Overview

• Last time
  – Antialiasing
  – Super-Sampling

• Today
  – The Human Visual System
    • The eye
    • Early vision
    • High-level analysis
    • Color perception

• Next lecture
  – Color spaces
Light

- Electromagnetic radiation
- Visible spectrum: ~ 400 to 700 nm
Radiation Law

- **Physical model for light**
  - Wave/particle-dualism
    - Electromagnetic radiation wave model
    - Photons: $E_{ph} = h\nu$
  - Plenoptic function
    - $L = L(x, \omega, t, \nu, \gamma)$, 5 dimensional,

**Ignored parameters:**
- No polarization
- No fluorescence
  - Decoupling of the spectrum
- Not time dependent
  - Instant propagation with speed of light
  - No phosphorescence

**Used parameters:**
- Direction
- Location
Photometry

- **Equivalent units to radiometry**
  - Weight with *luminous efficiency function* $V(\lambda)$ (luminous efficiency function)
  - Spectral or “total” units

\[ \Phi_v = K_m \int V(\lambda) \Phi_e(\lambda) d\lambda \]

\[ K_m = 680 \text{ lm} / \text{W} \]

- Distinction in English simple:
  - “rad”: radiometric unit
  - “lum”: photometric unit
# Radiometric Units

<table>
<thead>
<tr>
<th>Specification</th>
<th>Definition</th>
<th>Symbol</th>
<th>Unit</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energie</td>
<td>energy</td>
<td>$Q_e$</td>
<td>$[J=Ws]$ Joule</td>
<td>Strahlungsenergie radiant energy</td>
</tr>
<tr>
<td>Leistung, Fluß</td>
<td>power, flux</td>
<td>$dQ/dt$</td>
<td>$\Phi_e$</td>
<td>$[W=J/s]$ Strahlungsfluß radiant flux</td>
</tr>
<tr>
<td>Flußdichte</td>
<td>flux density</td>
<td>$dQ/dAdt$</td>
<td>$E_e$</td>
<td>$[W/m^2]$ Bestrahlungsstärke Irradiance</td>
</tr>
<tr>
<td>Flußdichte</td>
<td>flux density</td>
<td>$dQ/dAdt$</td>
<td>$M_e = B_e$</td>
<td>$[W/m^2]$ Radiom. Emissionsvermögen Radiosity</td>
</tr>
<tr>
<td>Intensität</td>
<td>intensity</td>
<td>$dQ/d\omega dt$</td>
<td>$L_e$</td>
<td>$[W/m^2/sr]$ Strahlungsdichte Radiance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$dQ/d\omega dt$</td>
<td>$I_e$</td>
<td>$[W/sr]$ Strahlungsstärke radiant intensity</td>
</tr>
</tbody>
</table>
## Photometric Units

With luminous efficiency function weighted units

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<th>Units</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Energie</td>
<td>$Q_v$</td>
<td>$[\text{talbot}]$</td>
<td>Lichtmenge</td>
<td>luminous energy</td>
</tr>
<tr>
<td>Leistung, Fluß</td>
<td>$dQ/dt$</td>
<td>$\Phi_v$</td>
<td>$[\text{lm (Lumen)} = \text{talbot/s}]$</td>
<td>Lichtstrom luminous flux</td>
</tr>
<tr>
<td>Flußdichte</td>
<td>$dQ/dAdt$</td>
<td>$E_v$</td>
<td>$[\text{lux} = \text{lm/m}^2]$</td>
<td>Beleuchtungsstärke</td>
</tr>
<tr>
<td>flux density</td>
<td></td>
<td></td>
<td></td>
<td>Illuminance</td>
</tr>
<tr>
<td>Flußdichte</td>
<td>$dQ/dAdt$</td>
<td>$[M_v=] B_v$</td>
<td>$[\text{lux}]$</td>
<td>Photom. Emissionsvermögen</td>
</tr>
<tr>
<td>flux density</td>
<td></td>
<td></td>
<td></td>
<td>Luminosity</td>
</tr>
<tr>
<td></td>
<td>$dQ/dA^\Phi d\omega dt$</td>
<td>$L_v$</td>
<td>$[\text{lm/m}^2/\text{sr}]$</td>
<td>Leuchtdichte Luminance</td>
</tr>
<tr>
<td>Intensität</td>
<td>$dQ/d\omega dt$</td>
<td>$I_v$</td>
<td>$[\text{cd (candela)} = \text{lm/sr}]$</td>
<td>Lichtstärke radiant intensity</td>
</tr>
<tr>
<td>intensity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Luminance Range

Luminance [cd/m²]

10⁻⁶  10⁻⁴  10⁻²  10⁰  10²  10⁴  10⁶  10⁸
Contrast (Dynamic Range)

- Luminance [cd/m²]
  - 10⁻⁶
  - 10⁻⁴
  - 10⁻²
  - 10⁰
  - 10²
  - 10⁴
  - 10⁶
  - 10⁸

Dynamic Range

- 1:500
- 1:1500
- 1:30
High Dynamic Range (HDR)
## Illumination: samples

- **Typical illumination intensities**

<table>
<thead>
<tr>
<th>Light source</th>
<th>Illumination intensity [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>
Percept. Effects – Vision Modes

Simulation requires:
- control over color reproduction
- local reduction of detail visibility
  *(computationally expensive)*
Adaptation to dark much slower

Simulation requires:
- time-dependent filtering of light adaptation
Human Visual Perception

• Determines how real-world scenes appear to us
• Understanding of visual perception is necessary to reproduce appearance in tone mapping
Distribution of Rods and Cones

- approximate a Poisson disc distribution

Wikler & Rakic 1990
Human Visual System

- Physical structure well established
- Perceptual behaviour is a complex process
Human Visual System

