Tone Mapping

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Outline

- What is tone-mapping?
- Arithmetic of HDR images
- The perception of HDR scenes
- Major approaches to tone-mapping
  - Illumination & reflectance separation
  - Forward visual model
  - Forward & inverse visual model
  - Constraint mapping problem

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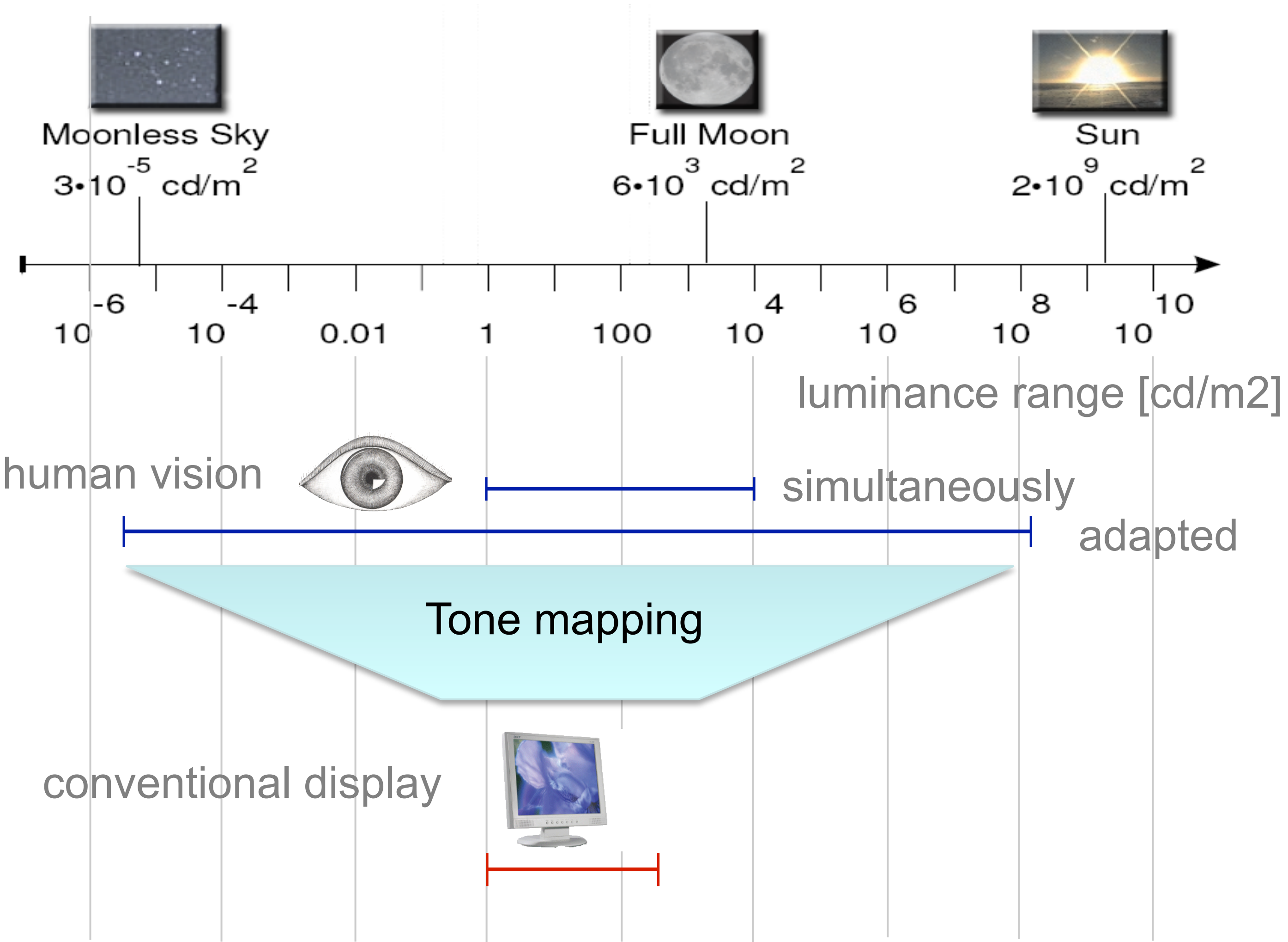
Tone-mapping problem



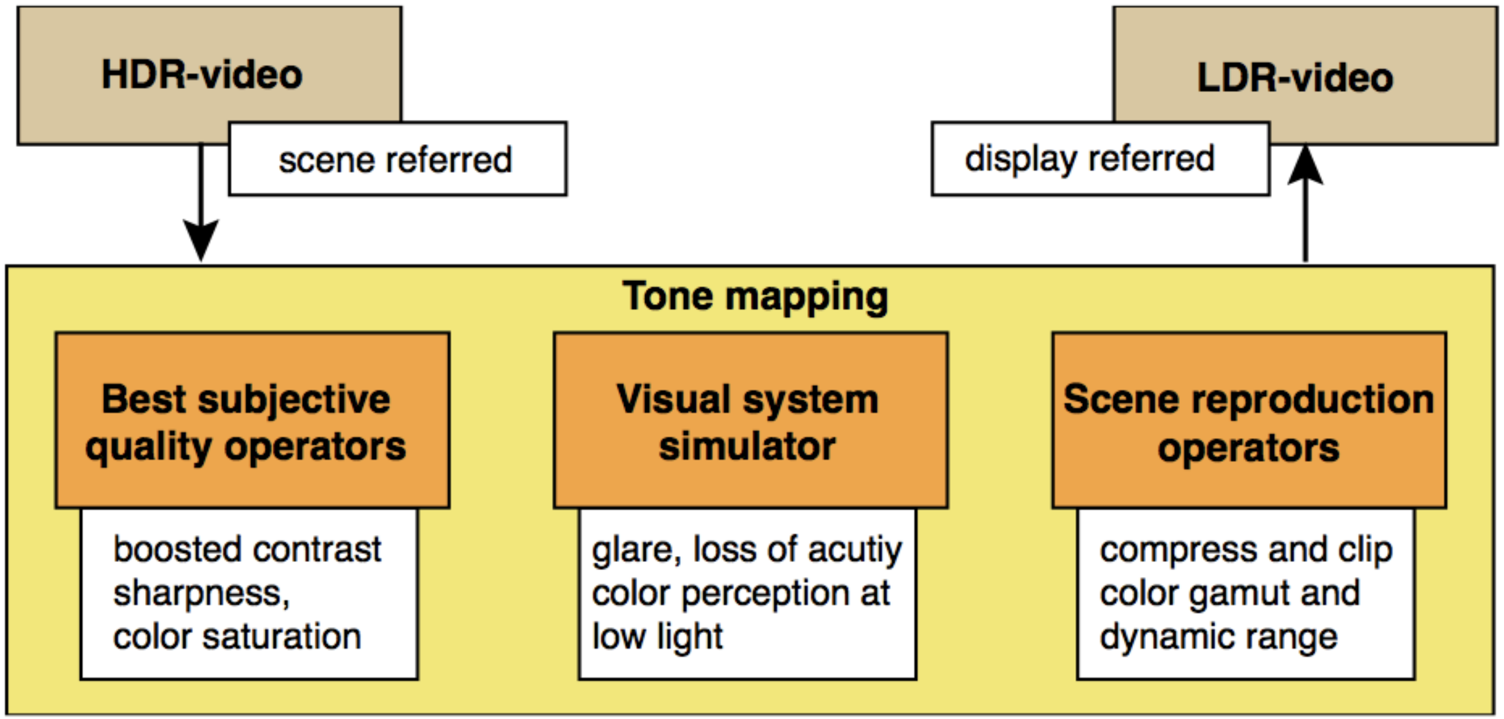
Question

- Who has never used a tone-mapping operator?

Each camera needs to tone-map a real-world captured light before it can be stored as a JPEG. This is essentially the same process as tone-mapping, although knows as ‘color reproduction’ or ‘color processing’.

Three intents of tone-mapping

1. Scene reproduction operator
2. Visual system simulator
3. Best subjective quality



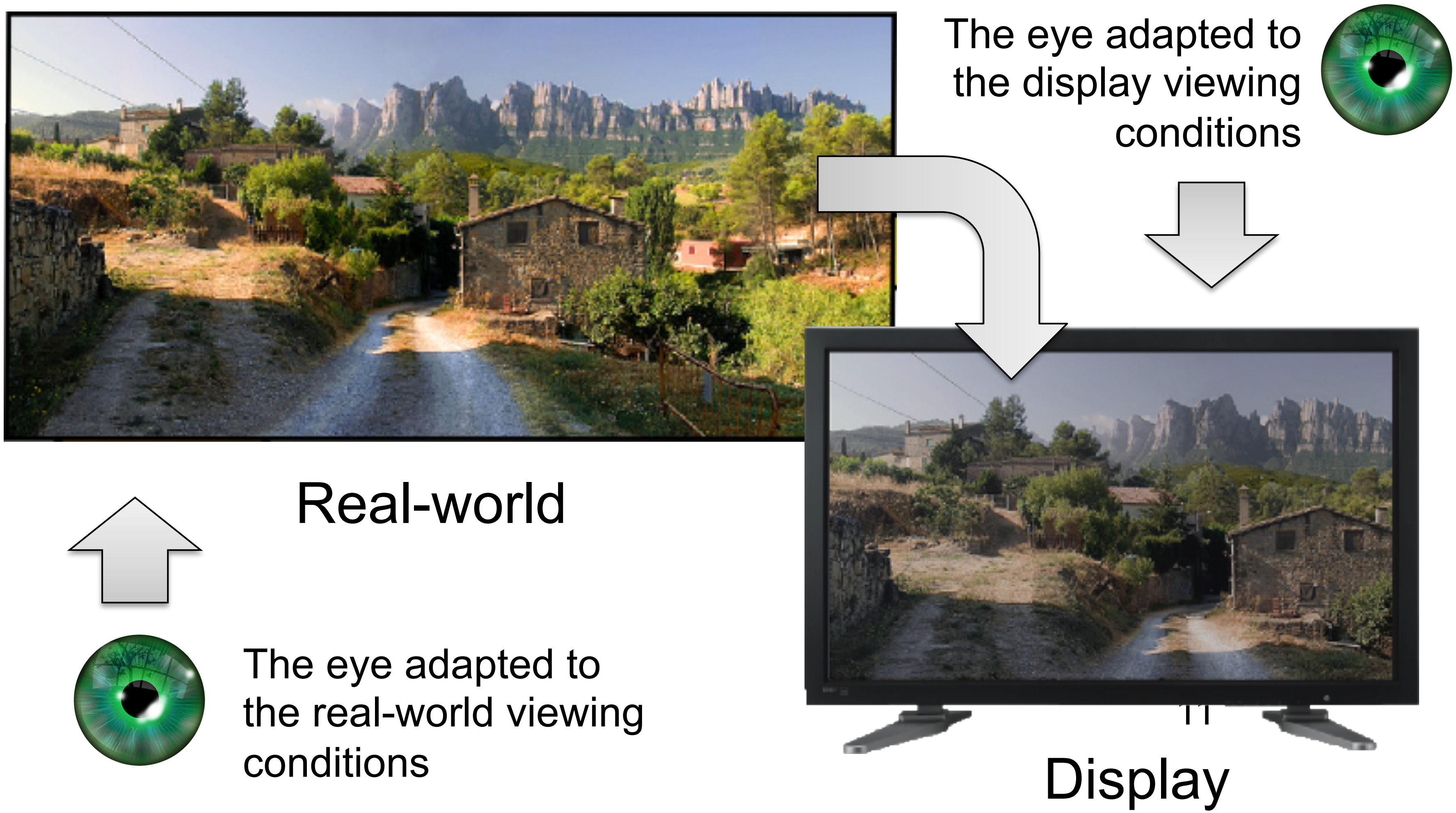
Intent #1: Scene reproduction problem

Real-world

Display

Goal: map colors to a restricted color space

Intent #2: Visual system simulator



Goal: match color appearance

Visual system simulator - example

- Simulation of glare

Intent #3:
Best subjective quality

- Tools
  - Photoshop
  - Lightroom
  - Photomatix
- Techniques
  - Color-grading
- Often artistic intent

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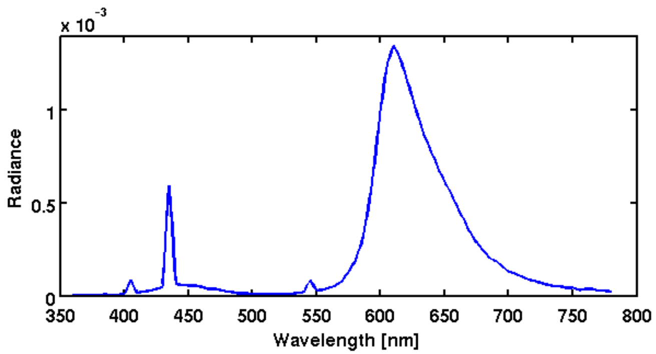
Luminance

- Luminance – perceived brightness of light, adjusted for the sensitivity of the visual system to wavelengths

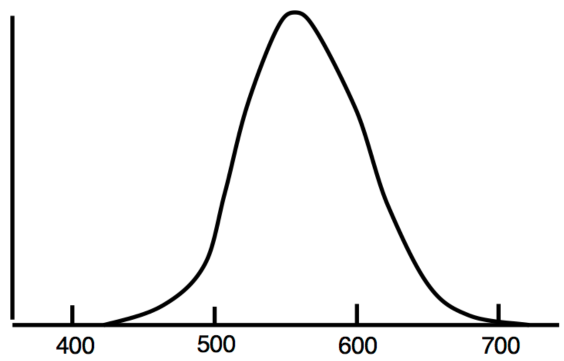
Luminance

$$L_V = \int_0^{\infty} L(\lambda) \cdot V(\lambda) d\lambda$$

Light spectrum (radiance)



Luminous efficiency function (weighting)



Luminance and Luma

- Luminance
  - Photometric quantity defined by the spectral luminous efficiency function
- $L \approx 0.2126\ R + 0.7152\ G + 0.0722\ B$
- Units: cd/m^2

- Luma
  - Gray-scale value computed from LDR (gamma corrected) image
- $Y = 0.2126\ R' + 0.7152\ G' + 0.0722\ B'$
- Unitless

Do HDR images contain luminance values?

- Not exactly, because:
  - the combination of camera red, green and blue spectral sensitivity curves will not match the luminous efficiency function
- But they contain a good-enough approximation for most applications
  - For multi-exposure camera capture the error in luminance measurements is 10-15%

Dynamic range (contrast)

- As ratio:

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

  - Usually written as 1000:1, etc.

- As "orders of magnitude" or log10 units:

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

- As f-stops:

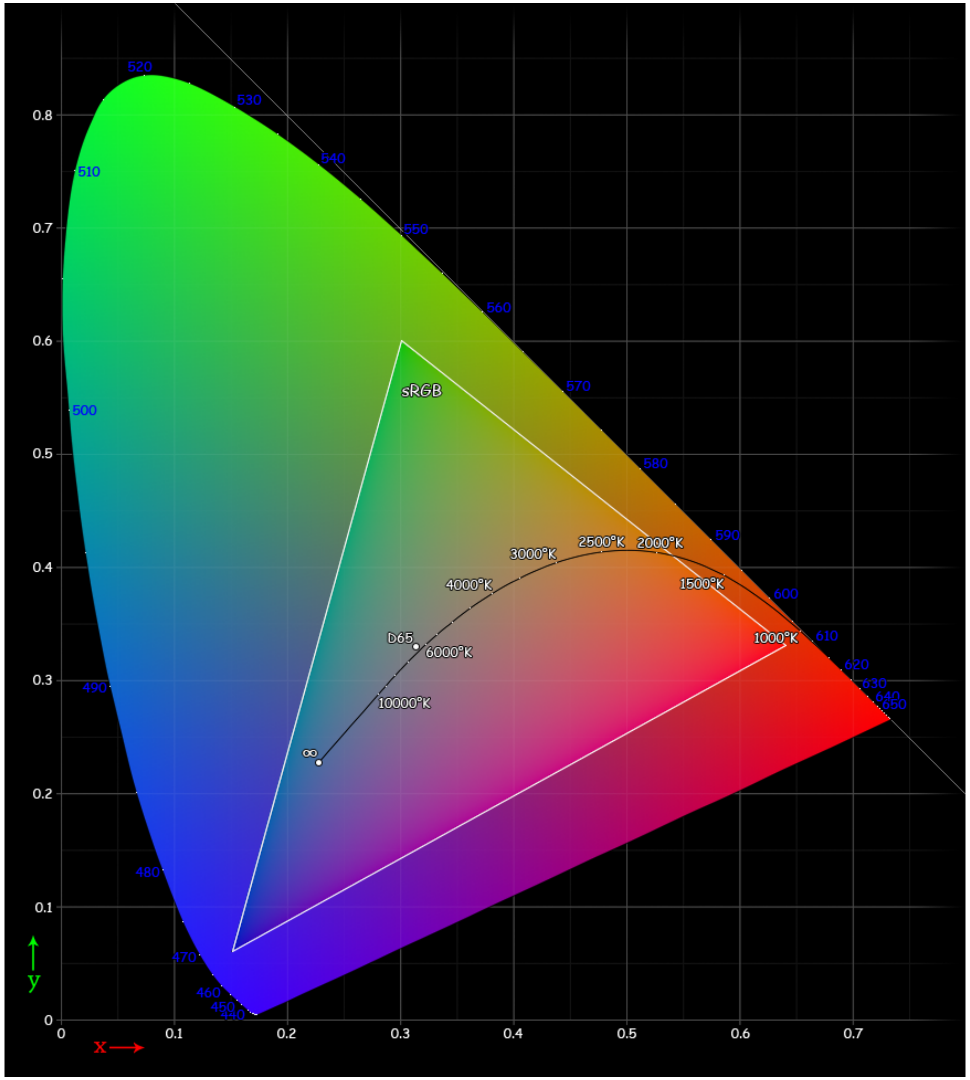
$$C_2 = \log_2 \frac{L_{\max}}{L_{\min}}$$

One f-stop is doubling of halving the amount of light

sRGB color space (LDR)

- “RGB” color space is not a standard. Colors may differ depending on the choice of the primaries
- “sRGB” is a standard color space, which most displays try to mimic.

