

Advanced Graphics and Image Processing

High dynamic range and tone mapping

Part 1/2 – context, the need for tone-mapping

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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:

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

- ▶ Usually written as C:I, for example 1000:1.
- As "orders of magnitude" or log 10 units:

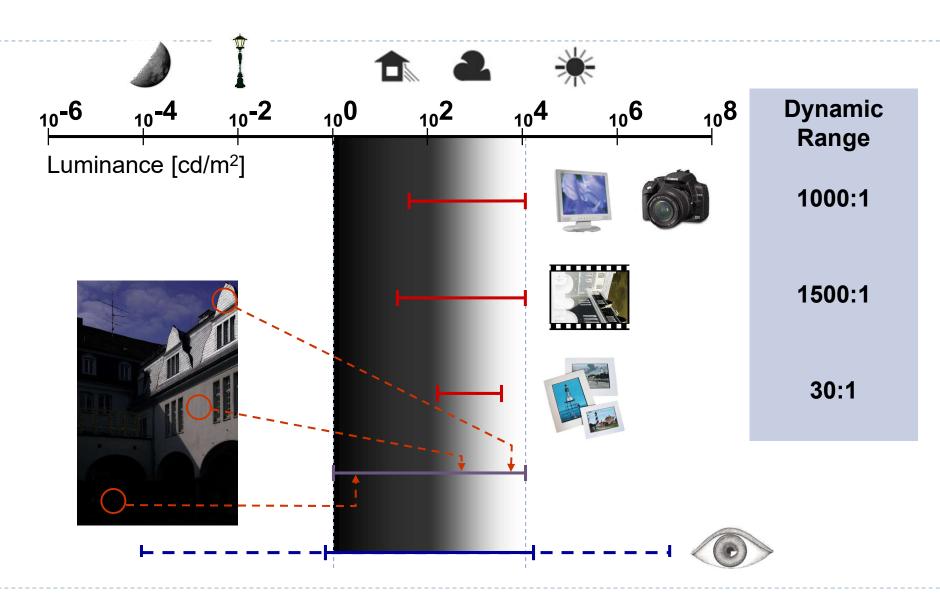
$$C_{10} = \log_{10} \frac{L_{\text{max}}}{L_{\text{min}}}$$

As stops:

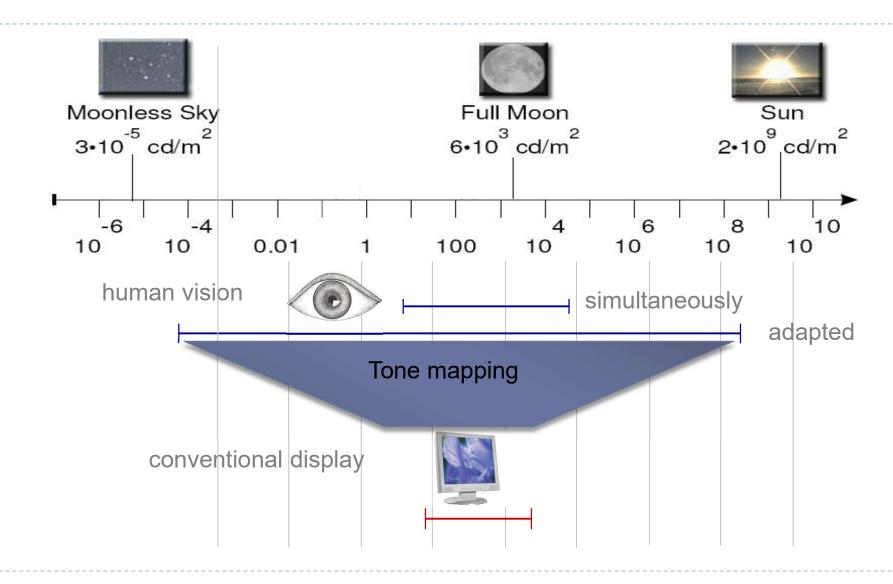
$$C_2 = \log_2 \frac{L_{\text{max}}}{L_{\text{min}}}$$

One stop is doubling of halving the amount of light

High dynamic range (HDR)



Tone-mapping problem



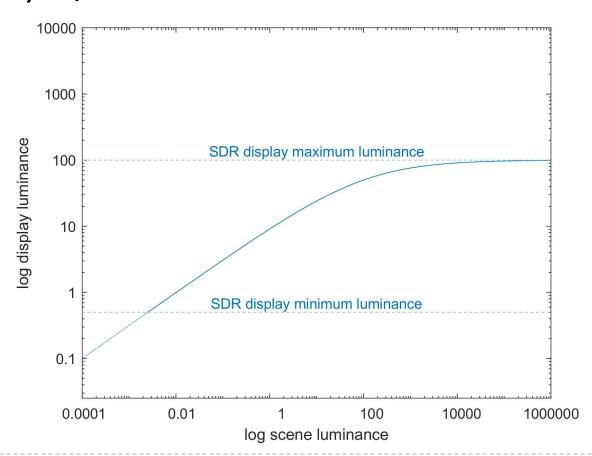
Why do we need tone mapping?

- To reduce 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
- To map from scene- to display-referred colours
- Different tone mapping operators achieve different goals



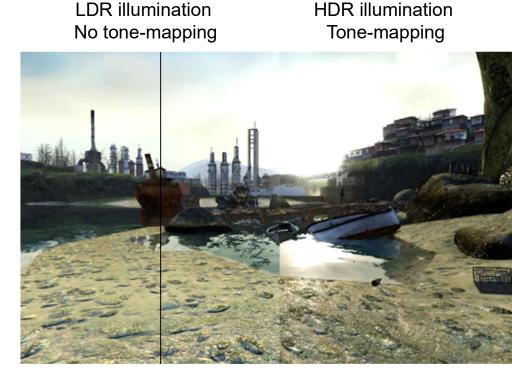
From scene- to display-referred colours

The primary purpose of tone mapping is to transform an image from scene-referred to display-referred colours

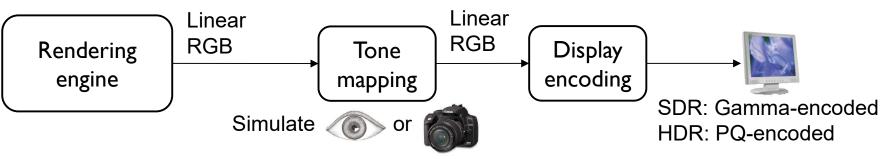


Tone-mapping in rendering

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



Half-Life 2: Lost coas



Basic tone-mapping and display coding

The simplest form of tone-mapping is the exposure/brightness adjustment:

