High dynamic range in VR

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These slides are a part of the tutorial

Cutting-edge VR/AR Display Technologies (Gaze-, Accommodation-, Motion-aware and HDR-enabled)

Presented at IEEE VR in Reutlingen on the 18th of March 2018

The latest version of the slides and the slides for the remaining part of the tutorial can be found at:

https://vrdisplays.github.io/ieeevr2018/

HDR & VR ?

- Do we have HDR VR headsets?

http://www.oculusvr.com/

- OLED contrast 1,000,000:1

ToC & Benefits

- HDR in a nutshell
- Display technologies in VR
- Perception & image quality

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:

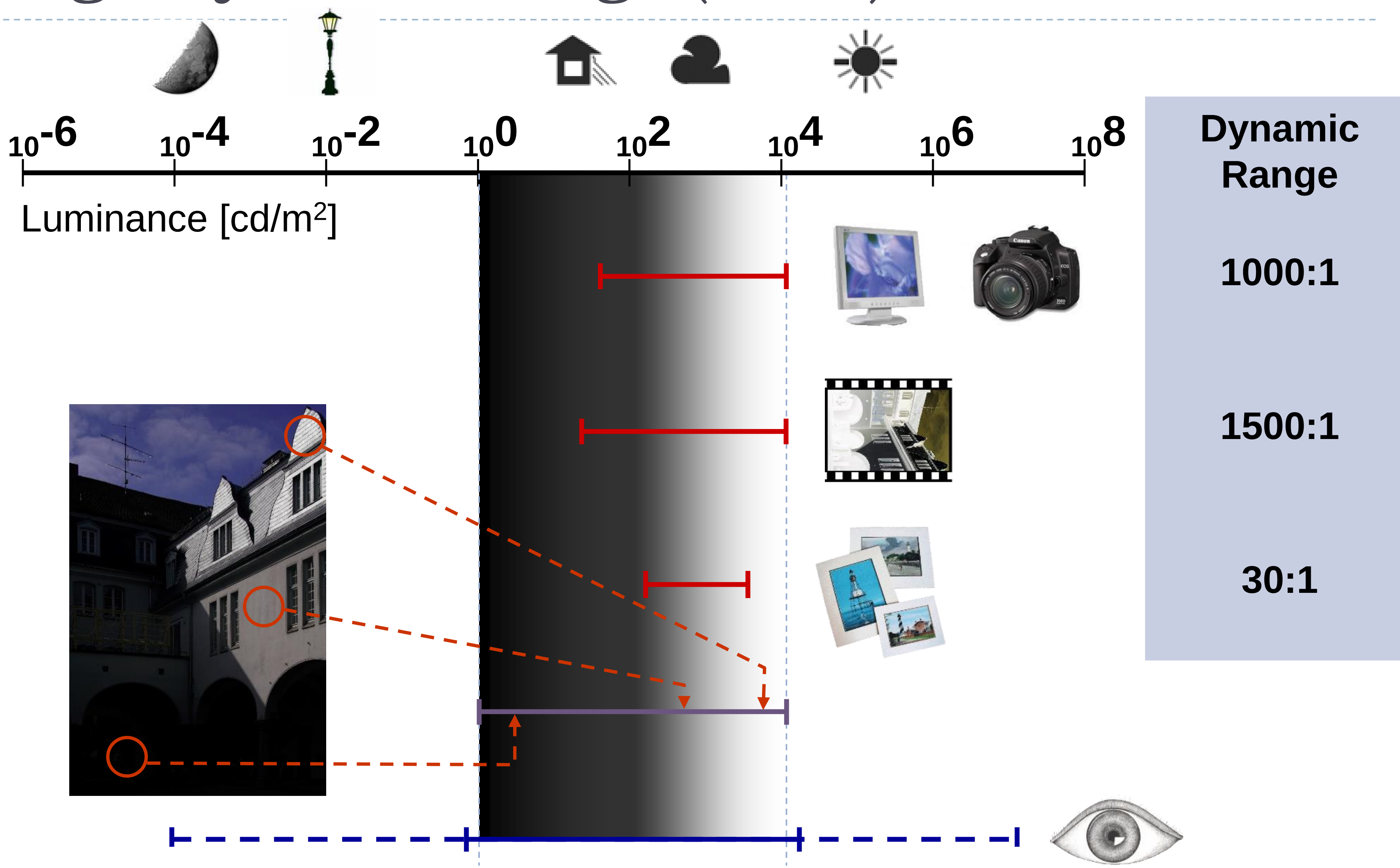
$$C_{10} = \log_{10} \frac{L_{\max}}{L_{\min}}$$

- As stops:

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

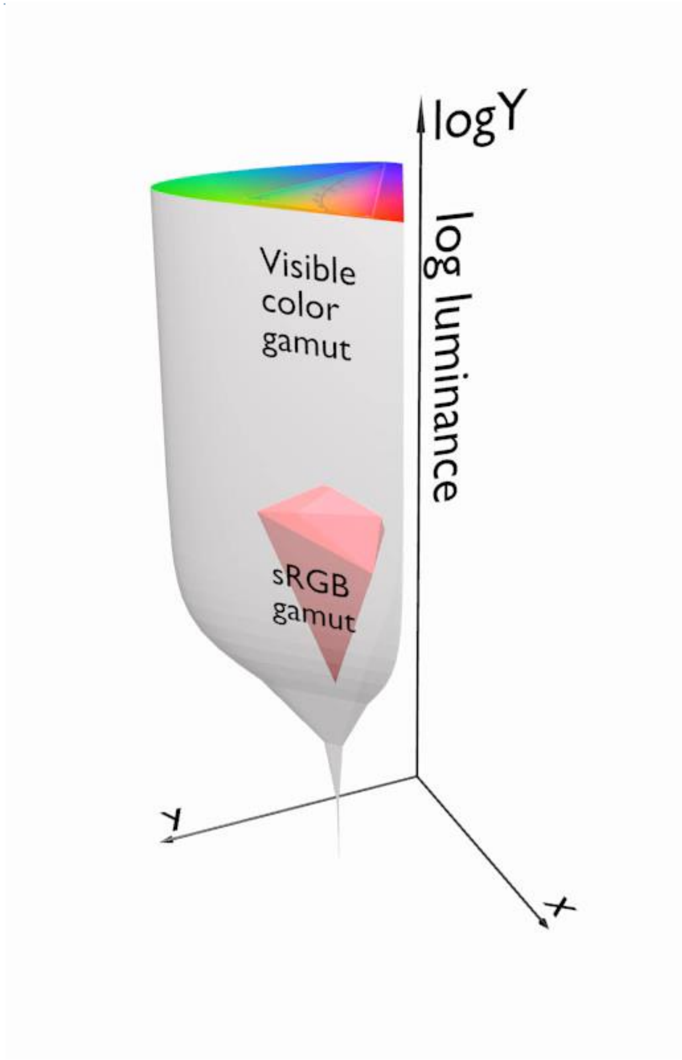
One stop is doubling of halving the amount of light

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



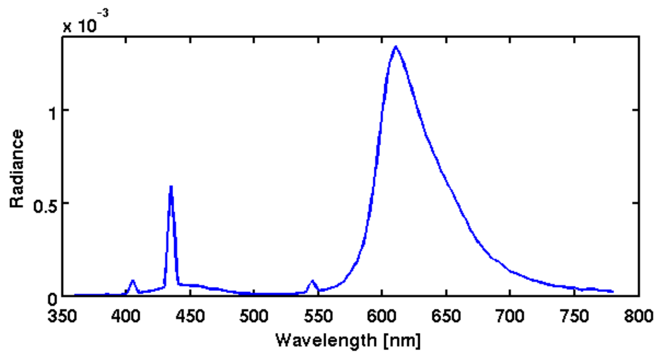
Luminance

- Luminance – how bright the surface will appear regardless of its colour. Units: cd/m²

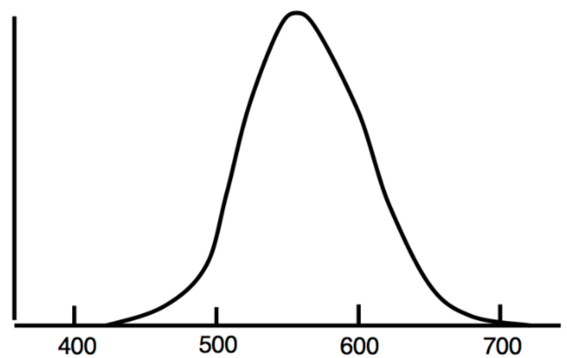
Luminance

$$L_V = \int_{350}^{700} kL(\lambda)V(\lambda)d\lambda \qquad k = \frac{1}{683.002}$$

Light spectrum (radiance)



Luminous efficiency function (weighting)



Luminance and Luma

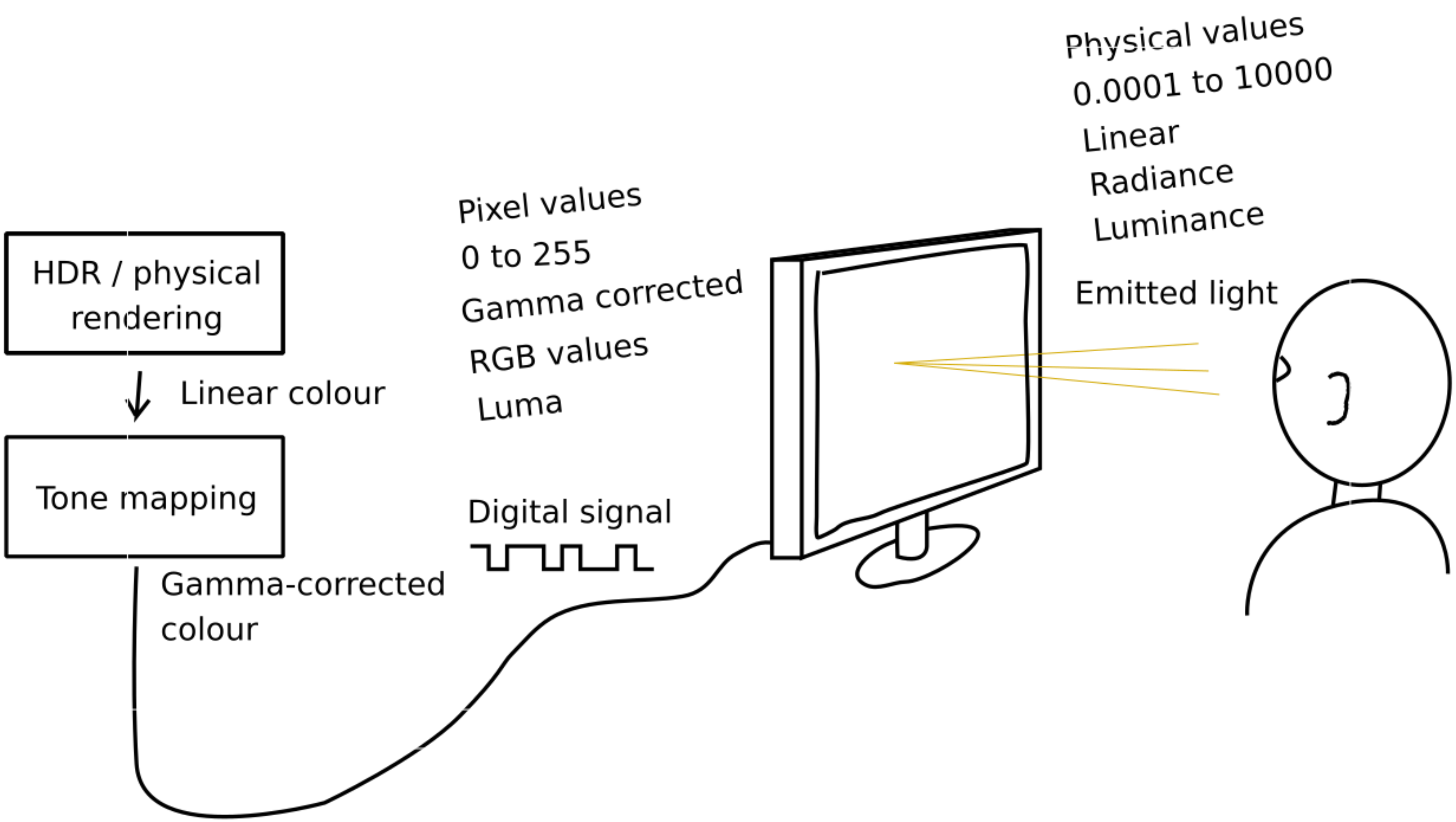
- Luminance
  - Photometric quantity defined by the spectral luminous efficiency function
- $L \approx 0.2126\ R + 0.7152\ G + 0.0722\ B$
- Units: cd/m^2

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

$$R' = R^{1/g}$$

- Unitless

Linear vs. gamma-corrected values



Sensitivity to luminance

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

Ernst Heinrich Weber
[From wikipedia]

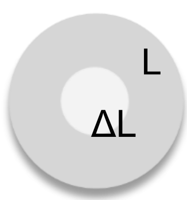
The smallest detectable luminance difference

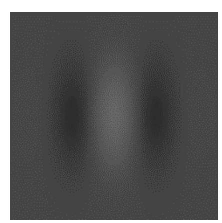
$$\frac{\Delta L}{L} = k$$

Background (adapting) luminance

Constant

Typical stimuli:





Consequence of the Weber-law

- Smallest detectable difference in luminance

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

For k=1%

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, luminance values are **not** perceptually uniform!

