High dynamic range and tone mapping

Advanced Graphics

Rafał Mantiuk
Computer Laboratory, University of Cambridge

Cornell Box: need for tone-mapping in graphics

Rendering

Photograph

Real-world scenes are more challenging

- The match could not be achieved if the light source in the top of the box was visible
- The display could not reproduce the right level of brightness

Dynamic range

Dynamic range (contrast)

- As ratio:

$$C = \frac{L_{\max}}{L_{\min}}$$

  - Usually written as C:1, for example 1000:1.

- As "orders of magnitude" or log10 units:

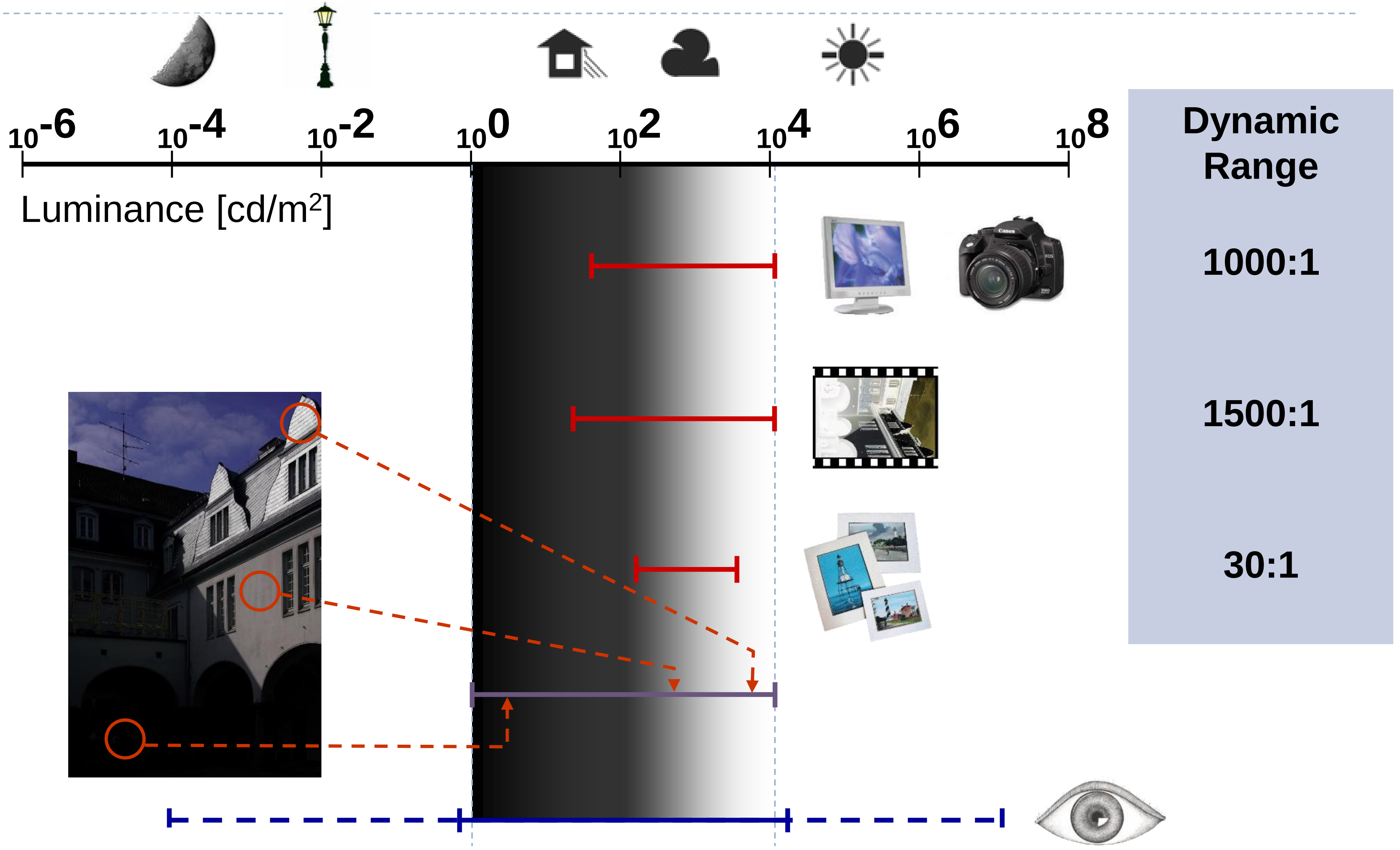
$$C_{10} = \log_{10} \frac{L_{\max}}{L_{\min}}$$

- As stops:

$$C_2 = \log_2 \frac{L_{\max}}{L_{\min}}$$

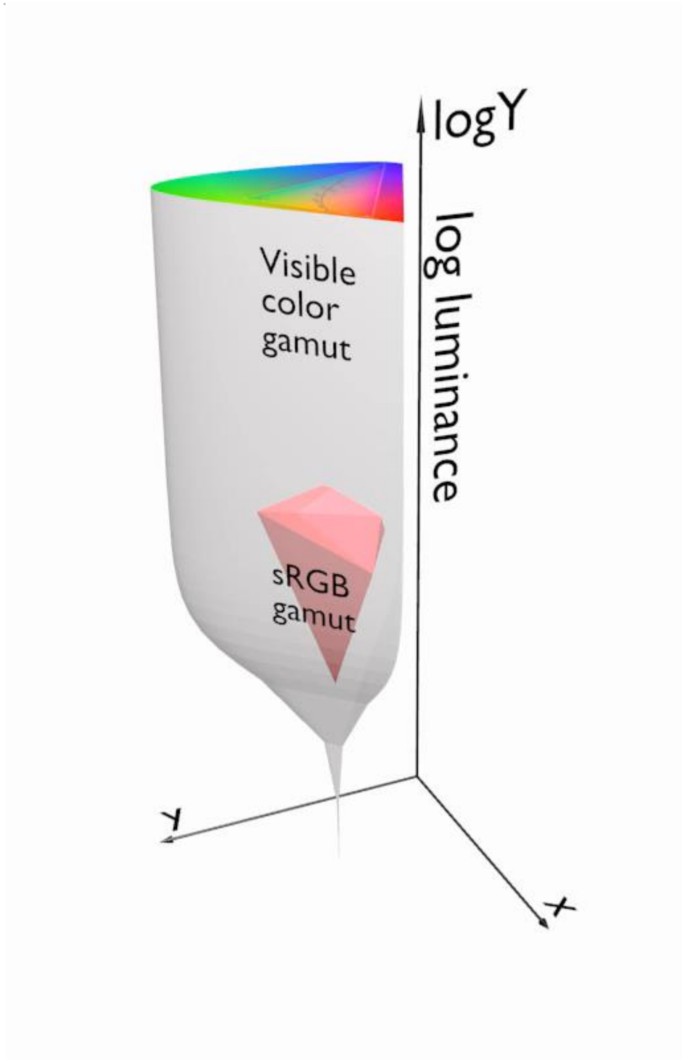
One stop is doubling of halving the amount of light

High dynamic range (HDR)

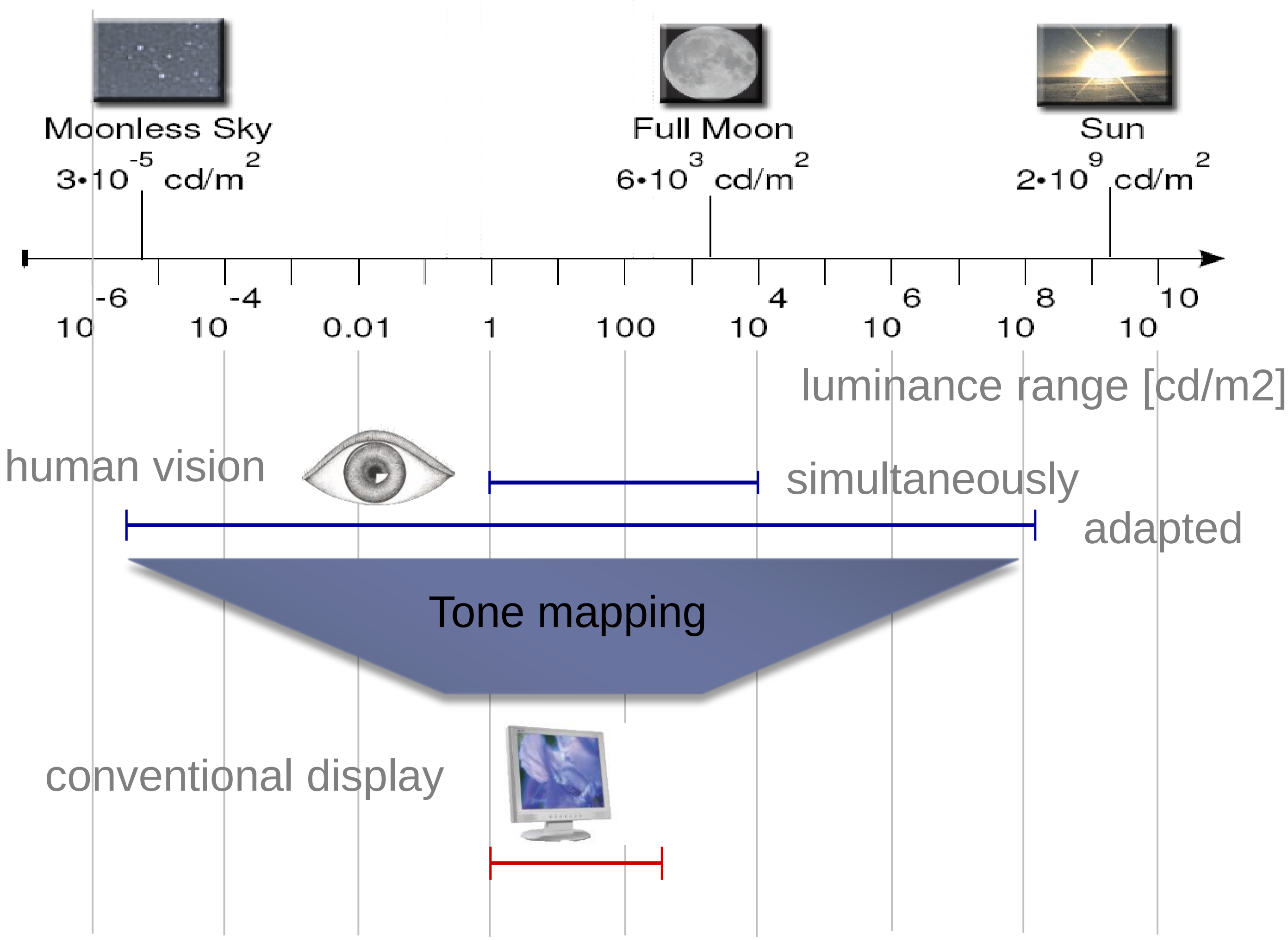


Visible colour gamut

- The eye can perceive more colours and brightness levels than
  - a display can produce
  - a JPEG file can store
- The premise of HDR:
  - Visual perception and not the technology should define accuracy and the range of colours
  - The current standards not fully follow to this principle



Tone-mapping problem



Why do we need tone mapping?

- To reduce excessive dynamic range
- To customize the look (colour grading)
- To simulate human vision
  - for example night vision
- To adapt displayed images to a display and viewing conditions
- To make rendered images look more realistic

- Different tone mapping operators achieve different goals

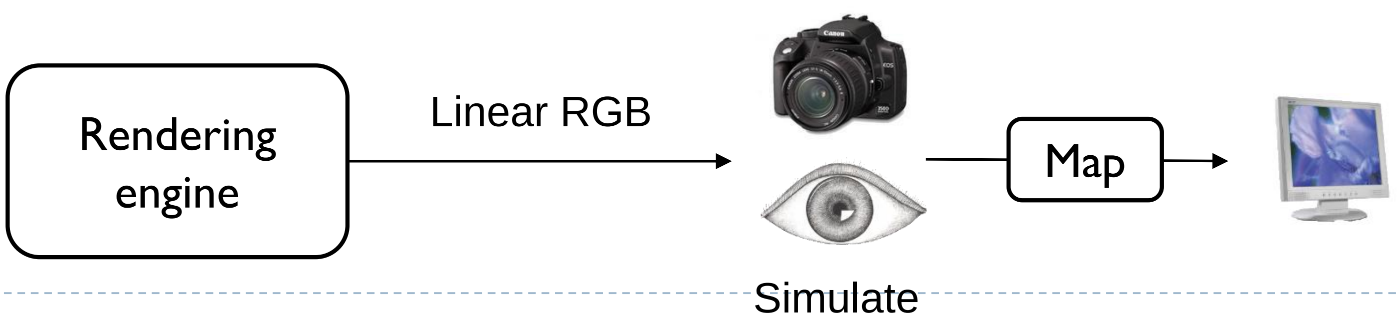
Tone-mapping in rendering

- Any physically-based rendering requires tone-mapping
- “HDR rendering” in games is pseudo-physically-based rendering
- Goal: to simulate a camera or the eye
- Greatly enhances realism

LDR illumination
No tone-mapping

HDR illumination
Tone-mapping

Half-Life 2: Lost coast



Techniques

- Arithmetic of HDR images
- Display model
- Tone-curve
- Color transfer
- Base-detail separation
- Glare
- Simulation of night vision

Arithmetic of HDR images

- How does the basic arithmetic operations
  - Addition
  - Multiplication
  - Power function
- affect the appearance of an HDR image?
- We work in the luminance space (NOT luma)
- The same operations can be applied to linear RGB
  - Or to luminance-only and the colour can be transferred

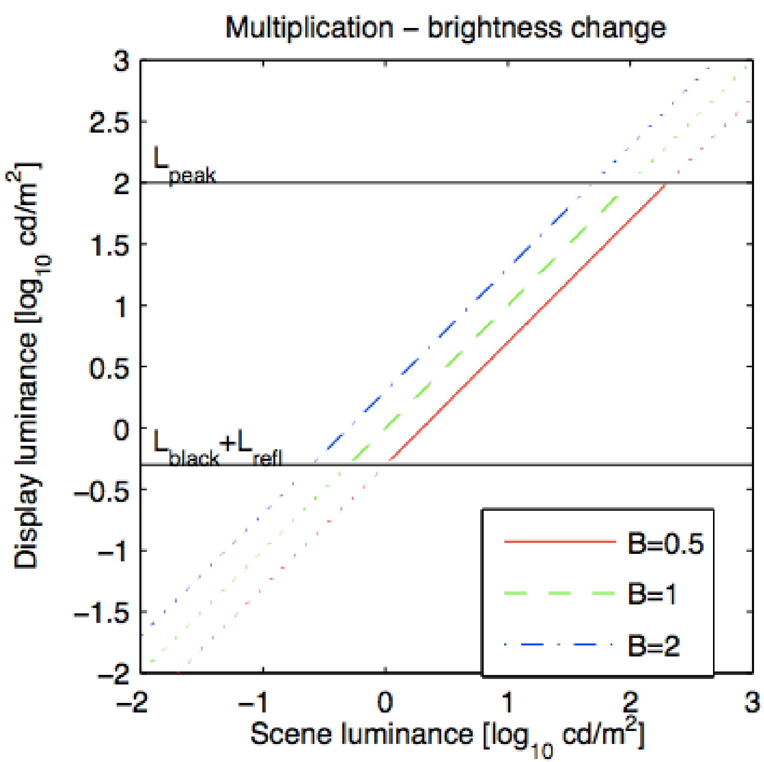
Multiplication – brightness change

Resulting luminance

Input luminance

$$T(L_p) = B \cdot L_p$$

Brightness change parameter



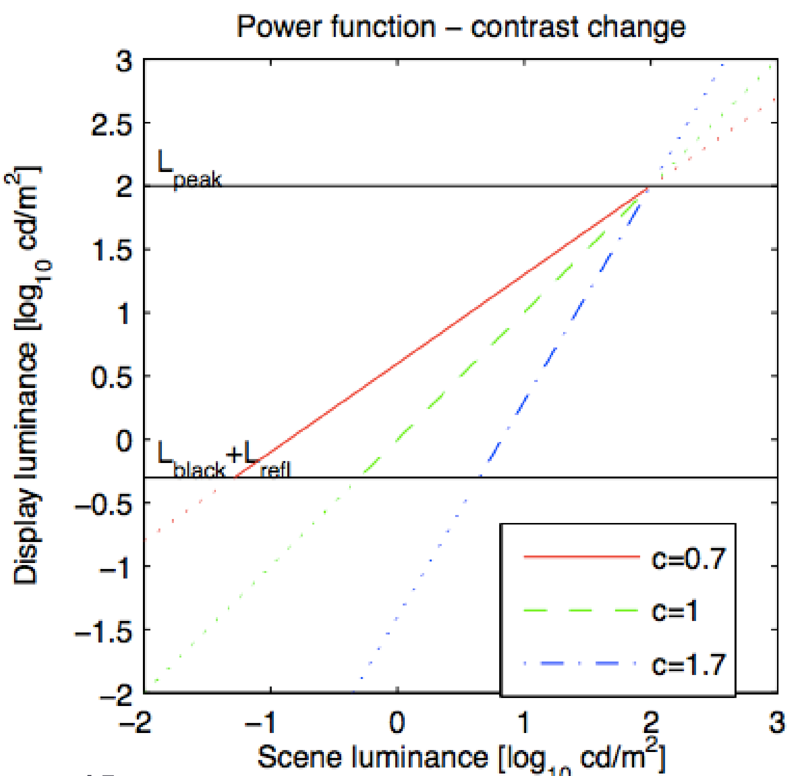
- Multiplication makes the image brighter or darker
- It does not change the dynamic range!