Display-referred red value
$$R_d = \frac{R_S}{L_{white}} \qquad \begin{array}{c} \text{Scene-referred} \\ \text{Scene-referred} \\ \text{Iuminance of white} \end{array}$$

- No contrast compression, only for a moderate dynamic range
- The simplest form of display coding is the "gamma"

Prime (') denotes a gamma-corrected value
$$R' = (R_d)^{\frac{1}{\gamma}}$$
 Typically γ =2.2

For SDR displays only



Advanced Graphics and Image Processing

High dynamic range and tone mapping Part 2/2 – tone mapping techniques

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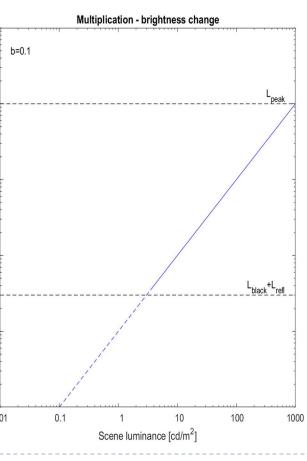
Techniques

- Arithmetic of HDR images
- Display model
- Tone-curve
- Colour transfer
- Base-detail separation
- Glare

Arithmetic of HDR images

- How do 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 only to luminance and the colour can be transferred

Multiplication – brightness change





Resulting luminance $T(L_p) = b \cdot L_p$ Brightness change parameter

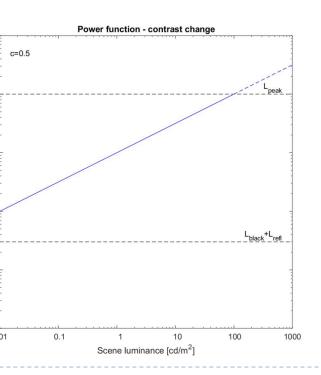
- Multiplication makes the image brighter or darker
- It does not change the dynamic range!

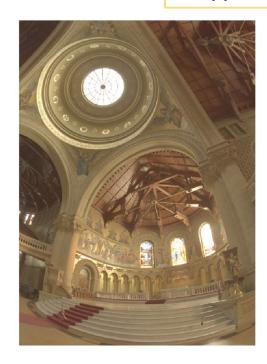
Power function – contrast change

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

Contrast change (gamma)

Luminance to be mapped to white

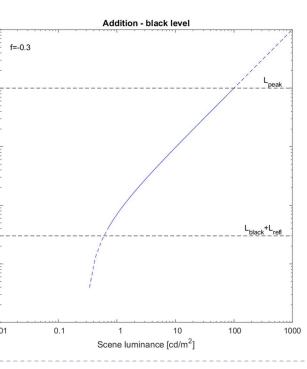


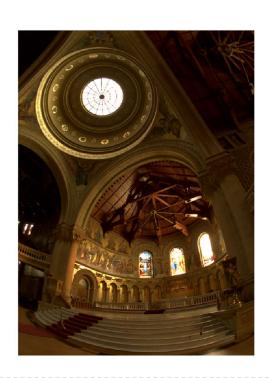


- Power function stretches or shrinks the dynamic range of an image
- It is usually performed relative to a reference white colour (and luminance)
- Side effect: brightness of the dark image part will change
- Slope on a log-log plot explains contrast change

Addition – black level

$$T(L_p) = L_p + f$$
 Black level (flare, fog)





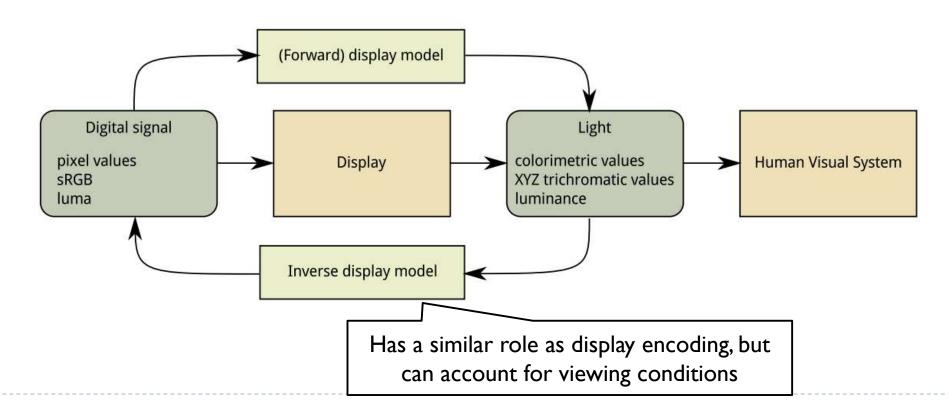
- Addition elevates black level, adds "fog" to an image
- It affects mostly darker tones
- It reduces image dynamic range
- Subtraction can compensate for ambient light

Techniques

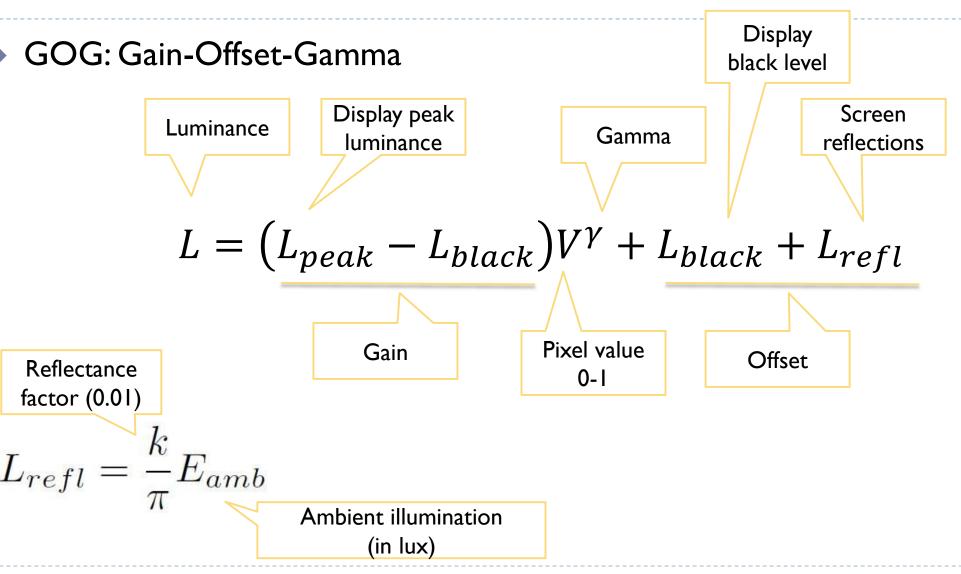
- Arithmetic of HDR images
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Display-adaptive tone mapping