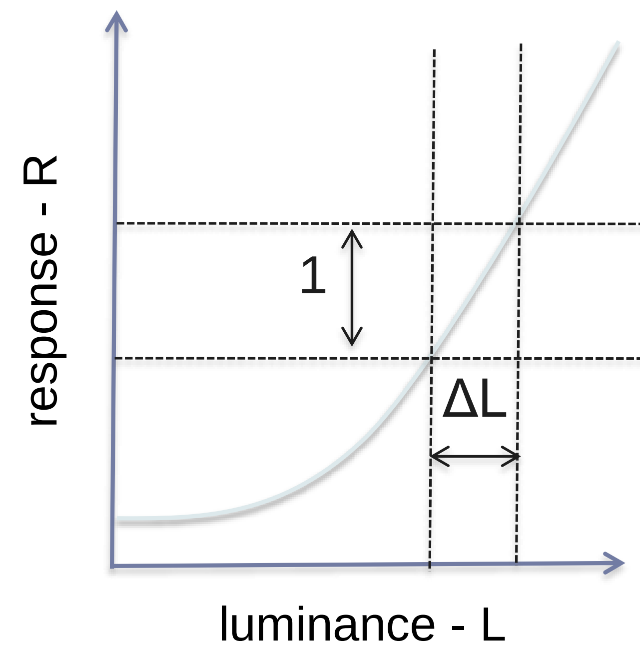
How to make luminance (more) perceptually uniform?

- Using "Fechnerian" integration

$$\frac{dR}{dl}(L) = \frac{1}{DL(L)}$$

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:

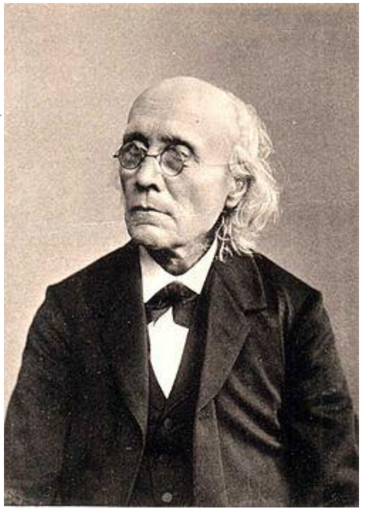
$$R(L) = \int \frac{1}{kL} dL = \frac{1}{k} \ln(L) + k_1$$

Fechner law

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

- Response of the visual system to luminance is **approximately** logarithmic

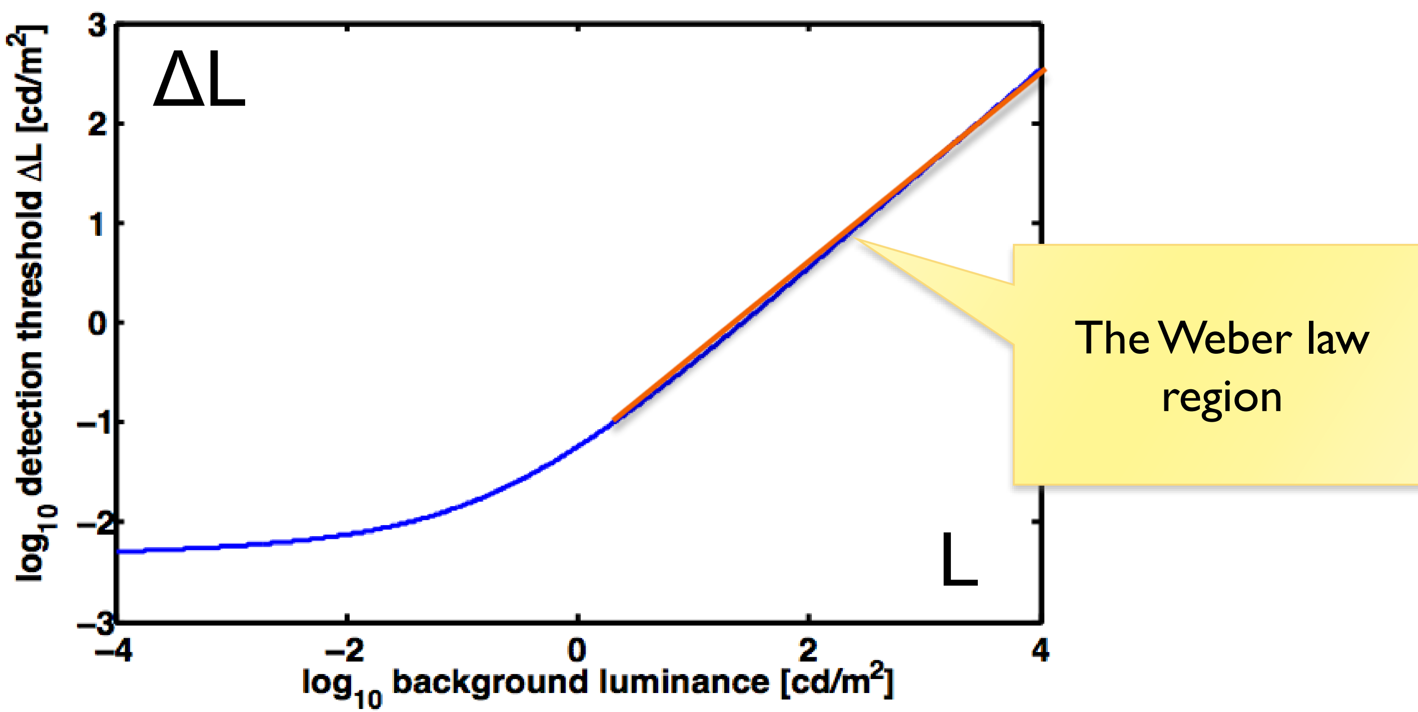
- The values of HDR pixel values are much more intuitive when they are plotted / considered / processed in the logarithmic domain



Gustav Fechner
[From Wikipedia]

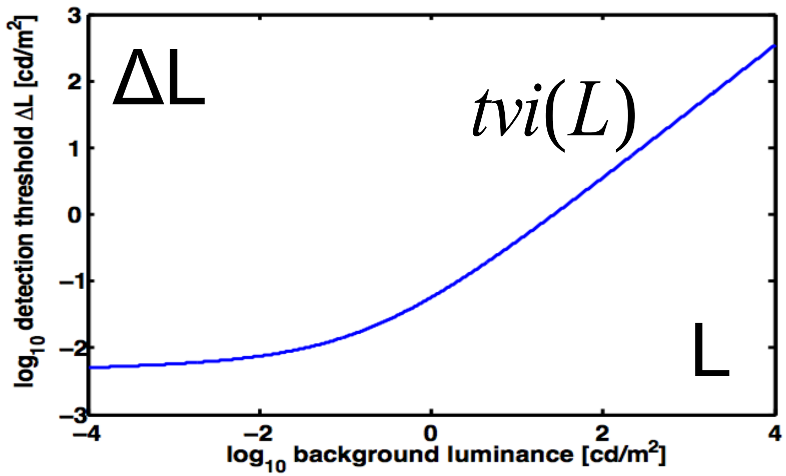
But…the Fechner law does not hold for the full luminance range

- 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:

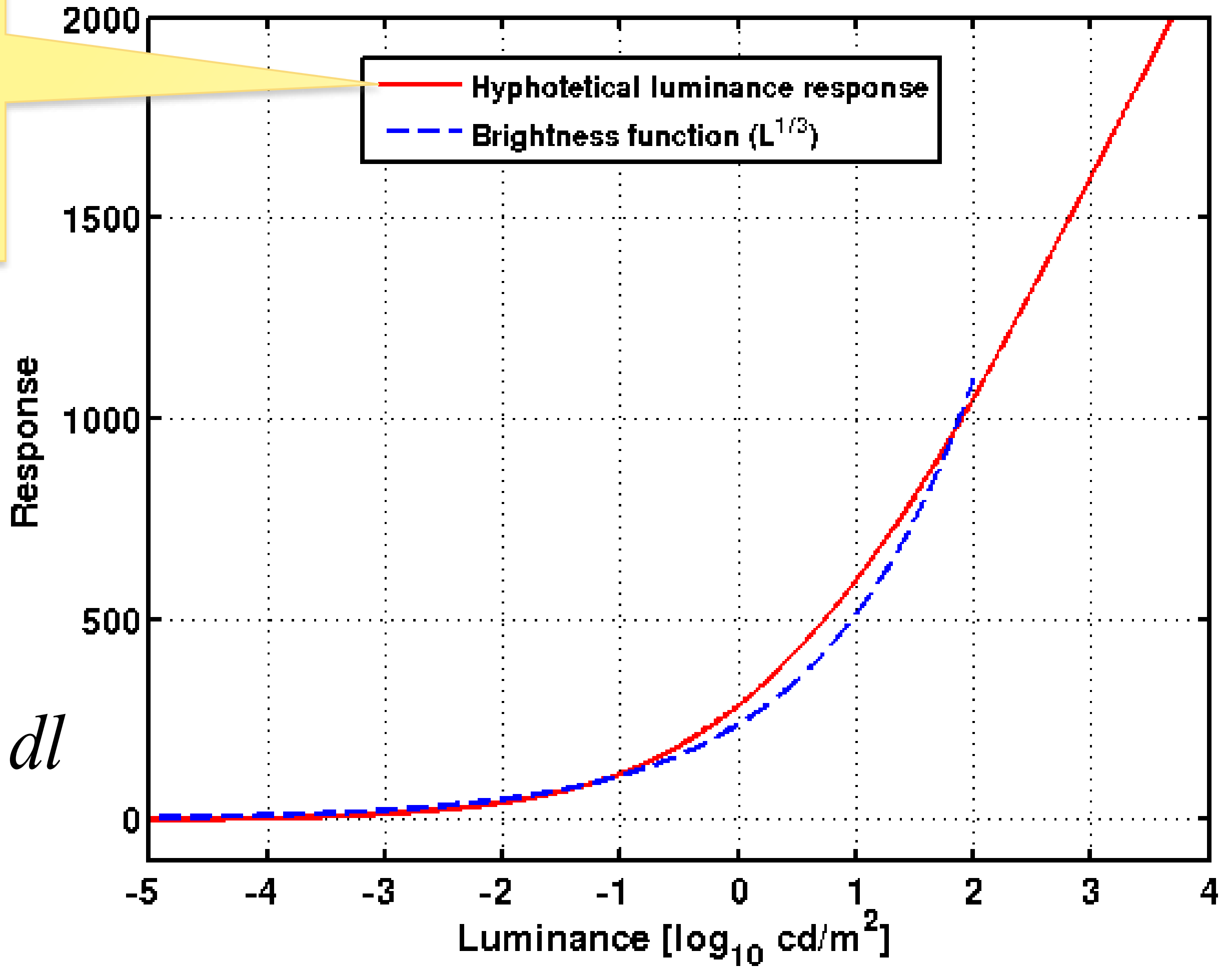


- we can get more accurate estimate of the "response":

