High Dynamic Range Imaging

Martin Čadík

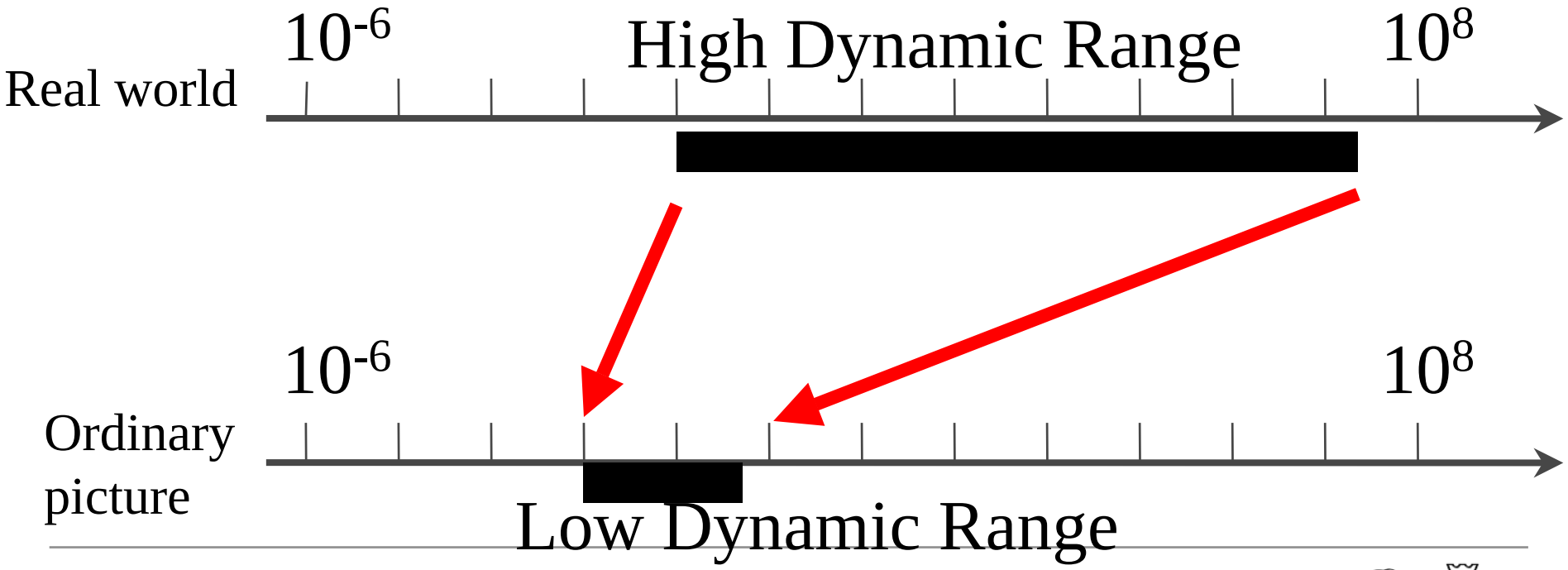
Czech Technical University in Prague, Czech Republic





What is HDR?

- HDR = High Dynamic Range
  - typically **highest : lowest** luminance [cd/m^2]
  - peak signal:noise level, exposure (f-stops), log-10 units…
- several orders of magnitude
- INT is not enough



Content

- Motivation
  - applications
- HDR
  - image acquisition
  - file formats
- HVS
  - fundamental properties
- Tone mapping
  - global, local methods
  - time-dependent methods
  - Glare



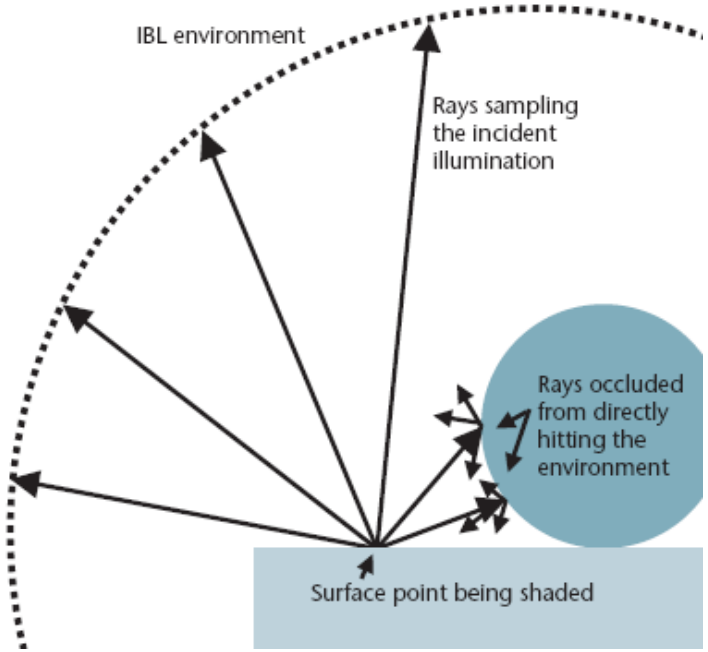
Motivation

- real world is HDR!
- physically-based rendering outputs
- photography
- digital cinema
- games (explosions are really HDR ☺), video [2:24]
- ...



HDR Applications

- Image-Based Lighting
  - [Debevec 98]
  - using HDR radiance maps to illuminate synthetic objects
  - RNL - **videos**







HDR Applications

- physically-based rendering (global illumination)
- image-based rendering and modeling
- HDR panoramic imaging
- visualization (i.e. medical imaging)
- computer vision (algorithms perform better)
- human vision simulation and psychophysics



HDR Applications

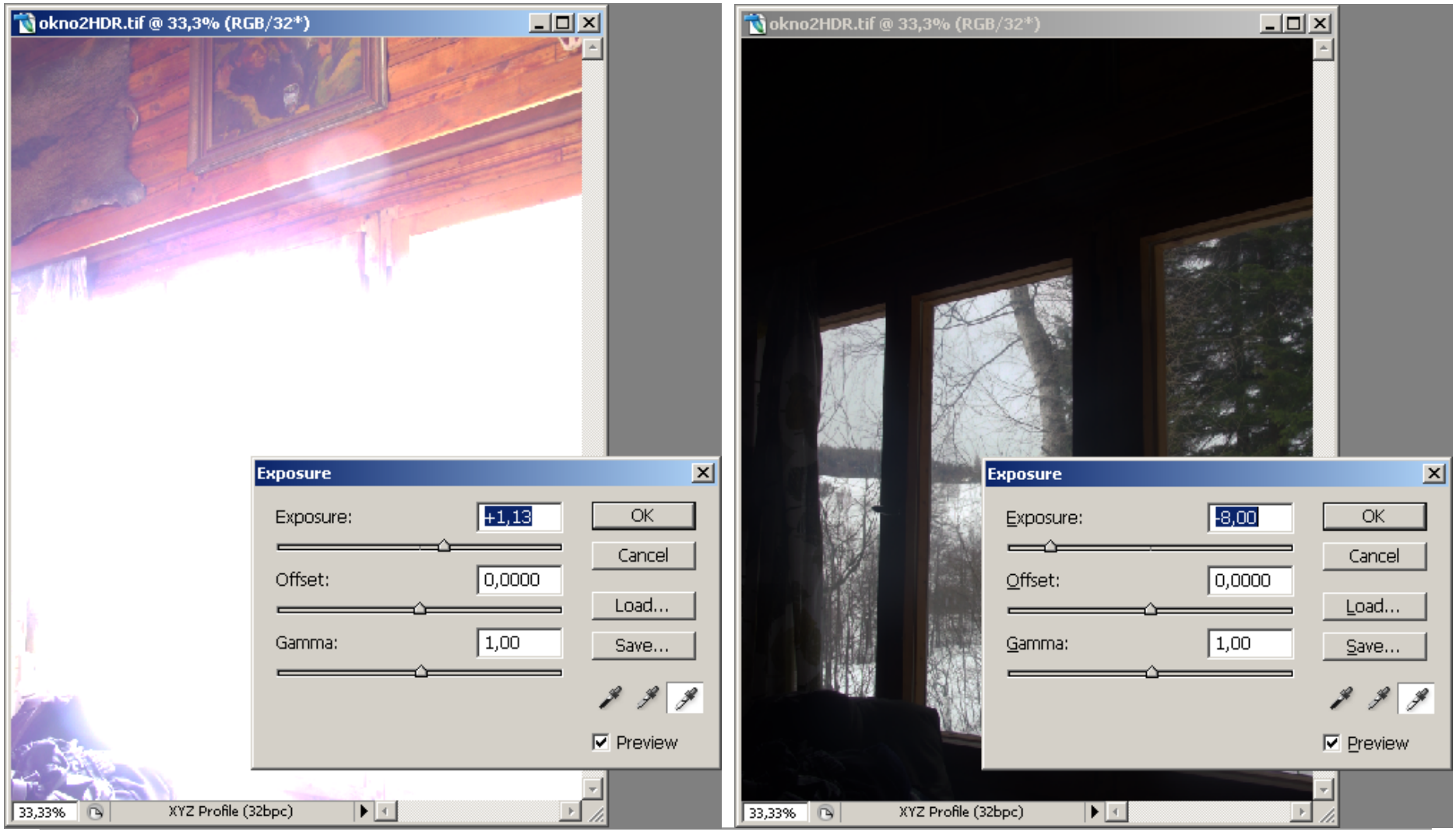
Adobe Photoshop

- digital photography in PS_CS2, CS_3
  - HDR first in version: 9.0 (CS2)
  - 32 bits-per-channel HDR images
  - Merge To HDR command
  - Photoshop (PSD, PSB), Radiance (HDR), Portable Float Map (PFM), OpenEXR, TIFF (LogLuv just reads)



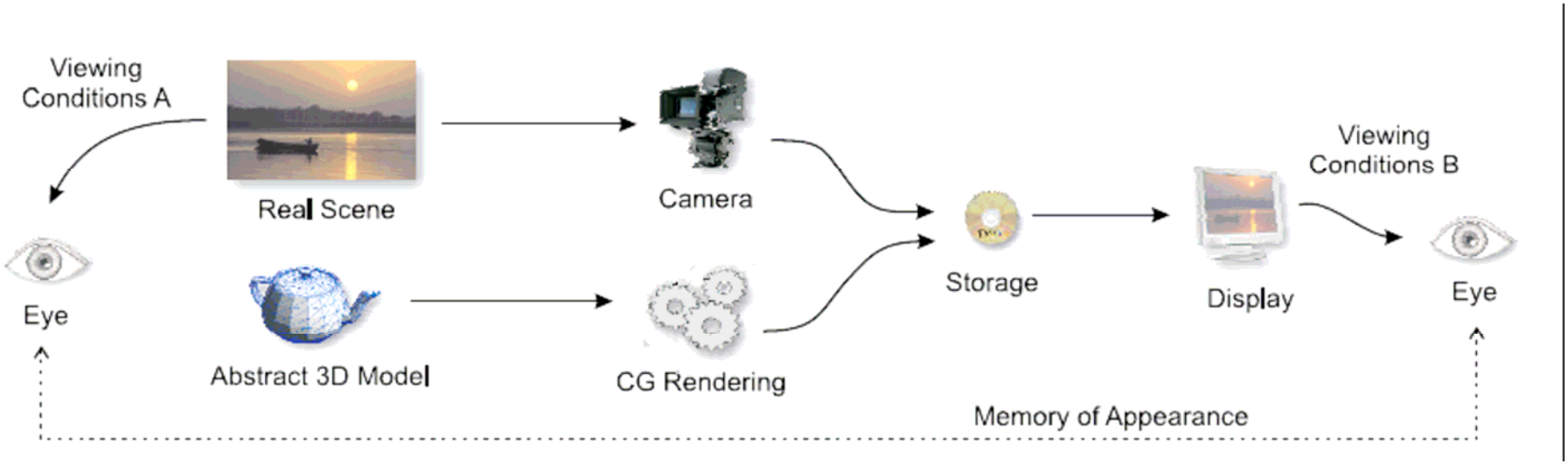
HDR Applications

Adobe® Photoshop®



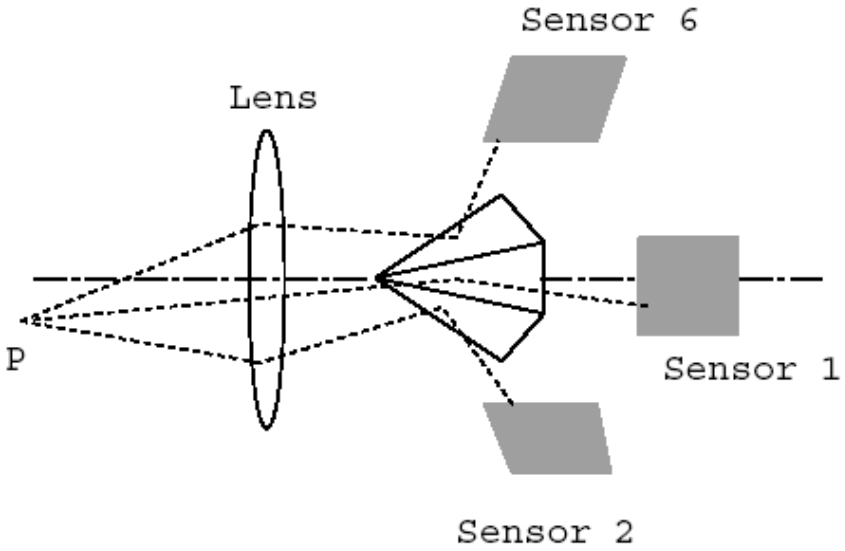
HDR Imaging Pipeline

- traditional LDR pipeline not sufficient
- new generations of input/output devices
- supported by new graphics hardware



HDR Image Acquisition

- Software simulation
  - physically based methods
- Specialized input devices
  - Panoscan Mark3, SpheronVR (scanning panoramic cameras), HDR video, etc.
- HDR from multiple photographs







HDR Image Acquisition



f/8, 1/1000s



f/5.6, 1/250s



f/5.6, 1/30s



f/5.6, 1/4s



f/5.6, 2s



f/5.6, 8s

HDR Image Acquisition

- [Debevec and Malik 1997]
  - film response function recovery:

  we have:

  Z_{ij} [-] – value of pixel i with exposure time j

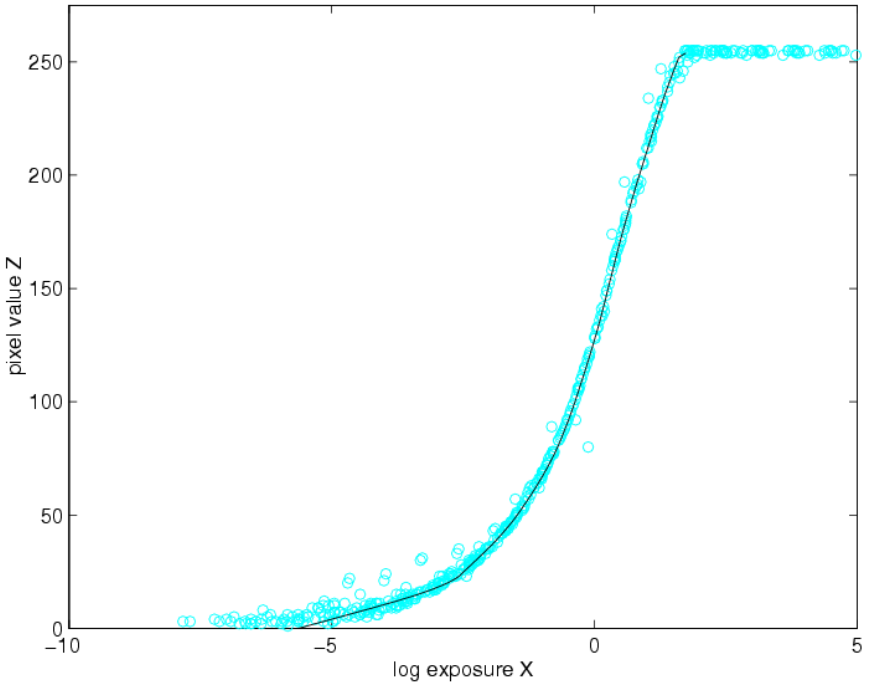
  E_i [W/m^2] – Irradiance constant for pixel i

  Δt_j [s] – exposure time

  $Z_{ij}=f(E_i\ \Delta t_j)$

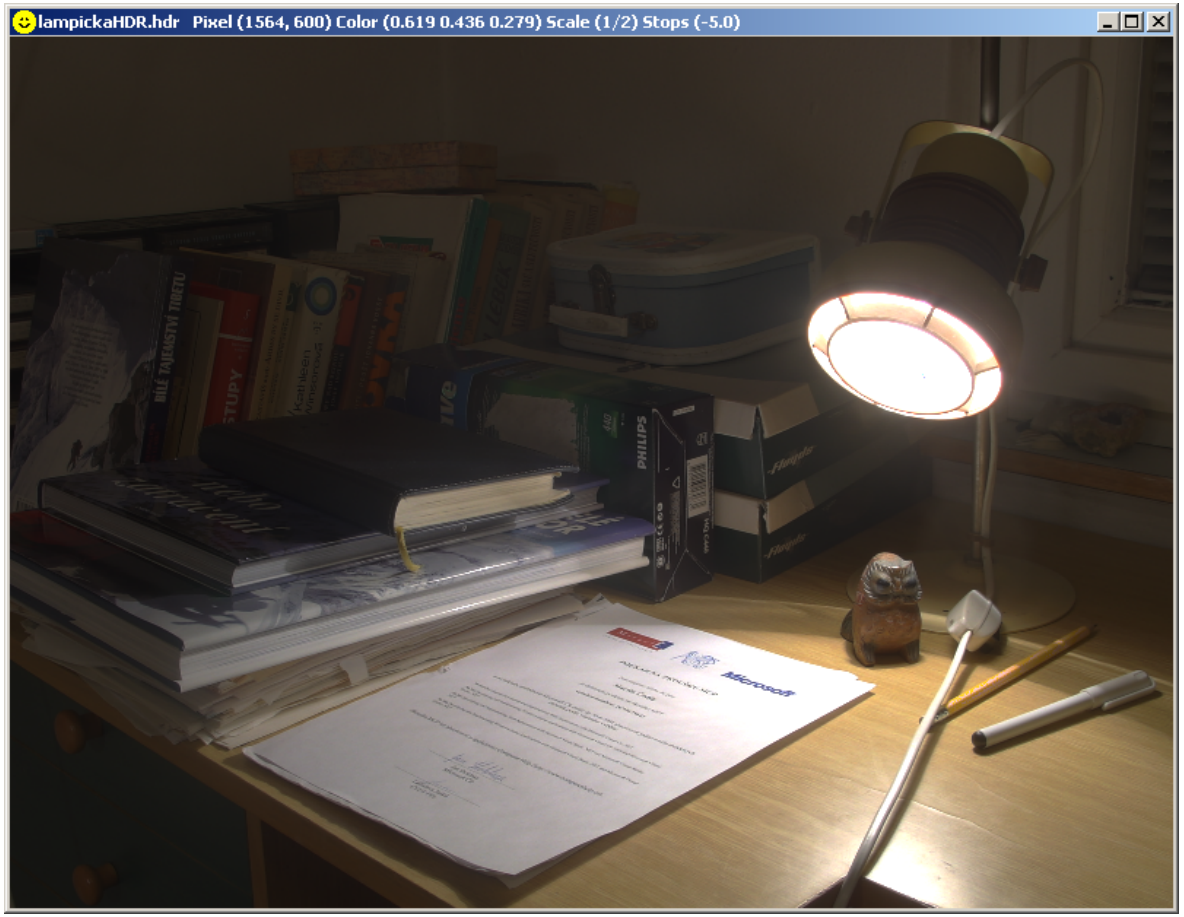
  we wish to recover f and E_i, that best satisfy the overdetermined set of eqns. (least sq. error)

  - construction of HDR radiance map



HDR Image Acquisition

- [Debevec and Malik 1997]
  - sample

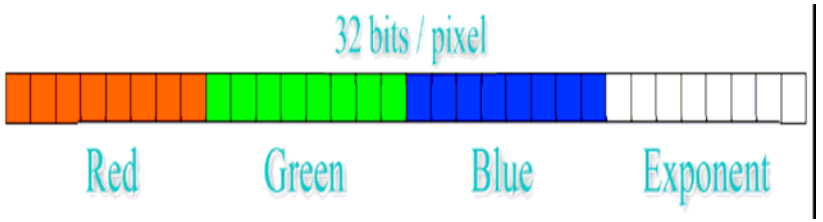


HDR Image File Formats

- we need **FLOATS** (at least)
  - precision, dynamic range
  - typically 4B == 3.4 E+/- 38
  - the image file is **4x bigger** (96b/pixel x 24b/pixel) than usual!

