Bioinformatics II
Winter Term 2016/17

universitätbonn

Rheinische
Friedrich-Wilhelms-
Universität Bonn

# Chapter 1: Organization, Overview, Background on Perception

Jun.-Prof. Dr.-Ing. Thomas Schultz

URL: http://cg.cs.uni-bonn.de
E-Mail: schultz@cs.uni-bonn.de
Office: Friedrich-Ebert-Allee 144, 53113 Bonn

October 25, 2016

# 1.1 Organization

# Lecture Times and Exam

- **Lecture**
  - B-IT Building, Marschallsaal
  - Tuesday 9:30-11:00
- **Exercises**
  - Two practical projects, consisting of small weekly assignments
  - Will be due on **Dec 6** and **Jan 31**
  - You need 50% of the points to be admitted to the final exam
- **Credit**
  - 3 ECTS, written exam at end of semester

# People

- **Lecture:**
  Jun.-Prof. Dr. Thomas Schultz
  schultz@cs.uni-bonn.de

- **Exercises:**
  Michael Ankele
  ankele@cs.uni-bonn.de

  Shekoufeh Gorgi Zadeh
  gorgi@cs.uni-bonn.de

# Webpage

- Lecture webpage: http://cg.cs.uni-bonn.de/bioinf
  - Lecture notes / slides as PDF
  - Homework assignments
  - Password protected:
    - User name: bioinf
    - Password: bioinf-ws2016

# 1.2 Course Contents

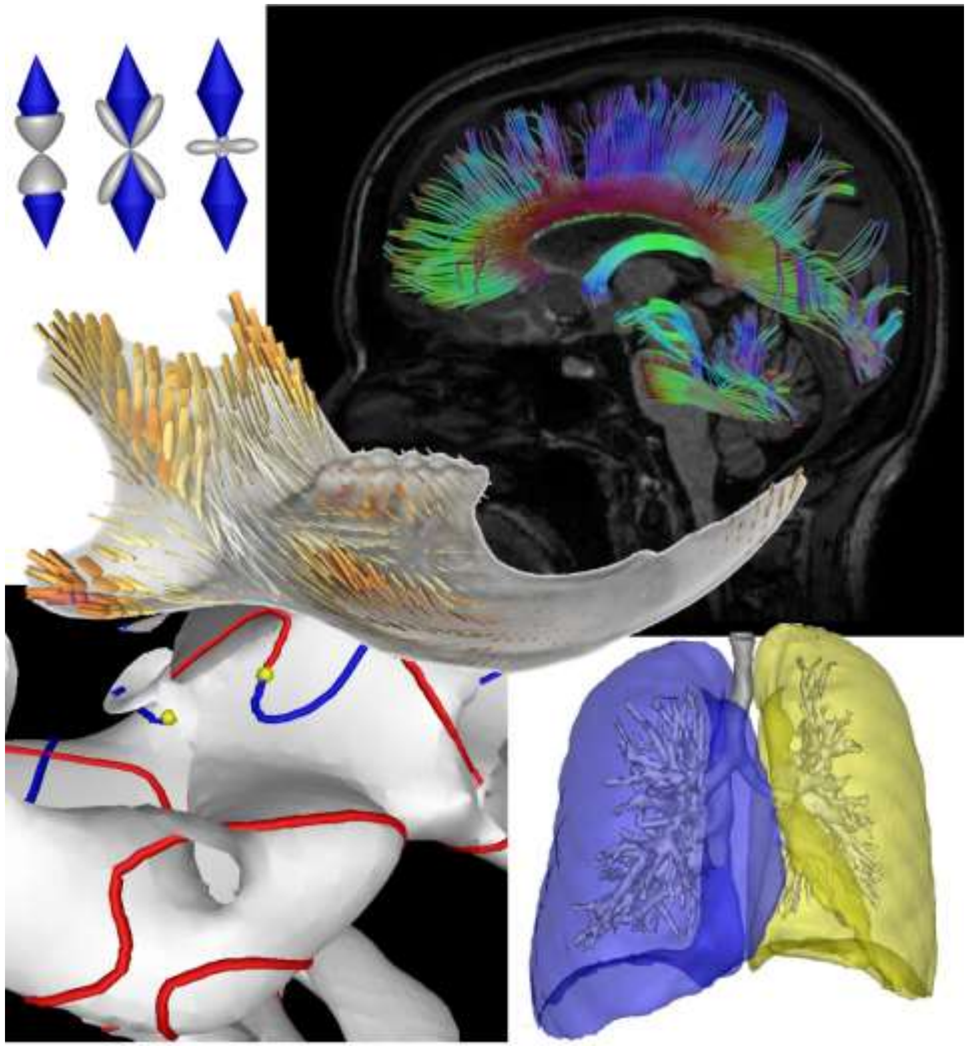
# Agenda

**Introduction to Visual Computing for Biology**

- **First half: Visualization in Biology**
  - Color and Perception
  - Visualizing Multidimensional Data
  - Graph Visualization
  - Visualization Design
  - Example Applications
- **Second half: Biomedical Image Analysis**
  - Biological Imaging Modalities
  - Image Registration
  - Image Segmentation
  - Statistical Image Analysis

# Visualization: What?

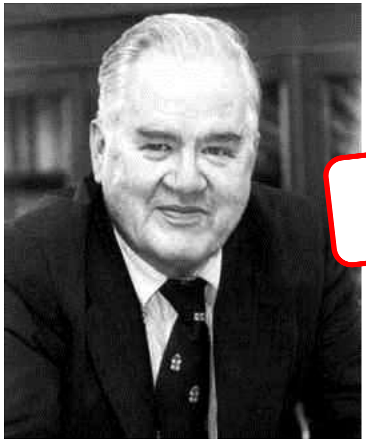
Some example results from our Visualization group here in Bonn:



# Visualization: Why?

"The ability to take data - to be able to understand it, to process it, to extract value from it, to visualize it, to communicate it - that's going to be a hugely important skill in the next decades."

Hal R. Varian

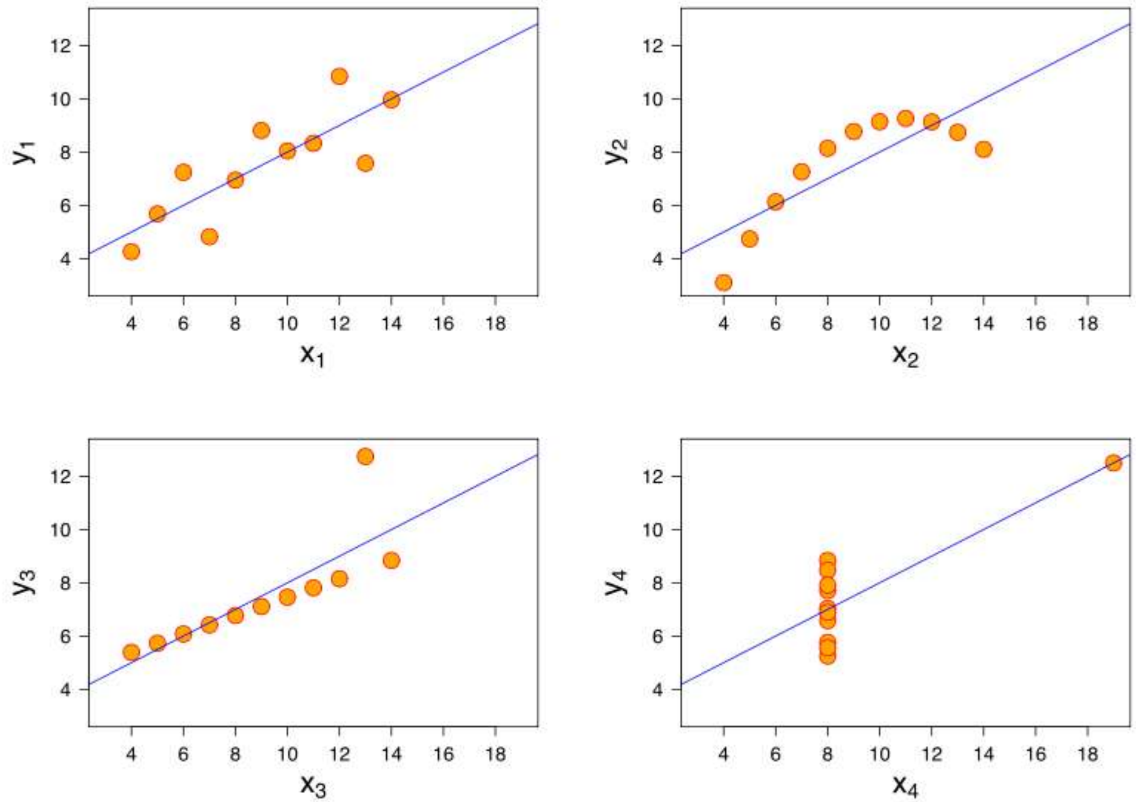


John W. Tukey

"The best thing about being in visualization is that you get to play in everyone's backyard."

# Visualization vs. Statistics

In 1973, Francis Anscombe constructed the "Anscombe Quartet", illustrating how different data with the same mean, variance, and linear regression can turn out to be when it is visualized



# Defining Visualization

- Definition by Oxford English Dictionary:
  - **to visualize:** to form a mental vision, image, or picture (of something not visible or present to sight, or of an abstraction); to make visible to the mind or imagination.
- In the words of Robert Spence (2007):
  - Visualization is solely a human cognitive activity and has nothing to do with computers

    Footnote: R. Spence, **Information Visualization,** Prentice Hall 2007
- To be more precise:
  - This lecture deals with **computer-supported data visualization**

# Motivating Visualization

- Motivation by Friedhoff and Kiley:
  - The standard argument to promote scientific visualization is that today's researchers must consume ever higher volumes of numbers that gush, as if from a fire hose, out of supercomputer simulations or high-powered scientific instruments. If researchers try to read the data, usually presented as vast numeric matrices, they will take in the information at snail's pace. If the information is rendered graphically, however, **they can assimilate it at a much faster rate.**

Footnote: R.M. Friedhoff and T. Kiely, **The Eye of the Beholder,** Computer Graphics World, Vol. 13.8, p. 46, August 1990

# Defining and Motivating Visualization

- Definition and motivation by Munzner:
  - **Computer-based visualization systems** provide visual representations of datasets designed to help people carry out tasks more effectively. Visualization is suitable when there is a need to **augment human capabilities** rather than replace people with computational decision-making methods.

Footnote: T. Munzner, **Visualization Analysis and Design,** A K Peters, 2015

# Visualization in Biology

- Benefits pointed out by Nielsen et al.:
  - Given the importance of human interpretation particularly in the early hypothesis generation stages of biological research, visual tools also provide a valuable complement to automated computational techniques in enabling us to derive scientific insight from large-scale genomic data sets. Visual and automated approaches are particularly powerful when used in combination, such that a user can seamlessly inspect and perform computations on their data, iteratively refining their analyses.