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

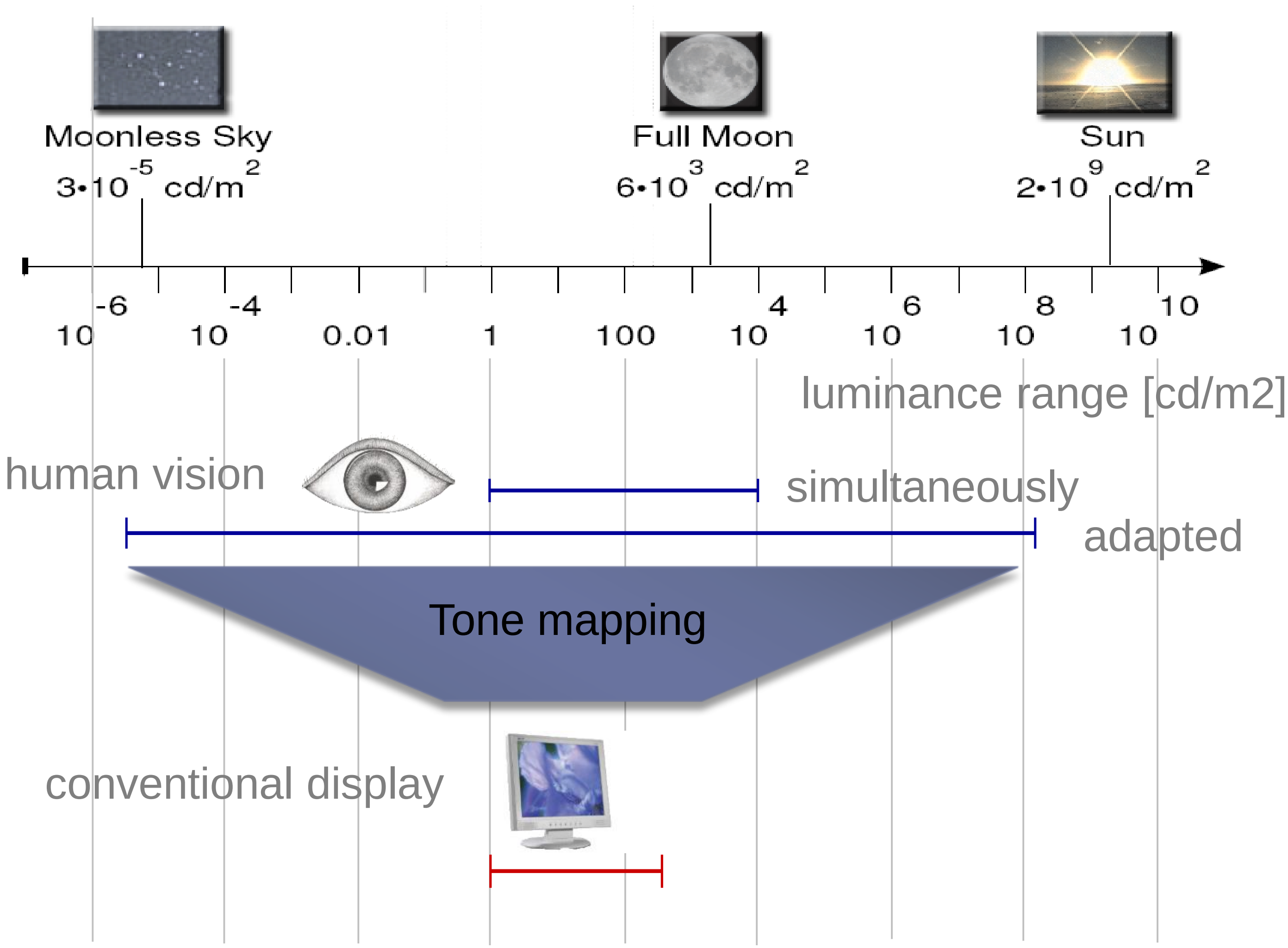
Fechnerian integration and Stevens' law

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



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

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

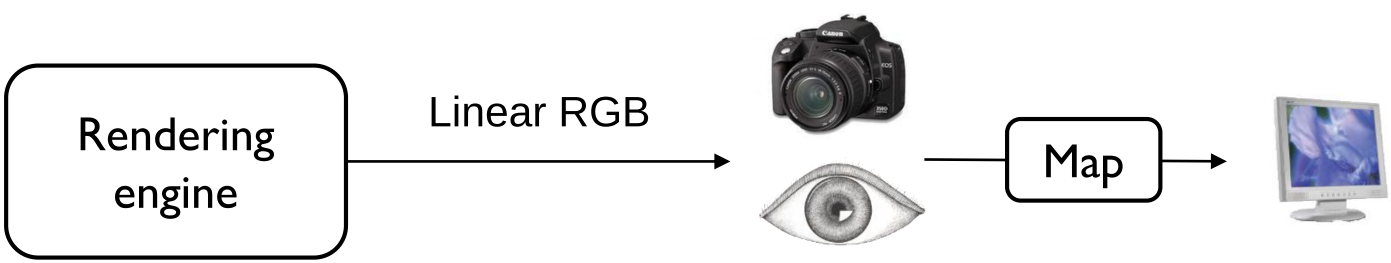
- To adapt displayed images to a display and viewing conditions
- To make rendered images look more realistic