- Physical structure well established
- Perceptual behaviour is a complex process

optic chiasm
HVS - Relationships

Psychophysics

Perception

Stimulus

Physiology

Neural response
Perception and Eye

Diagram of the human eye showing key components such as the iris, cornea, pupil, lens, fovea, optic disk, retina, and sclera, as well as the visual and optic axes. The diagram illustrates the process of light entering the eye, focusing on the lens, and forming a retinal image.
Retina
Eye as a Sensor

- **Relative Sensitivity of Cones**
  - S scaled by 3x
  - Z (Zäpfchen – cones) total sensitivity

![Graph showing relative sensitivity of cones](image)
Eye

• **Fovea:**
  - Ø 1-2 visual degrees
  - 6-7 Mio. *cones*, about 0.4 arc seconds wide
  - No rods, but three different cone types:
    - L(ong, 64%), M(edium, 32%), S(hort wavelength, 4%)
    - Results in varying resolution depending on color
    - Resolution: 10 arc minutes (S, blue), 0.5 arc minutes (L, M)
  - Linked directly with optical nerves
  - Adaptation of light intensity only through cones

• **Periphery:**
  - 75-150 Mio. *rods*, night vision, S/W
  - Response to stimulation of approx. 5 photons/sec. (@ 500 nm)
  - Many thousands of cells are combined before linked 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

Resolution in line-pairs/arc minute

Receptor density
Resolution of the Eye

- **Resolution-experiments**
  - Line pairs: 50-60/degree \(\Rightarrow\) resolution .5 arc minutes
  - Line offset: 5 arc seconds (hyperacuity)
    - Eye micro-tremor: 60-100 Hz, 5 \(\mu\)m (2-3 photoreceptor spacings)
      - Allows to reconstruct from super-resolution
    - Together corresponds to
      - 19" display at 60 cm: 18,000\(^2\) Pixel (3000\(^2\) w/out hyperacuity)

- **Automatic fixation of eye onto region of interest**
  - Automatic gaze tracking
  - Apparent overall high resolution of fovea

- **Visual acuity increased by**
  - Brighter objects
  - High contrast
Luminance Contrast Sensitivity
Contrast Sensitivity

- **Sensitivity:**  
  \[ \frac{1}{\text{threshold contrast}} \]

- **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)

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[Graph showing human contrast sensitivity]
Color Contrast Sensitivity

• Color vs. luminance vision system
  – Higher sensitivity at lower frequencies
  – High frequencies less visible

• Image compression
Threshold Sensitivity Function

- **Weber-Fechner Law (Threshold Versus Intensity, TVI)**
  - Perceived brightness = $\log$ (radiant intensity)
    \[ E = K + c \log I_v \]
  - Perceivable intensity difference
    - $10 \text{ cd vs. } 12 \text{ cd}: \Delta L = 2 \text{ cd}$
    - $20 \text{ cd vs. } 24 \text{ cd}: \Delta L = 4 \text{ cd}$
    - $30 \text{ cd vs. } 36 \text{ cd}: \Delta L = 6 \text{ cd}$
Weber-Fechner Examples
Mach Bands

• “Overshooting“ along edges
  – Extra-bright rims on bright sides
  – Extra-dark rims on dark sides
• Due to “Lateral Inhibition“
Lateral Inhibition

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

• High-pass filter
  – Enhances contrast along edges
  – Difference-of-Gaussians (DOG) function
Lateral Inhibition: Hermann Grid

• Dark dots at crossings

• Explanation
  – Crossings (A)
    • More surround stimulation
      (more bright area)
      ⇒ Less inhibition
      ⇒ Weaker response
  – Streets (B)
    • Less surround stimulation
      ⇒ More inhibition
      ⇒ Greater response

• Simulation
  – Darker at crossings, brighter in streets
  – Appears more steady
  – What if reversed?
some further weirdness
High-Level Contrast Processing
High-Level Contrast Processing

Checker-shadow illusion:
The squares marked A and B are the same shade of gray.

Edward H. Adelson
Cornsweet Illusion

- Apparent contrast due to **gradual darkening / brightening towards** a contrasting edge
Percept. Effects – Veiling Glare

Simulation requires:
- scatter (blur) of sources of high luminance
  *(computationally expensive)*
Shape Perception

- Depends on surrounding primitives
  - Directional emphasis
  - Size emphasis

http://www.panoptikum.net/optischetaeuschen/index.html
Shape Processing: Geometrical Clues

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

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

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

- Experience
- Expectation
- Local clue consistency

http://www.panoptikum.net/optischetaeuschen/index.html
Impossible Scenes

• Escher et.al.
  – Confuse HVS by presenting contradicting visual clues

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

- **Vergence**: both eyes rotate to look at the same spot
- **Accommodation**: focusing at a particular depth plane
SIRDS Construction

- Assign arbitrary color to $p_0$ 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
Another Optical Illusion

• If you stare for approx. 20 seconds some of you will actually see a giraffe.
caused by saccades, motion from dark to bright areas
Color

- **Physics**
  - Continuous spectral energy distribution

- **Human color perception**
  - Cones in retina
  - 3 different cone types
  - Spectral mapping to 3 channels
Visual Acuity and Color Perception

Photopic vision

Scotopic/mesopic 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
Color Perception

- **Di-chromaticity (dogs, cats)**
  - Yellow & blue-violet
  - Green, orange, red indistinguishable

- **Tri-chromaticity (humans, monkeys)**
  - Red, green, blue
  - Color-blindness
    - Most often men, green color-blindness

www.lam.mus.ca.us/cats/color/

www.colorcube.com/illusions/clrblind.html