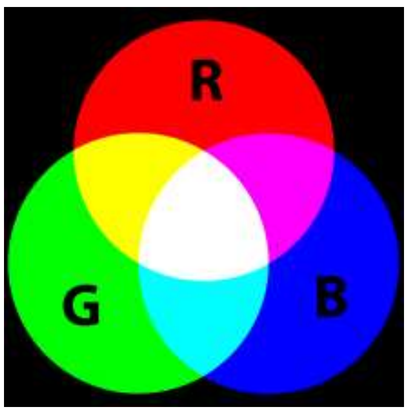
Footnote: C. Nielsen et al., **Visualizing Genomes: Techniques and Challenges,** Nature Methods 2010

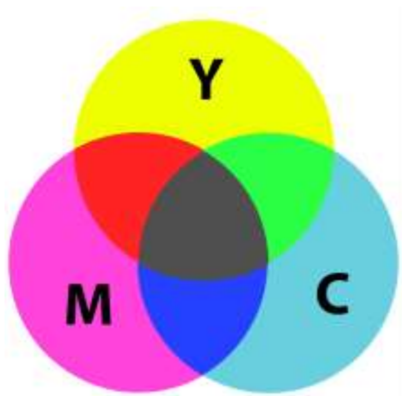
# Goals of Visualization

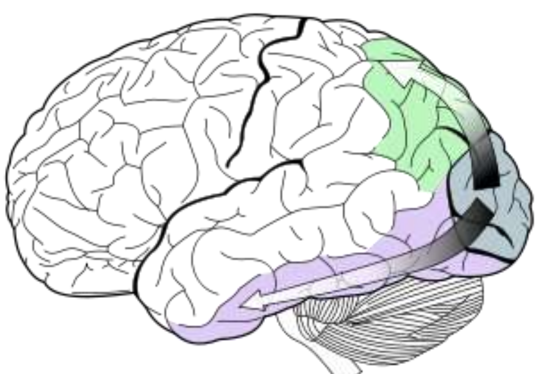
- **Analysis** leading to insight
  - Extract information from data
  - Discover new knowledge, generate hypotheses
- **Communication** and education
  - Present findings to others and discuss them
  - Teach non-experts
- **Steering**
  - Interactively control and drive simulations or longer-term measurements
  - Fast data analysis, get to insight sooner

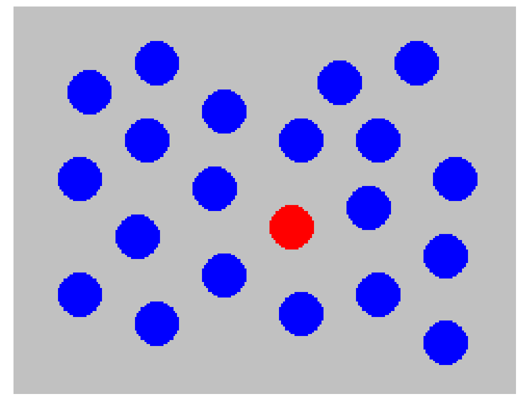
# Color and Perception

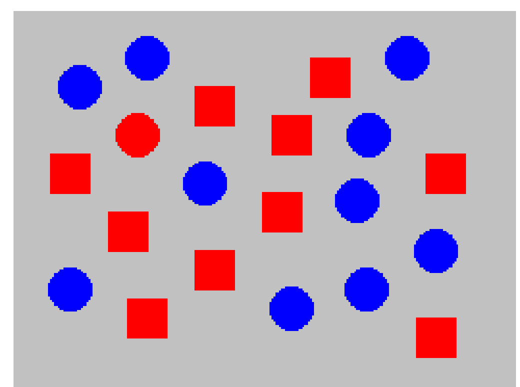
- Learn the basics of **human (visual) perception**
  - Different ways of representing color
  - Attentive vs. pre-attentive perception



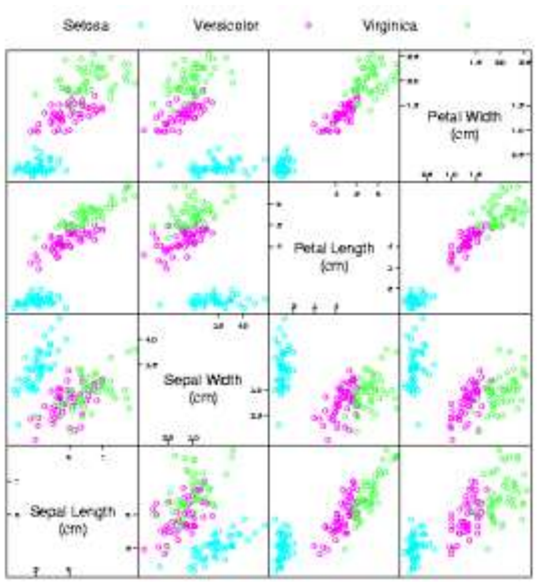



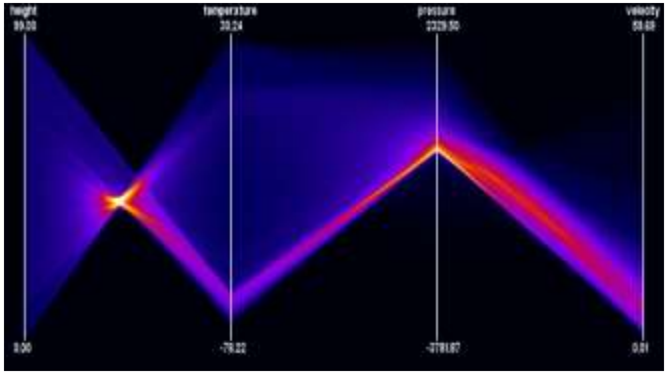


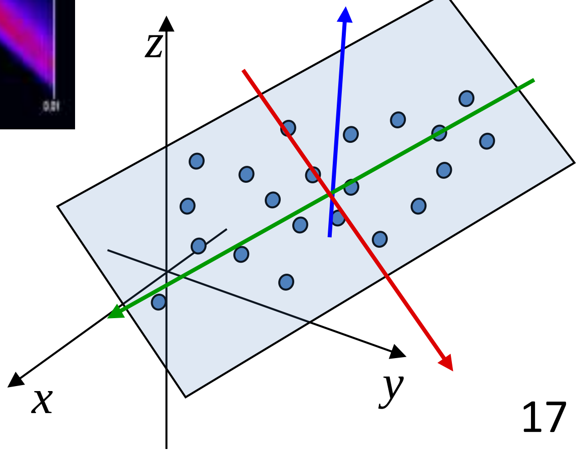


# Visualizing Multidimensional Data

- Learn how to deal with data that has **more than three dimensions**
  - Using suitable visualization techniques
  - Using dimensionality reduction

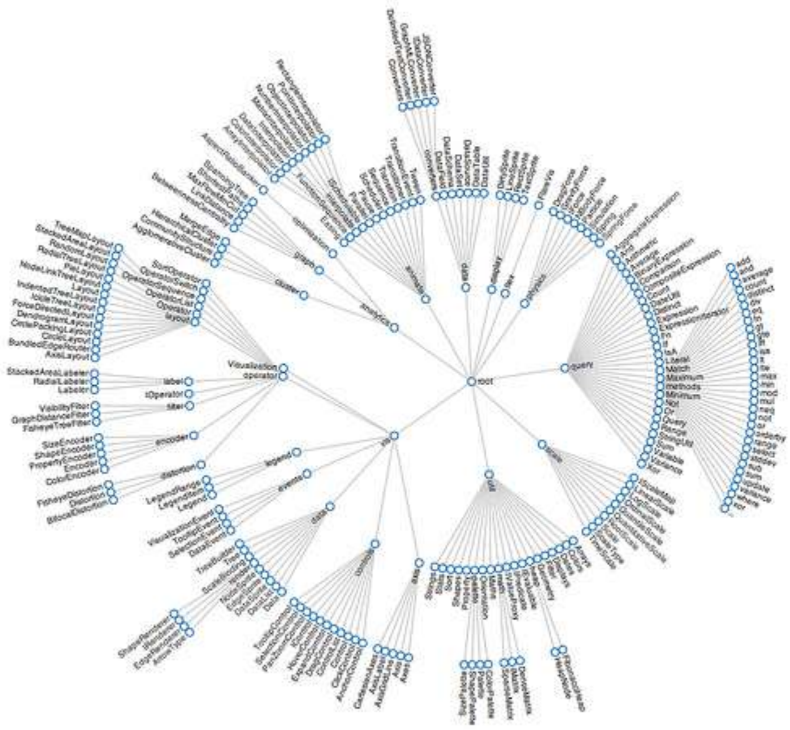


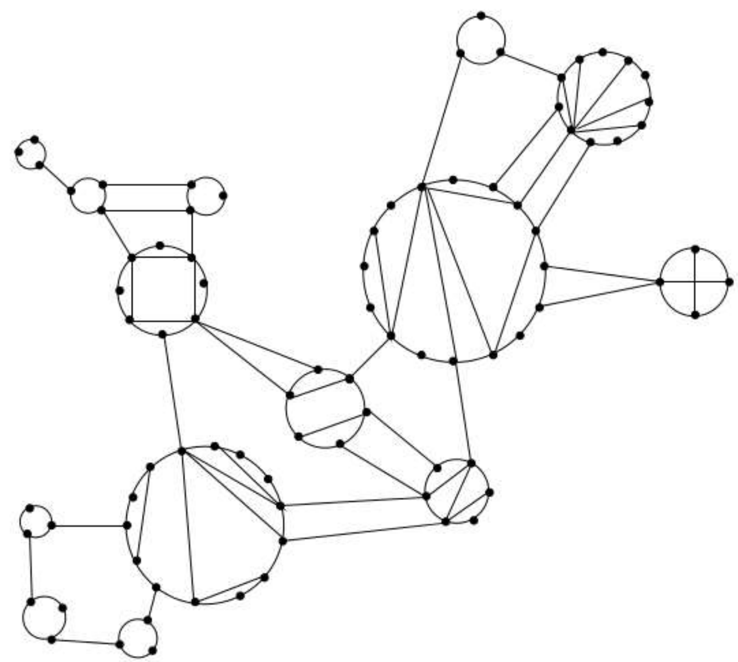



# Graph Visualization

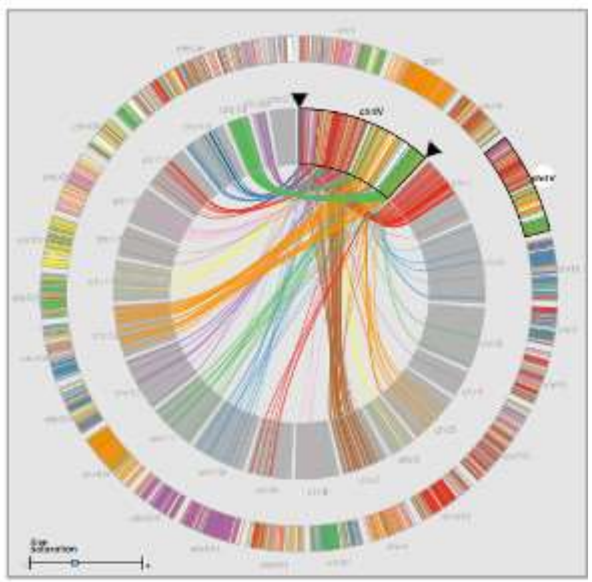
- Learn how to visualize **trees** and **general graph** structures



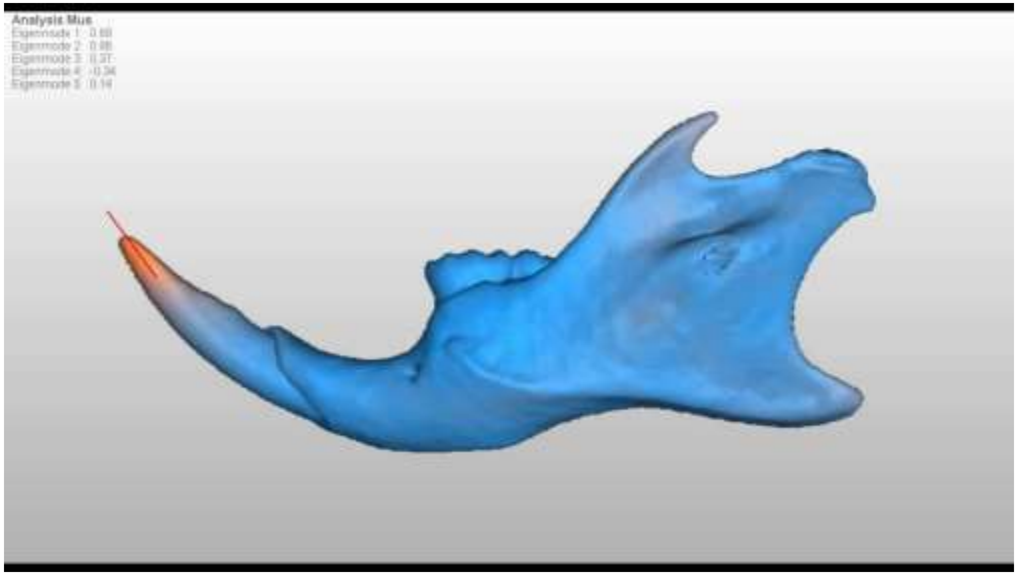


# Example Applications

- See how these techniques contribute to **biological insight**



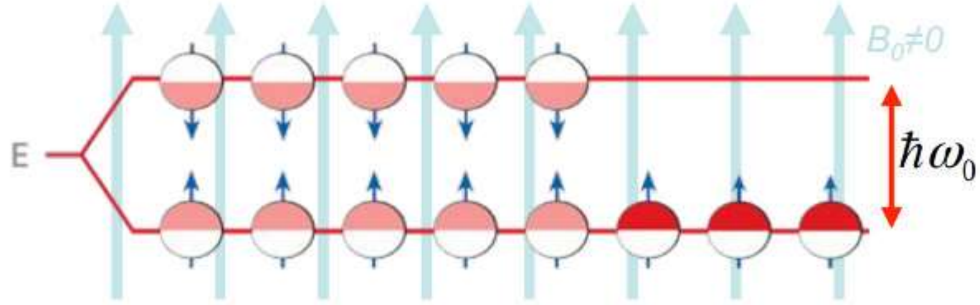
[Meyer et al. 2009]: Comparative Genomics