- Different tone mapping techniques achieve different goals

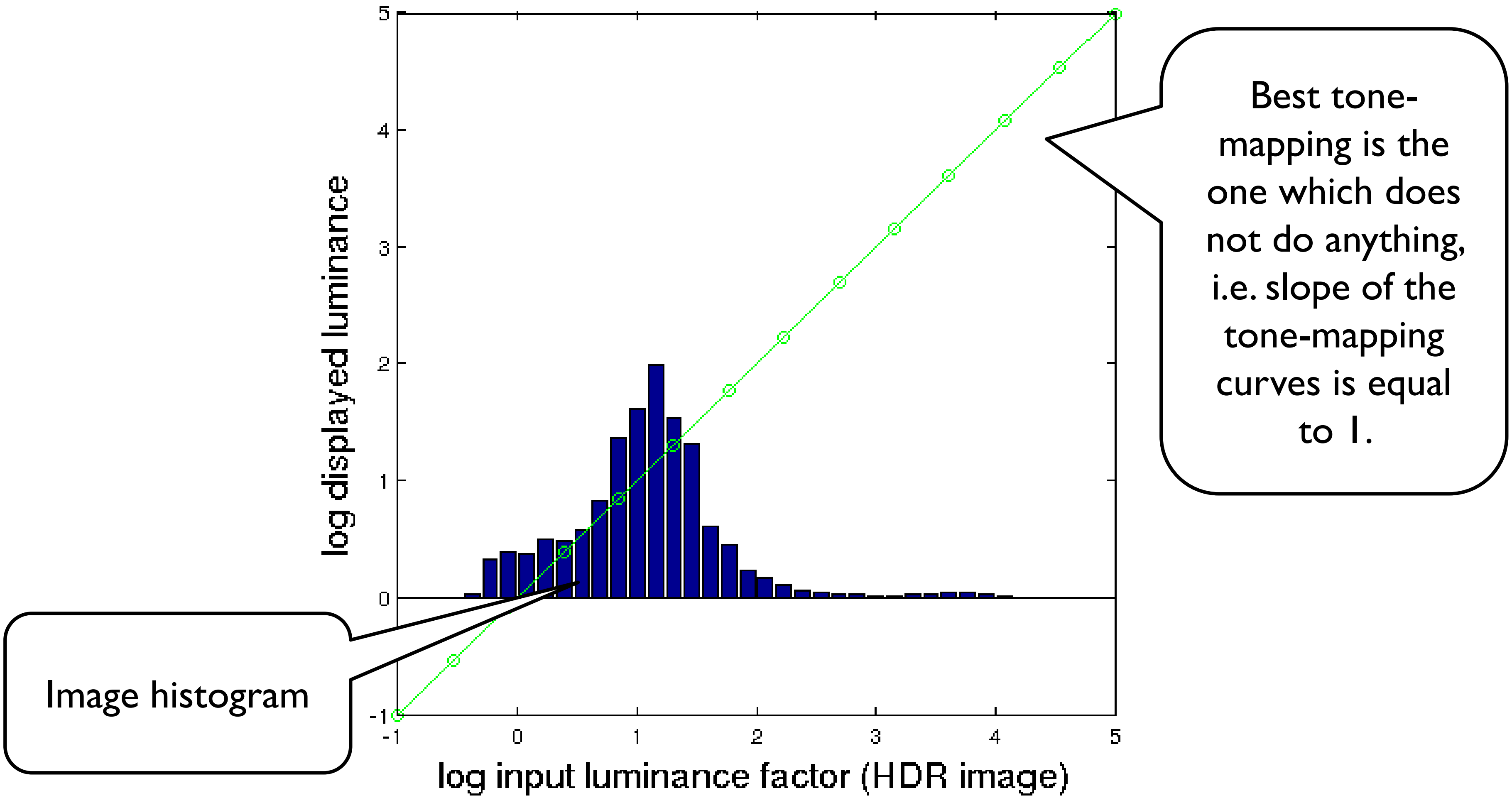
Tone-mapping in rendering

- 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

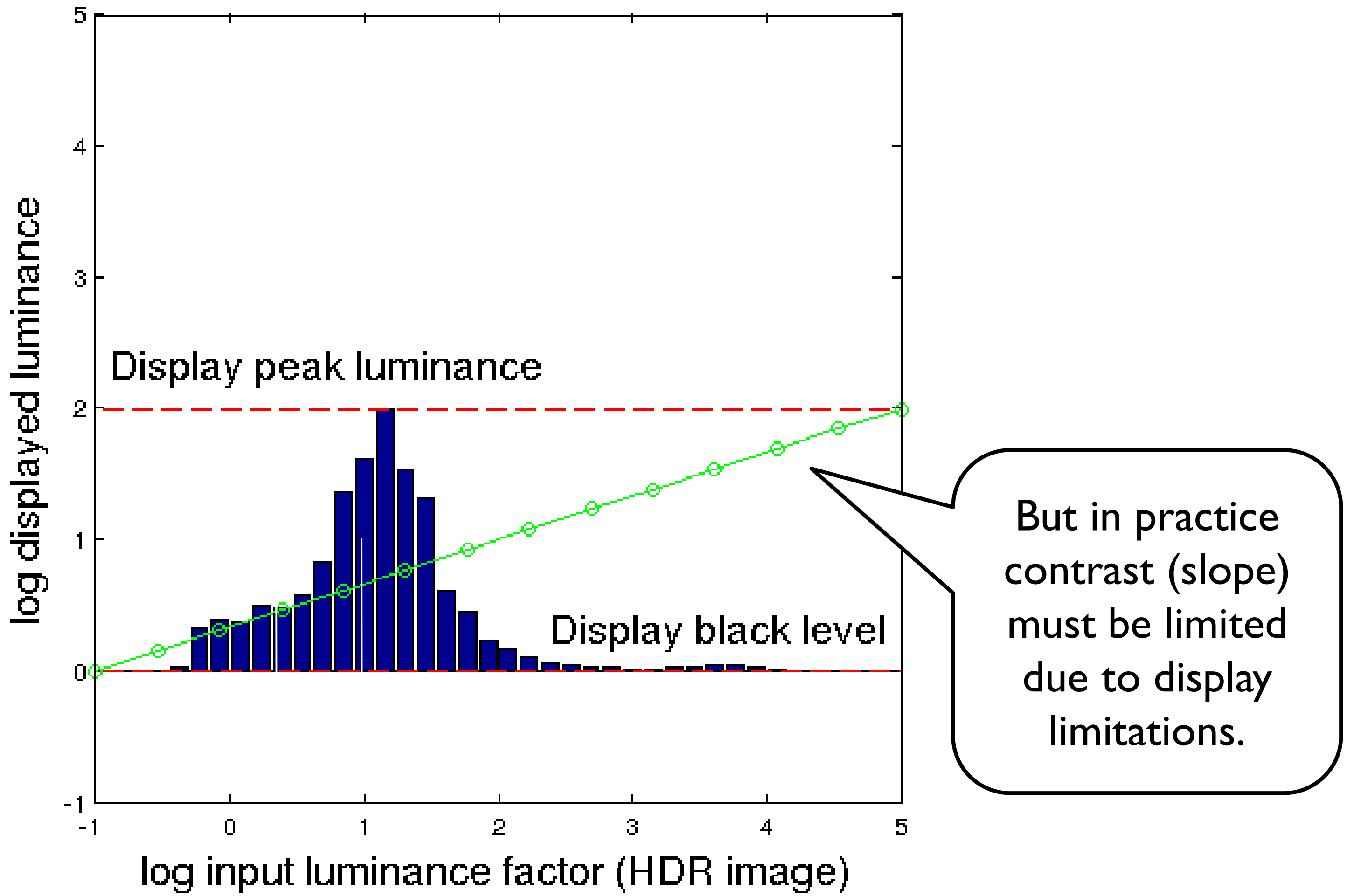
Half-Life 2: Lost coast



Tone-curve

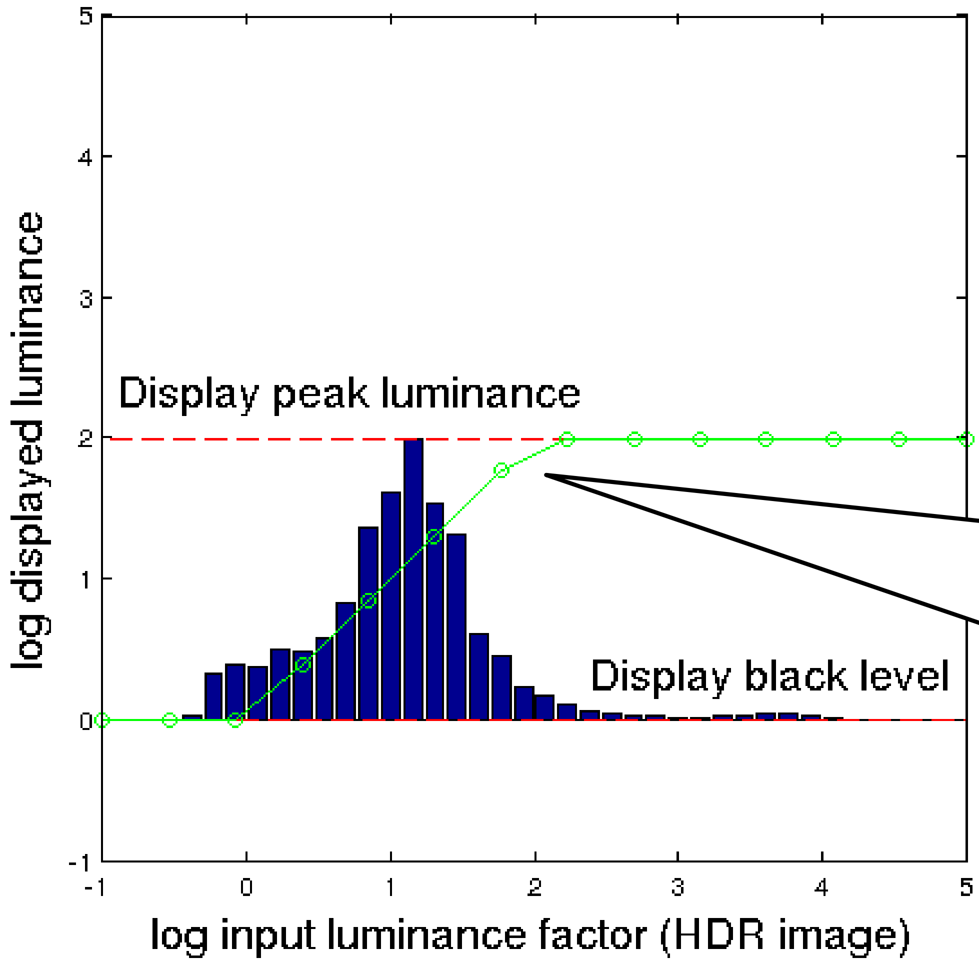

5
4
3
2
1
0
-1
-1
0
1
2
3
4
5
log displayed luminance
log input luminance factor (HDR image)
Image histogram
Best tone-mapping is the one which does not do anything, i.e. slope of the tone-mapping curves is equal to 1.

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.

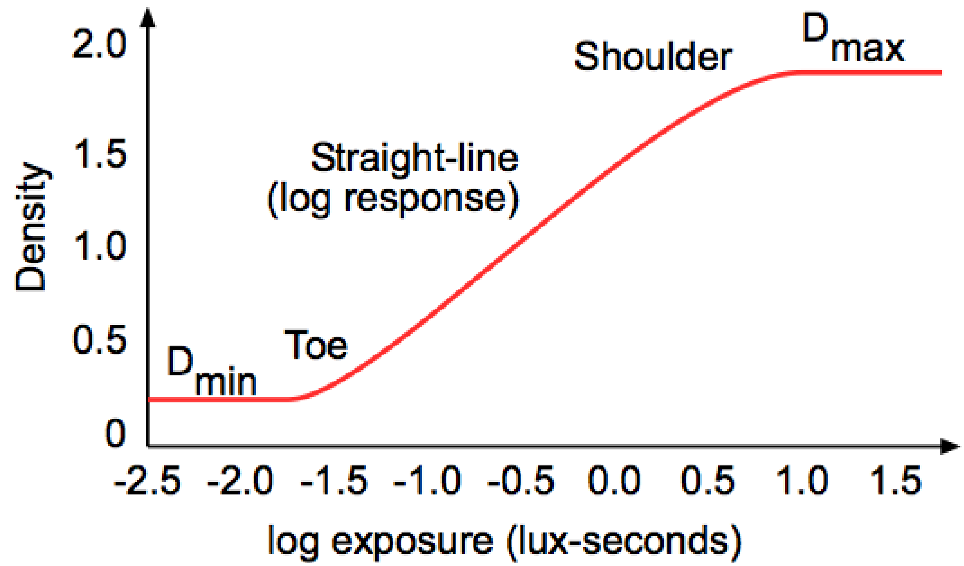
Tone-curve



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

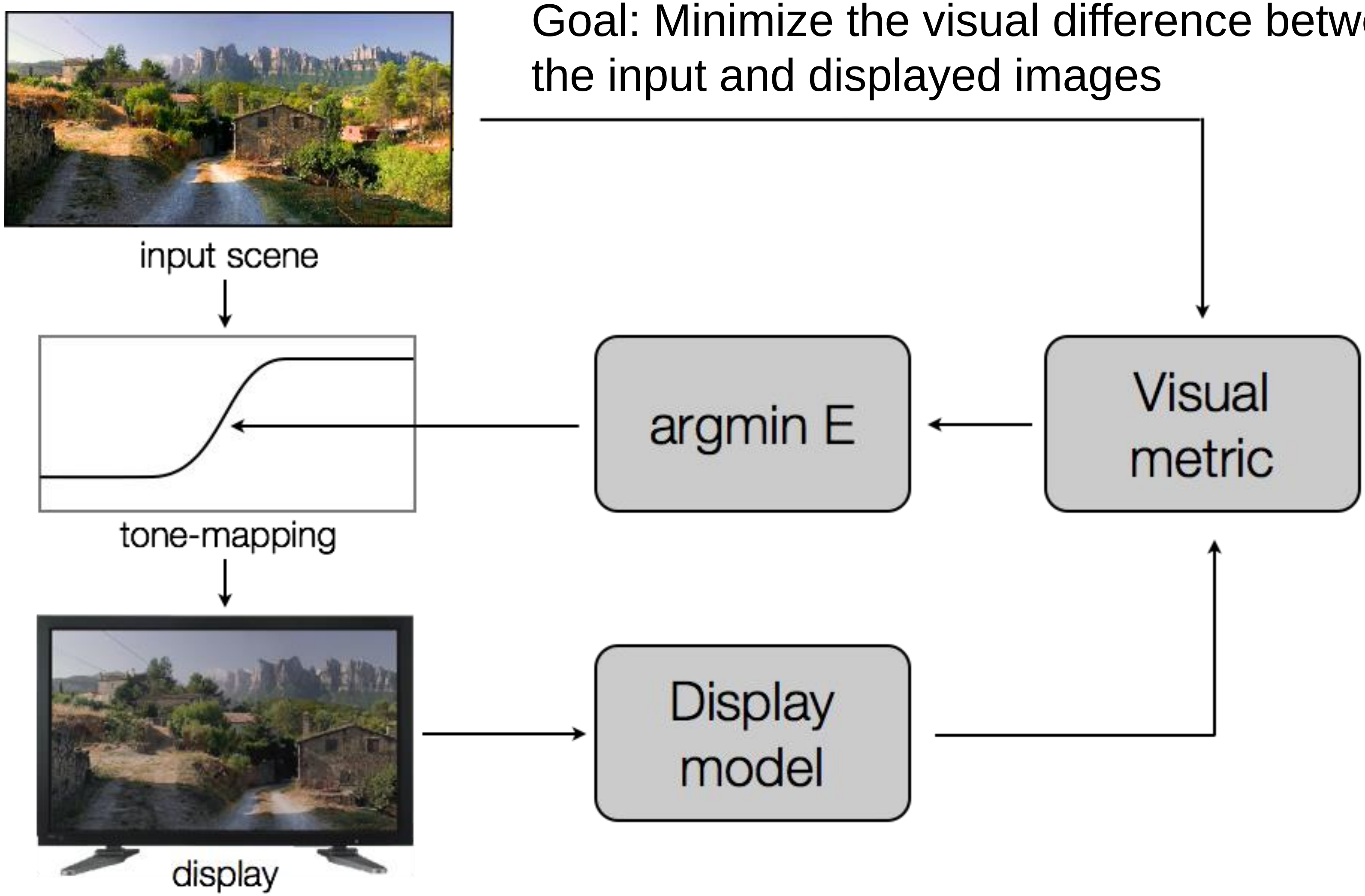
Sigmoidal tone-curves

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



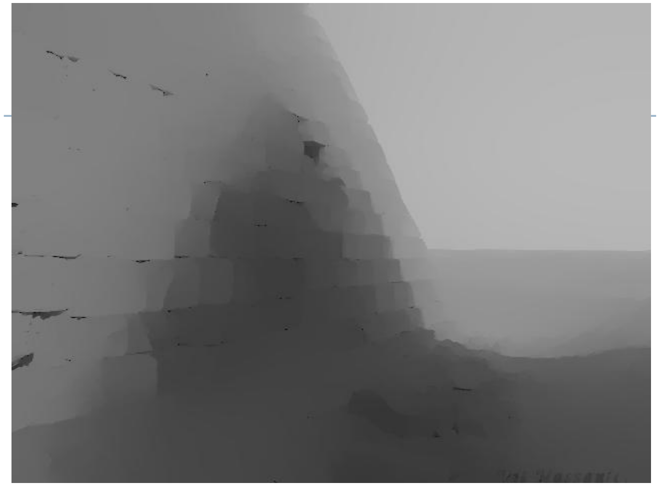
Tone-curve as an optimization problem

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



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

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

Tone-mapped image (L_d), Reflectance (R), Tone-mapping (T), Illumination (I)

- for example:

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

How to separate the two?

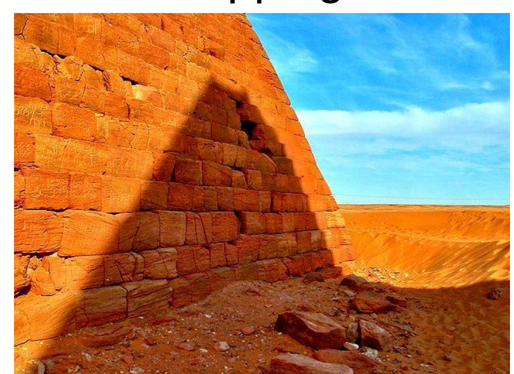
- (Incoming) illumination – slowly changing
  - except very abrupt transitions on shadow boundaries
- Reflectance – low contrast and high frequency variations