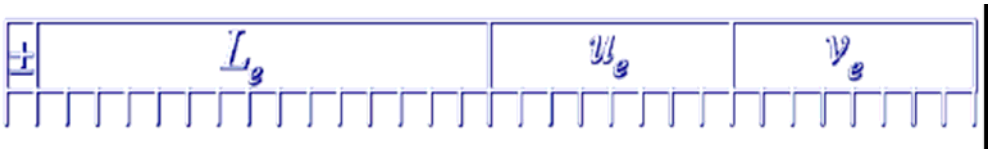
- Raw Binary Floating Point (`.raw`)
  - cameras, manufacturer-specific
  - not really HDR

- Radiance RGBE (`.pic, .hdr`)
  - [Ward92]
  - 32b/pixel
  - 3x 8b mantissa + 1x exponent
  - $10^{+/-38}$ (too much, $10^{+9/-7}$ would be enough), 1% relative accuracy

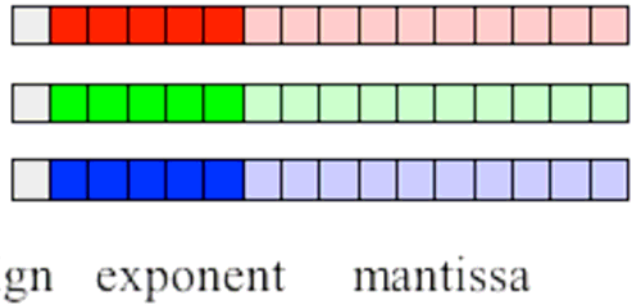


HDR Image File Formats

- SGI LogLuv TIFF (`.tif`)
  - [Ward 98]
  - human perception based:
    log encoding of luminance, $10^{+/-38}$, 0.3% relative accuracy
    CIE (u, v) encoding for chroma, errors under visible threshold
  - 3 variants: 24b/pixel, 30b/pixel, 32b/pixel



- OpenEXR (`.exr`)
  - Industrial Light and Magic [2003]
  - 16b float (Half data type)
  - 48 or 96b/pixel + lossless compression
  - multiresolution
  - supported by graphics hardware (NVidia, ATI frame buffers)



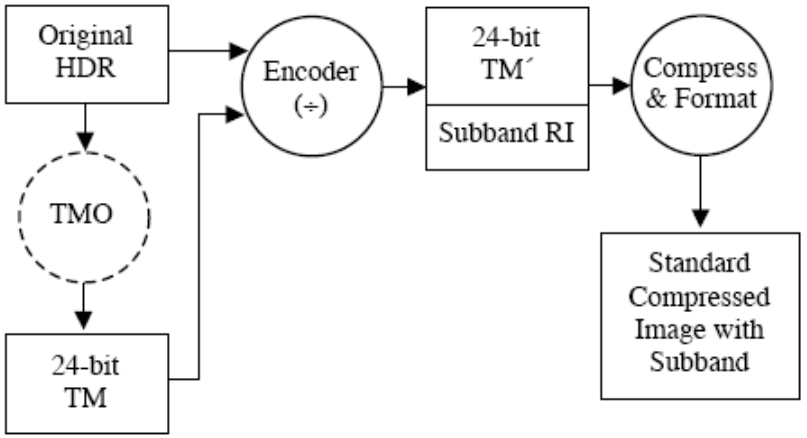
HDR Image File Formats

- JPEG HDR - Subband Encoding (`.jpeg`) [Ward and Simmons 04]
  - Tone-mapped version
    + Ratio image (subband – metadata JFIF)
  - Ratio Image:
  - allows lossy compression
  - naive software = tone mapped version, specialized software = HDR

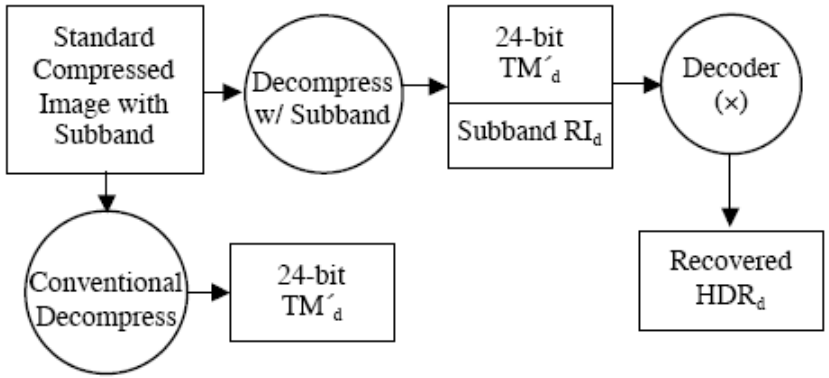
$$RI(x,y) = \frac{L(HDR(x,y))}{L(TM(x,y))}$$



Encoding pipeline

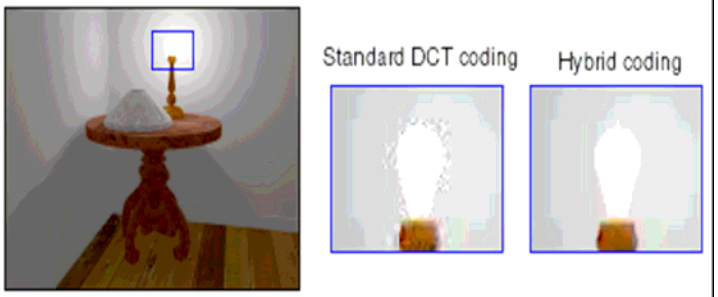


Alternate decoding paths

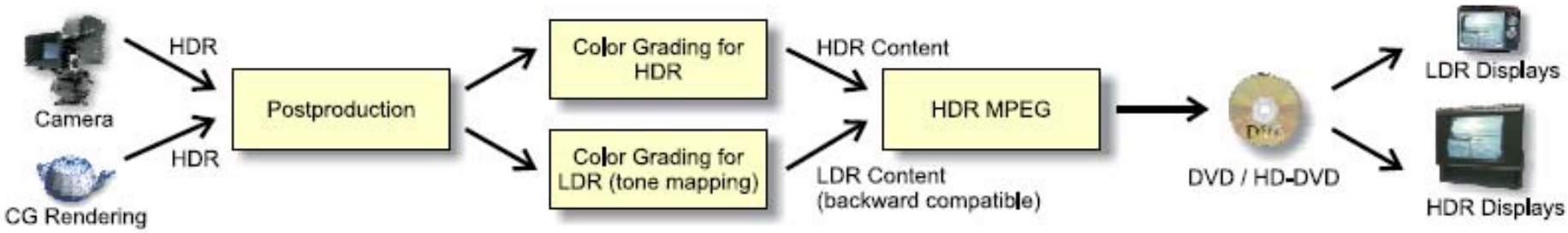


HDR Video

- HDRV – perception-motivated [Mantiuk et al. 04]
  - perceptual Luminance quantization
  - 11b for Luminance + 2x 8b for chrominance
  - based on MPEG-4
  - no LDR (pure HDR video)

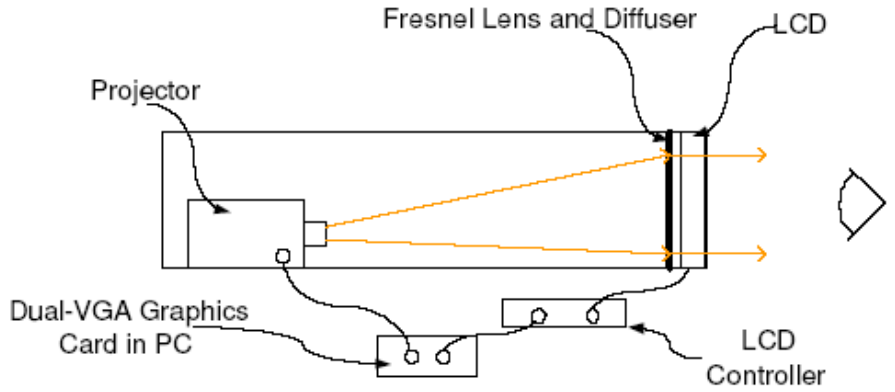


- HDR MPEG [Mantiuk et al. 06]
  - backward-compatible MPEG
  - residual stream + standard LDR stream
  - iust 30% data flow increase

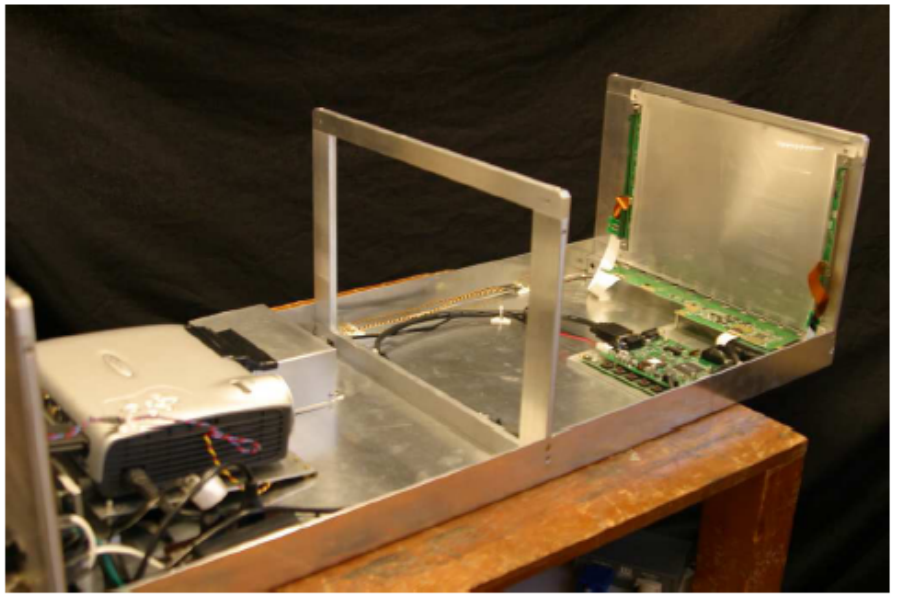


HDR Display Systems

- [Seetzen et al.]
  - LCD panel + projector
  - LCD panel + LED panel



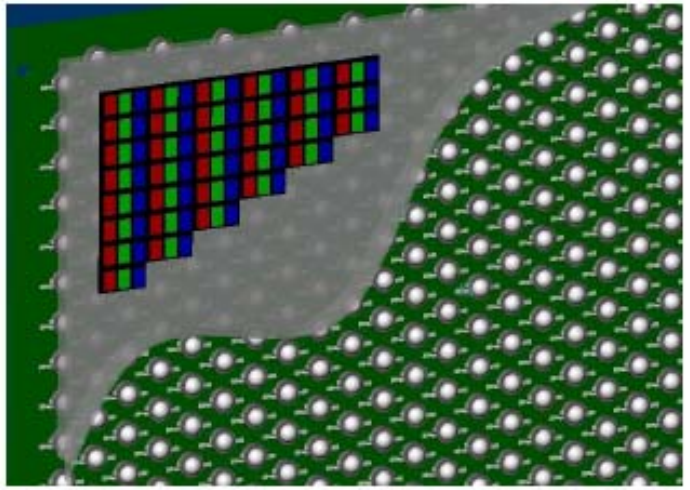
  - applications:
    - HDR image viewer
    - interactive photorealistic rendering
    - volume rendering
    - medical image viewer



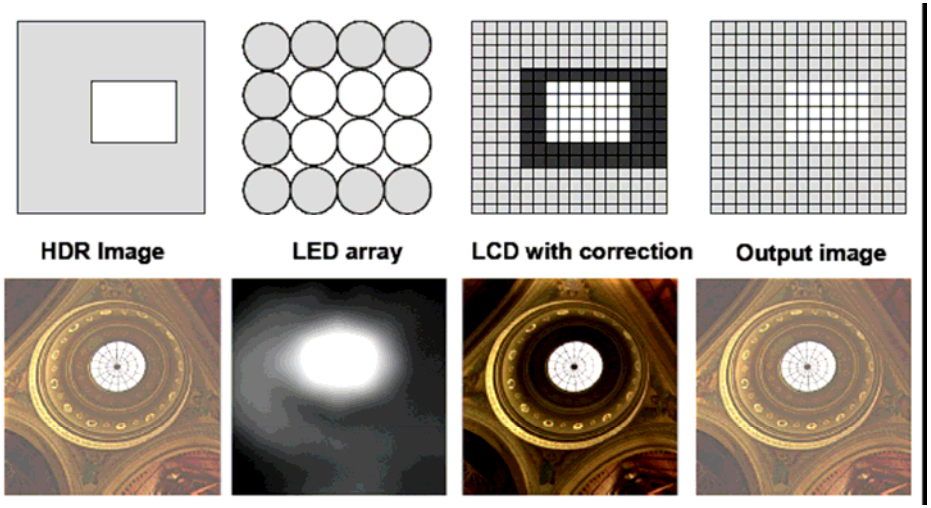
HDR Display Systems

BRIGHTSIDE™

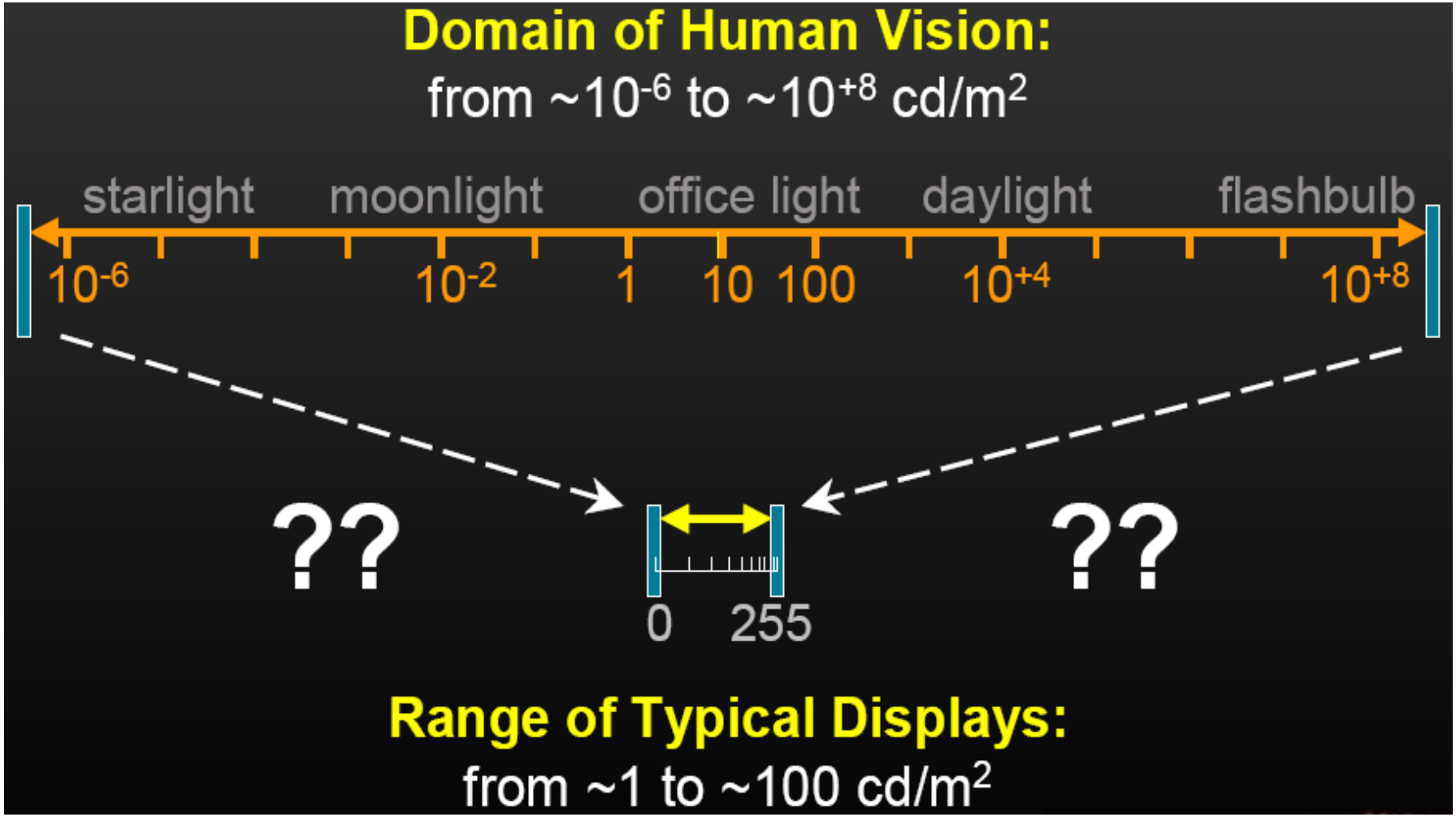
- ordinary LCD
  - 300:1 to 1000:1
  - black=0.1 to 1 cd/m^2
  - peak=300 to 500 cd/m^2