[Hermann et al. 2014]: Exploring Anatomical Variability

# Imaging in Biology

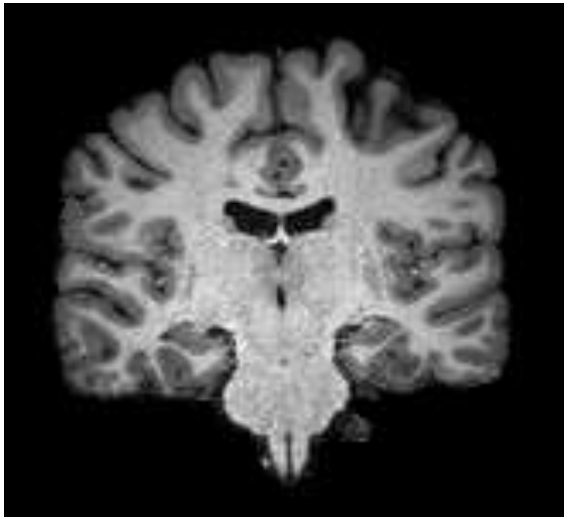
- Light microscopy
- Electron microscopy
- Magnetic Resonance Imaging

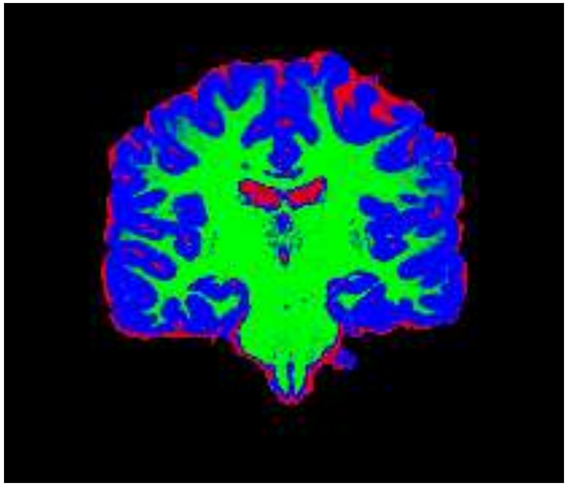



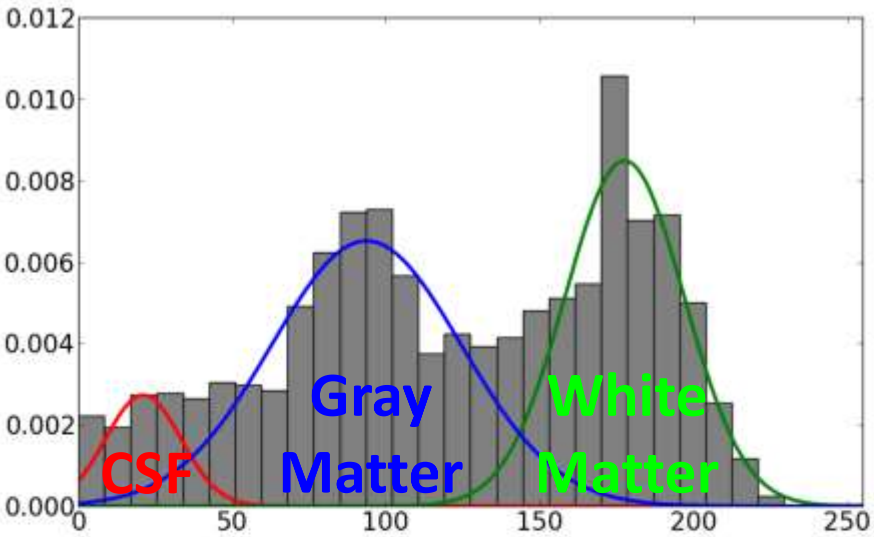
# 3D Image Segmentation

Learn to **segment** images using

- Gaussian Mixture Models
- Markov Random Fields



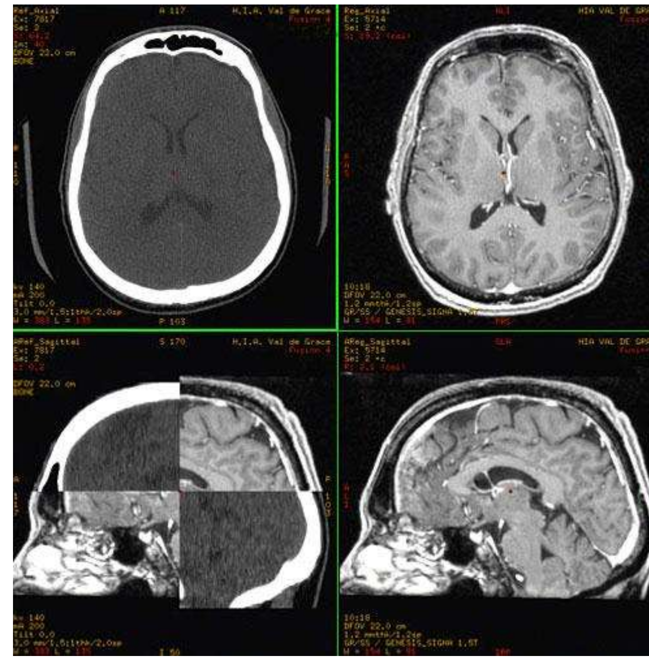




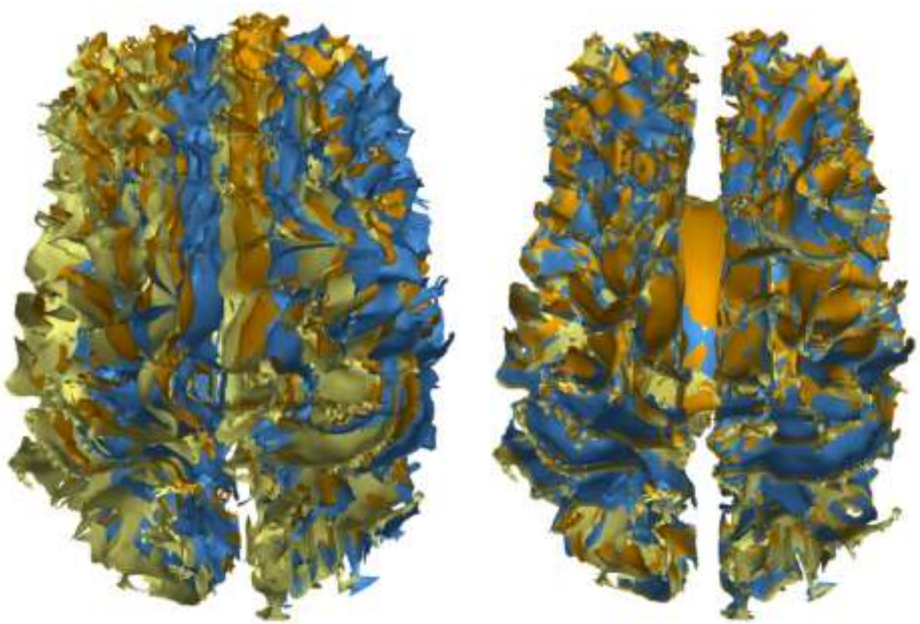
# 3D Image Registration

Learn to **register** images

- Spatial transformations
- Cost functions
- Optimization methods



CT/MRI Registration

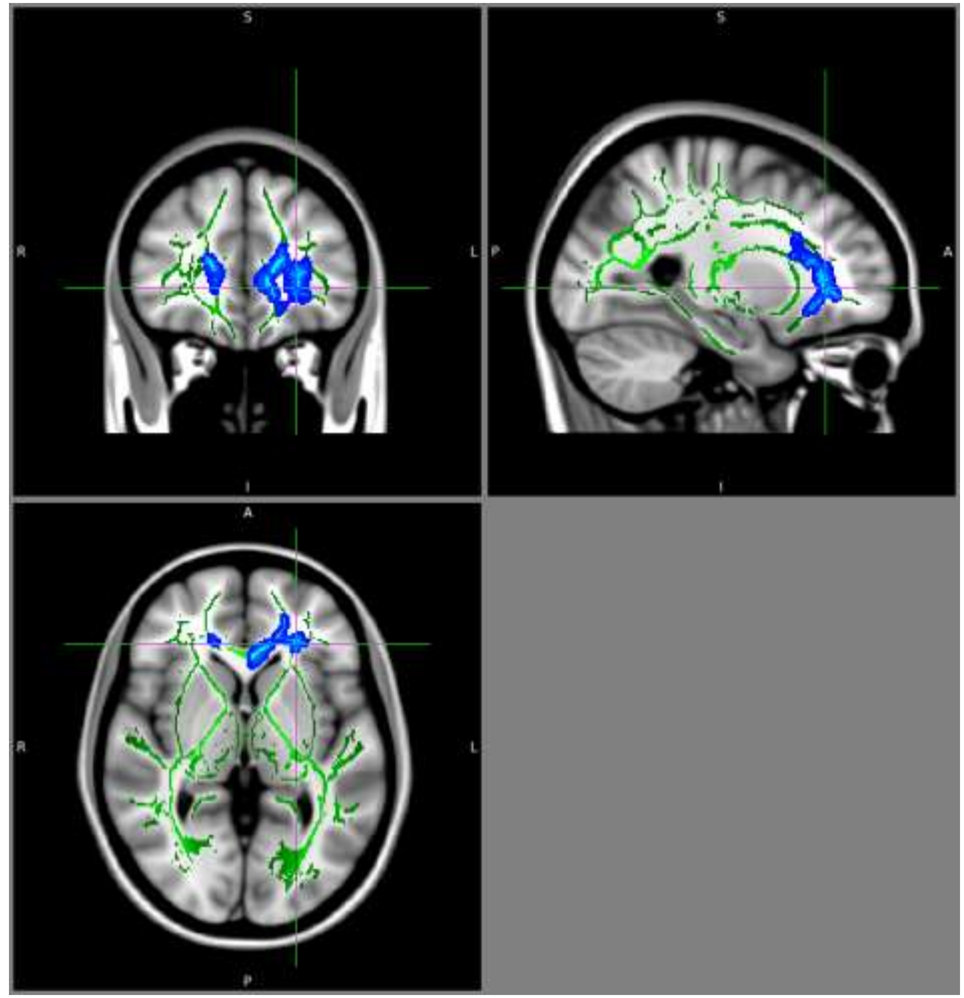


Alignment of different scans

# Statistical Image Analysis

Learn how to perform **statistical hypothesis testing** to get scientific insight from images

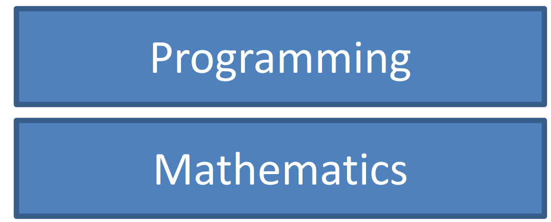
- t-Tests
- Family-wise error correction



Blue areas: Significantly reduced FA in Lupus patients

# Preliminaries

- Beside teaching you specific techniques, I would like to train your ability to
  - solve real-world problems
  - on a clear theoretical basis



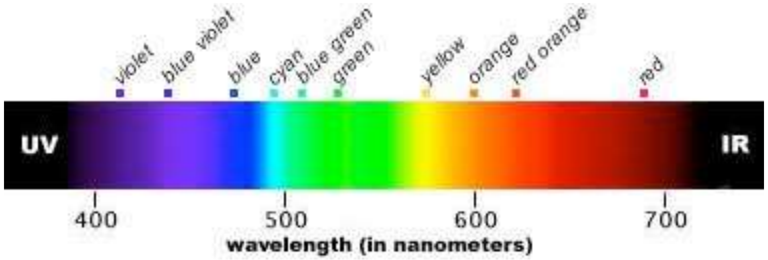

- I assume you have basic knowledge about
  - Programming (ideally in Python)
  - Calculus and linear algebra