Power function – contrast change

$$T(L_p) = \left(\frac{L_p}{L_{white}}\right)^c$$

Contrast change (gamma)

Luminance of white

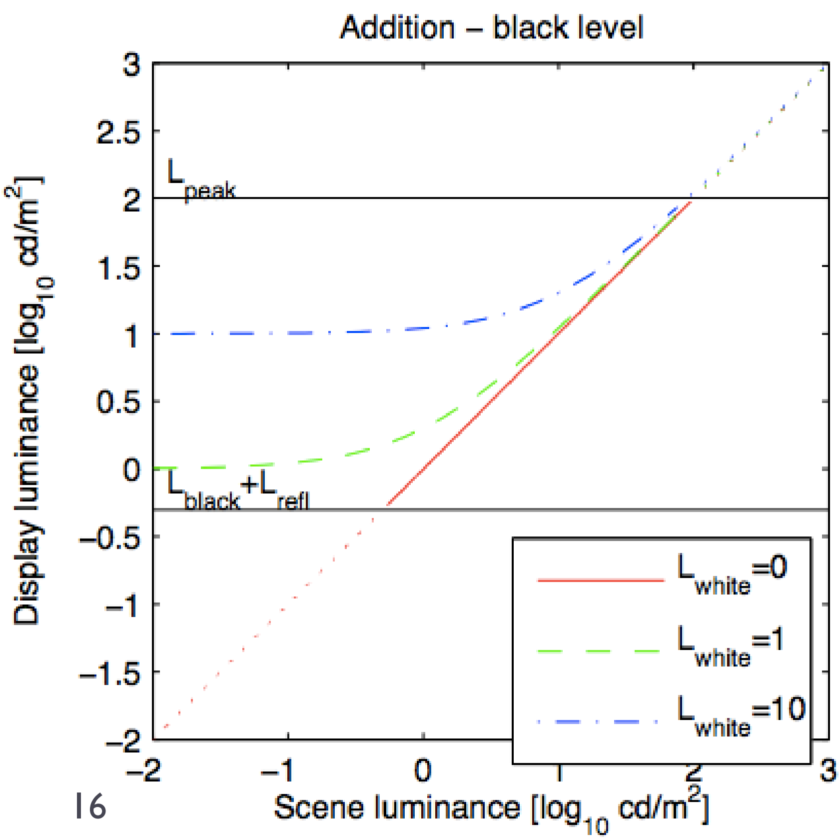


- Power function stretches or shrinks image dynamic range
- It is usually performed relative to reference white
- Apparent brightness changes is the side effect of pushing tones towards or away from the white point

Addition – black level

$$T(L_p) = L_p + F$$

Black level (flare, fog)



- Addition elevates black level, adds fog to an image
- It does NOT make the overall image brighter
- It reduces dynamic range

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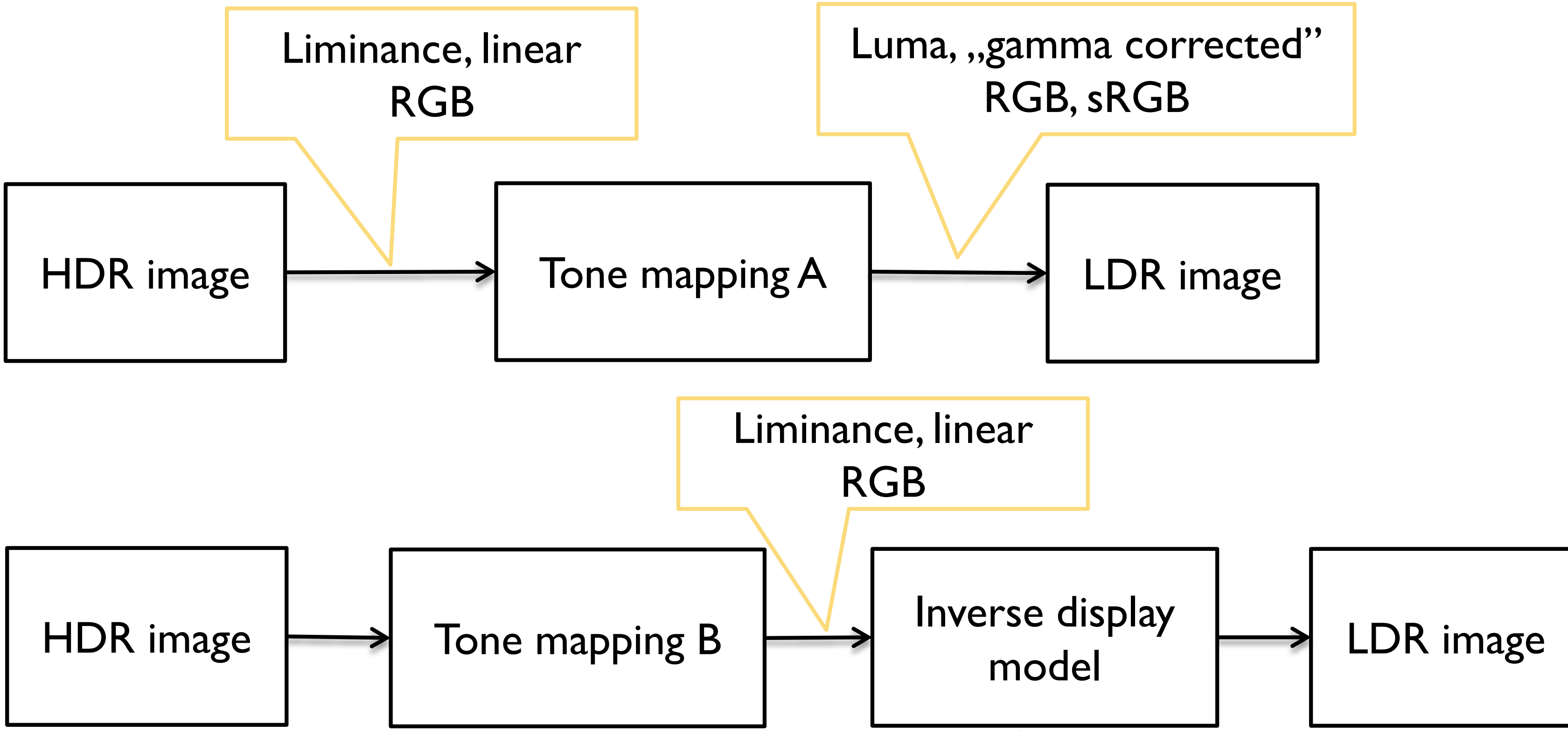
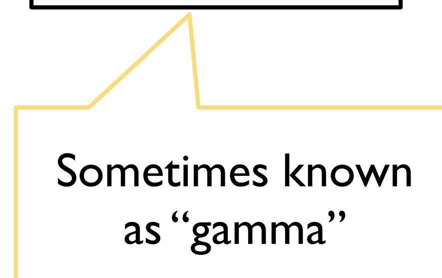
Two ways to do tone-mapping



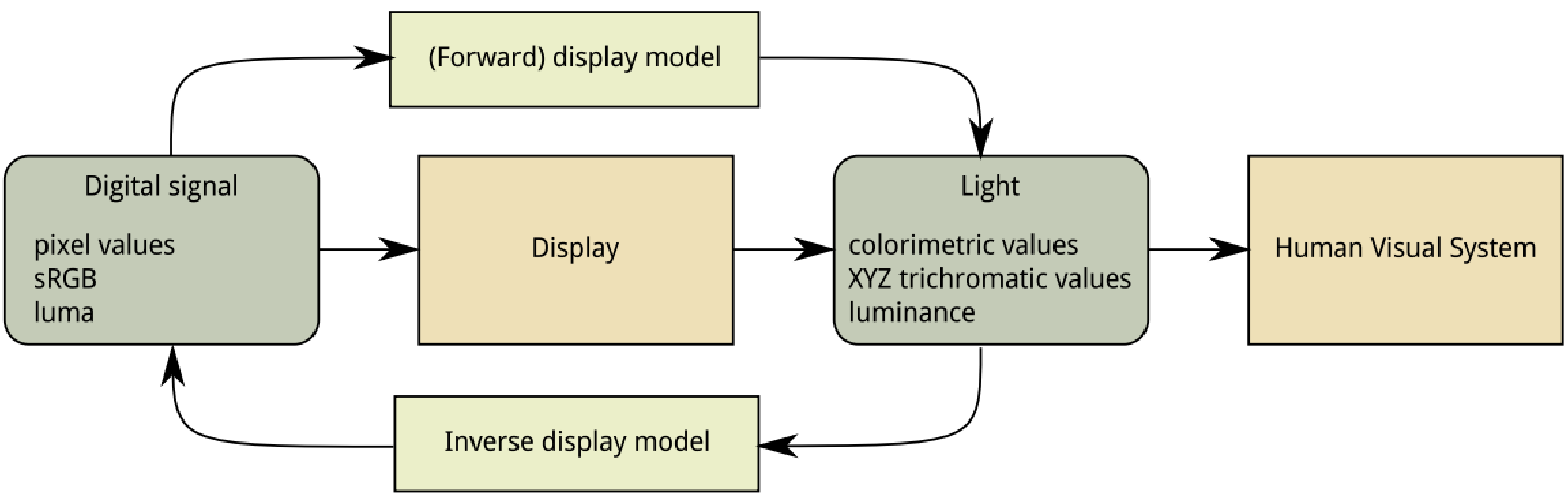
Display model can account for:

- Display peak luminance
- Display dynamic range (contrast)
- Ambient light



Display model

- Tone-mapping needs to account for the physical model of a display
  - How a display transforms pixel values into emitted light



(Forward) Display model

- GOG: Gain-Gamma-Offset

Display black level

Luminance

Peak luminance

Gamma

Screen reflections

$$L = (L_{peak} - L_{black})V^{\gamma} + L_{black} + L_{refl}$$

Gain

Pixel value 0-1

Offset

Reflectance factor (0.01)

$$L_{refl} = \frac{k}{\pi} E_{amb}$$

Ambient illumination (in lux)

Inverse display model

Symbols are the same as for the forward display model

$$V = \left(\frac{L - L_{black} - L_{refl}}{L_{peak} - L_{black}} \right)^{(1/\gamma)}$$

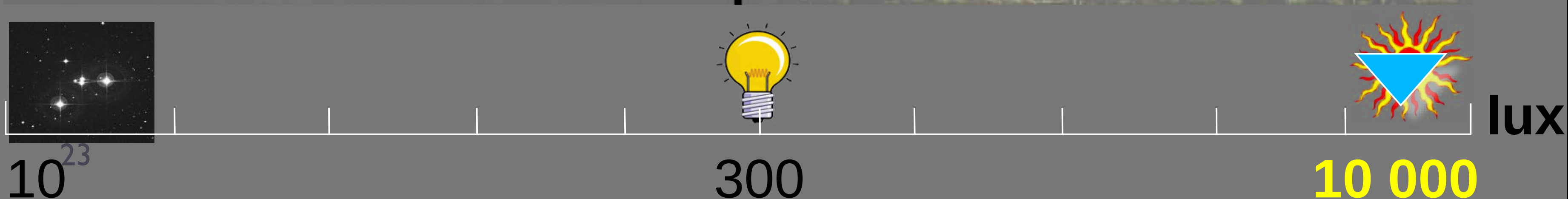
Note: This display model does not address any colour issues. The same equation is applied to red, green and blue color channels. The assumption is that the display primaries are the same as for the sRGB color space.

Ambient illumination compensation

Non-adaptive TMO | Display adaptive TMO

Ambient illumination compensation

Non-adaptive TMO | Display adaptive TMO



Example: Ambient light compensation

- We are looking at the screen in bright light

$$L_{peak} = 100\ [cd \cdot m^{-2}] \qquad k = 0.005$$

Modern screens have reflectivity of around 0.5%

$$L_{black} = 0.1\ [cd \cdot m^{-2}]$$

$$E_{amb} = 2000\ [lux] \qquad L_{refl} = \frac{0.005}{\pi} 2000 = 3.183\ [cd \cdot m^{-2}]$$

- We assume that the dynamic of the input is 2.6 (≈400:1)

$$r_{in} = 2.6 \qquad r_{out} = \log_{10} \frac{L_{peak}}{L_{black} + L_{refl}} = 1.77$$

- First, we need to compress contrast to fit the available dynamic range, then compensate for ambient light

$$L_{out} = \left(\frac{L_{in}}{L_{peak}} \right)^{\frac{r_{out}}{r_{in}}} - L_{refl}$$

The resulting value is in luminance, must be mapped to display luma / gamma corrected values

