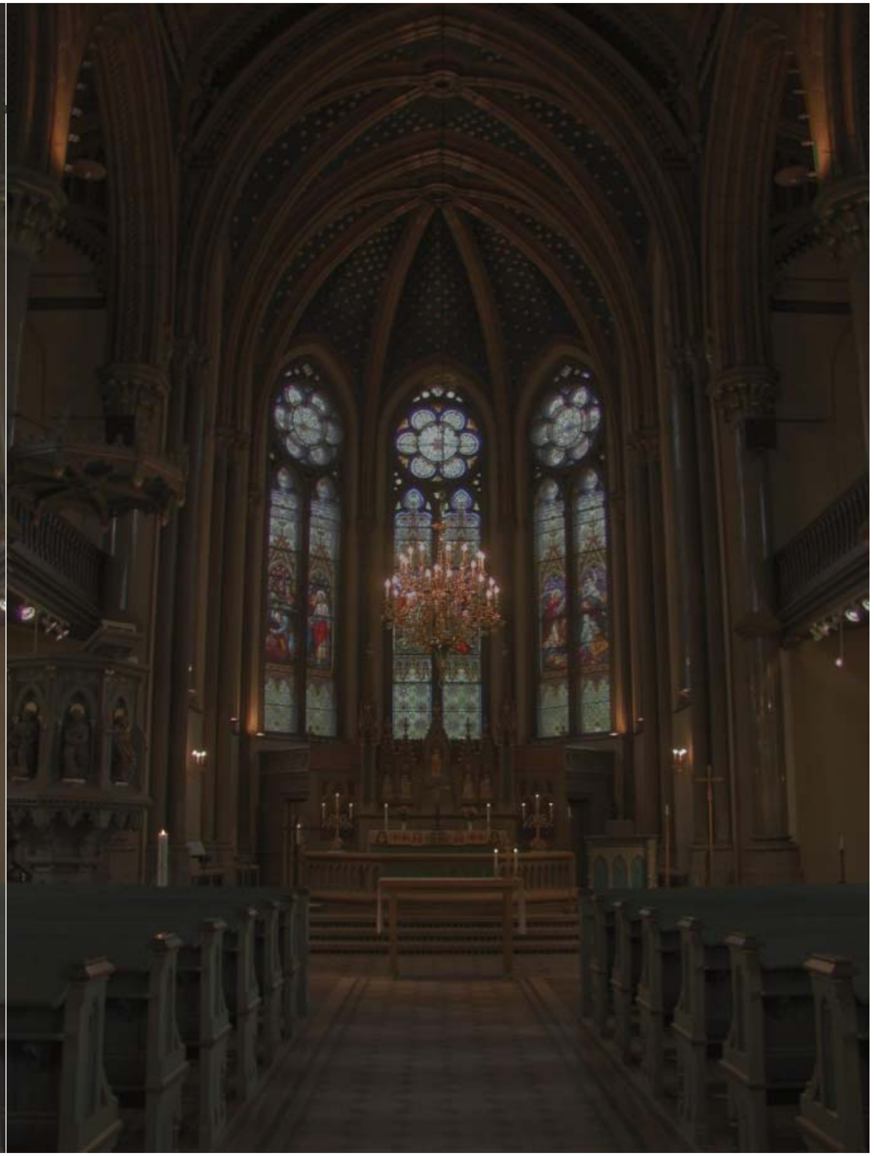


# Bilateral filter is slow!

- 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

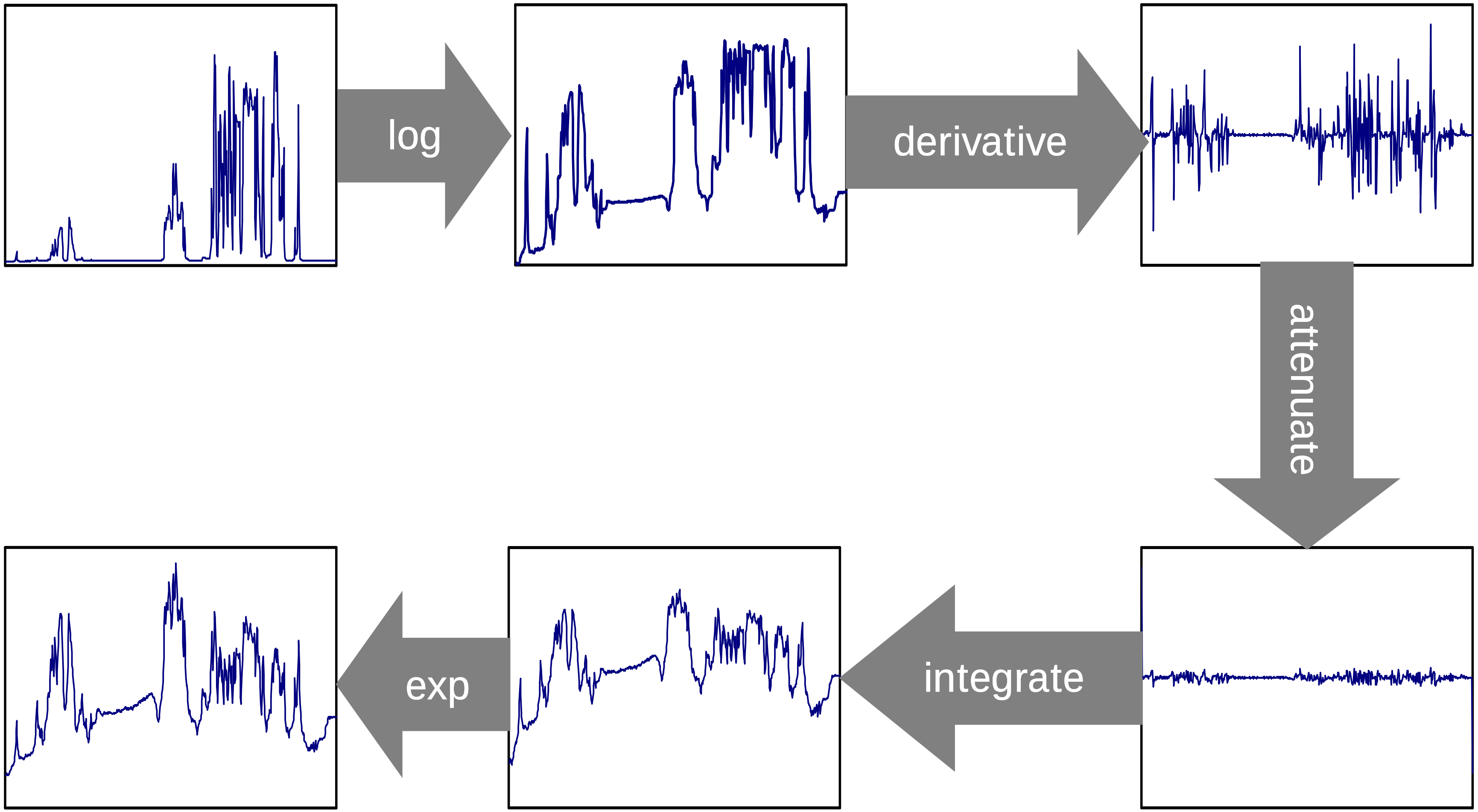
Raanan Fattal Dani Lischinski Michael Werman

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* $\Phi\left(\left\|\nabla H\right\|\right)$
- Compute an attenuated gradient field $\boldsymbol{G}$:

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

- Problem: $\boldsymbol{G}$ may not be integrable!

# Solution

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

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

$$\Rightarrow \quad \frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2} = \frac{\partial G_x}{\partial x} + \frac{\partial G_y}{\partial y}$$