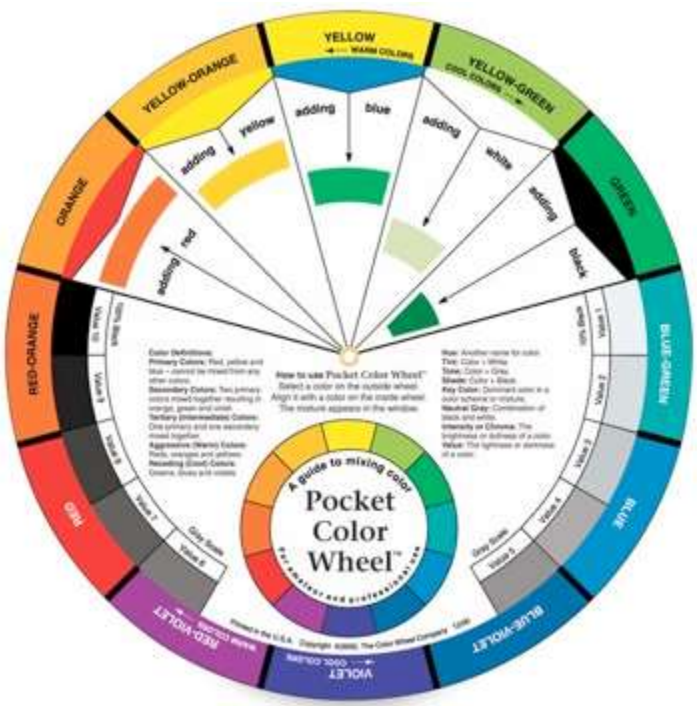
# Learning Goals

- Learn about important **visualization and image processing techniques** and how they apply to biology
- **Solve small problems** in visualization and image analysis, work in small teams and present your results
- Prepare for a potential **lab, seminar,** or **MSc thesis** in the field

# 1.3 Background on Perception

# What is Color?

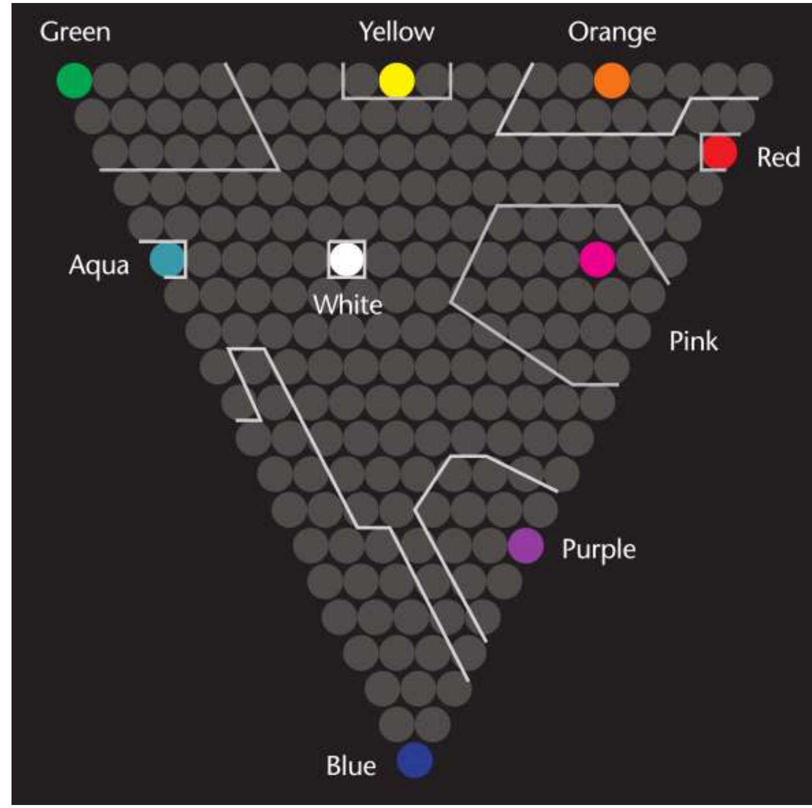



- **Physicist's view:** *Linear* range of wavelengths of visible EM radiation
- **Artist's view:** *Circle* of hues, with mixing of white or black

# Naming Color

- **Color is a perception**
  - Out of 210 colors, 8 names were consistently used by at least 75% of subjects
  - Most people called monitor red "orange"
  - Most set "pure green" around 514nm, about 30% of the population set it around 525nm
  - Subjects typically agree on "pure yellow" within 2nm



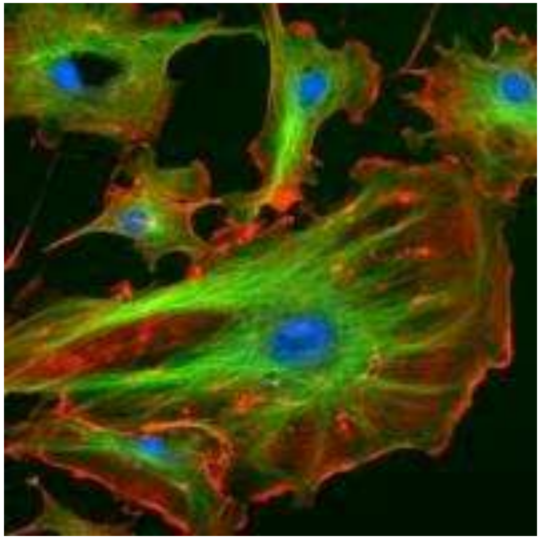

[Post and Greene 1986]

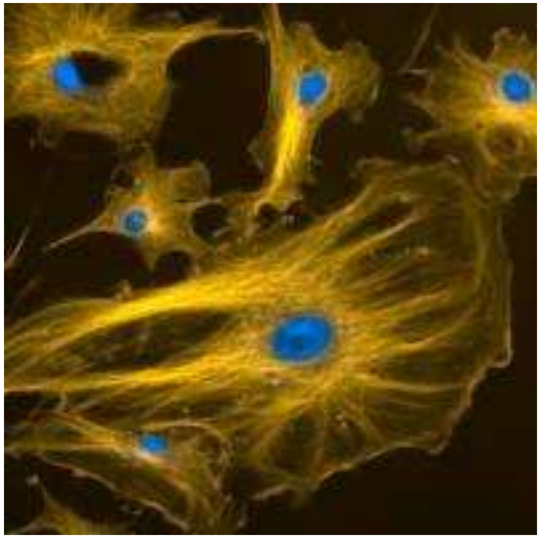
# Visual Illusions

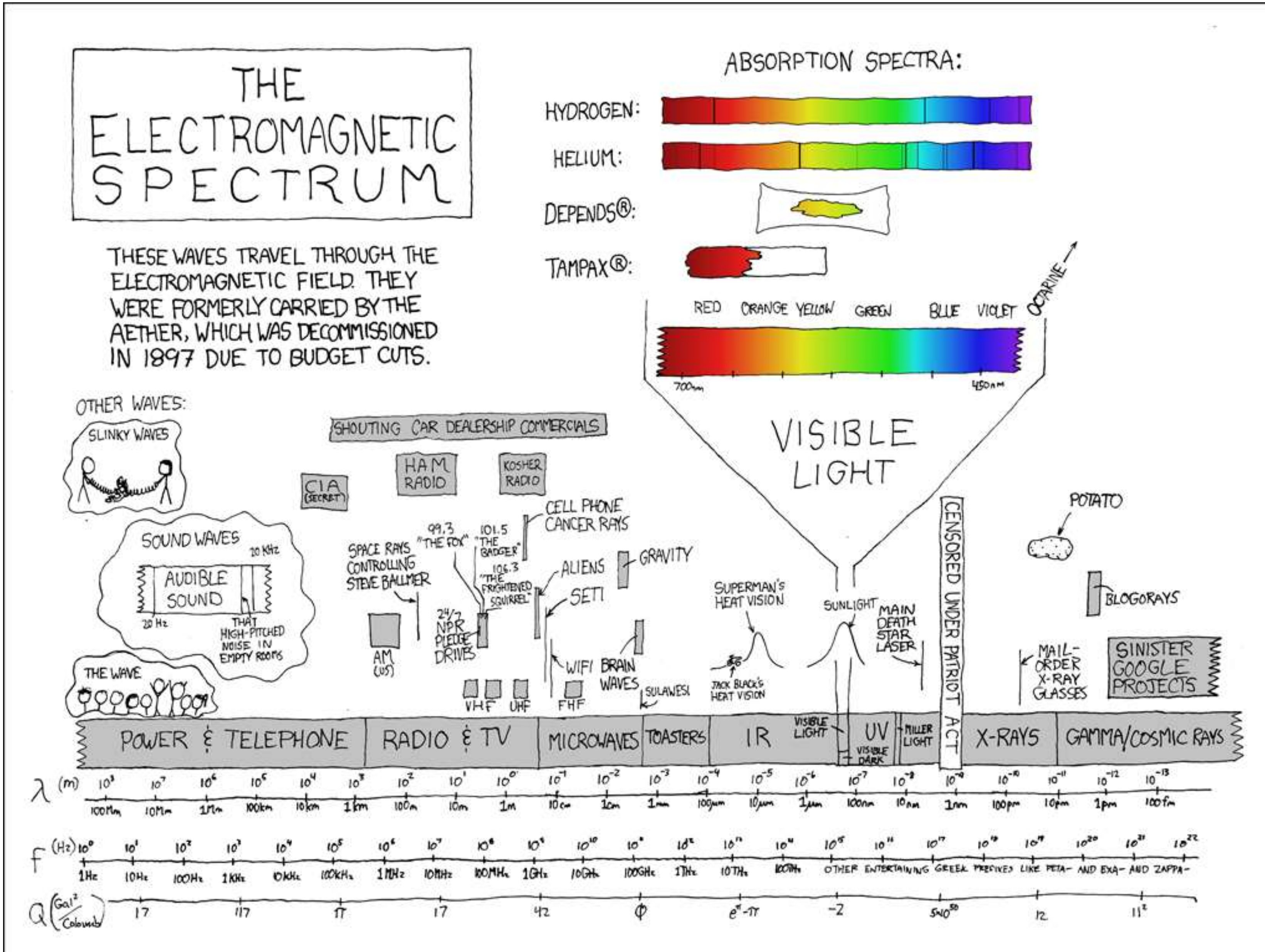
The human visual system is **not** an objective measurement device!

# Color Impairment

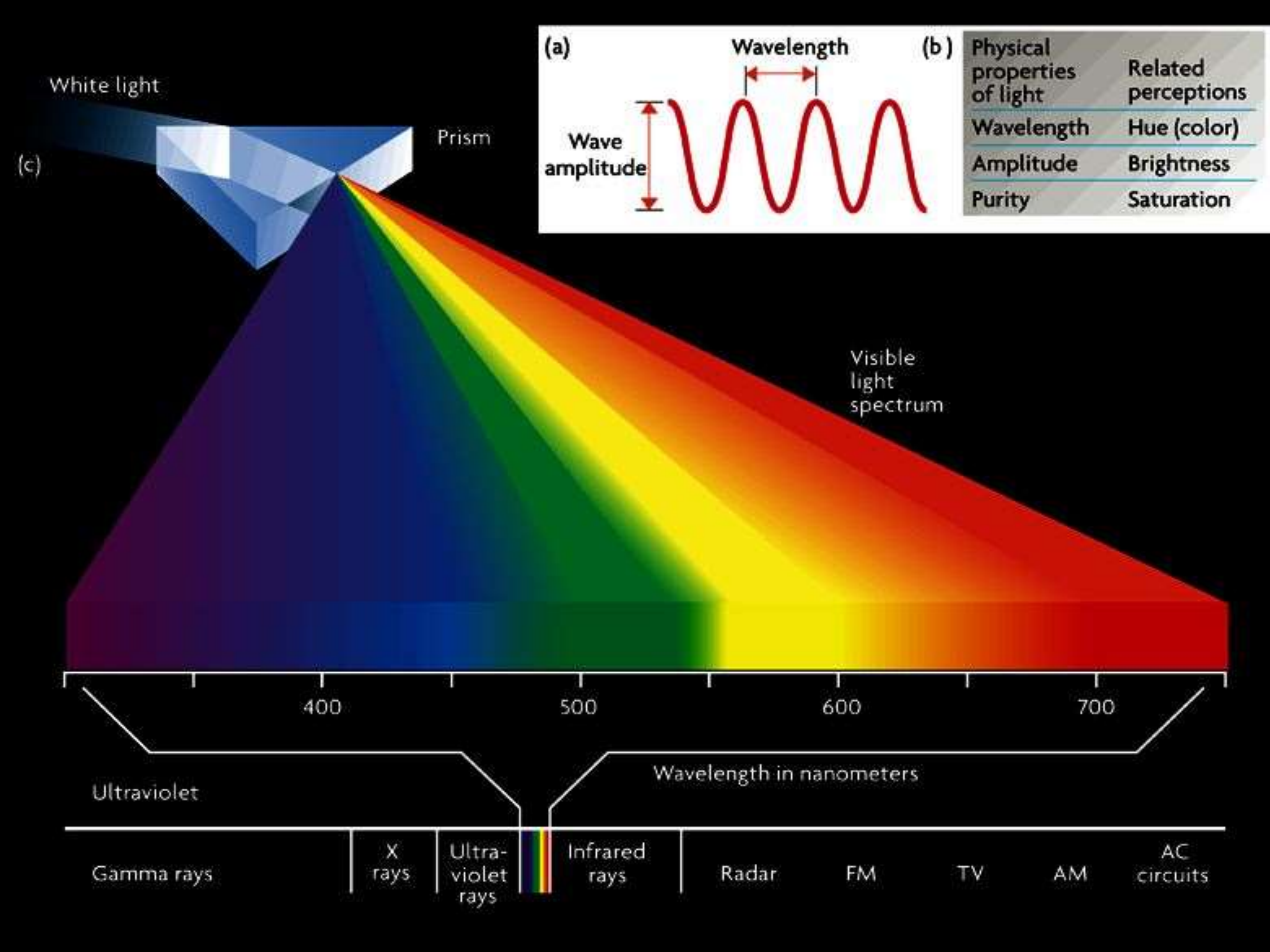
- About 8% of the male and about 1% of the female population suffer from some kind of **impaired color vision**
  - Most common: Red/green weakness
  - Should keep this in mind when designing visualizations
- Color is not that important after all…