- [brightsidetech.com]
  - HDR LCD
  - individually modulated LEDs (not uniform backlight)
  - 200 000:1
  - black=0 cd/m^2
  - peak=4000 cd/m^2
  - HDR from LDR

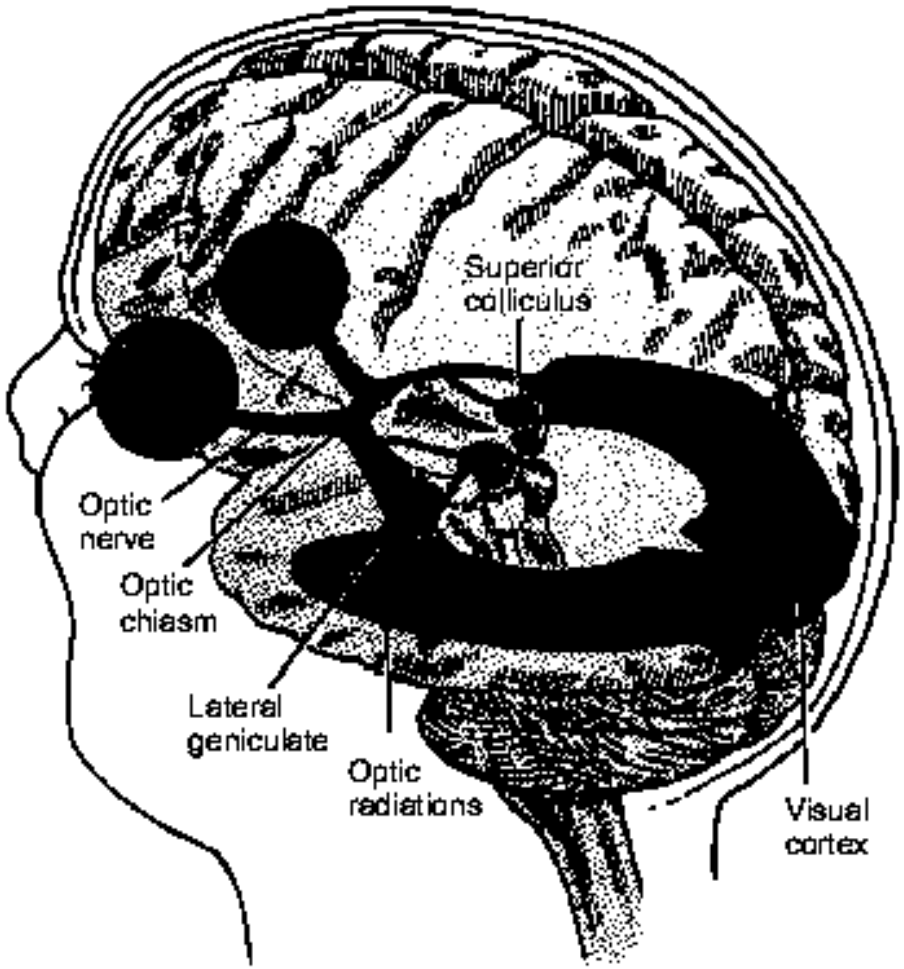


Tone Mapping Issue

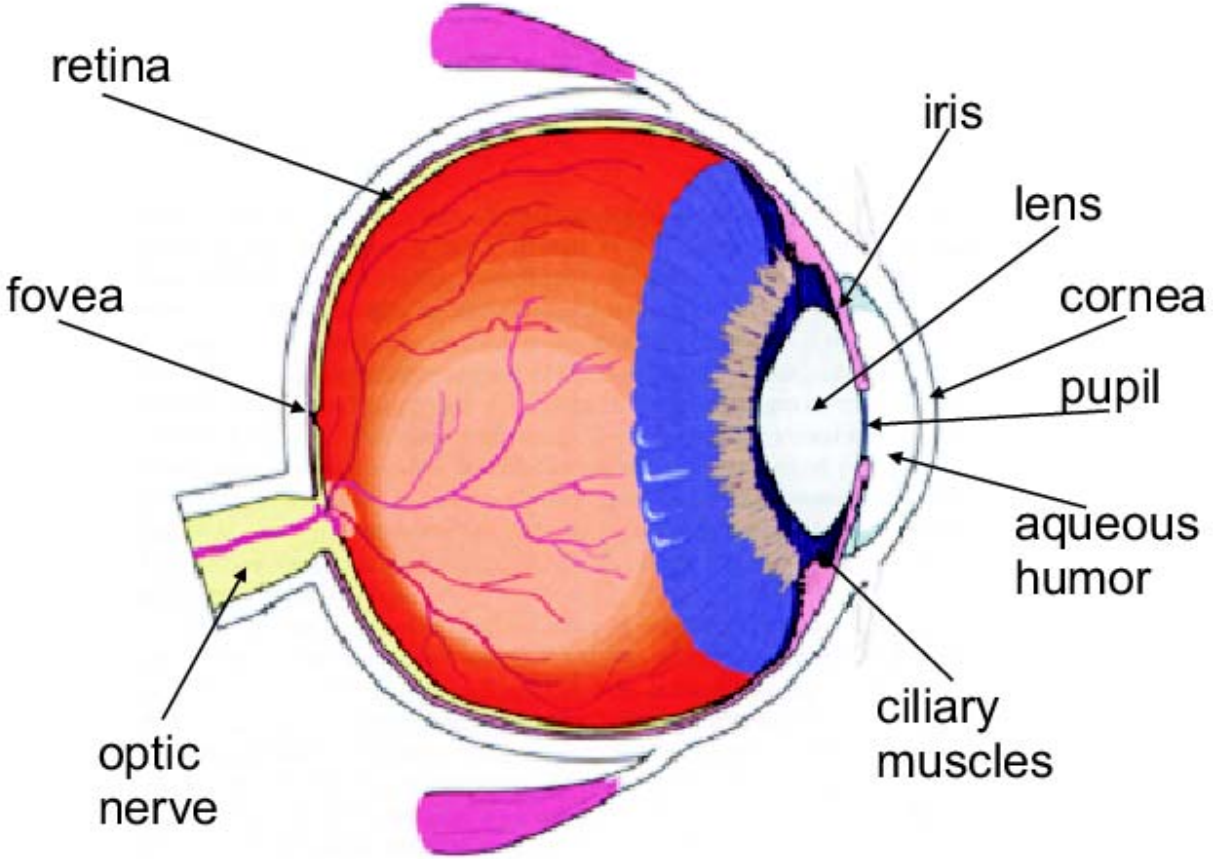


Human Visual System

- eye
- retina
- LGN
- visual pathways
- visual cortex

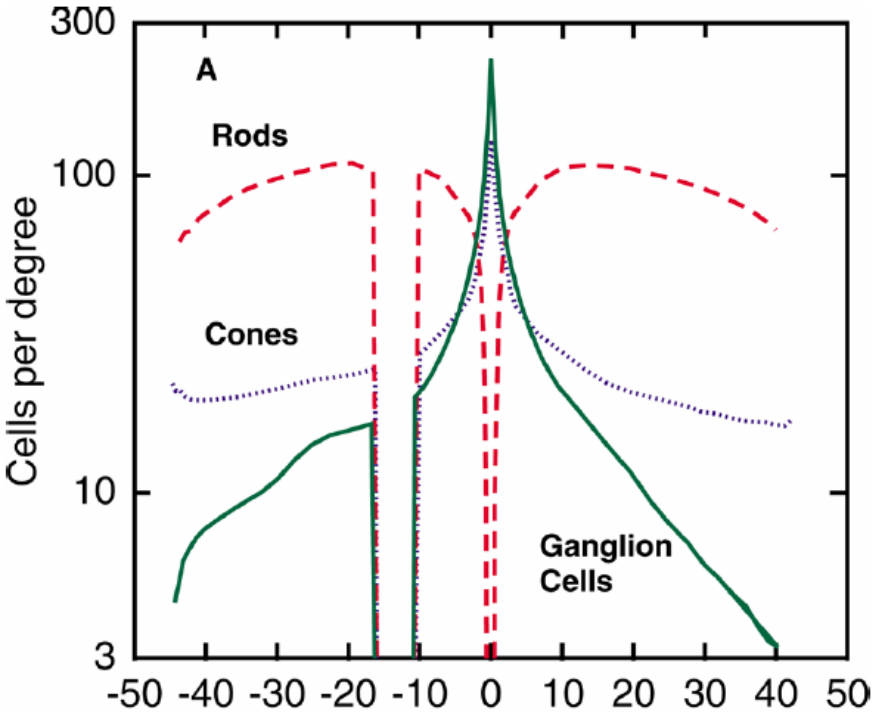


Eye


retina
iris
lens
fovea
cornea
pupil
aqueous
humor
ciliary
muscles
optic
nerve

Retina

- Photoreceptors
  - **Rods** (~120 000 000), scotopic vision
  - **Cones** (~ 8 000 000), photopic vision, colour
- Fovea
  - just cones, no rods
- Blind spot
  - no receptors

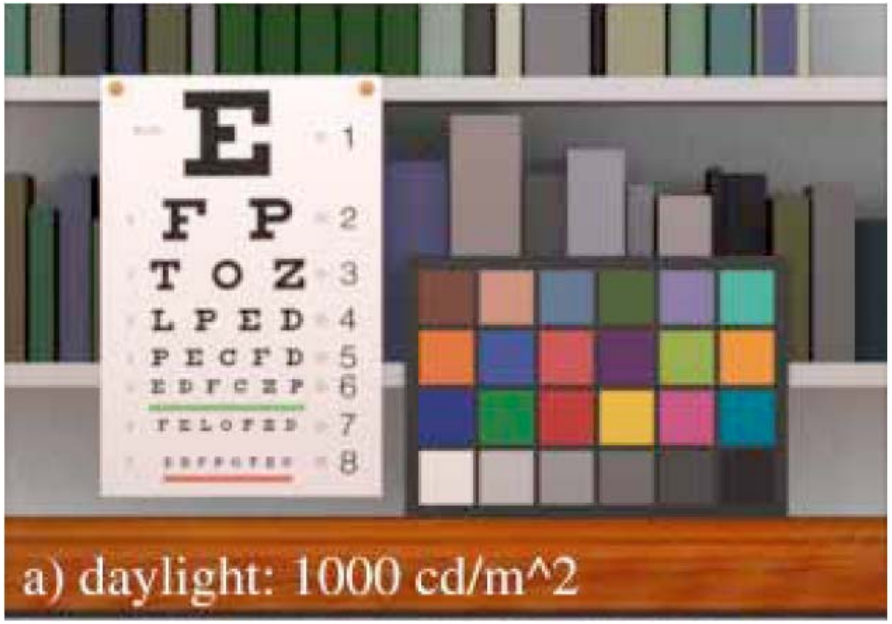




Photopic & Scotopic vision

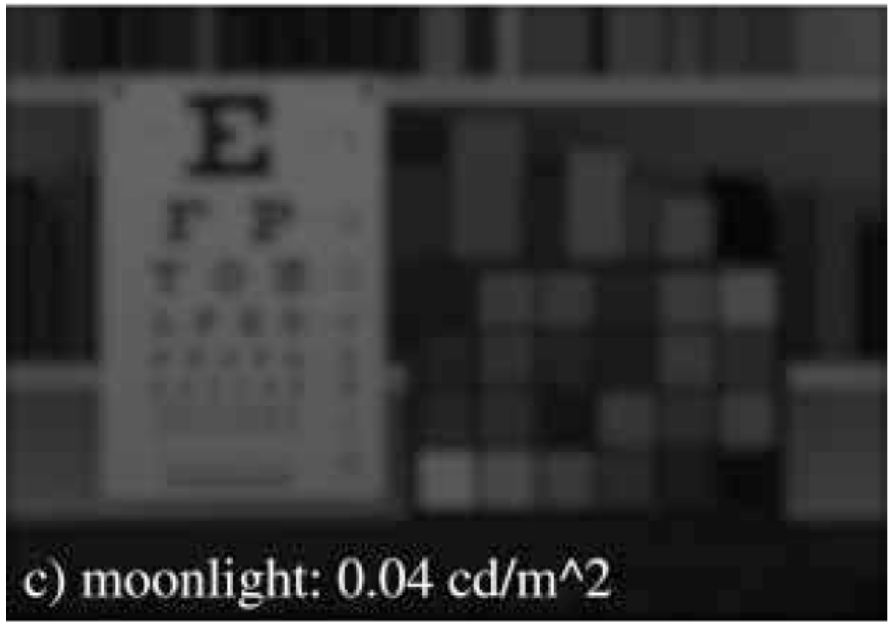
- [Ferwerda 96]

Photopic (daylight)



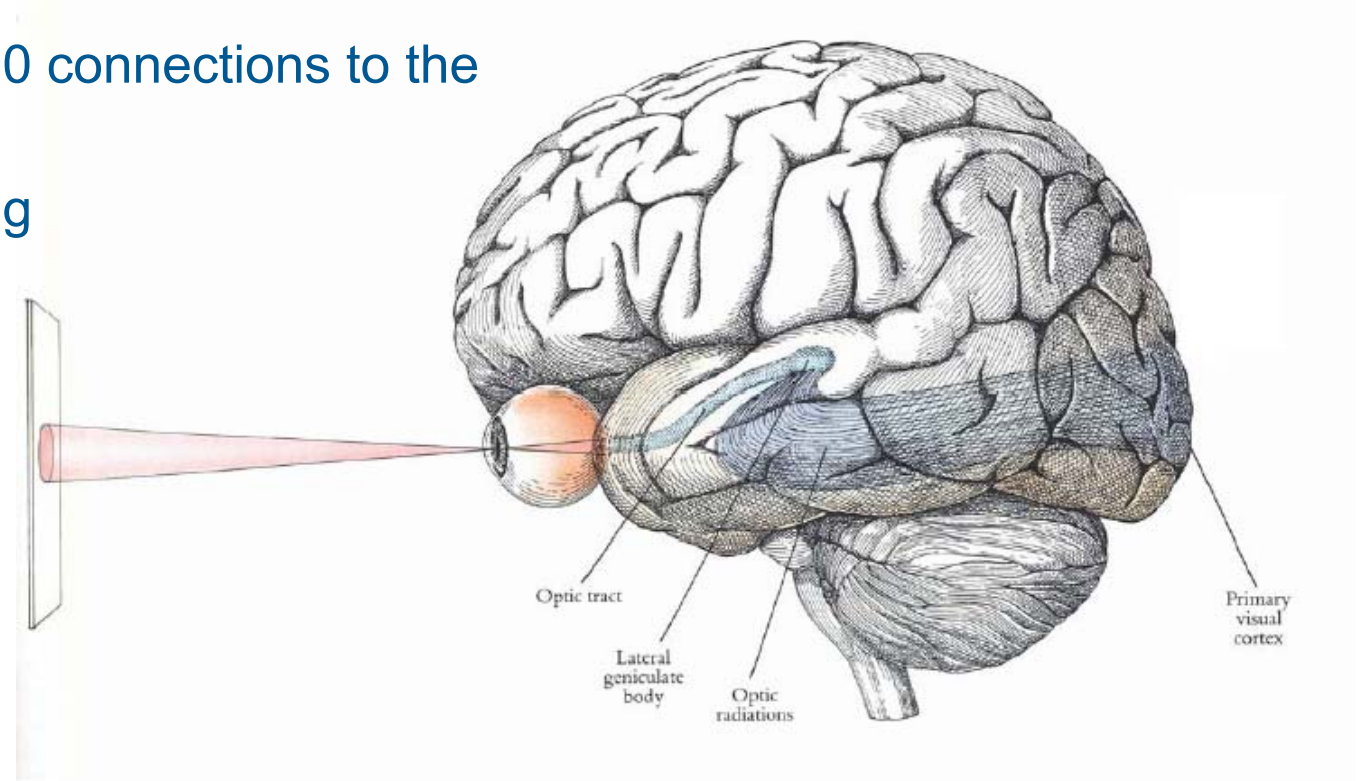
Scotopic (moonlight)

Purkinje shift (sensitivity shift towards blue)



Visual Cortex

- visual cortex ~50% of the whole brain
- 100 000 000 000 visual cells in the brain
- each cell has 4000 connections to the others
- parallel processing



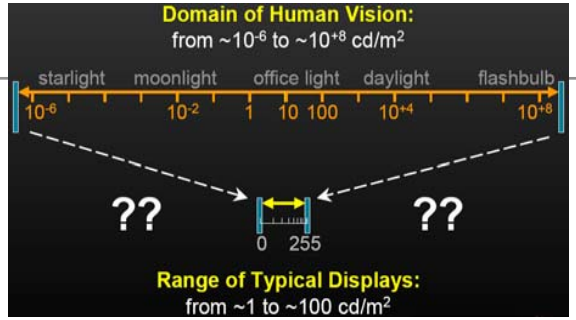
Visual Adaptation

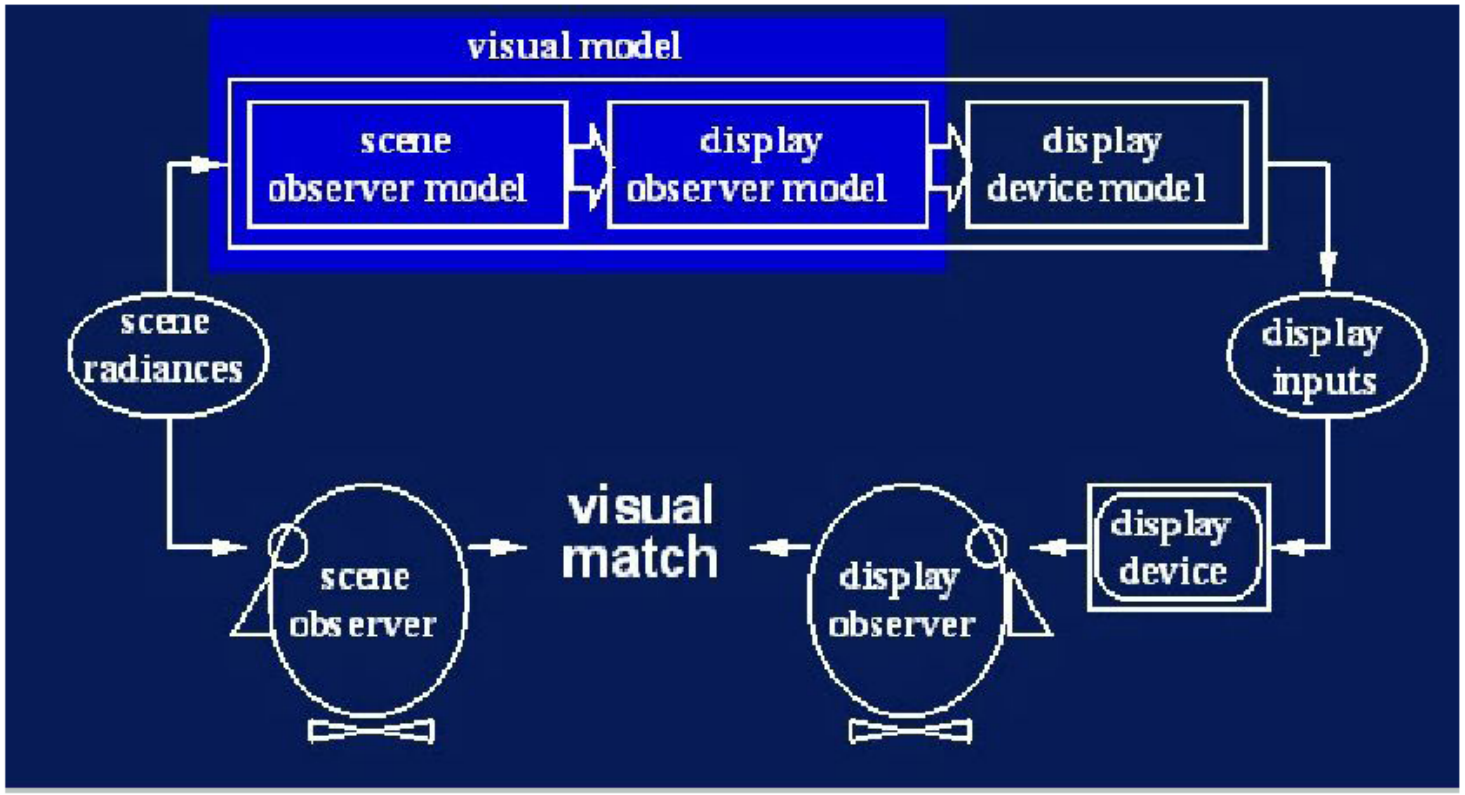
- Let more light in
  - Pupil (Human 10:1)
- Use more sensitive photoreceptors
  - rods, cones
- Add up more light
  - Temporal integration
  - Spatial integration (poor acuity)

