Computational Photography and Video:

High-Dynamic Range Imaging

Prof. Marc Pollefeys

Dr. Gabriel Brostow

ETH

inf | Informatik Computer Science

Today's schedule

- Last week's recap
- High Dynamic Range Imaging (LDR->HDR)
- Tone mapping (HDR->LDR display)

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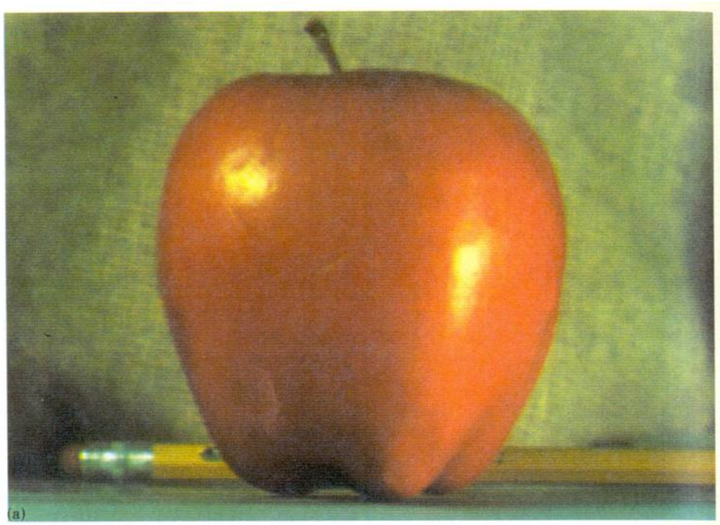
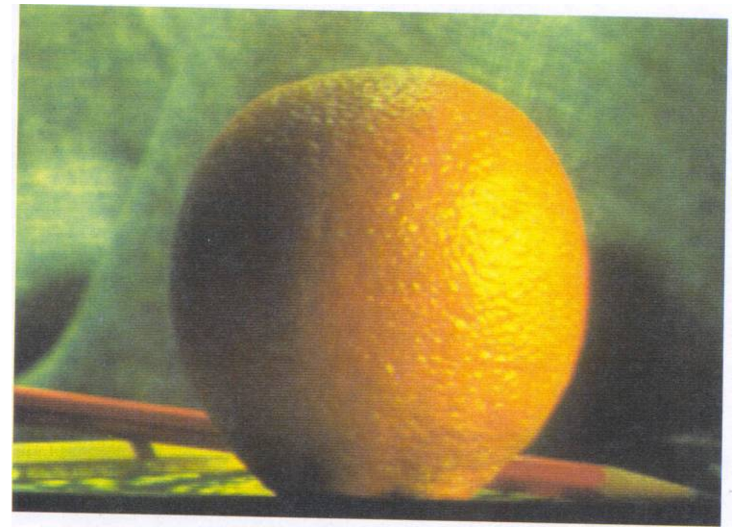
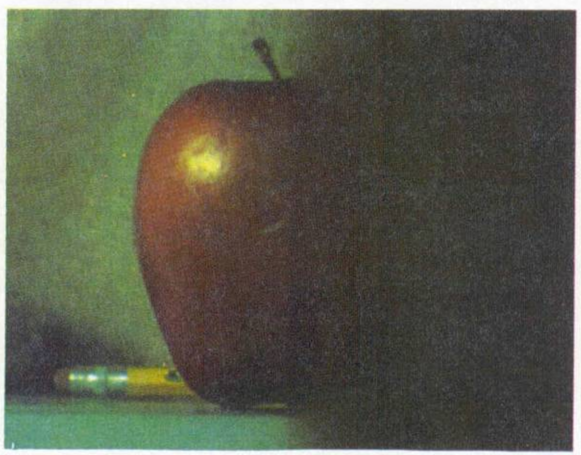
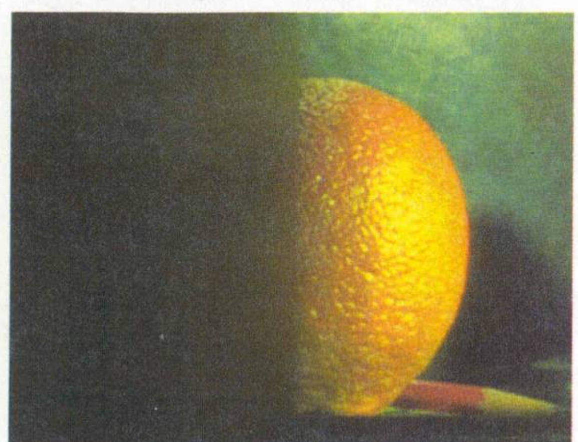
Pyramid Blending



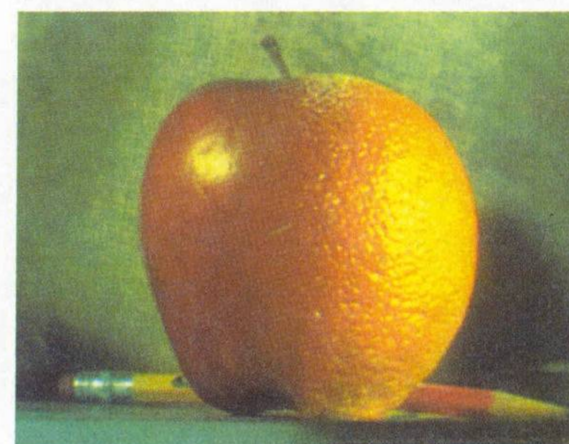




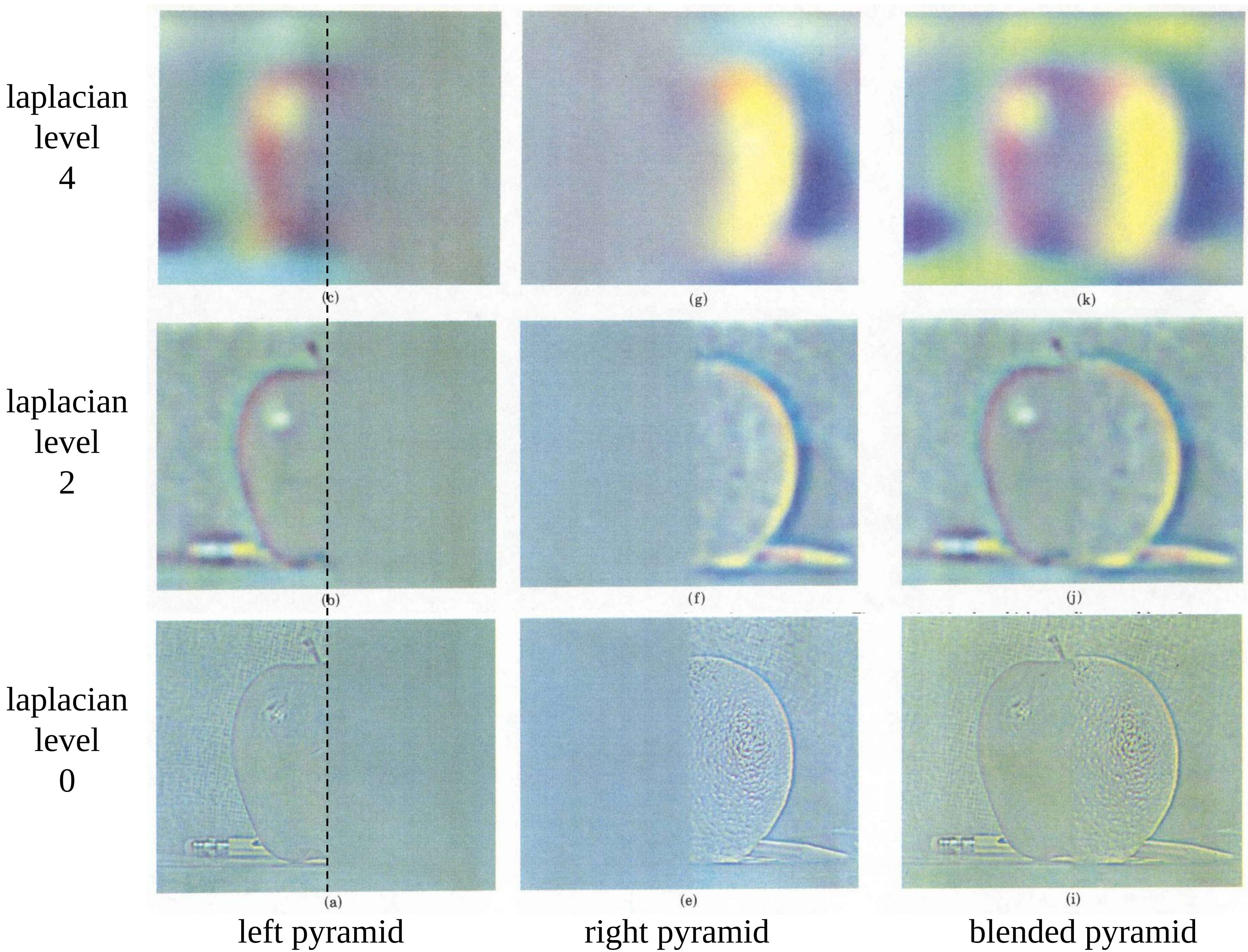
(d)



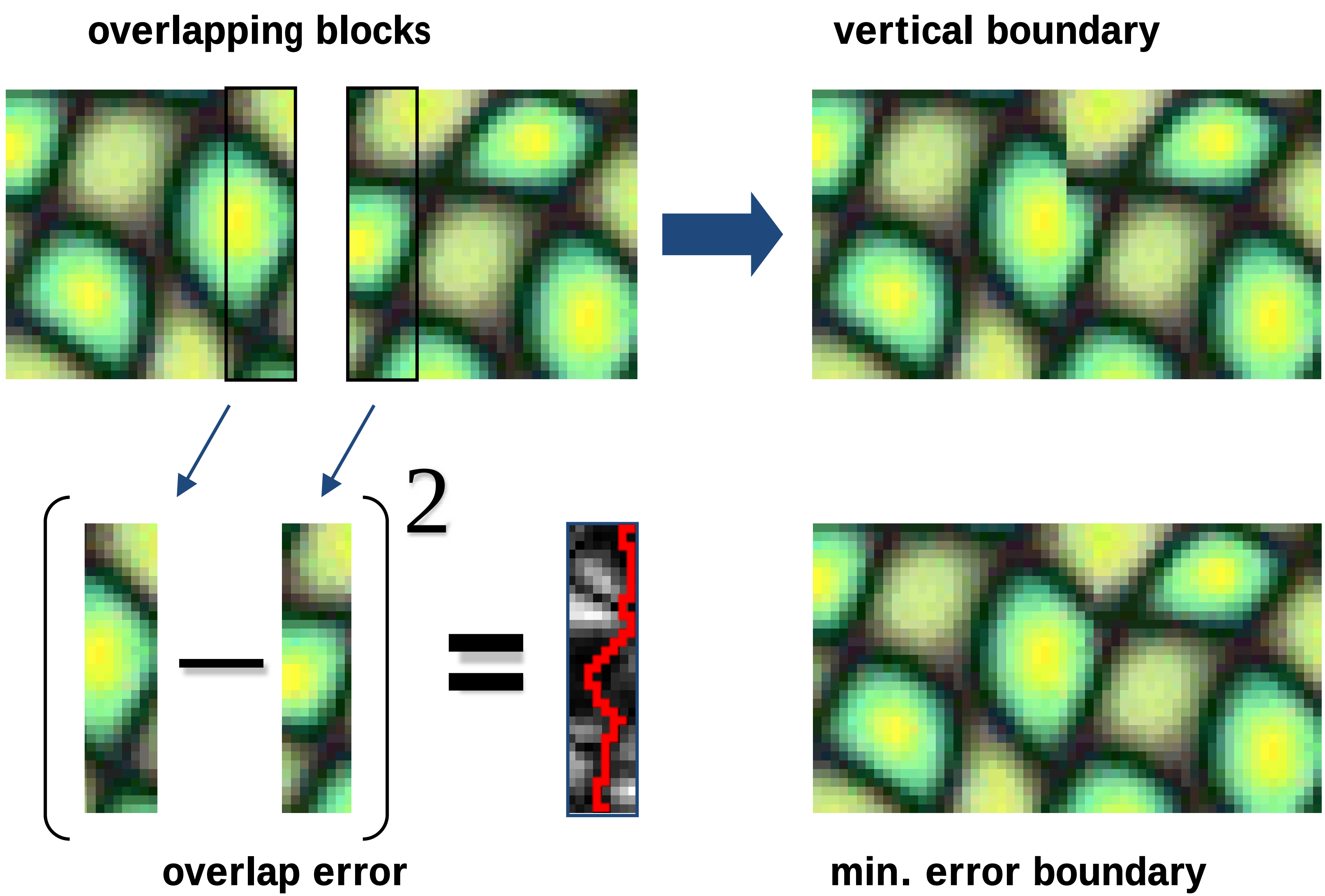
(h)



(l)


laplacian level 4
laplacian level 2
laplacian level 0
(c)
(g)
(k)
(b)
(f)
(j)
(a)
(e)
(i)
left pyramid
right pyramid
blended pyramid

Minimal error boundary



Schedule	Computational Photography and Video	
20 Feb	Introduction to Computational Photography	
27 Feb	More on Cameras, Sensors and Color	Assignment 1: Color
5 Mar	Warping, morphing and mosaics	Assignment 2: Alignment
12 Mar	Image pyramids, Graphcuts	Assignment 3: Blending
19 Mar	Dynamic Range, HDR imaging, tone mapping	Assignment 4: HDR
26 Mar	*Easter holiday – no classes*	
2 Apr	TBD	Project proposals
9 Apr	TBD	Papers
16 Apr	TBD	Papers
23 Apr	TBD	Papers
30 Apr	TBD	Project update
7 May	TBD	Papers
14 May	TBD	Papers
21 May	TBD	Papers
28 May	TBD	Final project presentation

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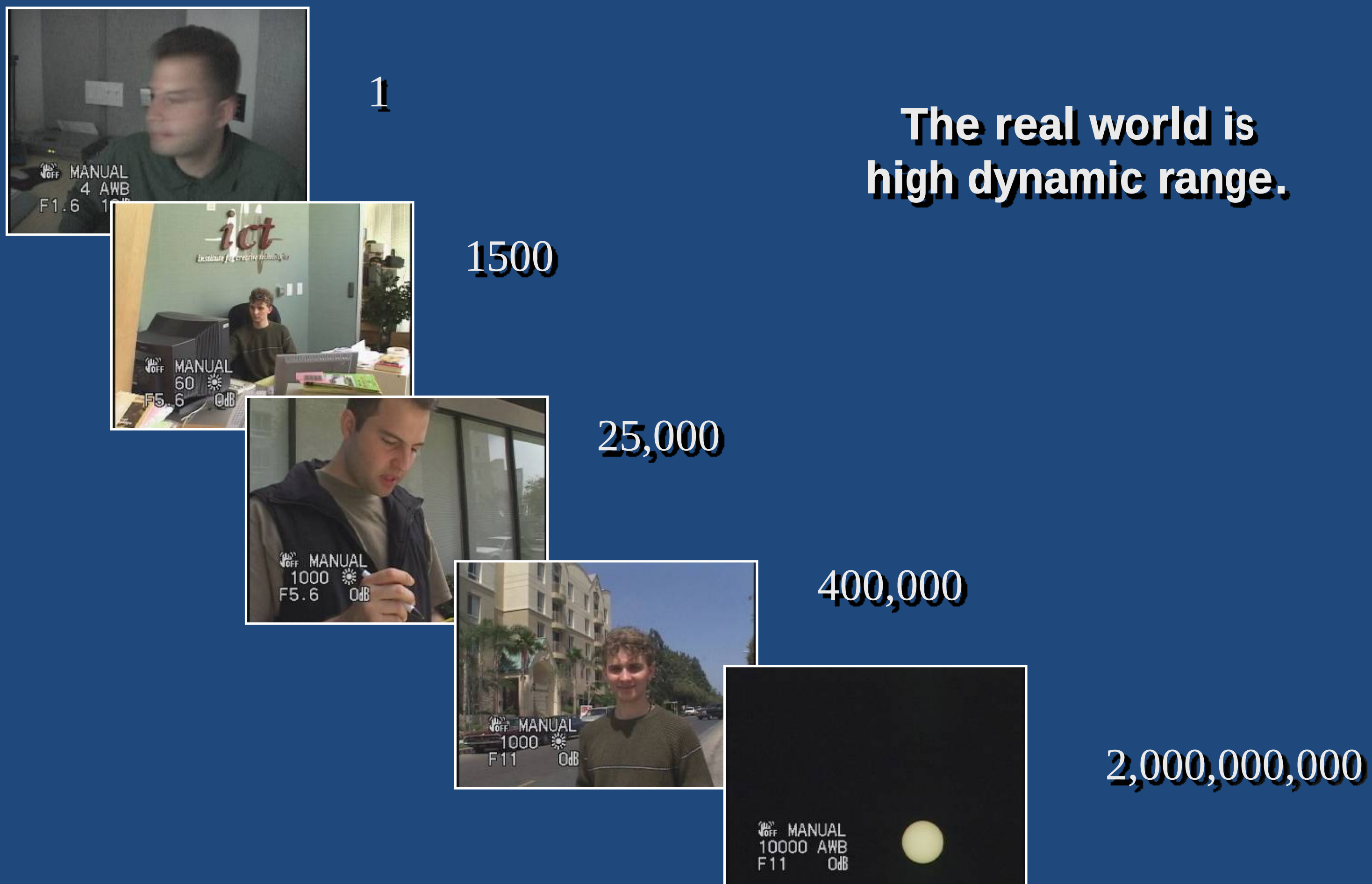
The Problem

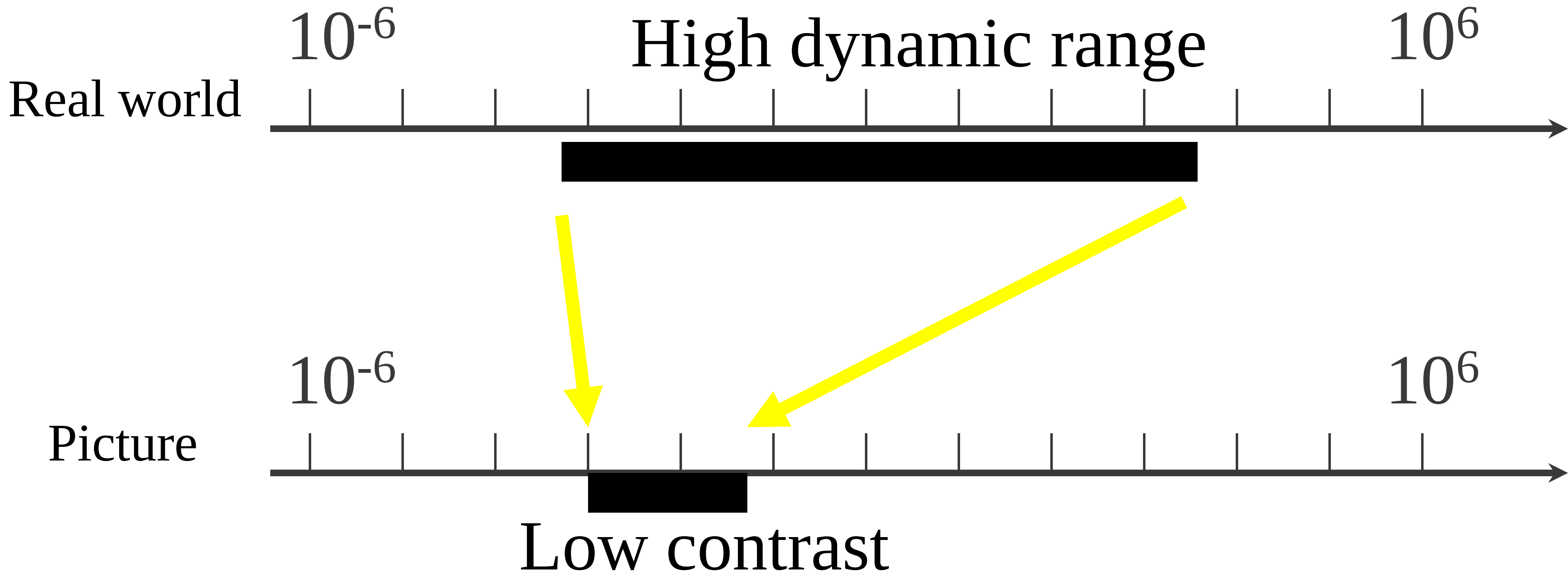
Problem: Dynamic Range



The real world is high dynamic range.