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

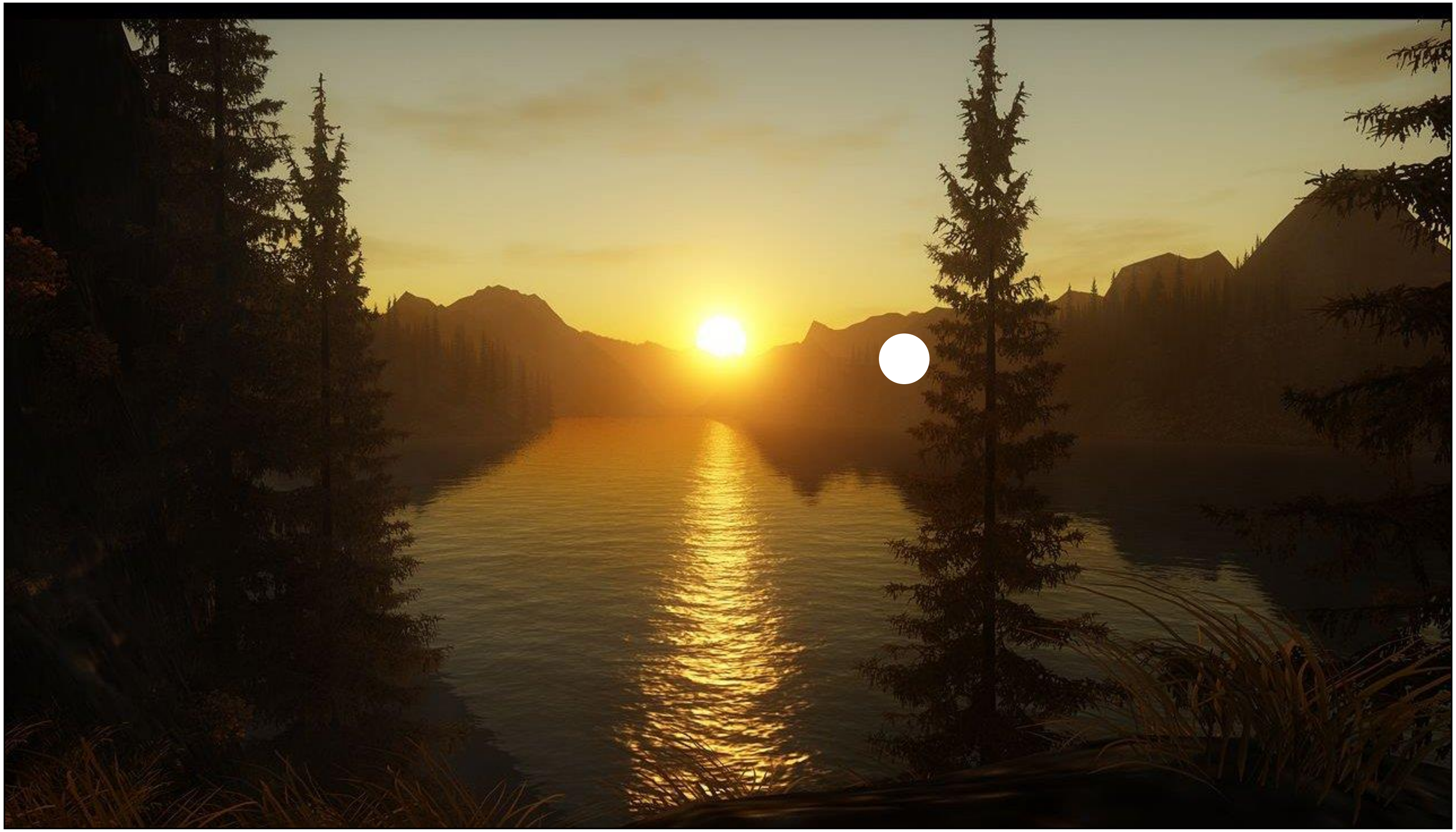
Tone mapping result



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

[Durand & Dorsey, SIGGRAPH 2002]

Glare



"Alan Wake" © Remedy Entertainment

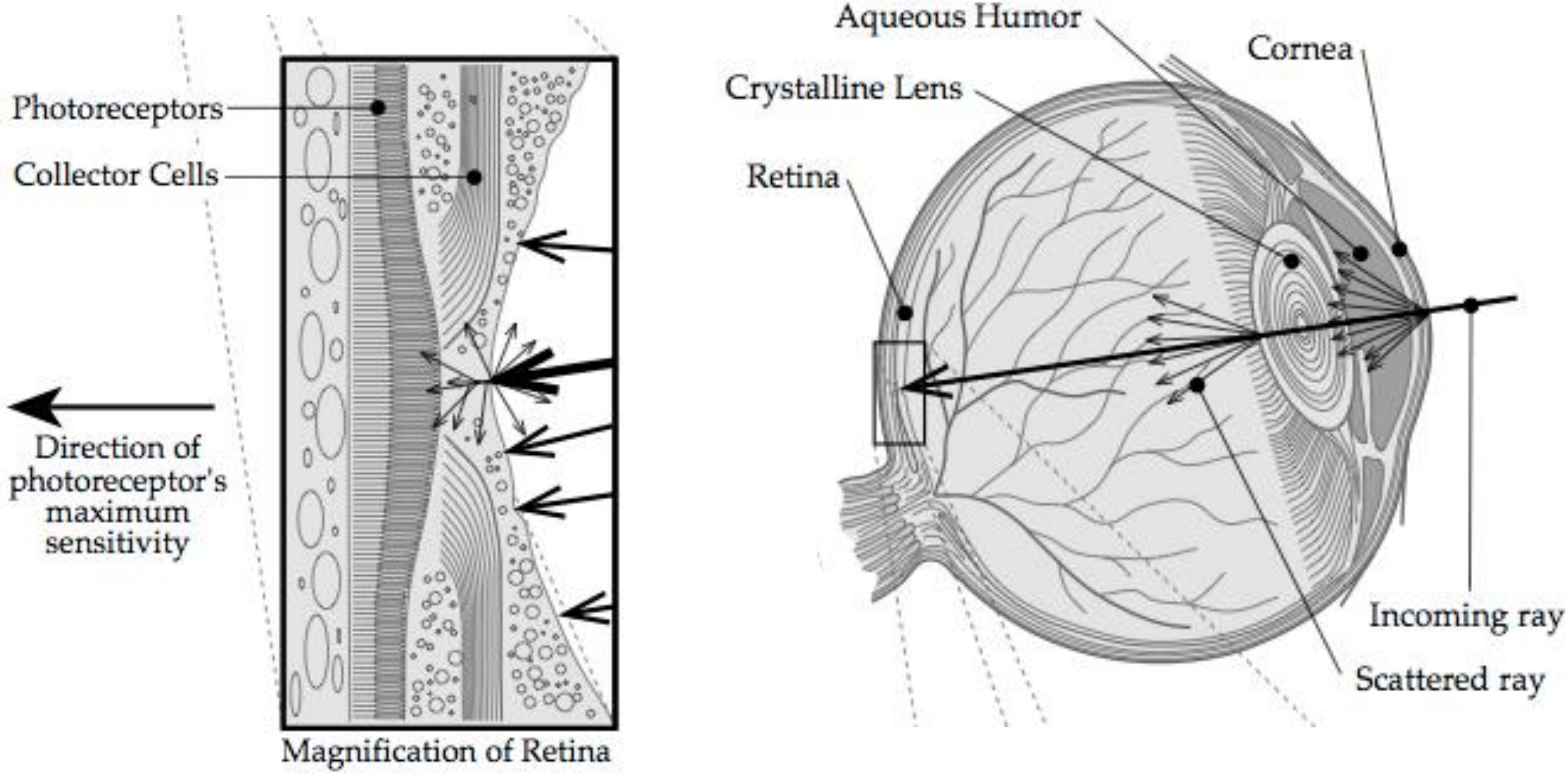
Glare Illusion

Photography

Painting

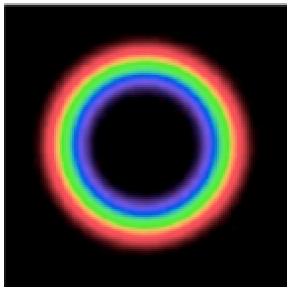
Computer Graphics
HDR rendering in games

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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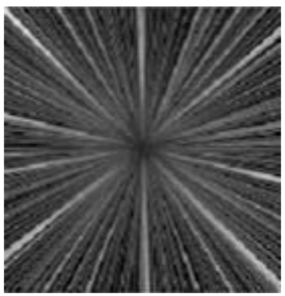

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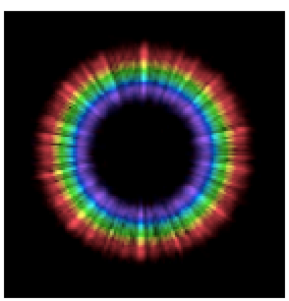

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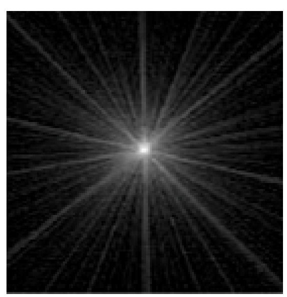

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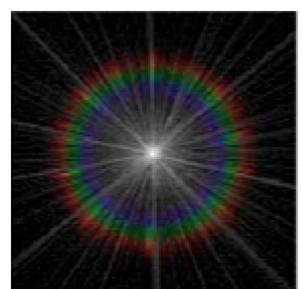
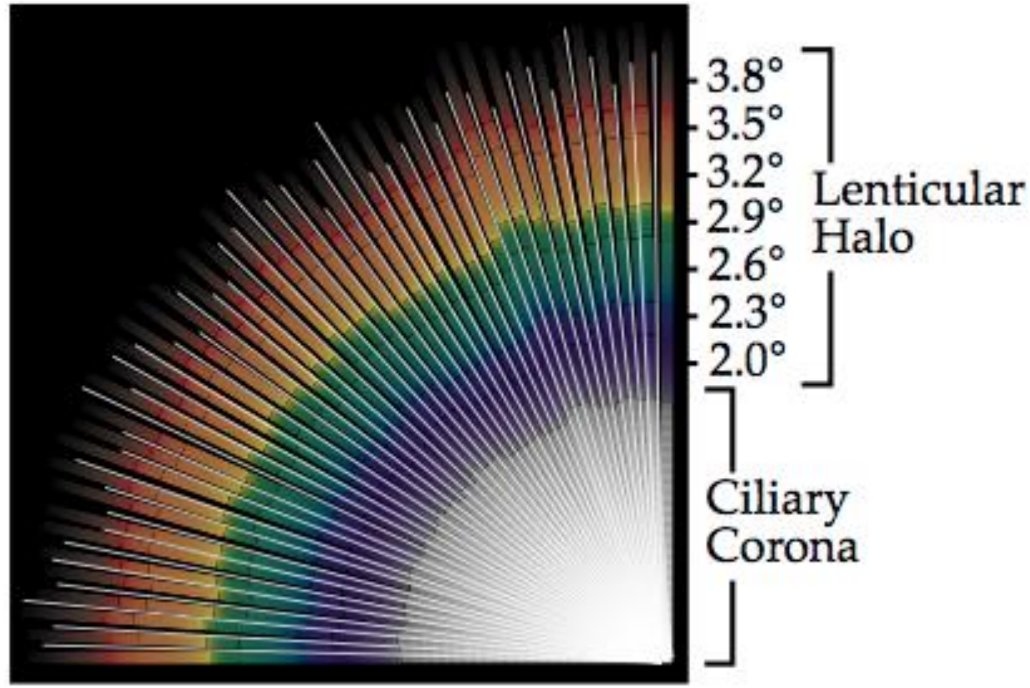
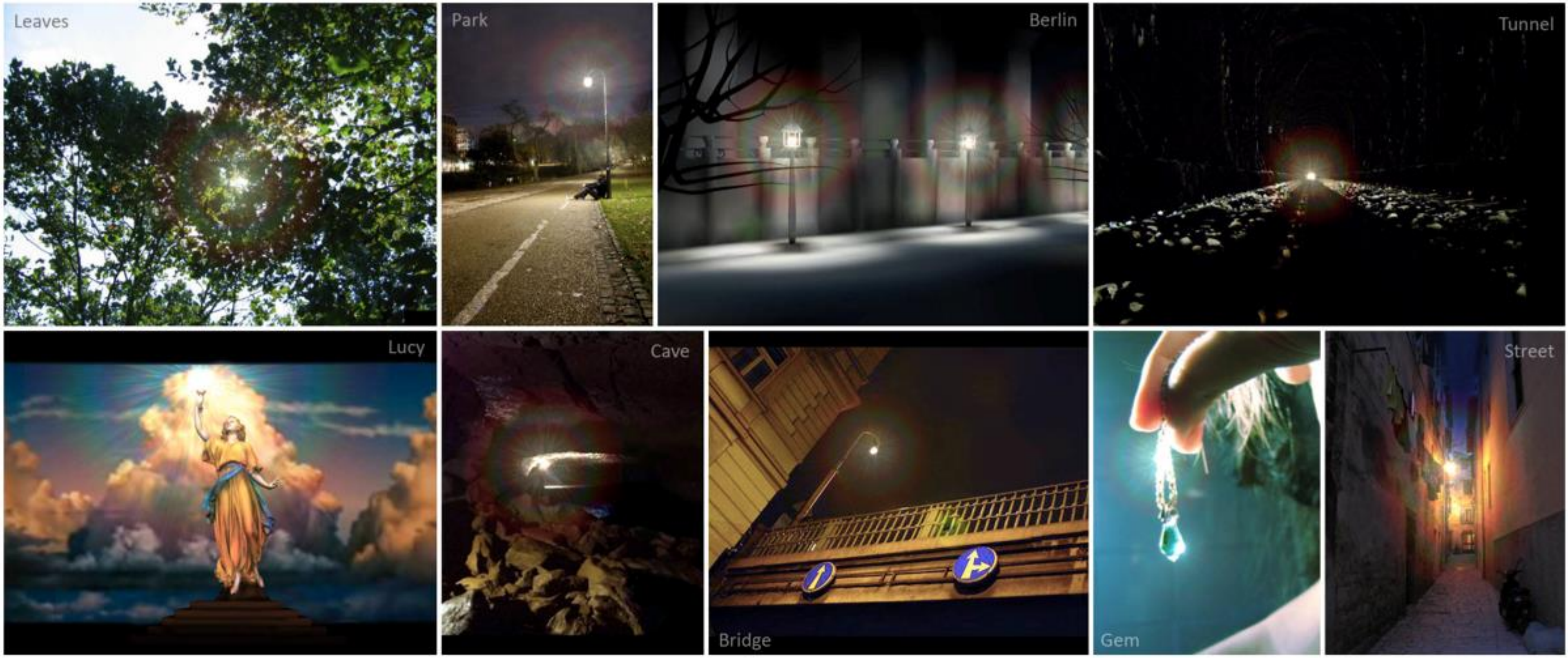