- Tone-mapping can account for the physical model of a display
 - ▶ How a display transforms pixel values into emitted light
 - Useful for ambient light compensation



(Forward) Display model (SDR)



Inverse display model

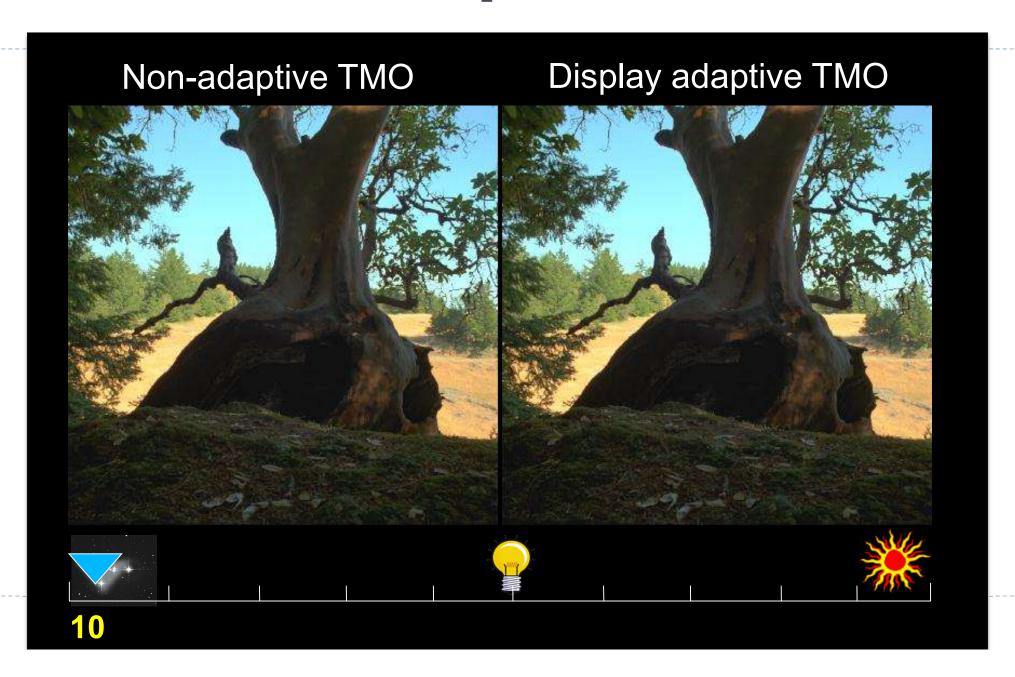
Symbols are the same as for the forward display model

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

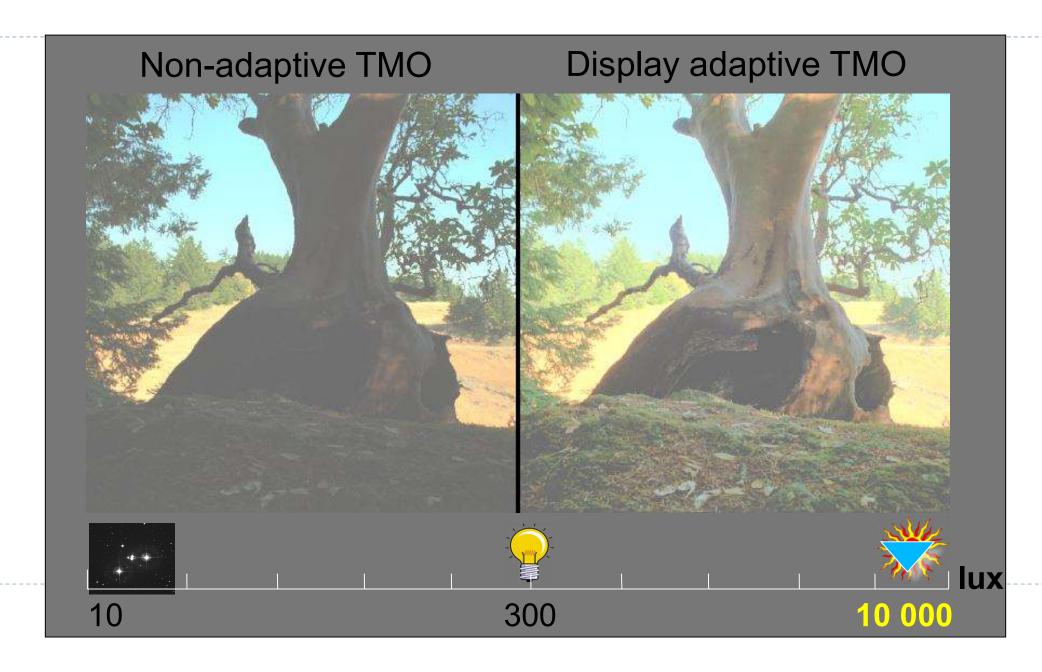
Note: This display model does not address any colour issues. The same equation is applied to red, green and blue color channels. The assumption is that the display primaries are the same as for the sRGB color space.

21

Ambient illumination compensation



Ambient illumination compensation



Example: Ambient light compensation

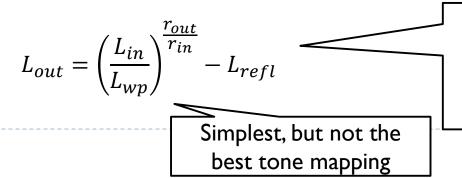
We are looking at the screen in bright light

$$L_{peak} = 100 \ [cd \cdot m^{-2}]$$
 $k = 0.005$ Modern screens have reflectivity of around 0.5% $E_{amb} = 2000 \ [lux]$ $L_{refl} = \frac{0.005}{\pi} 2000 = 3.183 \ [cd \cdot m^{-2}]$