Multiple exposure photography

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



Multiple exposure photography

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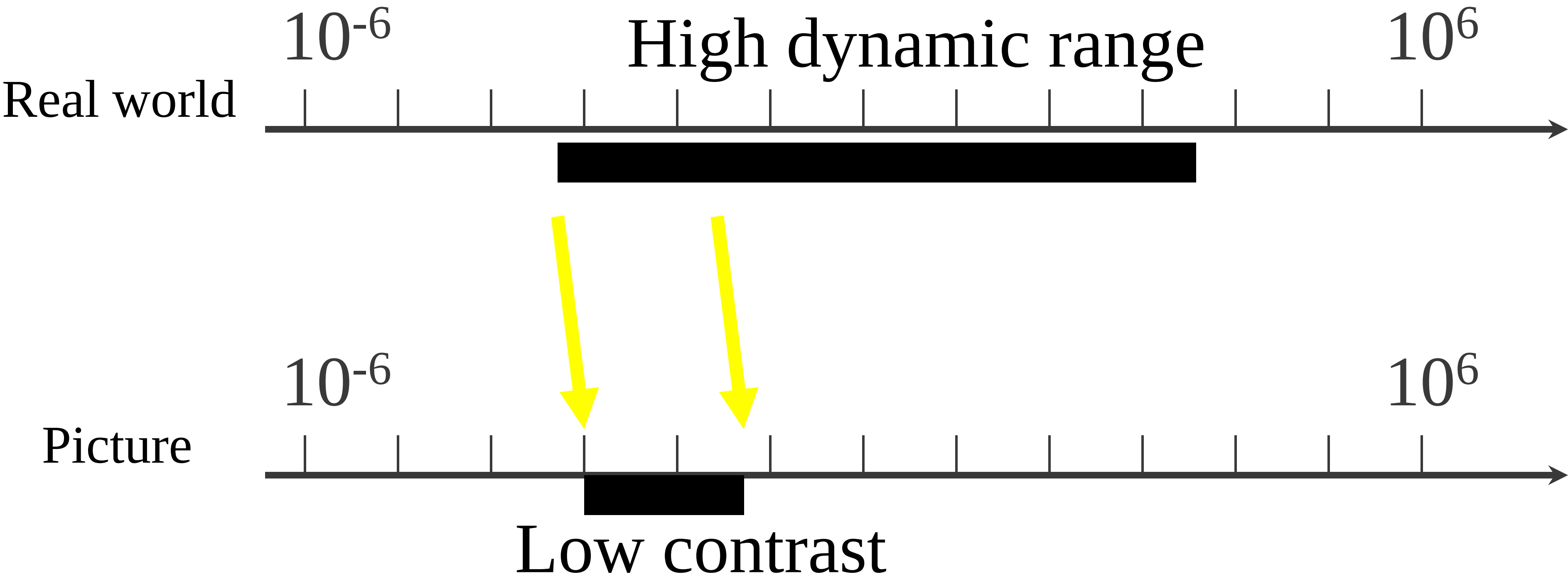

Multiple exposure photography

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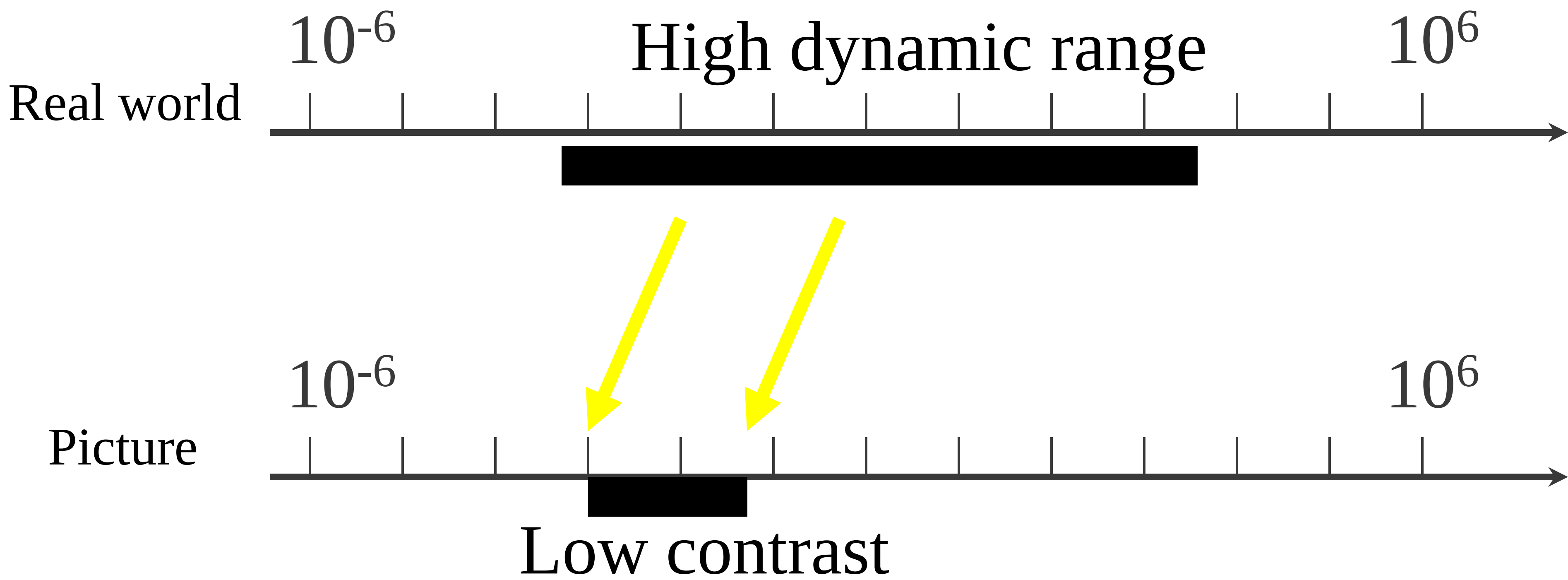

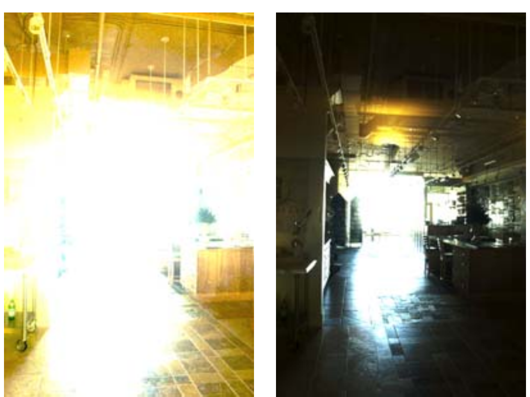

Multiple exposure photography

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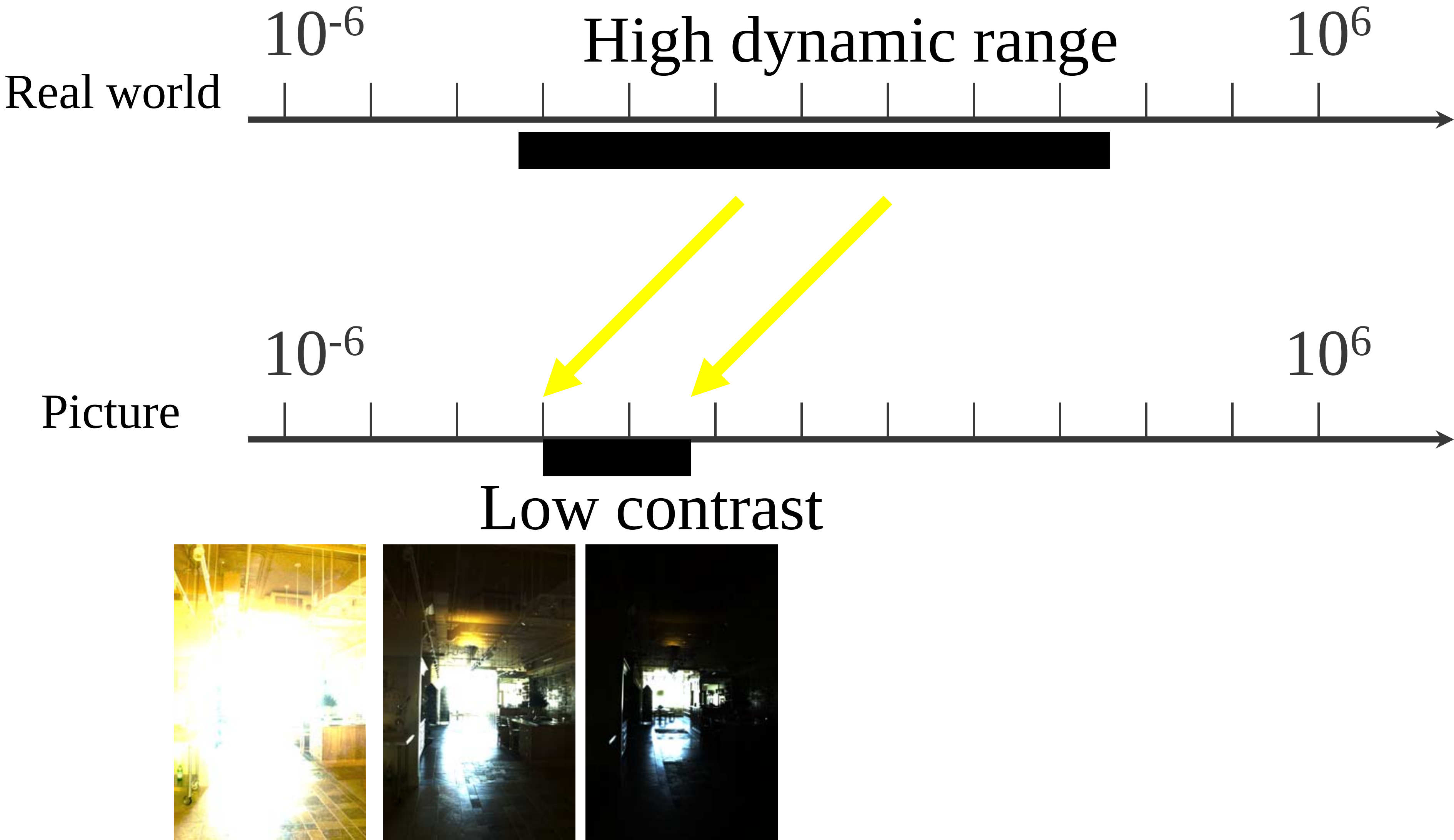

Multiple exposure photography

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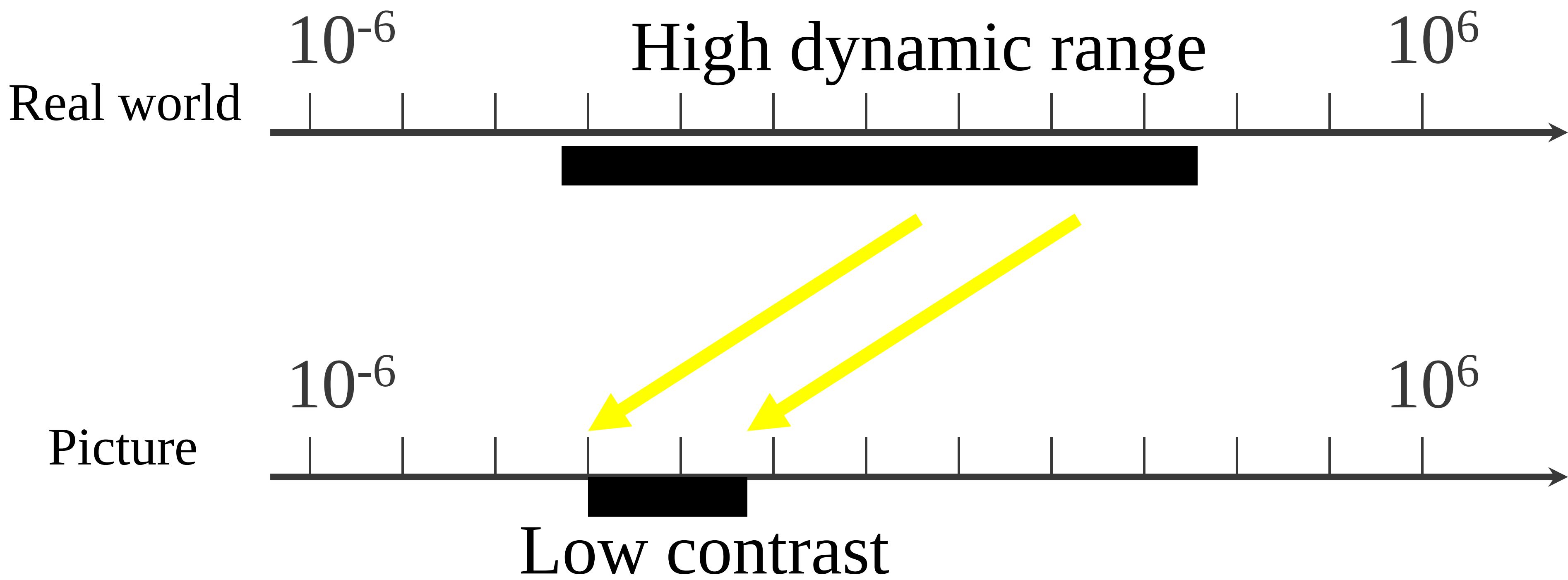

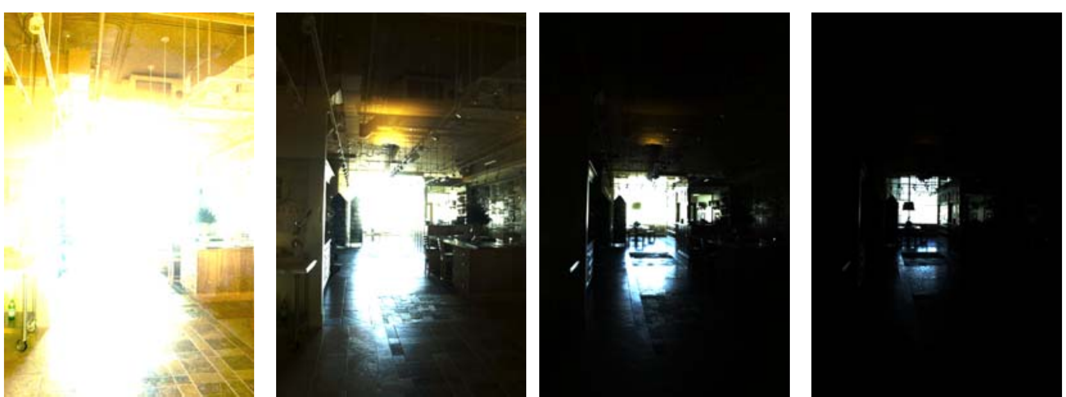

Multiple exposure photography

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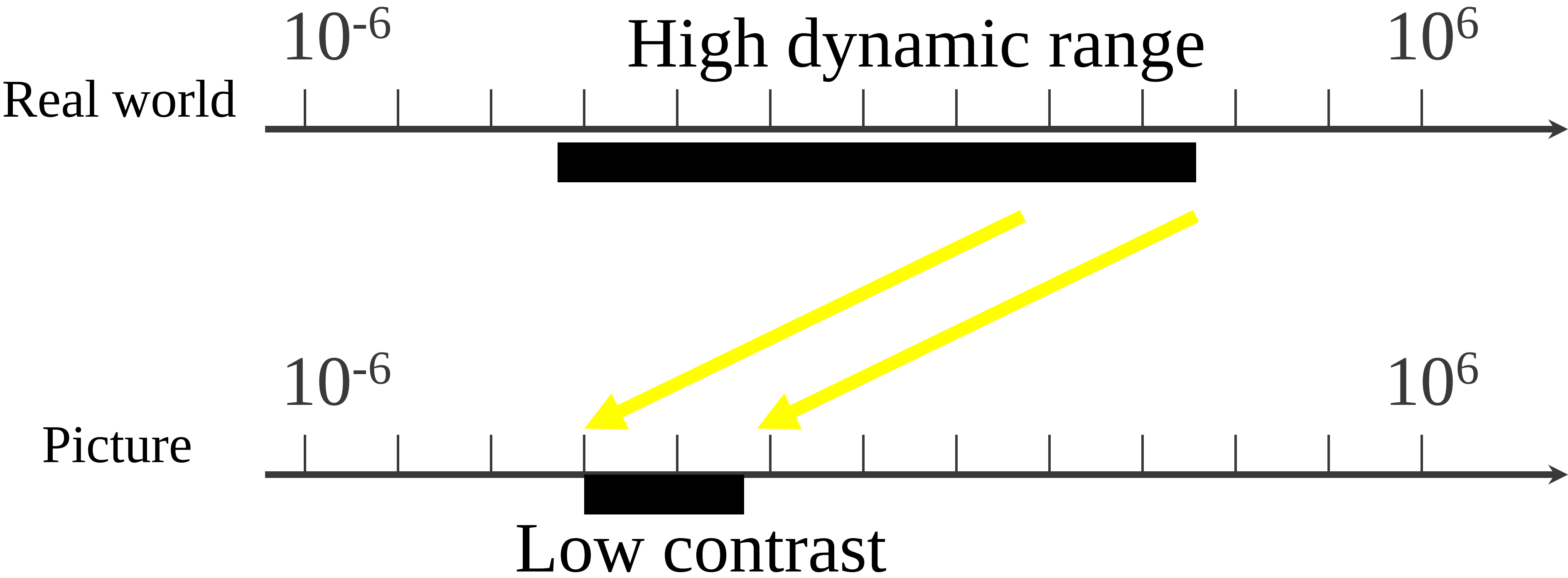
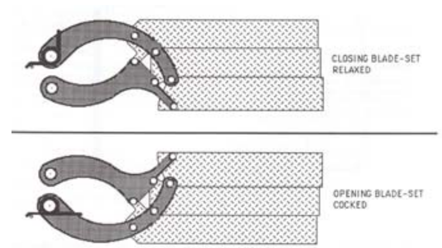
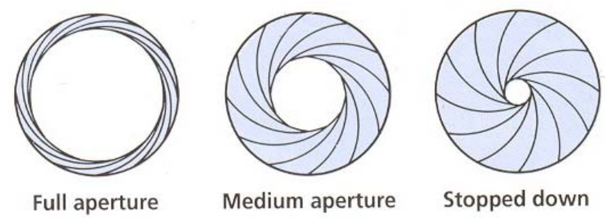


How do we vary exposure?

- **Options:**
  - Shutter speed
  - Aperture
  - ISO
  - Neutral density filter

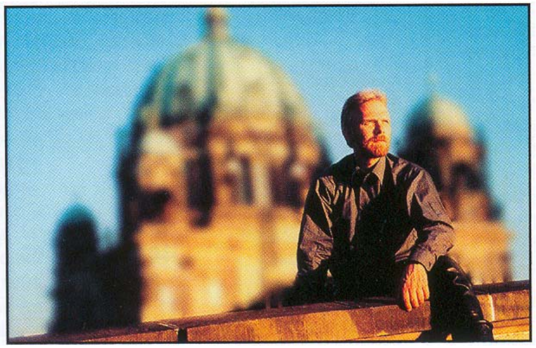


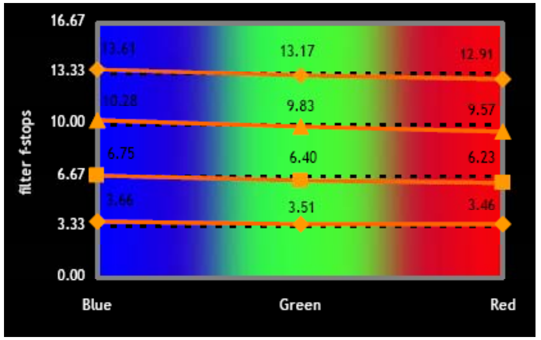


Slide inspired by Siggraph 2005 course on HDR

Tradeoffs

- **Shutter speed**
  - Range: ~30 sec to 1/4000sec (6 orders of magnitude)
  - Pros: reliable, linear
  - Cons: sometimes noise for long exposure
- **Aperture**
  - Range: ~f/1.4 to f/22 (2.5 orders of magnitude)
  - Cons: changes depth of field
  - Useful when desperate
- **ISO**
  - Range: ~100 to 1600 (1.5 orders of magnitude)
  - Cons: noise
  - Useful when desperate
- **Neutral density filter**
  - Range: up to 4 densities (4 orders of magnitude) & can be stacked
  - Cons: not perfectly neutral (color shift), not very precise, need to touch camera (shake)
  - Pros: works with strobe/flash, good complement when desperate





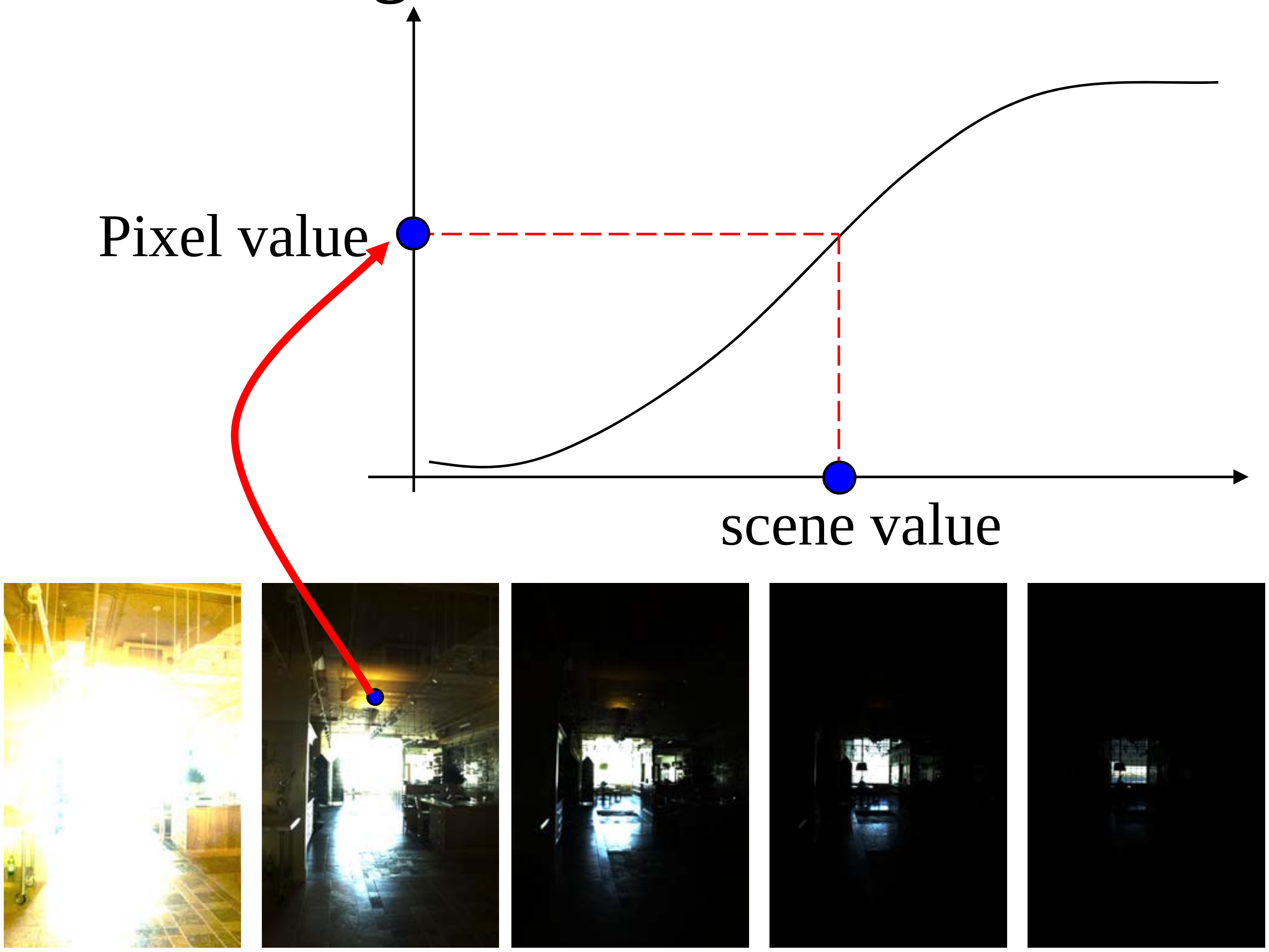
Slide after Siggraph 2005 course on HDR

HDR image using multiple exposure

- **Given N photos at different exposure**
- **Recover a HDR color for each pixel**