- **Light** adaptation, **Dark** adaptation
  - pigment bleaching/regeneration

Tone Mapping

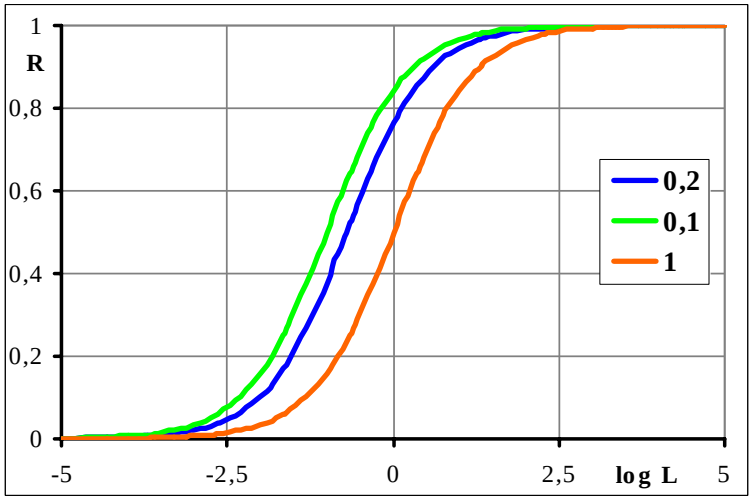
- [Tumblin and Rushmeier 93]





Tone Mapping

- Tone mapping methods (operators)
  - Global
    - same function for each pixel
    - suitable for interactive applications
    - suitable just for “medium HDR”
    - easy to implement
  - Local
    - different mapping for each pixel
    - computationally demanding
    - perfect local contrast
    - more compression possible
    - possible artifacts



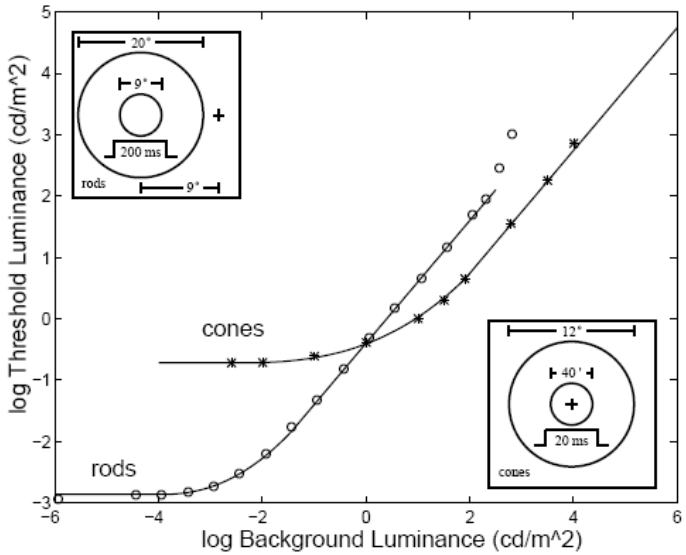
Tone Mapping – Global

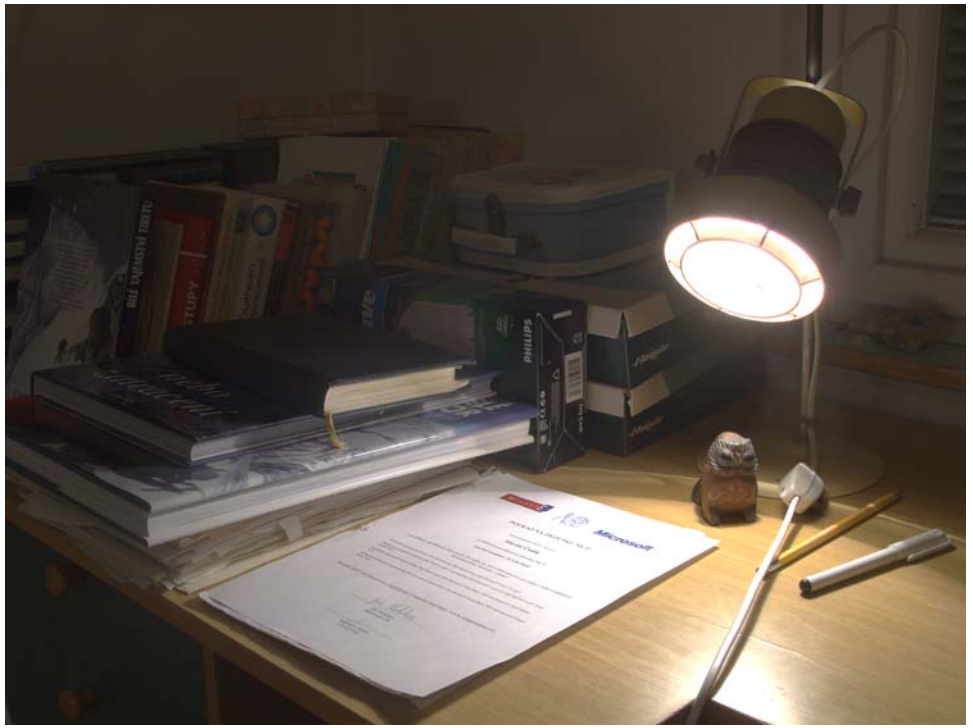
- linear scaling
  - Display luminance: L_d
  - World luminance: L_w
  - $L_d = L_w * 1/L_{w_max}$



Tone Mapping – Global

- [Ward 94, Ferwerda et al. 96]
  - linear scaling based on TVI functions (JND_w->JND_d)
  - dark scenes appear dark, bright scenes appear bright



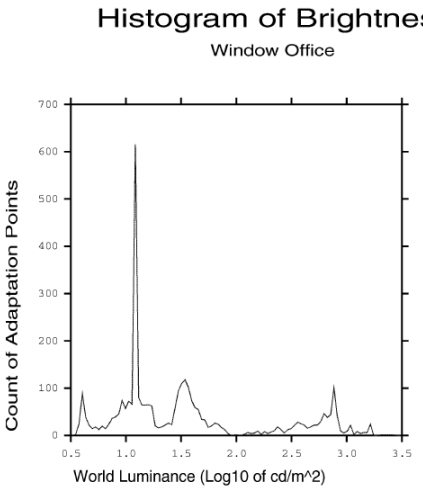


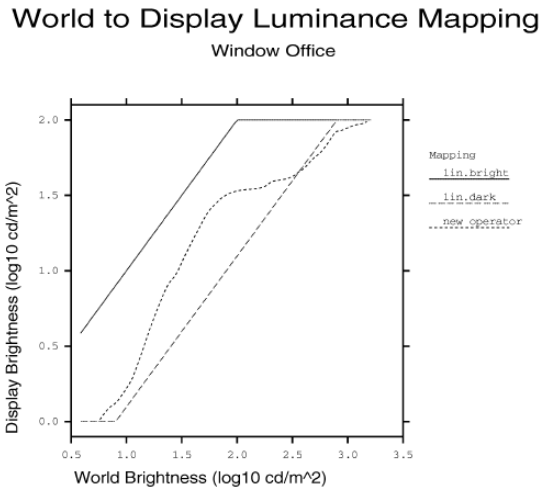
$$L_d = m \cdot L_w \qquad m = \left[\frac{1.219 + L_{da}^{0.4}}{1.219 + L_{wa}^{0.4}}\right]^{2.5}$$

$$t(L_{da}) = m(L_{wa}, L_{da}) t(L_{wa})$$

Tone Mapping – Global

- [Ward et al. 97]
  - visibility matching
  - histogram-based

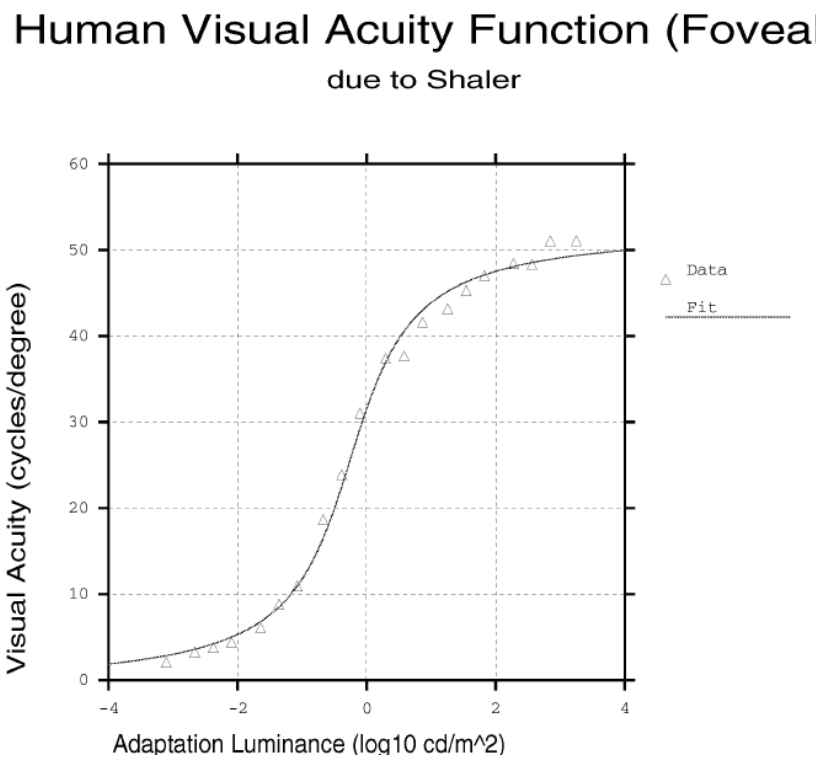


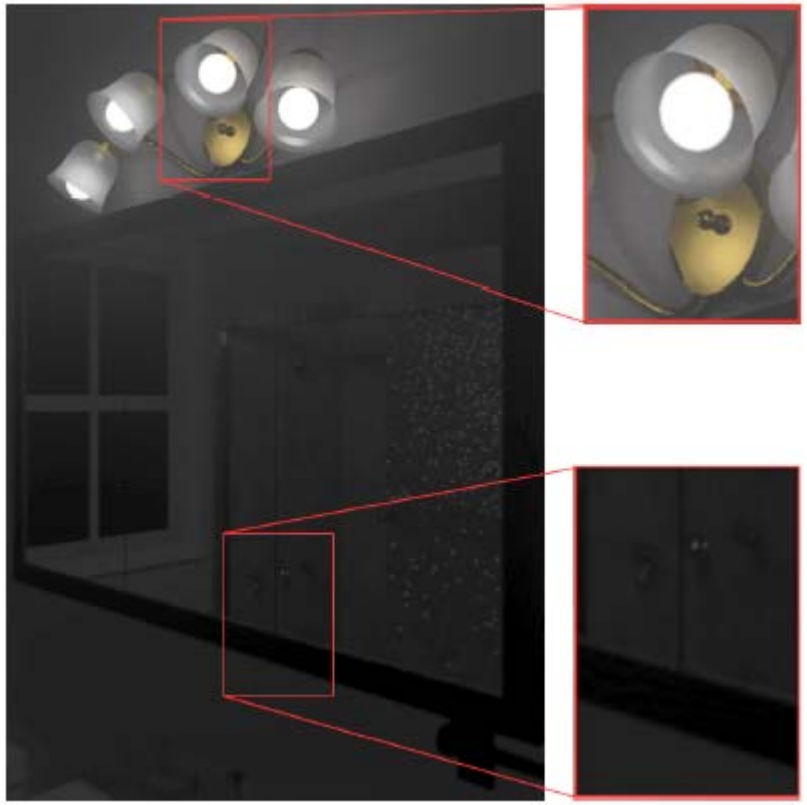



```
procedure
  match_visibility()
generate histogram of
  effective adaptation
  image
adjust histogram to
  contrast sensitivity
  function
apply histogram adjustment
  to image
translate CIE results to
  display RGB values
end
```

Tone Mapping – Global

- [Ward et al. 97]
  - [Shaler 37]



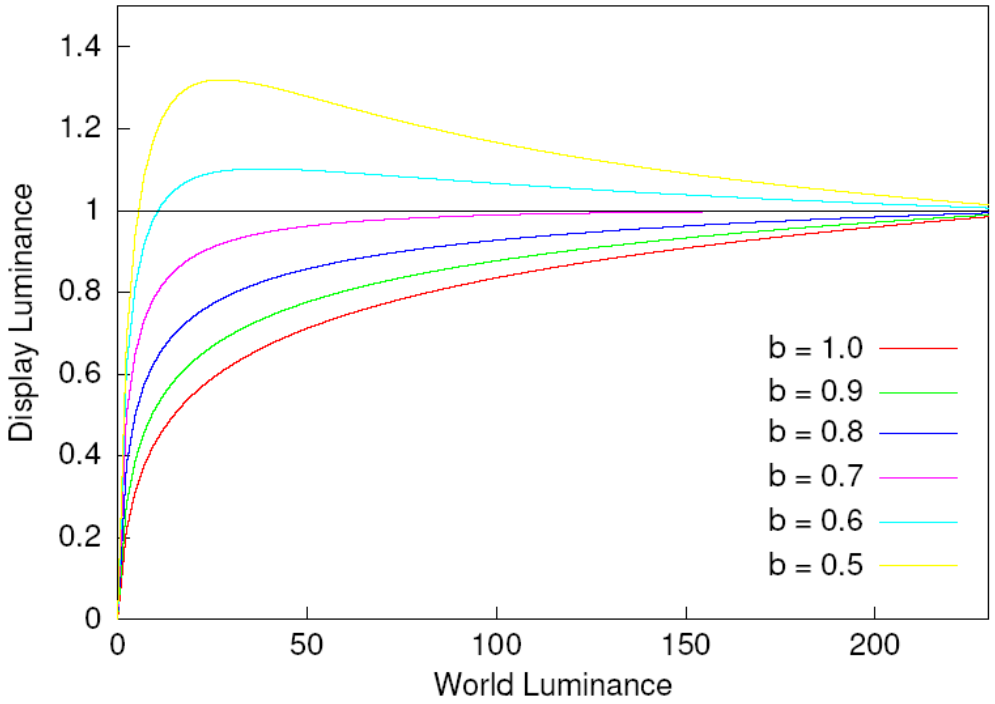


Tone Mapping – Global

- [Drago et al. 03]
  - logarithmic compression of luminance
  - adaptive base of logarithm

$$\log_{base}(x) = \frac{\log(x)}{\log(base)}$$

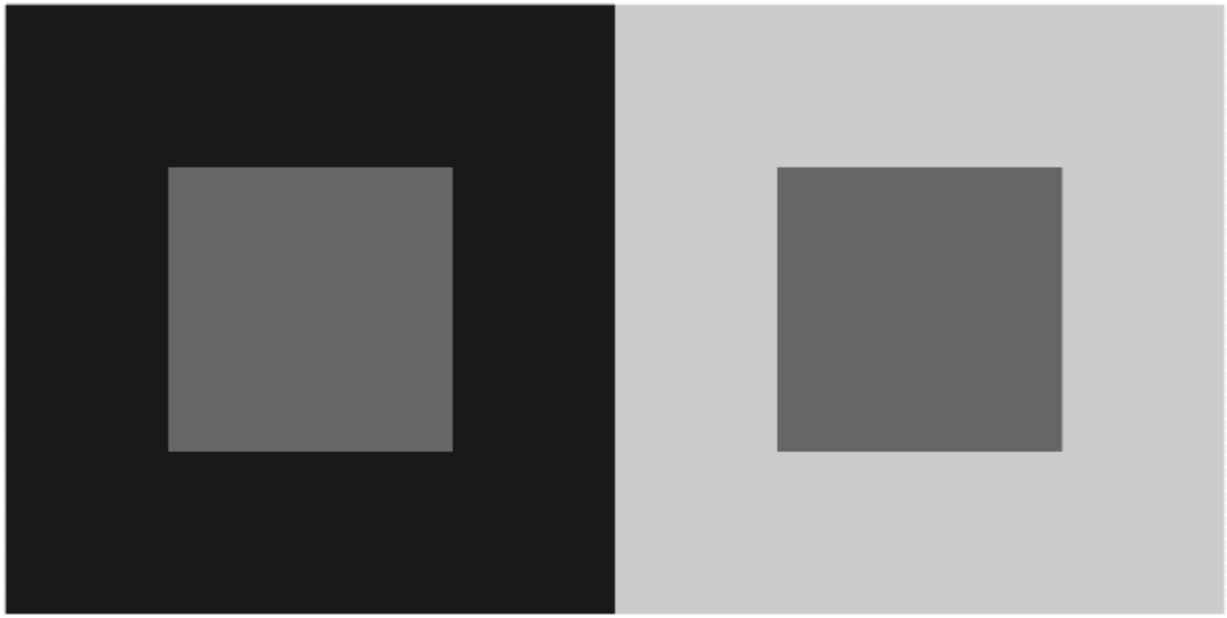
(depends on each pixel)



$$L_d = \frac{L_{dmax} \cdot 0.01}{\log_{10}(L_{wmax}+1)} \cdot \frac{\log(L_w+1)}{\log\left(2+\left(\left(\frac{L_w}{L_{wmax}}\right)^{\frac{\log(b)}{\log(0.5)}}\right)\cdot 8\right)}$$