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

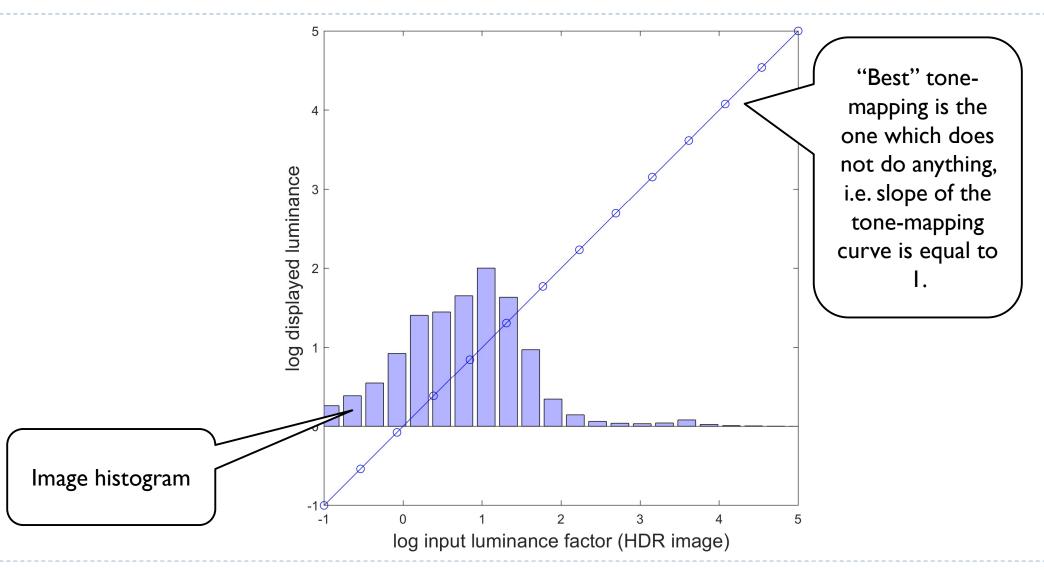


The resulting value is in luminance, must be mapped to display luma / gamma corrected values (display encoded)

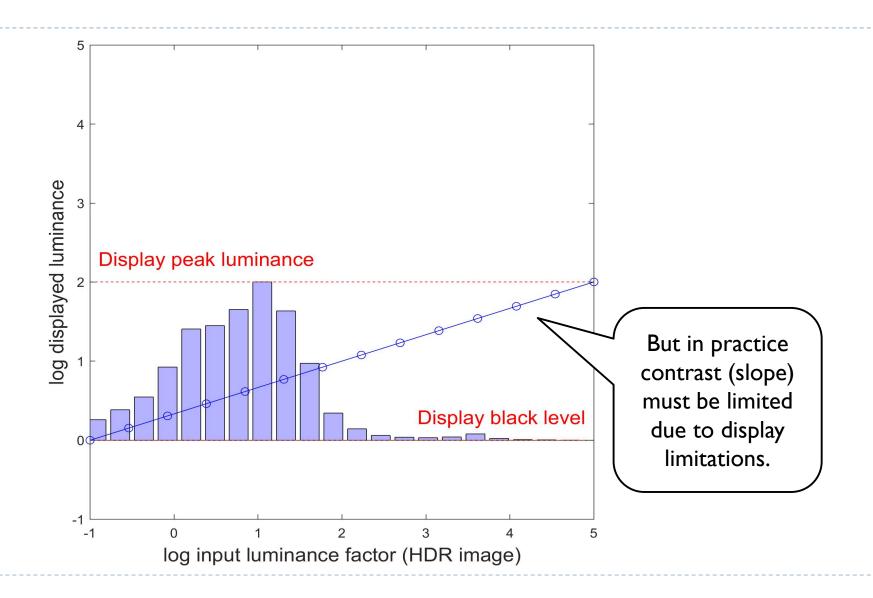
Techniques

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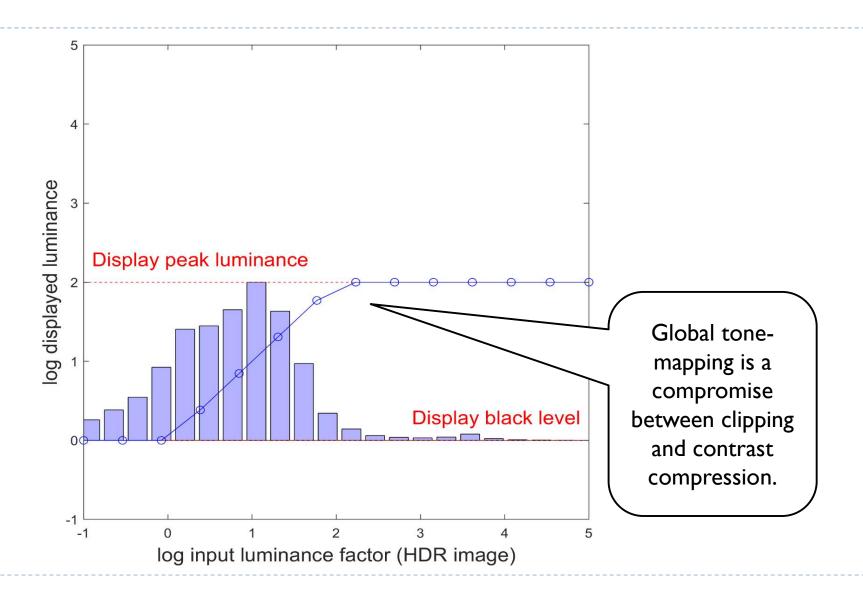
Tone-curve



Tone-curve

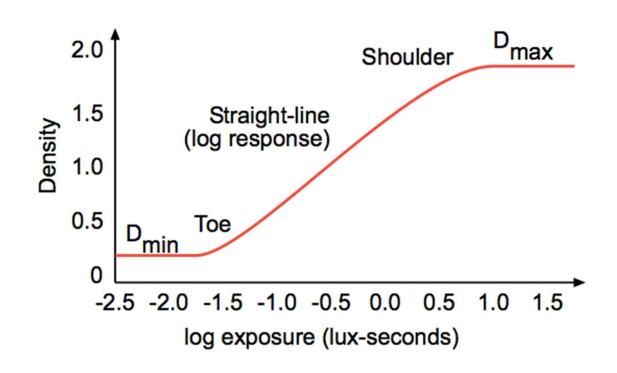


Tone-curve



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-reproduction
- Fast to compute



Sigmoidal tone mapping

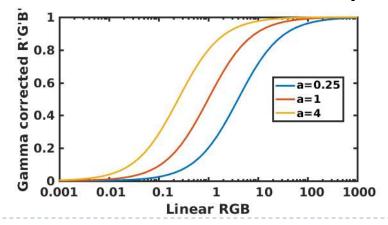
Simple formula for a sigmoidal tone-curve:

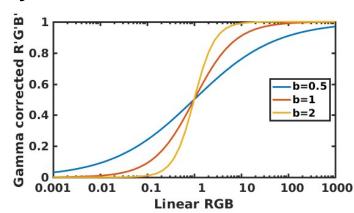
$$R'(x,y) = \frac{R^b(x,y)}{\left(\frac{L_m}{a}\right)^b + R^b(x,y)}$$