If we know the response curve

- **Just look up the inverse of the response curve**
- **But how do we get the curve?**



Calibrating the response curve

- **Two basic solutions**
  - Vary scene luminance and see pixel values
    - Assumes we control and know scene luminance
  - Vary exposure and see pixel value for one scene luminance
    - But note that we can usually not vary exposure more finely than by 1/3 stop
- **Best of both:**
  - Vary exposure
  - Exploit the large number of pixels

The Algorithm

Image series

$\Delta t =$ 10 sec	$\Delta t =$ 1 sec	$\Delta t =$ 1/10 sec	$\Delta t =$ 1/100 sec	$\Delta t =$ 1/1000 sec

$$\text{Pixel Value } Z = f(\text{Exposure})$$

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

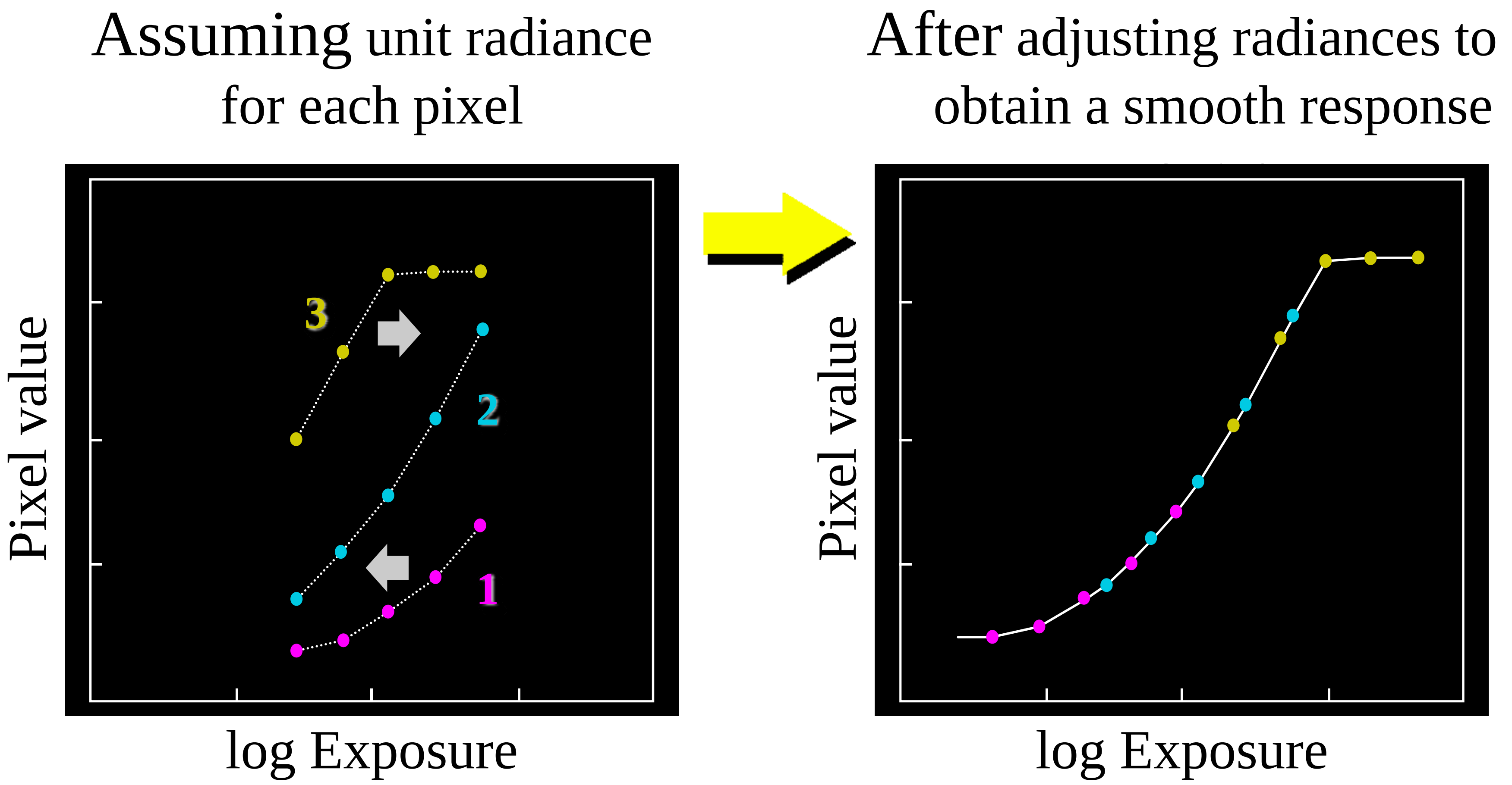
$$\log \text{Exposure} = \log \text{Radiance} + \log \Delta t$$

Slide stolen from Fredo Durand who adapted it from Alyosha Efros who borrowed it from Paul Debevec

Δ t don't really correspond to pictures. Oh well.

Response curve

- **Exposure is unknown, fit to find a smooth curve**



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The Math

- **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:**

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

fitting term

smoothness term

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Matlab code

```
function [g,lE]=gsolve(Z,B,l,w)

n = 256;
A = zeros(size(Z,1)*size(Z,2)+n+1,n+size(Z,1));
b = zeros(size(A,1),1);

k = 1;                     %% Include the data-fitting equations
for i=1:size(Z,1)
  for j=1:size(Z,2)
    wij = w(Z(i,j)+1);
    A(k,Z(i,j)+1) = wij; A(k,n+i) = -wij; b(k,1) = wij * B(i,j);
    k=k+1;
  end
end

A(k,129) = 1;              %% Fix the curve by setting its middle value to 0
k=k+1;

for i=1:n-2                %% Include the smoothness equations
  A(k,i)=l*w(i+1); A(k,i+1)=-2*l*w(i+1); A(k,i+2)=l*w(i+1);
  k=k+1;
end

x = A\b;                   %% Solve the system using SVD

g = x(1:n);
lE = x(n+1:size(x,1));
```

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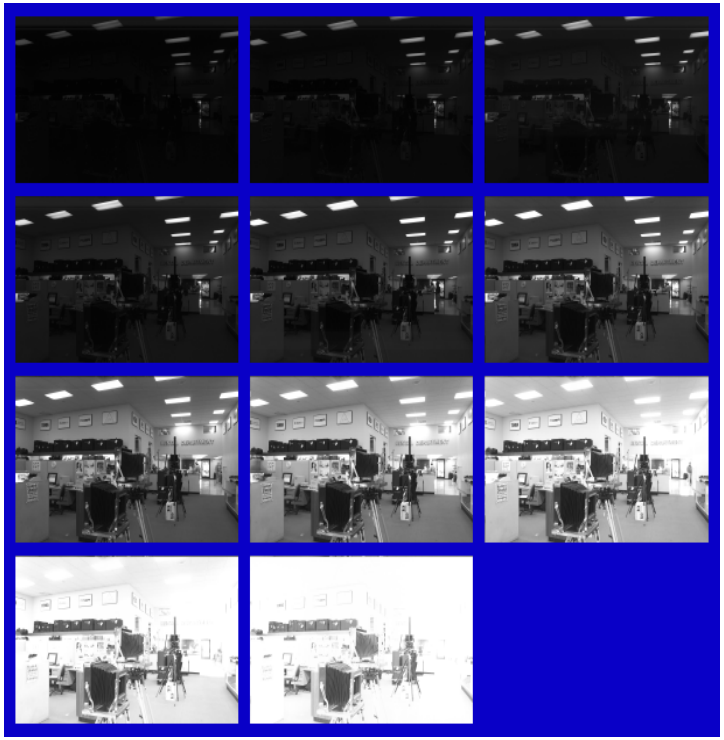
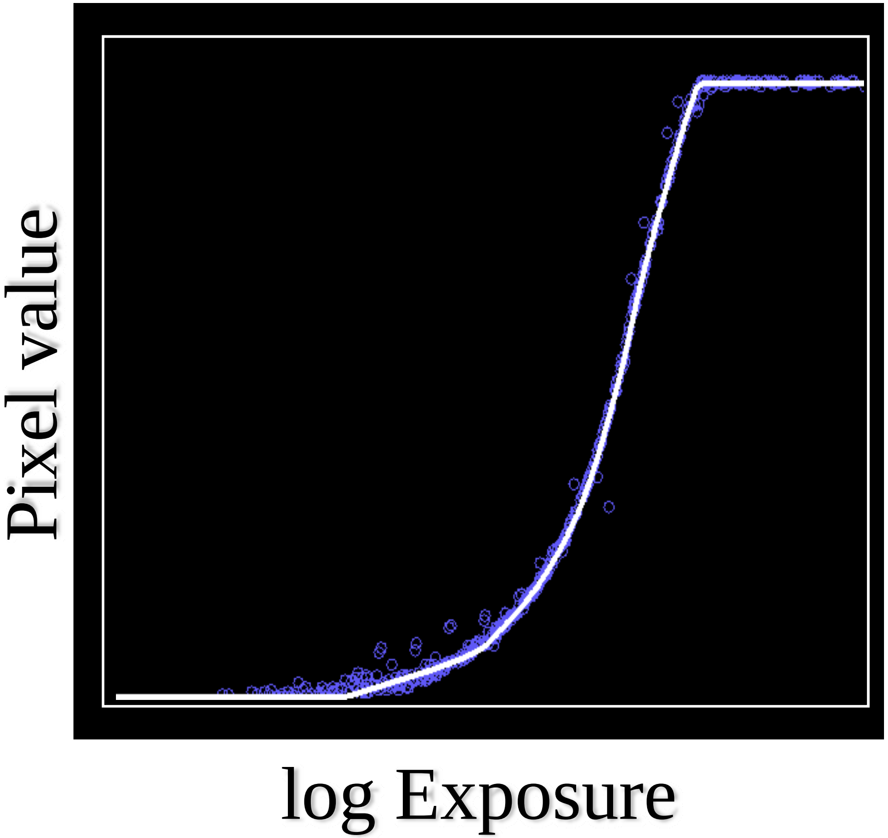
Result: digital camera

Kodak DCS460
1/30 to 30 sec



Recovered response curve



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Reconstructed radiance map

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Result: color film

- **Kodak Gold ASA 100, PhotoCD**

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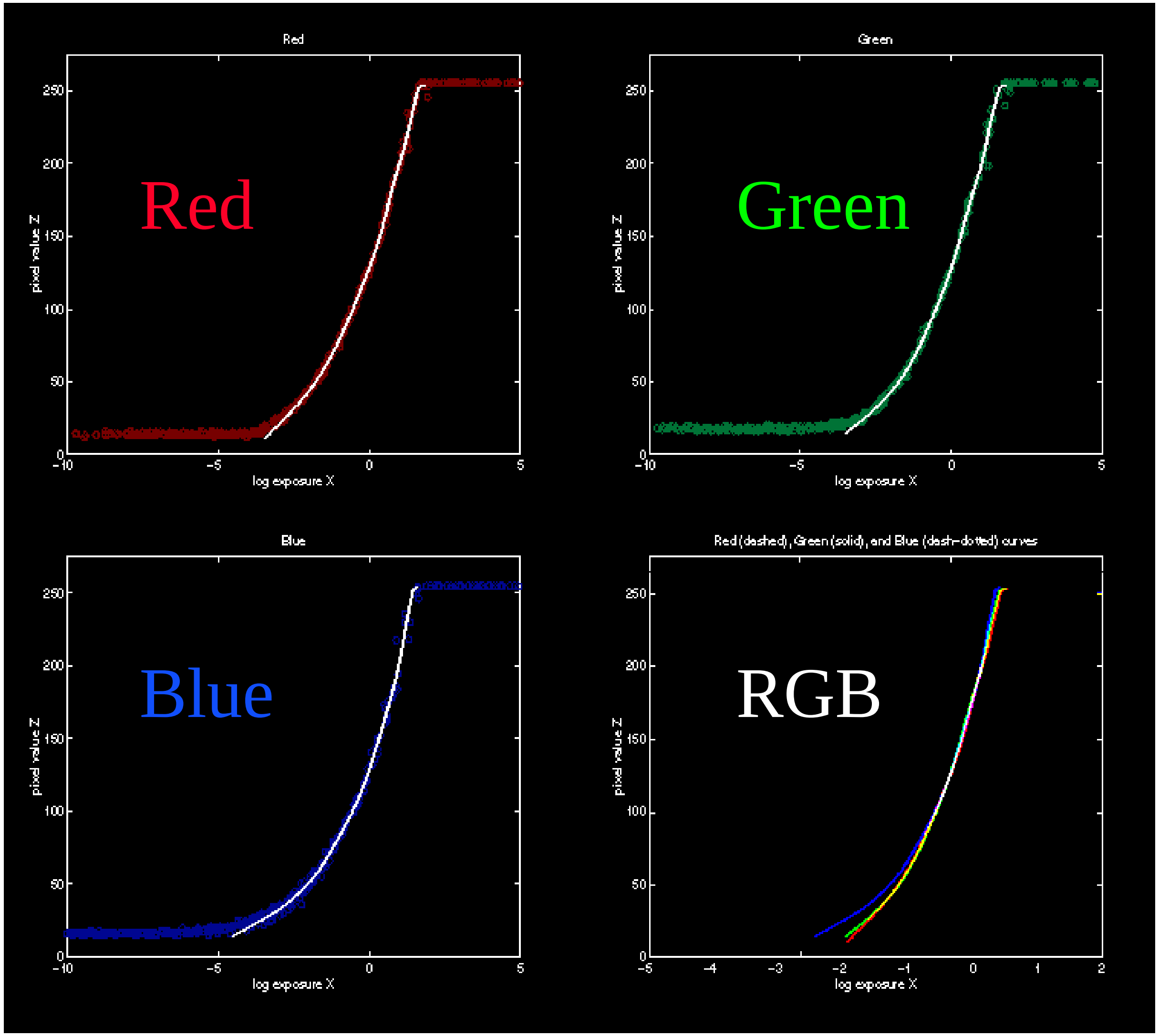
Recovered response curves



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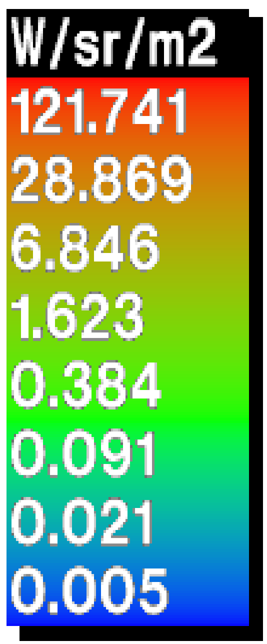
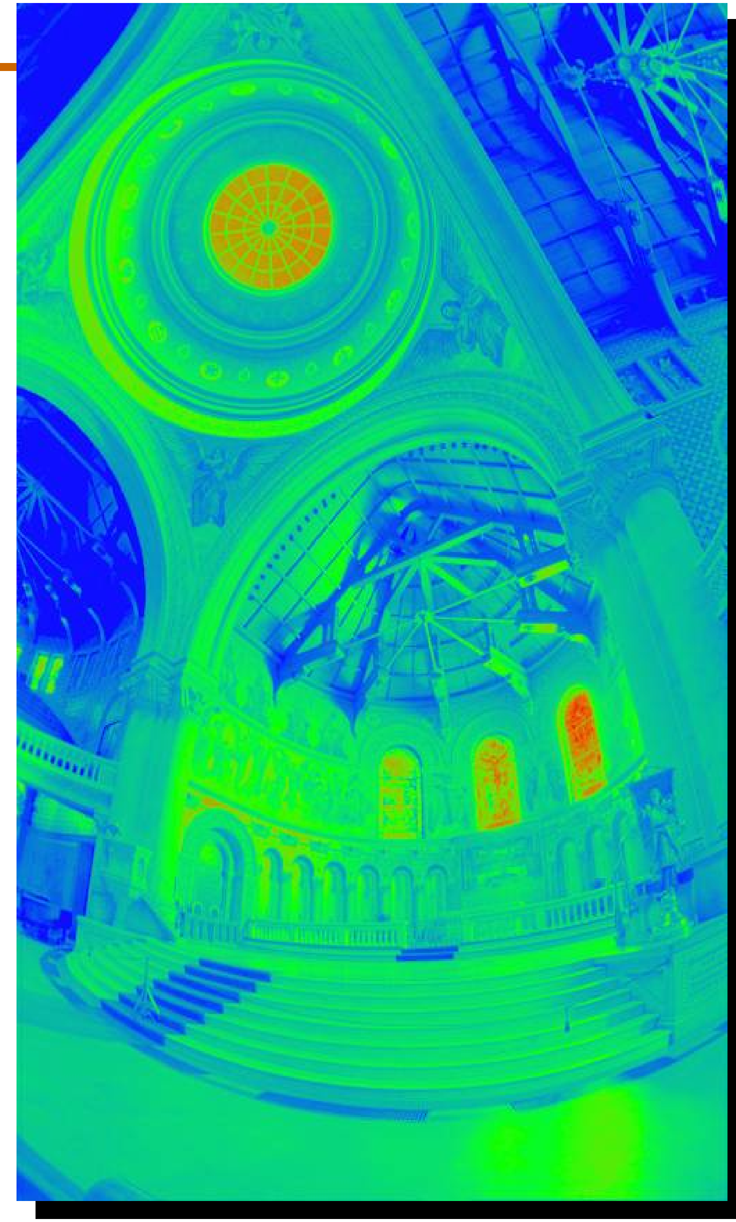
The Radiance map





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The Radiance map

Linearly scaled to
display device

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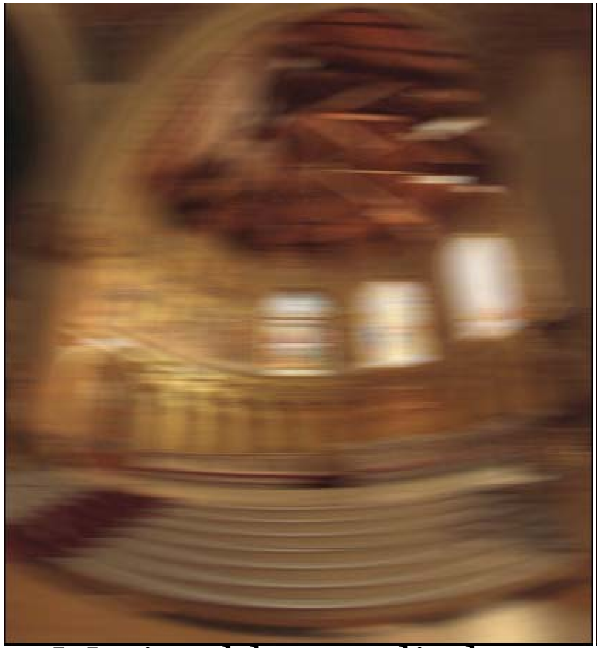
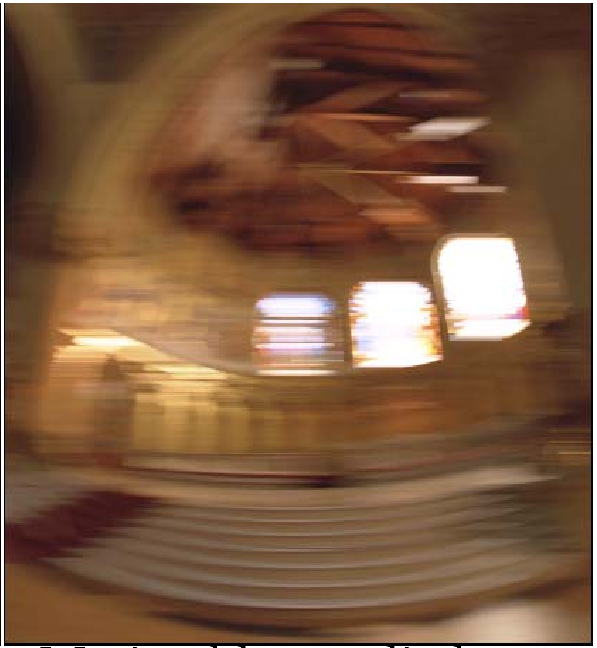
HDR image processing