Tone Mapping – Local

- local adaptation
  - for each pixel, consider its neighbouring as well
  - HVS do it similarly
- simultaneous contrast

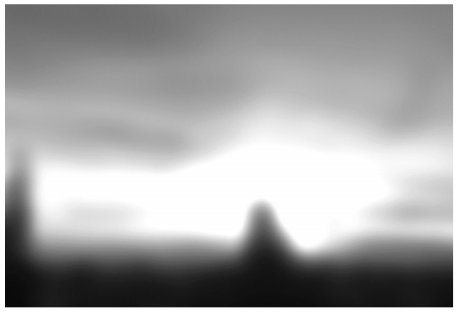


Tone Mapping – Local

- [Chiu et al. 93]
  - local adaptation
  - low-pass filtered (blurred) image

$$L_d(x,y) = \frac{L_w(x,y)}{k\, L_w^{\mathrm{LPF}}(x,y)}$$

halo artifacts (esp. for strong edges)





Tone Mapping – Local

- Halo artifacts

exaggerated artifacts

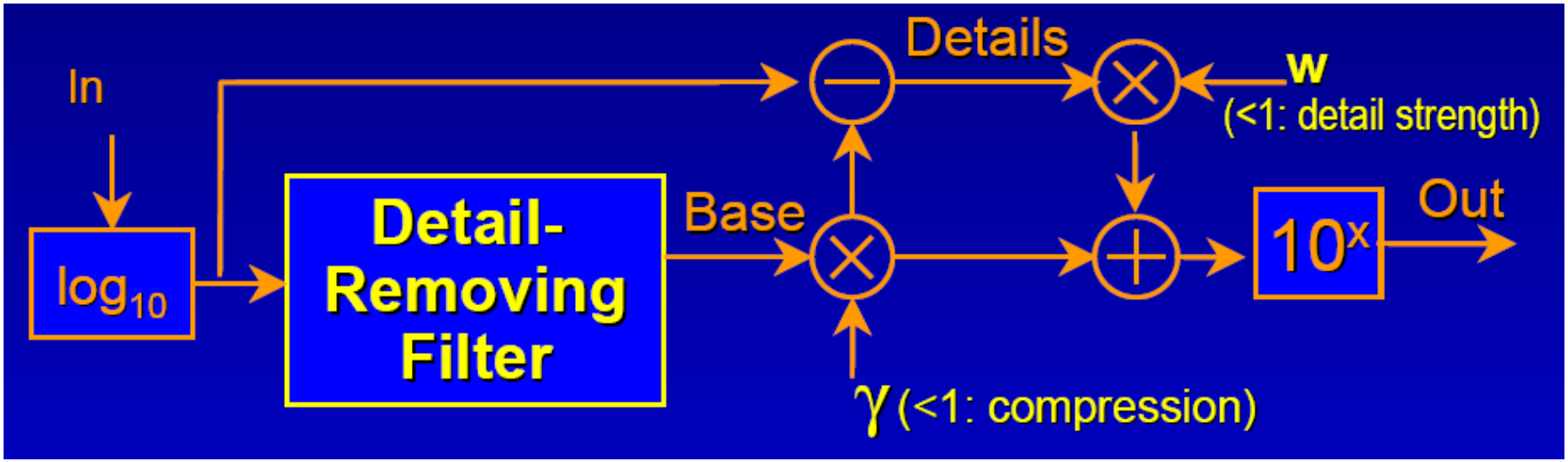


no artifacts



Tone Mapping – Local

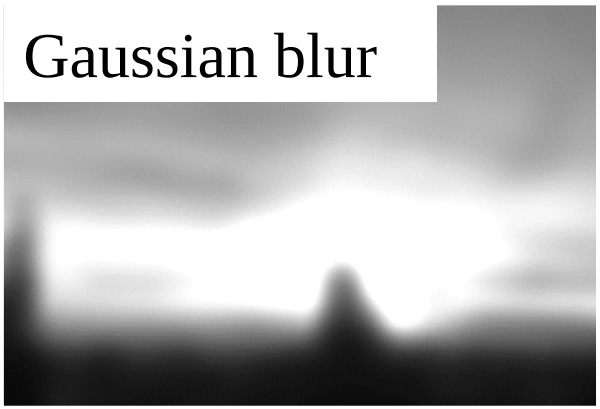
- [Oppenheim et al. 68]
  - illuminance (HDR, slowly varying)
  - reflectance (details)
- [Tumblin and Turk 99] - LCIS, [Durand and Dorsey 02] – bilateral filter, [Choudhury and Tumblin 03] – trilateral filter, [Xu and Pattanaik 03] - level-set framework
  - edge-preserving smoothing operators



Tone Mapping – Local

- [Durand and Dorsey 02]
  - edge-preserving **bilateral filter** [Tomasi and Maduci 98]



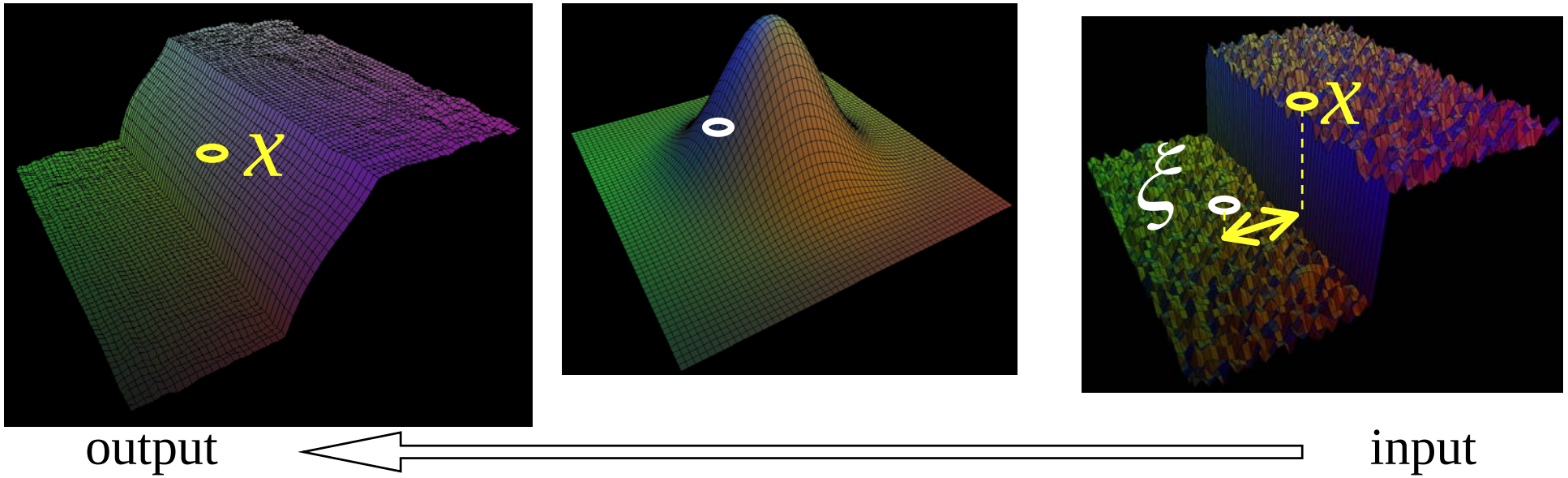




Gaussian filter as weighted average

- Weight of ξ depends on distance to x

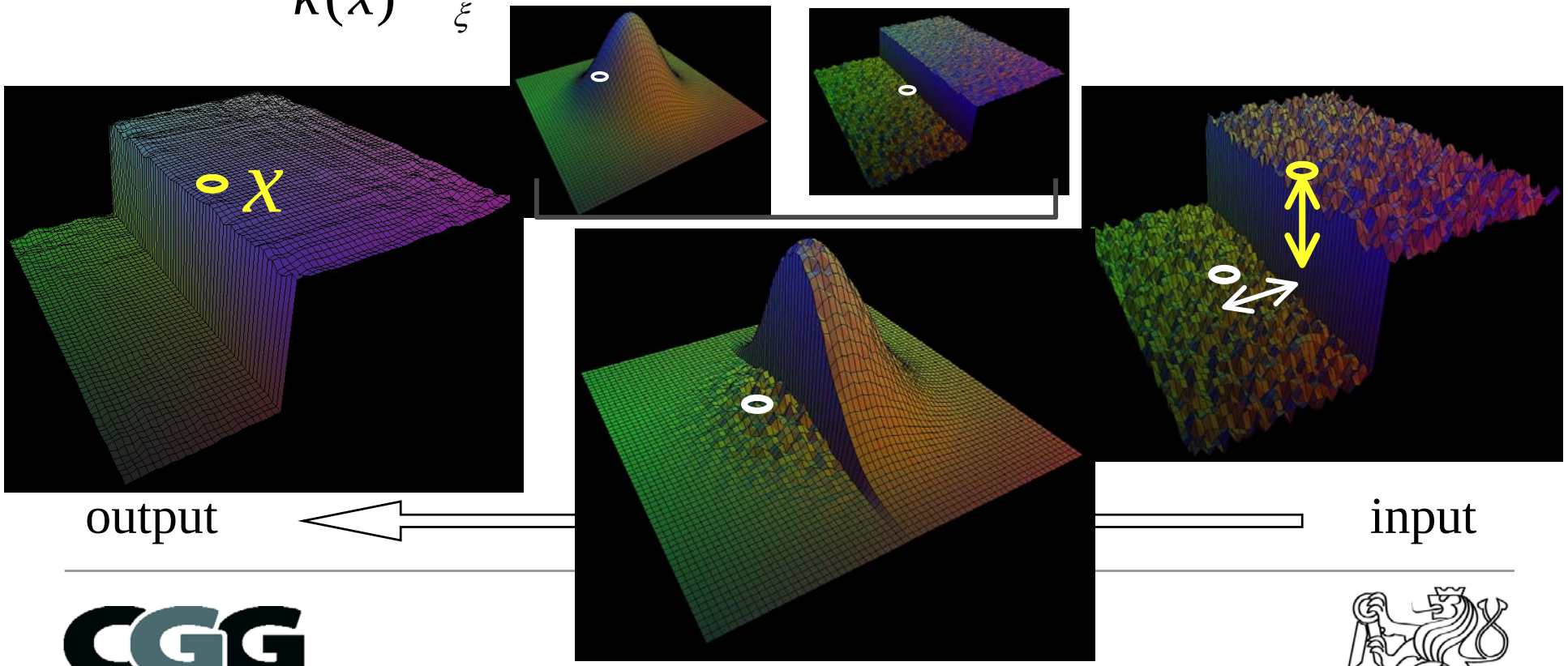
$$J(x) = \sum_{\xi} f(x,\xi) \quad I(\xi)$$



Bilateral filtering

- Spatial Gaussian f
- Penalty g on the intensity difference

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

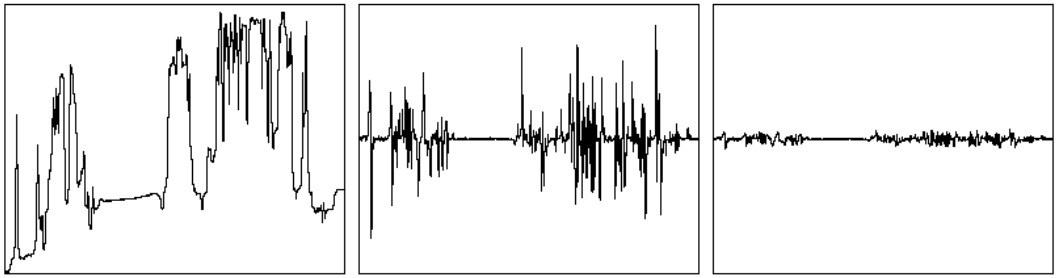


Tone Mapping – Local

- [Fattal et al. 02]
  - **gradient-domain** based approach
  - illuminance – small gradients, large gradients (edges of light sources)
  - reflectance – sharp spikes, small gradients
  - **attenuation of large gradients**
  - finally – integration (Poisson equation)

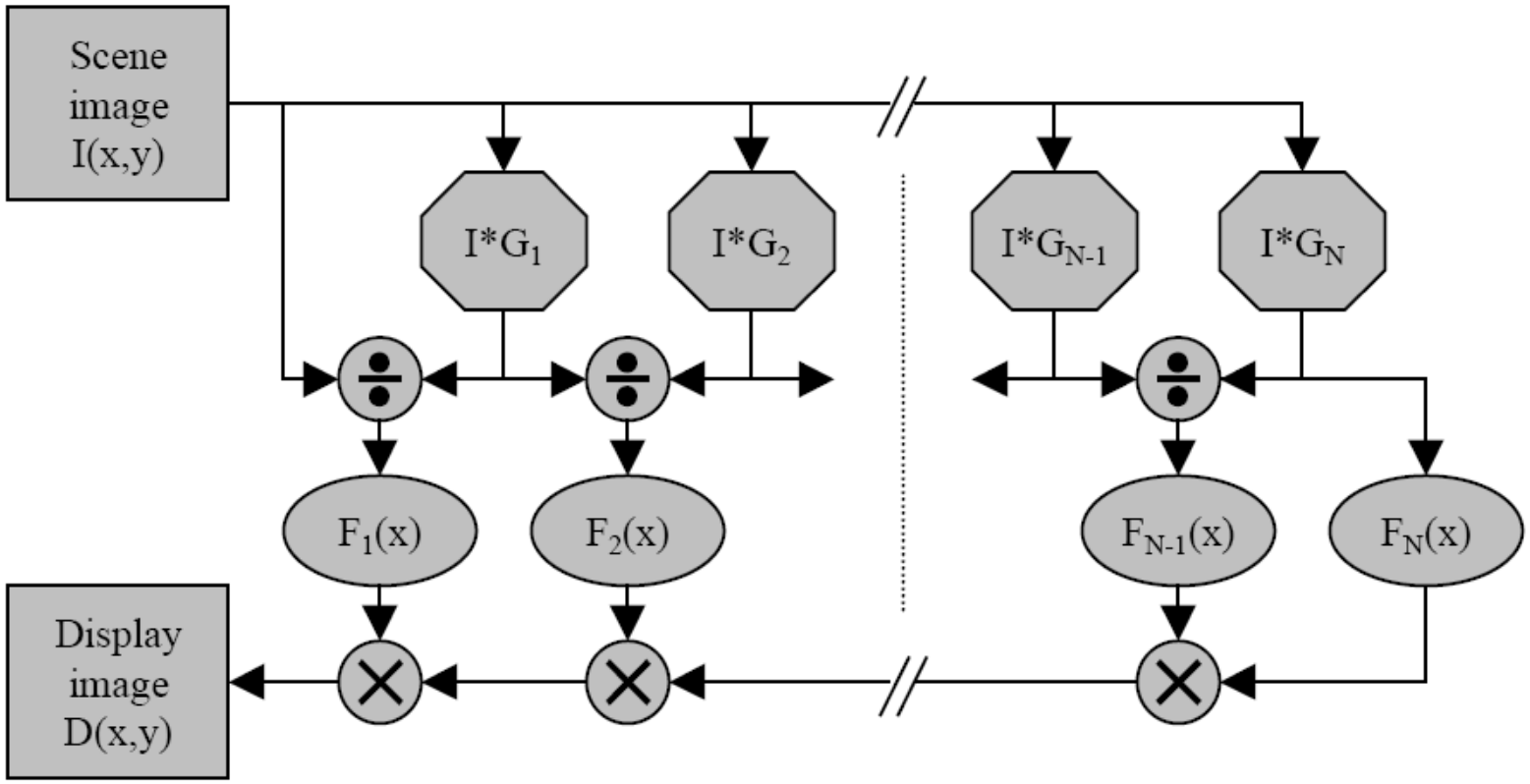
Gradient attenuation function (generated from multiple scales):





Tone Mapping – Local

- Multiscale methods
  - [Peli 90] – Local band-limited contrast



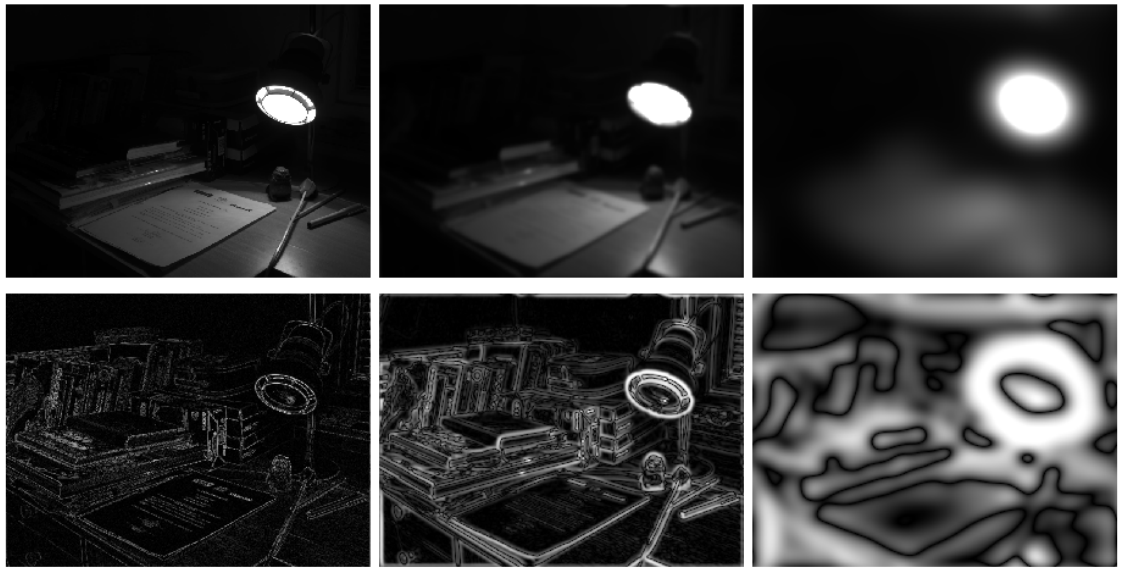
Tone Mapping – Local

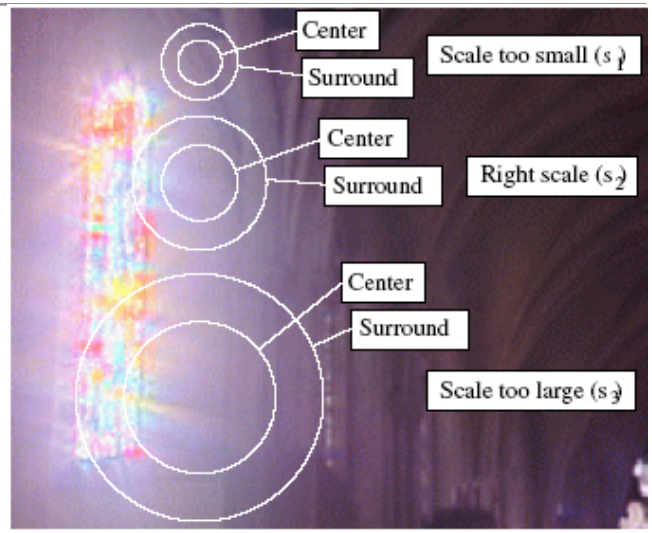
- Multiscale methods: [Jobson 96, Pattanaik 98, Reinhard et al. 02, Ashikhmin 02]
- Ganglion cells
  - receptive fields

