Computer Graphics

The Human Visual System (HVS)

Philipp Slusallek
Light

- **Electromagnetic (EM) radiation**
  - From long radio waves to ultra short wavelength gamma rays

- **Visible spectrum: ~400 to 700 nm (all animals)**
  - Likely due to development of early eyes in water
  - Only very small window that lets EM radiation pass through
Radiation Law

- **Physical model for light**
  - Wave/particle-dualism
    - Electromagnetic radiation wave model
    - Photons: $E_{ph} = h\nu$ → particle model & ray optics (h: Planck constant)
  - *Plenoptic function* defined at any point in space
    - $L = L(x, \omega, t, \nu, \gamma) \rightarrow$ 5 dimensional

  **Ignored parameters:**
  - No polarization
  - No fluorescence
    - Decoupling of the spectrum
  - No time dependence
    - Instant propagation with speed of light
    - No phosphorescence

  **Used parameters:**
  - Direction
  - Location
# Radiometric Units

<table>
<thead>
<tr>
<th>Specification</th>
<th>Definition</th>
<th>Symbol</th>
<th>Unit</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Q_e</td>
<td></td>
<td>[J = W·s] (joule)</td>
<td>Radiant energy</td>
</tr>
<tr>
<td>Power, flux</td>
<td>dQ/dt</td>
<td>Φ_e</td>
<td>[W = J/s] (watt)</td>
<td>Radiant flux</td>
</tr>
<tr>
<td>Flux density</td>
<td>dQ/dAdt</td>
<td>E_e</td>
<td>[W/m²]</td>
<td>Irradiance</td>
</tr>
<tr>
<td>Flux density</td>
<td>dQ/dAdt</td>
<td>B_e</td>
<td>[W/m²]</td>
<td>Radiosity</td>
</tr>
<tr>
<td>Intensity</td>
<td>dQ/dωdt</td>
<td>I_e</td>
<td>[W/sr]</td>
<td>Radiant intensity</td>
</tr>
<tr>
<td></td>
<td>dQ/dAdωdt</td>
<td>L_e</td>
<td>[W/(m²·sr)]</td>
<td>Radiance</td>
</tr>
</tbody>
</table>
Photometry

- **Equivalent units to radiometry**
  - Weighted with luminous efficiency function $V(\lambda)$
  - Considers the spectral sensitivity of the human eye
    - Measured across different humans
  - Spectral or (typically) “total” units
    - Integrate over the entire spectrum and deliver a single scalar value
      
      $$\Phi_v = K_m \int V(\lambda) \Phi_e(\lambda) d\lambda$$
      
      $$K_m = 680 \text{ lm/W}$$

- Simple distinction (in English!):
  - Names of radiometric quantities contain “radi”
  - Names of photometric quantities contain “lumi”
## Photometric Units

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<tr>
<td>Energy</td>
<td></td>
<td>$Q_v$</td>
<td>$[T = \text{lm} \cdot \text{s}]$ (talbot)</td>
<td>Luminous energy</td>
</tr>
<tr>
<td>Power, flux</td>
<td>$dQ/dt$</td>
<td>$\Phi_v$</td>
<td>$[\text{Im} = \text{T}/\text{s}]$ (lumen)</td>
<td>Luminous flux (e.g. emitted power of lamp)</td>
</tr>
<tr>
<td>Flux density</td>
<td>$dQ/dAdt$</td>
<td>$E_v$</td>
<td>$[\text{lx} = \text{lm}/\text{m}^2]$ (lux)</td>
<td>Illuminance</td>
</tr>
<tr>
<td>Flux density</td>
<td>$dQ/dAdt$</td>
<td>$B_v$</td>
<td>$[\text{lx} = \text{lm}/\text{m}^2]$ (lux)</td>
<td>Luminosity (e.g. illumination on a desk)</td>
</tr>
<tr>
<td>Intensity</td>
<td>$dQ/d\omega dt$</td>
<td>$I_v$</td>
<td>$[\text{cd} = \text{lm}/\text{sr}]$ (candela)</td>
<td>Luminous intensity (e.g. intensity of a point light)</td>
</tr>
<tr>
<td>Intensity</td>
<td>$dQ/dA\omega dt$</td>
<td>$L_v$</td>
<td>$[\text{Im}/(\text{m}^2 \cdot \text{sr})]$ (nits)</td>
<td>Luminance (e.g. brightness of a monitor)</td>
</tr>
</tbody>
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With luminous efficiency function weighted units
Illumination: Examples

- **Typical illumination intensities**

<table>
<thead>
<tr>
<th>Light source</th>
<th>Illuminance [lux]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct solar radiation</td>
<td>25,000 – 110,000</td>
</tr>
<tr>
<td>Day light</td>
<td>2,000 – 27,000</td>
</tr>
<tr>
<td>Sunset</td>
<td>1 – 108</td>
</tr>
<tr>
<td>Moon light</td>
<td>0.01 – 0.1</td>
</tr>
<tr>
<td>Starry night</td>
<td>0.0001 – 0.001</td>
</tr>
<tr>
<td>TV studio</td>
<td>5,000 – 10,000</td>
</tr>
<tr>
<td>Shop lighting</td>
<td>1,000 – 5,500</td>
</tr>
<tr>
<td>Office lighting</td>
<td>200 – 550</td>
</tr>
<tr>
<td>Home lighting</td>
<td>50 – 220</td>
</tr>
<tr>
<td>Street lighting</td>
<td>0.1 – 20</td>
</tr>
</tbody>
</table>
Luminance Range