Images from Debevec & Malik 1997



Motion blur applied to **low**-dynamic-range picture



Motion blur applied to **high**-dynamic-range picture

Real motion-blurred picture

- **Important also for depth of field post-process**

Available in HDRShop

Slide from Siggraph 2005 course on HDR

Smarter HDR capture

Ward, Journal of Graphics Tools, 2003

http://www.anyhere.com/gward/papers/jgtpap2.pdf

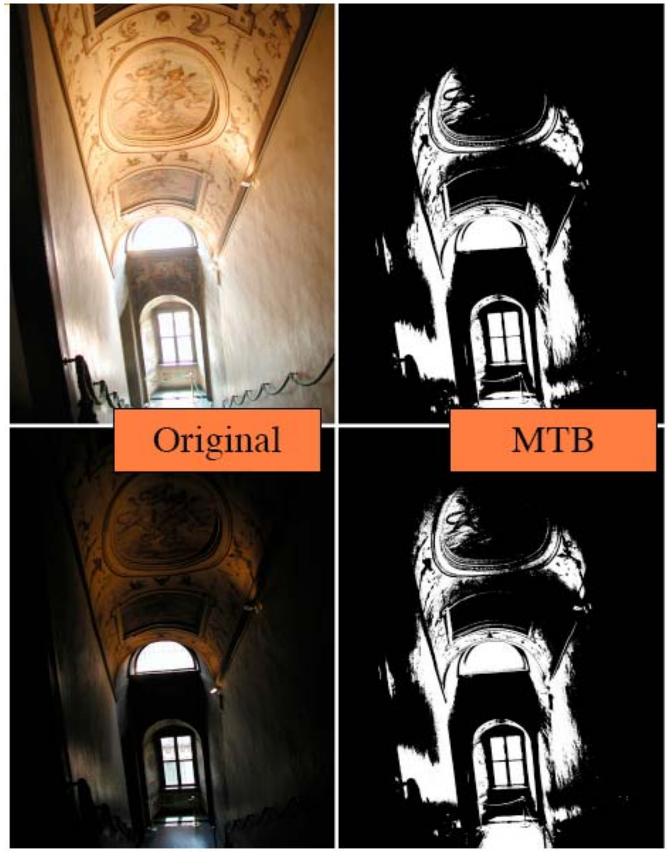
Implemented in Photosphere http://www.anyhere.com/

- **Image registration (no need for tripod)**
- **Lens flare removal**
- **Ghost removal**

Images Greg Ward

Image registration

- **How to robustly compare images of different exposure?**
- **Use a black and white version of the image thresholded at the median**
  - Median-Threshold Bitmap (MTB)
- **Find the translation that minimizes difference**
- **Accelerate using pyramid**



Alignment Results

5 unaligned exposures | Close-up detail | MTB alignment

Time: About .2 second/exposure for 3 MPixel image

Slide from Siggraph 2005 course on HDR

Extension: HDR video

- **Kang et al. Siggraph 2003 http://portal.acm.org/citation.cfm?id=882262.882270**

Figure 1: High dynamic range video of a driving scene. *Top row: Input video with alternating short and long exposures. Bottom row: High dynamic range video (tonemapped).*

Extension: HDR video

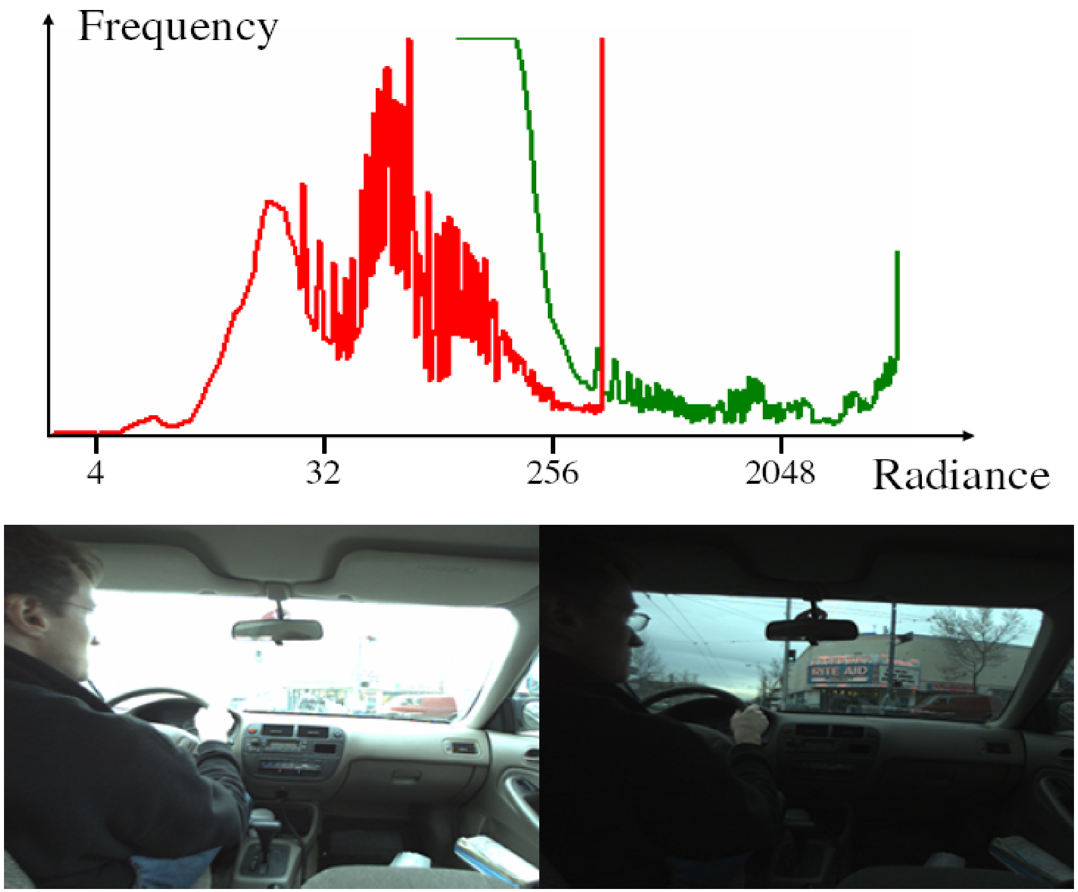


Figure 3: Two input exposures from the driving video. *The radiance histogram is shown on top. The red graph goes with the long exposure frame (bottom left), while the green graph goes with the short exposure frame (bottom right). Notice that the combination of these graphs spans a radiance range greater than a single exposure can capture.*

Radiometric camera calibration

(Kim and Pollefeys, PAMI08)

Robustly estimate cameras photometric response curve, exposure and white balance changes of (moving) cameras

video-to-3D →

uncalibrated video → photo-consistent HDR video

Radiometric camera calibration

(Kim and Pollefeys, PAMI08)

Robustly estimate cameras photometric response curve, exposure and white balance changes of (moving) cameras

… and also estimate vignetting

original images courtesy of Brown and Lowe

Panorama with vignetting → Compensated panorama

(Kim and Pollefeys, PAMI08)
robust + linear

(Goldman and Chen, ICCV05)
non-linear

(Litvinov and Schechner,CVPR05)
linear

More work on exposure and non-linear response estimation during tracking Kim et al. ICCV07 and for static camera with changing lighting (Kim et al. CVPR08)

HDR encoding

- **Most formats are lossless**
- **Adobe DNG (digital negative)**
  - Specific for RAW files, avoid proprietary formats
- **RGBE**
  - 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
- **JPEG 2000**
  - Has a 16 bit mode, lossy

HDR formats

- **Summary of all HDR encoding formats (Greg Ward): http://www.anyhere.com/gward/hdrenc/hdr_encodings.html**
- **Greg's notes: http://www.anyhere.com/gward/pickup/CIC13course.pdf**
- **http://www.openexr.com/**
- **High Dynamic Range Video Encoding**

(MPI) http://www.mpi-sb.mpg.de/resources/hdrvideo/

HDR code

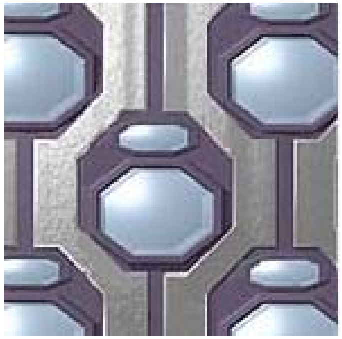
- **HDRShop http://gl.ict.usc.edu/HDRShop/ (v1 is free)**
- **Columbia's camera calibration and HDR combination with source code Mitsunaga, Nayar , Grossberg http://www1.cs.columbia.edu/CAVE/projects/rad_cal/rad_cal.php**
- **Greg Ward Phososphere HDR browser and image combination with regsitration (Macintosh, command-line version under Linux) with source code http://www.anyhere.com/**
- **Photoshop CS2**
- **Idruna http://www.idruna.com/photogenicshdr.html**
- **MPI PFScalibration (includes source code) http://www.mpii.mpg.de/resources/hdr/calibration/pfs.html**
- **EXR tools http://scanline.ca/exrtools/**
- **HDR Image Editor http://www.acm.uiuc.edu/siggraph/HDRIE/**
- **CinePaint http://www.cinepaint.org/**
- **Photomatix http://www.hdrsoft.com/**
- **EasyHDR http://www.astro.leszno.net/easyHDR.php**
- **Artizen HDR http://www.supportingcomputers.net/Applications/Artizen/Artizen.htm**
- ***Automated High Dynamic Range Imaging Software & Images* http://www2.cs.uh.edu/~somalley/hdri_images.html**
- **Optipix http://www.imaging-resource.com/SOFT/OPT/OPT.HTM**

HDR images

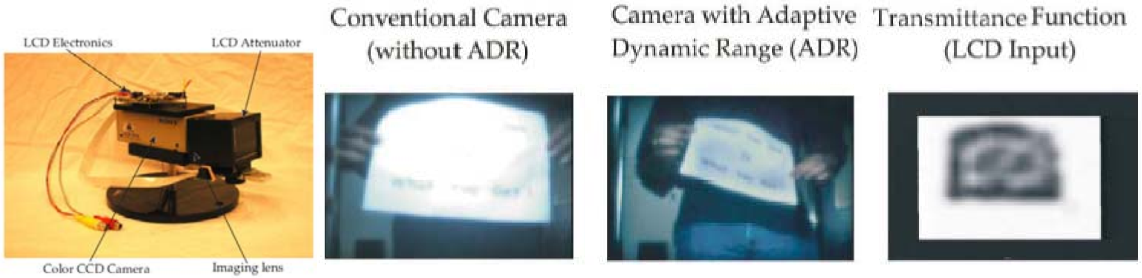
- **http://www.debevec.org/Research/HDR/**
- **http://www.mpi-sb.mpg.de/resources/hdr/gallery.html**
- **http://people.csail.mit.edu/fredo/PUBLI/Siggraph2002/**
- **http://www.openexr.com/samples.html**
- **http://www.flickr.com/groups/hdr/**
- **http://www2.cs.uh.edu/~somalley/hdri_images.html#hdr_others**
- **http://www.anyhere.com/gward/hdrenc/pages/originals.html**
- **http://www.cis.rit.edu/mcsl/icam/hdr/rit_hdr/**
- **http://www.cs.utah.edu/%7Ereinhard/cdrom/hdr.html**
- **http://www.sachform.de/download_EN.html**
- **http://lcavwww.epfl.ch/%7Elmeylan/HdrImages/February06/February06.html**
- **http://lcavwww.epfl.ch/%7Elmeylan/HdrImages/April04/april04.html**
- **http://books.elsevier.com/companions/0125852630/hdri/html/images.html**

HDR Cameras

- **HDR sensors using CMOS**
  - Use a log response curve
  - e.g. SMaL,
- **Assorted pixels**
  - Fuji
  - Nayar et al.
- **Per-pixel exposure**
  - Filter
  - Integration time
- **Multiple cameras using beam splitters**
- **Other computational photography tricks**



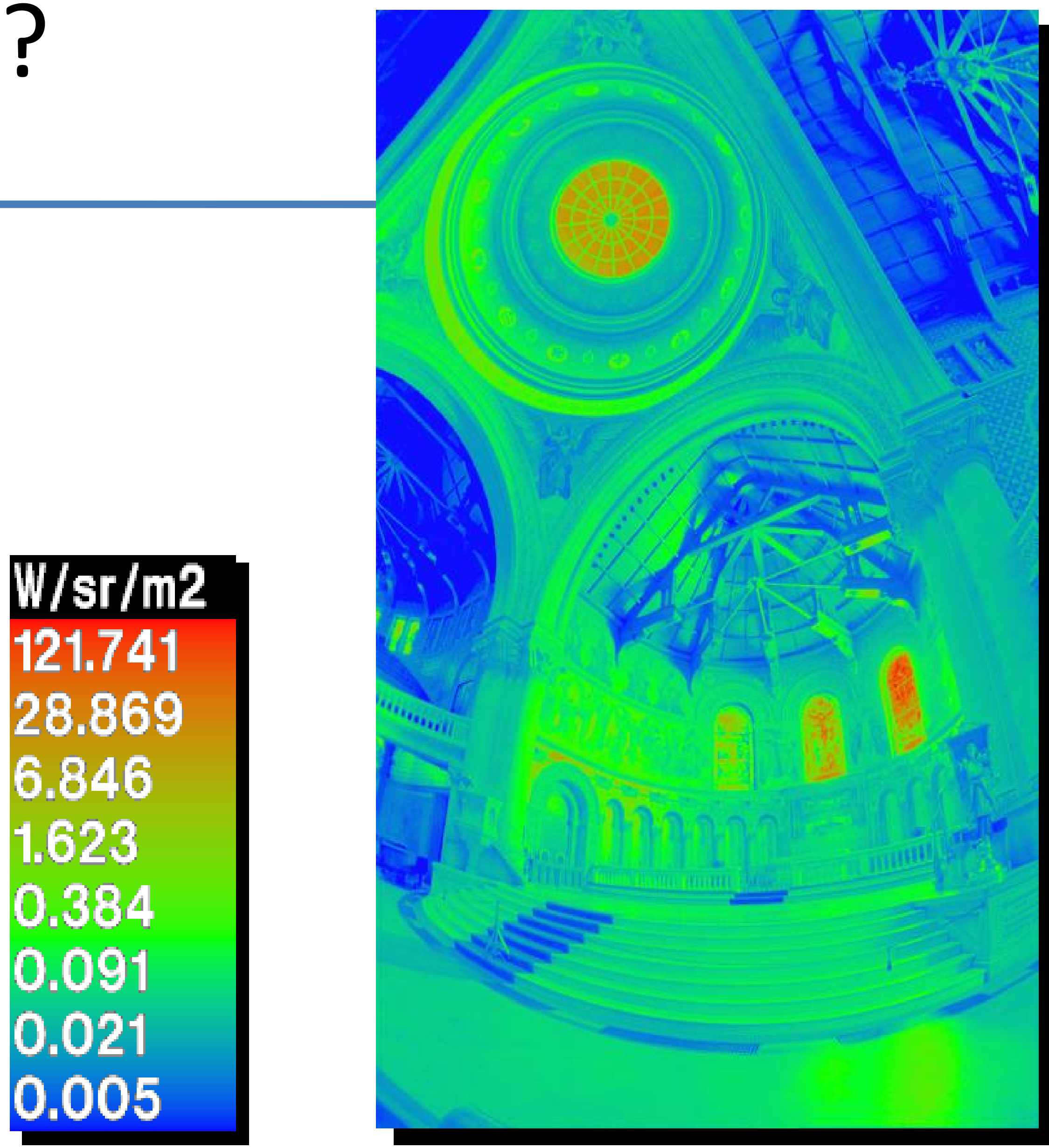
Fuji SuperCCD



HDR cameras

- http://www.hdrc.com/home.htm
- http://www.smalcamera.com/technology.html
- http://www.cfar.umd.edu/~aagrawal/gradcam/gradcam.html
- http://www.spheron.com/spheron/public/en/home/home.php
- http://www.ims-chips.com/home.php3?id=e0841
- http://www.thomsongrassvalley.com/products/cameras/viper/
- http://www.pixim.com/
- http://www.ptgrey.com/
- http://www.siliconimaging.com/
- http://www-mtl.mit.edu/researchgroups/sodini/PABLOACO.pdf
- http://www1.cs.columbia.edu/CAVE/projects/adr_lcd/adr_lcd.php
- http://www1.cs.columbia.edu/CAVE/projects/gen_mos/gen_mos.php
- http://www1.cs.columbia.edu/CAVE/projects/pi_micro/pi_micro.php
- http://www.cs.cmu.edu/afs/cs/usr/brajovic/www/labweb/index.html

Now What?



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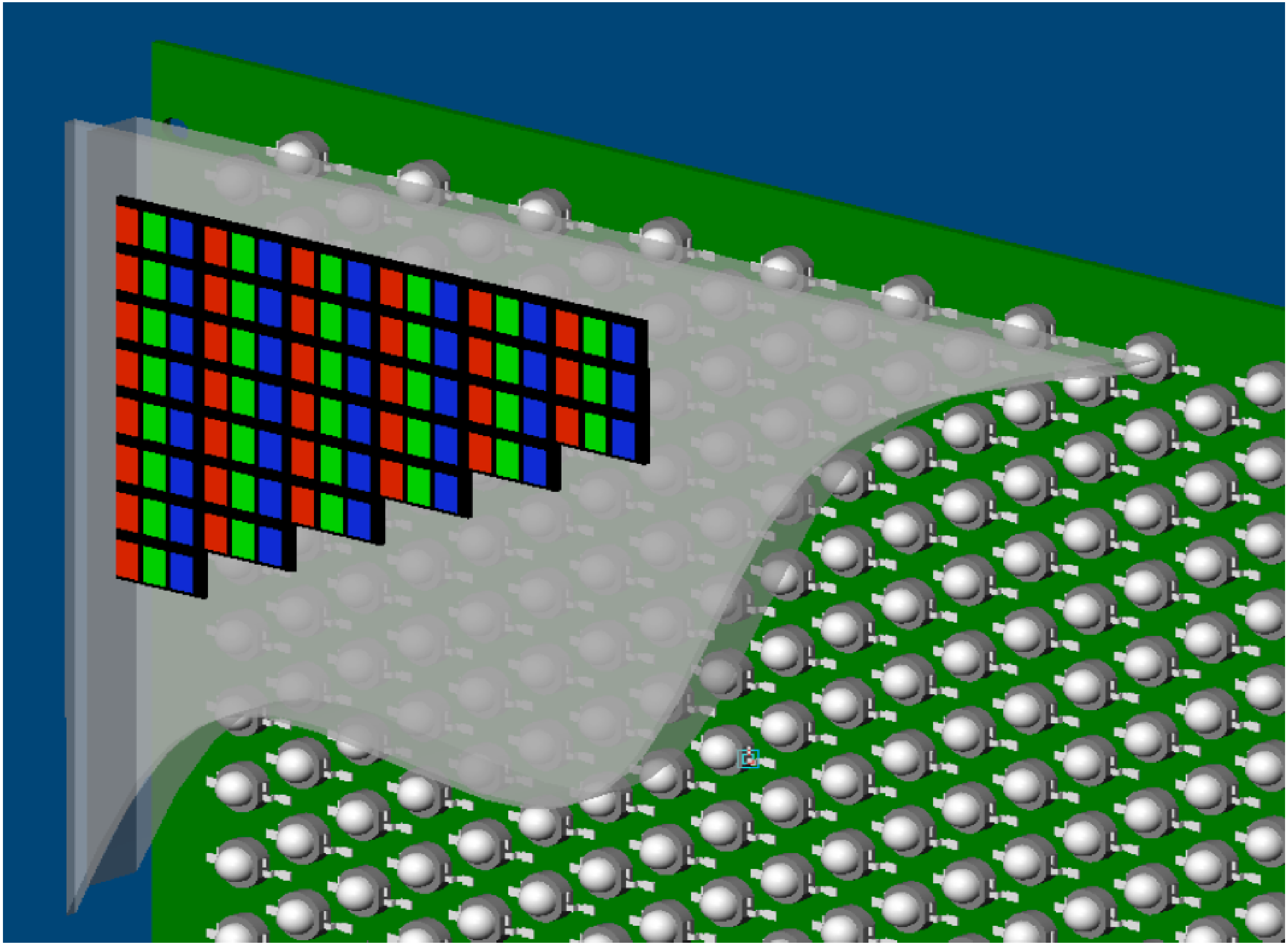
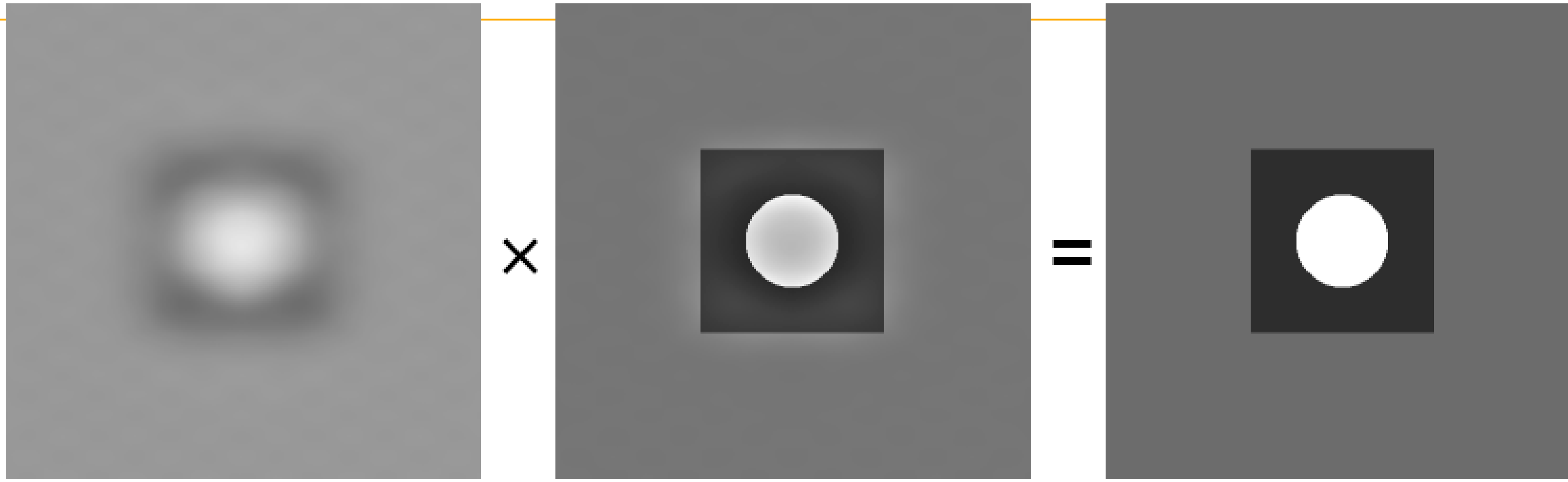
Sunnybrook HDR display