Poisson equation

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

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

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

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

# Solving Poisson equation

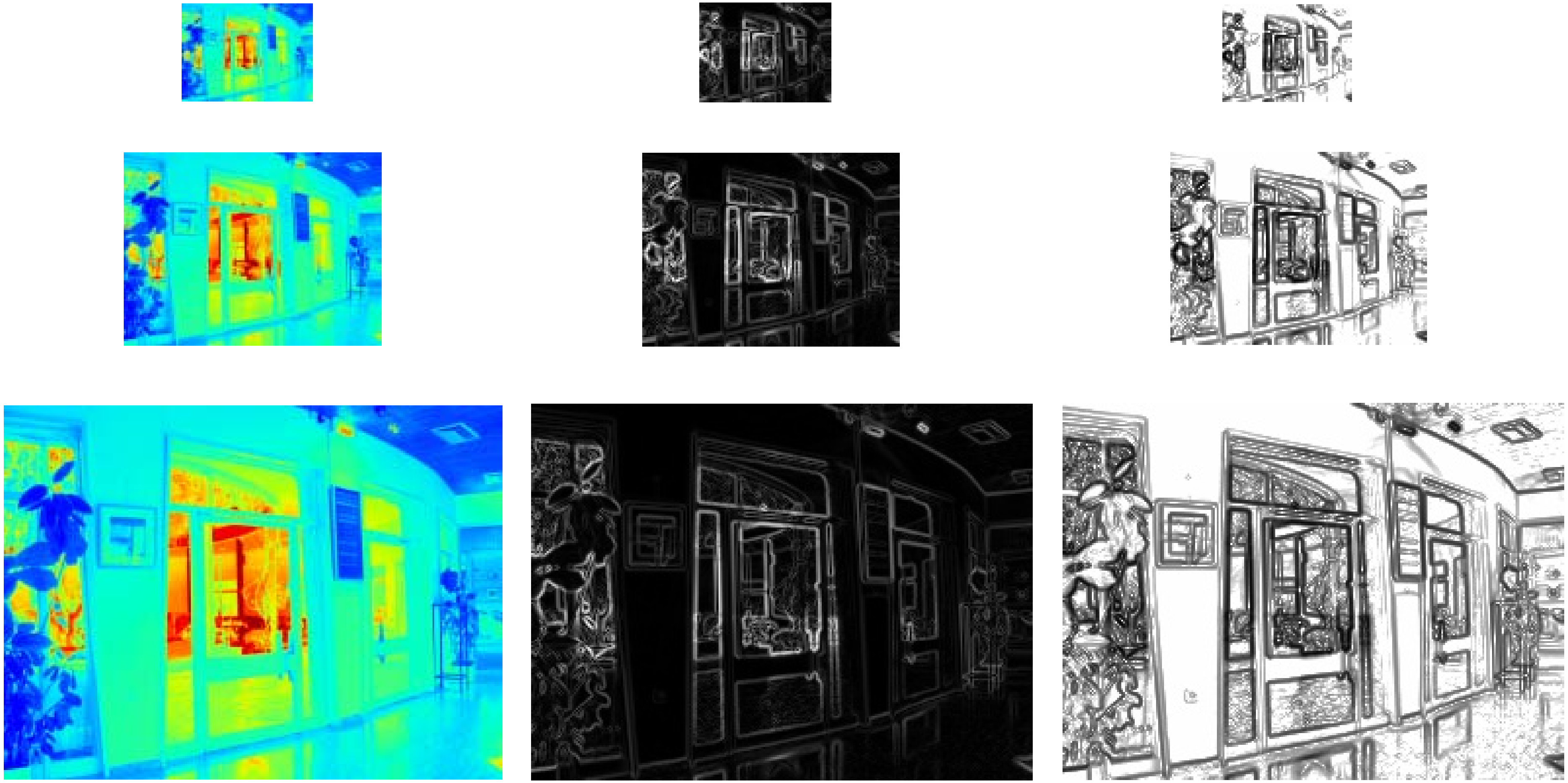
- No analytical solution
- Multigrid method
- Conjugate gradient method