From: Spencer, G. et al. 1995. Proc. of SIGGRAPH. (1995)

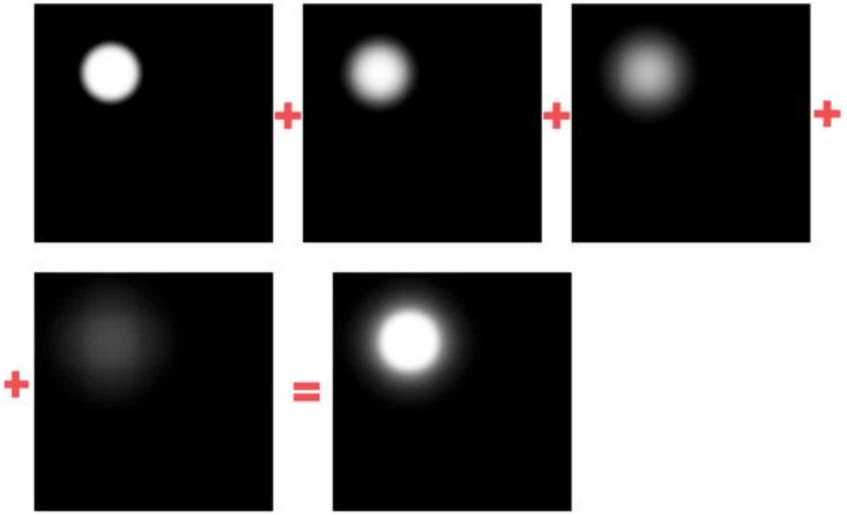
Examples of simulated glare



[From Ritschel et al, Eurographics 2009]

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



Simulation of night vision [Wanat 2014]

Age-adaptive night vision

Video 4

Rivoli

Simulation of age-adaptive night vision

ToC & Benefits

- HDR in a nutshell
- Display technologies in VR
- Perception & image quality

VR display technologies

TFT-LCD

TN, STN, MVA, PVA, IPS

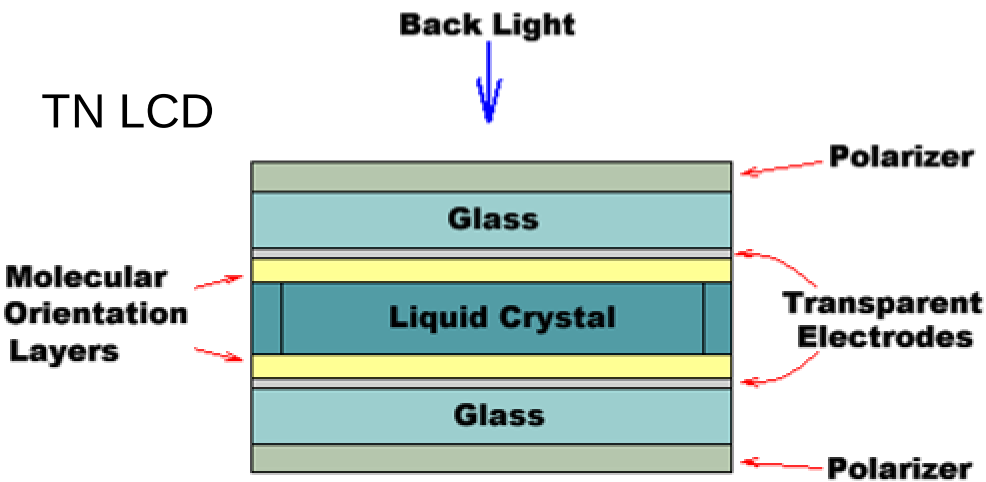
- Contrast: <3000:1
- Transmissive
- Complex temporal response
- Arbitrary bright
- Constant power at constant backlight

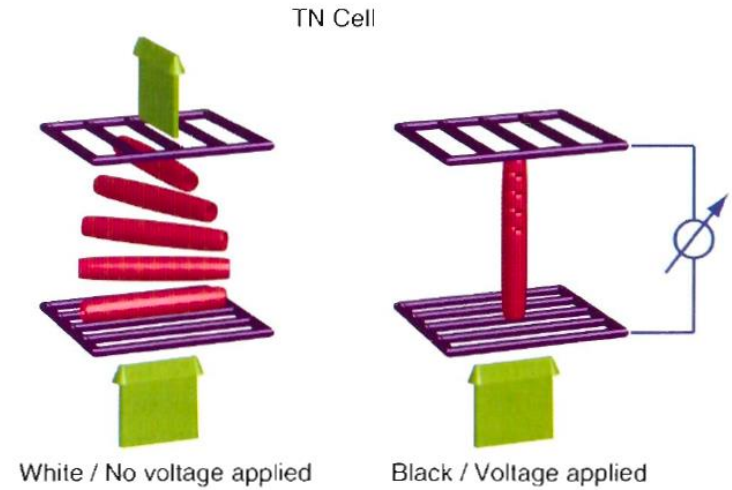
AMOLED

- Contrast: >10,000:1
- Emmisive
- Rapid response
- Brightness affects longevity
- Power varies with image content

LCD

TN LCD

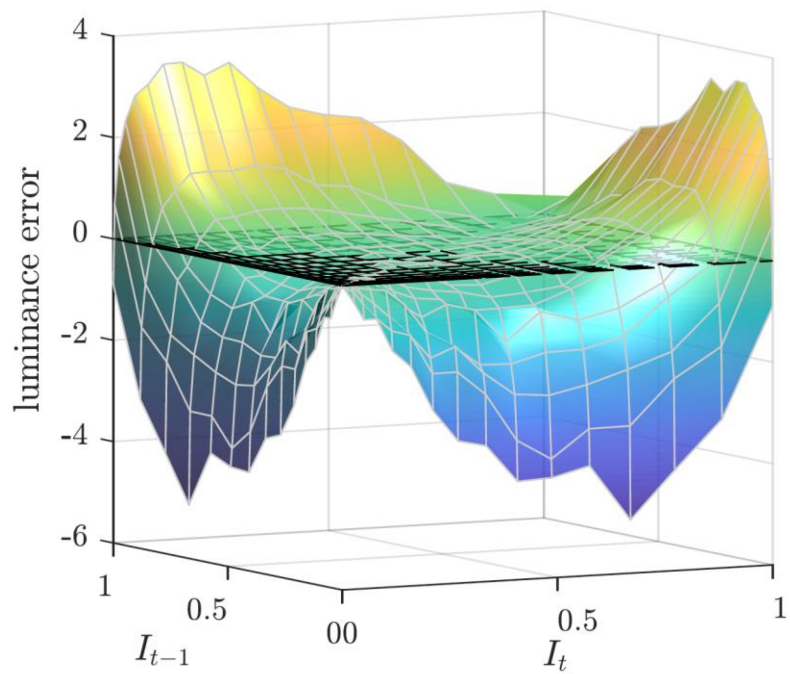




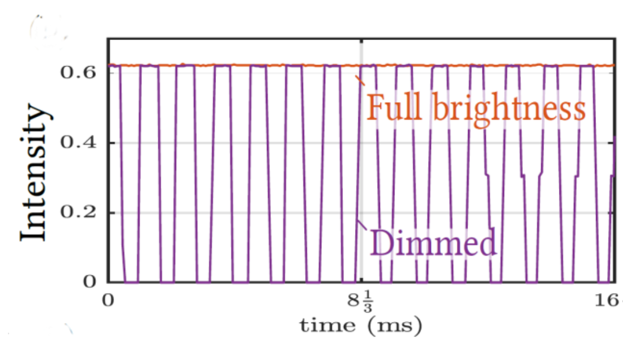
- color may change with the viewing angle
- contrast up to 3000:1
- higher resolution results in smaller fill-factor
- color LCD transmits only up to 8% (more often close to 3-5%) light when set to full white

LCD temporal response

- Experiment on an IPS LCD screen
- We rapidly switched between two intensity levels at 120Hz
- Measured luminance integrated over 1s
- The top plot shows the difference between expected ($\frac{I_{t-1}+I_t}{2}$) and measured luminance



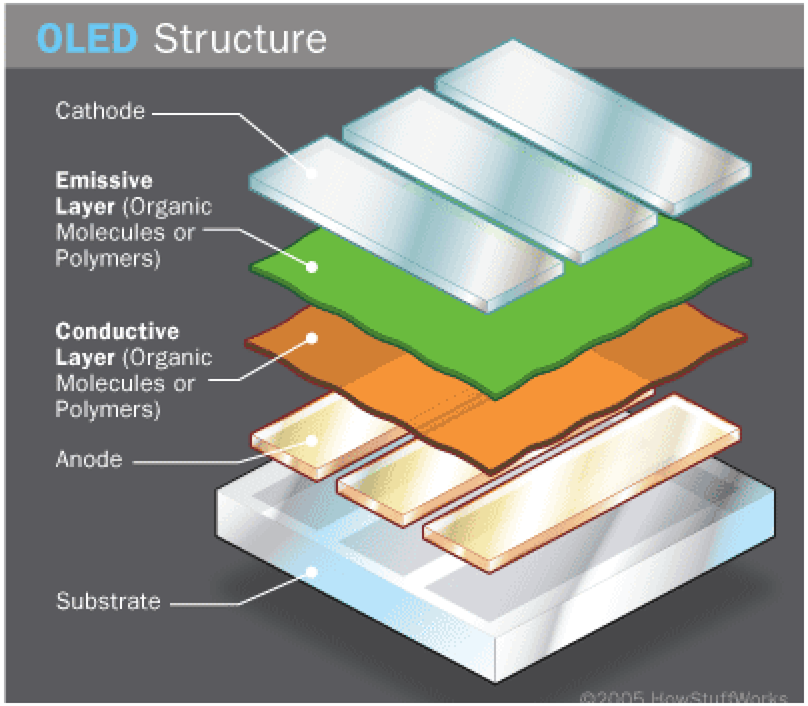
- The bottom plot: intensity measurement for the full brightness and half-brightness display settings



Rafał Mantiuk, Univ. of Cambridge

OLED

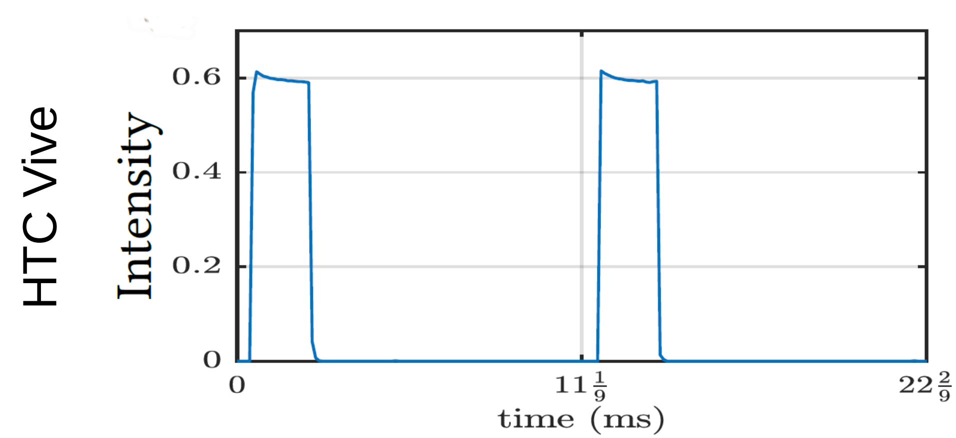
- based on electrophosphorescence
- large viewing angle
- the power consumption varies with the brightness of the image
- fast (< 1 microsec)
- arbitrary sizes