Simplest, but not the best tone mapping

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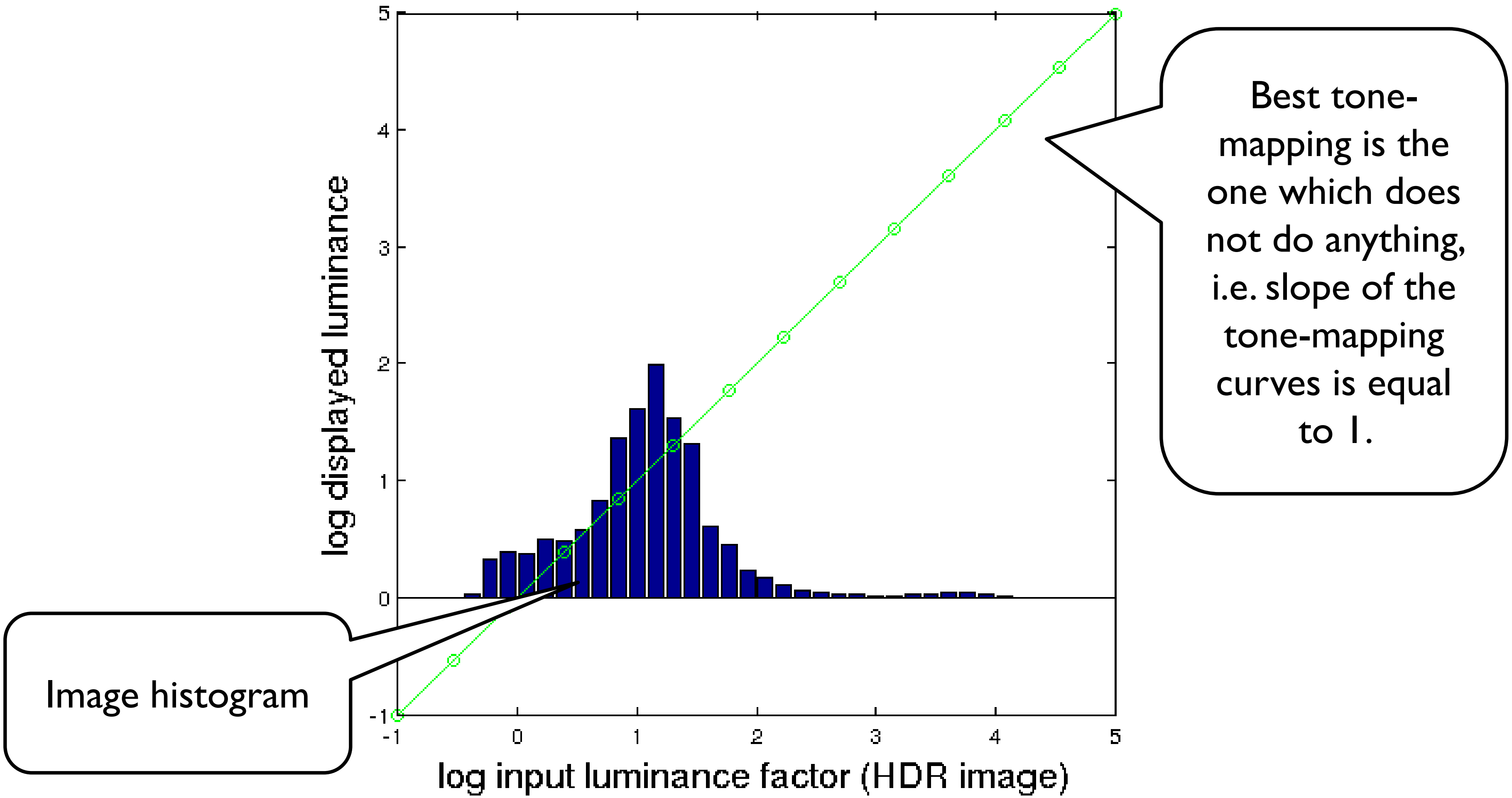
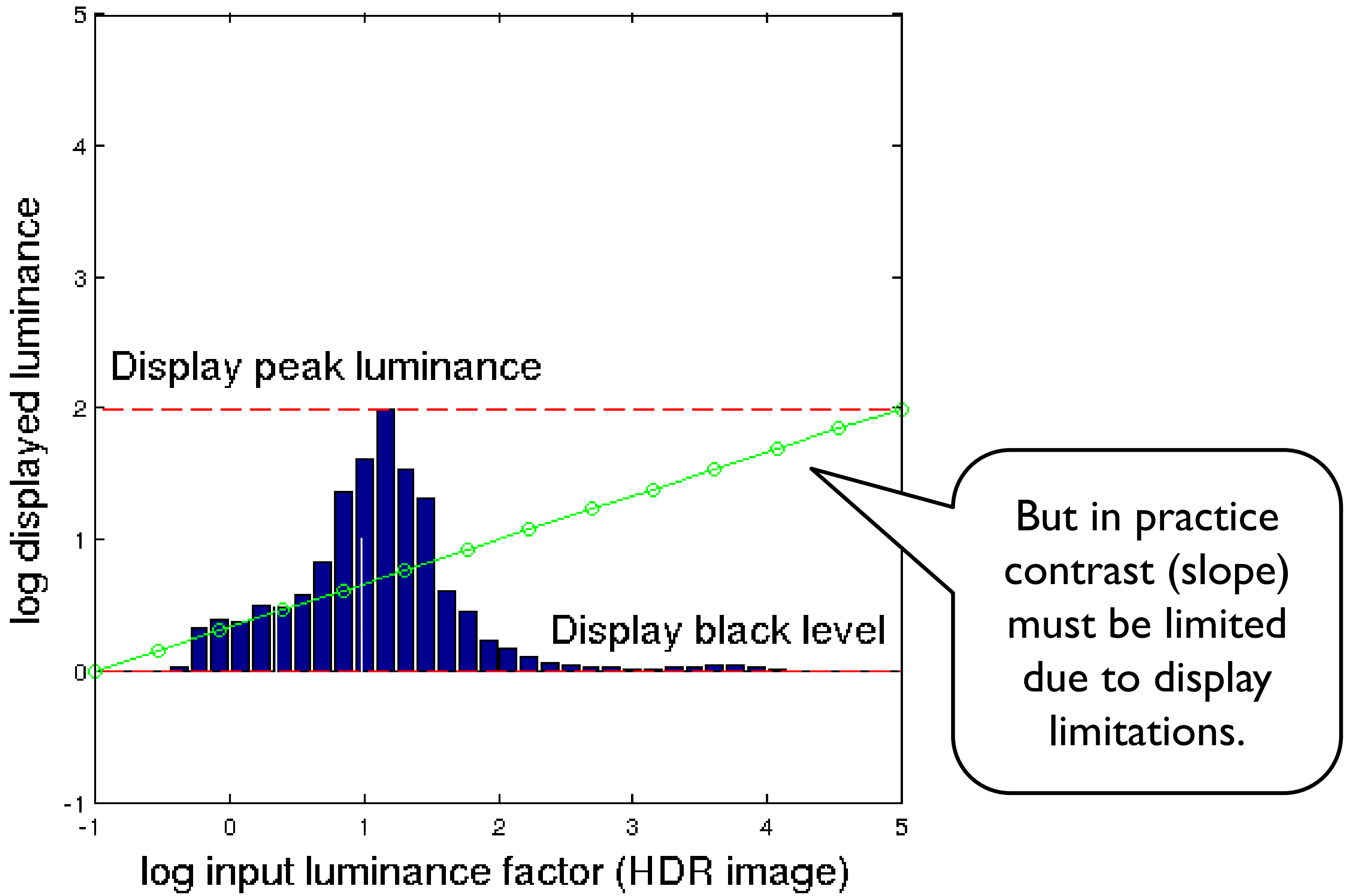
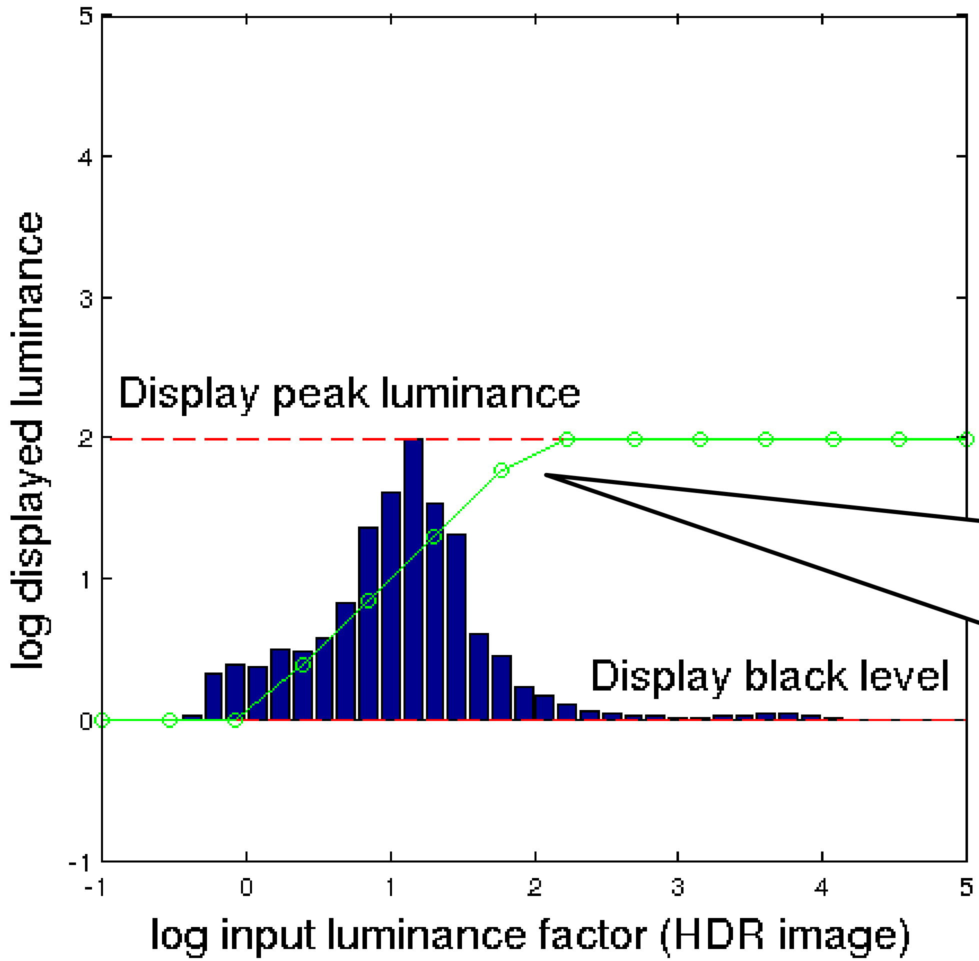
Tone-curve


5
4
3
2
1
0
-1
-1
0
1
2
3
4
5
log displayed luminance
log input luminance factor (HDR image)
Best tone-mapping is the one which does not do anything, i.e. slope of the tone-mapping curves is equal to 1.
Image histogram

Tone-curve


Display peak luminance
Display black level
log displayed luminance
log input luminance factor (HDR image)
5
4
3
2
1
0
-1
-1
0
1
2
3
4
5
But in practice contrast (slope) must be limited due to display limitations.

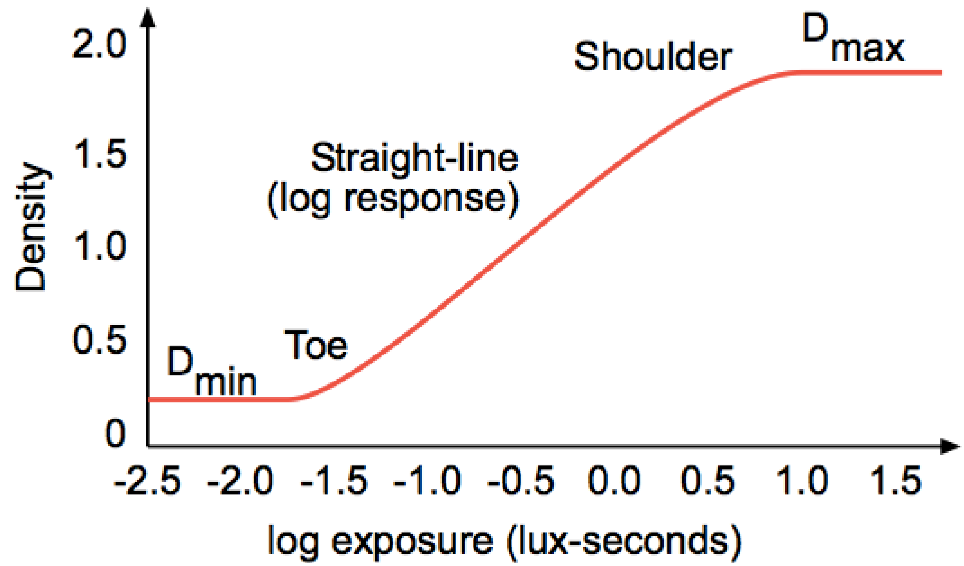
Tone-curve



Global tone-mapping is a compromise between clipping and contrast compression.

Sigmoidal tone-curves

- Very common in digital cameras
  - Mimic the response of analog film
  - Analog film has been engineered over many years to produce good tone-reproductior
- Fast to compute



Sigmoidal tone mapping

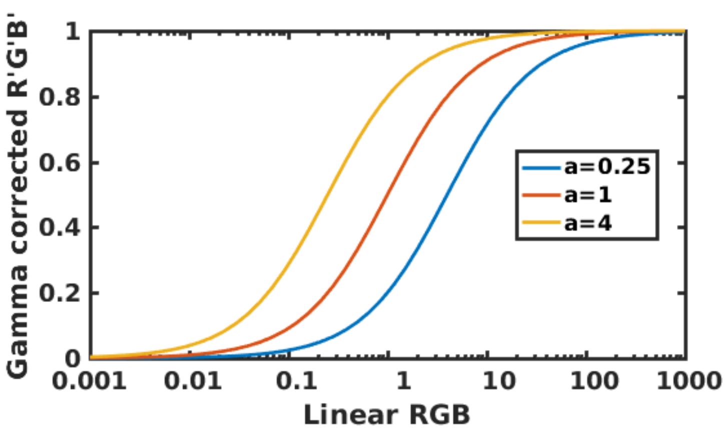
- Simple formula for a sigmoidal tone-curve:

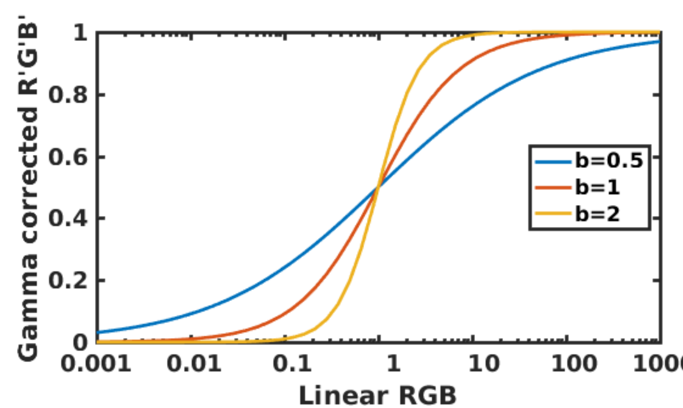
$$R'(x,y) = \frac{R(x,y)^b}{\left(\frac{L_m}{a}\right)^b + R(x,y)^b}$$

where L_m is the geometric mean (or mean of logarithms):

$$L_m = exp\left(\frac{1}{N}\sum_{(x,y)} \ln(L(x,y))\right)$$

and $L(x,y)$ is the luminance of the pixel (x,y).





Sigmoidal tone mapping example

a=0.25
a=1
a=4

b=0.5 b=1 b=2

Histogram equalization

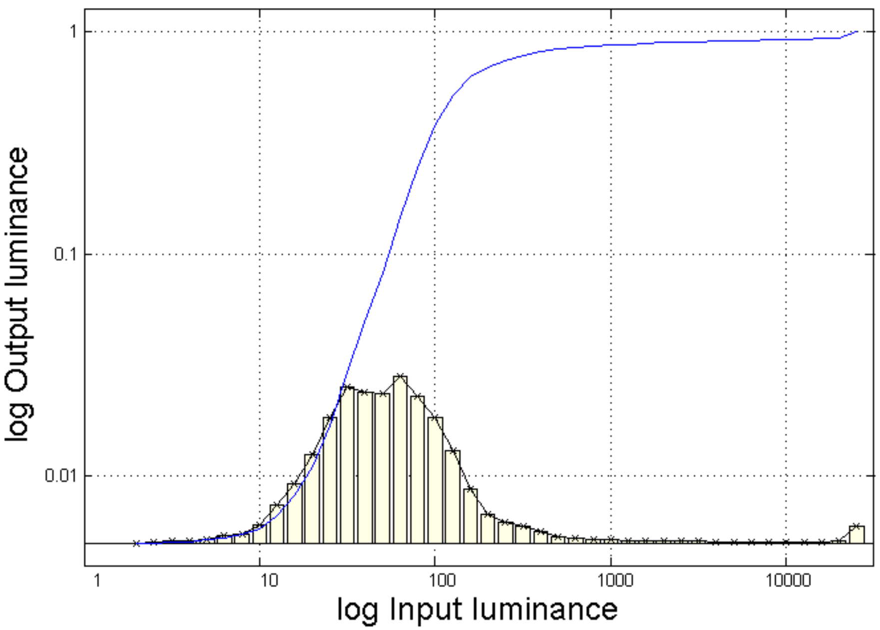
- 1. Compute cummulative image histogram

$$c(I) = \frac{1}{N}\sum_{i=0}^{I} h(i) = c(I-1) + \frac{1}{N}h(I)$$

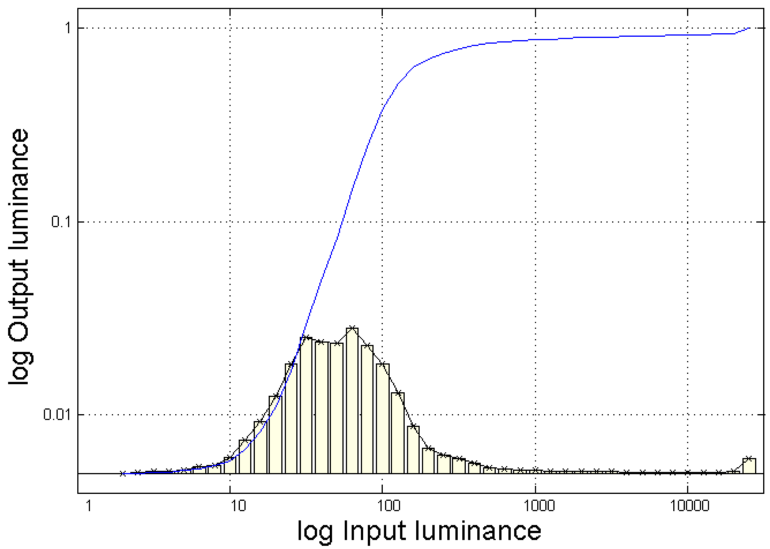
  - For HDR, operate in the log domain
- 2. Use the cummulative histogram as a tone-mapping function

$$Y_{out} = c(Y_{in})$$

  - For HDR, map the log-10 values to the [$-dr_{out}$; 0] range
    - where dr_{out} is the target dynamic range (of a display)