# 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 $H_i$

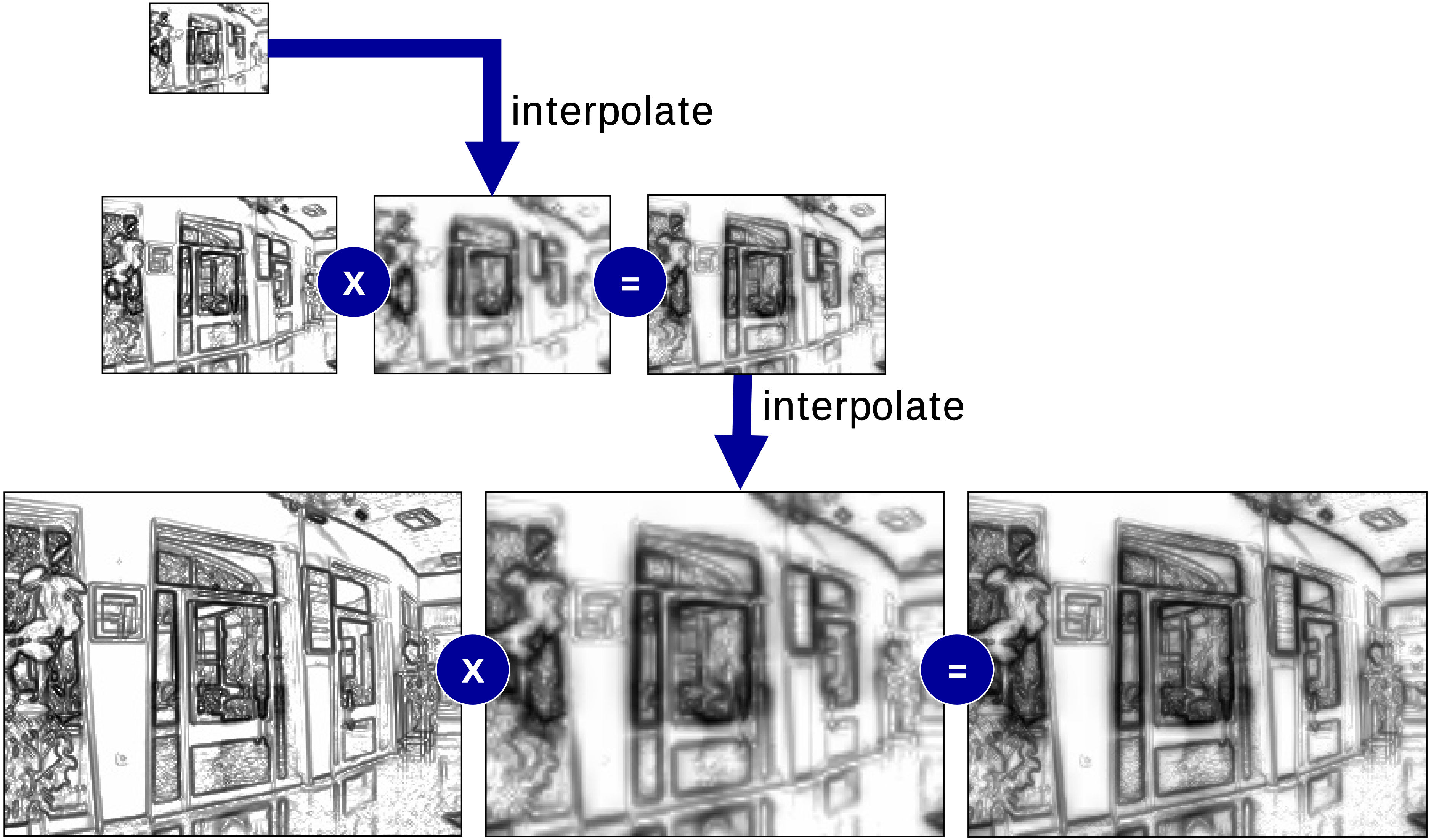
# Attenuation

$$\varphi_k(x,y) = \left( \frac{\left\| \nabla H_k(x,y) \right\|}{\alpha} \right)^{\beta - 1} \qquad \beta \sim 0.8 \qquad \alpha = 0.1\overline{\nabla H}$$