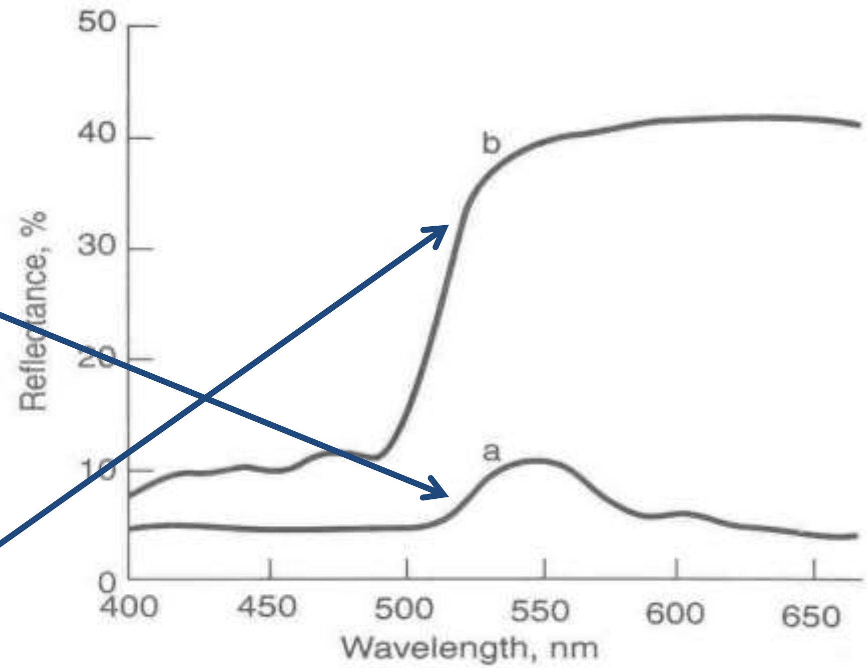



Source: www.xkcd.org

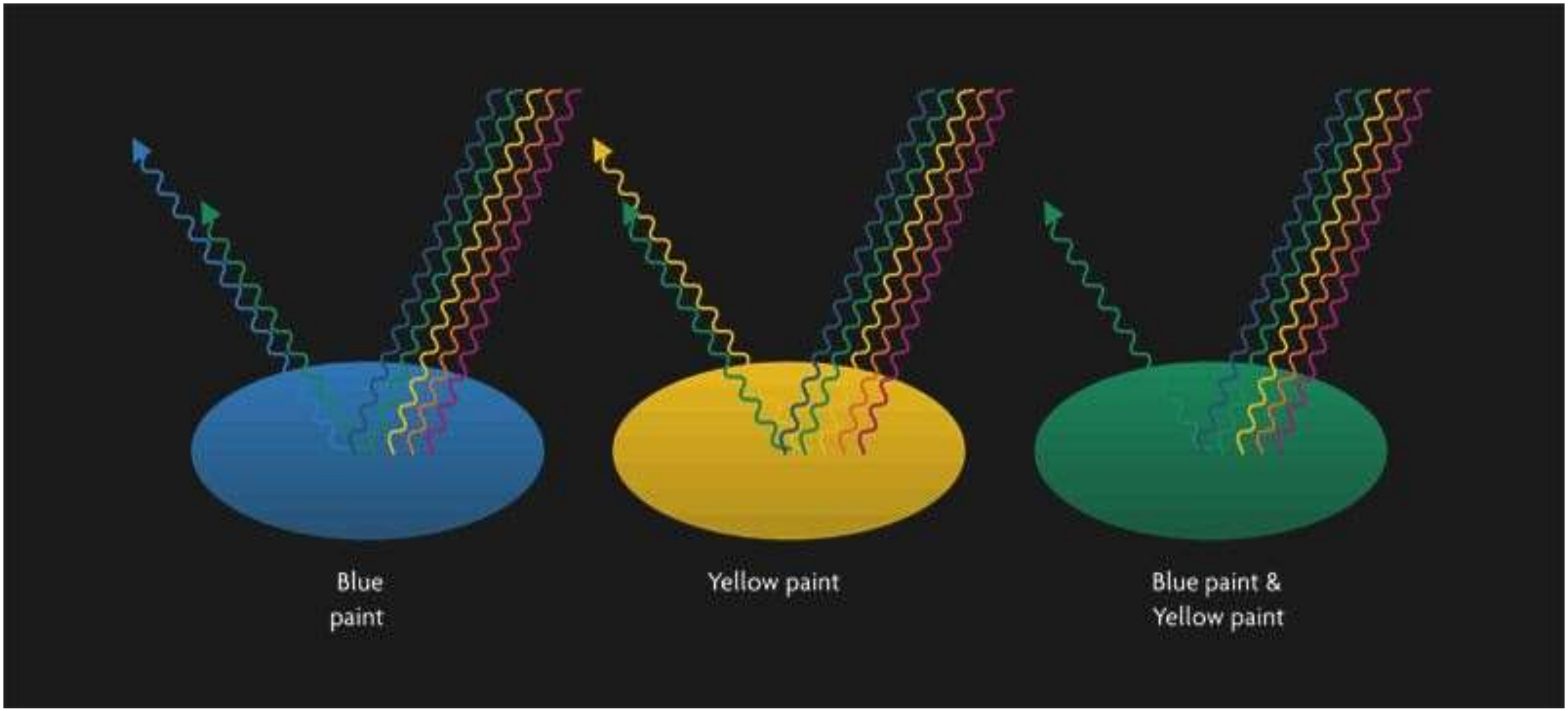


White light
Prism
(c)
(a)
Wavelength
Wave amplitude
(b)
Physical properties of light
Related perceptions
Wavelength
Hue (color)
Amplitude
Brightness
Purity
Saturation
Visible light spectrum
400
500
600
700
Wavelength in nanometers
Ultraviolet
Gamma rays
X rays
Ultra-violet rays
Infrared rays
Radar
FM
TV
AM
AC circuits