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

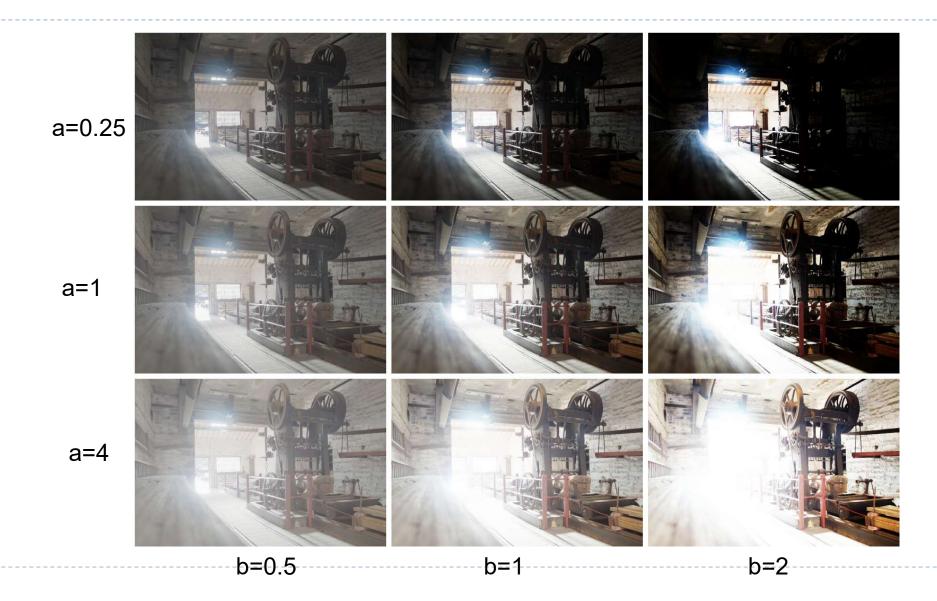
$$L_m = exp\left(\frac{1}{N}\sum_{(x,y)}\ln(L(x,y))\right)$$

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





Sigmoidal tone mapping example



31

Histogram equalization

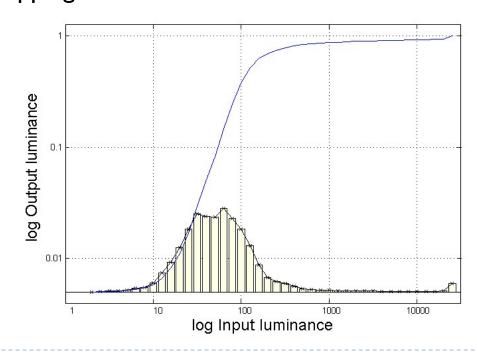
I. Compute normalized cummulative image histogram

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

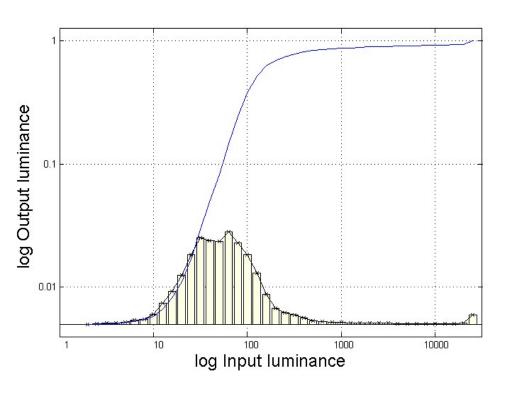
- ▶ For HDR, operate in the log domain
- 2. Use the cummulative histogram as a tone-mapping function

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

- 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

CLAHE: Contrast-Limited Adaptive Histogram Equalization

[Pizer et al. Adaptive histogram equalization and its variations. Comput Vision, Graph Image Process 1987], [Larson et al. 1997, IEEE TVCG]

Linear mapping



Histogram equalization

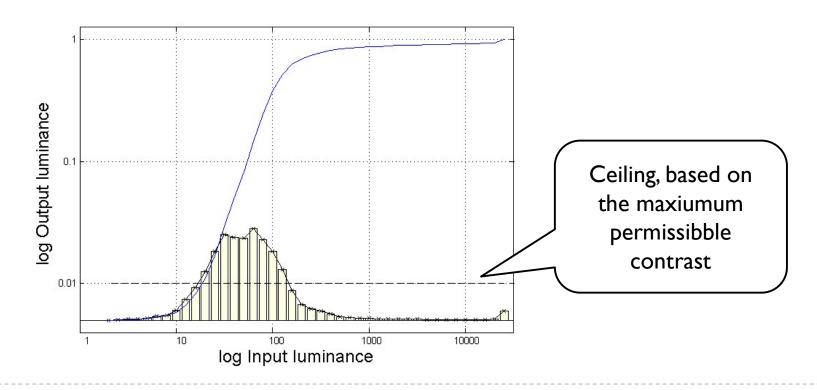


CLAHE



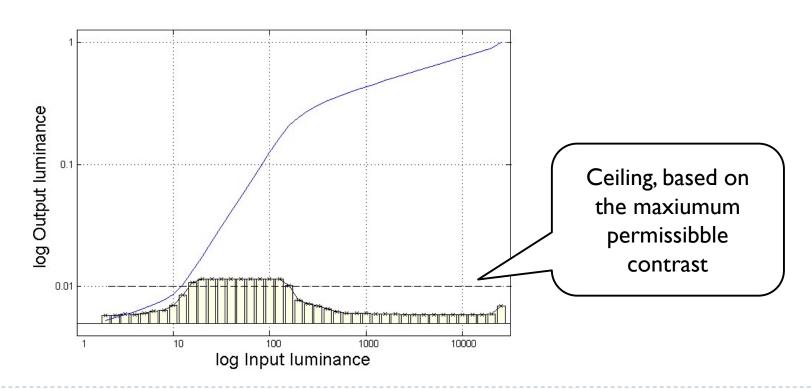
CLAHE: Contrast-Limited Adaptive Histogram Equalization

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



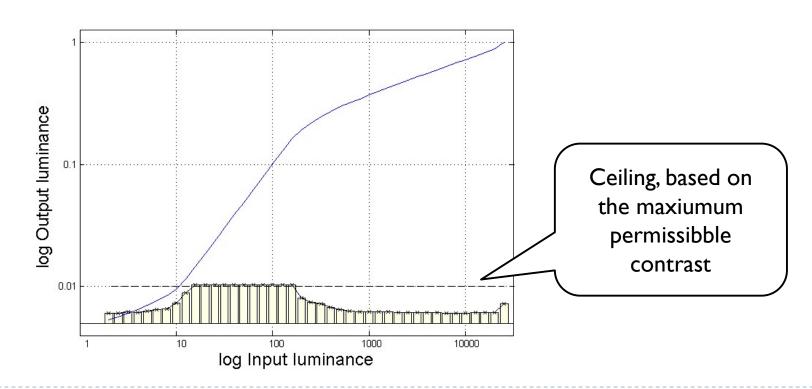
CLAHE: Contrast-Limited Adaptive Histogram Equalization