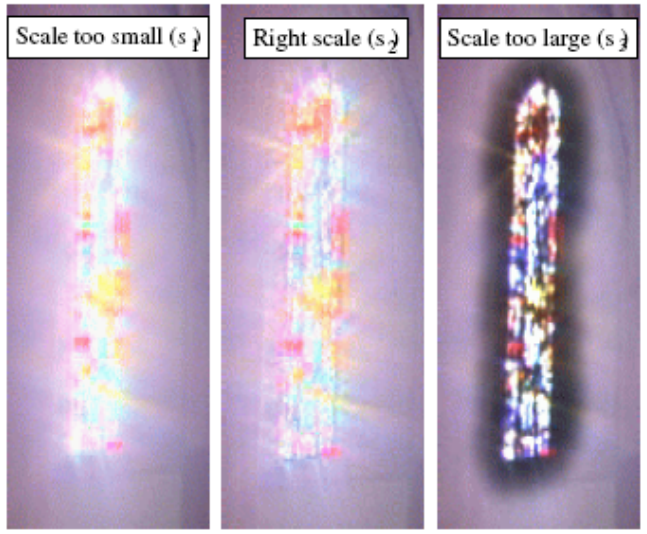


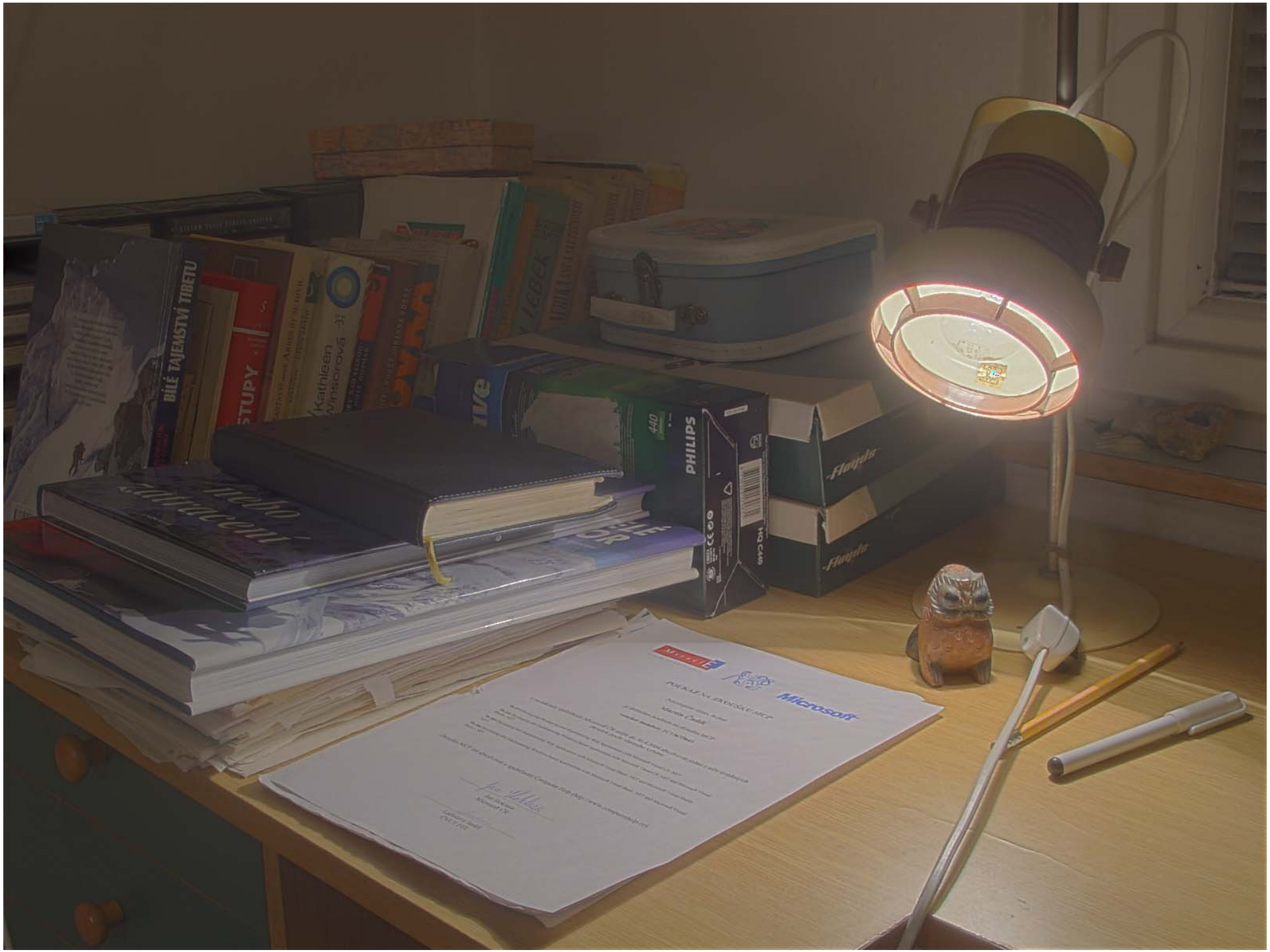
- Scale selection mechanism

Multiple spatial scales [Peli90]



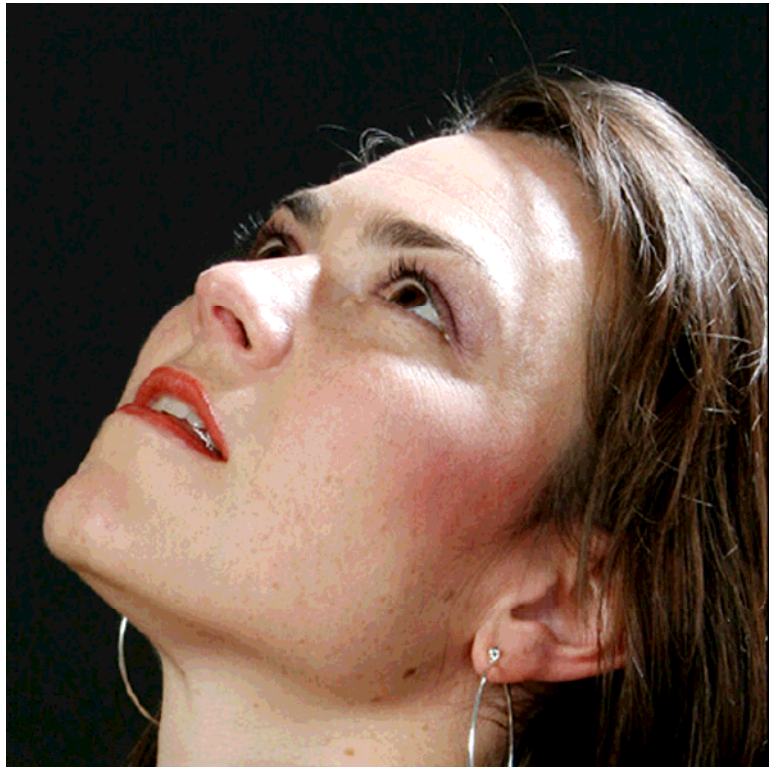


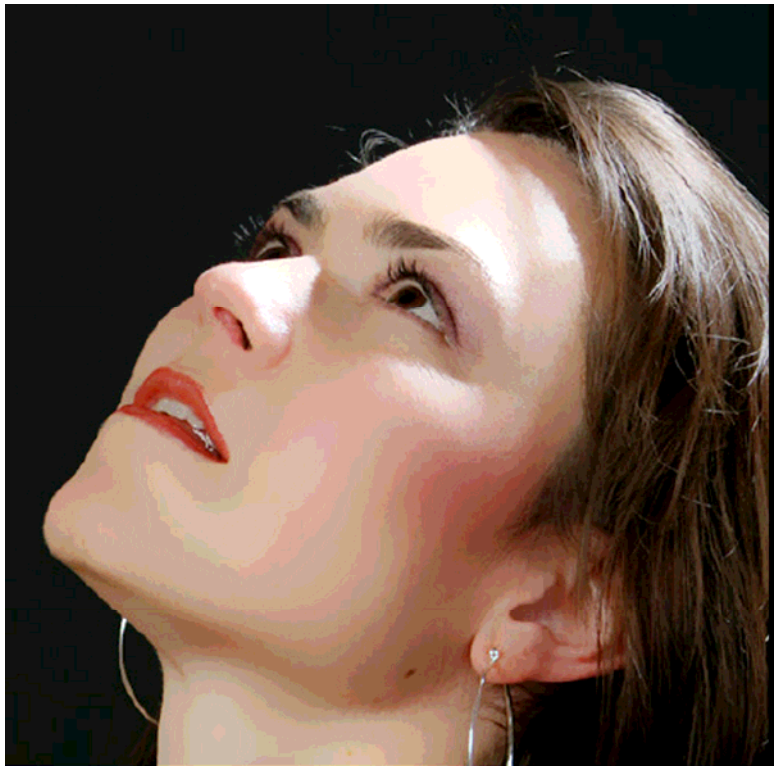



BÍLÉ TAJEMSTVÍ TIBETU
Kathleen Winsorová
PHILIPS
Microsoft

Applications in LDR?

- YES, i.e. Bilateral filter [Weiss06fast]

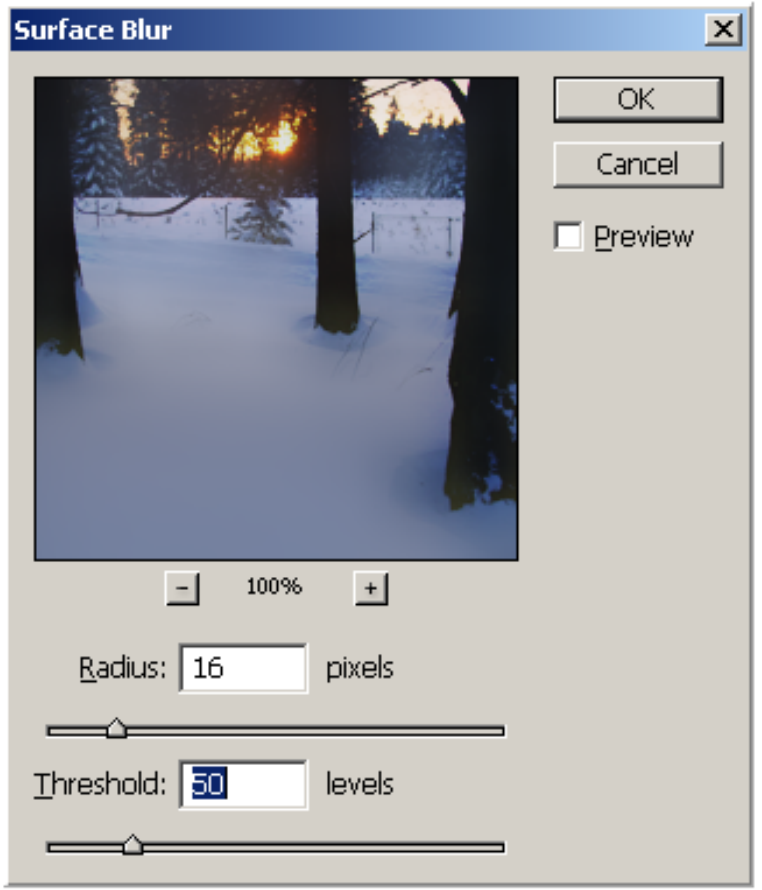




Bilateral Filter in Adobe Photoshop CS2

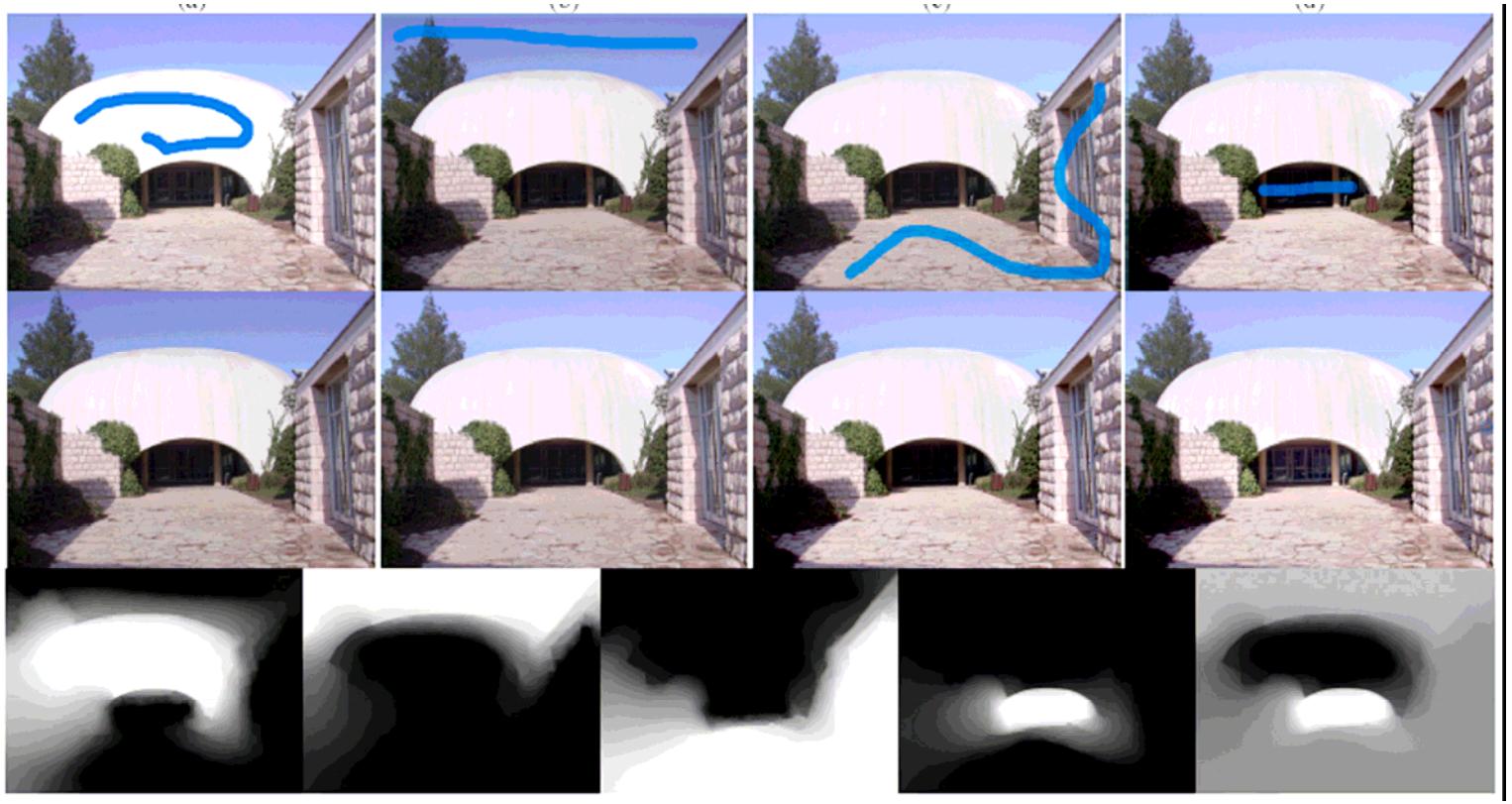
- PS_CS2, CS_3
  - Bilateral Filter = Surface Blur filter





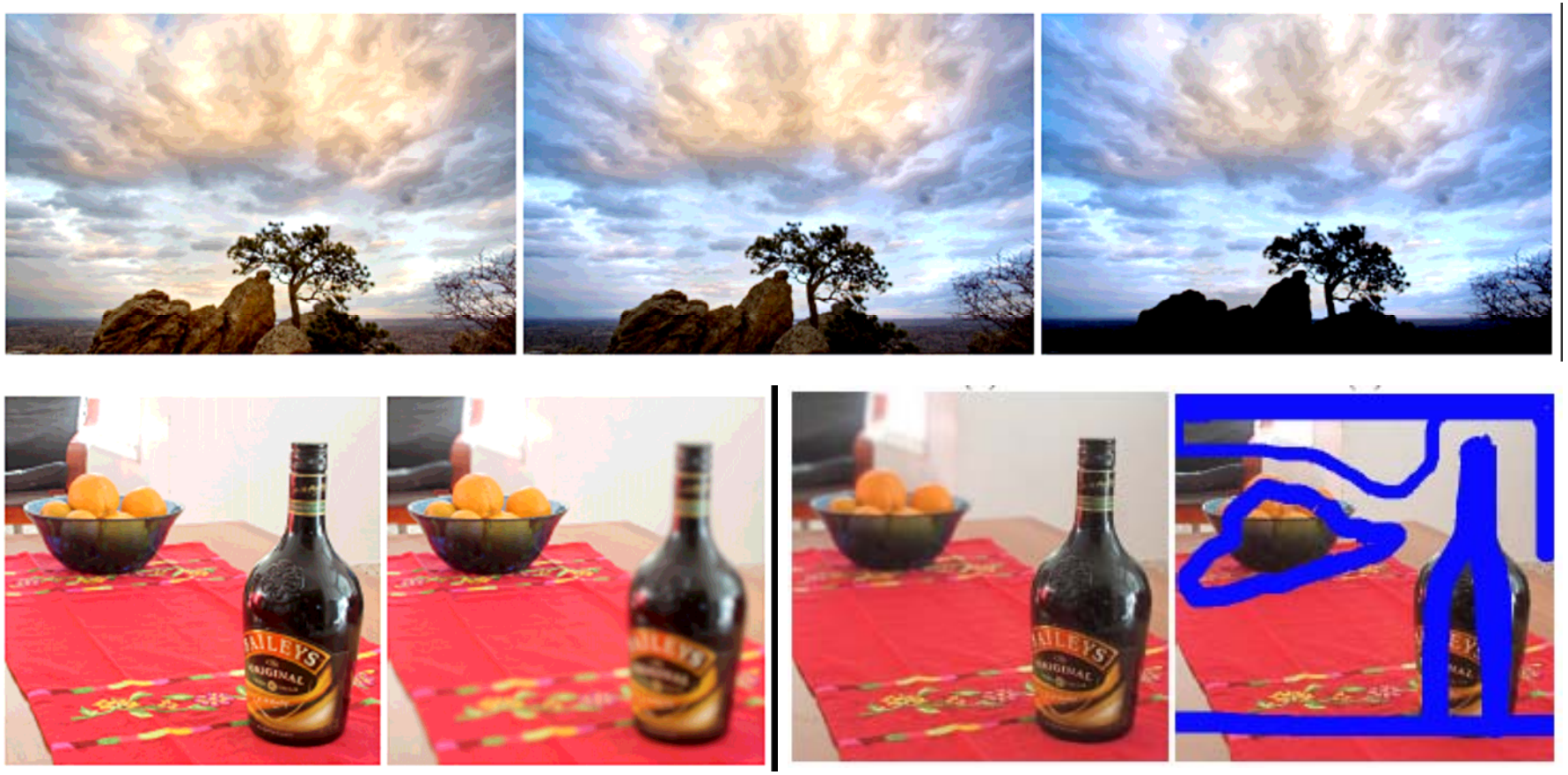
Interactive Tone Mapping

- [Lischinski06]
  - ‘manual’ tone mapping
  - fast approximate solution



Interactive Tone Mapping

- Interactive tonal adjustment [Lischinski06]