Chromaticity	Red	Green	Blue	White point
x	0.6400	0.3000	0.1500	0.3127
y	0.3300	0.6000	0.0600	0.3290
z	0.0300	0.1000	0.7900	0.3583



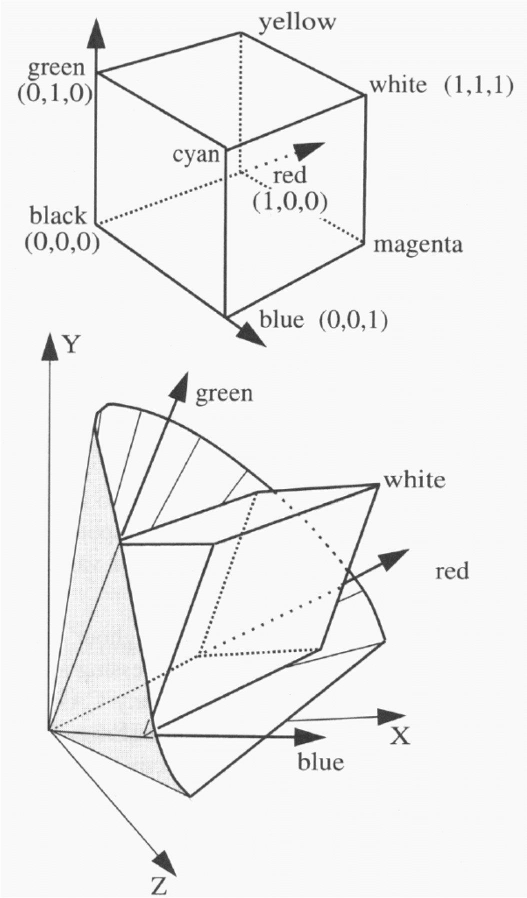
sRGB color space

- Two step XYZ – sRGB transformation:
  - Step 1: Linear color transform

$$\begin{bmatrix} R_{\text{linear}} \\ G_{\text{linear}} \\ B_{\text{linear}} \end{bmatrix} = \begin{bmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

  - Step 2: Non-linearity

$$C_{\text{srgb}} = \begin{cases} 12.92 C_{\text{linear}}, & C_{\text{linear}} \le 0.0031308 \\ (1+a) C_{\text{linear}}^{1/2.4} - a, & C_{\text{linear}} > 0.0031308 \end{cases}$$



- What is the dynamic range of the sRGB color space (white to black)?

Task 1: “sRGB” TMO

- Convert an HDR image to the sRGB color space and display
- You need to select the white point for the image. How do you do this?
- Hint: Use the *lin2srgb* function
- This is probably the simplest form of tone mapping
  - Equivalent to “gamma”.
  - It will faithfully reproduce colors (except brightness-related effects) if there are not brighter than the white point, and not too dark.

Solution

```
% Load an HDR image
rgb = hdrread( 'slate_mines.hdr' );

% Choose the white point
Wp = 800;

% Transform to the sRGB color space
srgb = lin2srgb( srgb/Wp )

% Display
imshow( srgb );
```

Is sRGB a display model?

- It maps colorimetric values (XYZ or linear RGB) to the pixel values on the display
- But the mapping does not model any realistic display
- For example:
  - $RGB_{display}$=[0 0 0] maps to RGB_{linear} = [0 0 0]
  - But the display black level is almost never zero

(Forward) Display model

- GOG: Gain-Gamma-Offset

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

Luminance

Peak luminance

Gamma

Display black level

Screen reflections

Gain

Pixel value 0-1

Offset

Reflectance factor (0.01)

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

Ambient illumination (in lux)

Task 2: Dynamic range

- Compute the dynamic range of a display:

  gamma = 2.2

  L_peak = 500 cd/m2

  L_black = 0.5 cd/m^2

  k = 0.005

  a) in a dark room (E_amb = 0)

  b) outdoors (E_amb = 10000)

Hint: Use gog_fw_display_model function

Solution

```
L_peak = 500;
L_black = 0.5;
k = 0.005;
gamma = 2.2;
E_amb = 0;

% Ratio of the luminance produced by white(1) and black (0) pixels
Log10( ...
 gog_fw_display_model( 1, gamma, L_peak, L_black, E_amb, k )/ ...
 gog_fw_display_model( 0, gamma, L_peak, L_black, E_amb, k ) )
```

Inverse display model

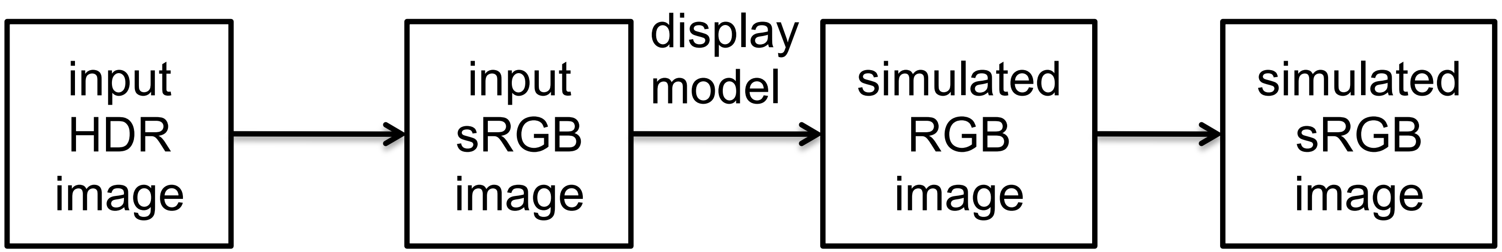
Symbols are the same as for the forward display model

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

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.

Task 3: Simulate a display

- Simulate how an image would look on the display whose
  - gamma is 2.3
  - peak luminance is 100 and black level 1 cd/m^2
  - is seen in a bright room (400 lux) and reflectivity of the panel is 0.01 (1%)
  - Implement the processing chain:



  - Experiment with different display parameters

Solution

```
img = hdrread( 'slate_mines.hdr' );

L_peak = 100;
L_black = 1;
k = 0.005;
gamma = 1.9;

E_amb = 10000;

P = lin2srgb(img/100);
display_img = gog_fw_display_model( P, gamma, L_peak,
L_black, E_amb, k );

imshow( lin2srgb( display_img/100 ) );
```

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)
- Task 4:
  - Read HDR image, apply each of these basic operations, apply the display model before displaying
  - Answer the question: which operation is responsible for the change of:
  - Contrast / Brightness / Black level

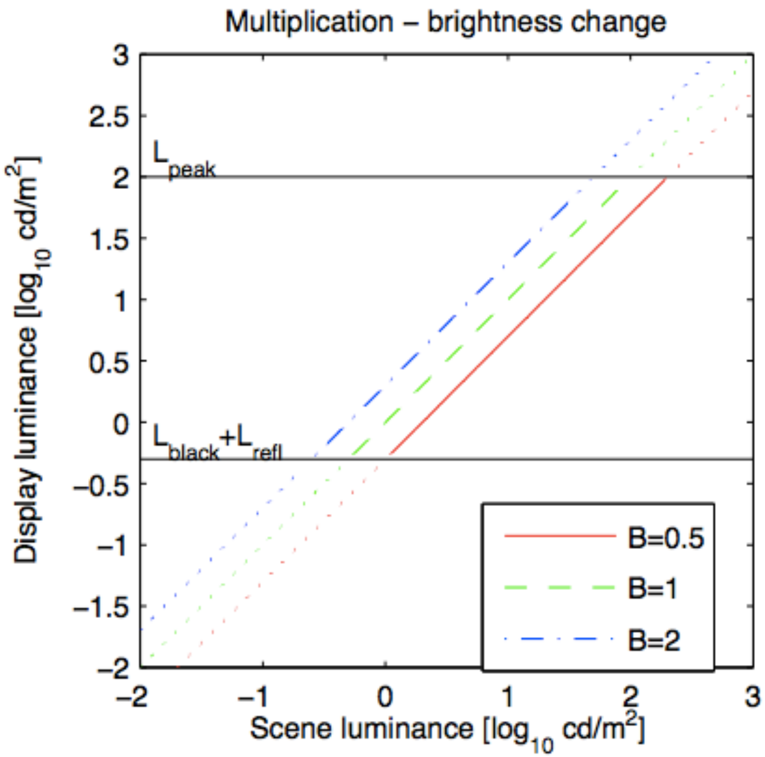
Multiplication – brightness change

Resulting luminance

Input luminance

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

Brightness change parameter



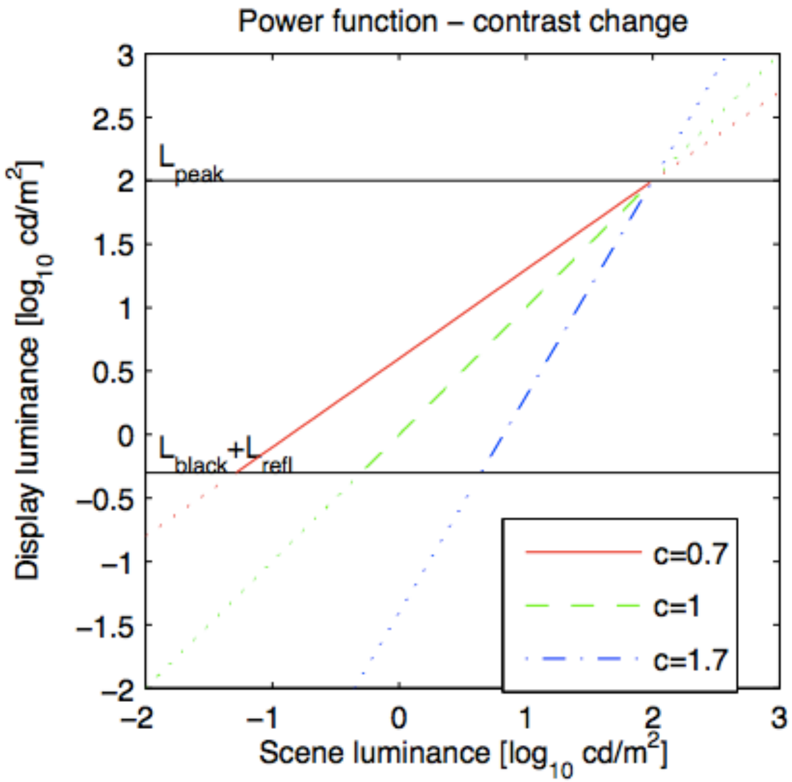
- Multiplication makes the image brighter or darker
- It does not change the dynamic range!

Power function – brightness change

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

Contrast change (gamma)

Luminance of white

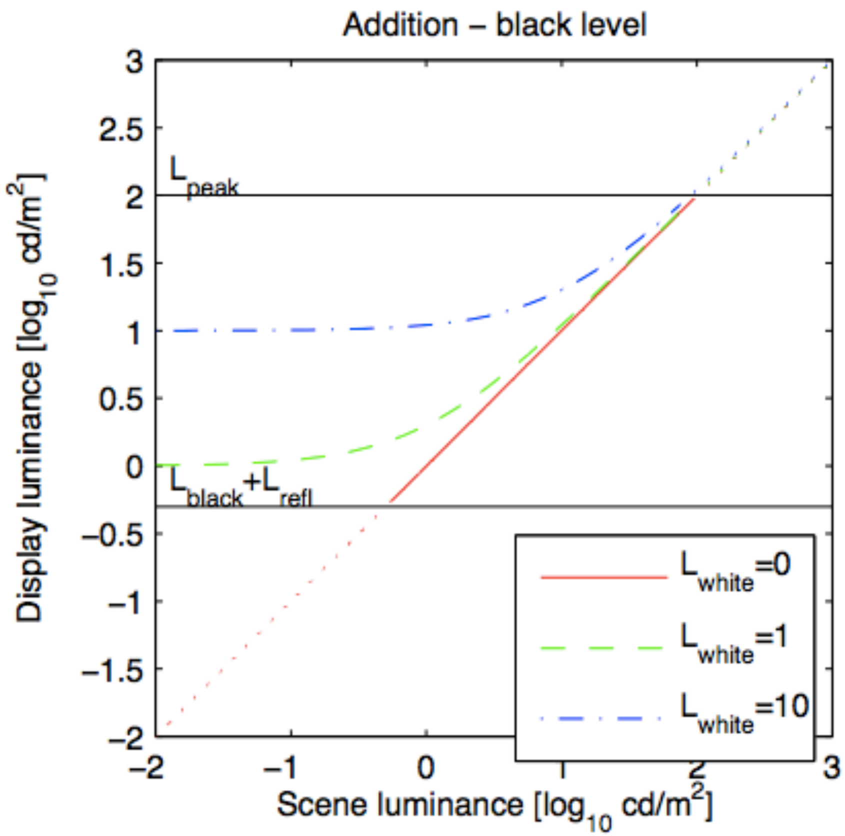


- Power function stretches or shrinks image dynamic range
- It is usually performed relative to reference white
- Apparent brightness changes is the side effect of pushing tones towards or away from the white point

Addition – black level

Black level
(flare, fog)

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



- 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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Sensitivity to luminance

- Weber-law – the just-noticeable difference is proportional to the magnitude of a stimulus

Ernst Heinrich Weber
[From wikipedia]

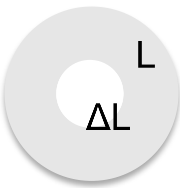
The smallest detectable luminance difference

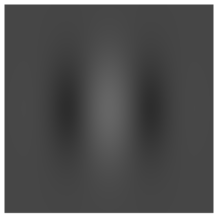
Background (adapting) luminance

$$\frac{\Delta L}{L} = k$$

Constant

Typical stimuli:





Consequence of the Weber-law

- Smallest detectable difference in luminance

$$\frac{\Delta L}{L} = k,$$

L	ΔL
100 cd/m^2	1 cd/m^2
1 cd/m^2	0.01 cd/m^2

- Adding or subtracting luminance will have different visual impact depending on the background luminance
- Unlike LDR luma values, HDR luminance values are not perceptually uniform!

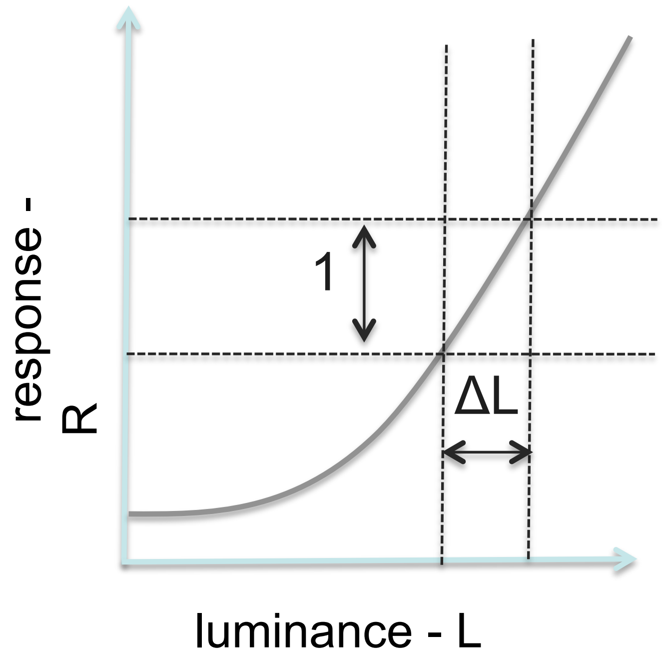
How to make luminance (more) perceptually uniform?

- Using Fechnerian integration

$$dR(L) = \frac{1}{\Delta L(L)}$$

Derivative of response

Detection threshold



Luminance transducer:

$$R(L) = \int_0^L \frac{1}{\Delta L(l)} dl$$

Assuming the Weber law

$$\frac{\Delta L}{L} = k,$$

- and given the luminance transducer

$$R(L) = \int_0^L \frac{1}{\Delta L(l)} dl$$

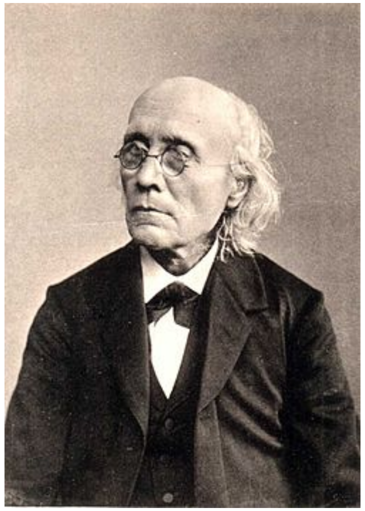
- the response of the visual system to light is:

$$R(L) = \int \frac{1}{kL} dL = \frac{1}{k} \ln(L) + k_1$$

Fechner law

$$R(L) = a\ln(L)$$

- Practical insight from the Fechner law:
  - The easiest way to adopt image processing algorithms to HDR images is to convert luminance (radiance) values to the logarithmic domain



Gustav Fechner
[From Wikipedia]

Arithmetic of HDR in log space

- Linear
- Logarithmic

$$Y = B \cdot L_p$$

$$\log(Y) = \log(B) + \log(L_p)$$

$$Y = L_p{}^C$$

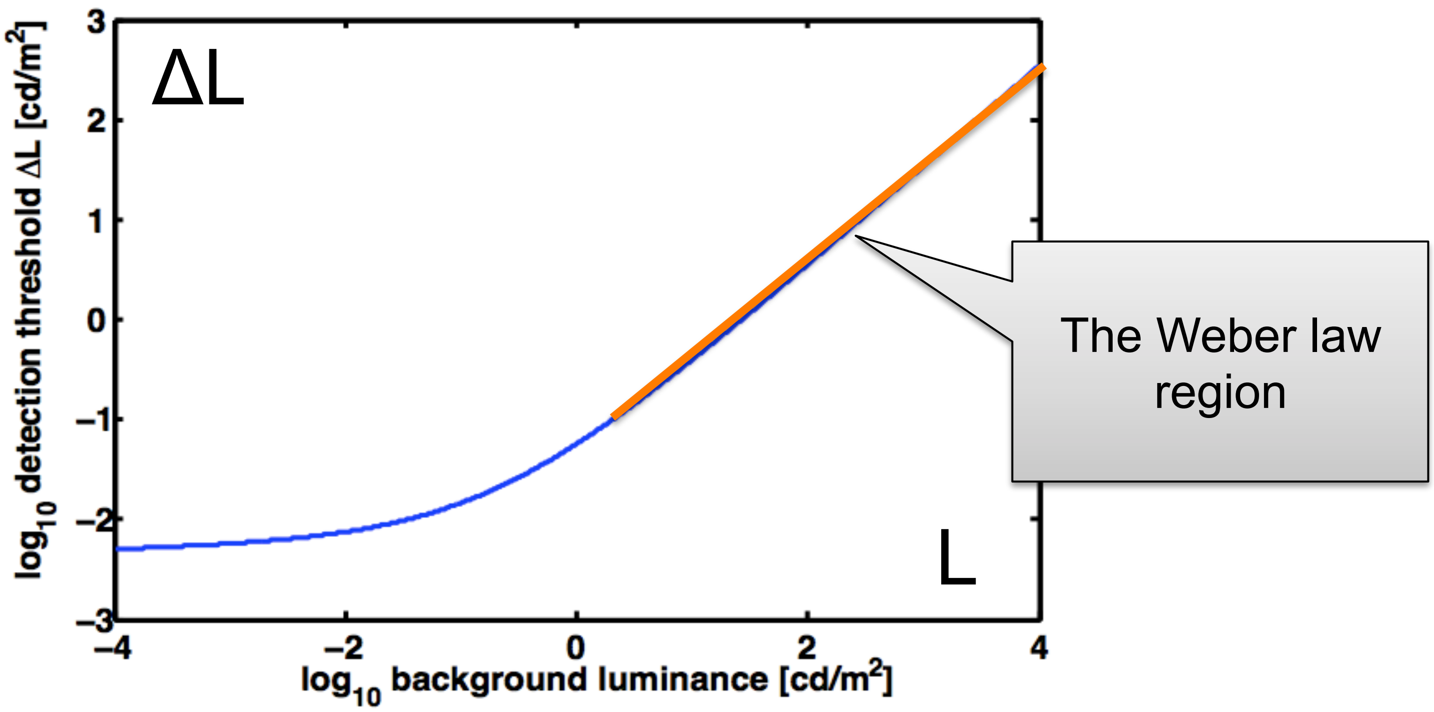
$$\log(Y) = C \cdot \log(L_p)$$

$$Y = L_p + F$$

Cannot be expressed in the log domain

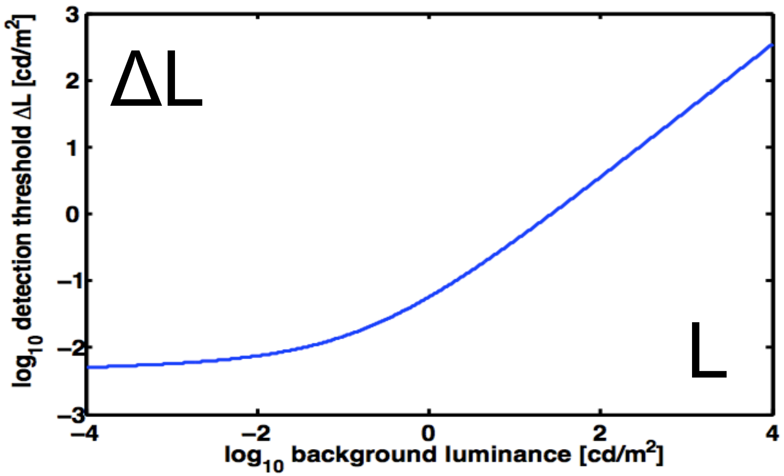
But…the Fechner law does not hold for the full luminance range