- Truncate the bins that exceed the ceiling;
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CLAHE: Contrast-Limited Adaptive Histogram Equalization

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



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Colour transfer in tone-mapping

- Many tone-mapping operators work on luminance, mean or maximum colour channel value
 - 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
$$Resulting luminance$$

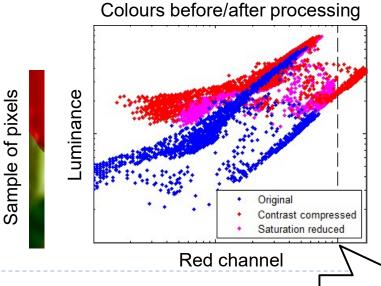
The same formula applies to green (G) and blue (B) linear colour values

Colour transfer: out-of-gamut problem

Colours often fall outside the colour gamut when contrast is compressed



Original image



Reduction in saturation is needed to bring the colors into gamut



Contrast reduced (s=1)

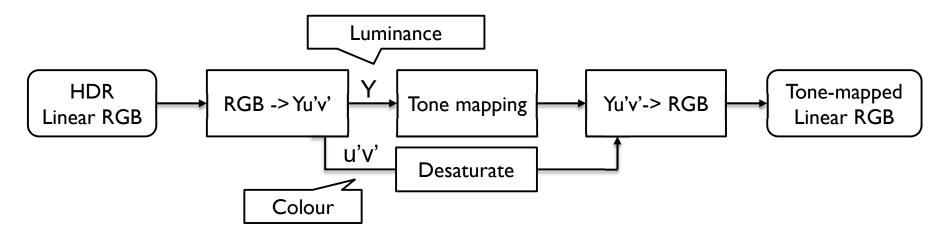


Saturation reduced (s=0.6)

Gamut boundary

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:

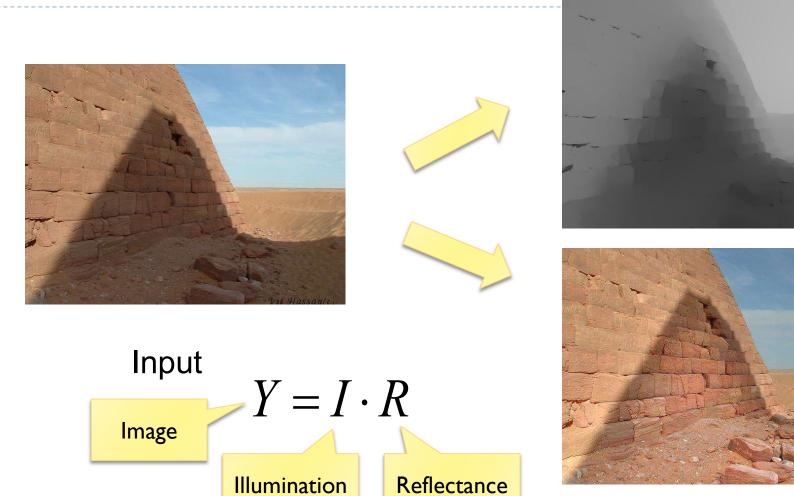
Chroma of the white

$$u'_{out} = (u'_{in} - u'_{w}) \cdot s + u'_{w}$$
 $u'_{w} = 0.1978$
 $v'_{out} = (v'_{in} - v'_{w}) \cdot s + v'_{w}$ $v'_{w} = 0.4683$

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llumination & reflectance separation







Reflectance

Illumination and reflectance

Reflectance

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

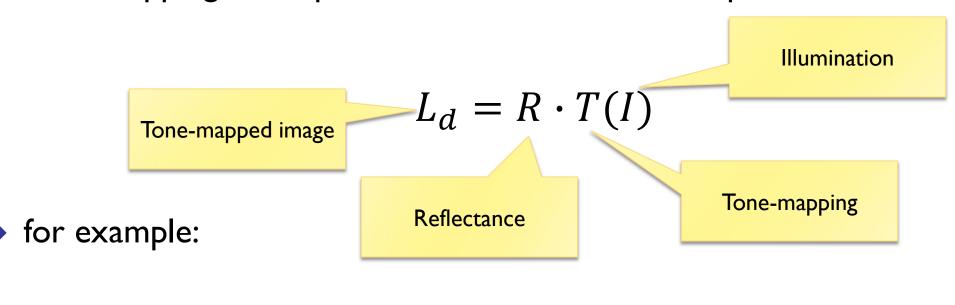
Illumination

- ► Sun $\approx 10^9$ cd/m²
- Lowest perceivable luminance ≈ 10⁻⁶ cd/m²
- Dynamic range 10,000:1 or more
- Visual system partially discounts illumination

[Tumblin et al. 1999]

Reflectance & Illumination TMO

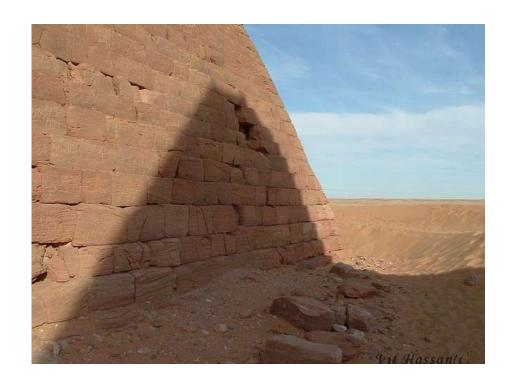
- Hypothesis: Distortions in reflectance are more apparent than the distortions in illumination
- Tone mapping could preserve reflectance but compress illumination



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

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

Weighted-least-squares (WLS) filter

Stronger smoothing and still distinct edges







Tone mapping result



Can produce stronger effects with fewer artifacts

See "Advanced image processing" lecture

[Farbman et al., SIGGRAPH 2008]

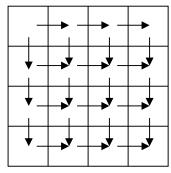
Retinex

Retinex algorithm was initially intended to separate reflectance from illumination [Land 1964]