Luminance [cd/m²]

- About 10-order of magnitude absolute span
- About 4-order of magnitude simultaneous span
Contrast (Dynamic Range)

Luminance [cd/m²]

- LCD/CCD: 1:500
- Film: 1:1500
- Print: 1:30
High Dynamic Range (HDR)

- How to display computed/measured HDR values on an LDR device?
  - Tone mapping
Percept. Effects: Vision Modes

- **Simulation requires:**
  - Control over color reproduction
  - Local reduction of detail visibility (computationally expensive)
Visual Acuity and Color Perception

- Photopic vision
- Scotopic/mesopic transition
- Mesopic/photopic transition
- Scotopic vision

a) daylight: 1000 cd/m^2
b) interior: 10 cd/m^2
c) moonlight: 0.04 cd/m^2
d) starlight: 0.001 cd/m^2

- Adaptation to dark much slower

Simulation requires:
  - Time-dependent filtering of light adaptation
HVS - Relationships

Real-World Stimulus

Psychophysics (qualitative measurements)

Perception

Neural response

Physiology (quantitative measurements)
Human Visual System

- Physical structure well established
- Percept. behavior complex & less understood process

Optic chiasm
Optical Chiasm

• Right half of the brain operates on left half of the field of view
  – From both eyes!!
• And vice versa
  – Damage to one half of the brain can result in loss of one half of the field of view
Perception and Eye

- Iris
- Cornea
- Pupil
- Lens
- Visual axis
- Optic axis
- Fovea
- Optic disk
- Retina
- Sclera
- Optic nerve
- Object
- Retinal image
Human Visual Perception

- Determines how real-world scenes appear to us
- Understanding of visual perception is necessary to reproduce appearance, e.g. in tone mapping

early vision (eyes)
Distribution of Rods and Cones

- High-res. foveal region with highest cone density
- Poisson-disc-like distribution

Cone mosaic in fovea which subtends small solid angle

Cone mosaic in periphery with almost 180° field of view

L-cones ~ M-cones >> S-cones
Retina

- Receptors on opposite side of incoming light
- Early cellular processing between receptors & nerves
  - Mainly for rods
Eye as a Sensor

• Relative sensitivity of cones

![Graph showing sensitivity vs. wavelength for different colors: Green, Yellow, and Blue. The x-axis represents wavelength (nm), and the y-axis represents sensitivity. The graph peaks for each color at different wavelengths. Green peaks around 550 nm, Yellow around 580 nm, and Blue around 440 nm.](image-url)
Luminous Sensitivity Function

- Different for cones (black, diff. studies) & rods (green)
Eye

- **Fovea (centralis):**
  - Ø 1-2 visual degrees
  - 50,000 cones each of ~0.5 arcminutes angle and ~2.5 μm wide
  - No rods in central fovea, but three different cone types:
    - L(ong, 64%), M(edium, 32%), S(hort wavelength, 4%)
    - Varying resolution: 10 arcminutes for S vs. 0.5 arcminutes for L & M
  - Linked directly 1:1 with optical nerves,
    - 1% of retina area but covers 50% visual cortex in brain
  - Adaptation of light intensity only through cones

- **Periphery:**
  - 75-150 M. rods: night vision (B/W)
  - 5-7 M. cones (color)
  - Response to stimulation by single 1 photons (@ 500 nm)
    - 100x better than cones, integrating over 100 ms
  - Signals from many rods are combined before linking with nerves
    - Bad resolution, good flickering sensitivity
This is a text in red

This is a text in green

This is a text in blue
Visual Acuity

Receptor density

Resolution in line-pairs/arcminute
Resolution of the Eye

• Resolution-experiments
  – Line pairs: eye ~ 50-60 p./degree → resolution of 0.5 arcminutes
  – Line offset: 5 arcseconds (hyperacuity)

  ![Resolution Example](image)

  – Eye micro-tremor: 60-100 Hz, 5 μm (2-3 photoreceptor spacing)
    • Allows to reconstruct from super-resolution (w/ Poisson pattern)
  – Together corresponds to 19” display at 60 cm away from viewer: 18,000² pixels with hyperacuity - 3,000² without hyperacuity

• Fixation of eye onto (moving) region of interest
  – Automatic gaze tracking, autom. compensation of head movement
  – Apparent overall high resolution of fovea

• Visual acuity increased by
  – Brighter objects
  – High contrast
Poisson-Disk Experiment

- **Human visual system**
  - Perception very sensitive to regular structures
  - Insensitive against (high-frequency) noise
  - Campbell-Robson sinusoidal contrast sensitivity chart