- Because the Weber law does not hold either
- Threshold vs. intensity function:



Weber-law revisited

- If we allow detection threshold to vary with luminance according to the t.v.i. function:



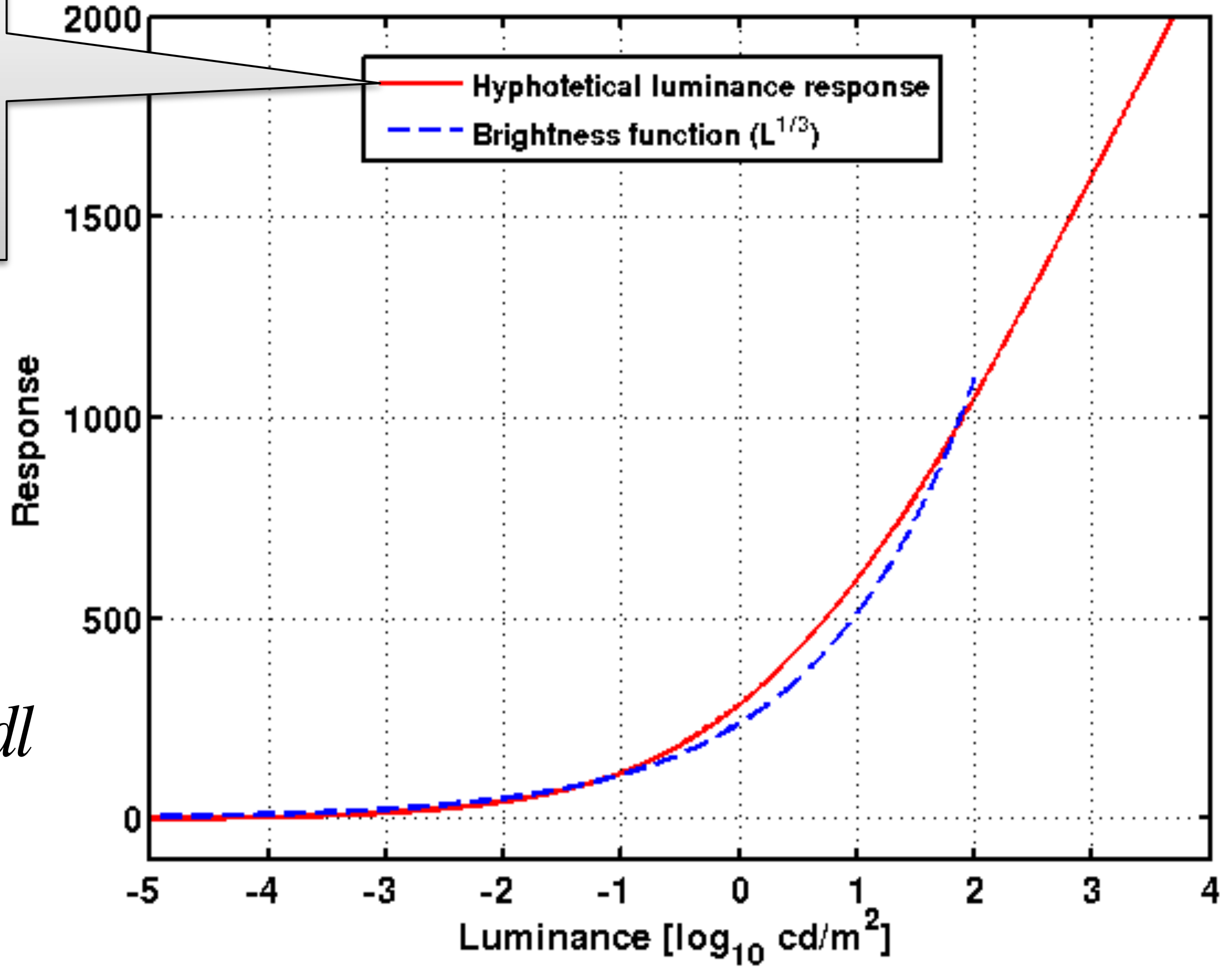
- we can get more accurate estimate of the "response":

$$R(L) = \int_0^L \frac{1}{\Delta L(l)}\, dl$$

Fechnerian integration and Steven's law

R(L) - function derived from the t.v.i. function

$$R(L) = \int_0^L \frac{1}{\Delta L(l)} dl$$



Color processing

- Existing methods
  - Apply the same processing to all color channels
    - works for simple TMO
  - **Operate on luminance, transfer color from the original HDR image**
  - Model color appearance

Color processing

- Transfer color from the original image

Output color channel

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

Saturation parameter

Resulting luminance

- The heuristic from Fattal et al. 2002
  - works well in practice
- Difficulty:
  - How to select value ‘s’
  - Solution for some operators:
    - Mantiuk et al. “Color correction for tone mapping”. Computer Graphics Forum. 2009;28(2):193–202.

Task 5: Luminance only TMO

- Transform input image to luminance
  - Hint: use “get_luminance” function
- Compress luminance contrast (using power function)
- Restore colors using the formula:

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

- Experiment with s.

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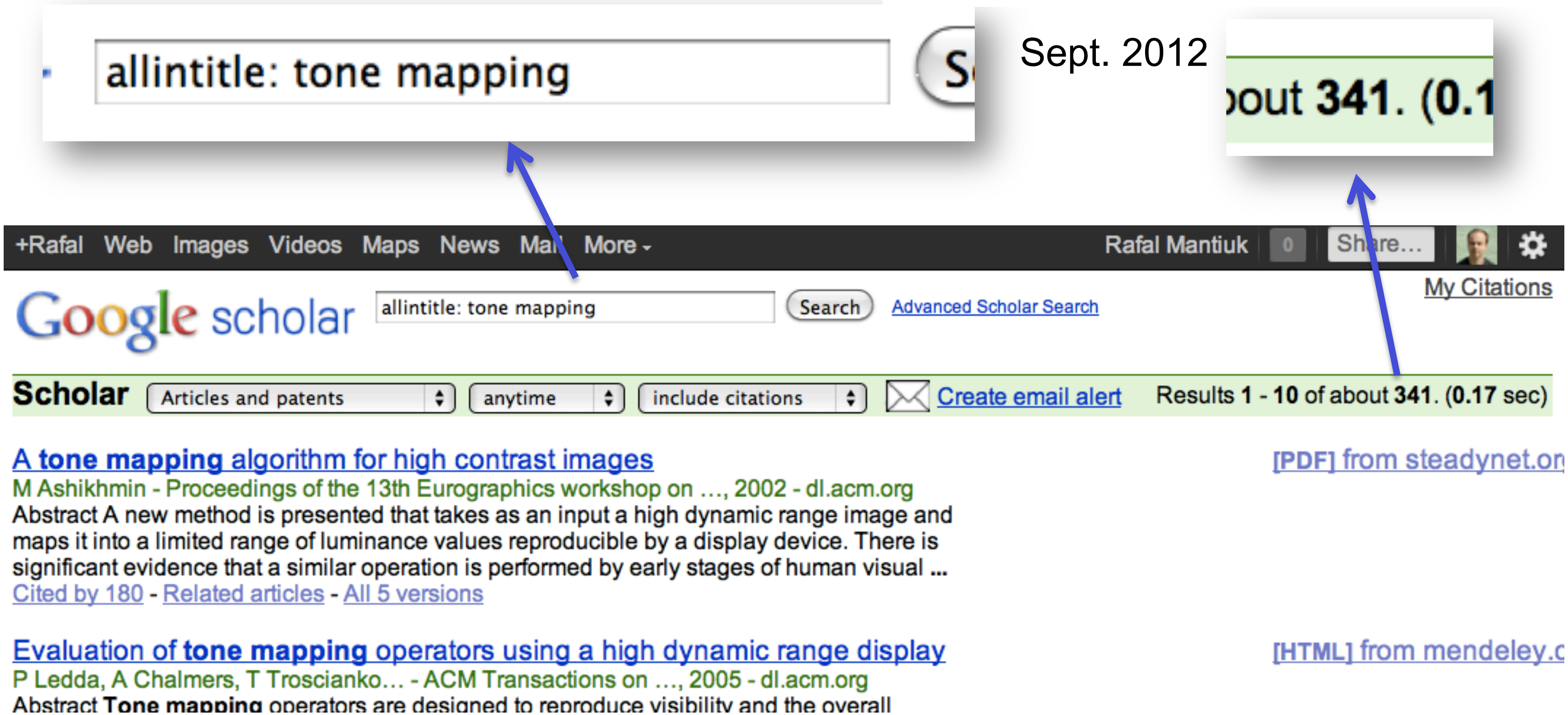
How many operators are out there?

September 2013 About 501 results (0.06 sec)

Sept. 2012



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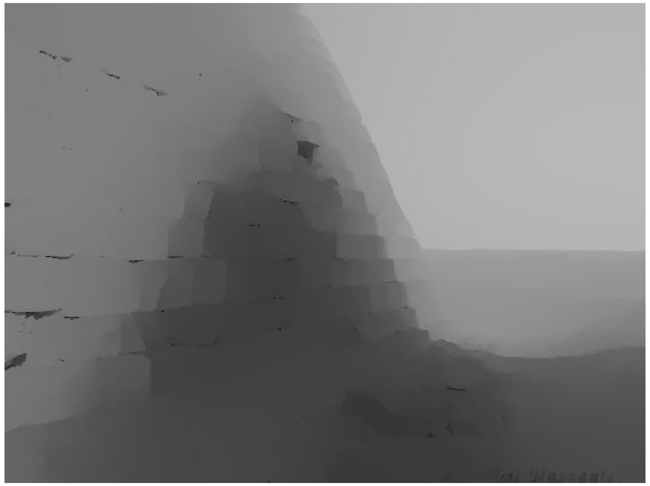
Illumination & reflectance separation

Input



Illumination

Reflectance

Illumination and reflectance

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

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

Reflectance & Illumination TMO

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

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

Tone-mapped image (L_d)

Reflectance (R)

Tone-mapping (T)

Illumination (I)

- for example: $L_d = R \cdot I^{1/\gamma}$

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

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

Tone mapping result

[Durand & Dorsey, SIGGRAPH 2002]

WLS filter

- Weighted-least-squares optimization

Make reconstructed image u possibly close to input g

Smooth out the image by making partial derivatives close to 0

$$\sum_p \left((u_p - g_p)^2 + \lambda \left(a_{x,p}(g) \left(\frac{\partial u}{\partial x} \right)_p^2 + a_{y,p}(g) \left(\frac{\partial u}{\partial y} \right)_p^2 \right) \right) \text{ -> min}$$

Spatially varying smoothing – less smoothing near the edges

- [Farbman et al., SIGGRAPH 2008]

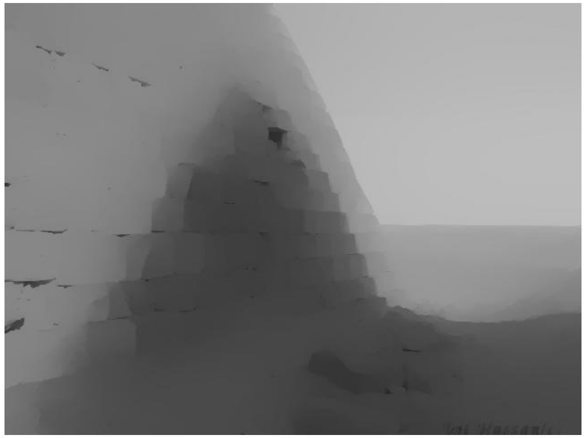
Task 6: Reflectance & illumination TMO

- Create reflectance & illumination TMO that
  - a) uses Gaussian filter
  - b) uses Bilateral filter (function bilateral_fast)
  - both filters operate on an image in the logarithmic domain!!
  - operates on gray-scale and adds color later (Task 5)
  - employs contrast compression for the TMO

$$\log(L_d) = \log(R) + \gamma \cdot \log(I)$$

WLS filter

- Stronger smoothing and still distinct edges



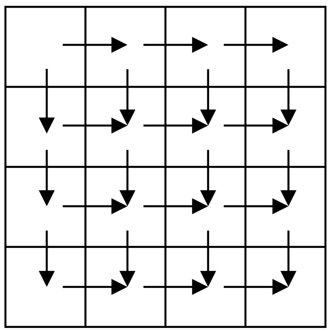
Tone mapping result

- Can produce stronger effects with fewer artifacts

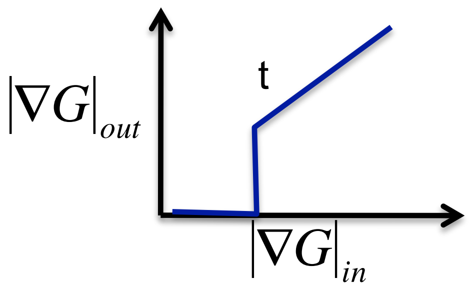
Retinex

- 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

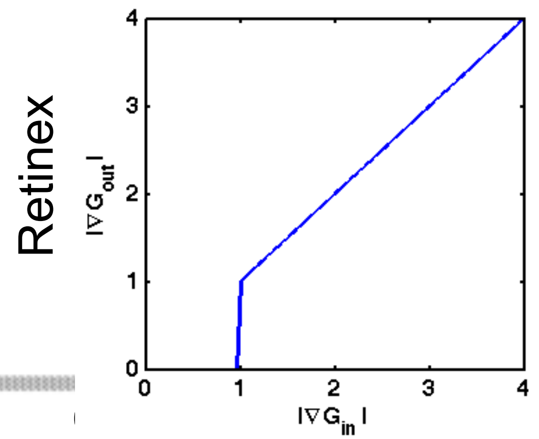
From: http://dragon.larc.nasa.gov/retinex/757/

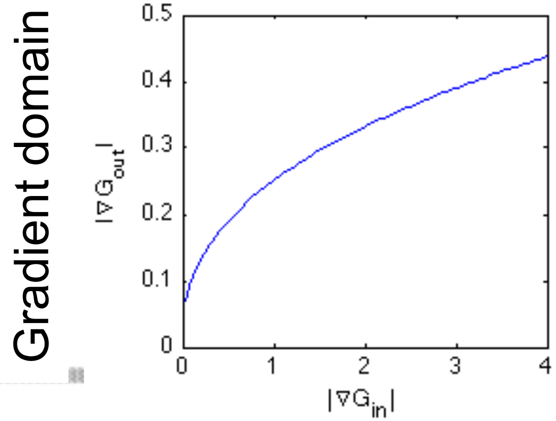
From:http://www.ipol.im/pub/algo/lmps_retinex_poisson_equation/#ref_1

Gradient domain HDR compression

[Fattal et al., SIGGRAPH 2002]