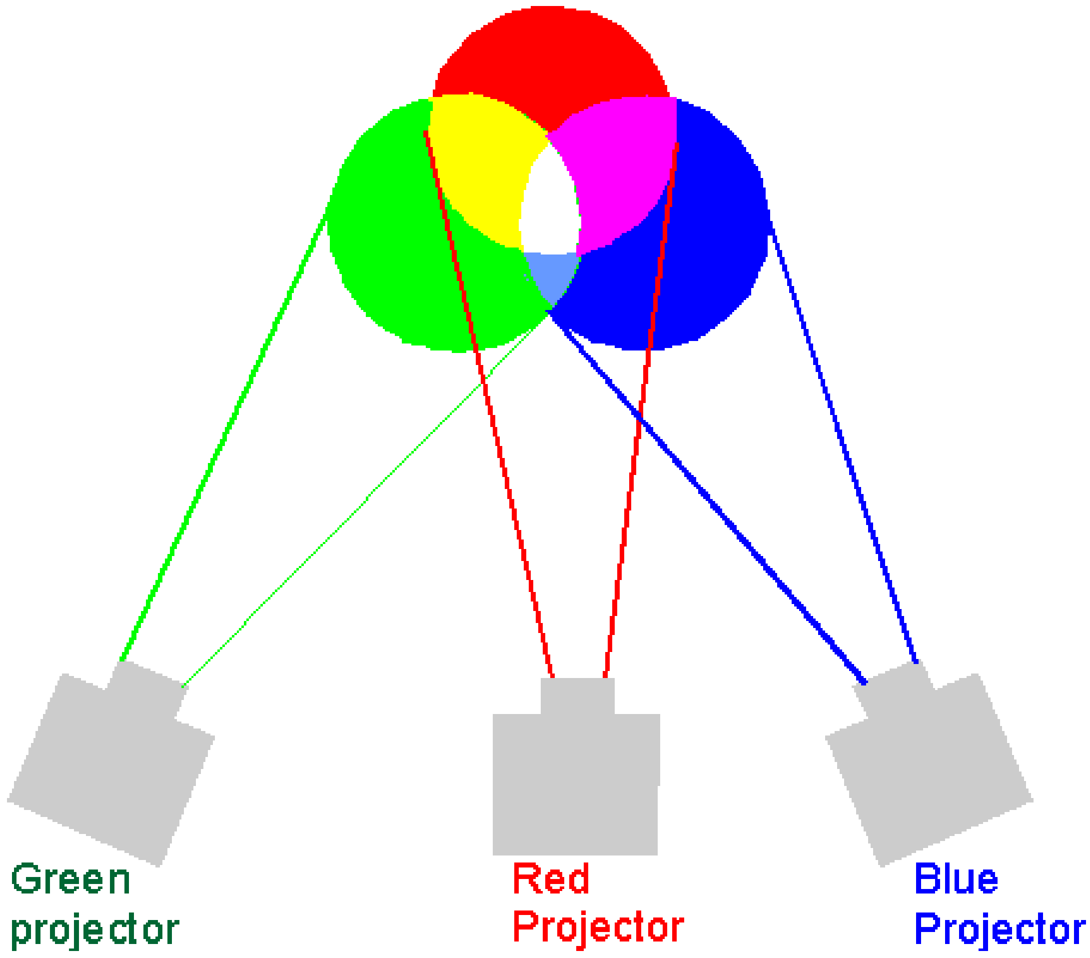
# Color vs. Wavelength



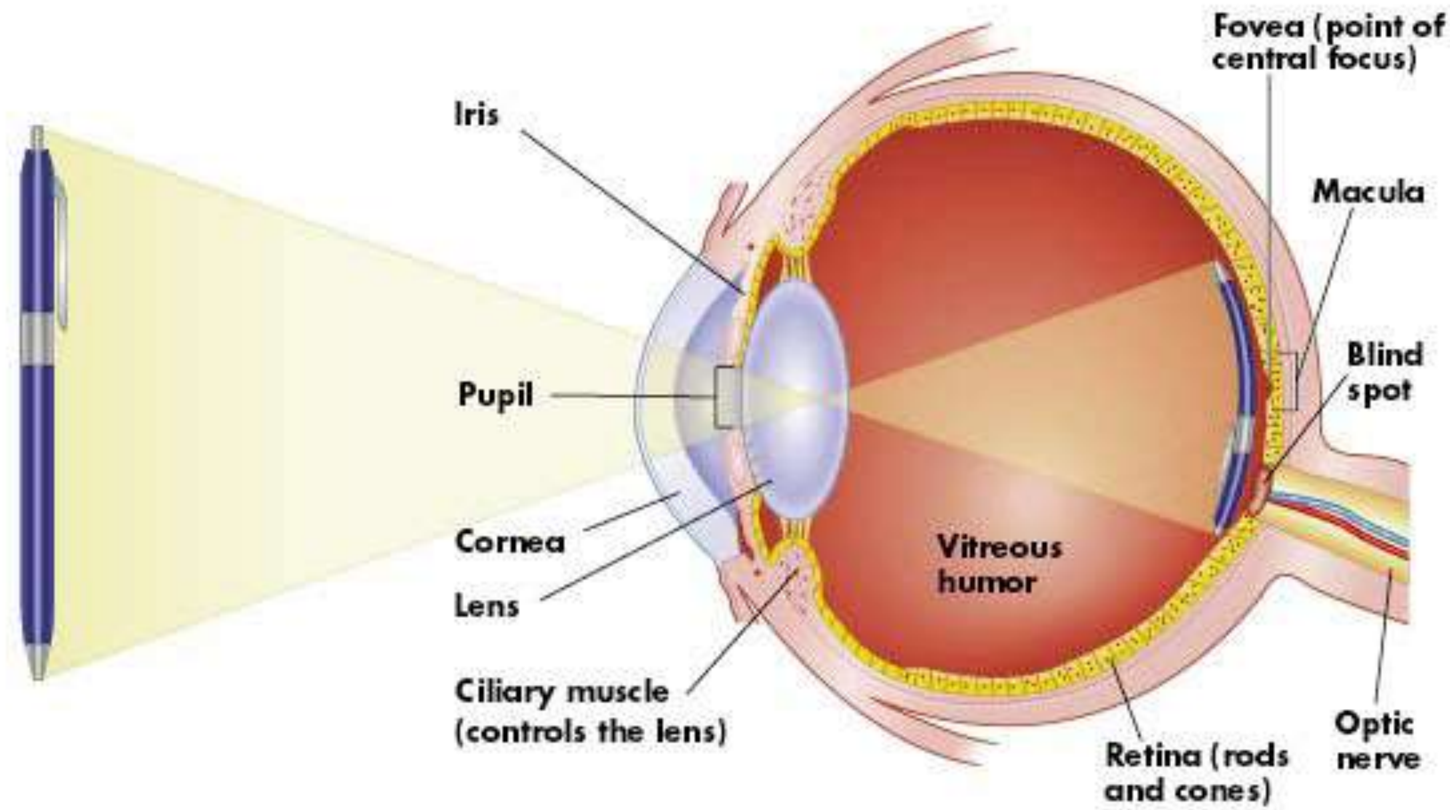
# Subtractive Color Mixing



# Additive Color Mixing

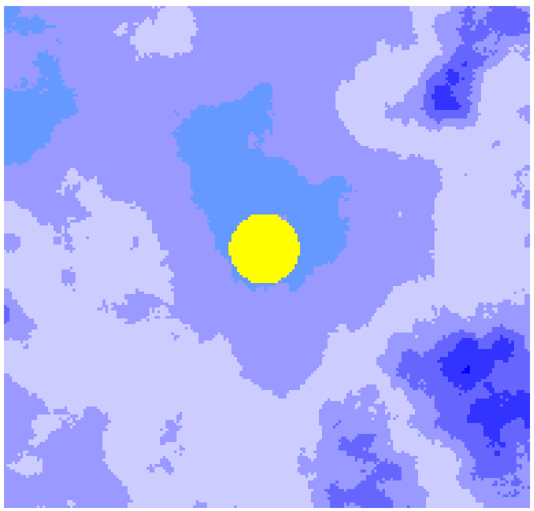


# Anatomy of the Eye



# The Blind Spot

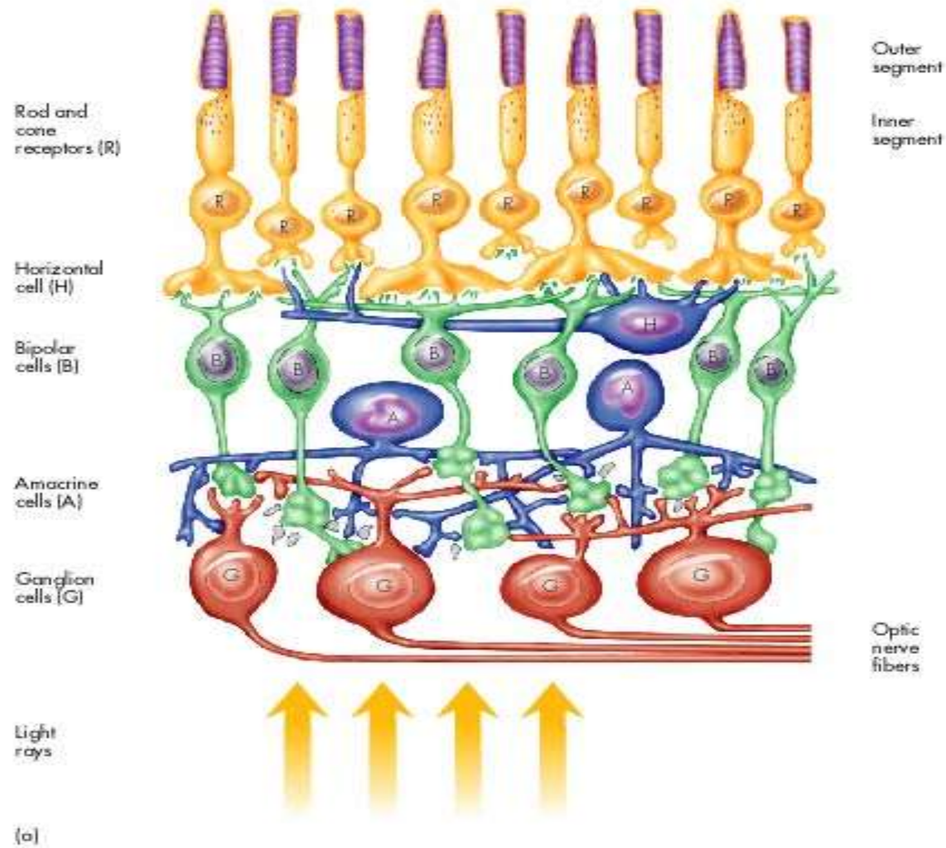
- Close your **right** eye!



1 2 3 4 5 6

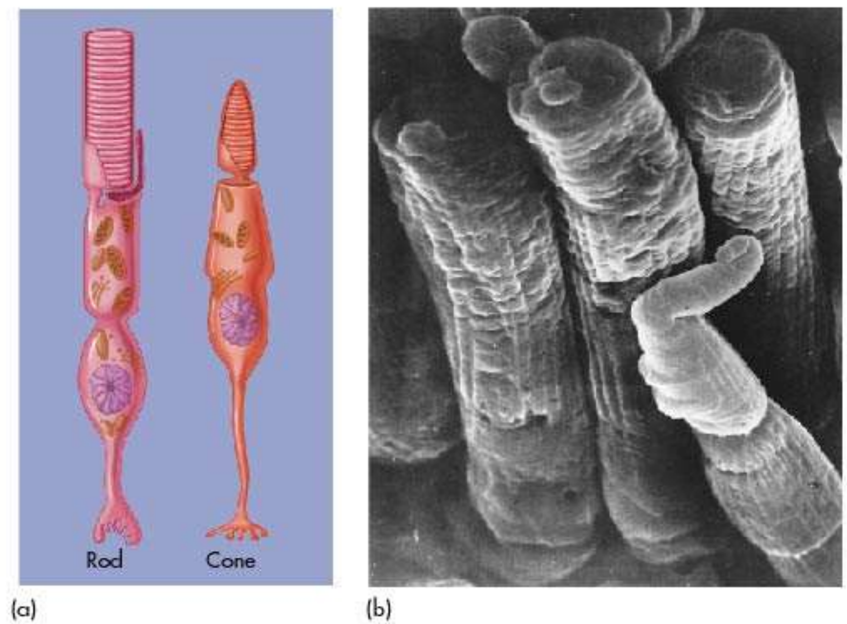
# Anatomy of the Retina

- The **retina**
  - Transduces light energy into electrical impulses
  - Performs initial encoding / processing
  - Is counted as part of the brain

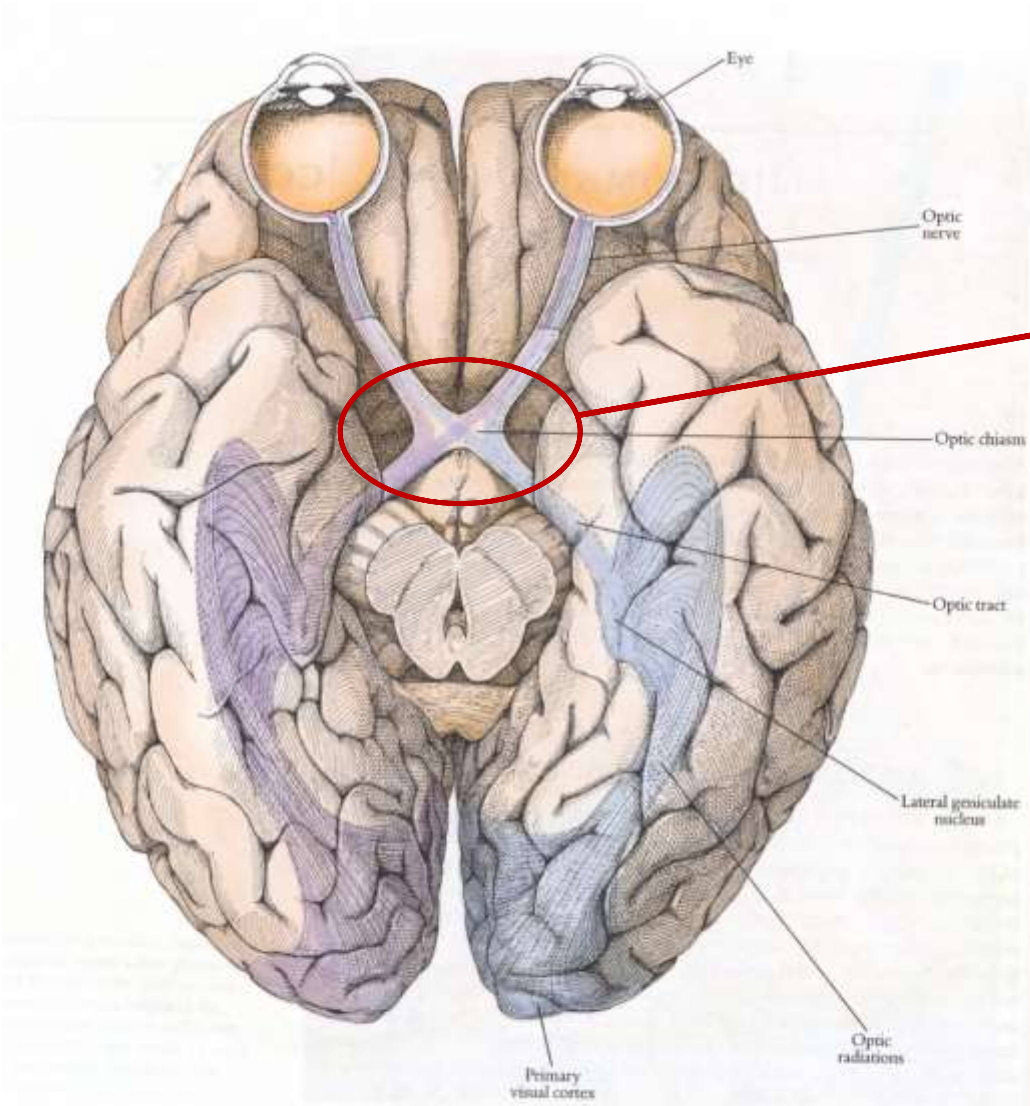


# Rods vs. Cones

- The retina has approx. 120 million rods and 5 million cones
- **Rods:**
  - Used for night (scotopic) vision
  - Achromatic
  - Peripheral vision
  - Less acuity
- **Cones:**
  - Require strong illumination (photopic vision)
  - Chromatic
  - Central vision
  - Higher acuity