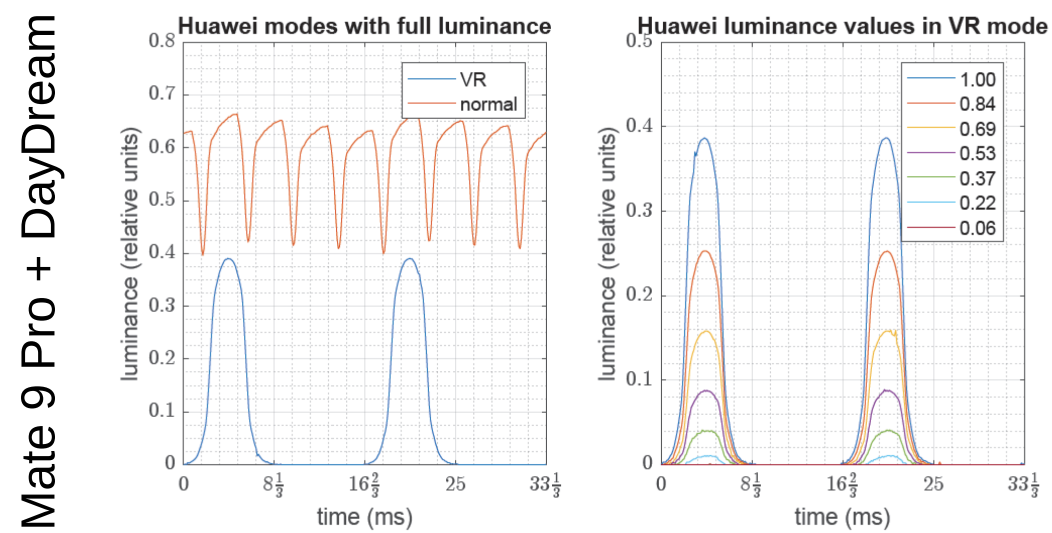


- life-span is a concern
- more difficult to produce

Low persistence displays

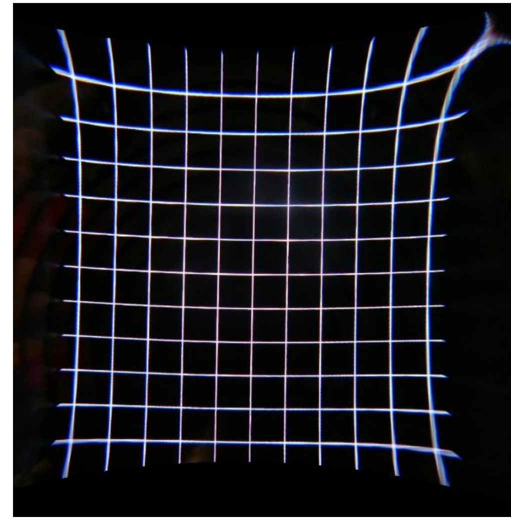
- Most VR displays flash an image for a fraction of frame duration
- This reduces hold-type blur
- And also reduces the perceived lag of the rendering





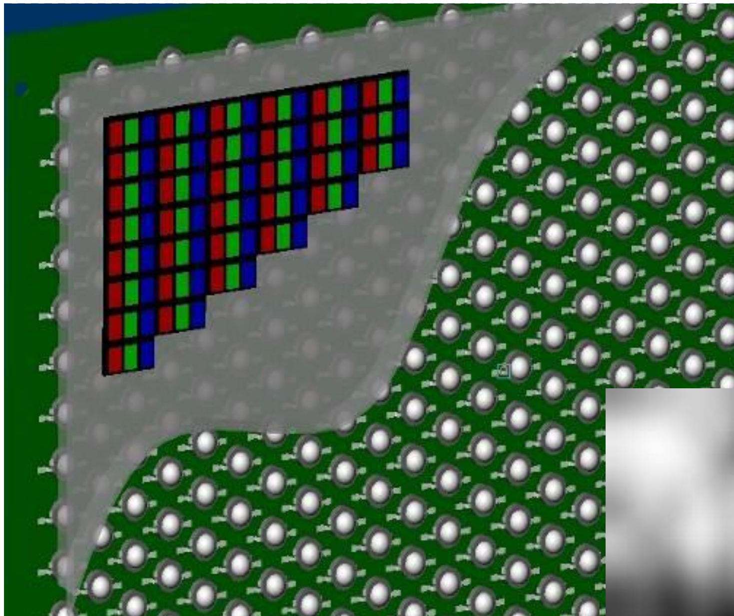
Lens in VR displays

- Aberrations when viewing off-center
  - Chromatic aberration
  - Loss of resolution
  - Difficult to eliminate if the exact eye position is unknown
- Glare
  - Scattering of the light in the lens
  - From Fresnel fringes
  - Reduces dynamic range



Examples from: http://doc-ok.org/?p=1414

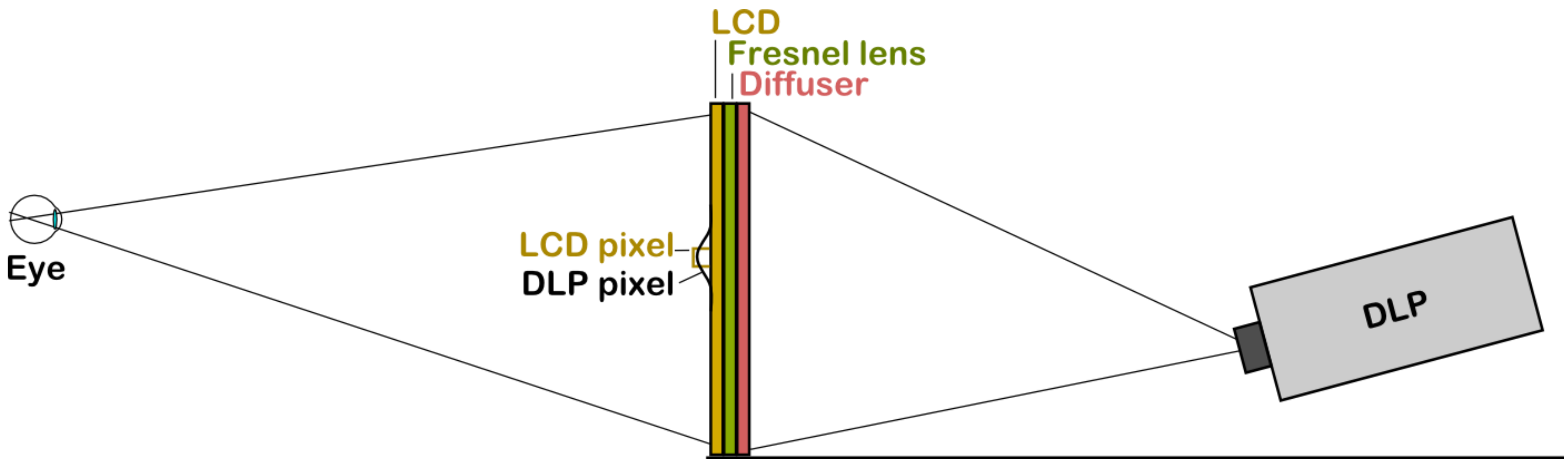
HDR Display



- Modulated LED array
- Conventional LCD
- Image compensation

Low resolution LED Array x High resolution Colour Image = High Dynamic Range Display

HDR display



Desired image

DLP blur (PSF)

$$\arg\min_{L,D} ||I - g\, D \circ L||_2$$

DLP image

LCD image

Subject to:

$$\forall(x,y) \quad L_{min} \leq L(x,y) \leq L_{max}$$

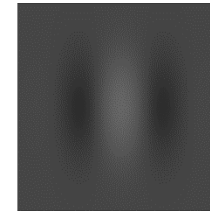
$$\forall(x,y) \quad D_{min} \leq D(x,y) \leq D_{max}$$

Resolution

- Relevant units: pixels per visual degree [ppd]
- Nyquist frequency in cycles per degree = ½ of ppd
- PC & mobile resolution
  - 1981: 12” 320x200 monitor @50cm: 10.9 ppd
  - 1990: 12” 1024x768 monitor @50cm: 37 ppd
  - 2011: 3.5” 960x640 iPhone @30cm: 68 ppd
  - 2016: 31” 4K monitor @50cm: 50 ppd
  - 2018: 6” phone @30cm: 117 ppd
- VR resolution
  - 2016 HTC Vive: 10 ppd
  - 2018 HTC Vive Pro: 13 ppd

ToC & Benefits

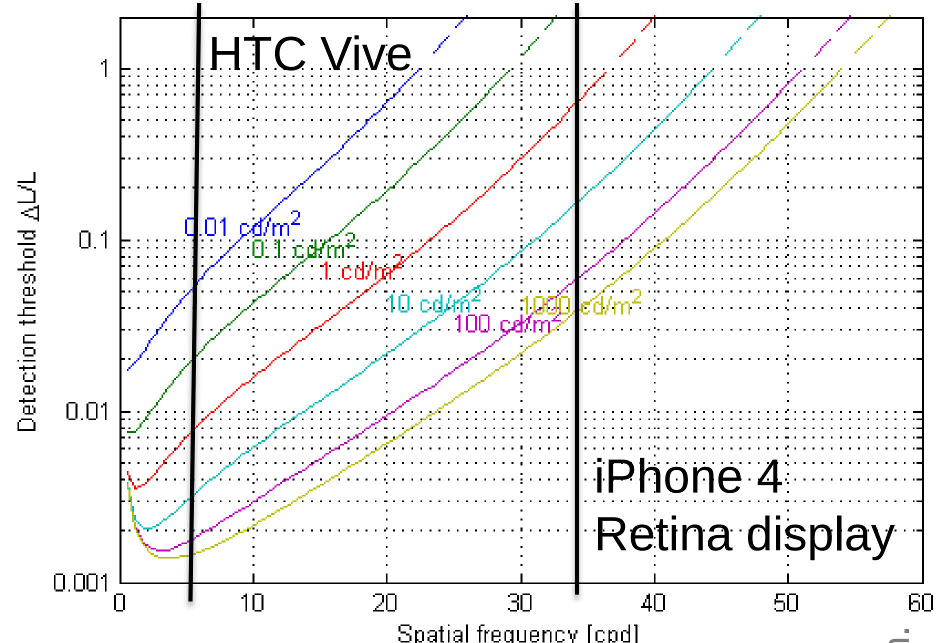
- HDR in a nutshell
- Display technologies in VR
- Perception & image quality

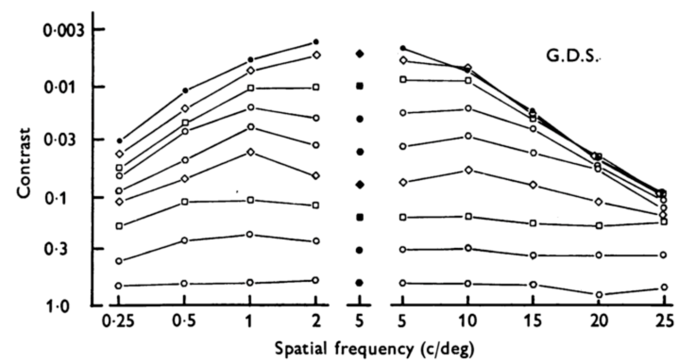


Contrast Sensitivity Function

- Detection of barely noticeable contrast on a uniform background
- Varies with luminance

- CSF is NOT MTF of visual system
  - Contrast constancy
  - There is little variation in magnitude of perceived contrast above the detection threshold



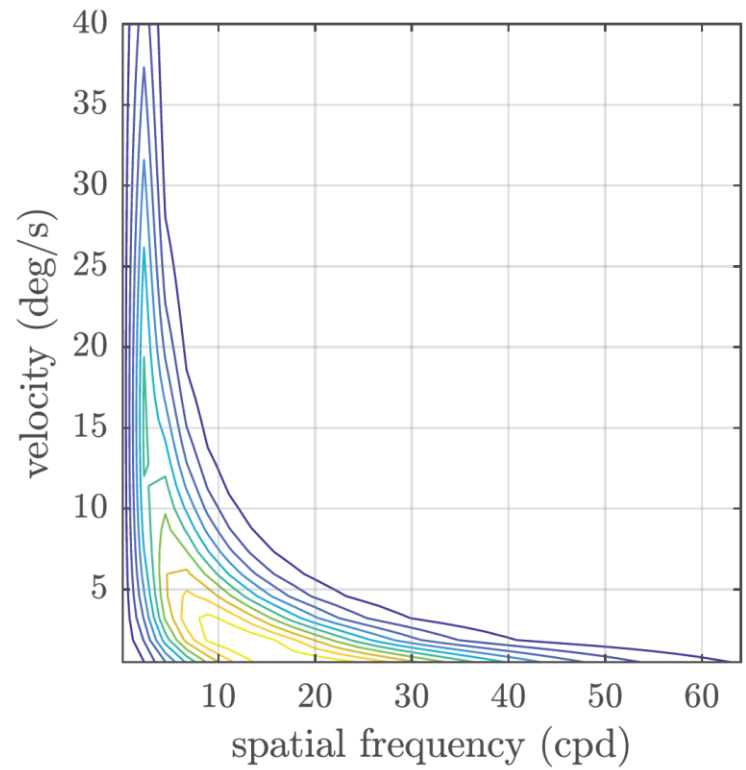


Georgeson and Sullivan. 1975. J. Physio

Retinal velocity

- Sensitivity drops rapidly once images start to move
- The eye tracks moving objects
  - Smooth Pursuit Eye Motion (SPEM)
  - Stabilizes images on the retina
  - But tracking is not perfect
- Loss of sensitivity mostly caused by imperfect SPEM
  - SPEM worse at high velocities
- Motion sharpenning
  - Relatively small effect