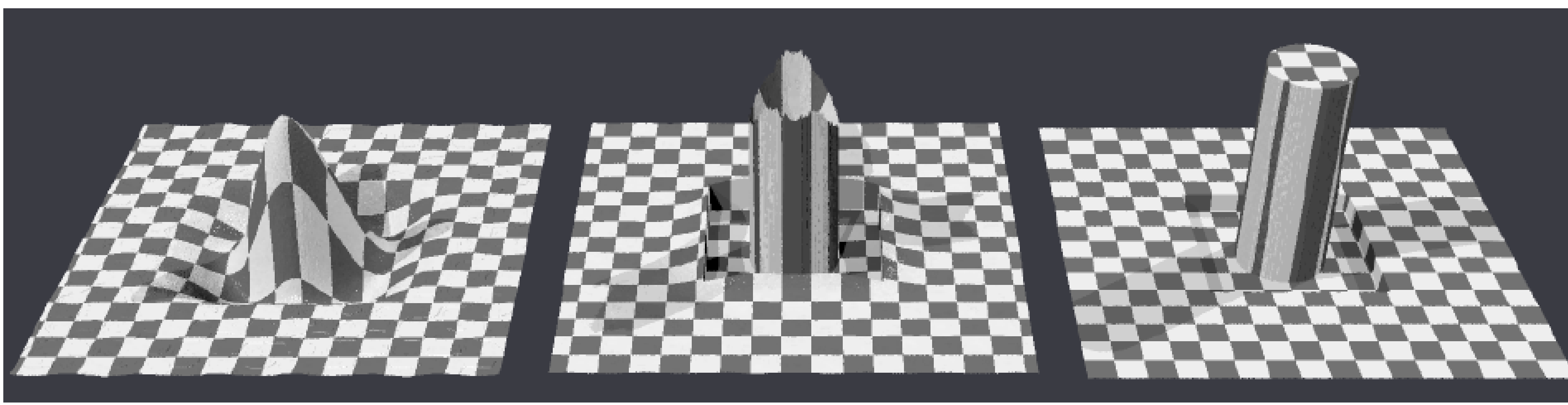
- Use Bright Source + Two 8-bit Modulators
  - Transmission multiplies together
  - Over 10,000:1 dynamic range possible



How It Works



LED Backlight | LCD Screen | Combined Result



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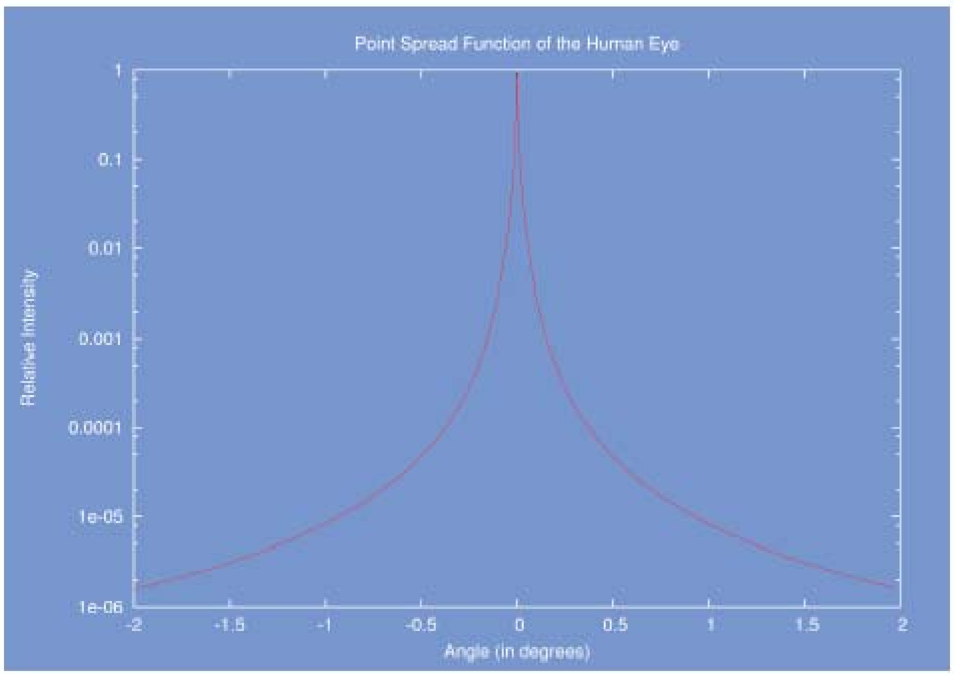
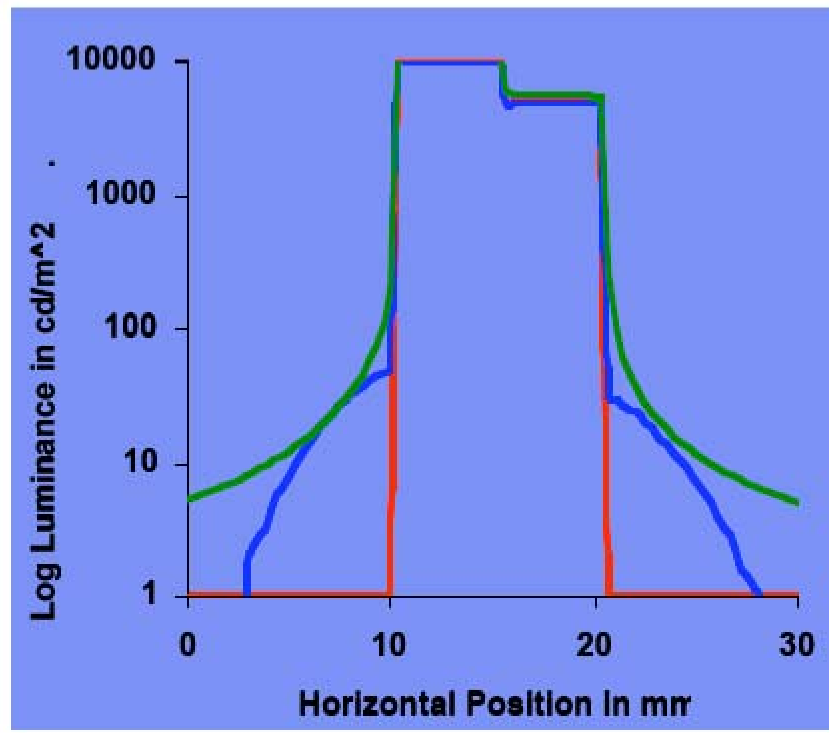
Slide from the 2005 Siggraph course on HDR

What If Edge Contrast Exceeds LCD Range?

SIGGRAPH2005

Observers cannot tell when this happens because the eye has limited local contrast capacity due to scattering





See Seetzen et al.. SIGGRAPH 2004

ETH

Slide from the 2005 Siggraph course on HDR

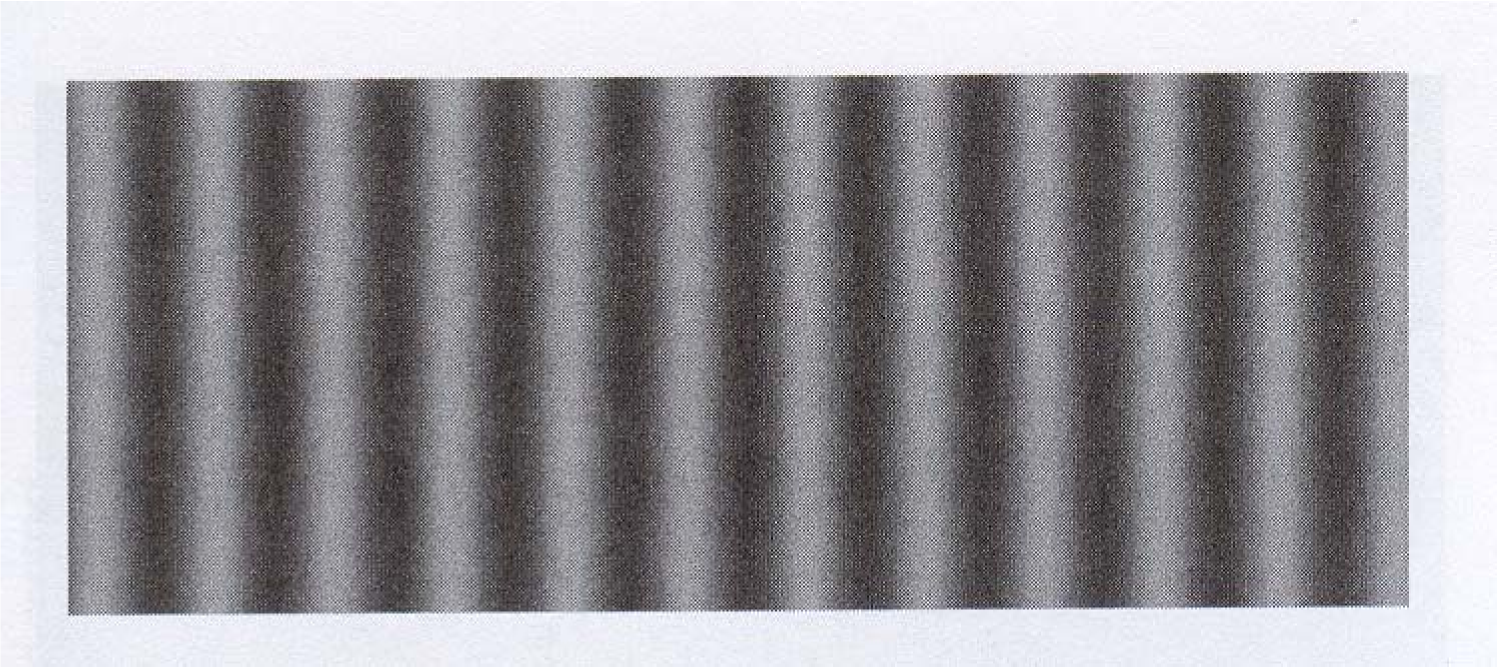
BrightSide DR37-P (now Dolby)

How humans deal with 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
  - 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

Contrast Sensitivity

- Sine Wave grating
- What contrast is necessary to make the grating visible?



Contrast Sensitivity Function (CSF)

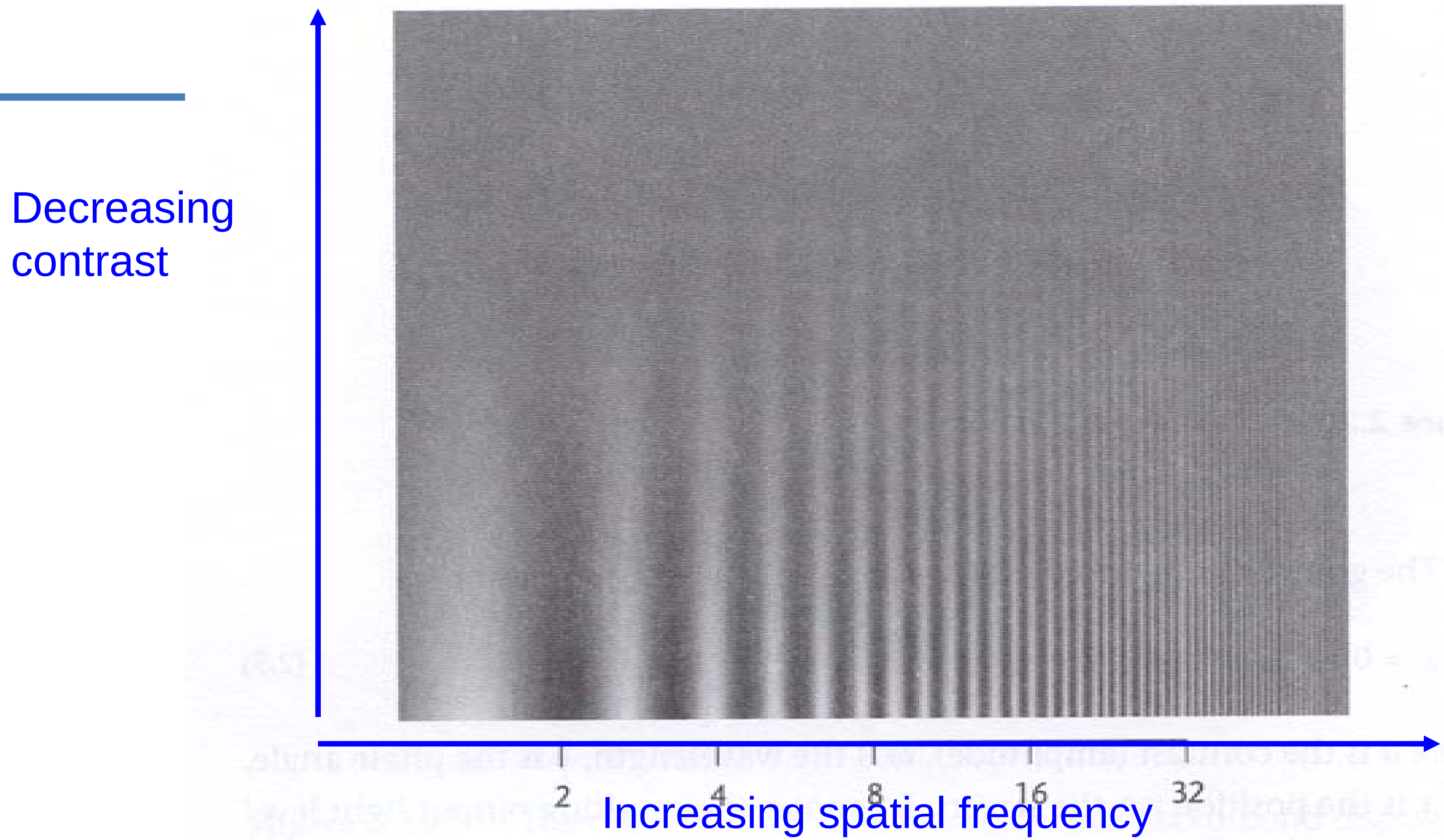


Figure 2.21 This grating pattern changes frequency exponentially from left to right and varies in contrast in a vertical direction. The highest frequency you can resolve depends on the distance from which you view the pattern. The scale gives the spatial frequency if it is viewed from 2.3 m.

Contrast Sensitivity Function (CSF)

- Low sensitivity to low frequencies
- Importance of medium to high frequencies
- Most methods to deal with dynamic range reduce the contrast of low frequencies
- But keep the color

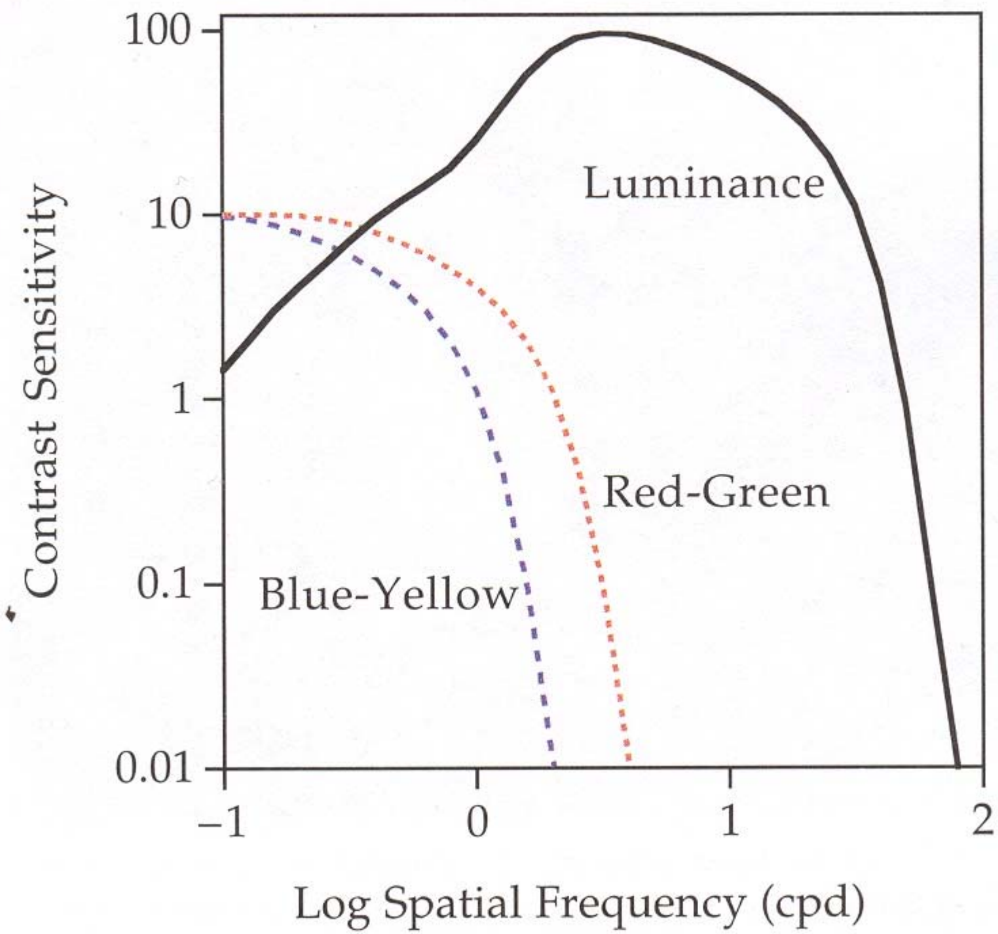


Figure 1-18. Spatial contrast sensitivity functions for luminance and chromatic contrast.

The second half: contrast reduction

- **Input: high-dynamic-range image**
  - (floating point per pixel)

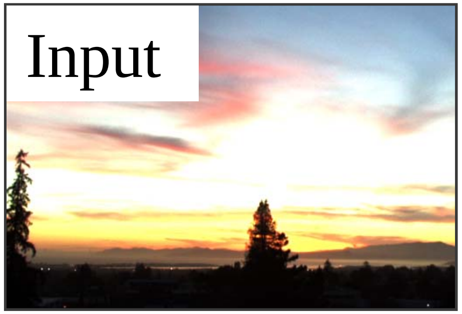
Naïve technique

- **Scene has *1:10,000* contrast, display has *1:100***
- **Simplest contrast reduction?**

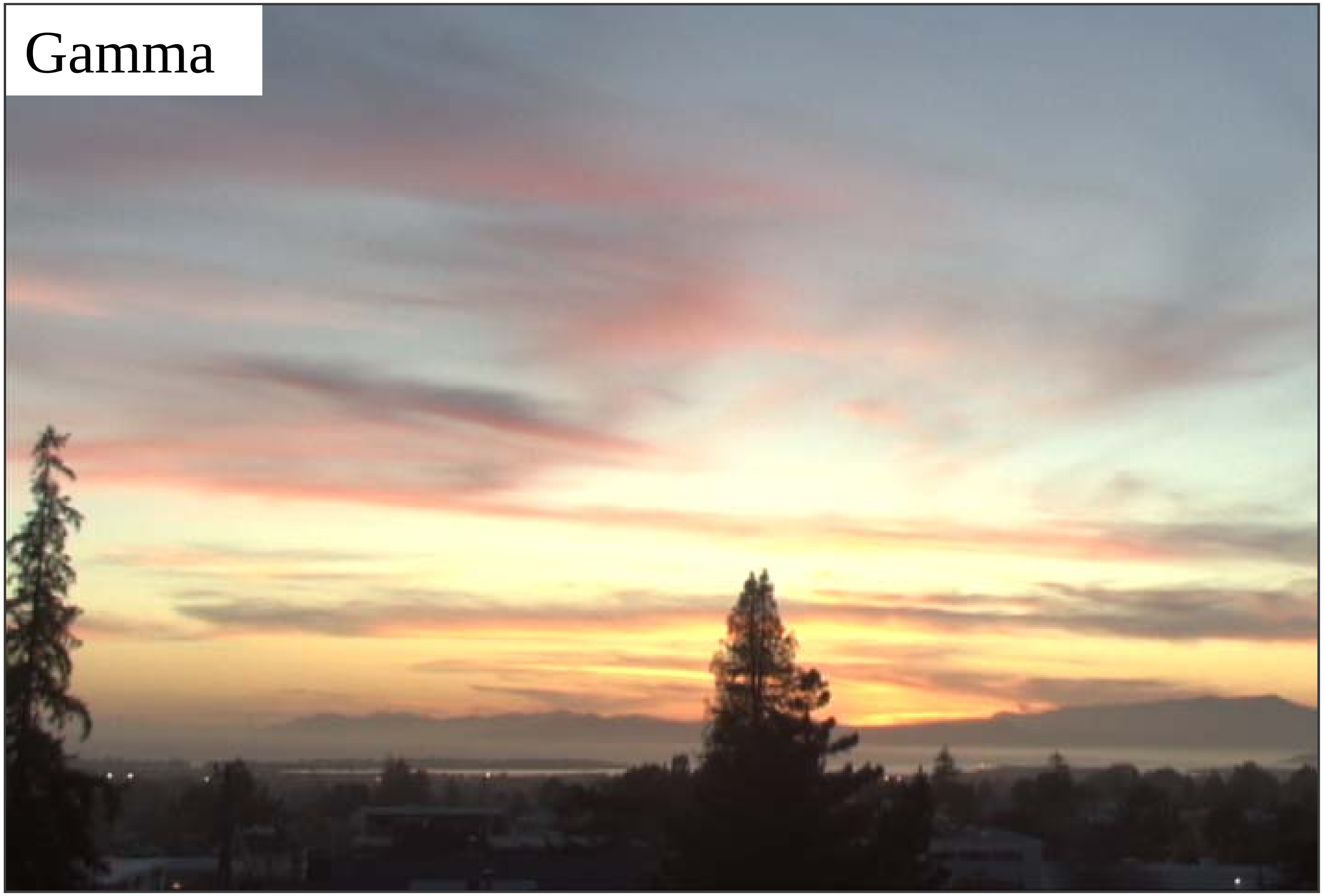
Naïve: Gamma compression

- $X \rightarrow X^{\gamma}$ (where γ=0.5 in our case)
- But… colors are washed-out. Why?