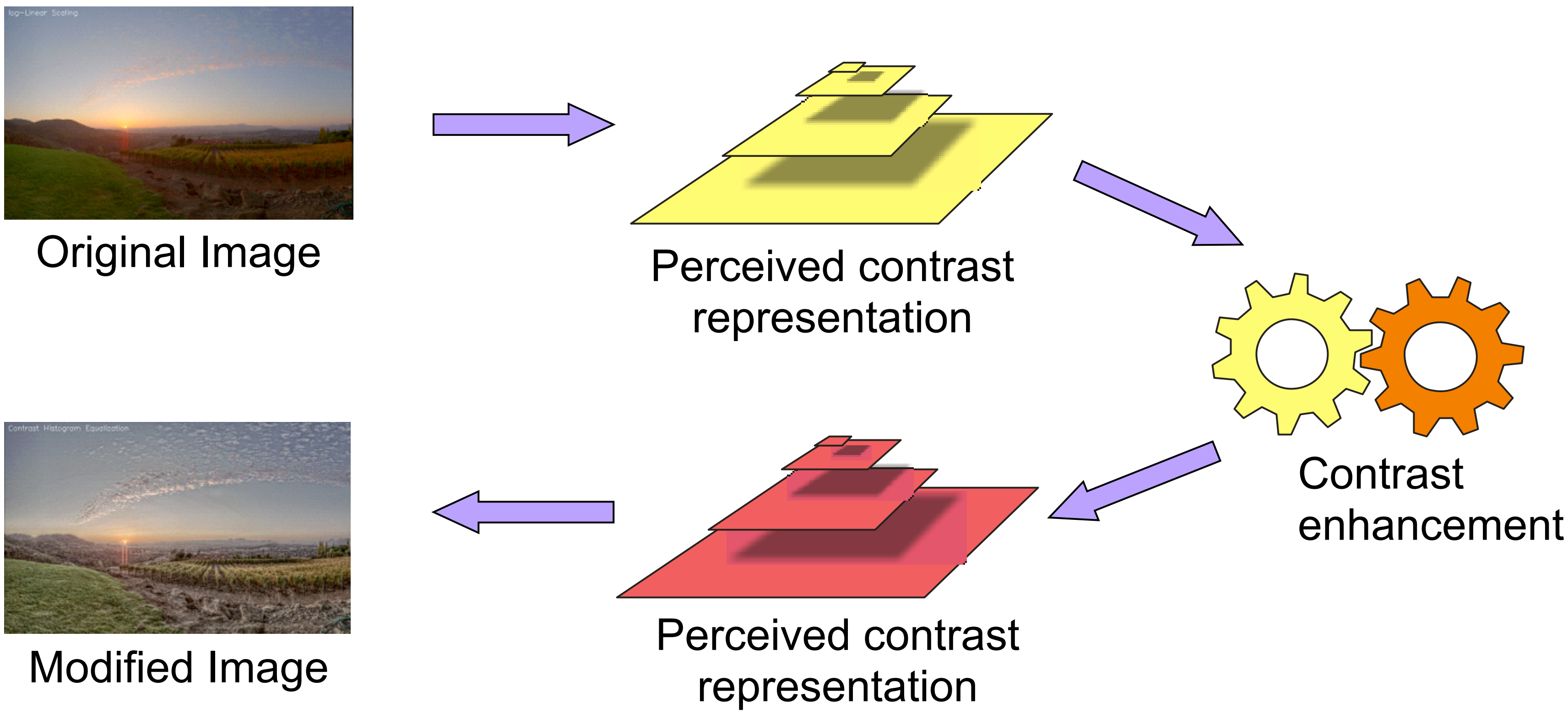
- Similarly to Retinex, it operates on log-gradients
- But the function amplifies small contrast instead of removing it





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

Contrast domain image processing



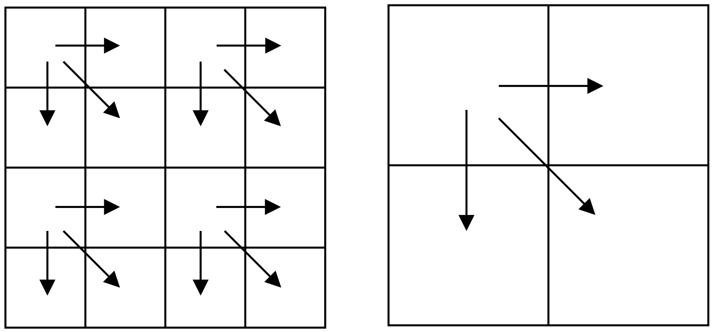
Rationale: Human eye is more sensitive to contrast than luminance

[Mantiuk et al., ACM Trans. Applied Perception, 2006]

Contrast domain image processing

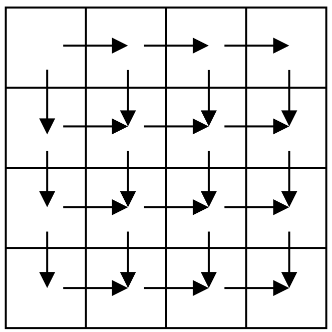
Image transform: Multi-scale contrast pyramid

Wavelets

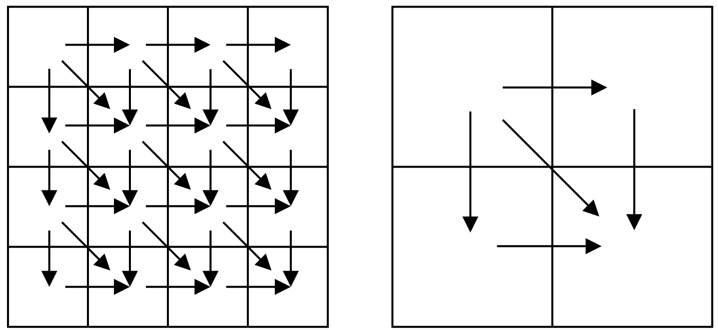


1st level 2nd level

Gradients



Contrast pyramid



1st level 2nd level

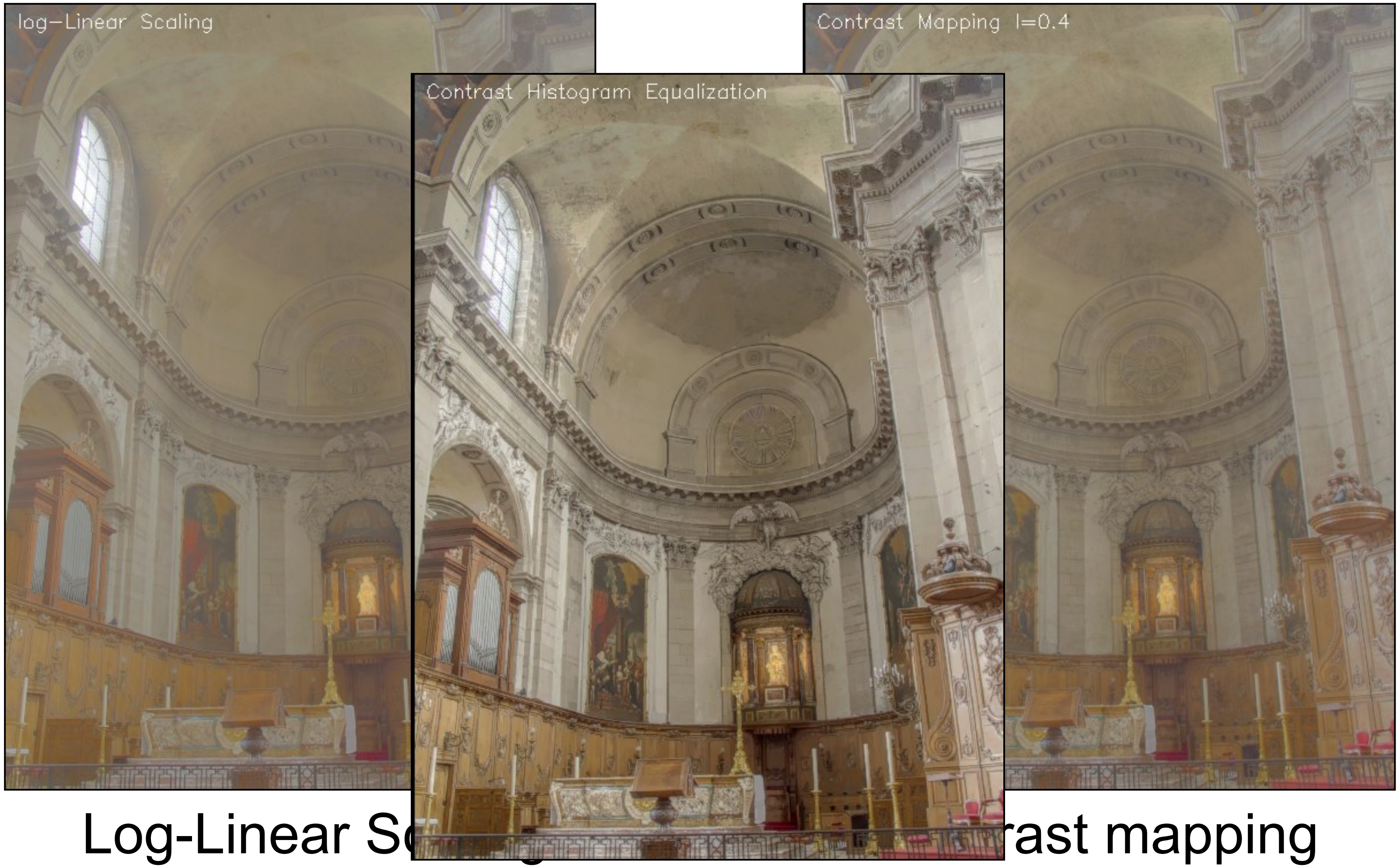
Contrast Equalization: Examples

Log-Linea

t mapping

Contrast equalization

Contrast Equalization: Examples



Log-Linear Sc... ...rast mapping

Contrast equalization

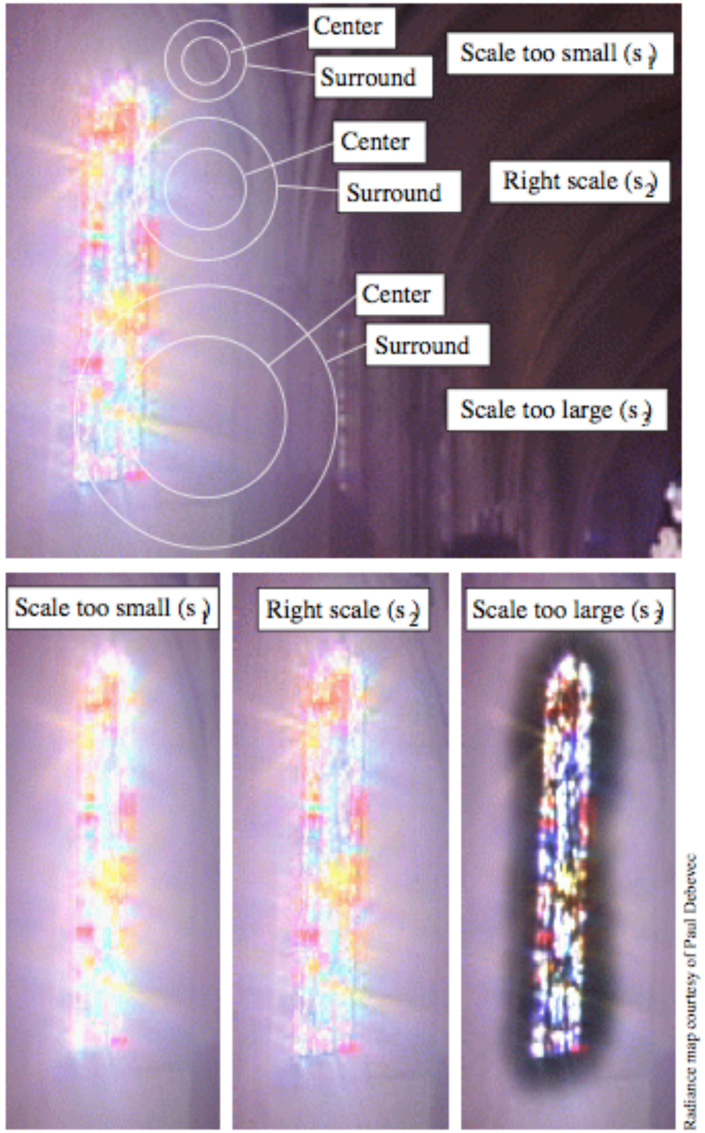
Tone mapping in photography

- Dodging and burning
  - Darken on brighten image parts by occluding photographic paper during exposure
  - Ansel Adams, *The print*, 1995
  - Photoshop tool

- Essentially – attenuate low-pass frequencies that contain scene illumination

Automatic dodging and burning

- Reinhard et al., *Photographic tone reproduction for digital images*. SIGGRAPH 2002
- Choose dodging an burning kernel size adaptively
  - depending on the response of the center-surround filter
  - thus avoid halo artifacts

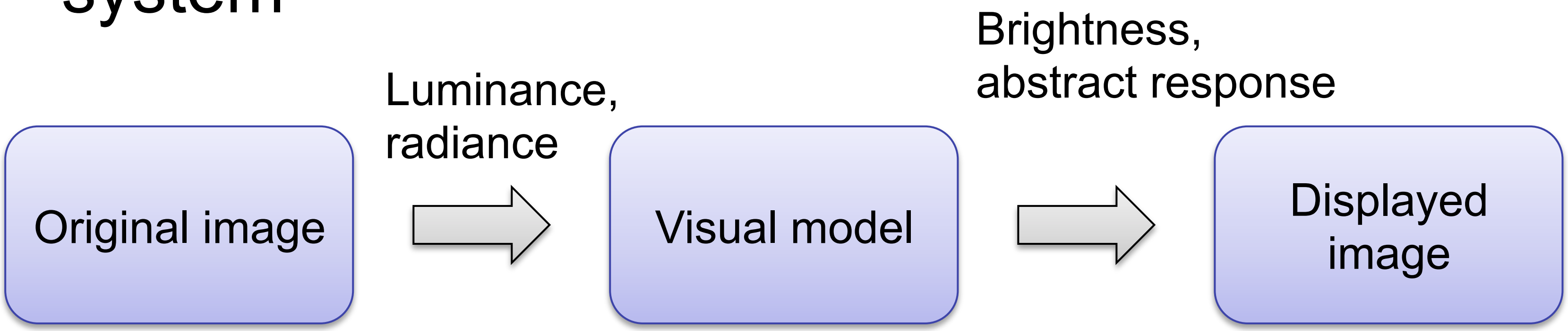


Outline

- What is tone-mapping?
- The perception of HDR scenes
- Major approaches to tone-mapping
  - Illumination & reflectance separation
  - Forward visual model
  - Forward & inverse visual model
  - Constraint mapping problem

Forward visual model

- Mimic the processing in the human visual system



- Assumption: what is displayed is brightness or abstract response of the visual system

Forward visual model: Retinex

- Remove illumination component from an image
  - Because the visual system also discounts illuminant
- Display ‘reflectance’ image on the screen

- Assumption:
  - The abstract ‘reflectance’ contains most important visual information
  - Illumination is a distraction for object recognition and scene understanding

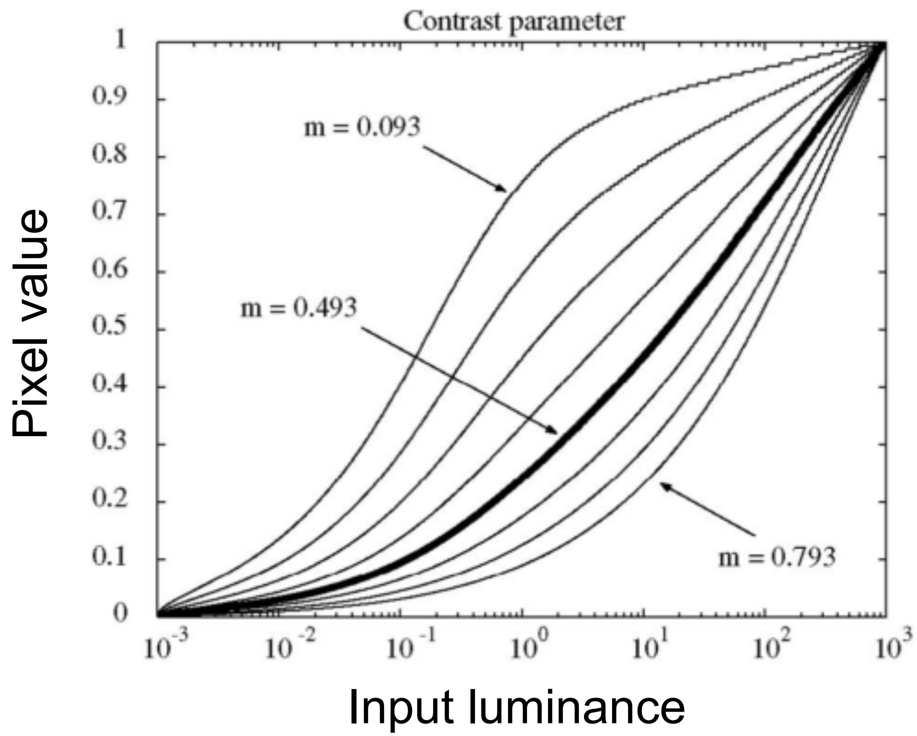
Photoreceptor response

- Dynamic range reduction inspired by photoreceptor physiology
  - [Reinhard & Devlin ‘05]

$$V = \frac{I}{I + \sigma(I_a)} V_{max}$$

$$\sigma(I_a) = (f I_a)^m.$$

- From gamma to sigmoidal response:



Task 7: Photoreceptor TMO

- Implement photoreceptor TMO

$$V = \frac{I}{I + \sigma(I_a)} V_{max}$$

$$\sigma(I_a) = (f I_a)^m$$

- Output pixel value (RGB)
- Input radiance (RGB)
- Maximum response (set it to 1)
- Parameter (set it to 1 and experiment with different values)
- Semi-saturation constant
- Global/local adaptation luminance (make it local and equal geoman(I))
- Parameter (between 0 and 1)

Results: photoreceptor TMO


Our operator


Bilateral filtering


Trilateral filtering


Histogram adjustment


Photographic tonemapping (global)


Photographic tonemapping (local)