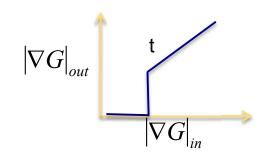


There are many variations of Retinex, but the general principle is to eliminate small gradients from an image. Small gradients are attributed to the illumination

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

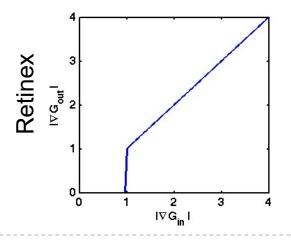




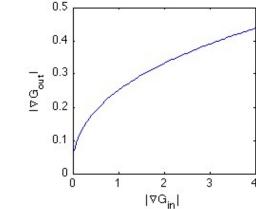


[Fattal et al., SIGGRAPH 2002]

- 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

Techniques

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Glare



"Alan Wake" © Remedy Entertainment

Glare Illusion



Photography



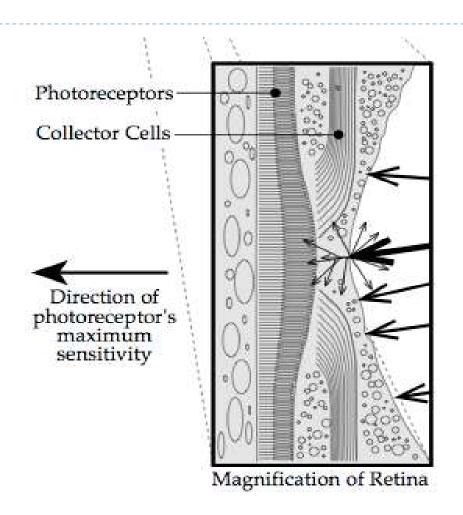
Painting

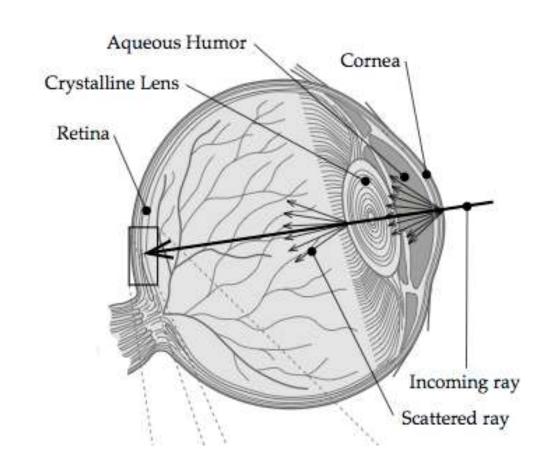


Computer Graphics
HDR rendering in games



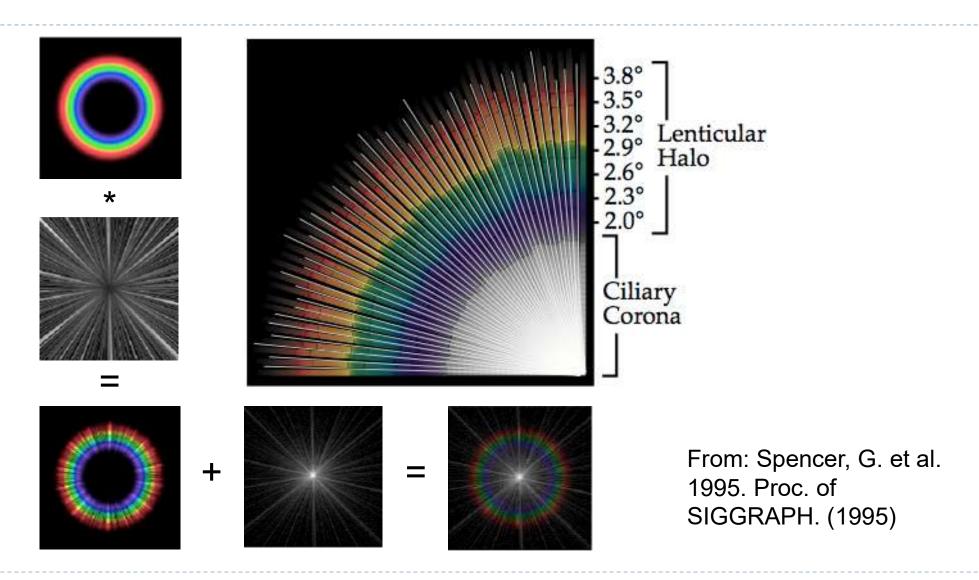
Scattering of the light in the eye



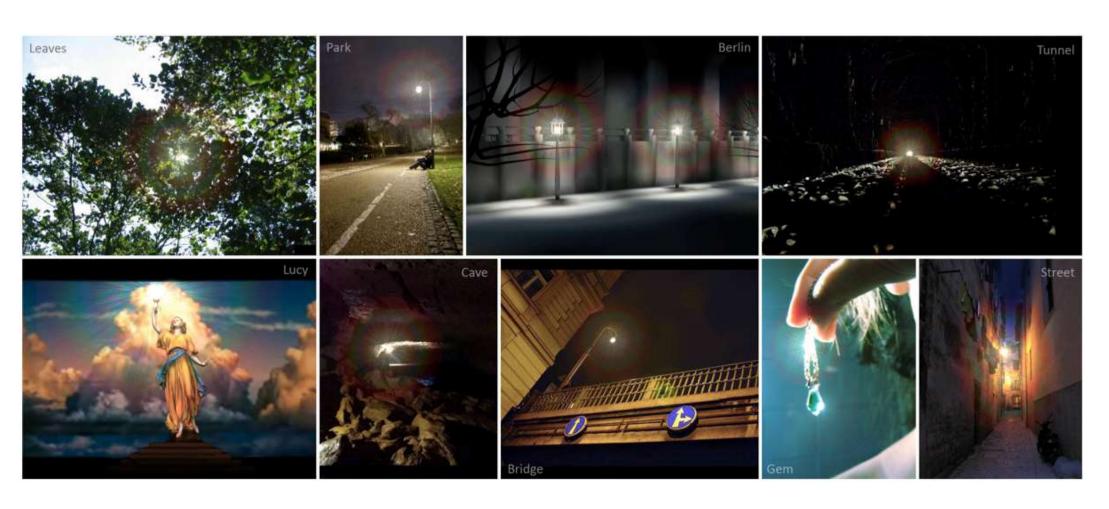


From: Sekuler, R., and Blake, R. Perception, second ed. McGraw- Hill, New York, 1990