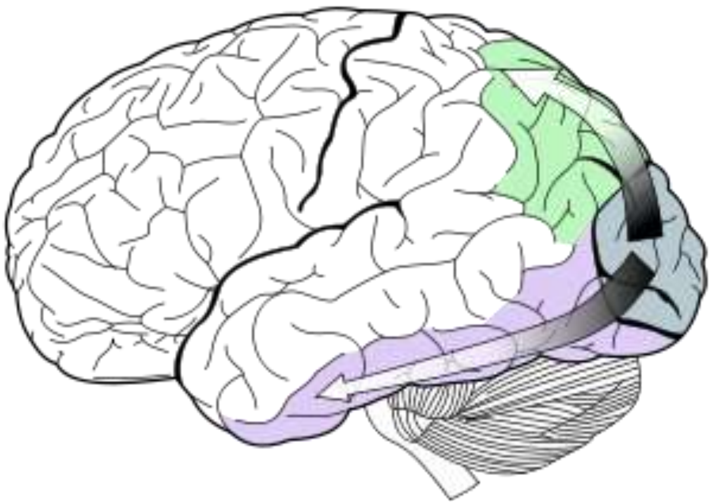
# Human Visual System




Each hemisphere processes information from the opposite half of the visual field

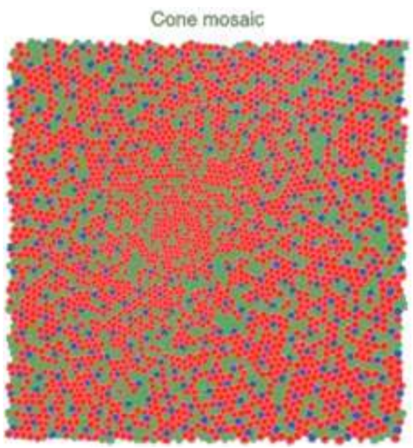
# Ventral vs. Dorsal Stream

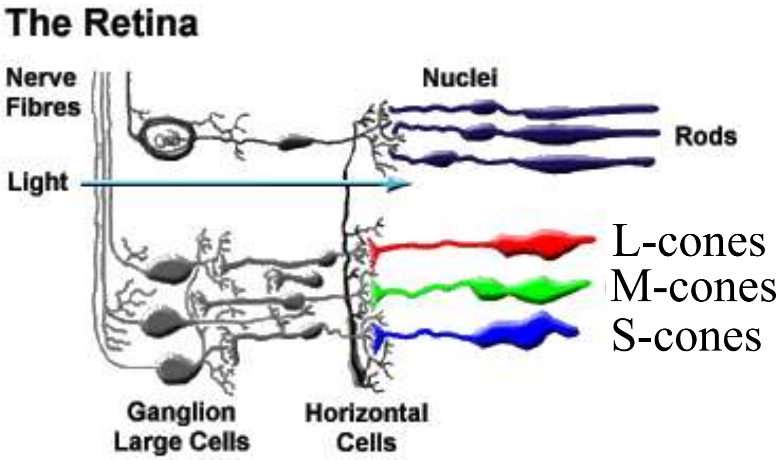
- **Two-streams hypothesis** of higher-level vision:
  - Dorsal stream ("where")
    - Guiding behavior
    - Relatively fast
    - High temporal resolution
    - Input from full retina
  - Ventral stream ("what")
    - Recognition and visual memory
    - Relatively slow
    - High spatial resolution
    - Input mostly from fovea
    - Conscious perception

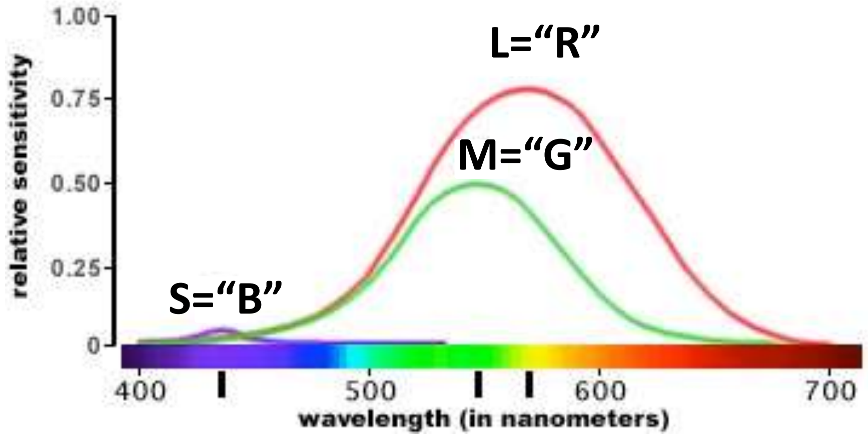


# Trichromacy

- Color vision is possible due to presence of **three different types of cones**
  - Respond more strongly to different parts of the spectrum (short/medium/long)
  - Human color perception is **fundamentally three-dimensional**
    - Eye projects continuous light intensity $I(\lambda)$ onto three numbers, e.g., $S = \int s(\lambda) I(\lambda) d\lambda$

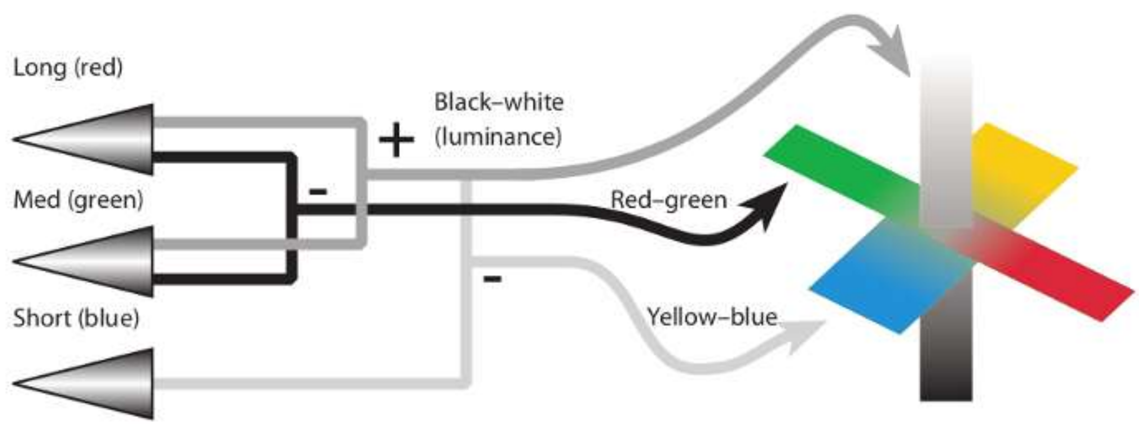


# Opponent Colors

- **Opponent Color Theory**
  – First proposed by Ewald Hering (around 1900)
  – Six elementary colors that form **three pairs**:
    - Black-white, red-green, yellow-blue
  – Supported by
    - Naming (greenish blue vs. reddish green)
    - Cross-cultural naming (languages with few color words)
    - Neuro-anatomy

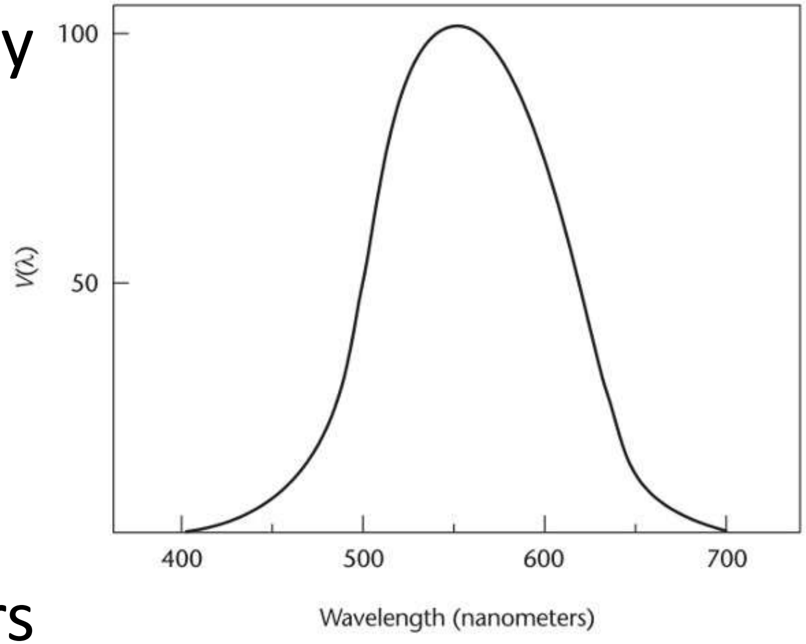


# Luminance

- **Luminance** = objective physical measure of the amount of visible light

$$L = \int V(\lambda) I(\lambda) d\lambda$$

  - Unit: candela / square meter
  - $V(\lambda)$ = luminous efficiency
    - Combined sensitivities of S/M/L receptors
  - Defined by *Commission Internationale de l'Éclairage* (CIE) based on experiments with standard human observers



# Luminance vs. Color

"Colors are only symbols. Reality is to be found in luminance alone..." (Pablo Picasso)

Poor People on Shore

Typically, luminance is the key to object recognition and colors are merely perceived as object attributes.

# Importance of Color

- Color can be helpful to quickly tell apart different **types of objects,** especially if they are similarly shaped

# Recoding Luminance to Color

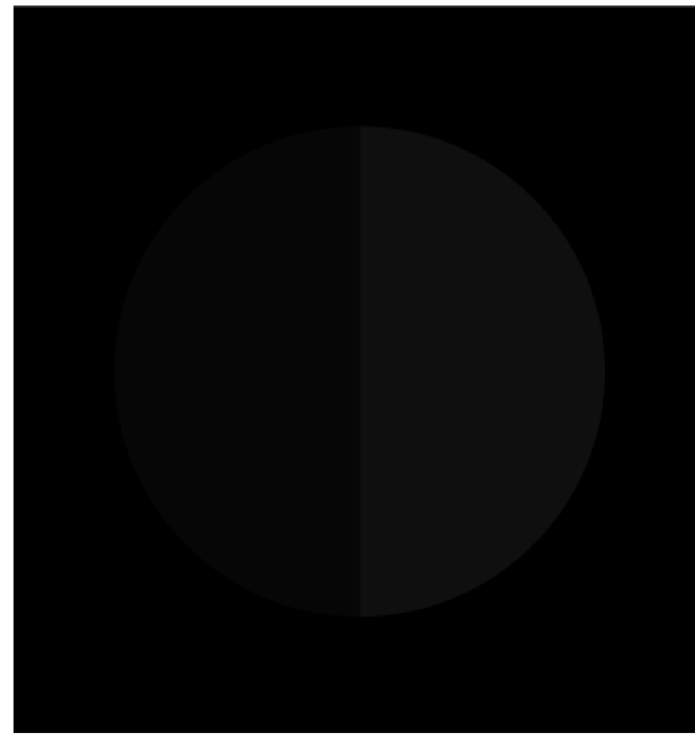
- Object detection becomes hard (or even impossible) when **mapping the black-white axis onto a color axis** (e.g.,yellow-blue)

# Brightness

- **Brightness** = *subjective* amount of a light from a self-luminous object in a darkened room
  - Related to luminance roughly according to a **power law:** $B \approx L^n$
  - Power *n* depends on size of object, $n \approx 0.3 \ldots 0.5$
  - Similar power laws have been found to approximate perception of loudness, smell, taste, heaviness, force, and touch
    - Motivates use of logarithmic unit decibel to measure sound pressure