Logarithmic mapping

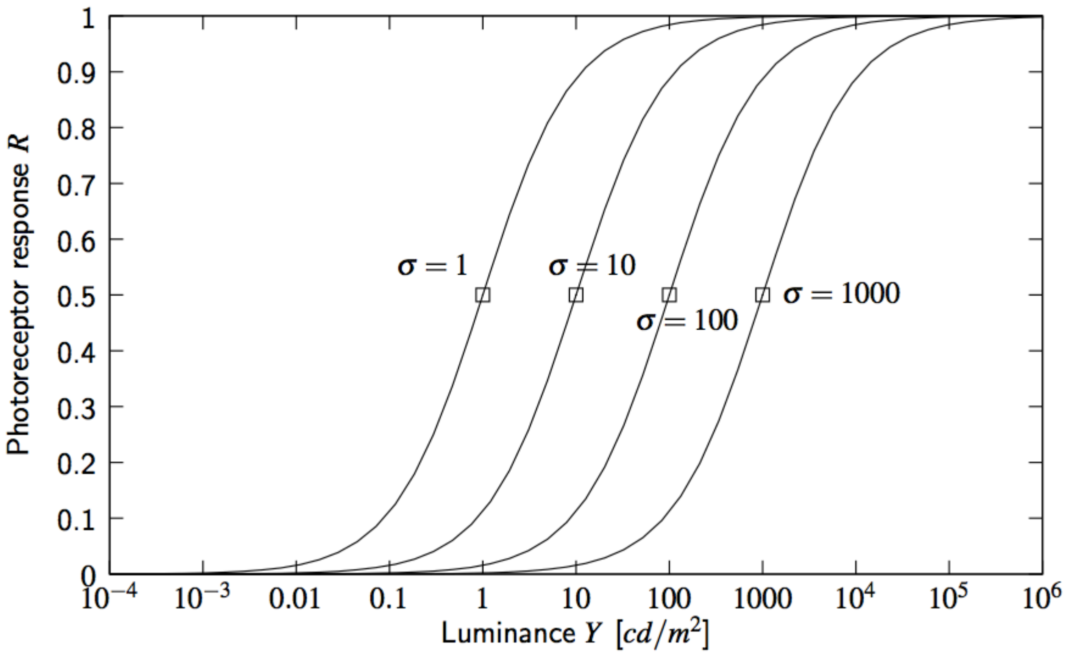

Adaptive logarithmic mapping


Ashikhmin's operator

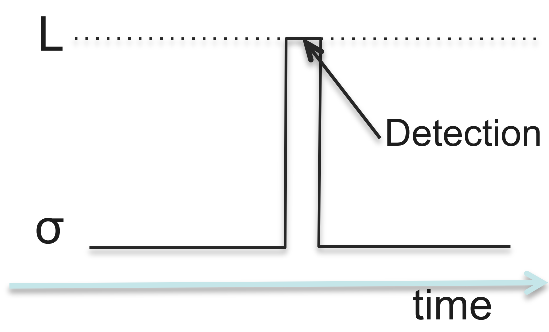
Photoreceptor models

- Naka-Rushton equation:

$$\frac{R}{R_{max}} = \frac{Y^n}{Y^n + \sigma^n}$$



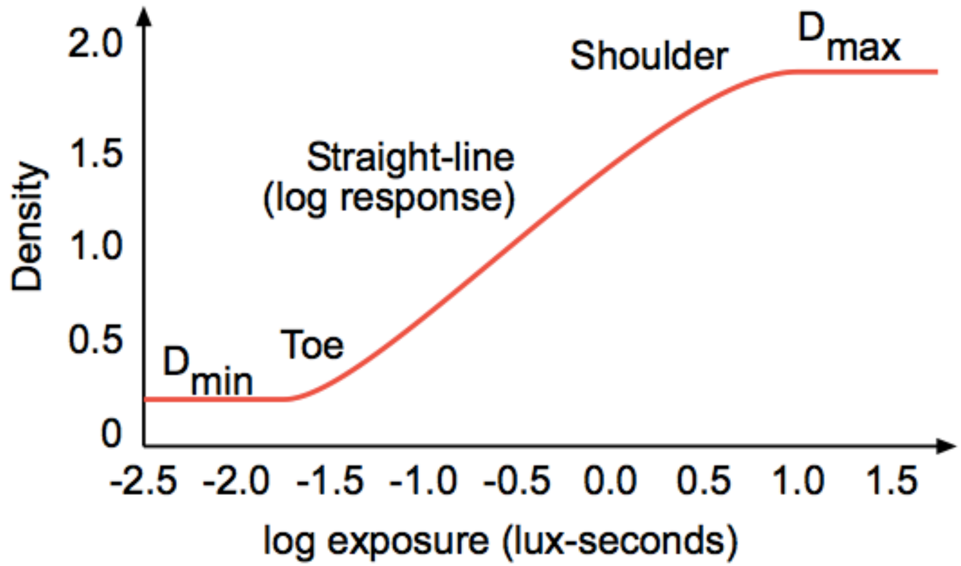
Experiment:



- Response of the photoreceptor to a short flicker of light - less applicable to viewing static images

Sigmoidal tone-curves

- Very common in digital cameras
  - Mimic the response of analog film
  - Analog film has been engineered for many years to produce optimum tone-reproduction (given that he tone curve must not change)



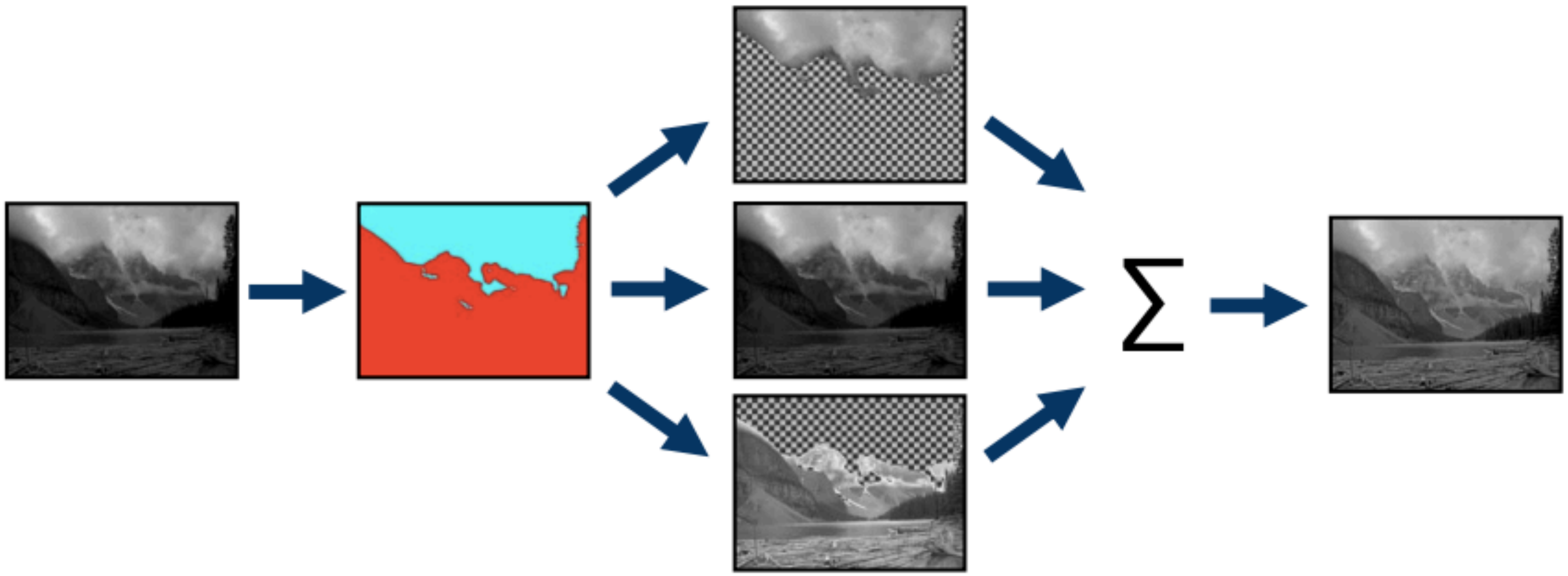
- In practice - the most commonly used tone-mapping!

[Speculative] Why do sigmoidal tone-curves work?

- Because they mimic photoreceptor response
  - Unlikely, because photoreceptor response to steady light is not sigmoidal
- Because they preserve contrast in mid-tones, which usually contains skin color
  - We are very sensitive to variation in skin color
- Because an image on average has Gaussian distribution of log-luminance
  - S-shape function is the result of histogram equalization of an image with a Gaussian-shape histogram

Lightness perception

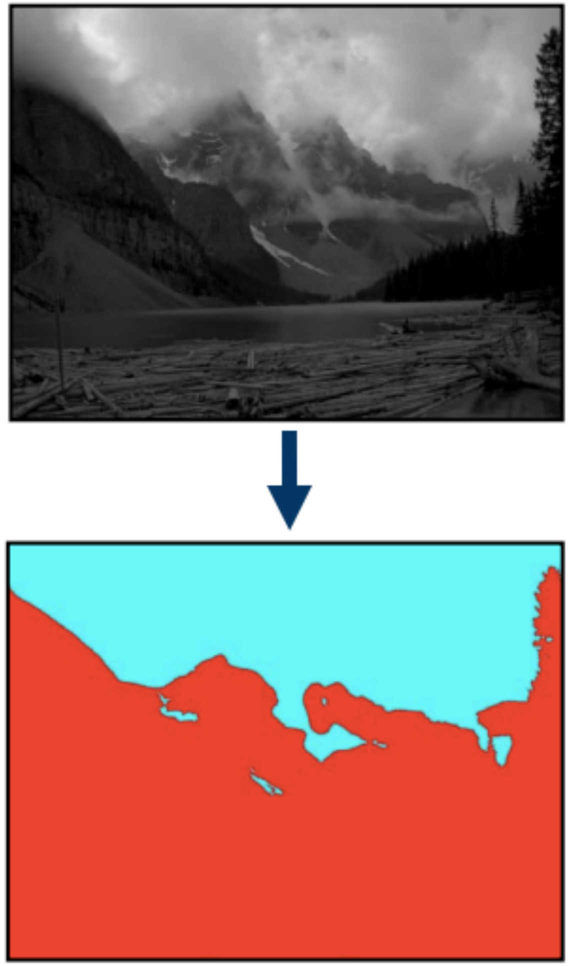
- Lightness perception in tone-reproduction for high dynamic range images [Krawczyk et al. '05]
- Based on Gilchrist lightness perception theory



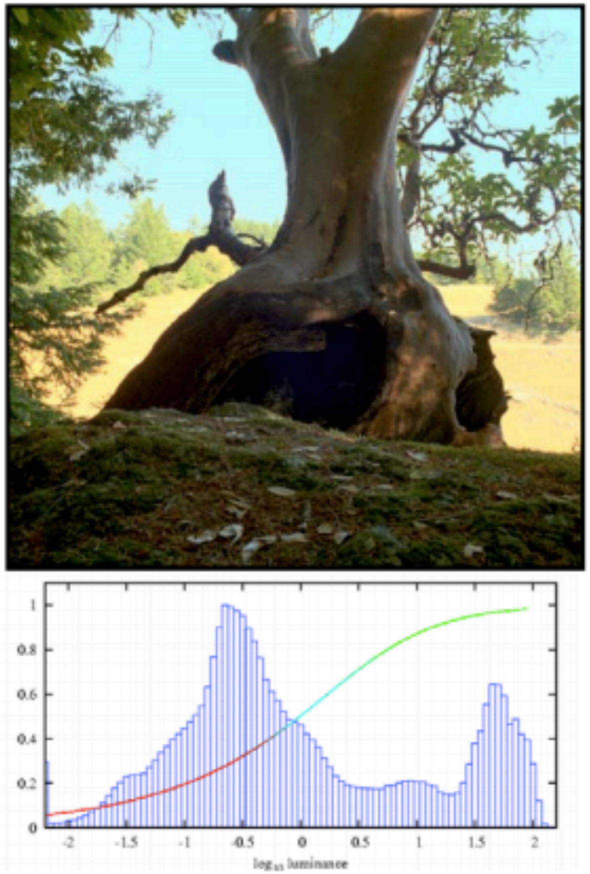
- Perceived lightness is anchored to several frameworks

Gilchrist lightness perception theory

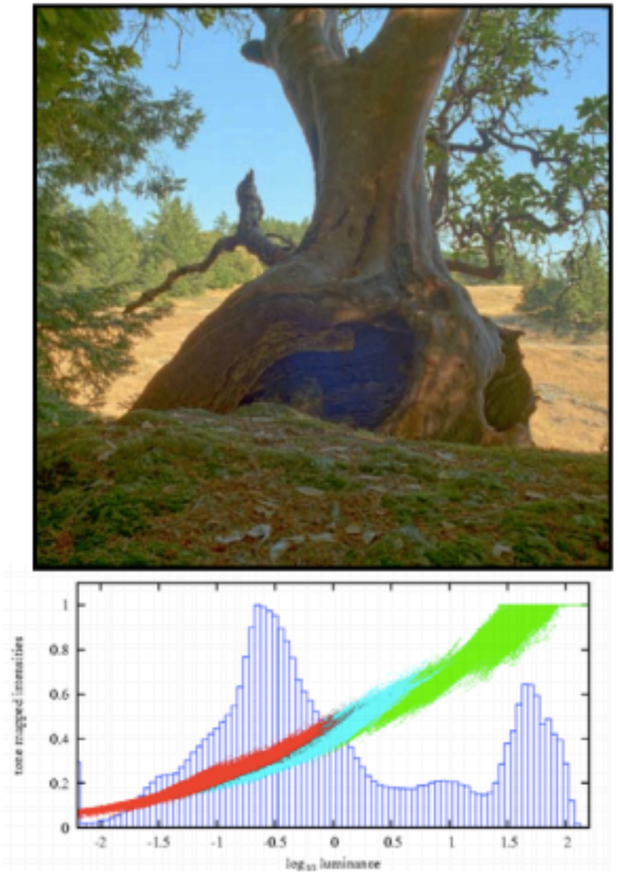
- Frameworks – areas of common illumination
- Anchoring – the tendency of
  - highest luminance
  - and largest area
  - to appear white
- Tone-mapping
  - Change brightness of each framework to its anchor



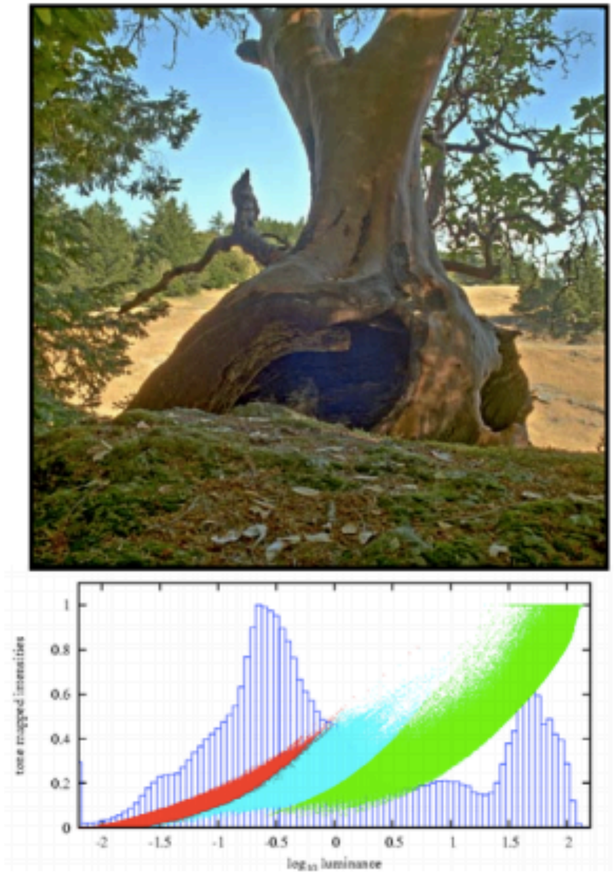
Results – lightness perception TMO



Photographic Tone Reproduction



Bilateral Filtering



Presented Computational Model

Outline

- What is tone-mapping?
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  - Forward & inverse visual model
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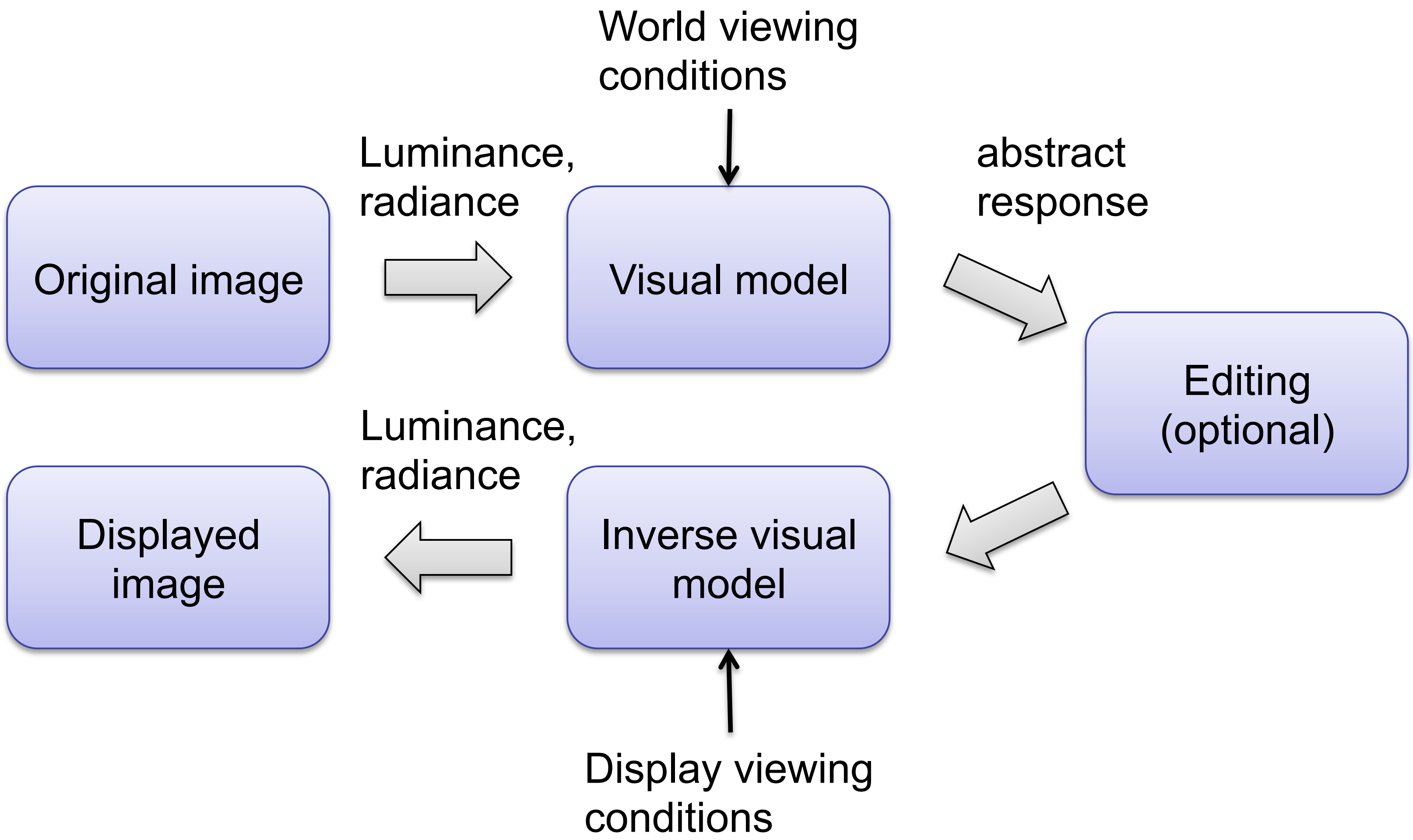
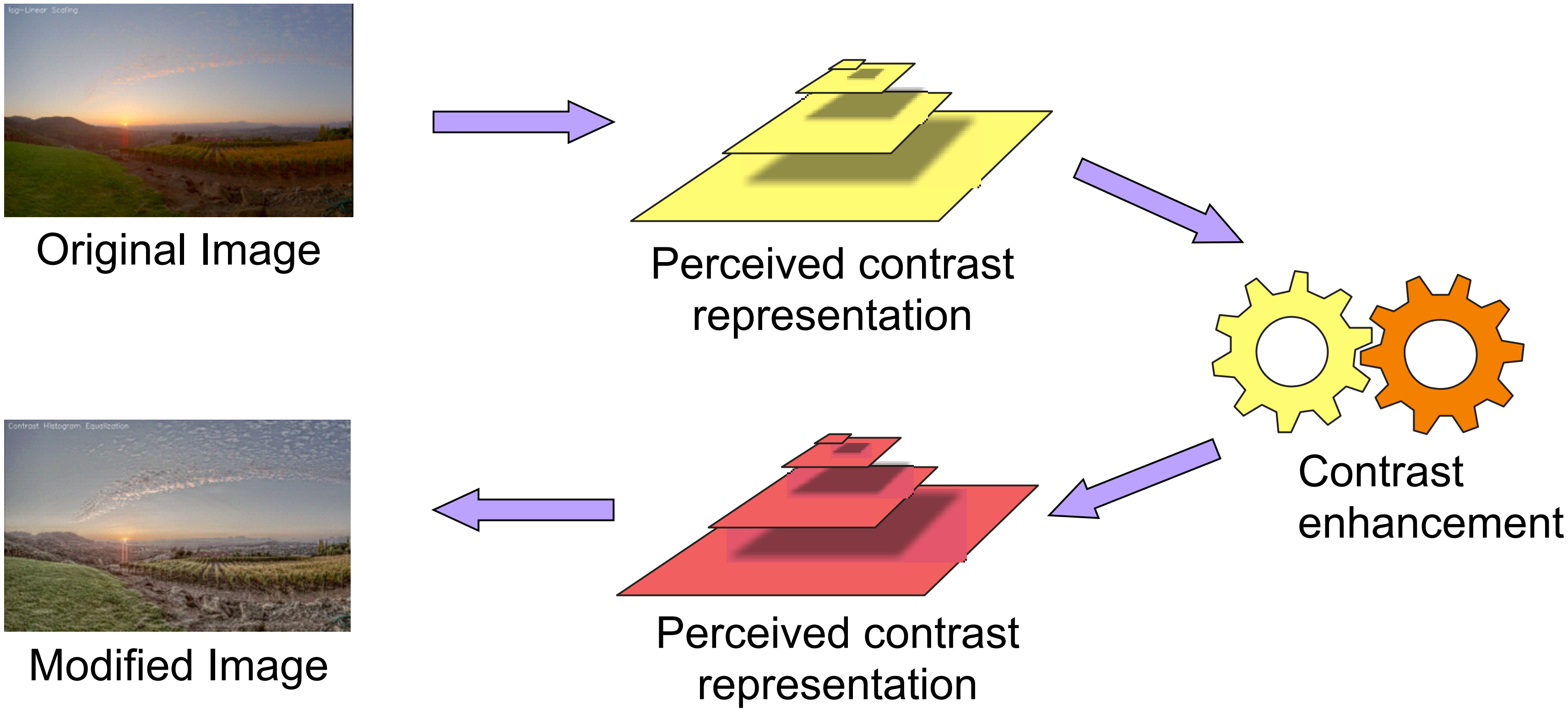
Forward and inverse visual model