Input

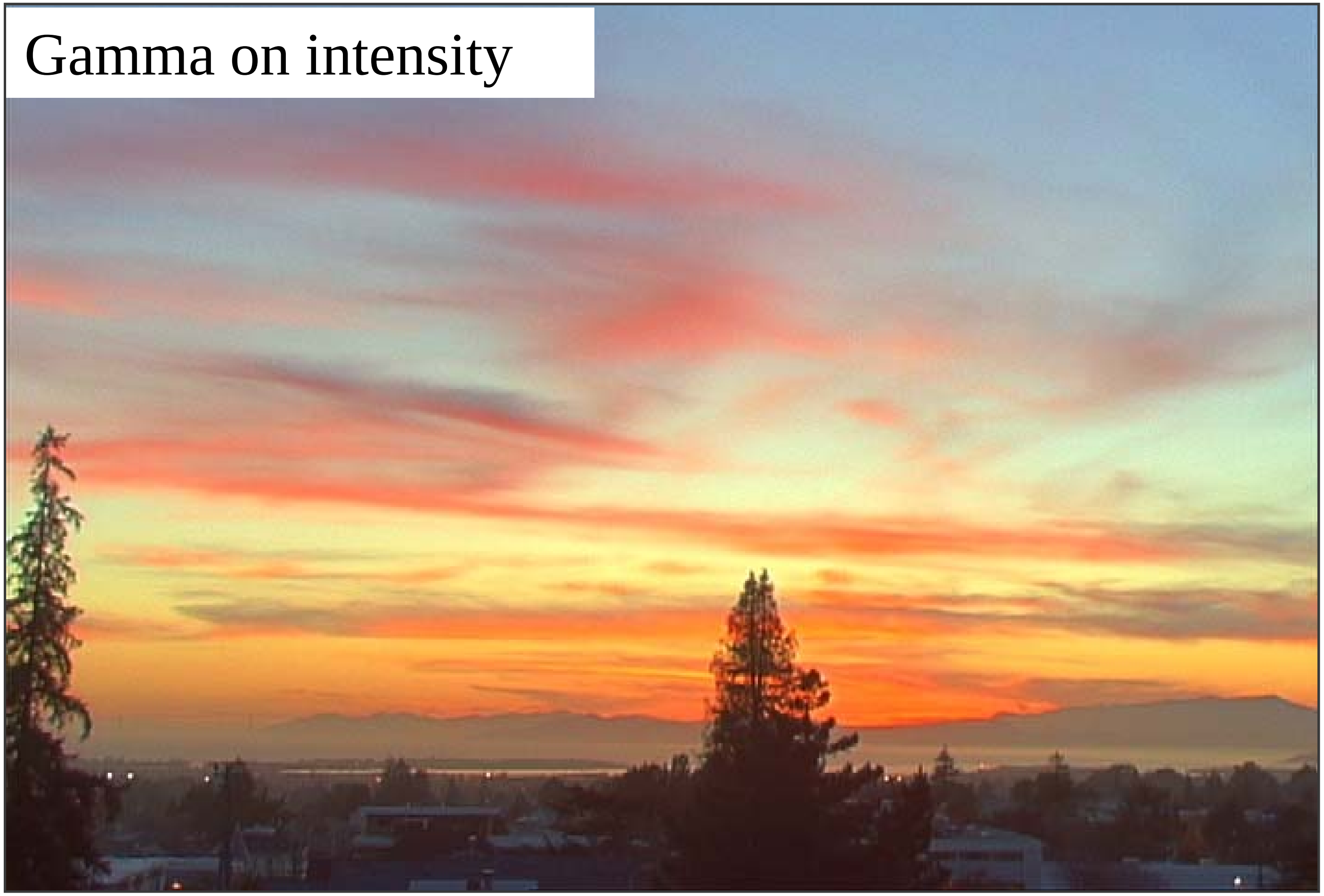


Gamma



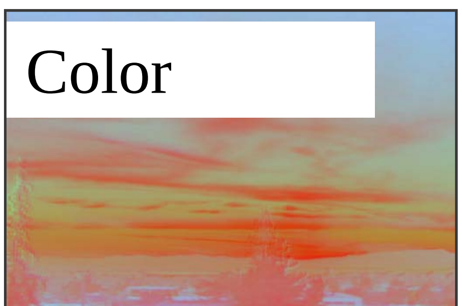
Gamma compression on intensity

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



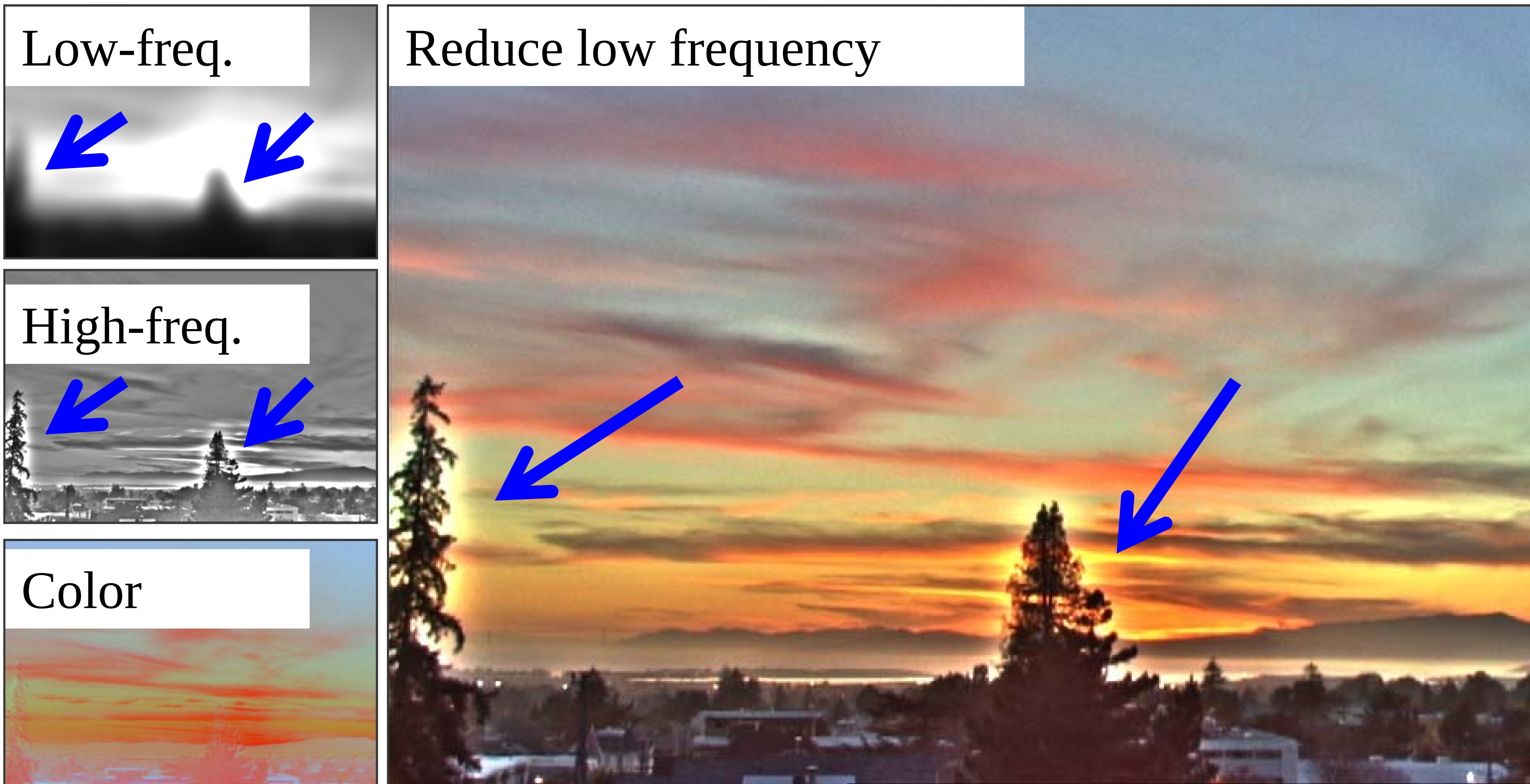
Oppenheim 1968, Chiu et al. 1993

- **Reduce contrast of low-frequencies**
- **Keep high frequencies**



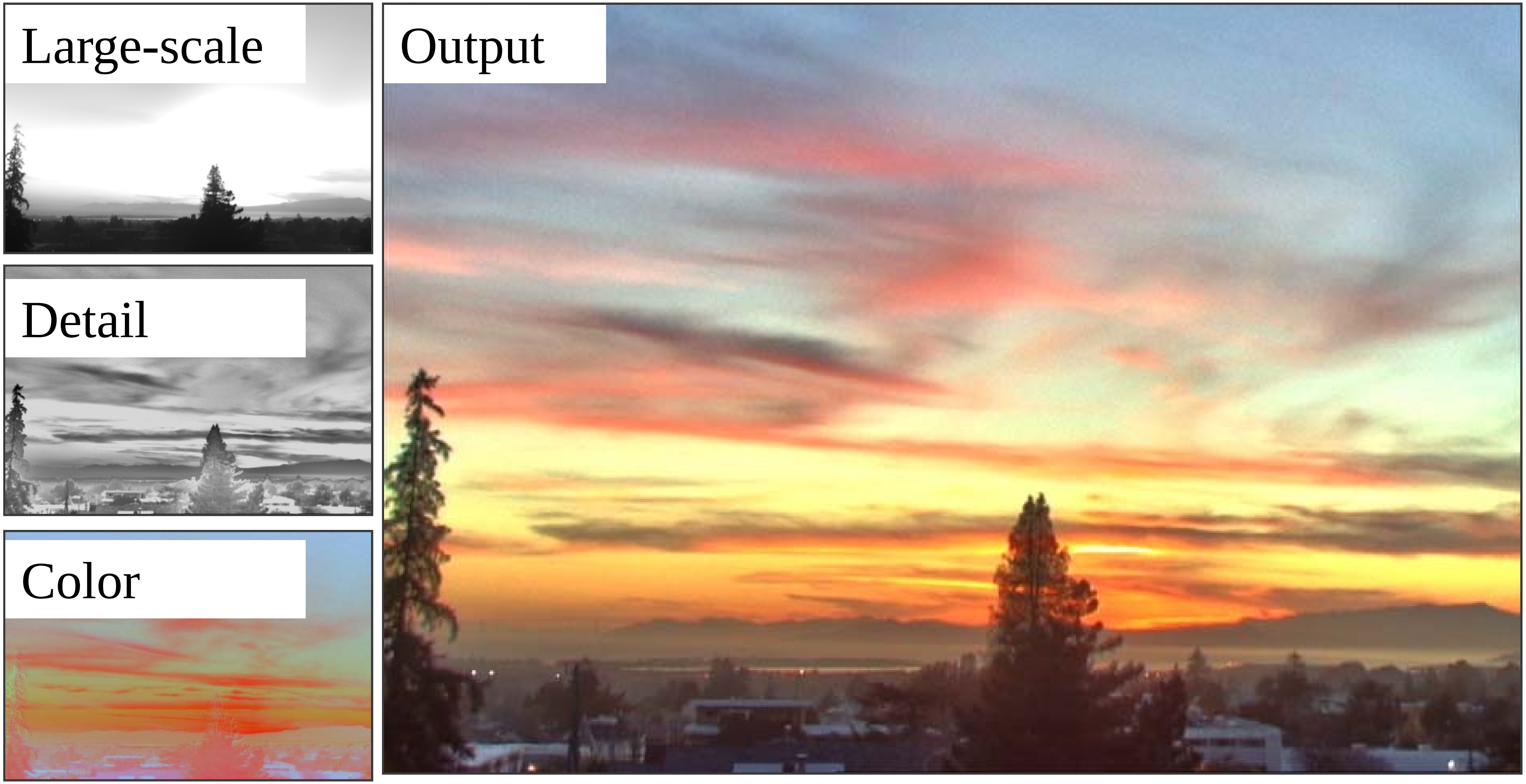
The halo nightmare

- **For strong edges**
- **Because they contain high frequency**



Our approach

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



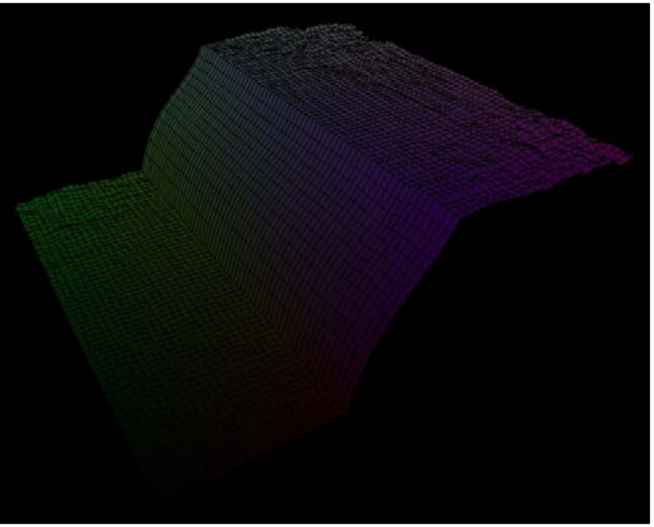
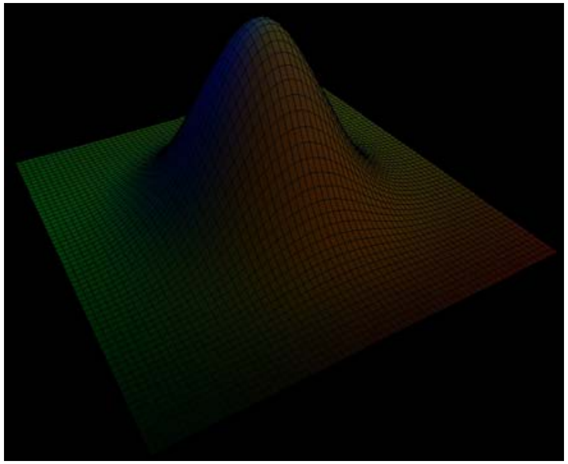
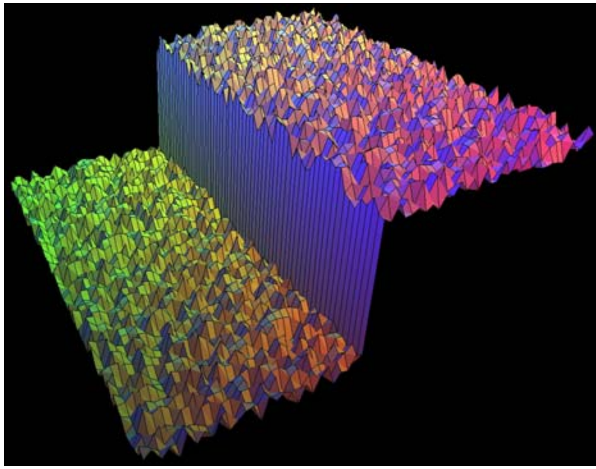
Bilateral filter

- **Tomasi and Manduci 1998 http://www.cse.ucsc.edu/~manduchi/Papers/ICCV98.pdf**
- **Related to**
  - SUSAN filter
    [Smith and Brady 95]
    http://citeseer.ist.psu.edu/smith95susan.html
  - Digital-TV [Chan, Osher and Chen 2001]
    http://citeseer.ist.psu.edu/chan01digital.html
  - sigma filter
    http://www.geogr.ku.dk/CHIPS/Manual/f187.htm

Start with Gaussian filtering

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

$$J = f \otimes I$$

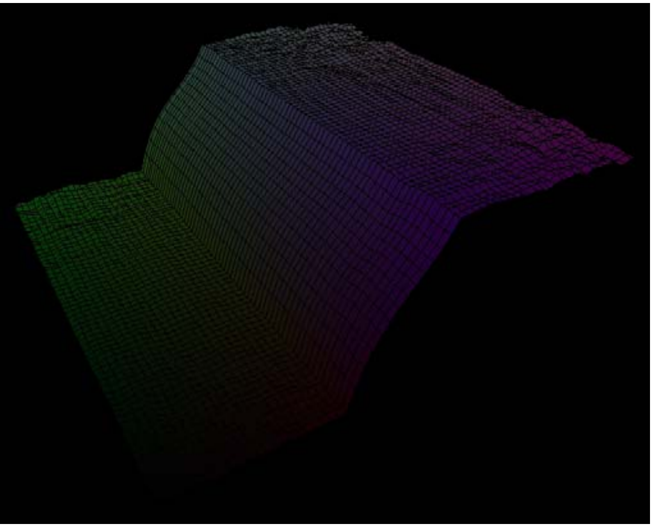
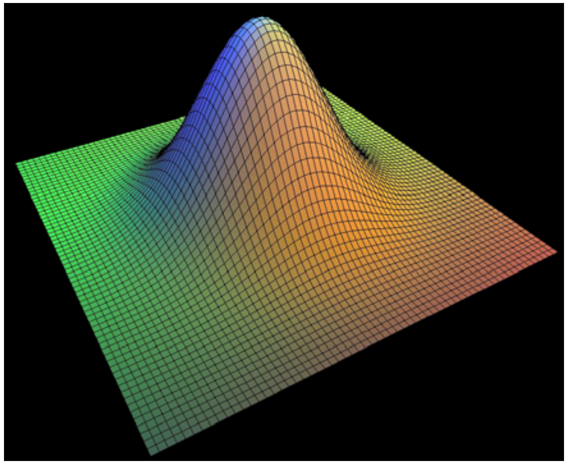
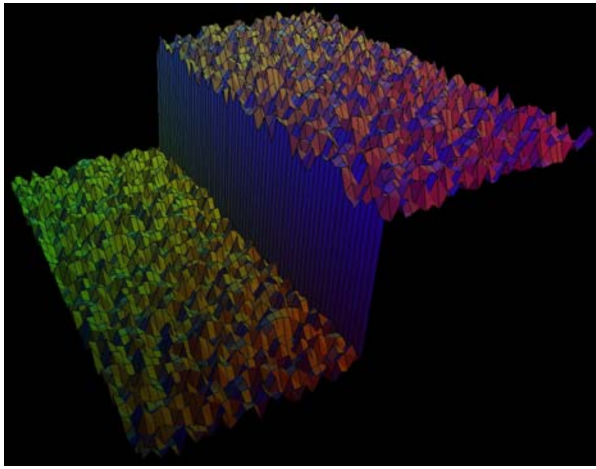
  