Histogram equalization



- Steepest slope for strongly represented bins
  - If many pixels have the same value - enhance contrast
  - Reduce contrast, if few pixels
- Histogram Equalization distributes contrast distortions relative to the "importance" of a brightness level

Histogram adjustment with a linear ceiling

- [Larson et al. 1997, IEEE TVCG]

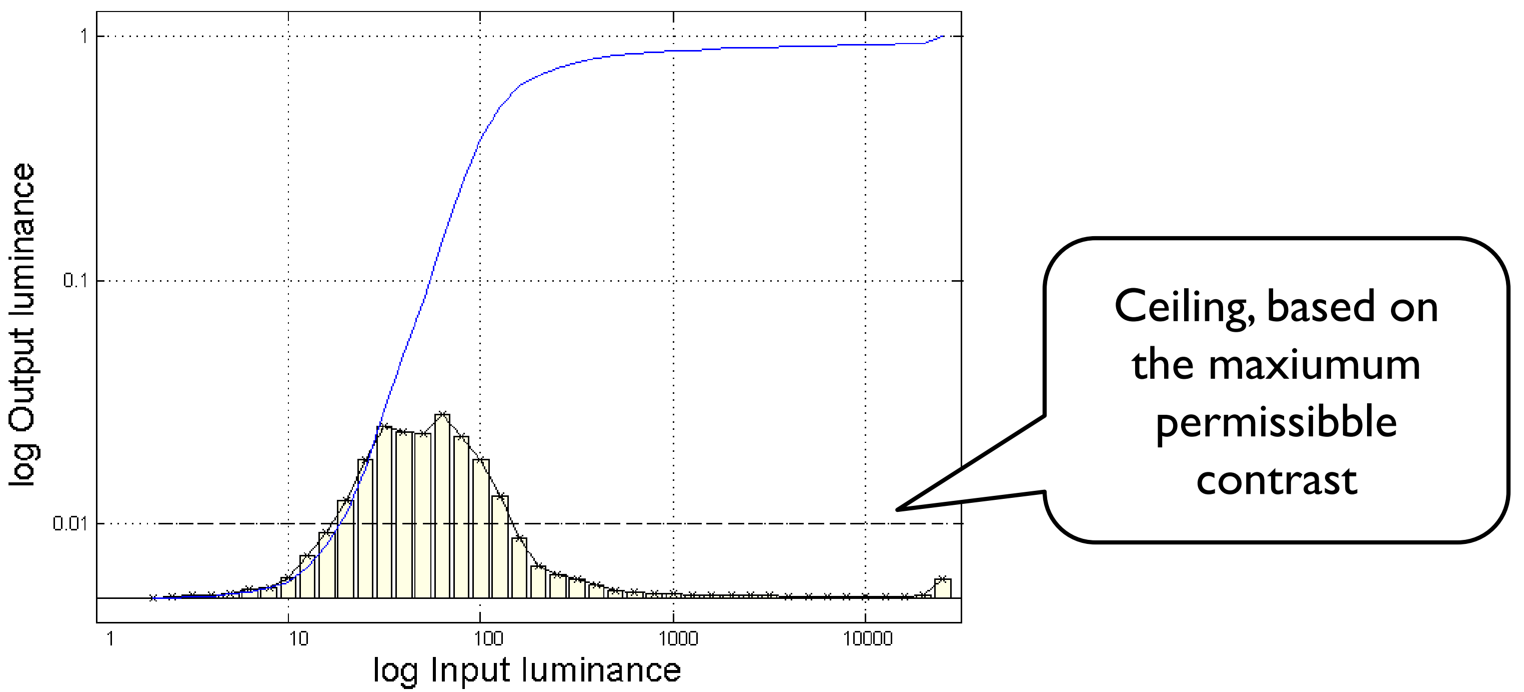
Linear mapping

Histogram equalization

Histogram equalization with ceiling

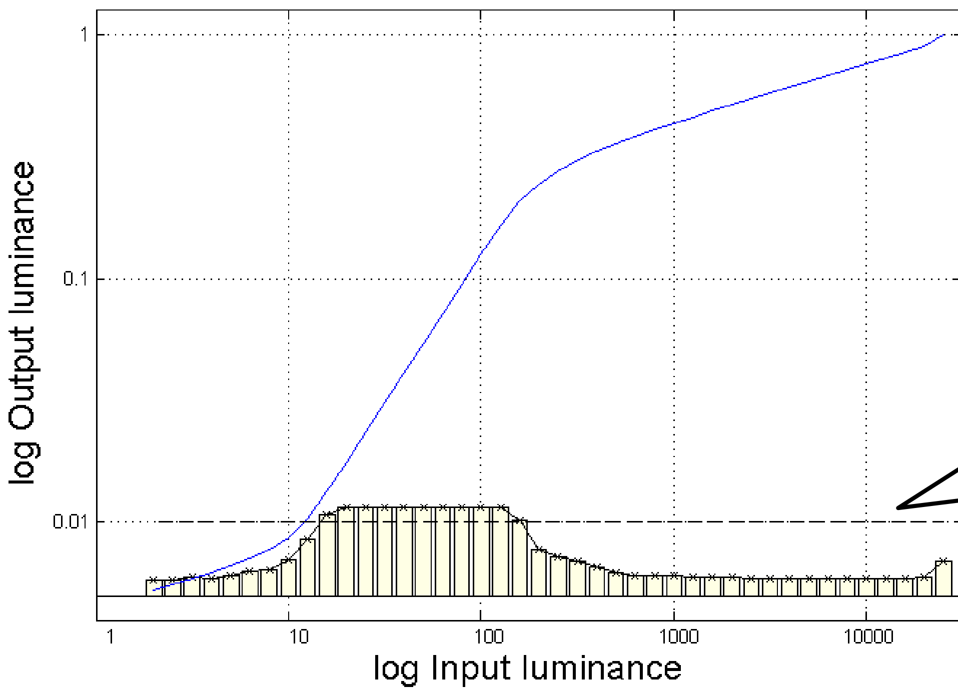
Histogram adjustment with a linear ceiling

- Truncate the bins that exceed the ceiling;
- Distribute the removed counts to all bins;
- Repeat until converges



Histogram adjustment with a linear ceiling

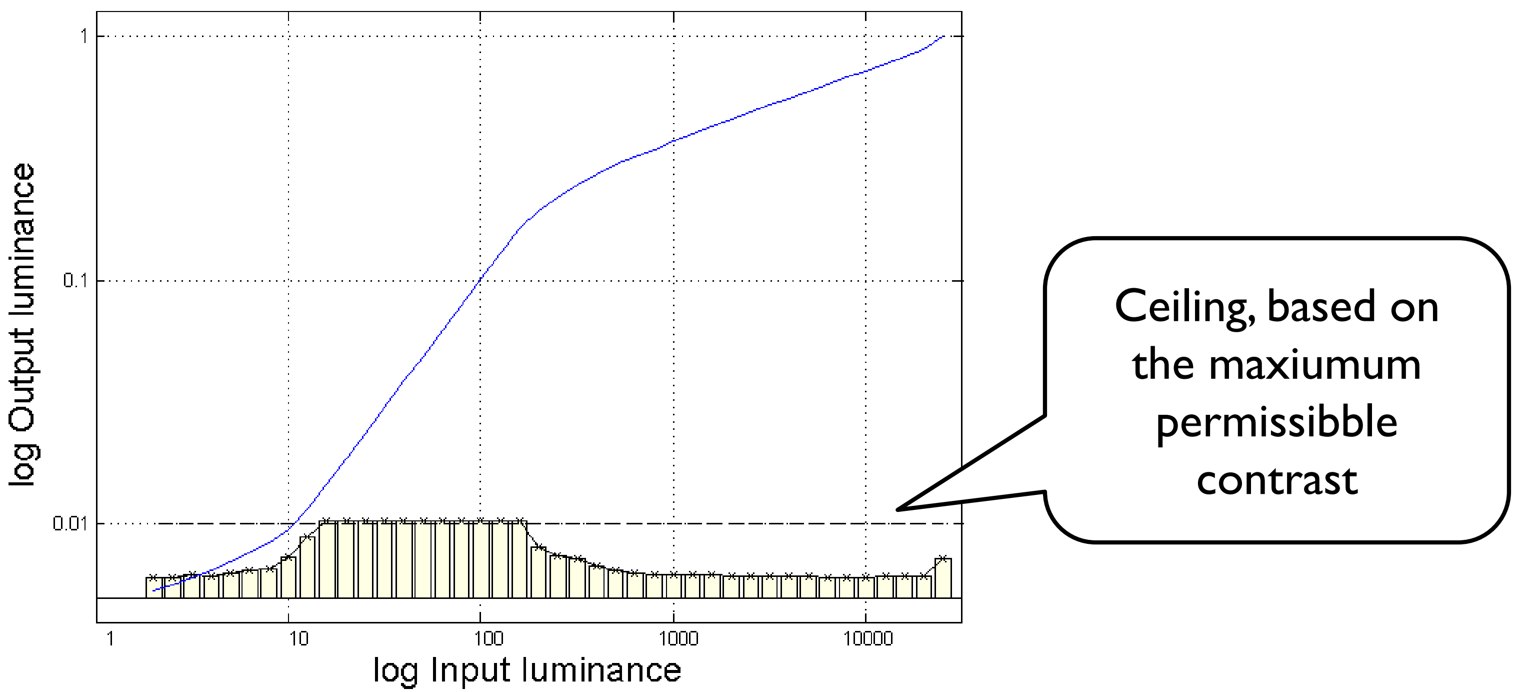
- Truncate the bins that exceed the ceiling;
- Distribute the removed counts to all bins;
- Repeat until converges



Ceiling, based on the maxiumum permissibble contrast

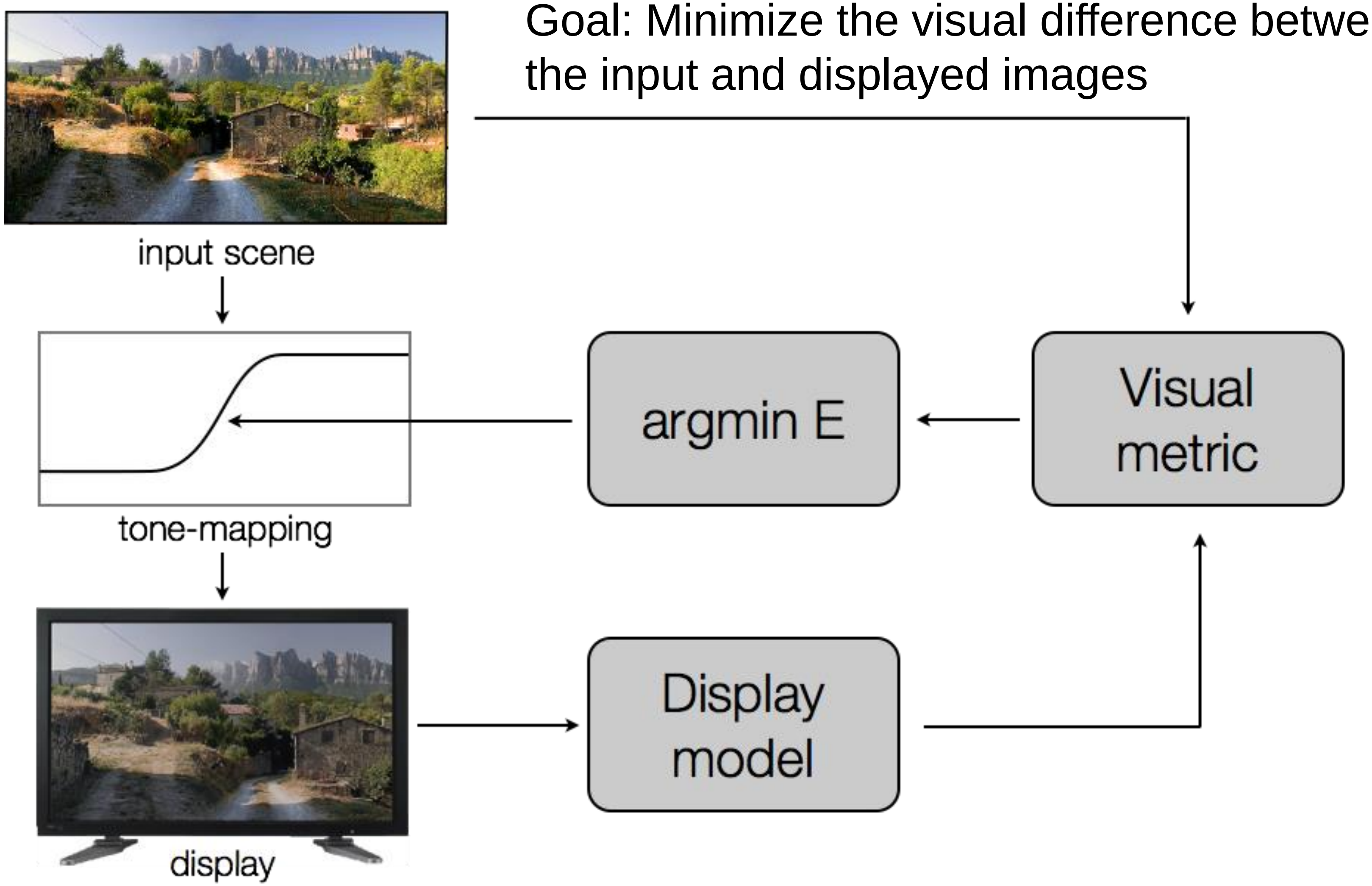
Histogram adjustment with a linear ceiling

- Truncate the bins that exceed the ceiling;
- Distribute the removed counts to all bins;
- Repeat until converges



Tone-curve as an optimization problem

Goal: Minimize the visual difference between the input and displayed images



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Colour transfer in tone-mapping

- Many tone-mapping operators work on luminance
  - For speed
  - To avoid colour artefacts
- Colours must be transferred later form the original image
- Colour transfer in the linear RGB colour space:

Output color channel (red)

$$R_{out} = \left(\frac{R_{in}}{L_{in}} \right)^{s} \cdot L_{out}$$

Saturation parameter

Resulting luminance

- The same formula applies to green (G) and blue (B) linear colour values.