Contrast domain image processing

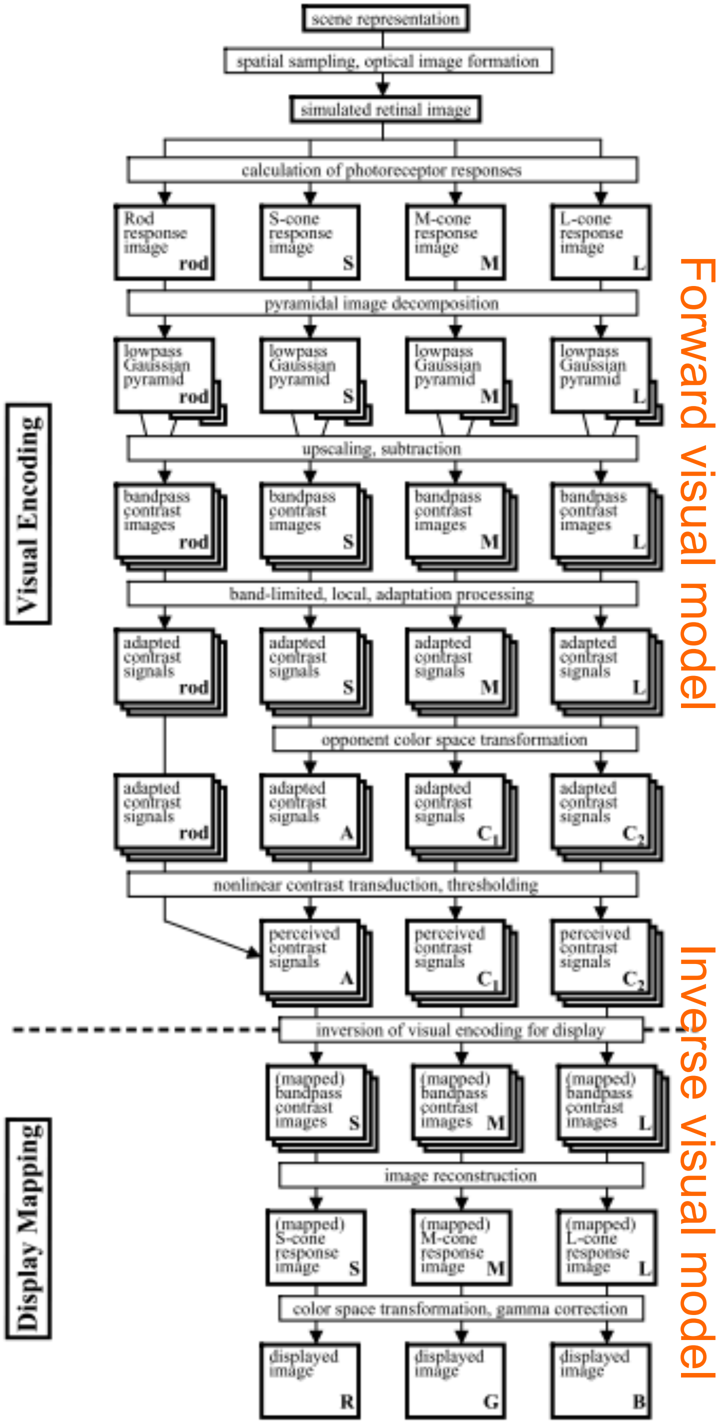
[Mantiuk et al., ACM Trans. Applied Perception, 2006]



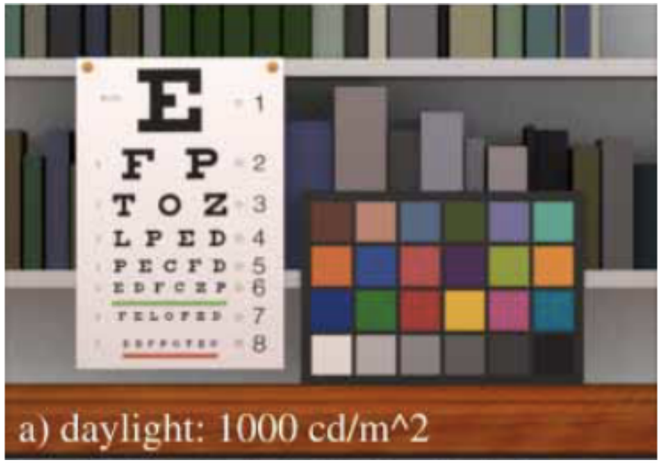
Rationale: Human eye is more sensitive to contrast than luminance

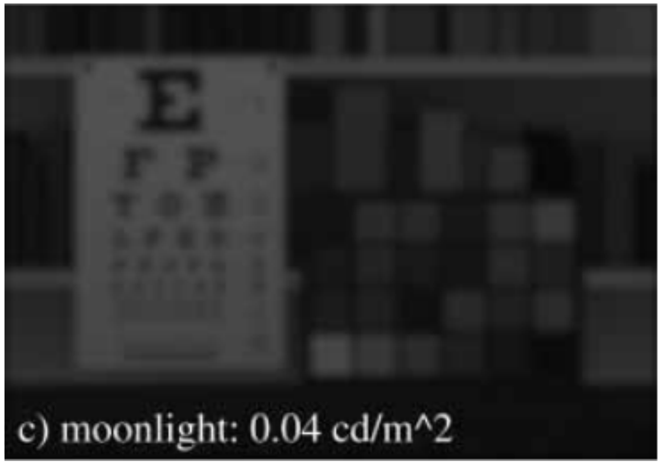
Multi-scale model

- Multi-scale model of adaptation and spatial vision and color appearance
  - [Pattanaik et al. ‘98]
- Combines
  - psychophysical threshold and superthreshold visual models
  - light & dark adaptation models
  - Hunt’s color appearance model
- One of the most sophisticated visual models



Results: multi-scale model …





Forward and inverse visual model

- Advantages of F&I visual models
  - Can render images for different viewing conditions
    - Different state of chromatic or luminance adaptation
  - Physically plausible
    - output in the units of luminance or radiance
- Shortcomings F&I visual models
  - Assume that a standard display can reproduce the impression of viewing much brighter or darker scenes
  - Cannot ensure that the resulting image is within the dynamic range of the display
    - Not necessary meant to reduce the dynamic range
  - Visual models are difficult to invert

Outline

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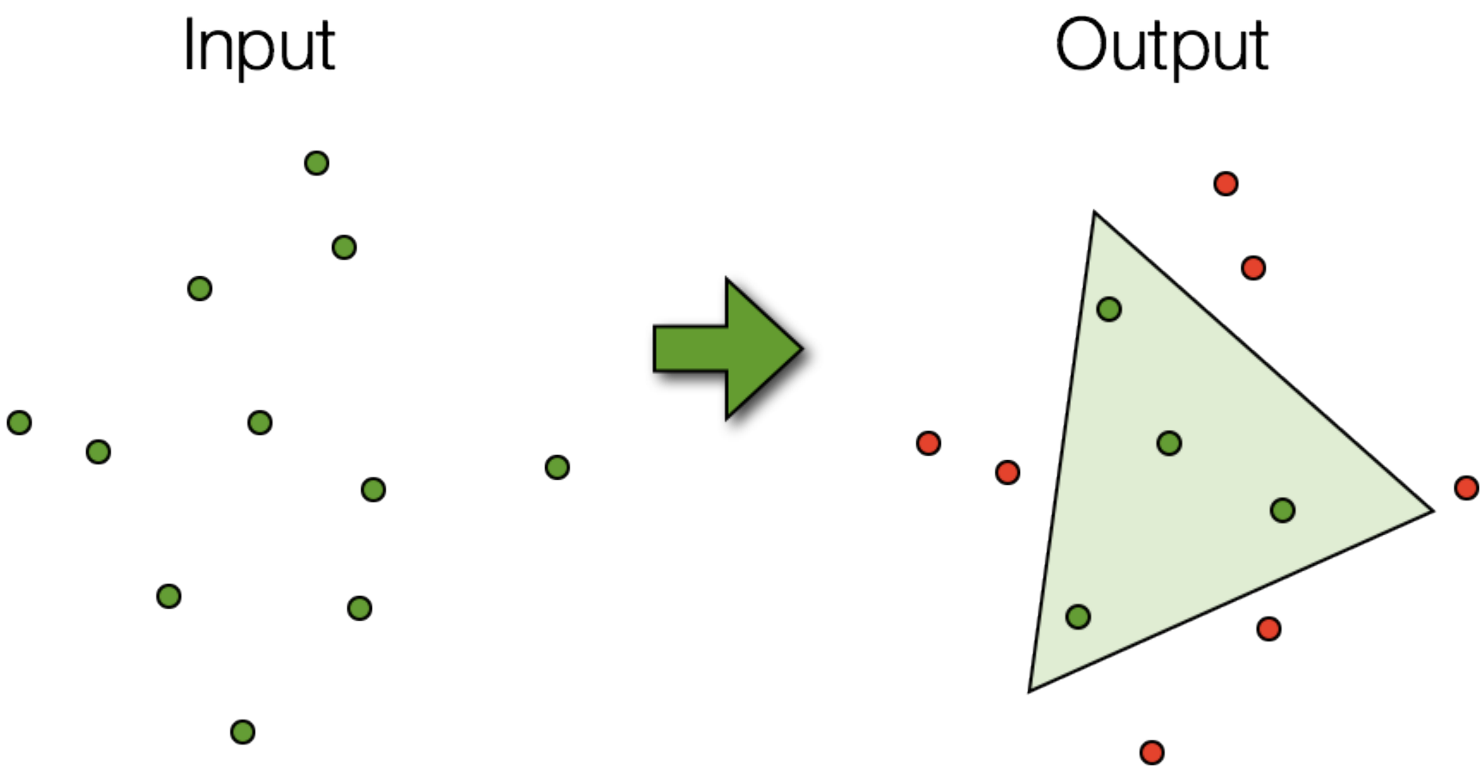
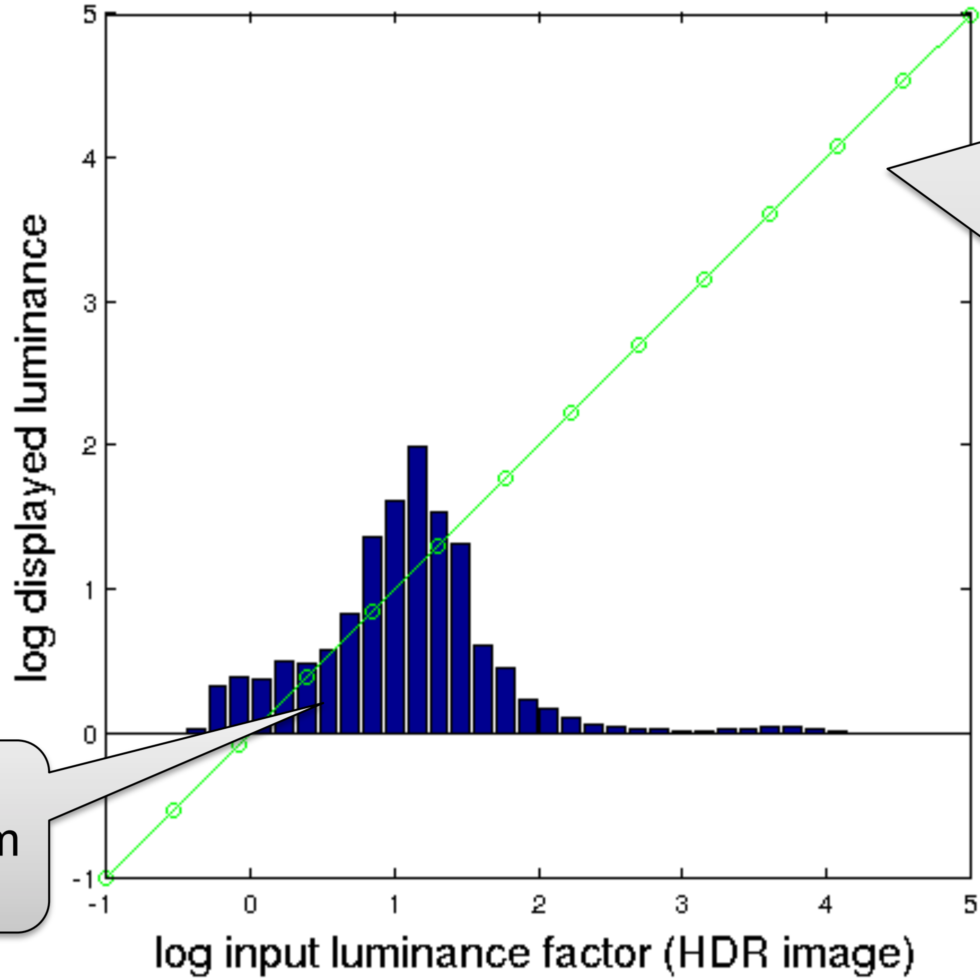
Constraint mapping problem

- Goal: to restrict the range of values while reducing inflicted damage



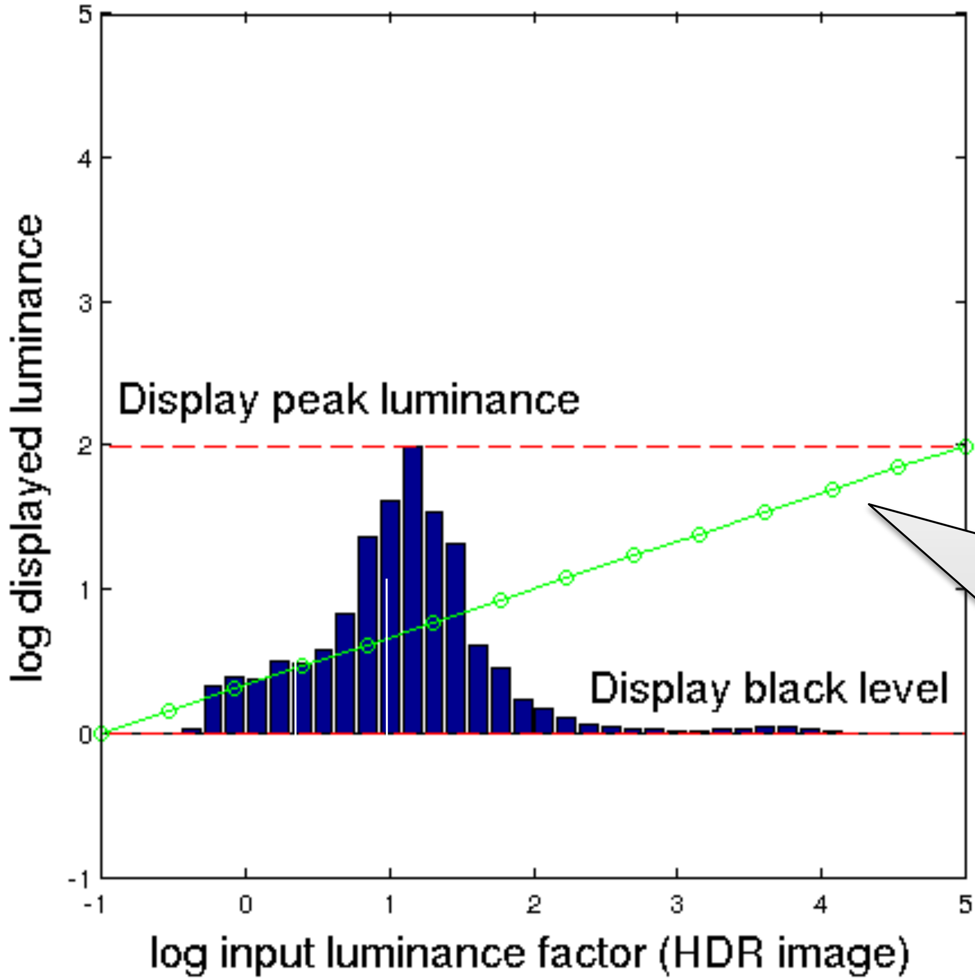
Global tone mapping operator



Best tone-mapping is the one which does not do anything, i.e. slope of the tone-mapping curves is equal to 1.