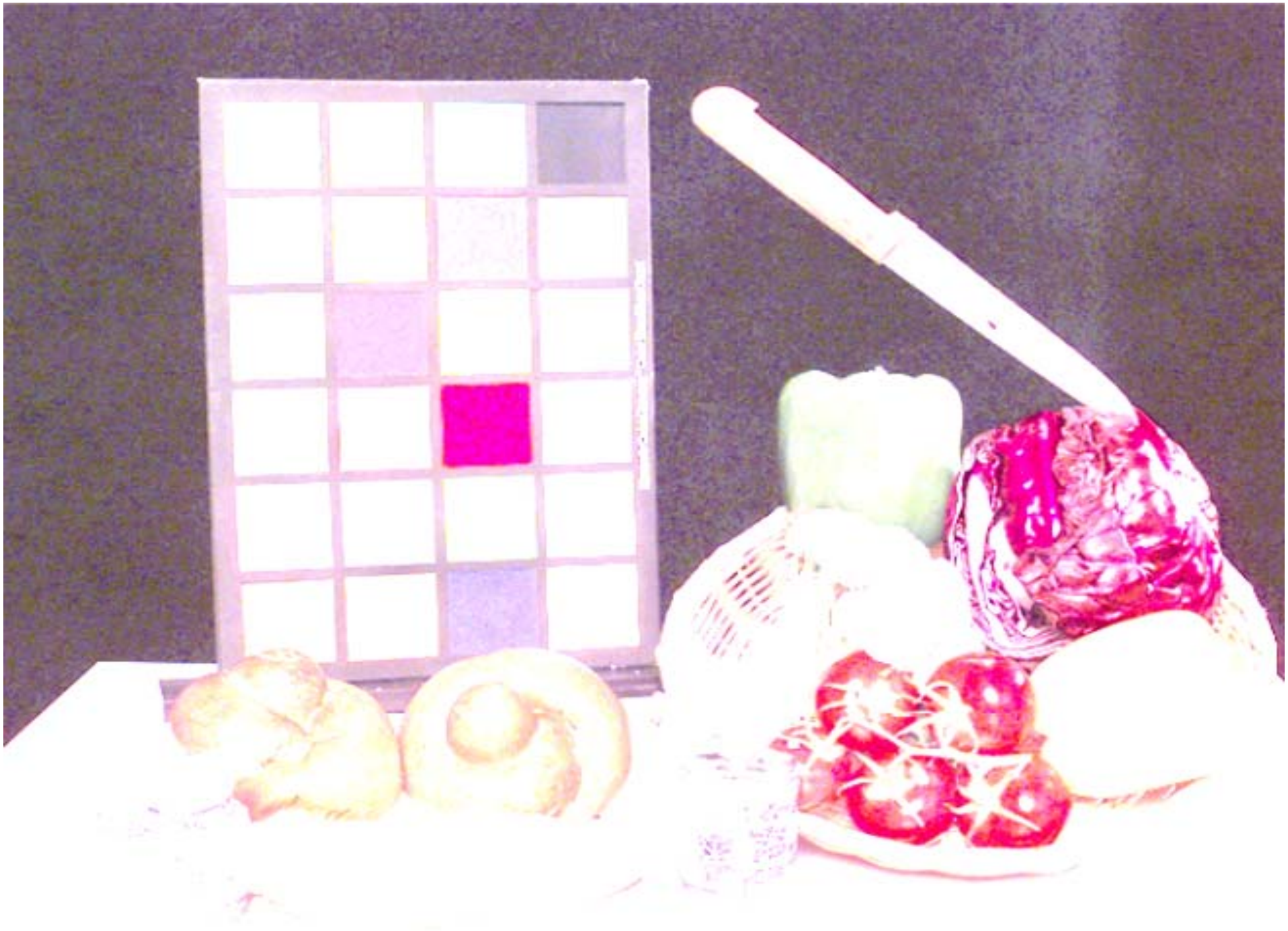
Tone Mapping – Time Dependent Methods

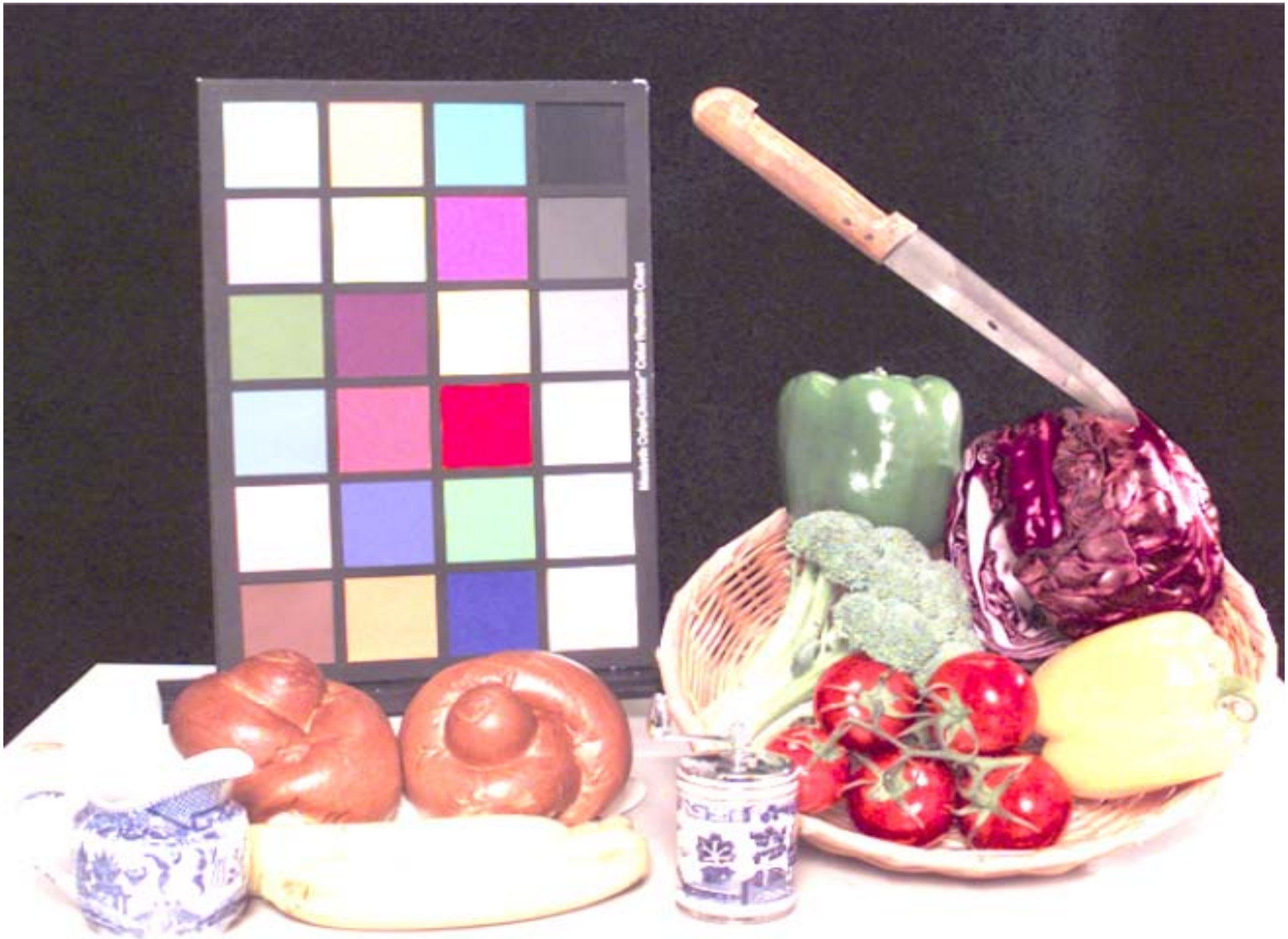
- Motivation
  - HVS simulation
    - ligt-dark adaptation
    - chromatic adaptation
  - temporal-aliasing
- Application
  - simulation of safety conditions
  - interactive applications, games
  - HDR video















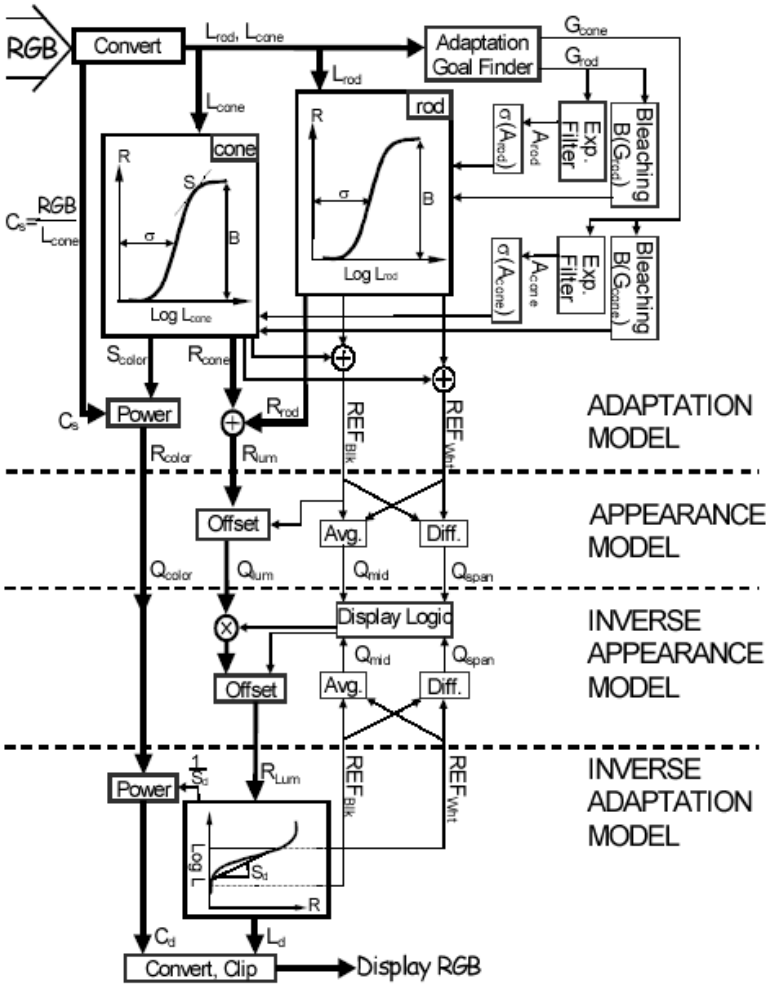
Tone Mapping – Time Dependent Methods

- [Pattanaik et al. 00]
  - physically-based
  - global TMO + exponential filters
  - S-shaped curve:

$$L_d(x,y) = \frac{L_w(x,y)^n}{L_w(x,y)^n + \sigma^n}$$

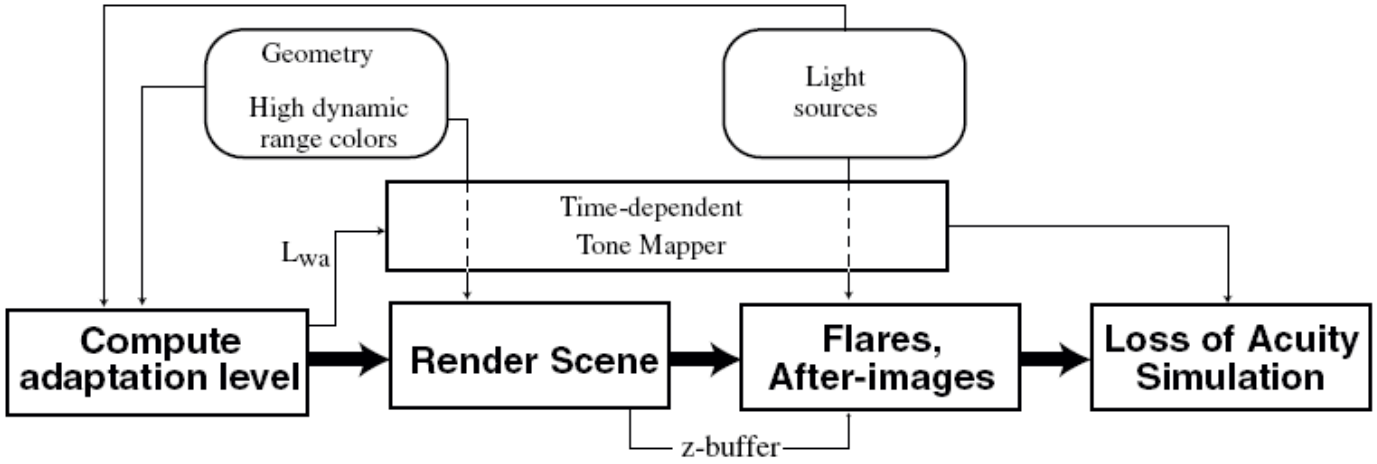
  - R – retina-like responses
  - B – photopigment bleaching
  - A – adaptation amounts (fast neural effects)
  - G – goal adaptation values
  - Q – luminance appearance val.

- [Artusi et al. 01]
  - extends [Pattanaik et al. 00]
  - chromatic adaptation



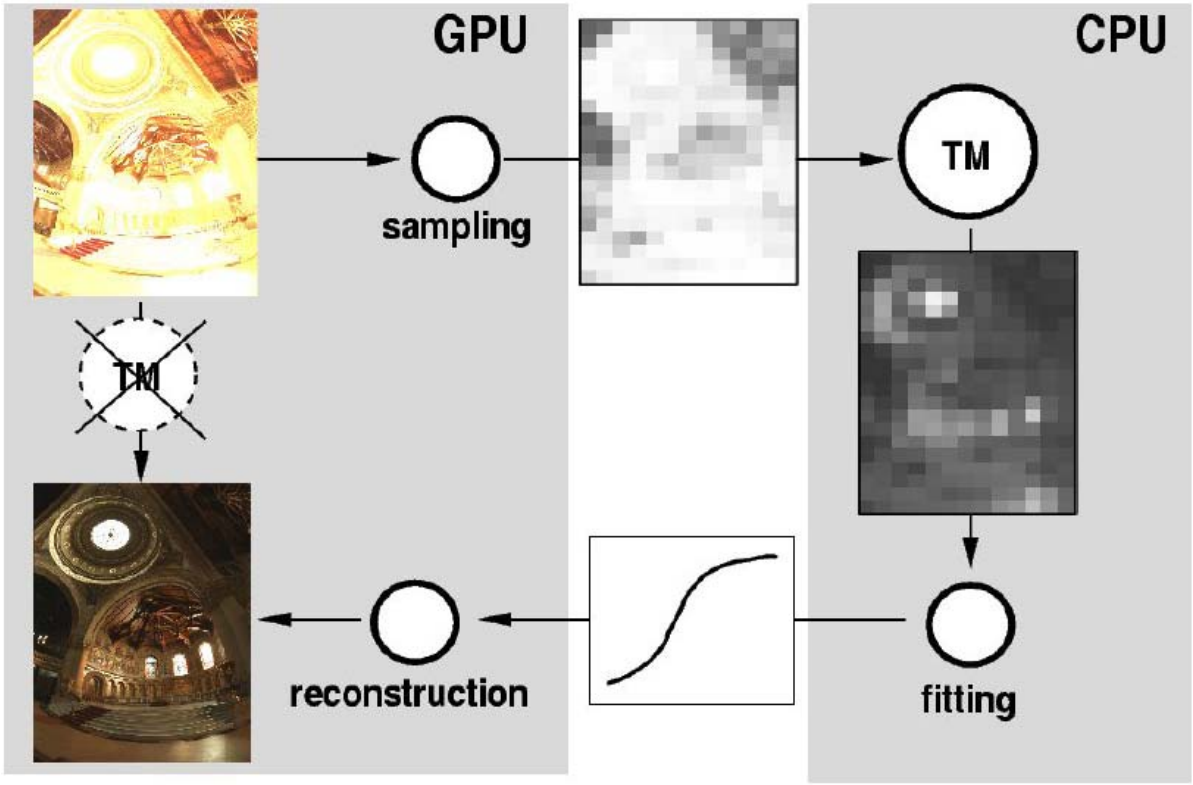
Tone Mapping – Time Dependent Methods

- [Durand & Dorsey 00]
  - interactive applications
  - model of time-dependent adaptation
    - global TMO: $\mathbf{L_d = m\ L_w}$ ([Ferwerda et al. 96])
    - exponential filter: $\mathbf{dm/dt = (m^* - m)/\tau}$
    - no dark adaptation
    - single world adaptation level L_{wa}



Tone Mapping – Time Dependent Methods

- GPU
  - [Artusi et al. 03]

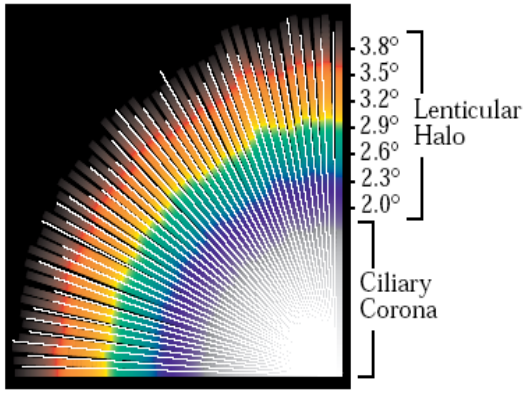


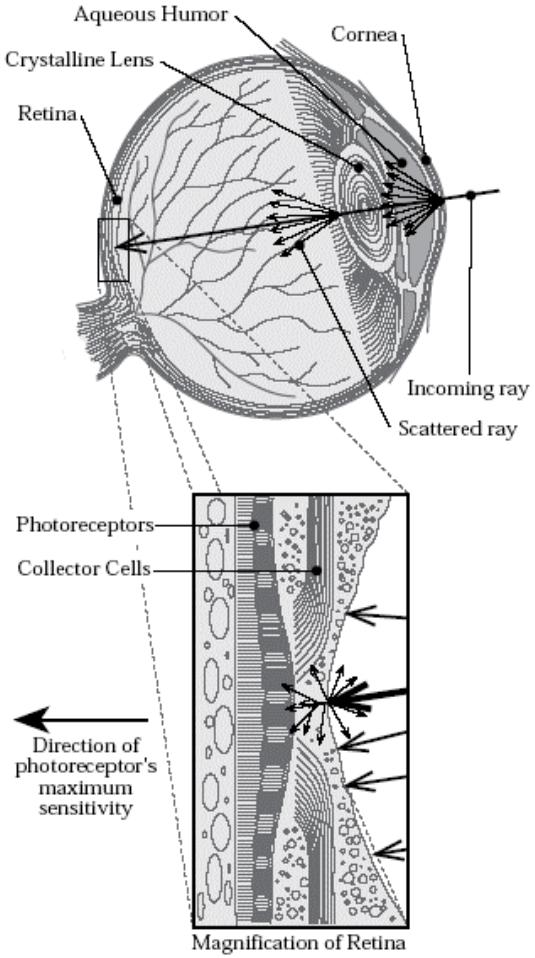
Glare Simulation

- increases subjective dynamic range
- Glare effects
  - **bloom** (veiling luminance)
  - **flare**
    - **lenticular halo**
    - **ciliary corona**