Colour transfer: out-of-gamut problem

- Colours often fall outside the colour gamut when contrast is compressed

Original image

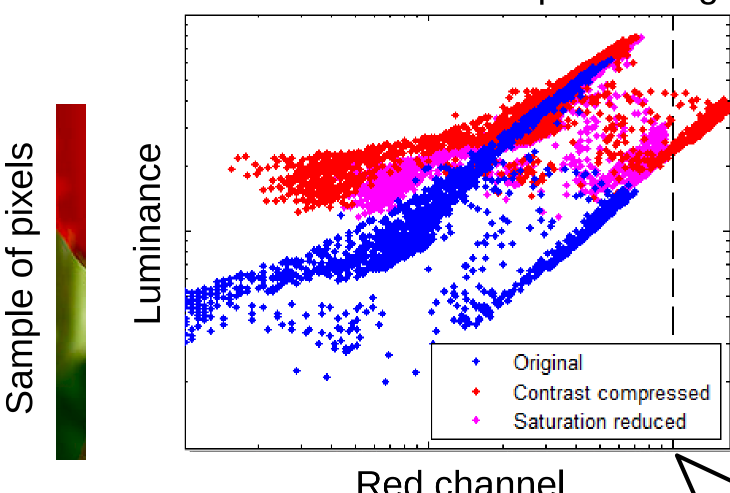
→

Contrast reduced (s=1)

↓

Saturation reduced (s=0.6)

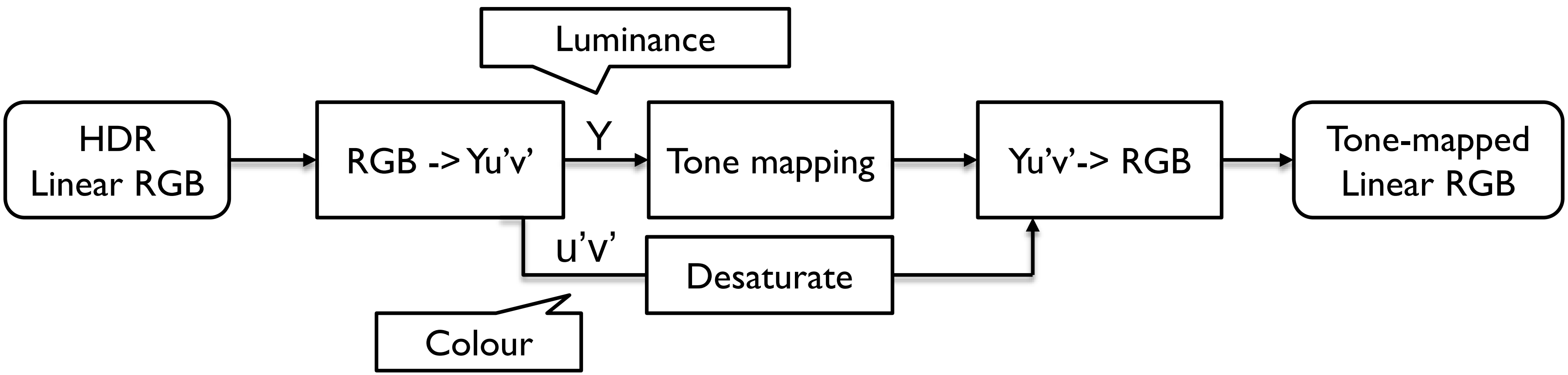
Colours before/after processing



- Reduction in saturation is needed to bring the colors into gamut

Colour transfer: alternative method

- Colour transfer in linear RGB will alter resulting luminance
- Colours can be also transferred and saturation adjusted using CIE u'v' chromatic coordinates



- To correct saturation:

$$u'_{out} = (u'_{in} - u'_{w}) \cdot s + u'_{w}$$
$$v'_{out} = (v'_{in} - v'_{w}) \cdot s + v'_{w}$$

Chroma of the white

$$u'_{w} = 0.1978$$
$$v'_{w} = 0.4683$$

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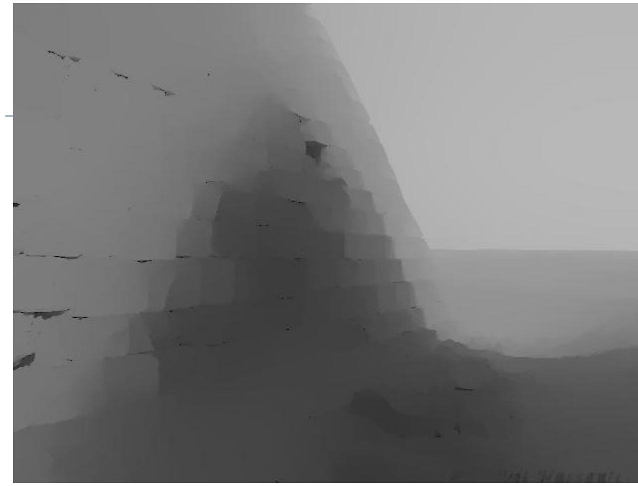
Illumination & reflectance separation

Input



Illumination

Reflectance

$$Y = I \times R$$

Image

Illumination

Reflectance

Illumination and reflectance

Reflectance

- White ≈ 90%
- Black ≈ 3%
- Dynamic range < 100:1
- Reflectance critical for object & shape detection

Illumination

- Sun ≈ 10^9 cd/m^2
- Lowest perceivable luminance ≈ 10^{-6} cd/m^2
- Dynamic range 10,000:1 or more
- Visual system partially discounts illumination

Reflectance & Illumination TMO

- Hypothesis: *Distortions in reflectance are more apparent than the distortions in illumination*
- Tone mapping could preserve reflectance but compress illumination

Illumination

Tone-mapped image

$$L_d = R \cdot T(I)$$

Reflectance

Tone-mapping

- for example:

$$L_d = R \cdot (I / L_{white})^c \cdot L_{white}$$

How to separate the two?

- (Incoming) illumination – slowly changing
  - except very abrupt transitions on shadow boundaries
- Reflectance – low contrast and high frequency variations

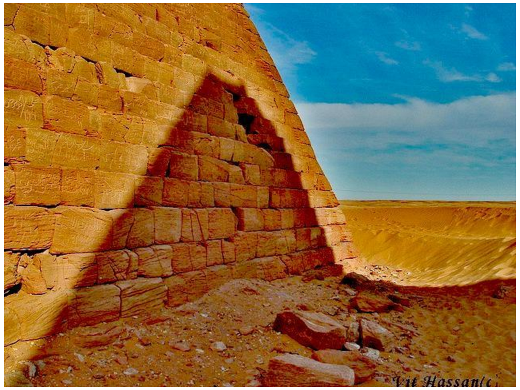
Gaussian filter

$$f(x) = \frac{1}{2\pi\sigma_s} e^{\frac{-x^2}{2\sigma_s^2}}$$

- First order approximation

- Blurs sharp boundaries
- Causes halos

Tone mapping result

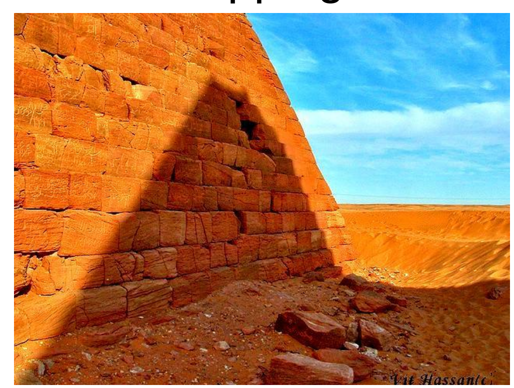


Bilateral filter

$$I_p \approx \frac{1}{k_s} \sum_{t \in \Omega} f(p-t)\, g(L_p - L_t)\, L_p$$

- Better preserves sharp edges

Tone mapping result

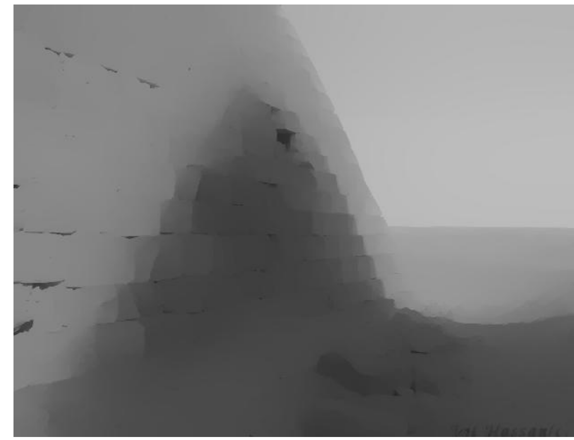


- Still some blurring on the edges
- Reflectance is not perfectly separated from illumination near edges

[Durand & Dorsey, SIGGRAPH 2002]

Weighted-least-squares (WLS) filter

- Stronger smoothing and still distinct edges



- Can produce stronger effects with fewer artifacts
- See image processing lecture

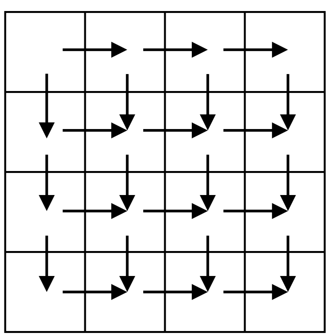
Tone mapping result

[Farbman et al., SIGGRAPH 2008]

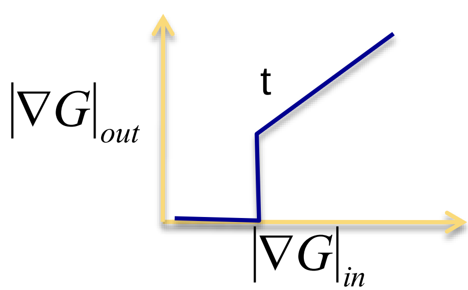
Retinex

- **Retinex algorithm was initially intended to separate reflectance from illumination [Land 1964]**
  - There are many variations of Retinex, but the general principle is to eliminate from an image small gradients, which are attributed to the illumination

1 step: compute gradients in log domain



2nd step: set to 0 gradients less than the threshold



3rd step: reconstruct an image from the vector field

$$\nabla^2 I = \operatorname{div} G$$

For example by solving the Poisson equation

Retinex examples

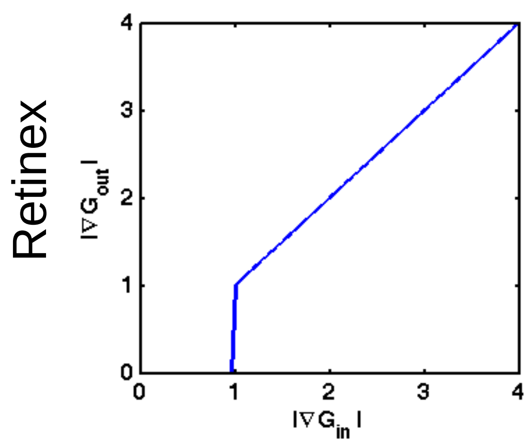
From: http://dragon.larc.nasa.gov/retinex/757/

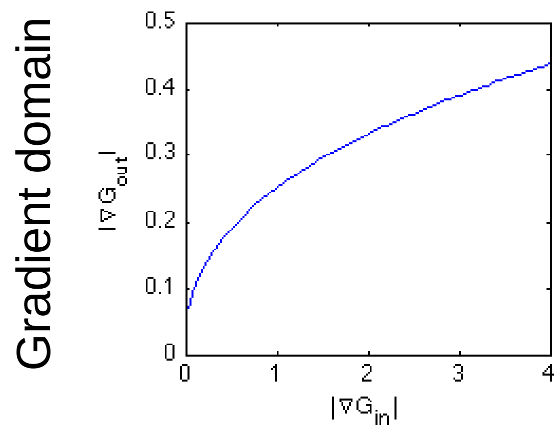
From:http://www.ipol.im/pub/algo/lmps_retinex_poisson_equation/#ref_1

Gradient domain HDR compression

[Fattal et al., SIGGRAPH 2002]

- Similarly to Retinex, it operates on log-gradients
- But the function amplifies small contrast instead of removing it





- Contrast compression achieved by global contrast reduction
  - Enhance reflectance, then compress everything

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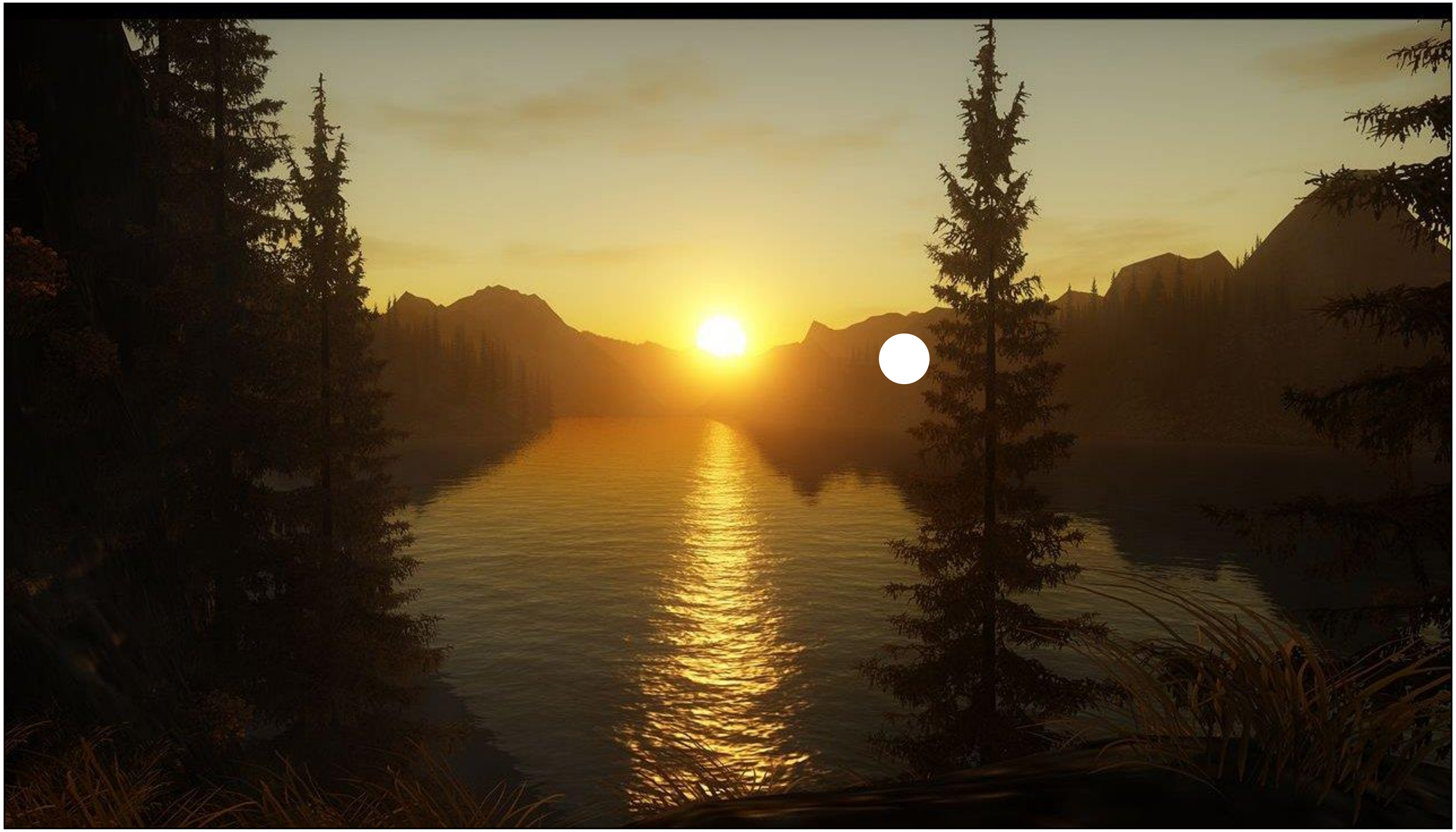
Glare



“Alan Wake” © Remedy Entertainment

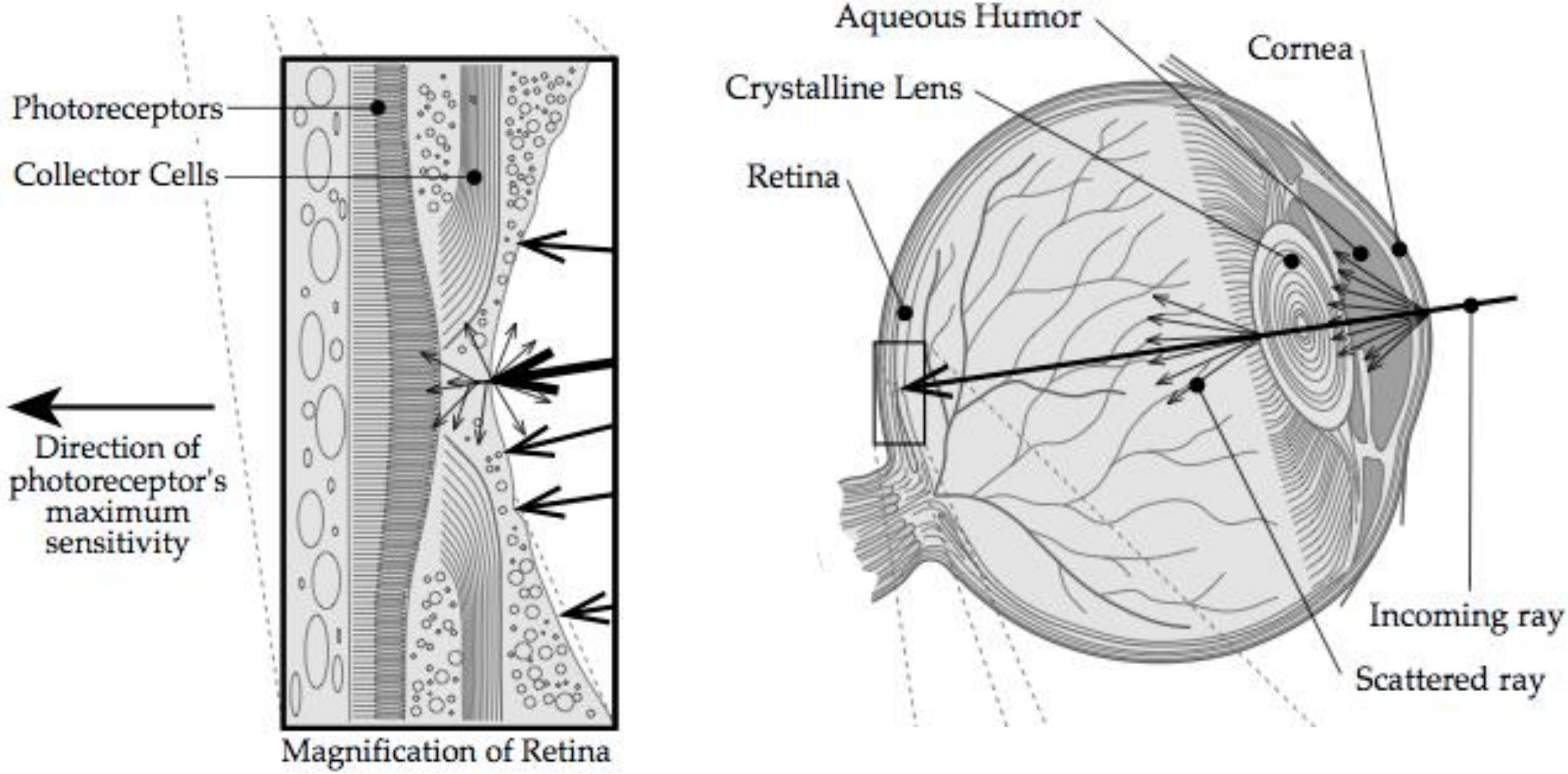
Glare Illusion

Photography

Painting

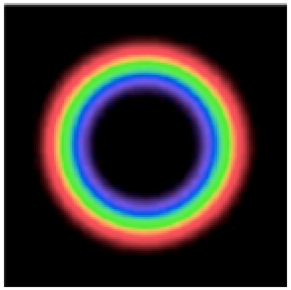
Computer Graphics
HDR rendering in games