output ⟵ input

Start with Gaussian filtering

- **Spatial Gaussian f**

$$J = f \otimes I$$

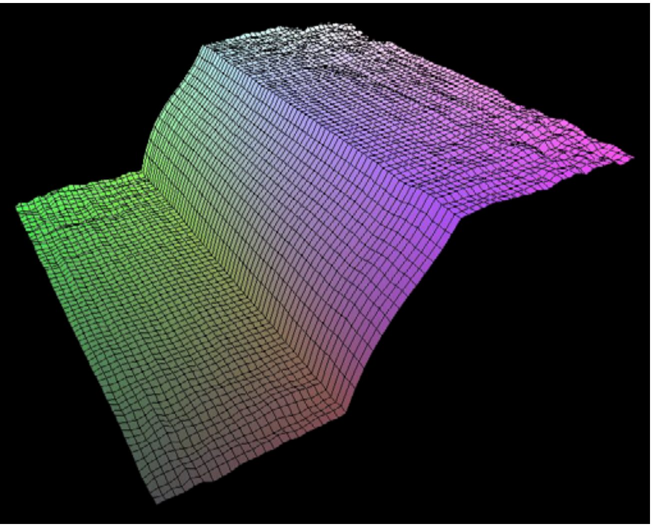




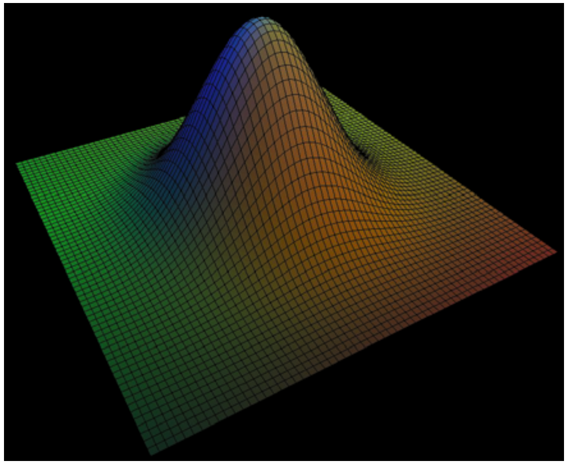
output input

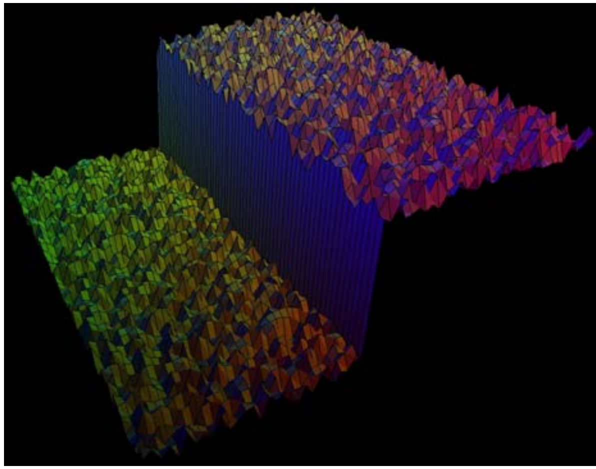
Start with Gaussian filtering

- **Output is blurred**

$$J = f \otimes I$$





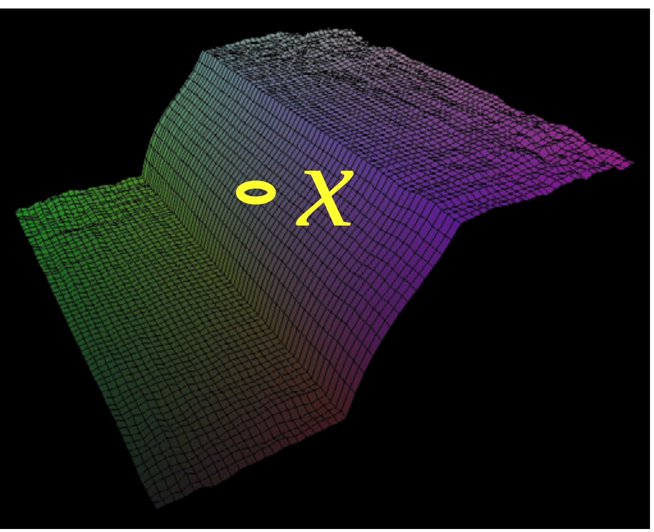


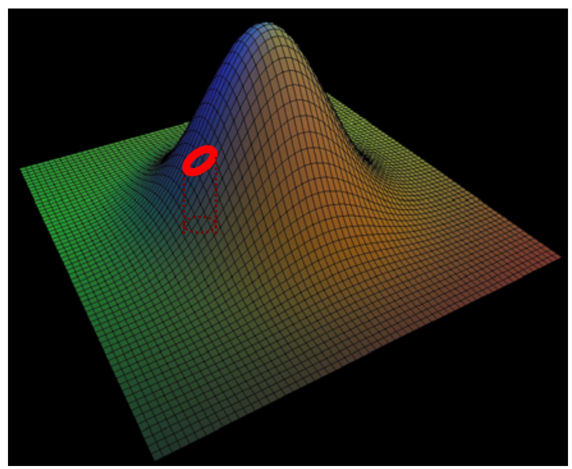
output ← input

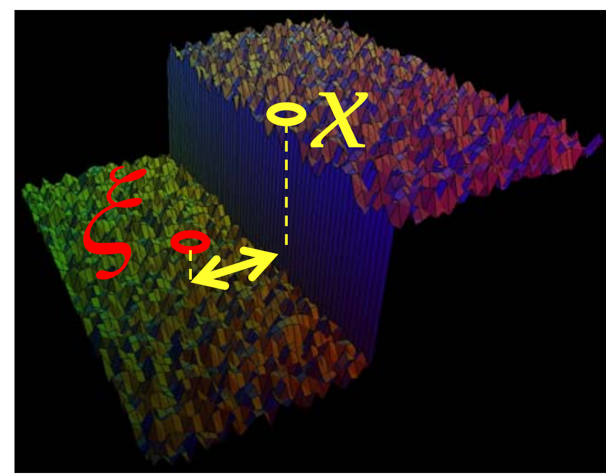
Gaussian filter as weighted average

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

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





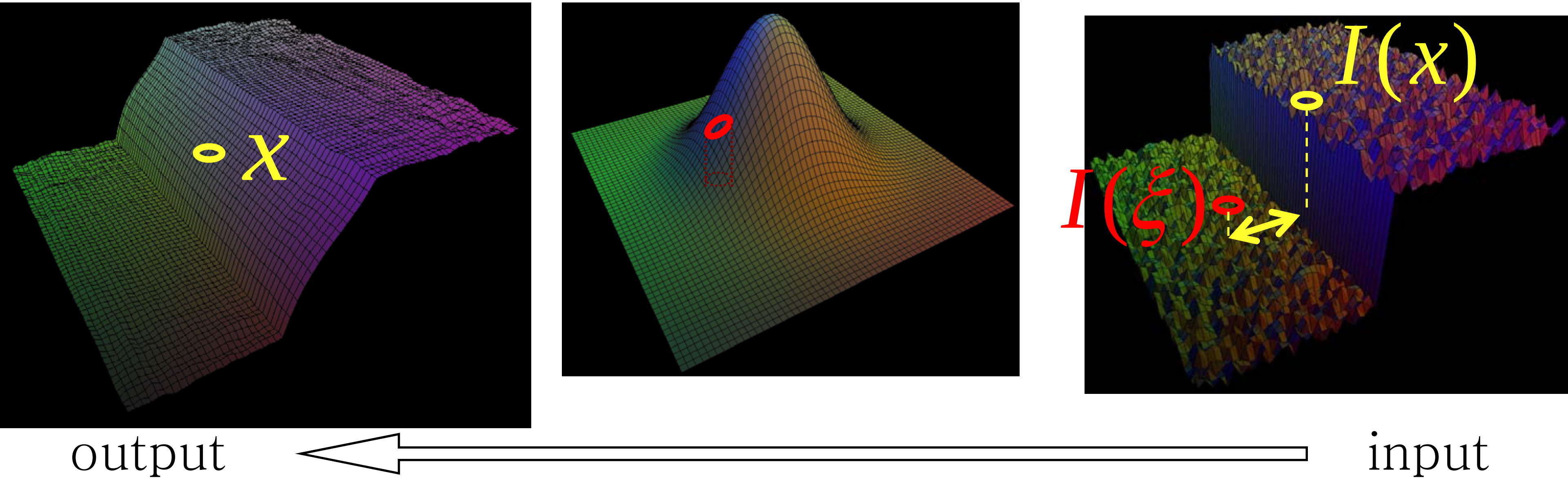


output ⟸ input

The problem of edges

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

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

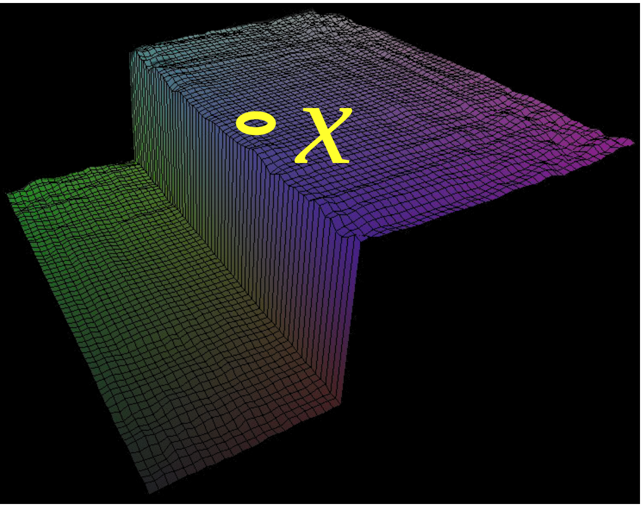


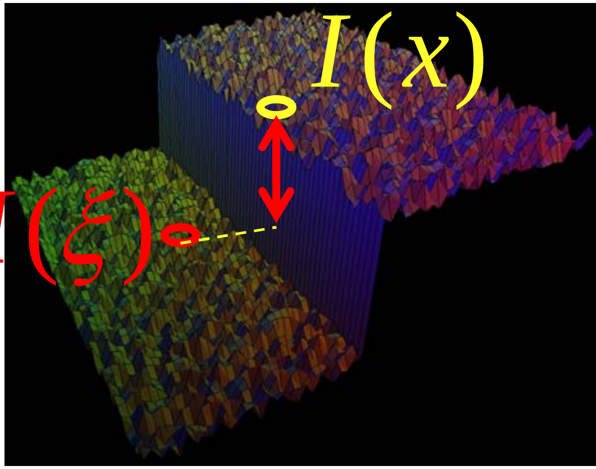
Principle of Bilateral filtering

[Tomasi and Manduchi 1998]

- **Penalty g on the intensity difference**

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





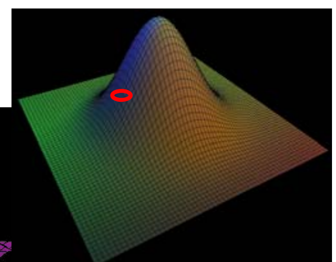
output ⟸ input

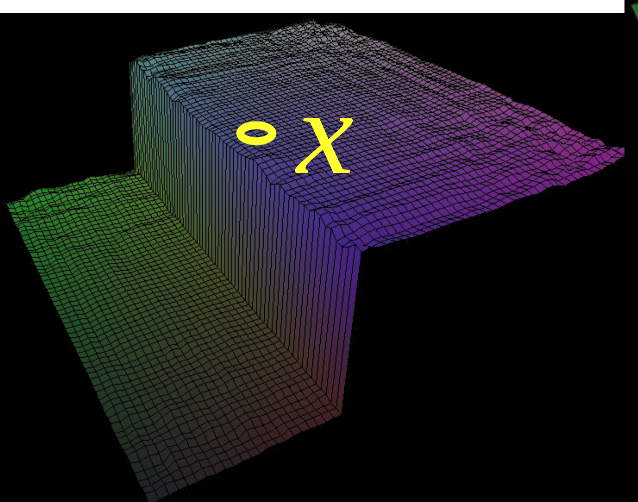
Bilateral filtering

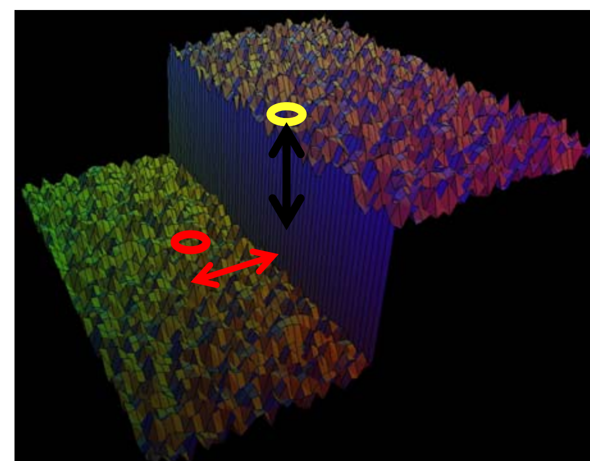
[Tomasi and Manduchi 1998]

- **Spatial Gaussian f**

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







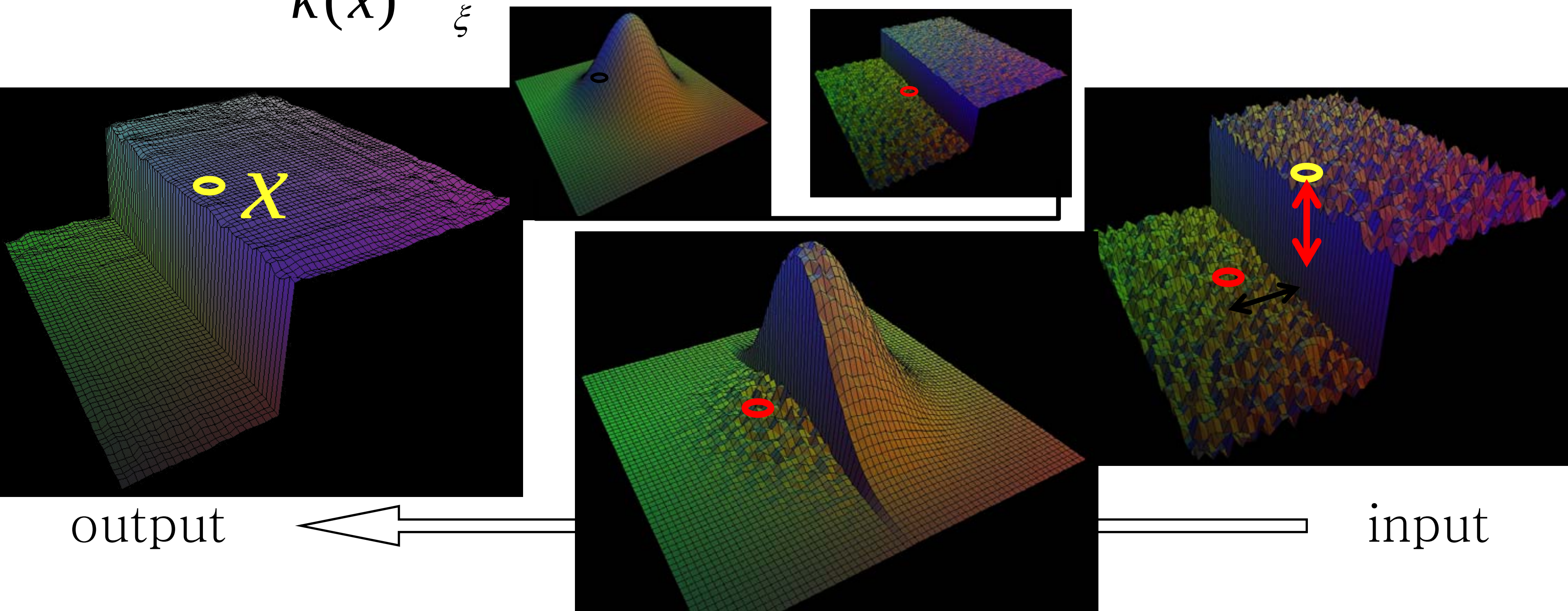
output ⟵ input

Bilateral filtering

[Tomasi and Manduchi 1998]

- **Spatial Gaussian f**
- **Gaussian g on the intensity difference**

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

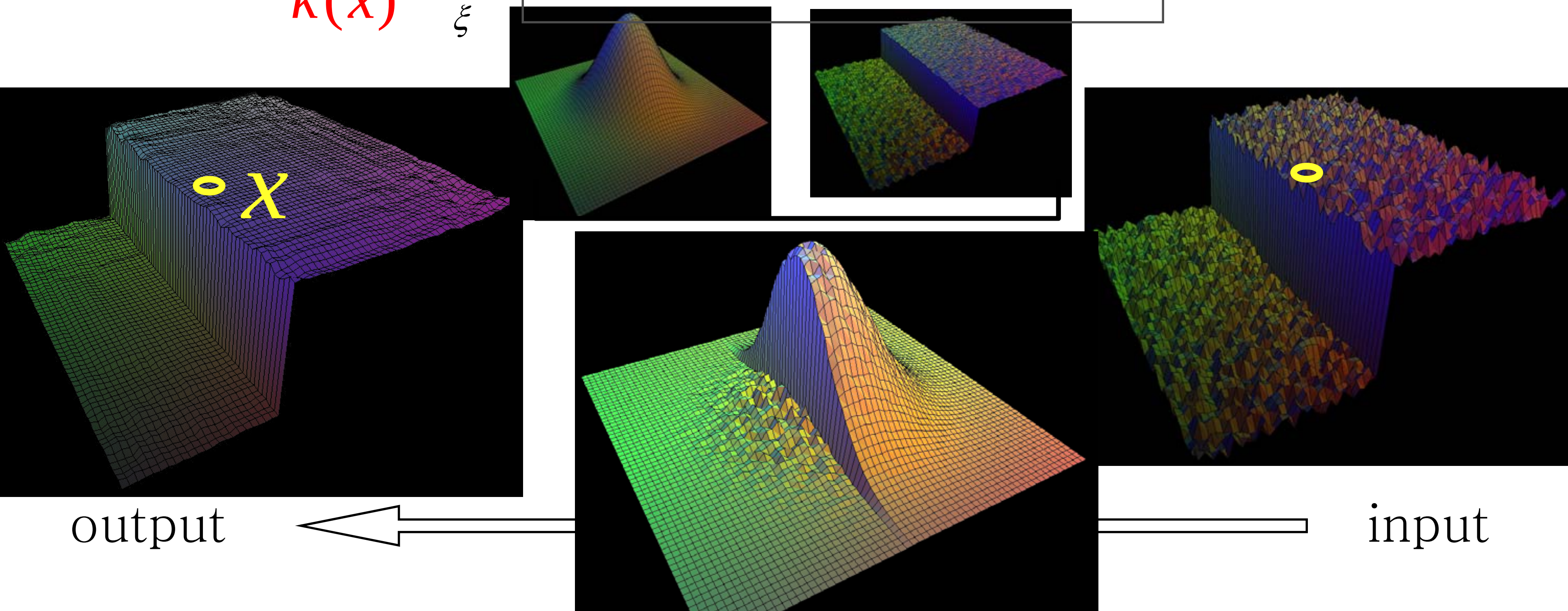


Normalization factor

[Tomasi and Manduchi 1998]

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

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

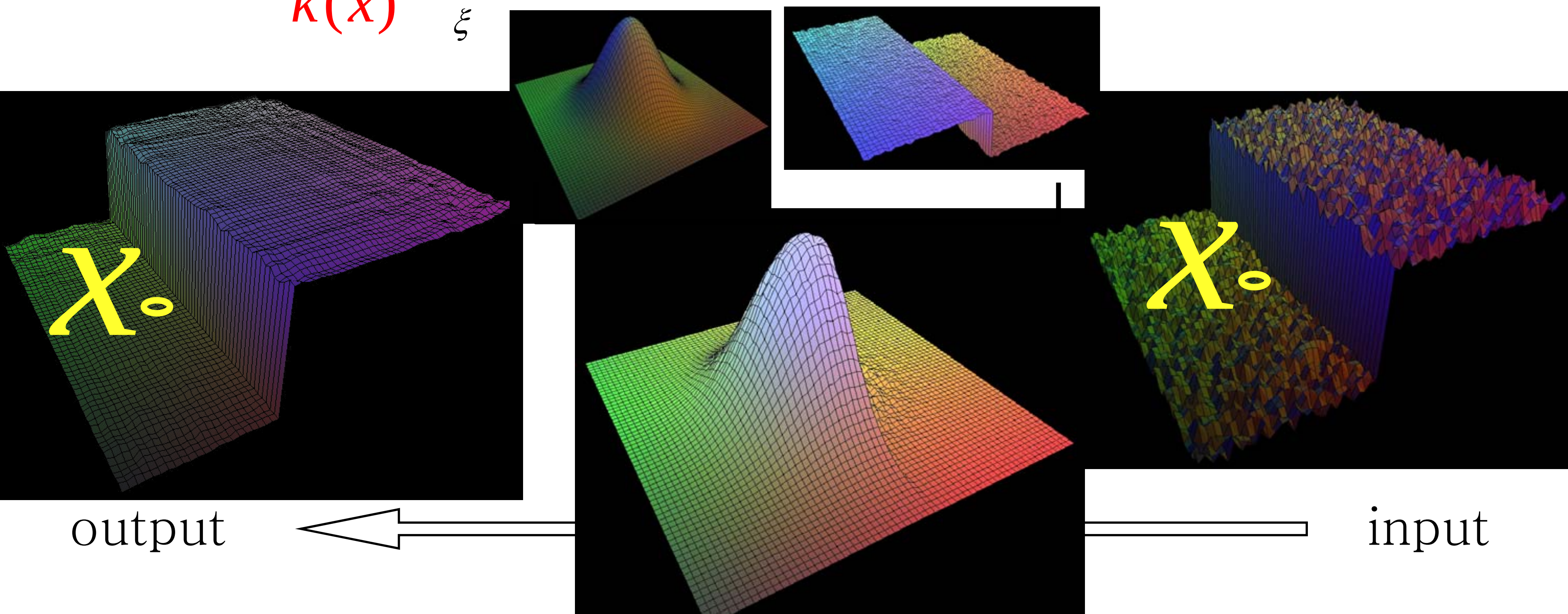


Bilateral filtering is non-linear

[Tomasi and Manduchi 1998]

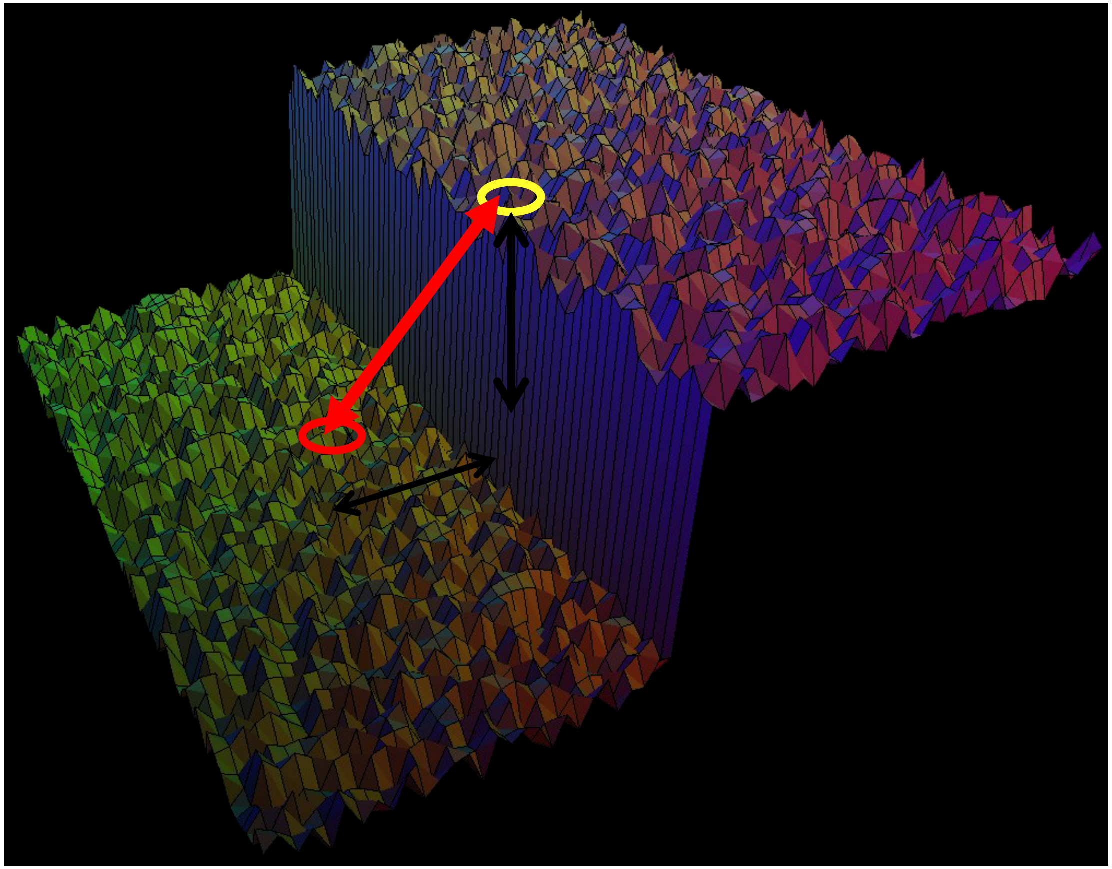
- **The weights are different for each output pixel**