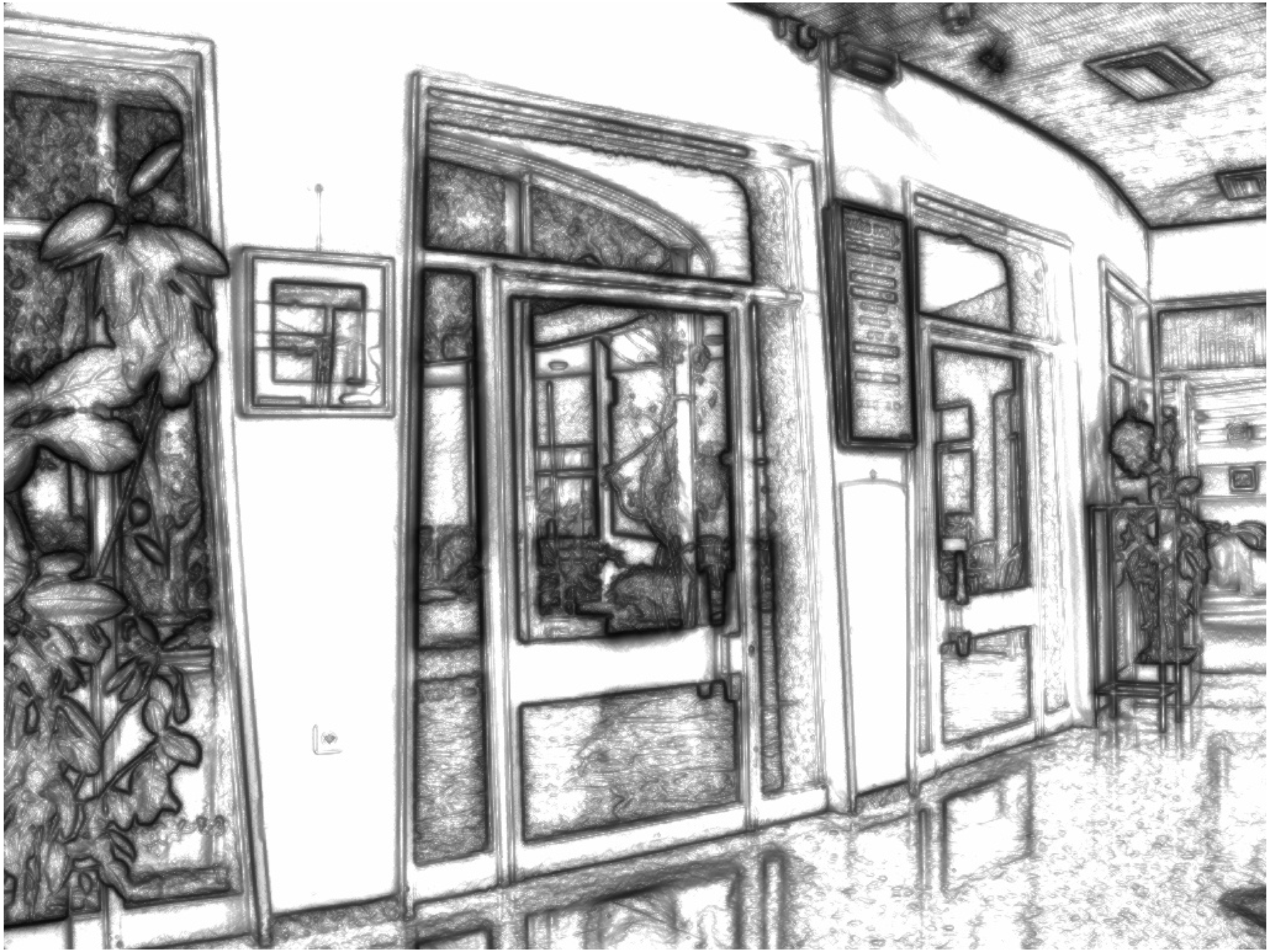


log(Luminance) gradient magnitude attenuation map

# Multiscale gradient attenuation

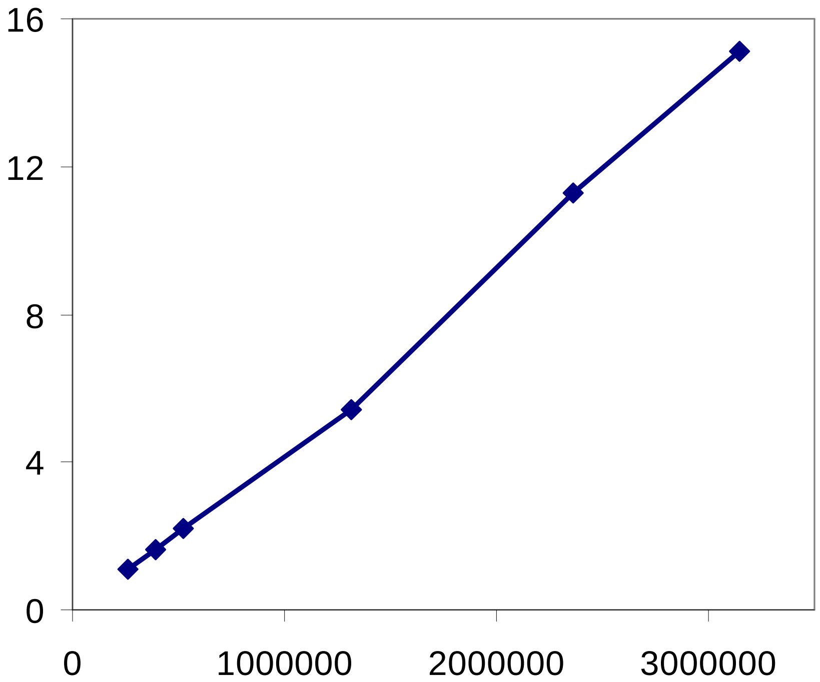


# Final gradient attenuation map



# 