Scattering of the light in the eye



From: Sekuler, R., and Blake, R. Perception, second ed. McGraw- Hill, New York, 1990

Ciliary corona and lenticular halo



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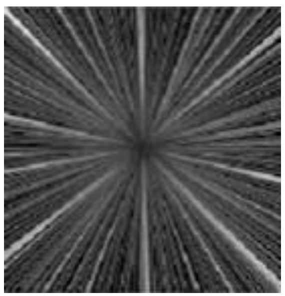

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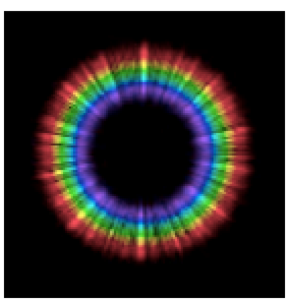

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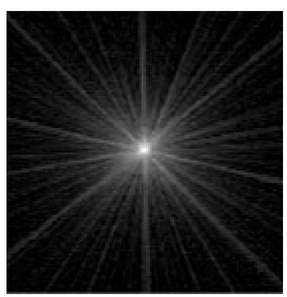

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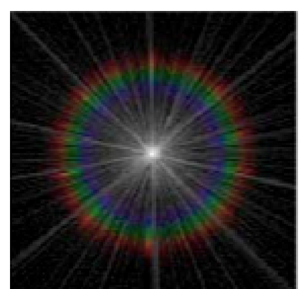
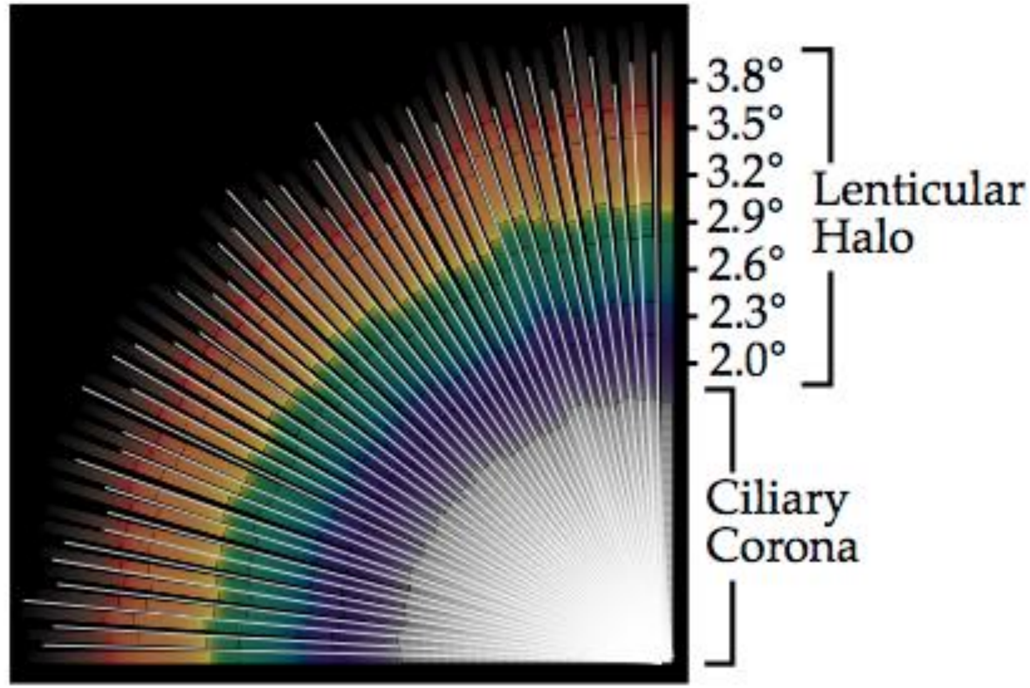
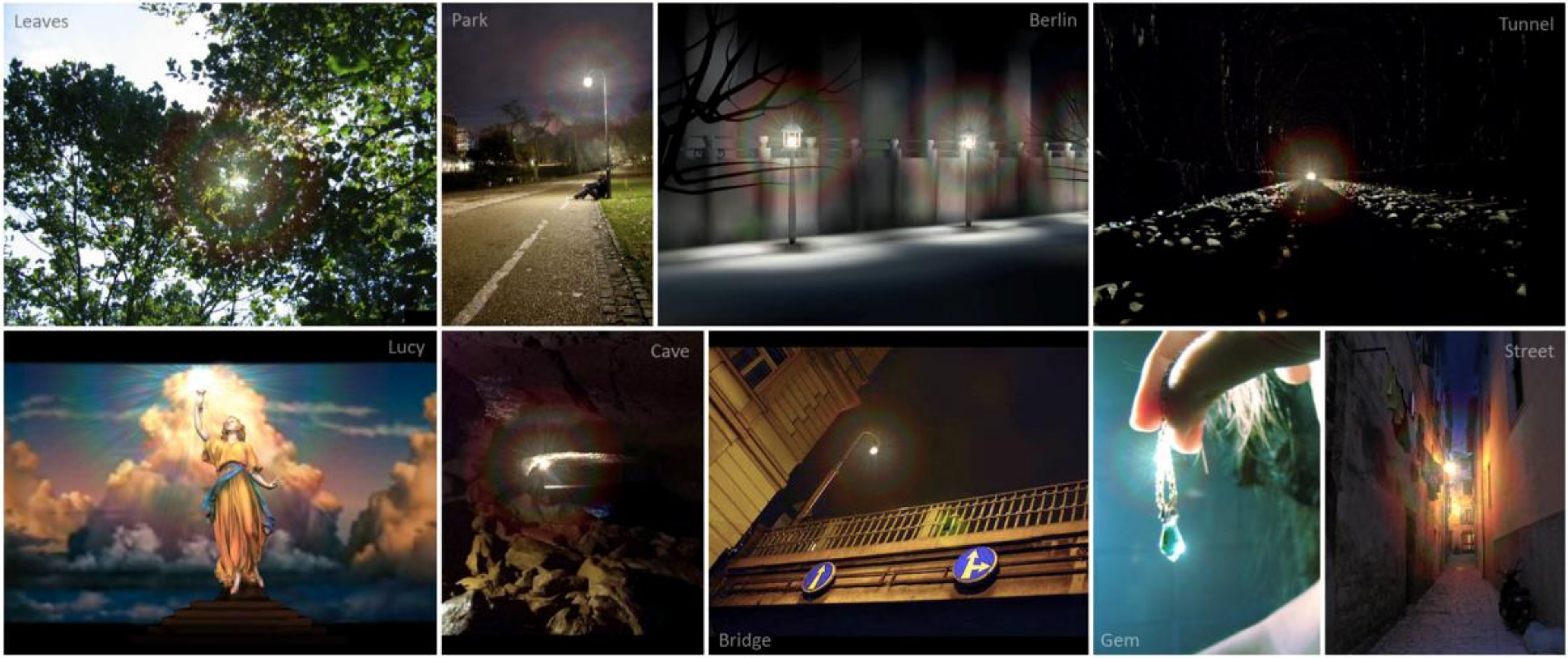




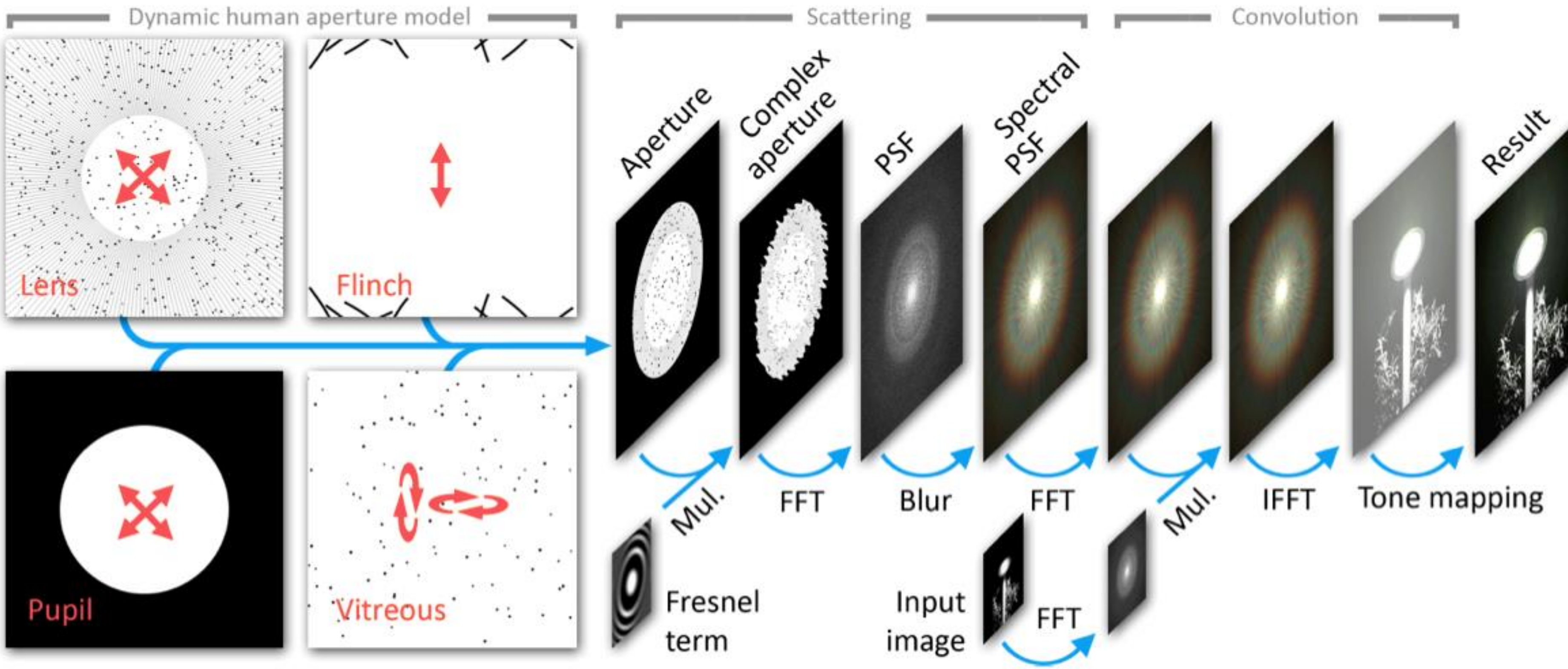
From: Spencer, G. et al. 1995. Proc. of SIGGRAPH. (1995)

Examples of simulated glare



[From Ritschel et al, Eurographics 2009]

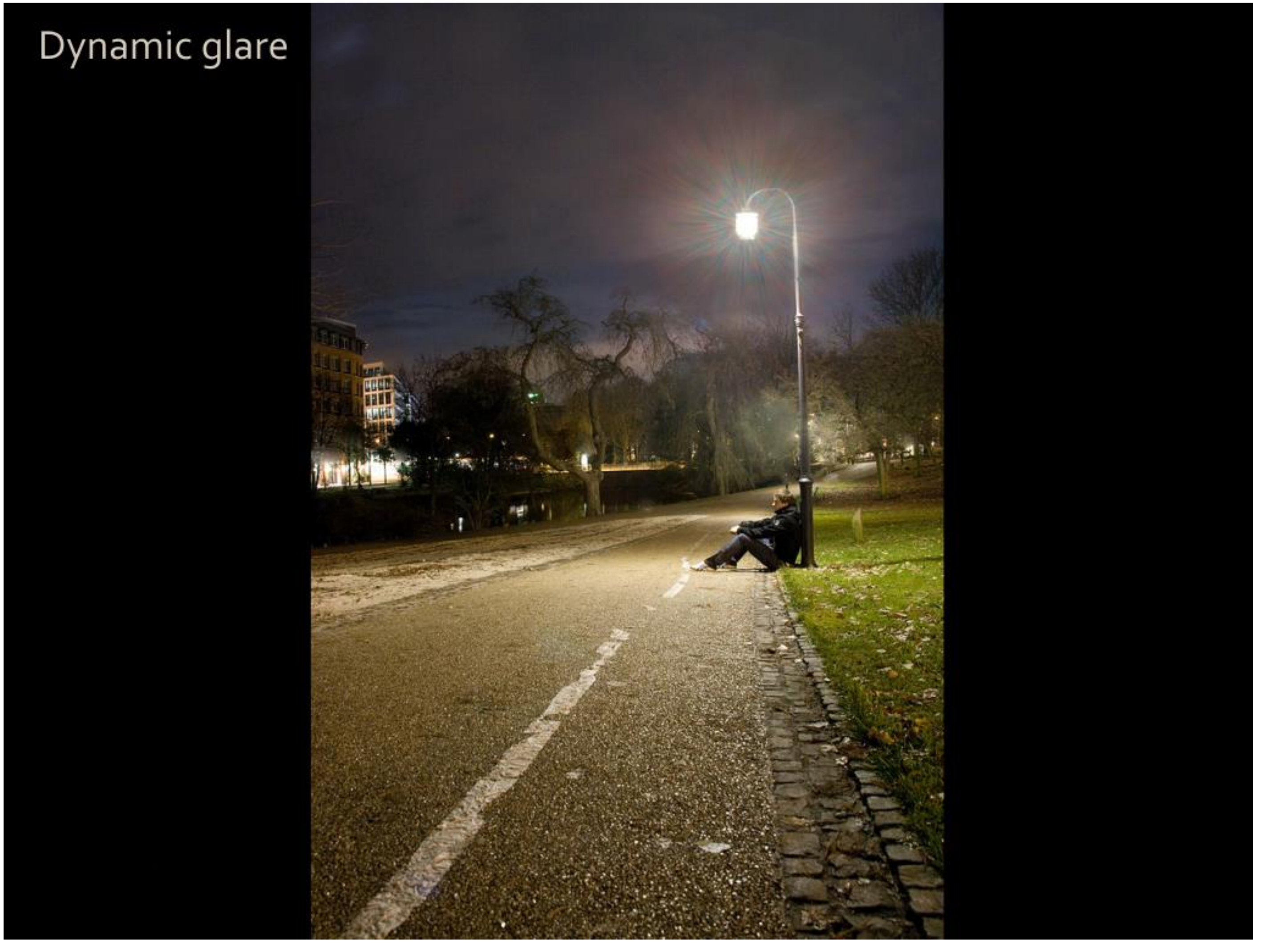
Temporal model of glare (low level)