![Visibility Limit Function Diagram](image-url)
Luminance Contrast Sensitivity

- **Sensitivity**: inverse of perceptible contrast threshold
- **Maximum acuity at 5 cycles/degree (0.2 %)**
  - Decrease toward low frequencies: lateral inhibition
  - Decrease toward high frequencies: sampling rate (Poisson disk)
  - Upper limit: 60 cycles/degree
- **Medical diagnosis**
  - Glaucoma (affects peripheral vision: low frequencies)
  - Multiple sclerosis (affects optical nerve: notches in contrast sensitivity)
Color Contrast Sensitivity

- **Color vs. luminance vision system**
  - Similar but slightly different curves
  - Higher sensitivity at lower frequencies
  - High frequencies less visible

- **Image compression**
  - Exploit color sensitivity in lossy compr.
Threshold Sensitivity Function

- **Weber-Fechner law (Threshold Versus Intensity, TVI)**
  - Perceived brightness varies linearly with $\log$(radiant intensity)
    - $E = K + c \log I$
  - Perceivable intensity difference
    - 10 cd vs. 12 cd: $\Delta L = 2$ cd
    - 20 cd vs. 24 cd: $\Delta L = 4$ cd
    - 30 cd vs. 36 cd: $\Delta L = 6$ cd
Weber-Fechner Examples
Mach Bands

• “Overshooting” along edges
  – Extra-bright rims on bright sides
  – Extra-dark rims on dark sides

• Due to “lateral inhibition”
Mach Bands

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Lateral Inhibition

• **Pre-processing step within retina**
  – Surrounding brightness level weighted negatively
    • A: high stimulus, maximal bright inhibition
    • B: high stimulus, reduced inhibition → stronger response
    • D: low stimulus, maximal dark inhibition
    • C: low stimulus, increased inhibition → weaker response

• **High-pass filter**
  – Enhances contrast along edges
  – Differential operator (Laplacian/difference of Gaussian)
Lateral Inhibition: Hermann Grid

• Apparent dark spots at perip. crossings
  – Weakly if within foveal Ω (B): smaller filter extent
  – Strongly within periphery (A): larger filter extent

• Explanation
  – Crossings (C): more surround stimulation
    • More inhibition ⇒ weaker response
  – Streets (D): less surround stimulation
    • Less inhibition ⇒ greater response

• Simulation
  – Convolution with differential kernel
  – Darker at crossings, brighter in streets
  – Appears more steady
  – What if inversed colors?
Some Further Weirdness
High-Level Contrast Processing
High-Level Contrast Processing
Cornsweet Illusion

- Apparent contrast between inner and outer shades
Cornsweet Illusion

- **Apparent contrast between inner and outer shades**
  - Due to gradual darkening/brightening towards a contrasting edge
  - Causes B to be perceived similarly to A
Optical Effects – Veiling Glare

- Internal scattering/blur of sources of high luminance
- Computationally expensive to simulate

Actual size

Perceived size
Shape Perception

• Depends on surrounding primitives
  – Size emphasis
  – Directional emphasis

http://www.panoptikum.net/optischetaeuschen/index.html
Geometric Cues

- **Automatic geometrical interpretation**
  - 3D perspective
  - Implicit scene depth

http://www.panoptikum.net/optischetaeusche/index.html
Visual “Proofs”

http://www.panoptikum.net/optischetaeuschungen/index.html
HVS: High-Level Scene Analysis

- **Experience & expectation**
  - Pictures usually horizontal

- **Local cue consistency**
  - Eyes and mouth look right, but actually are upside-down

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Impossible Scenes

- Escher et al.
  - Confuse HVS by presenting contradicting visual cues
  - Locally consistent but not globally

http://www.panoptikum.net/optischetaeuschungen/index.html
Single Image Random Dot Stereograms

- **Vergence**: Cross eyes to look at the same 3D spot
- **Accommodation**: Focusing at a particular depth plane
SIRDS Construction

• Assign arbitrary color to pixel \( p_0 \) in image plane
• Trace from eye points through \( p_0 \) to object surface
• Trace back from object to corresponding other eye
• Assign color at \( p_0 \) to intersection points \( p_{1L}, p_{1R} \) with image plane
• Trace from eye points through \( p_{1L}, p_{1R} \) to object surface
• Trace back to eyes
• Assign \( p_0 \) color to \( p_{2L}, p_{2R} \)
• Repeat until image plane is covered
Motion Illusion

• Appearance of movement in static image
  – Due to cognitive effects of interacting color contrast & shape pos.
  – Saccades → diff. in neural signals between dark and bright areas
Motion Illusion
Negative Afterimages

- Cones excited by color eventually lose sensitivity
  - Photoreceptors adapt to overstimulation and send a weak signal
Negative Afterimages

• **When switching to grey background**
  – Colors corresponding to adapted cones remain muted
  – Other freshly excited cones send out a strong signal
  – Same perceived signal as when looking at the inverse color
Another Optical Illusion

• If staring for ~ 15 sec., you may see a giraffe appear