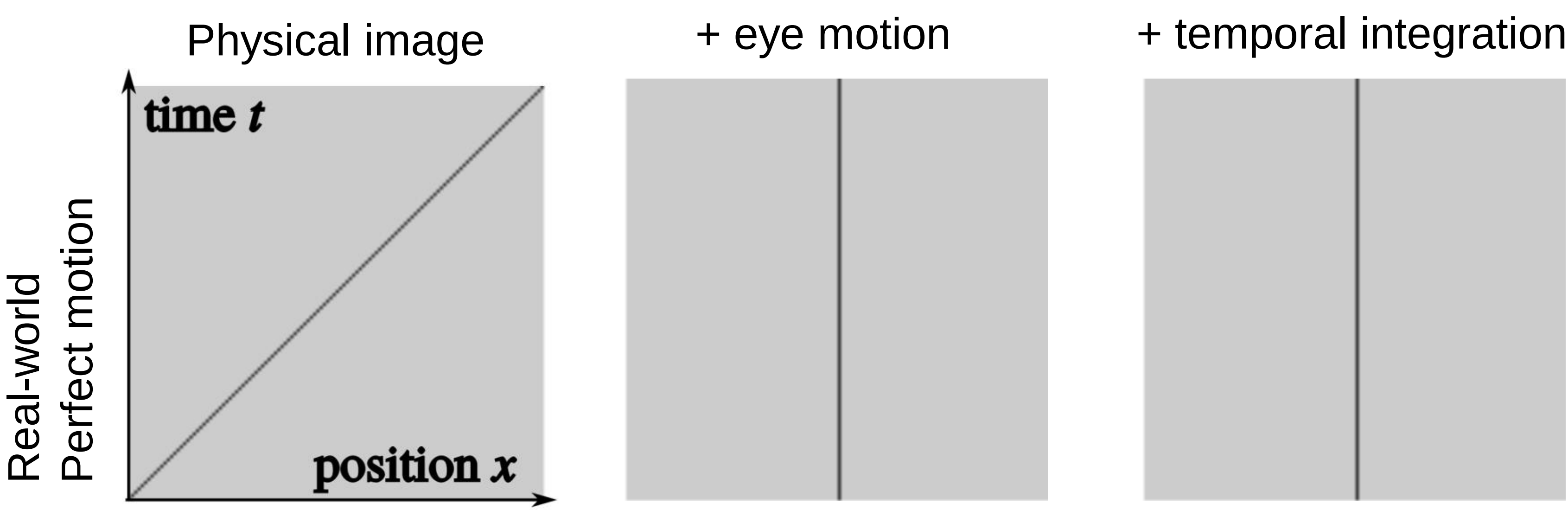
Spatio-velocity contrast sensitivity



Kelly's model [1979]

Hold-on blur

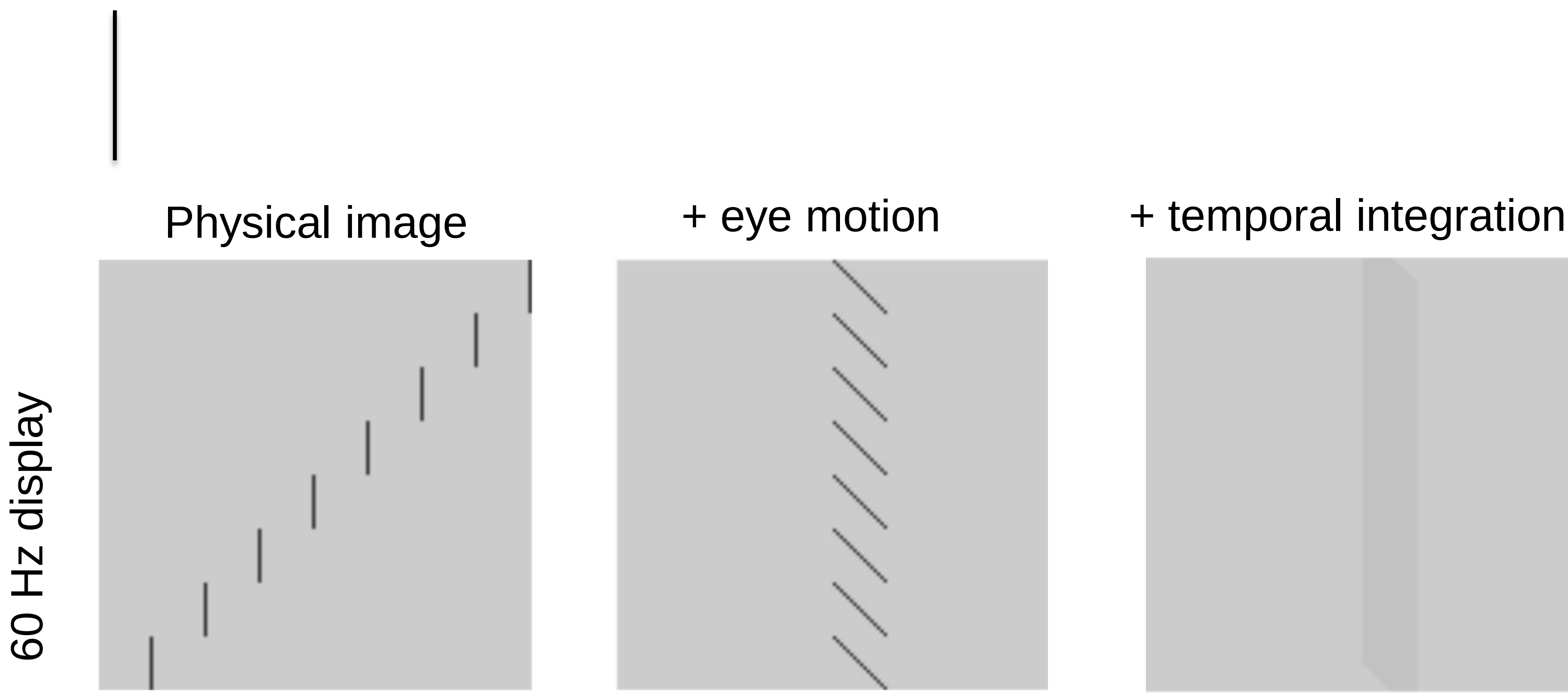
- The eye smoothly follows a moving object
- But the image on the display is "frozen" for 1/60th of a second



Rafał Mantiuk, Univ. of Cambridge

Hold-on blur

- The eye smoothly follows a moving object
- But the image on the display is "frozen" for 1/60th of a second



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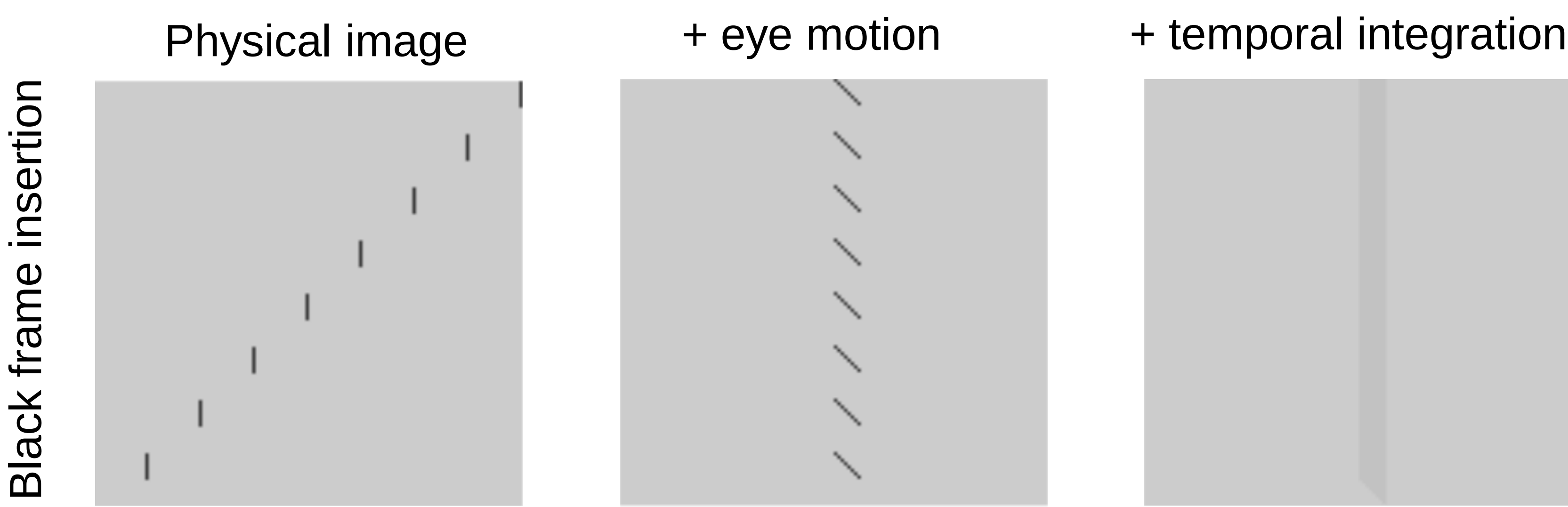
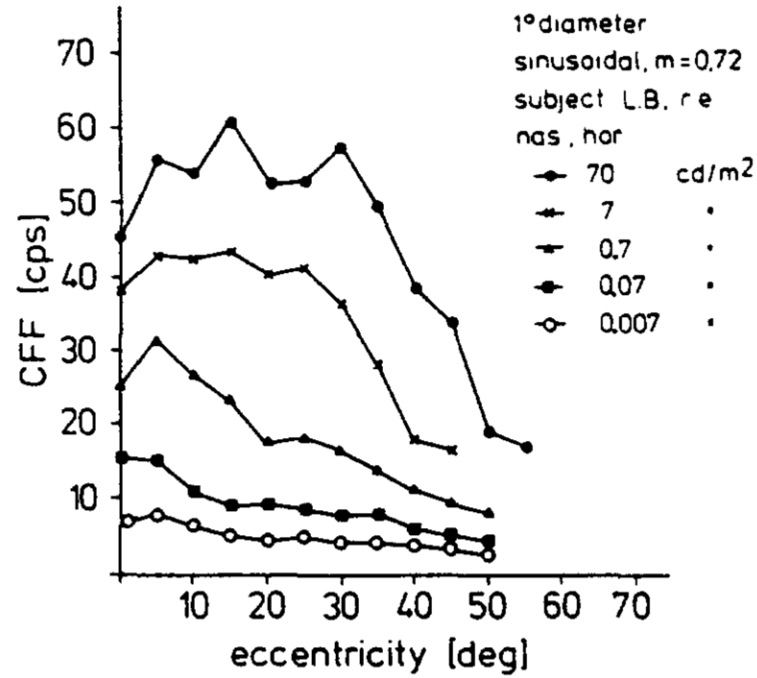


Flicker

- Critical Flicker Frequency
  - Strongly depends on luminance – big issue for HDR VR headsets
  - Increases with eccentricity
  - and stimulus size
  - It is possible to detect flicker even at 2kHz
    - For saccadic eye motion



[Hartmann et al. 1979]

Simulation sickness

- Conflict between vestibular and visual systems
  - When camera motion inconsistent with head motion
  - Frame of reference (e.g. cockpit) helps
  - Worse with larger FOV
  - Worse with high luminance and flicker

Summary

- HDR for VR is a great idea because
  - It gives more realistic experience
  - Better quality with the same number of pixels
  - Additional depth cues
- HDR for VR is bad idea because
  - Increased flicker visibility
  - Increased simulation sickness
  - Lens glare will reduce effective dynamic range
- In both cases
  - Tone-mapping will become an important part of VR rendering

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