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.]

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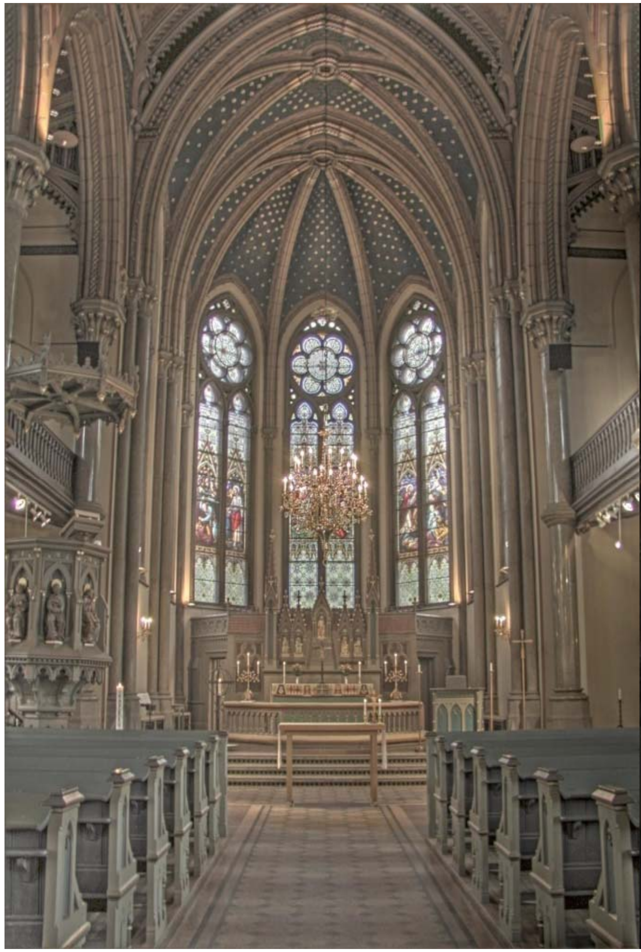
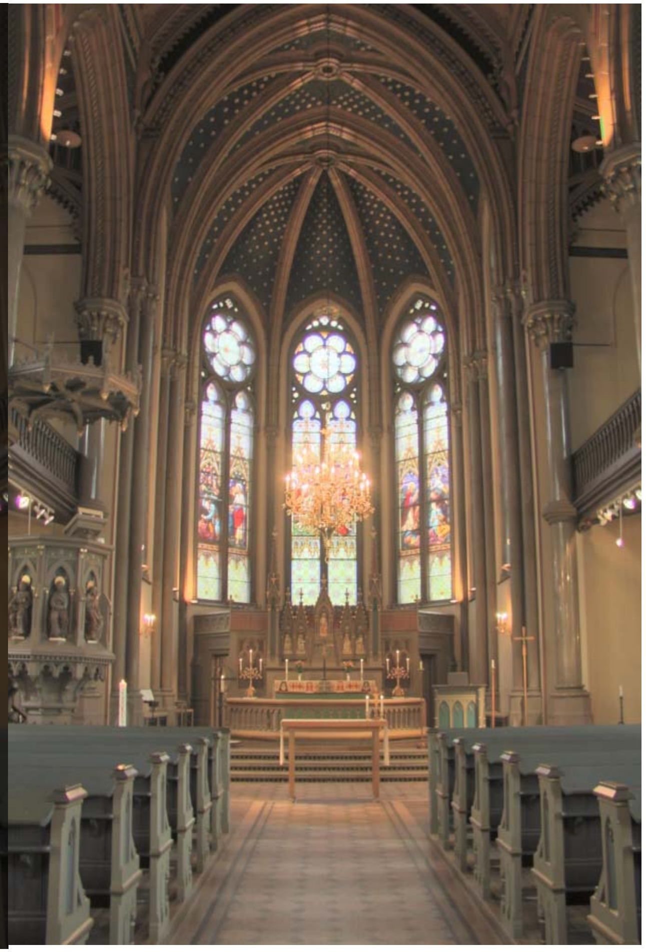
# Informal comparison