Ciliary corona and lenticular halo

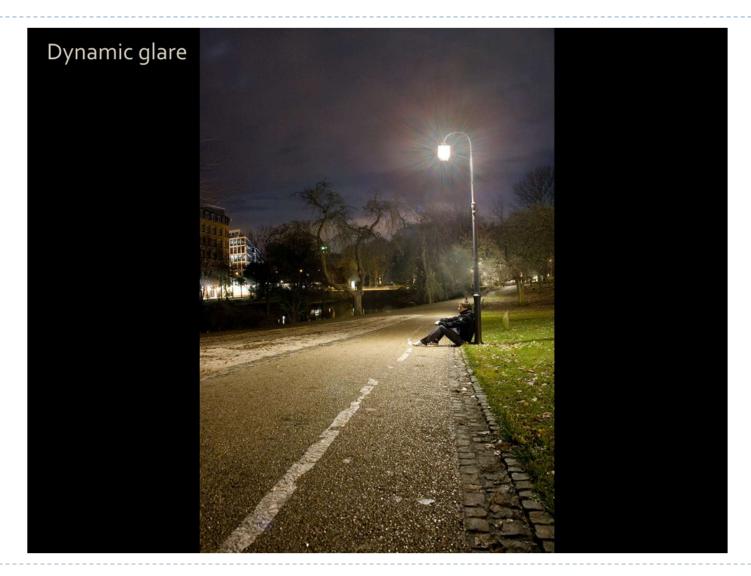


Examples of simulated glare

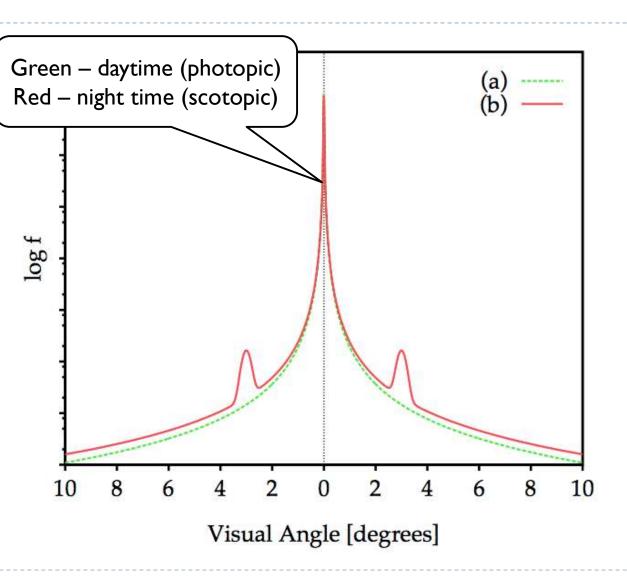


[From Ritschel et al, Eurographics 2009]

Temporal glare



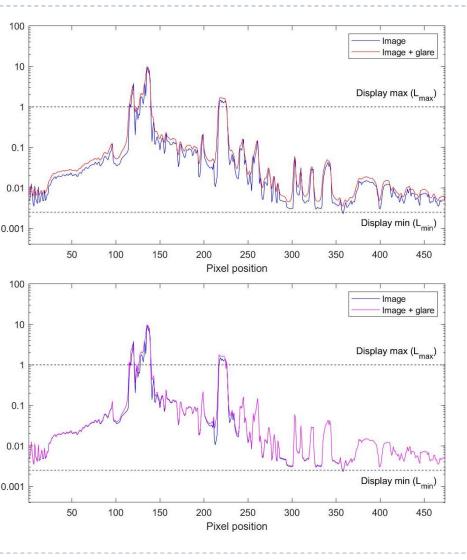
Point Spread Function of the eye



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

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

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



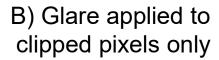
Original image

A) Glare applied to the entire image





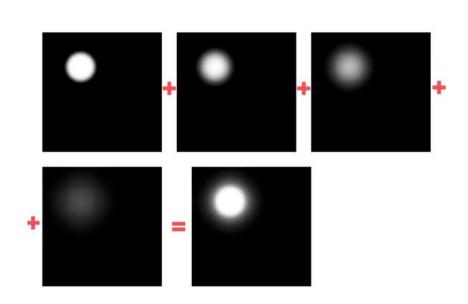






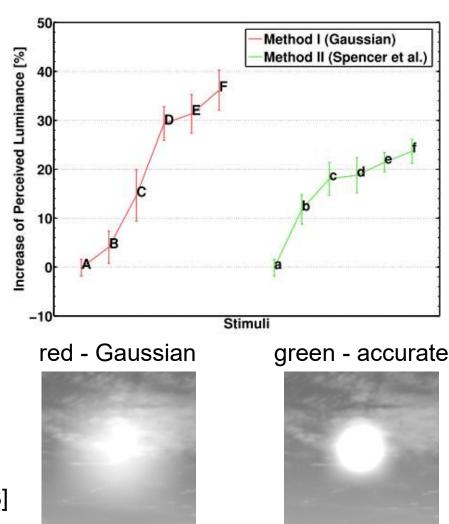
Glare (or bloom) in games

- 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



[Yoshida et al., APGV 2008]

HDR rendering – motion blur



From LDR pixels

From HDR pixels

References

Comprehensive book on HDR Imaging

E. Reinhard, W. Heidrich, P. Debevec, S. Pattanaik, G. Ward, and K. Myszkowski, High Dynamic Range Imaging: Acquisition, Display, and Image-Based Lighting, 2nd editio. Morgan Kaufmann, 2010.

Overview of HDR imaging & tone-mapping

http://www.cl.cam.ac.uk/~rkm38/hdri_book.html

Review of recent video tone-mapping

A comparative review of tone-mapping algorithms for high dynamic range video Gabriel Eilertsen, Rafal K. Mantiuk, Jonas Unger, Eurographics State-of-The-Art Report 2017.

Selected papers on tone-mapping:

- G.W. Larson, H. Rushmeier, and C. Piatko, "A visibility matching tone reproduction operator for high dynamic range scenes," *IEEE Trans. Vis. Comput. Graph.*, vol. 3, no. 4, pp. 291–306, 1997.
- R. Wanat and R. K. Mantiuk, "Simulating and compensating changes in appearance between day and night vision," ACM Trans. Graph. (Proc. SIGGRAPH), vol. 33, no. 4, p. 147, 2014.
- > Spencer, G. et al. 1995. Physically-Based Glare Effects for Digital Images. Proceedings of SIGGRAPH. (1995), 325–334
- Ritschel, T. et al. 2009. Temporal Glare: Real-Time Dynamic Simulation of the Scattering in the Human Eye. Computer Graphics Forum. 28, 2 (Apr. 2009), 183–192
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