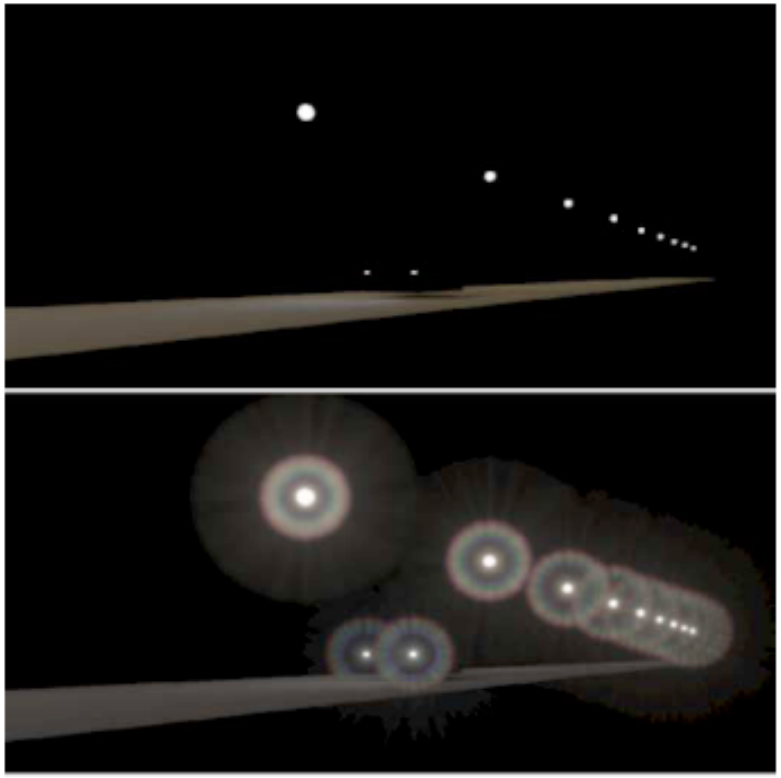
Carl Saltzmann, 1884





Glare Simulation [video]

- flare
  - lenticular halo
  - ciliary corona



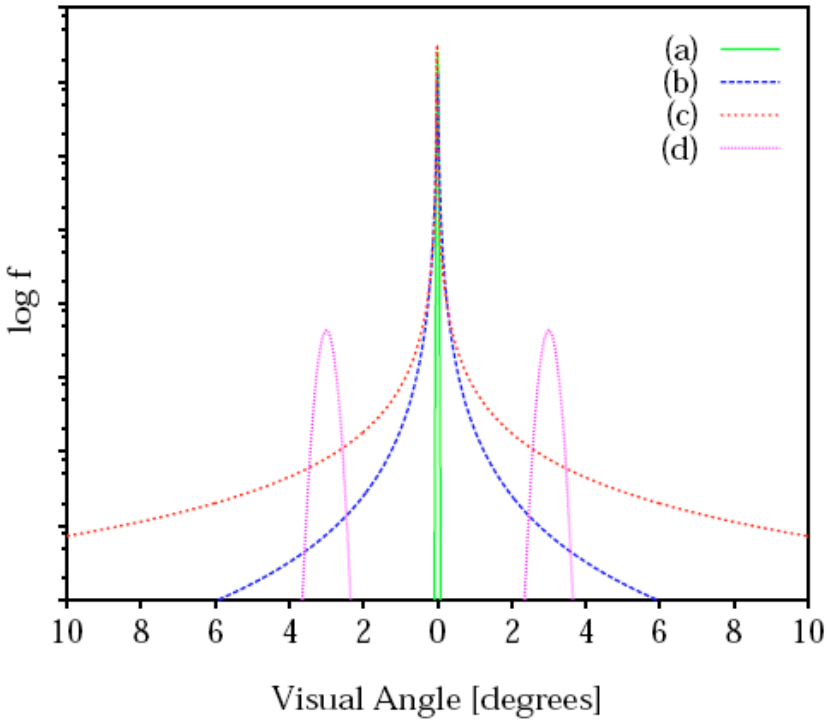
- bloom



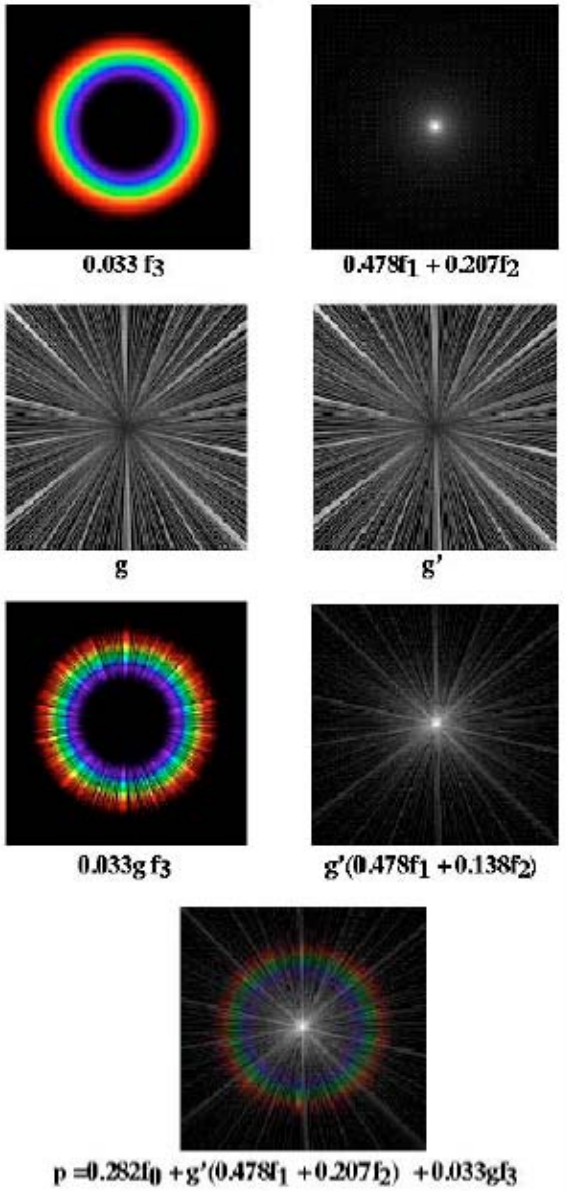


Glare Simulation

- [Spencer et al. 95]
  - digital filter
  - point-spread function (PSF) based

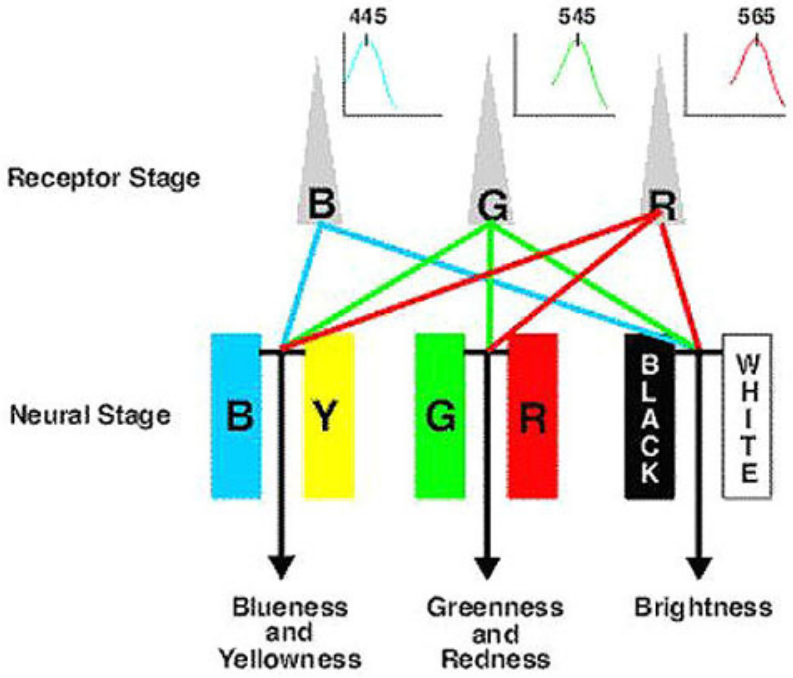


The PSF components (a) f_0, (b) f_1, (c) f_2, and (d) f_3.

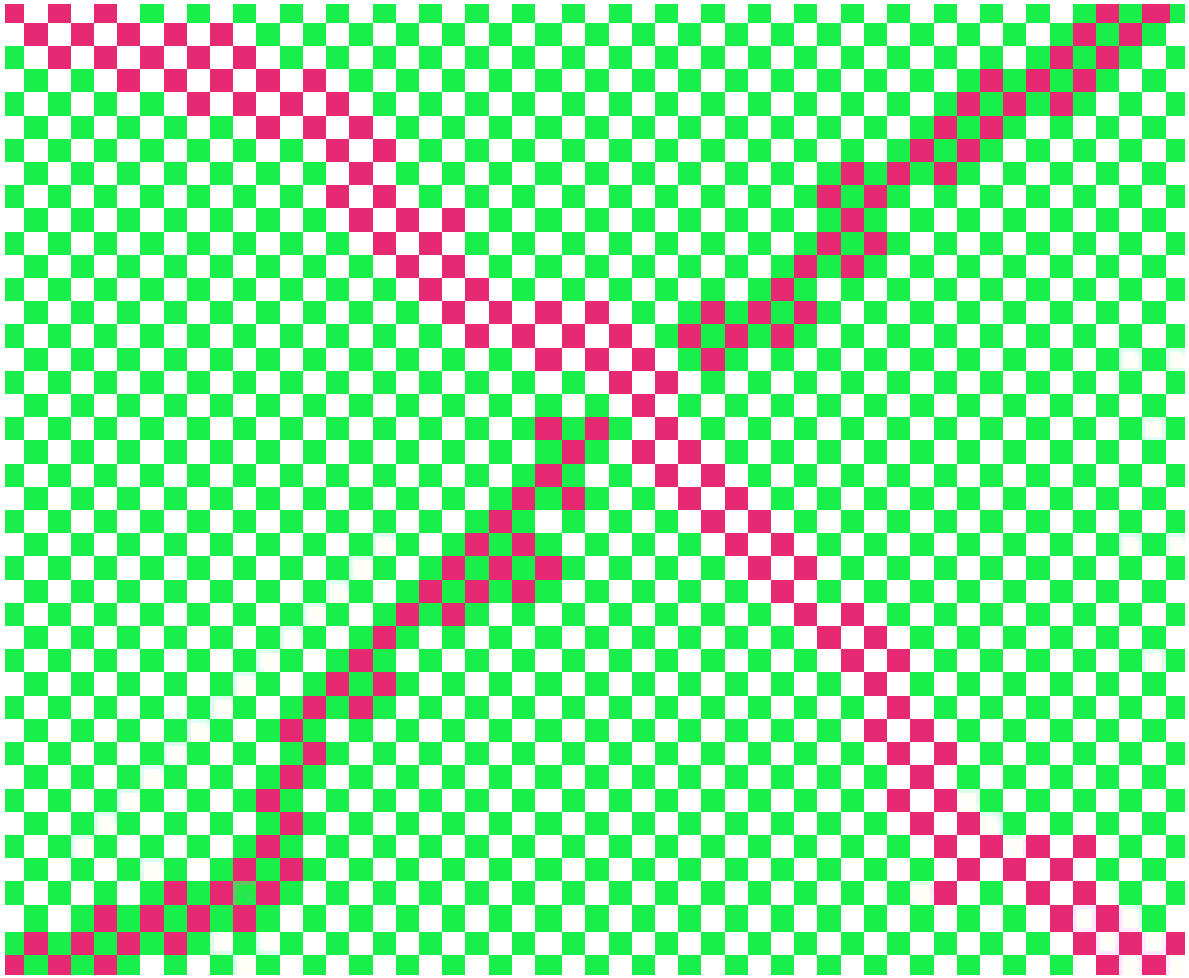


Colour Vision

- Component (Trichromatic) theory (Young 1802, Helmholtz 1866)
  - red (L), green (M), blue (S)
- Opponent colour theory (Hering 1872)
  - red-green, blue-yellow, black-white
- Stage theory
  - incorporates both the trichromatic theory and the opponent colour theory into two stages
- Chromatic adaptation
  - 3rd type of adaptation (light, dark, ~)



Color Contrast



Color – Chromatic Adaptation

- [Pattanaik 98]
  - multiscale processing
  - color processing resembles [Hunt 95]



Color – Chromatic Adaptation

- [Von Kries 1902]
  - "Individual components present in the organ of vision are completely independent of one another and each is fatigued or adapted exclusively to its own function."
  - simple gain-control:

$$L_a = k_L L \qquad k_L = 1/L_{white}$$
$$M_a = k_L M \qquad k_M = 1/M_{white}$$
$$S_a = k_L S \qquad k_S = 1/S_{white}$$

Color



- Retinex theory [Land, McCann 71]
  - enhanced von Kries model (treats spatial distribution of colors, for $c \to \infty$ =von Kries-like)
  - “gray-world” assumption
  - center-surround spatially opponent operation
  - retinex=retina, LGN, cerebral cortex
  - L, M, S retinex processed independently

$$R_i(x,y) = \log\ I_i(x,y) - \log\left[F(x,y) * I_i(x,y)\right]$$

$$F(x,y) = Ke^{-r^2/c^2}$$

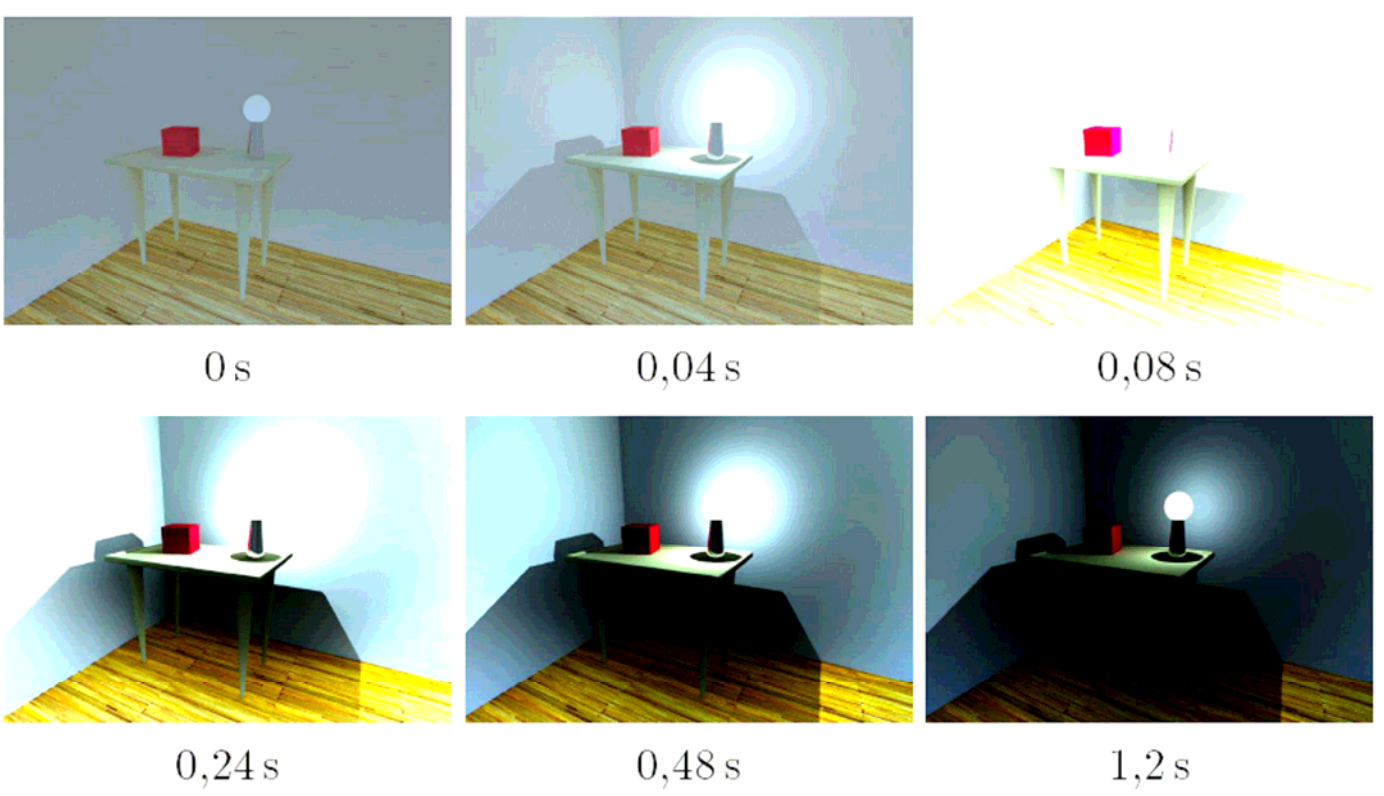
- Multiscale retinex [Jobson et al. 97]
  - based on multiple single-scale retinexes
  - color restoration

$$R_{\mathrm{MSR}_i} = \sum_{n=1}^{N} w_n R_{n_i}$$

$$F_n(x,y) = Ke^{-r^2/c_n^2}$$

Color Appearance Modeling

- iCAM [Fairchild et al. 02, 04], [Kuang et al. 06]
  - color appearance model
  - tone mapping operator
  - time-dependent



Conclusions

- HDR? - anywhere you would use conventional image
  - (HDR + tone-mapping)
  - superset of conventional image applications
- Graphics hardware support
  - floating point
- HDR displays available / available soon
  - but TMO always needed for prints

- Covered
  - HDR acquisition
  - HDR file formats
  - dynamic range compression
  - HVS simulation
- Not covered
  - color gamut mapping



Thank You for Your Attention

- ANY QUESTIONS/DIPLOMA THESES?

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