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



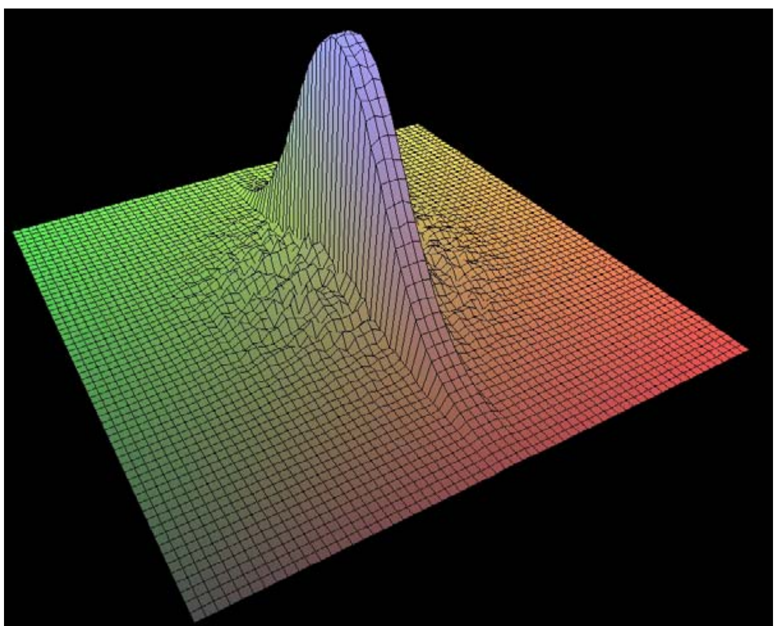
Other view

- **The bilateral filter uses the 3D distance**

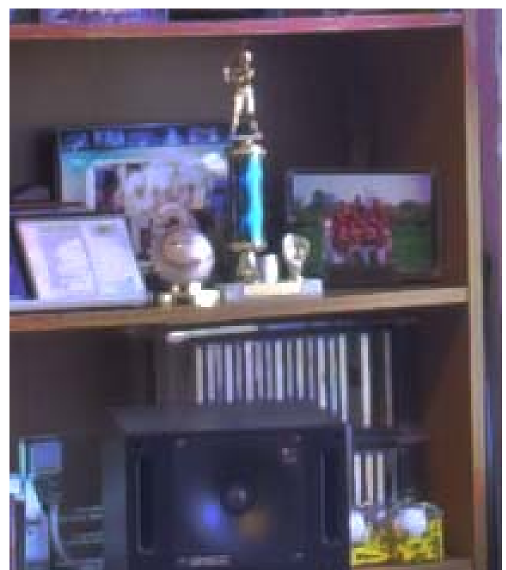


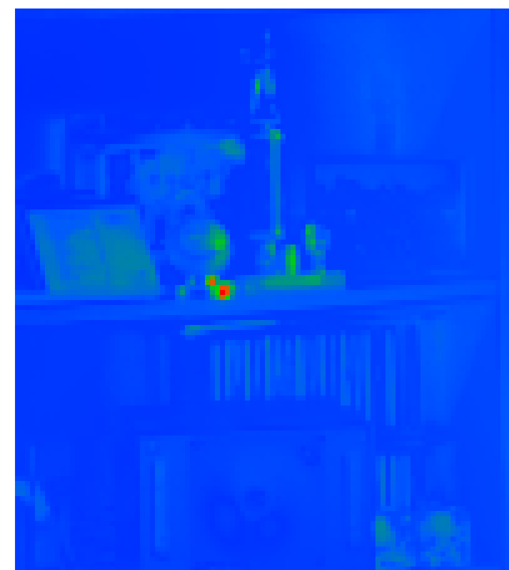
Handling uncertainty

- **Sometimes, not enough "similar" pixels**
- **Happens for specular highlights**
- **Can be detected using normalization k(x)**
- **Simple fix (average with output of neighbors)**



eights with high uncertainty





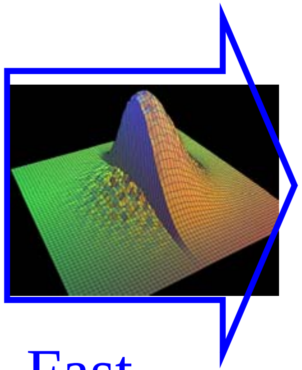
Uncertainty

Contrast reduction

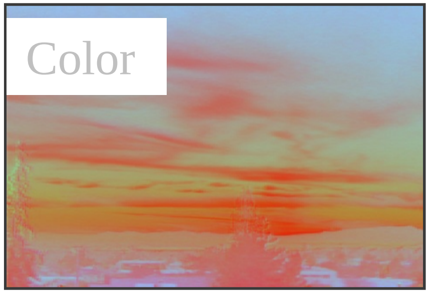
Contrast
too high!

Contrast reduction

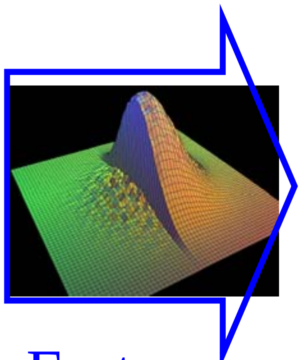
Contrast reduction



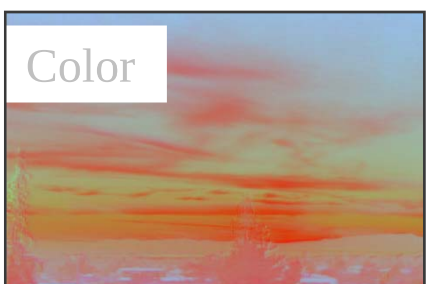
Fast
Bilateral
Filter



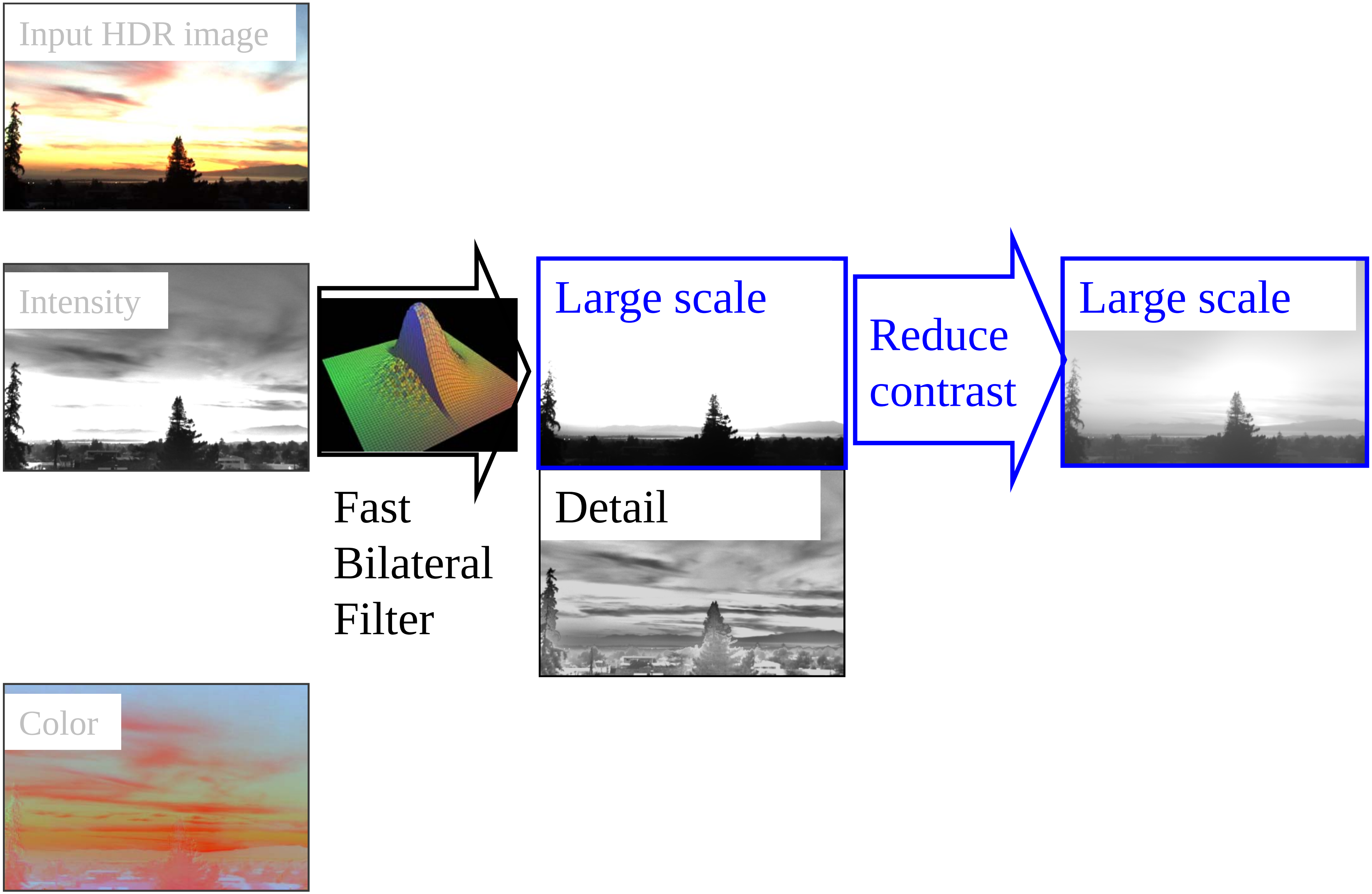
Contrast reduction



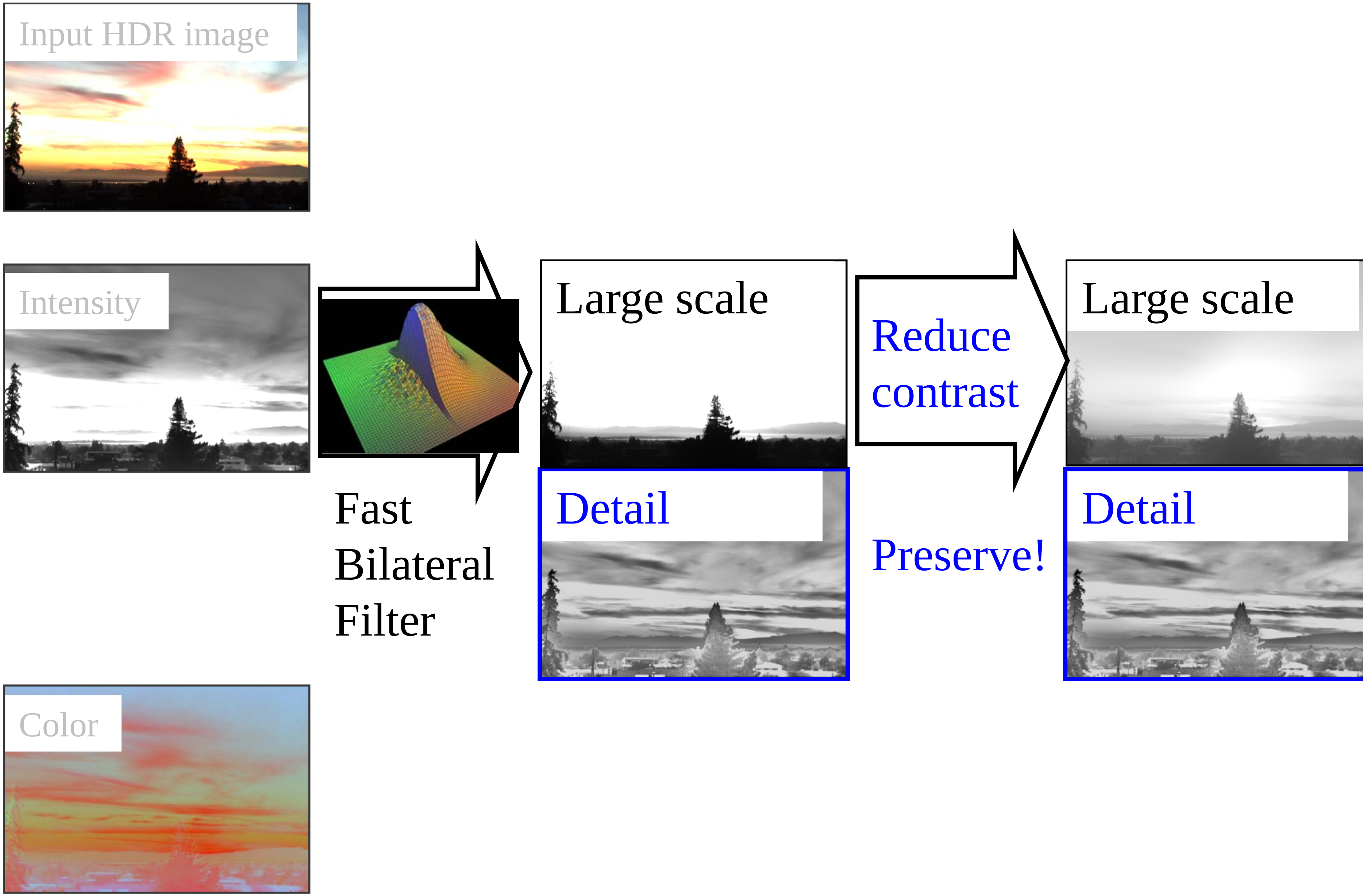
Fast Bilateral Filter



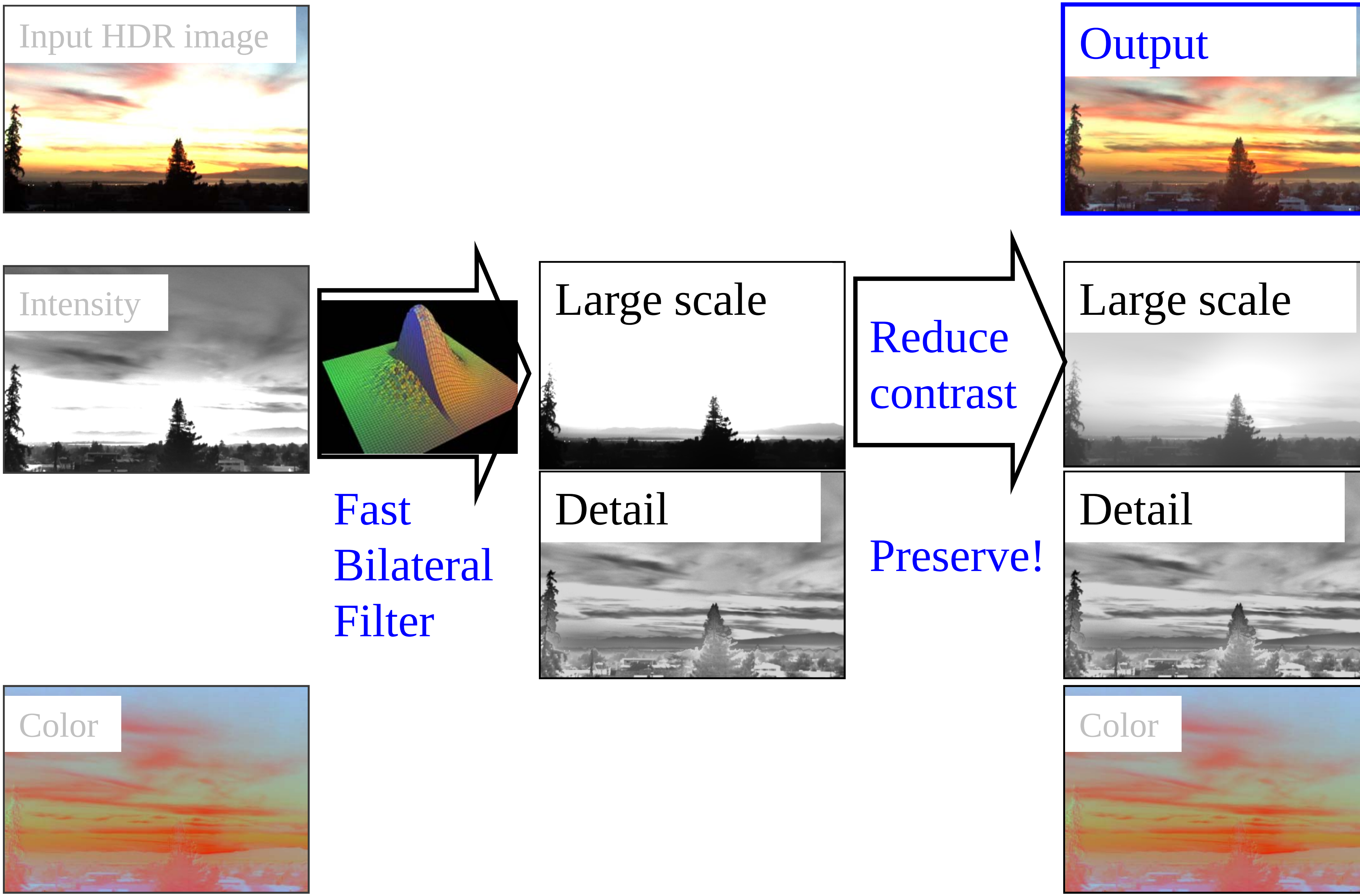
Contrast reduction



Contrast reduction



Contrast reduction



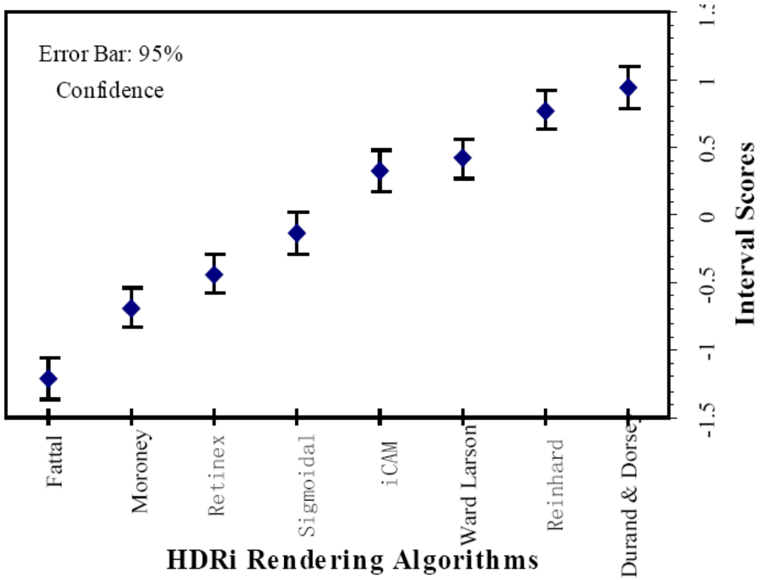
Reduction

- **To reduce contrast of base layer**
  - scale in the log domain

  ➔ γ exponent in linear space
- **Set a target range: $\log_{10}$ (5)**
- **Compute range in the base (log) layer: (max-min)**
- **Deduce γ using an elaborate operation known as *division***
- **You finally need to normalize so that the biggest value in the (linear) base is 1 (0 in log):**
  - Offset the compressed based by its max

Tone mapping evaluation

- **Recent work has performed user experiments to evaluate competing tone mapping operators**
  - Ledda et al. 2005
    http://www.cs.bris.ac.uk/Publications/Papers/2000255.pdf
  - Kuang et al. 2004
    http://www.cis.rit.edu/fairchild/PDFs/PRO22.pdf
- **Interestingly, the former concludes my method is the worst, the latter that my method is the best!**
  - They choose to test a different criterion: fidelity vs. preference
- **More importantly, they focus on algorithm and ignore parameters**



From Kuang et al.

	1st	2nd	3rd	4th	5th	6th
Scene 1	*P*	*B*	*A*	*H*	*I*	*L*
Scene 2	*I*	*P*	*H*	*A*	*B*	*L*
Scene 3	*P*	*I*	*A*	*H*	*L*	*B*
Scene 4	*P*	*L*	*I*	*A*	*H*	*B*
Scene 5	*I*	*H*	*A*	*P*	*L*	*B*
Scene 6	*I*	*H*	*A*	*P*	*L*	*B*
Scene 7	*I*	*A*	*P*	*H*	*B*	*L*
Scene 8	*I*	*P*	*A*	*H*	*L*	*B*
Scene 9	*P*	*A*	*L*	*H*	*B*	*I*

Adapted from Ledda et al.

Other tone mapping references

- **J. DiCarlo and B. Wandell, Rendering High Dynamic Range Images** http://www-isl.stanford.edu/%7Eabbas/group/papers_and_pub/spie00_jeff.pdf
- **Choudhury, P., Tumblin, J., "The Trilateral Filter for High Contrast Images and Meshes".** http://www.cs.northwestern.edu/~jet/publications.html
- **Tumblin, J., Turk, G., "Low Curvature Image Simplifiers (LCIS): A Boundary Hierarchy for Detail-Preserving Contrast Reduction."** http://www.cs.northwestern.edu/~jet/publications.html
- **Tumblin, J., "Three Methods For Detail-Preserving Contrast Reduction For Displayed Images"** http://www.cs.northwestern.edu/~jet/publications.html
- **Photographic Tone Reproduction for Digital Images**
  Erik Reinhard, Mike Stark, Peter Shirley and Jim Ferwerda
  http://www.cs.utah.edu/%7Ereinhard/cdrom/
- **Ashikhmin, M. ``A Tone Mapping Algorithm for High Contrast Images''** http://www.cs.sunysb.edu/~ash/tm.pdf
- **Retinex at Nasa** http://dragon.larc.nasa.gov/retinex/background/retpubs.html
- **Gradient Domain High Dynamic Range Compression Raanan Fattal, Dani Lischinski, Michael Werman** http://www.cs.huji.ac.il/~danix/hdr/
- **Li et al. : Wavelets and activity maps** http://web.mit.edu/yzli/www/hdr_companding.htm

Tone mapping code

- http://www.mpi-sb.mpg.de/resources/pfstools/
- http://scanline.ca/exrtools/
- http://www.cs.utah.edu/~reinhard/cdrom/source.html
- http://www.cis.rit.edu/mcsl/icam/hdr/

Next week

- Easter break!

ETH