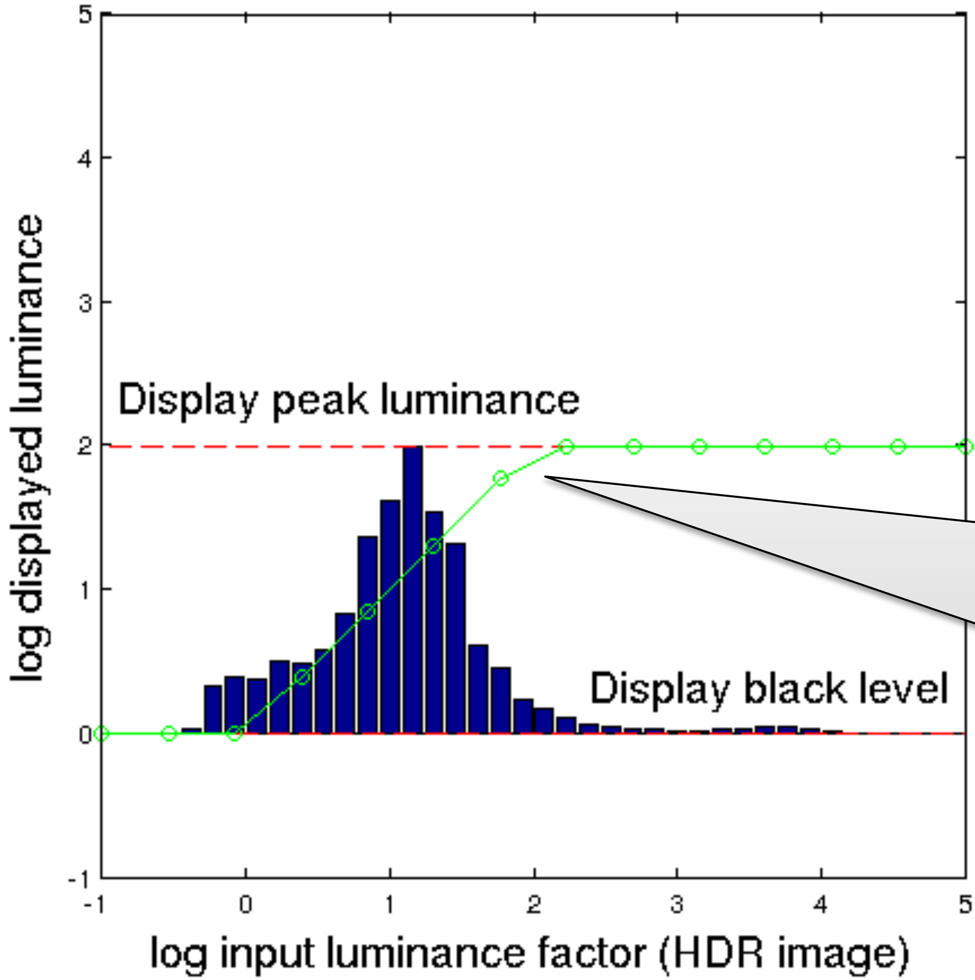
Image histogram

Display limitations



But in practice contrast (slope) must be limited due to display limitations.

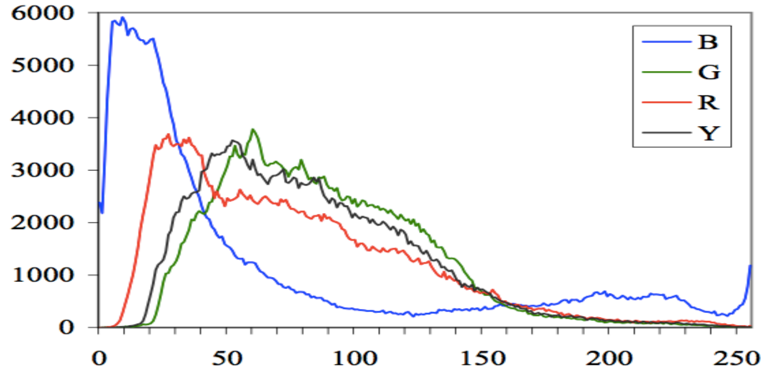
Tone mapping



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

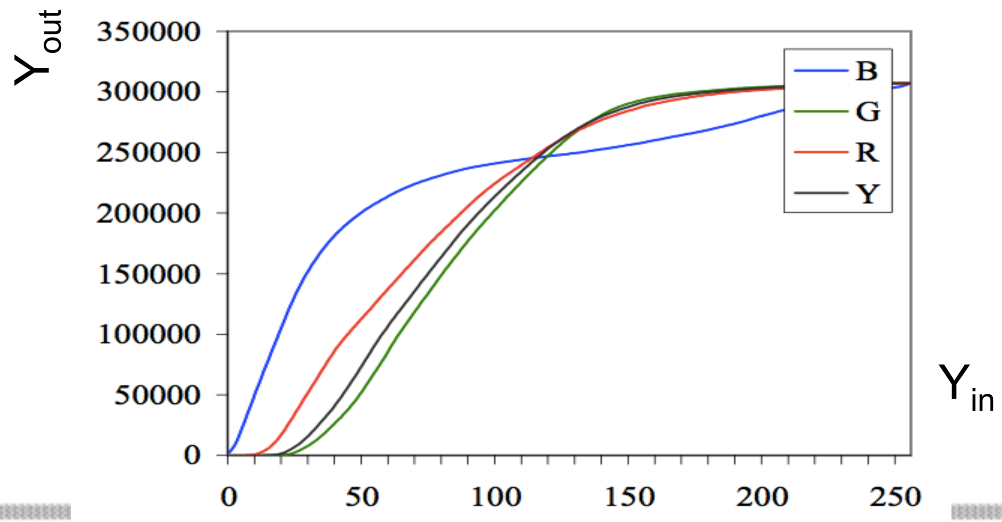
Histogram equalization

- 1. From histogram compute cumulative distribution funct.



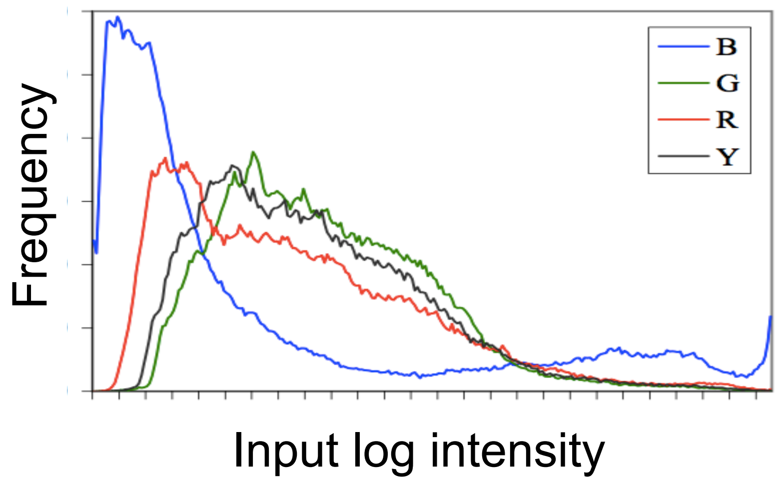
$$c(I) = \frac{1}{N} \sum_{i=0}^{I} h(i) = c(I-1) + \frac{1}{N} h(I)$$

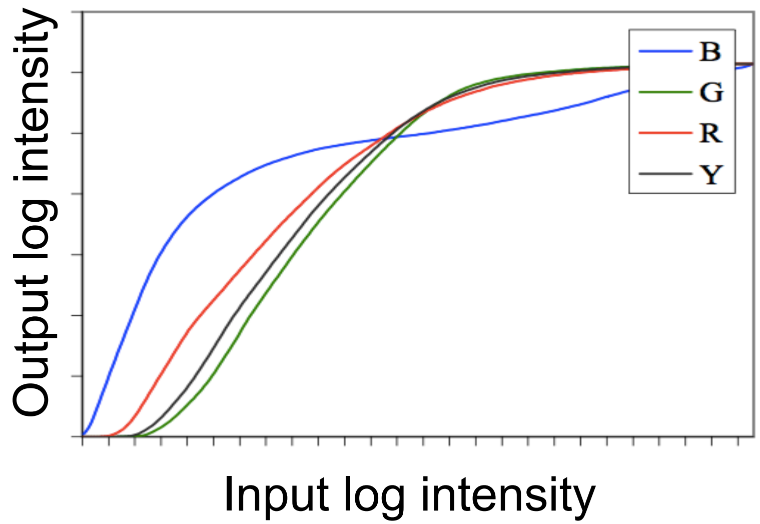
- 2. Use that function to assign new pixel values



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

Histogram equalization





- Steepest slope for strongly represented bins
  - Enhance contrast, if many pixels
  - Reduce contrast, if few pixels
- HE distributes contrast distortions relative to the “importance” of a brightness level

Histogram adjustment with a linear ceiling

- [Larson et al. 1997, IEEE TVCG]

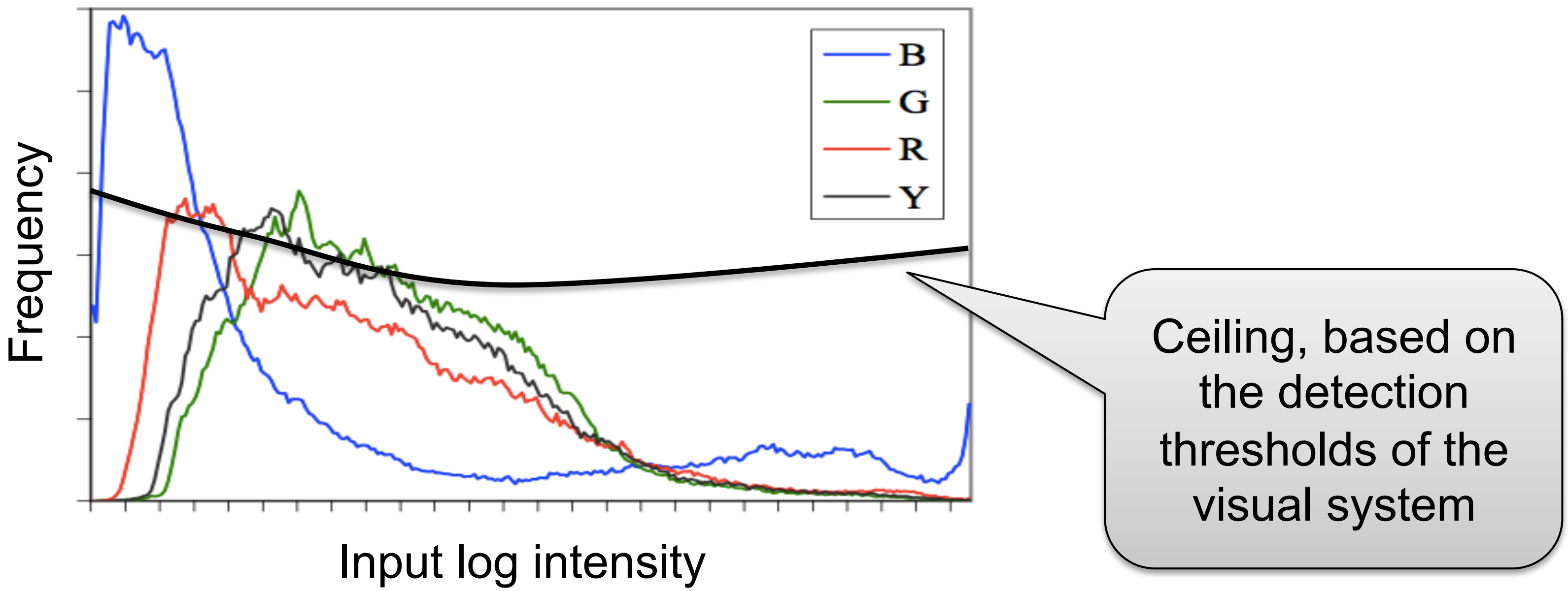
Linear mapping

Histogram equalization

Histogram equalization with ceiling

Histogram adjustment with a linear ceiling

- Truncate the bins that exceed the ceiling
- Recompute the ceiling based on the truncated histogram
- Repeat until converges

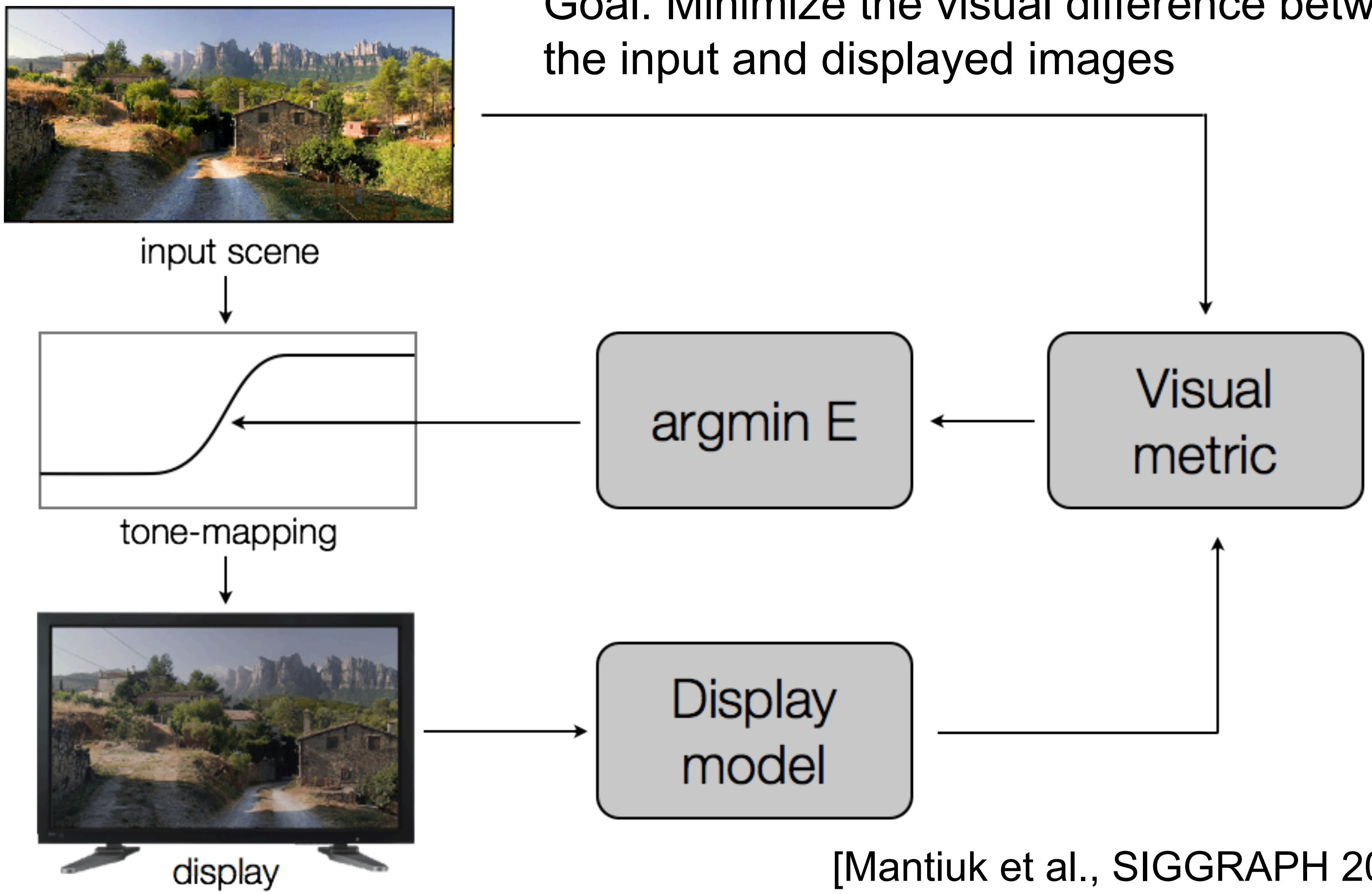


Task 8: Histogram equalization

- Implement histogram equalization of HDR images
- Operate on luminance only, then add color
- Operate in the $\log_{10}$ domain
- Rescale the result 0-2 (log domain) or 1-100 (linear domain)
- Use inverse display model to map from resulting luminance to pixel values
- Optional: implement capping histogram values, so that the maximum slope <= 1