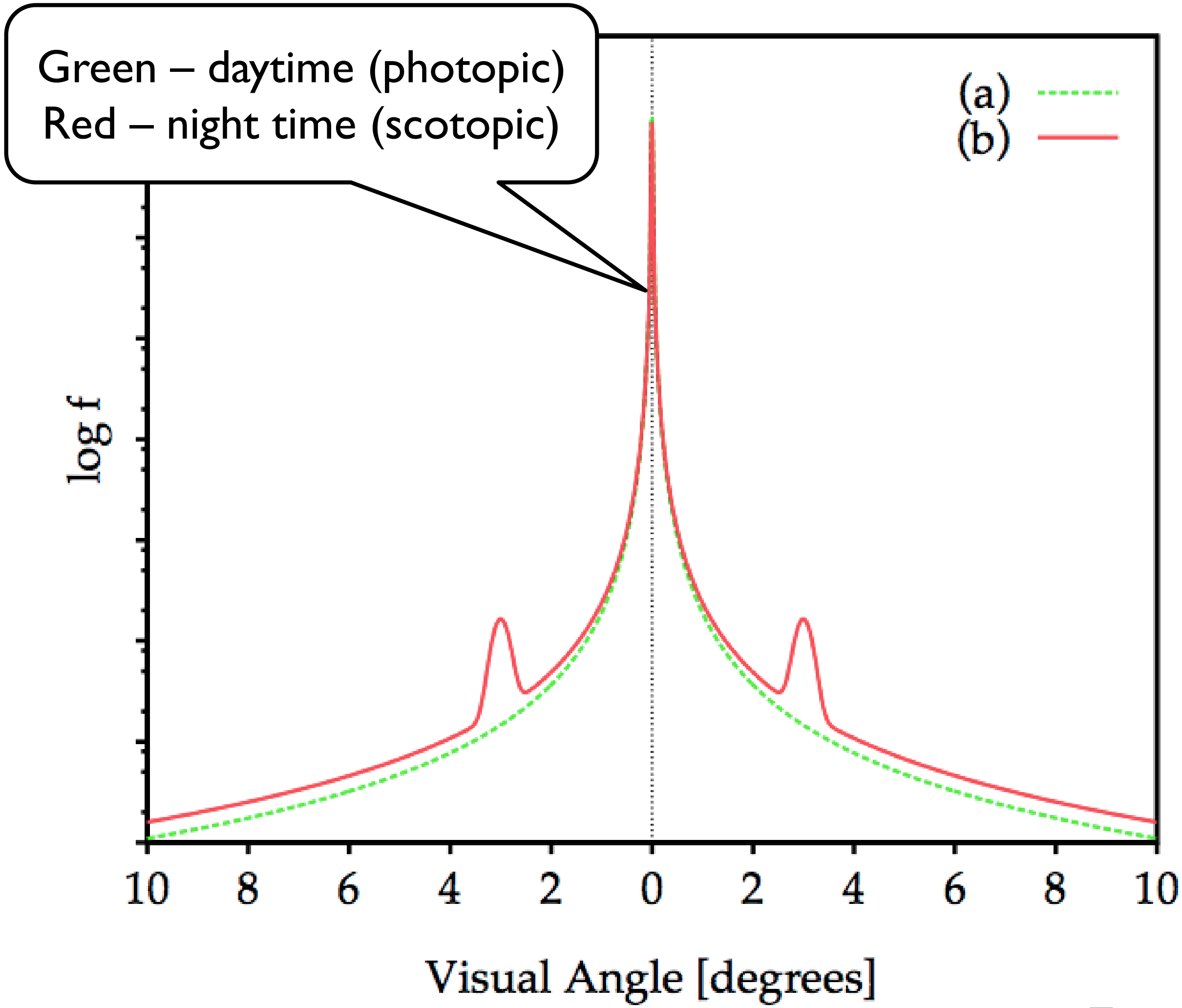
- The model assumes that glare is mostly caused by diffraction and scattering
- Can simulate temporal effects

[From Ritschel et al, Eurographics 2009]

Temporal glare



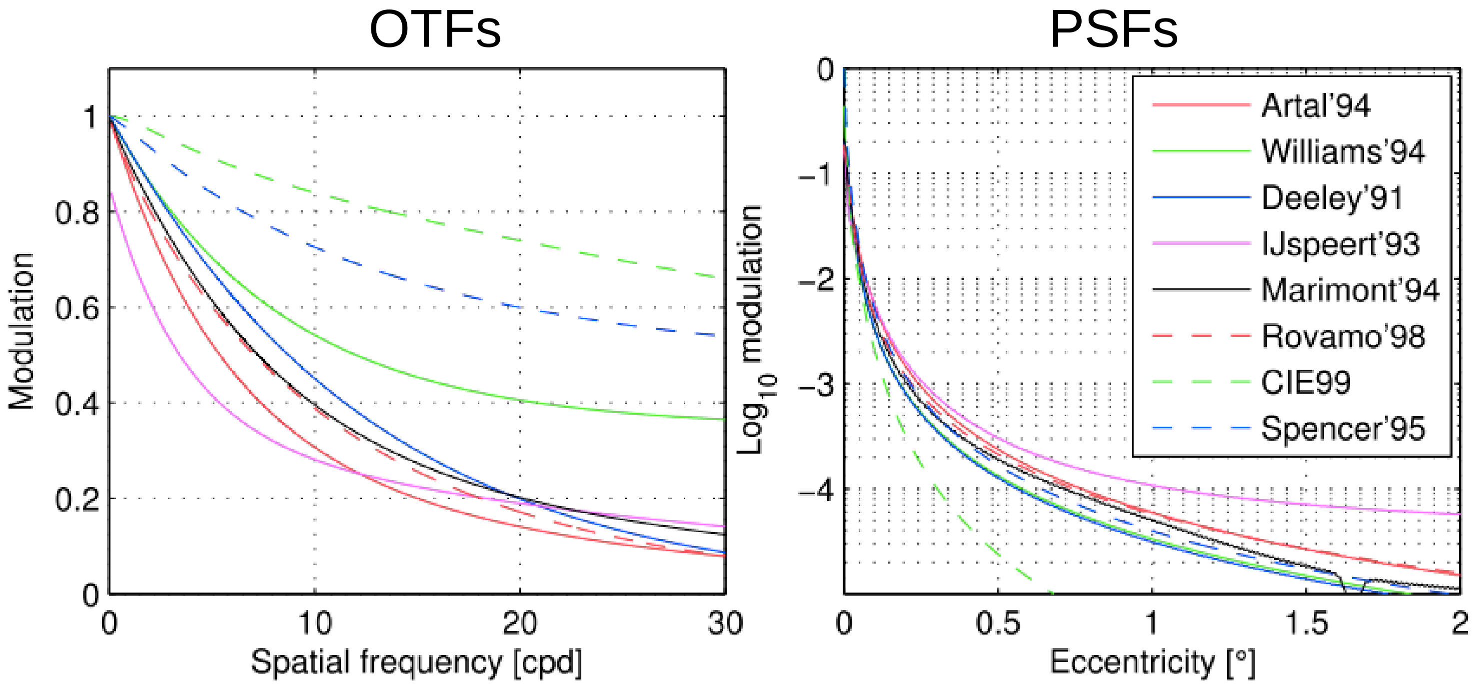
Point Spread Function of the eye



- What portion of the light is scattered towards a certain visual angle
- To simulate:
  - construct a digital filter
  - convolve the image with that filter

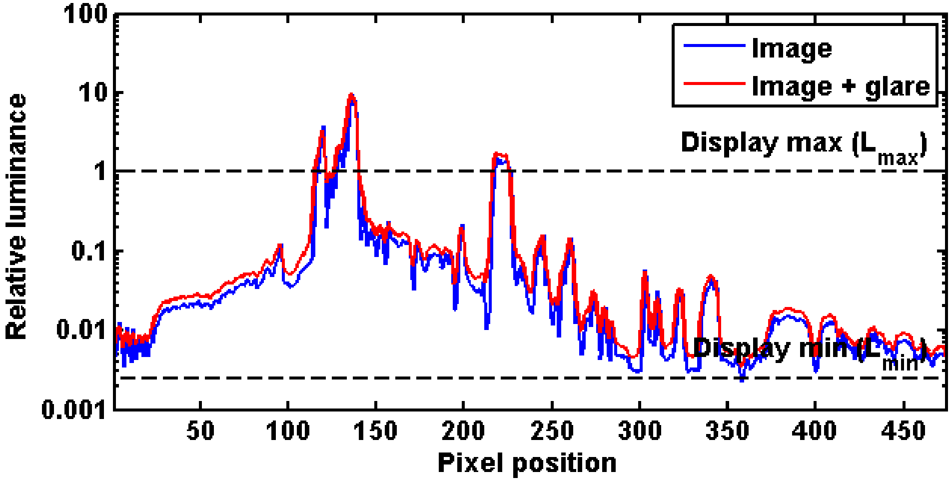
From: Spencer, G. et al. 1995. Proc. of SIGGRAPH. (1995)

PSF vs. OTF (Optical Transfer Function)



- An OTF is the Fourier transform of a PSF
- Convolution with larger kernels is faster in the Fourier domain

Selective application of glare

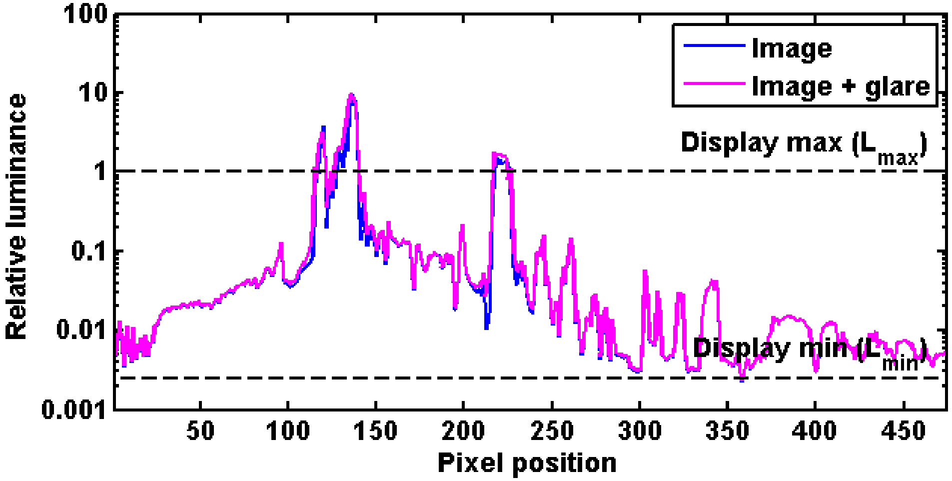


- A) Glare applied to the entire image

$$I_g = I * G$$

Glare kernel (PSF)

- Reduces image contrast and sharpness



B) Glare applied only to the clipped pixels

$$I_g = I + I_{cliped} * G - I_{cliped}$$

where $I_{cliped} = \begin{cases} I & for\ I > 1 \\ 0 & otherwise \end{cases}$

Better image quality

Selective application of glare

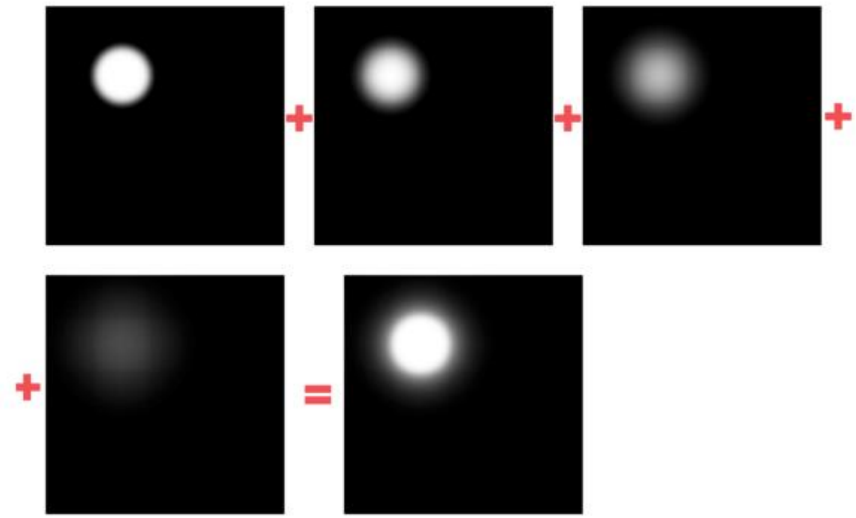
A) Glare applied to
the entire image

Original image

B) Glare applied to
clipped pixels only

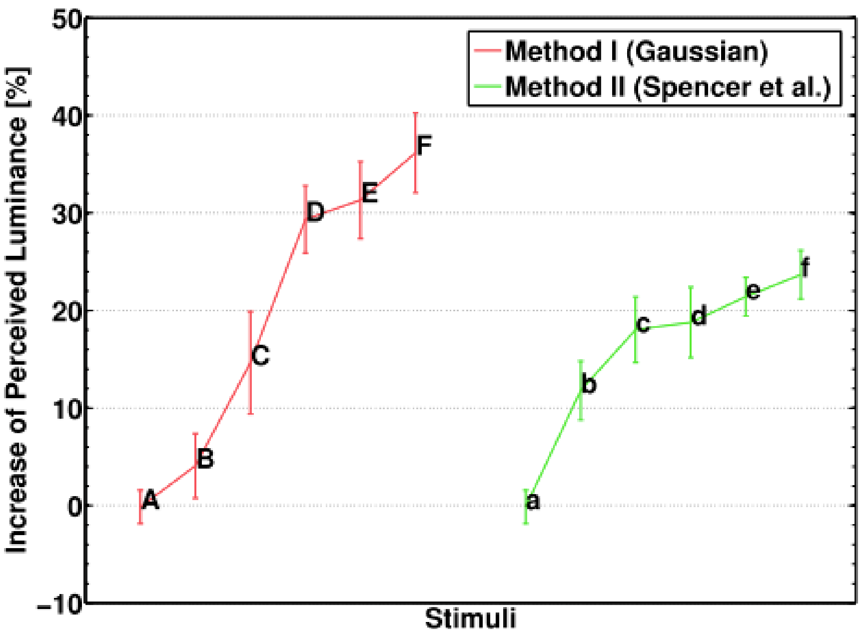
Glare (or bloom) in games

- Convolution with large, non-separable filters is too slow
- The effect is approximated by a combination of Gaussian filters
  - Each filter with different "sigma"
- The effect is meant to look good, not be be accurate model of light scattering
- Some games simulate camera rather than the eye



Does the exact shape of the PSF matter?

- The illusion of increased brightness works even if the PSF is very different from the PSF of the eye



red - Gaussian

green - accurate

[Yoshida et al., APGV 2008]

HDR rendering – motion blur

From LDR pixels From HDR pixels

Techniques

- Arithmetic of HDR images
- Display model
- Tone-curve
- Color transfer
- Base-detail separation
- Glare
- Simulation of night vision

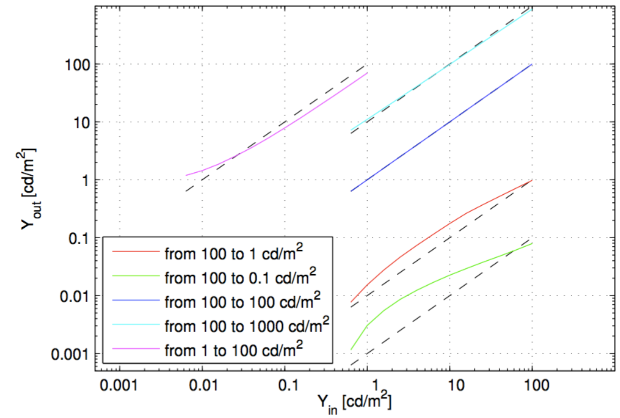
What changes at low illumination?