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

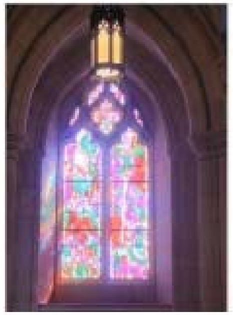
# 23 scenes

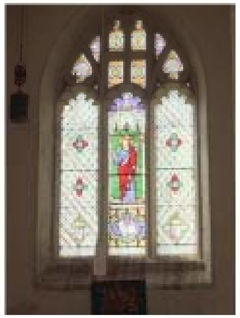

*Scene 1*


*Scene 2*


*Scene 3*


*Scene 4*

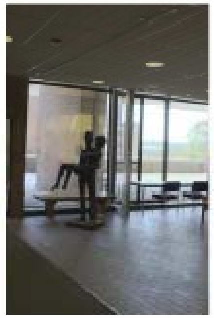

*Scene 5*

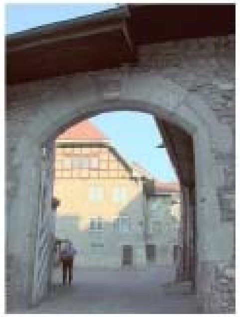

*Scene 6*

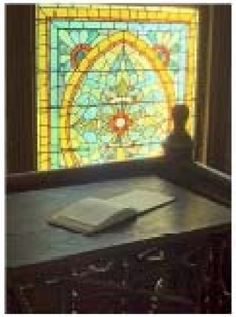

*Scene 7*


*Scene 8*


*Scene 9*


*Scene 10*


*Scene 11*


*Scene 12*


*Scene 13*


*Scene 14*


*Scene 15*

# Experiment setting

# Preference matrix

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

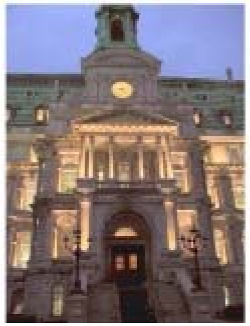
| | $tmo_1$ | $tmo_2$ | $tmo_3$ | $tmo_4$ | $tmo_5$ | $tmo_6$ | Score |
|---|---|---|---|---|---|---|---|
| $tmo_1$ | - | 1 | 0 | 0 | 1 | 1 | 3 |
| $tmo_2$ | 0 | - | 0 | 1 | 1 | 0 | 2 |
| $tmo_3$ | 1 | 1 | - | 1 | 1 | 1 | 5 |
| $tmo_4$ | 1 | 0 | 0 | - | 0 | 0 | 1 |
| $tmo_5$ | 0 | 0 | 0 | 1 | - | 1 |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

# References


- Raanan Fattal, Dani Lischinski, Michael Werman, Gradient Domain High Dynamic Range Compression, SIGGRAPH 2002.
- Fredo Durand, Julie Dorsey, Fast Bilateral Filtering for the Display of High Dynamic Range Images, SIGGRAPH 2002.
- Erik Reinhard, Michael Stark, Peter Shirley, Jim Ferwerda, Photographics Tone Reproduction for Digital Images, SIGGRAPH 2002.
- Patrick Ledda, Alan Chalmers, Tom Troscianko, Helge Seetzen, Evaluation of Tone Mapping Operators using a High Dynamic Range Display, SIGGRAPH 2005.
- Jiangtao Kuang, Hiroshi Yamaguchi, Changmeng Liu, Garrett Johnson, Mark Fairchild, Evaluating HDR Rendering Algorithms, ACM Transactions on Applied Perception, 2007.