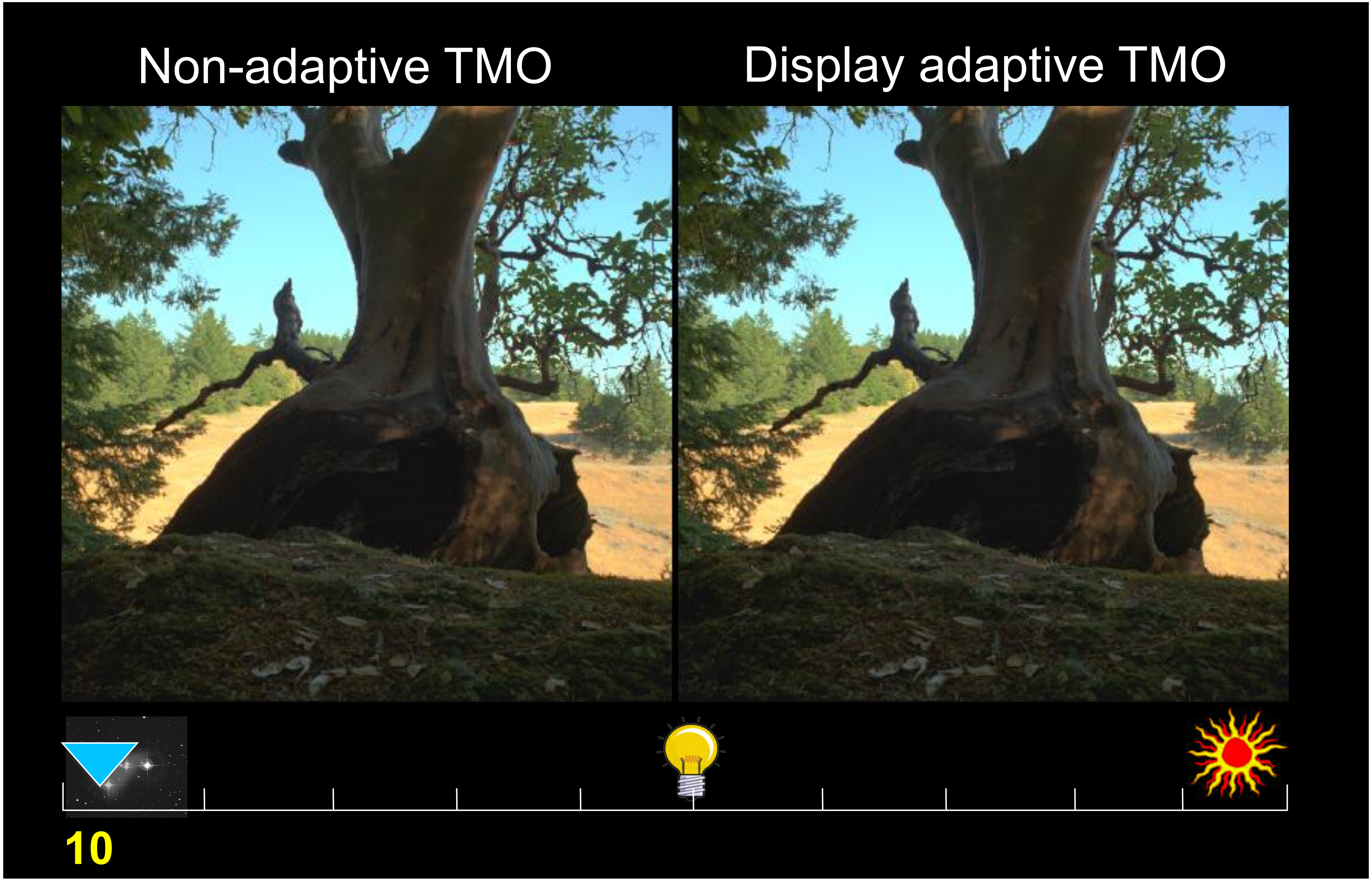
Display adaptive tone-mapping

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

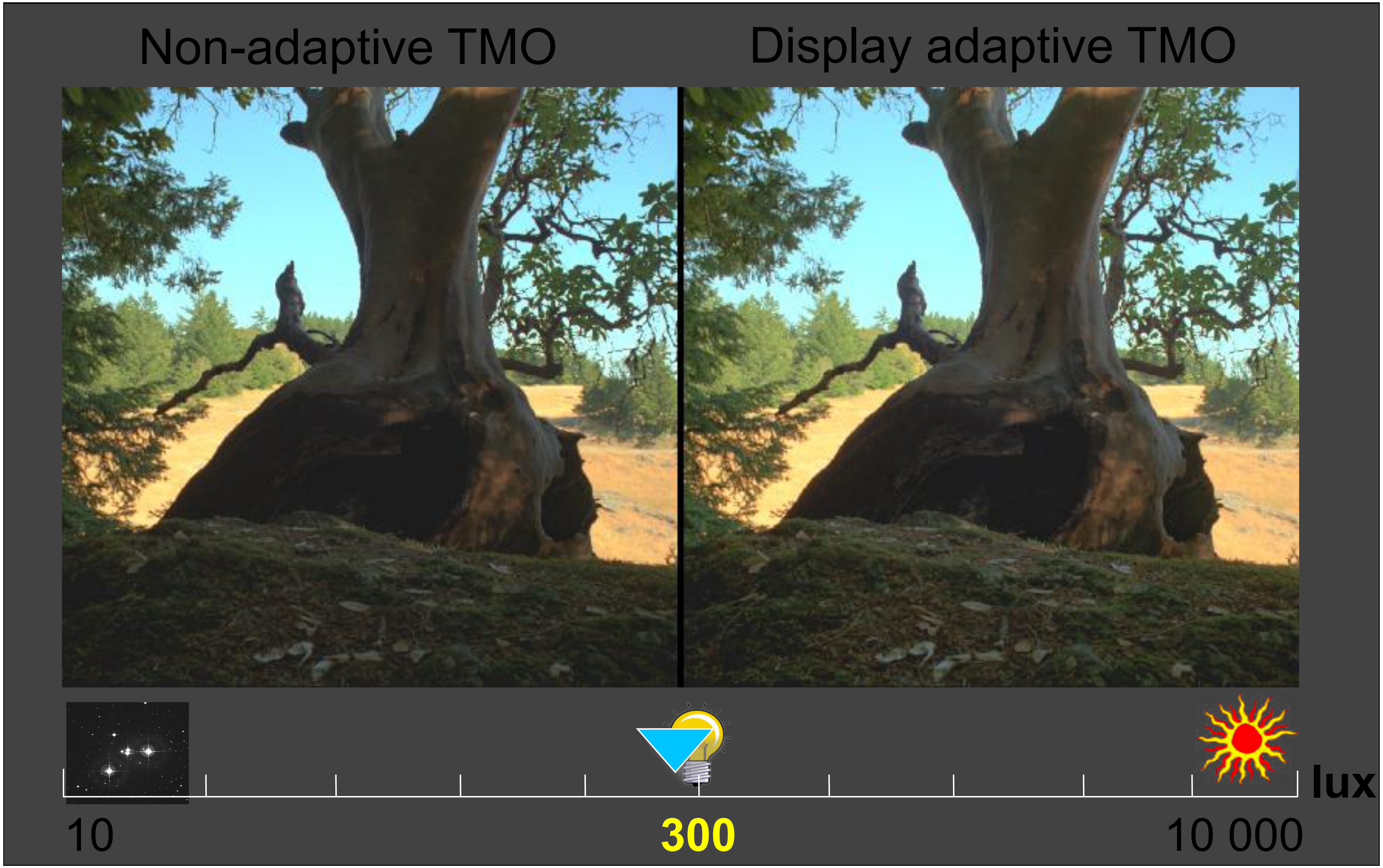


[Mantiuk et al., SIGGRAPH 2008]

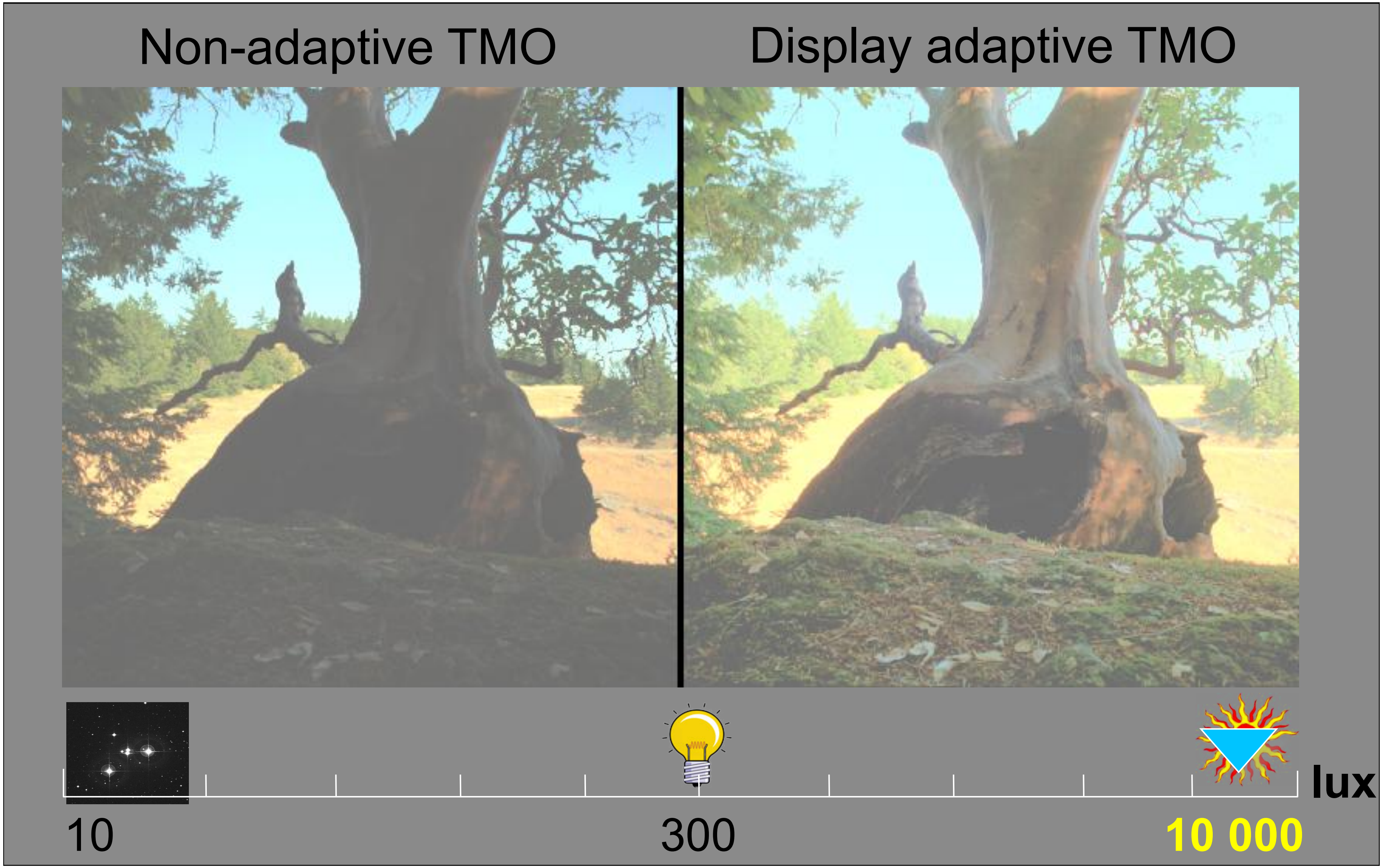
Results: ambient illumination compensation



Results: ambient illumination compensation

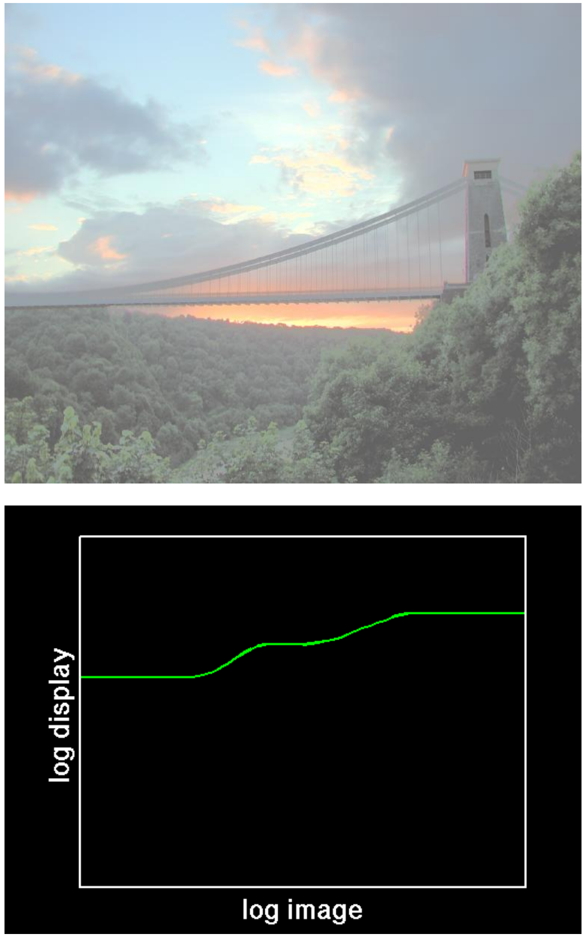


Results: ambient illumination compensation



Results: display contrast

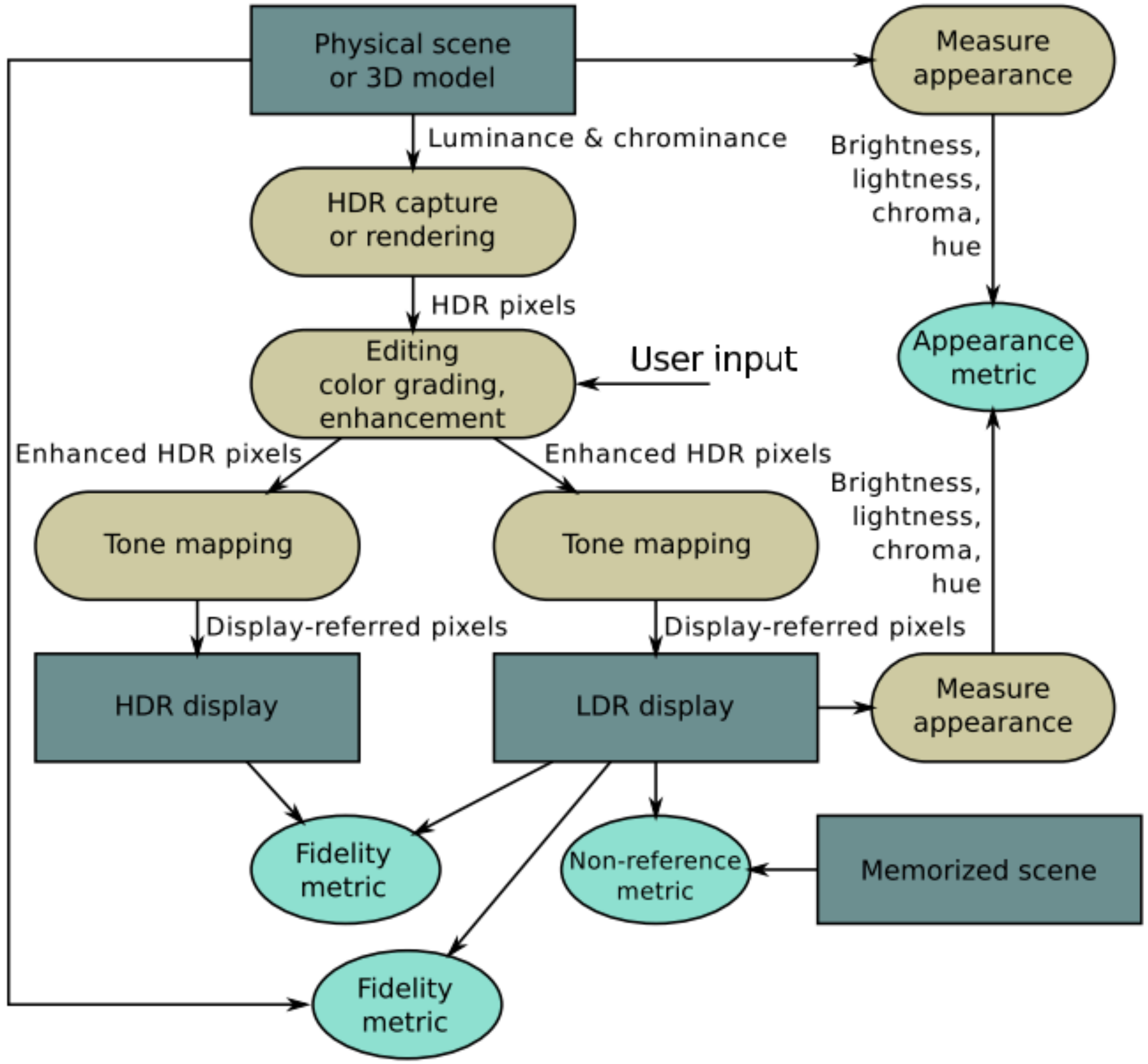
ePaper



standard LCD

HDR display

Evaluation of tone-mapping

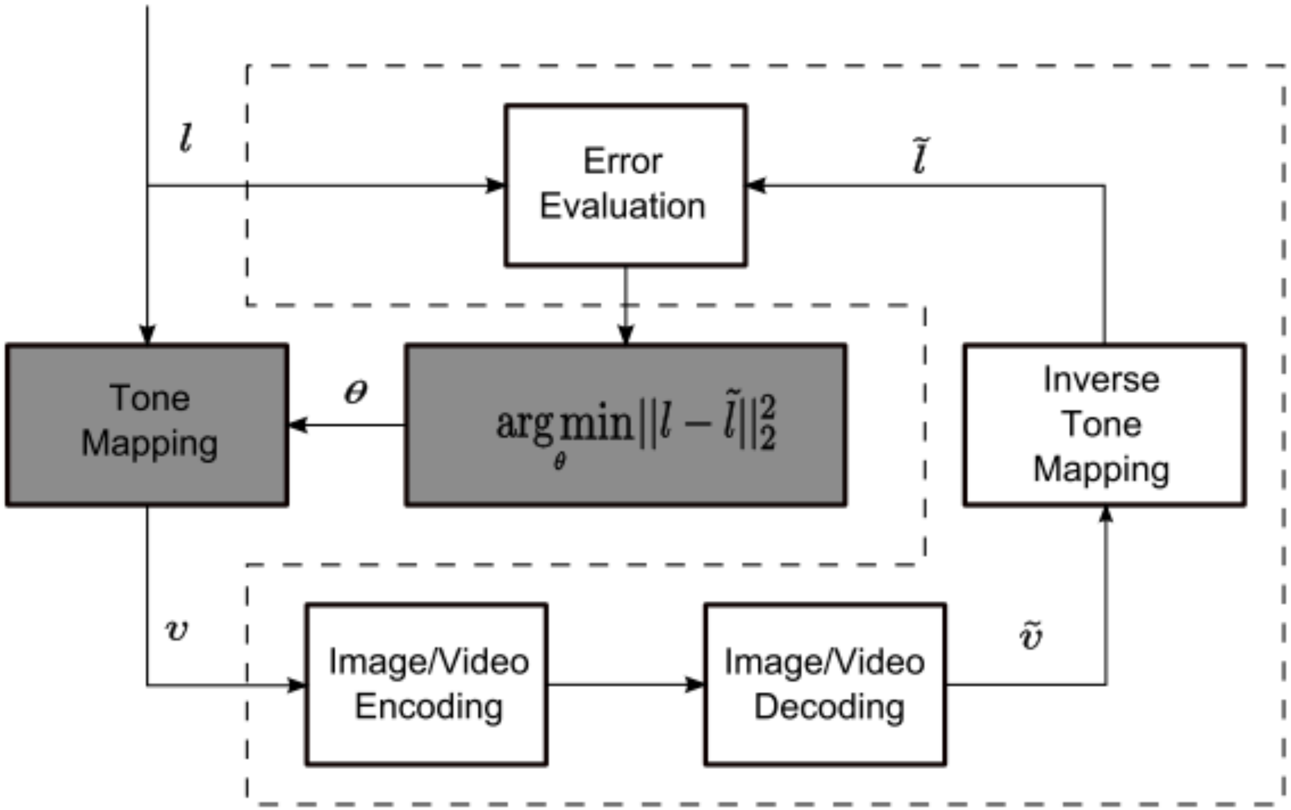


From: Eilertsen et al. Evaluation of Tone Mapping Operators for HDR-Video. Comp. Grap. Forum, 32(7).

Tone-mapping for video compression

- Find the tone-curve that minimizes distortion in a backward-compatible HDR video encoding

[Mai et al., IEEE TIP 2010]



Closed-form solution:

$$s_k = \frac{v_{max} \cdot p_k^{1/3}}{\delta \cdot \sum_{k=1}^{N} p_k^{1/3}}$$

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Which tone-mapping to choose?

- Illumination & reflectance separation
- Forward visual model
- Forward & inverse visual model
- Constraint mapping problem

1. Think what is the target application
   - and thus the goal of your tone-mapping
2. Consider which tone-mapping approach(es) and intents will deliver that goal

Future of tone-mapping

Tone-mapping of today

- Built into cameras
- Assumes that all displays are the same

Tone-mapping of tomorrow

- Display tone-maps content on demand
- Depending on viewing conditions, viewer, its capabilities
- Content recorded, stored and transmitted in an HDR format

Thank you