- Global contrast
  - Relative brightness
- Local contrast
  - Visibility of small details
- Color
  - Purkinje shift
  - Saturation

0.1 -> 100 cd/m^2

Brightness reduction – tone-curve

- Perceptualy-based night-vision tone-curve
  - [Wanat et al. 2014]
  - Requires rather complex optimization



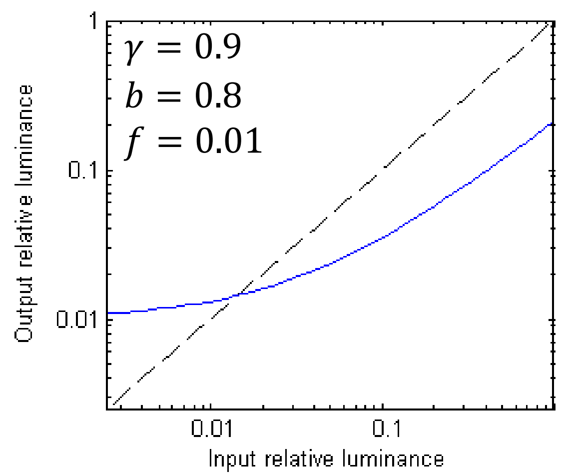
- Empirical approach (not perceptual)

Reduce brightness

Reduce contrast

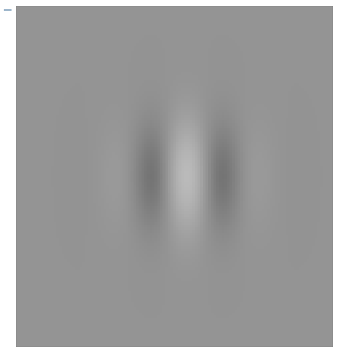
$$y_{out} = b \cdot y_{in}^{\gamma} + f$$

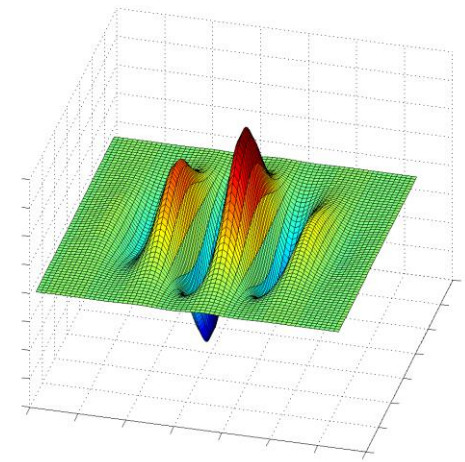
Add „fog"



Local contrast

- Gabor patch
  - basic contrast stimulus
  - the shape matches the response pattern of the receptive fields on the retina



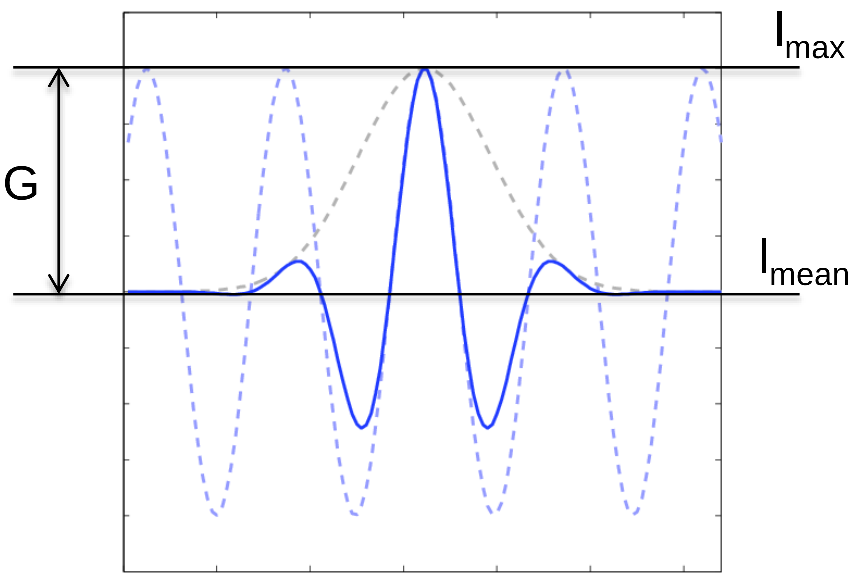


Contrast

$$G = l_{\max} - l_{mean}$$

Max log luminance

Mean log luminance



Supra-threshold contrast matching

- Kulikowski's model of matching contrast [Kulikowski 1976]
  - Contrast is perceived the same at different luminance levels when the physical contrast reduced by the corresponding detection threshold is equal at those luminance levels

Contrast at luminance A

Detection threshold at luminance A

$$G(L_A) - G_T(L_A) = G(L_B) - G_T(L_B)$$

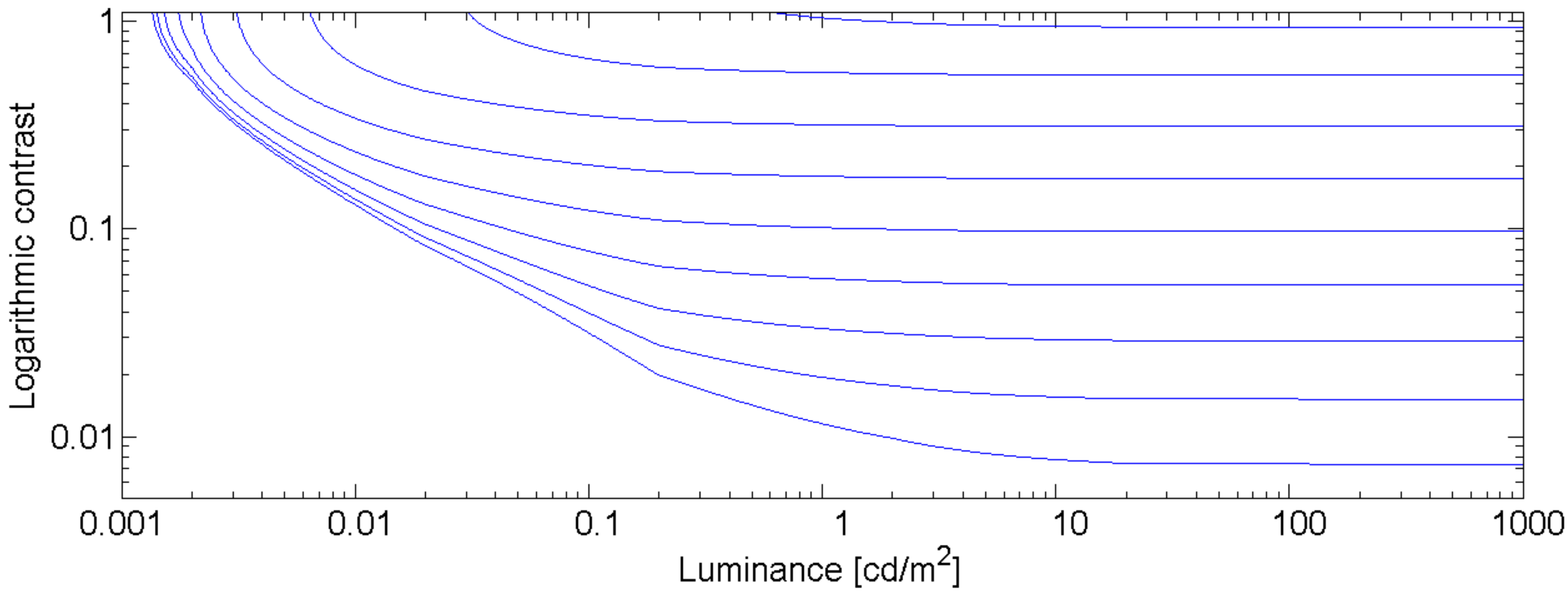
Contrast at luminance B

Detection threshold at luminance B

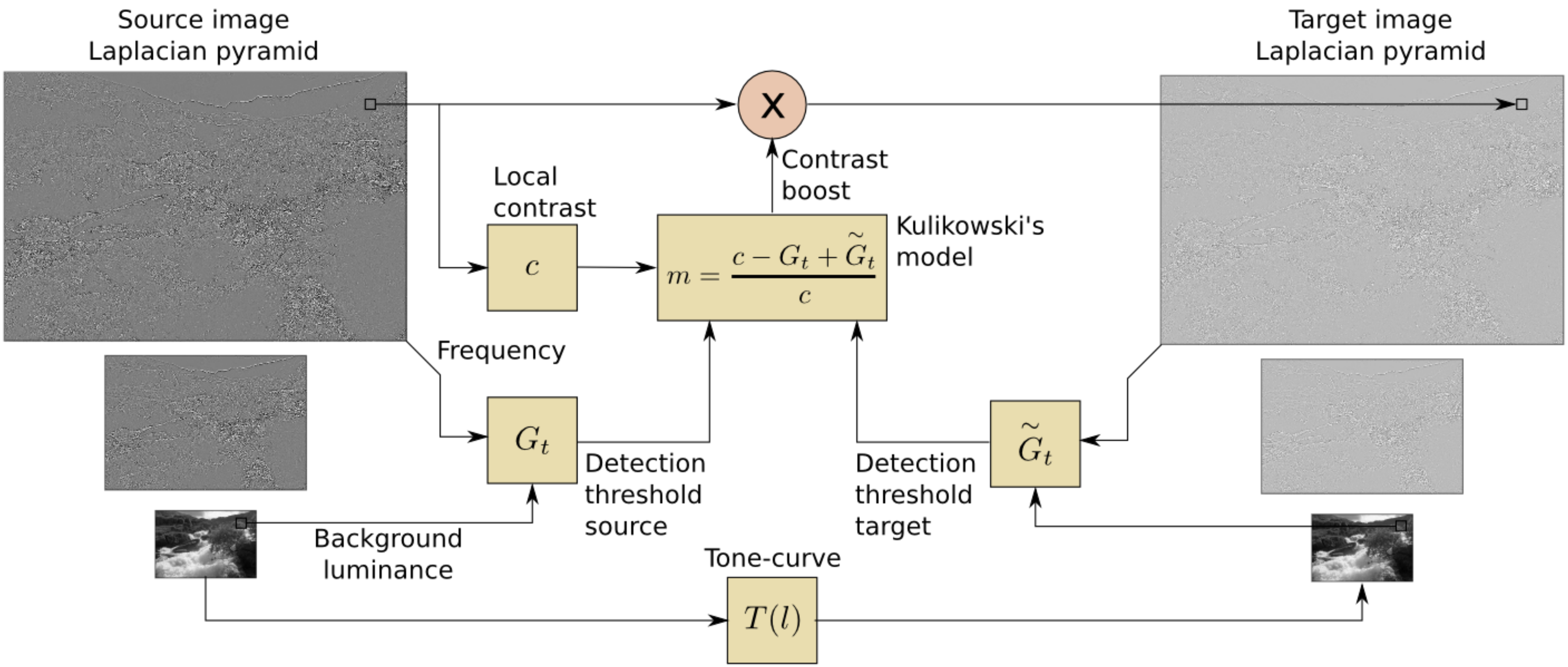
The detection thresholds can be predicted by the contrast sensitivity function

Supra-threshold contrast matching

- The lines connect contrast of the same perceived magnitude



Local contrast processing



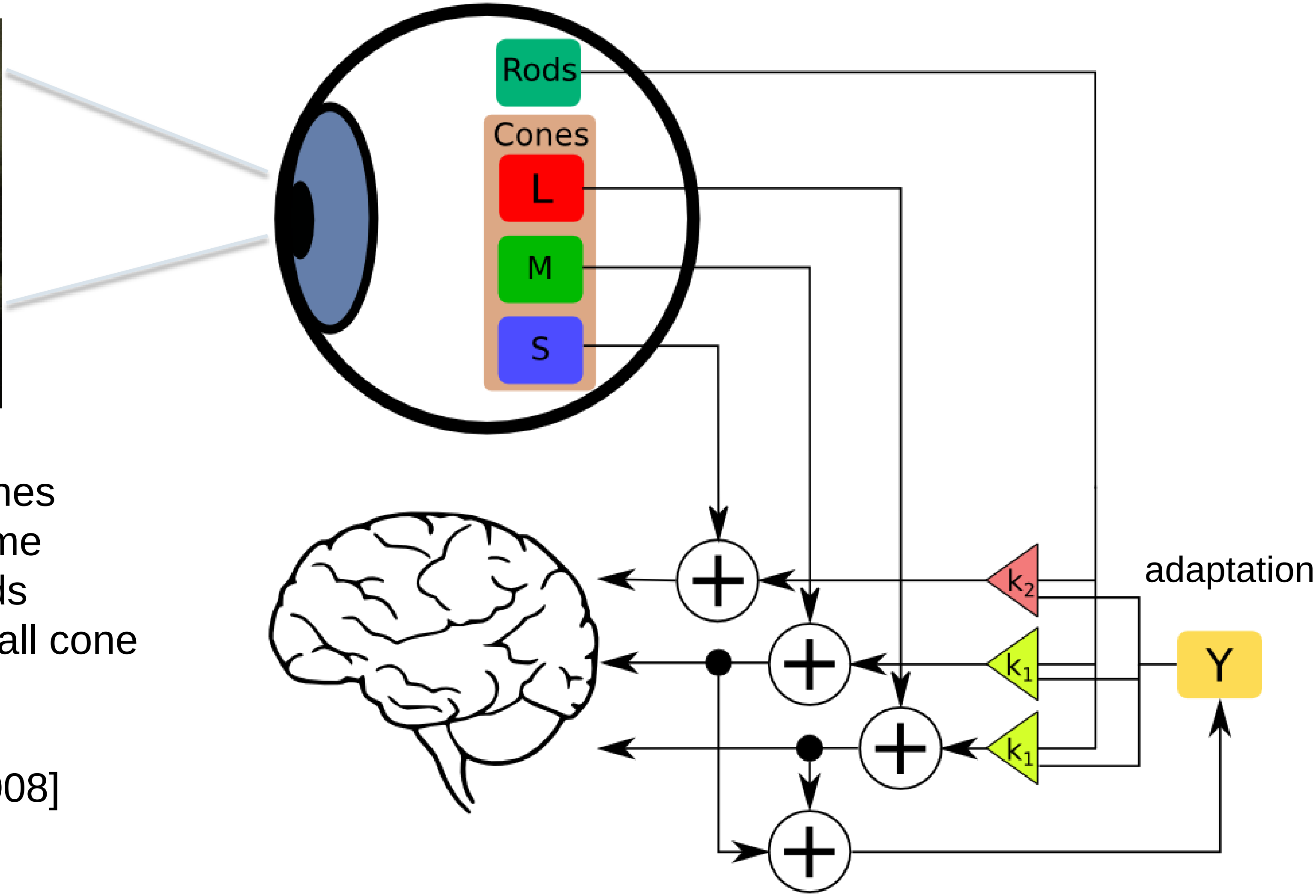
Example processing

Source

Simulation of night vision

Target

Rod contribution to colour vision

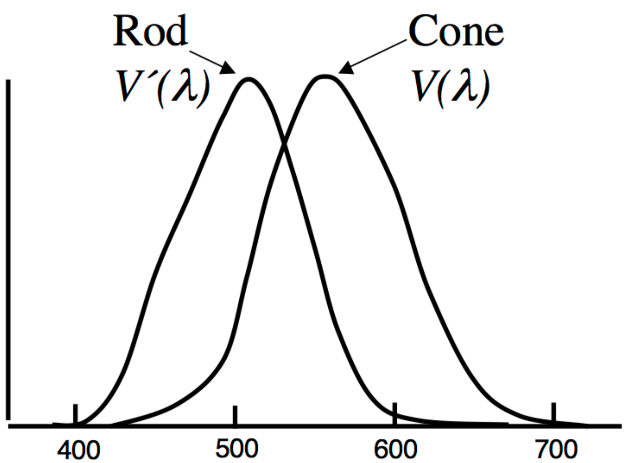


Rods and cones share the same pathway. Rods contribute to all cone responses.

[Cao et al. 2008]

Purkinje shift (effect)

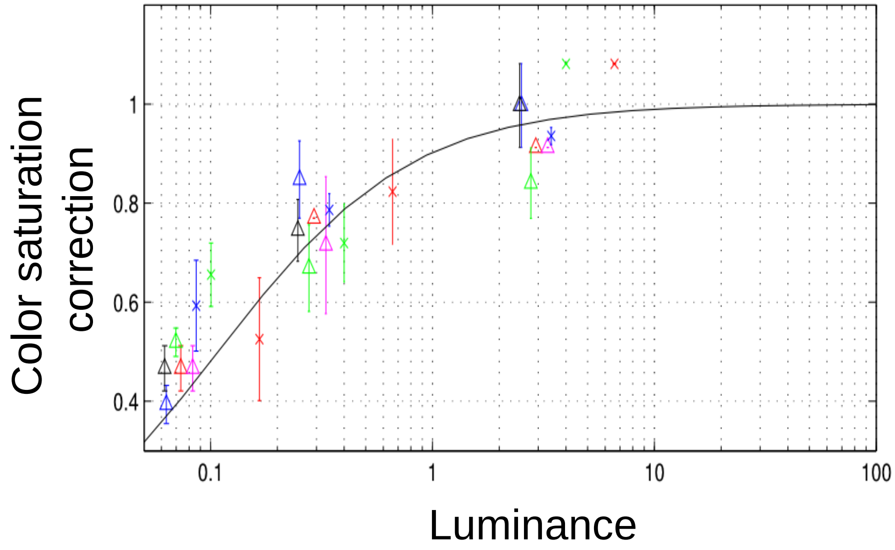
- A shift in spectral sensitivity associated with the transition of cone to rod vision
  - Blue appears brighter and red appears darker in twilight
  - And the reverse is observed in daylight
- The shift to bluish hues is sometimes attributed to the Purkinje effect
  - In practice the blue-shift is very subtle
  - Much more pronouced in movies



Perceptual Blue filter

Loss of colour saturation with luminance

- Cones become less sensitive at low light
- Colours become less saturated
- Empirical formula [Wanat 2014]



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