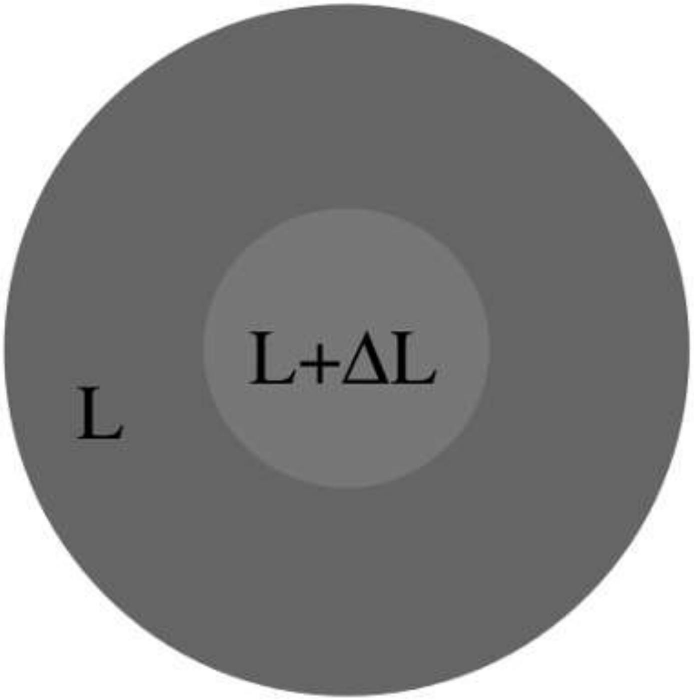
# Monitor Gamma

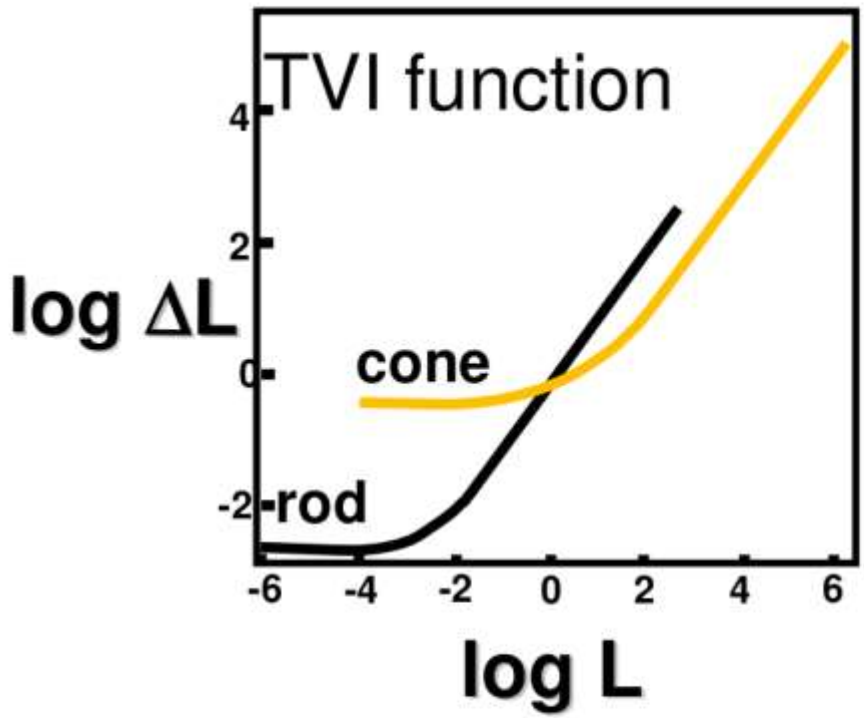
- The relationship between pixel voltage on a CRT monitor and luminance also follows a power law: $L = V^{\gamma}$
  - Typically, $\gamma \approx 2.2$, leading to an approximately linear relationship between *V* and *B*
  - Modern LCDs are built to have similar $\gamma$
  - To ensure correct color reproduction, **monitor gamma has to be calibrated**



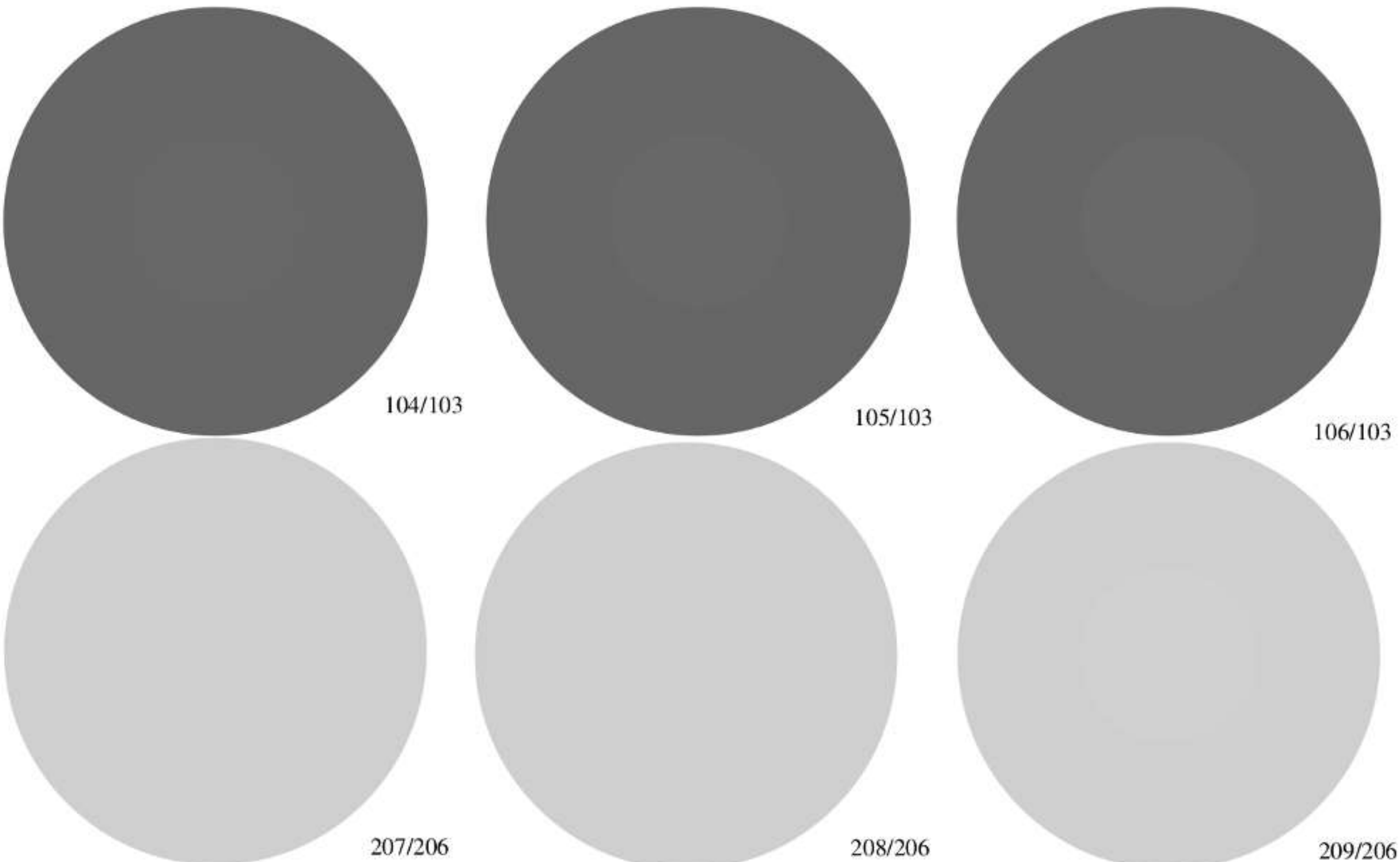
# Weber-Fechner Law

- **Just Noticable Differences** (JNDs) are proportional to baseline brightness



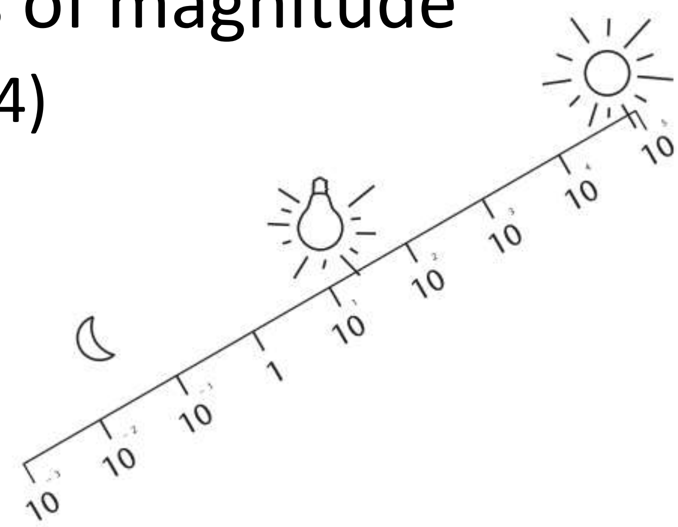



# Illustration: Weber-Fechner Law



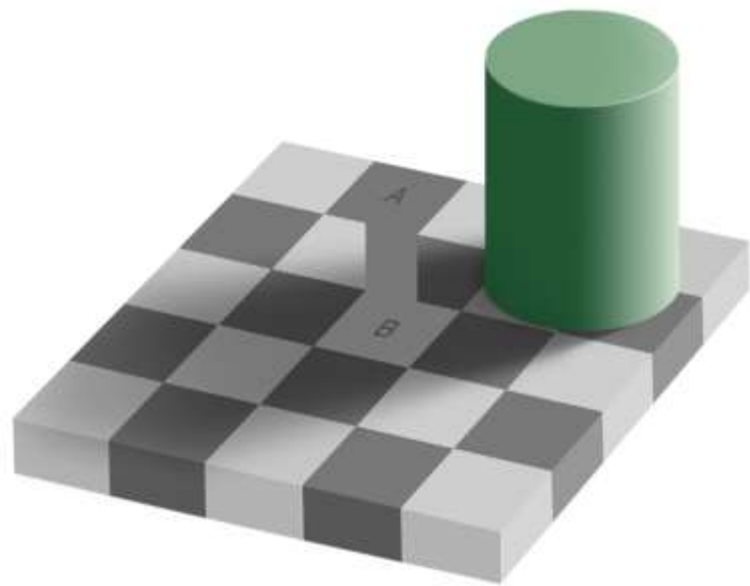
# Lightness

- **Lightness** = subjective reflectance of a surface
  - Do we perceive an object as dark or bright?
  - Depends on many factors apart from luminance
    - In different environments, the same luminance can be perceived as “black” or as “white”
    - **Lightness constancy**
- The eye can only see a contrast ratio of 1:1000, but can **adapt** over eight orders of magnitude
  - **Iris** opens and closes (factor 16-64)
  - Bleaching of **photopigment**
  - **Switchover** rods vs. cones
  - Full adaptation bright to dark:
    Up to 30 minutes



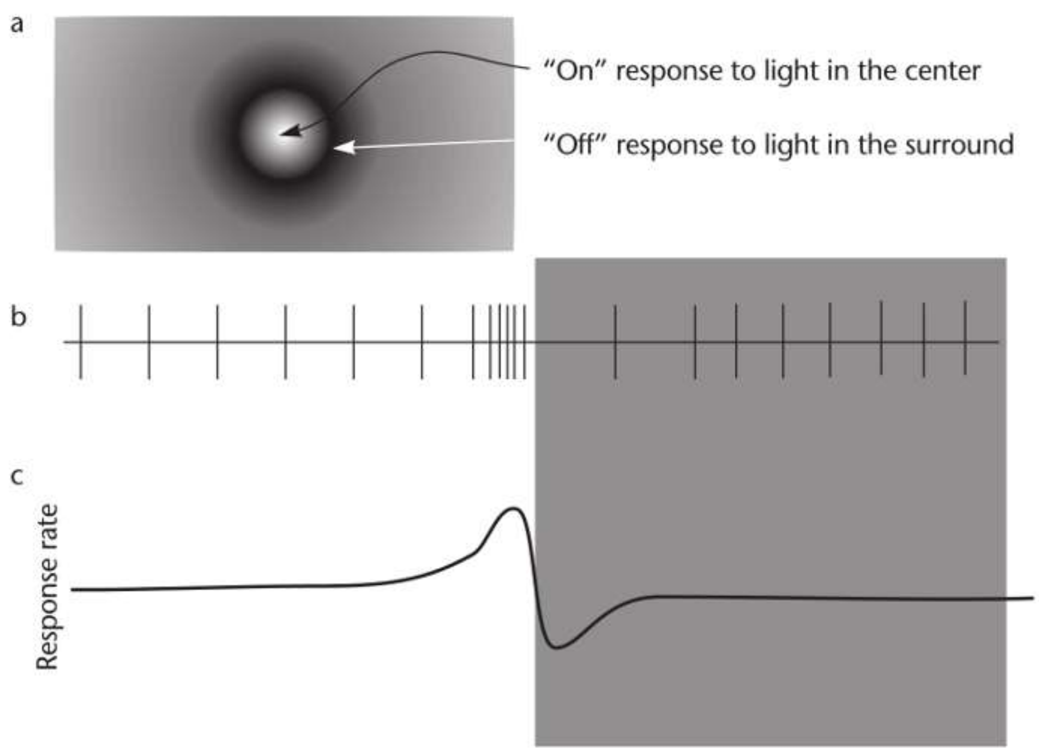
# Lightness Illusions

- Perceived lightness is influenced by complex factors such as **surface orientation, shadows** and **positions of light sources**



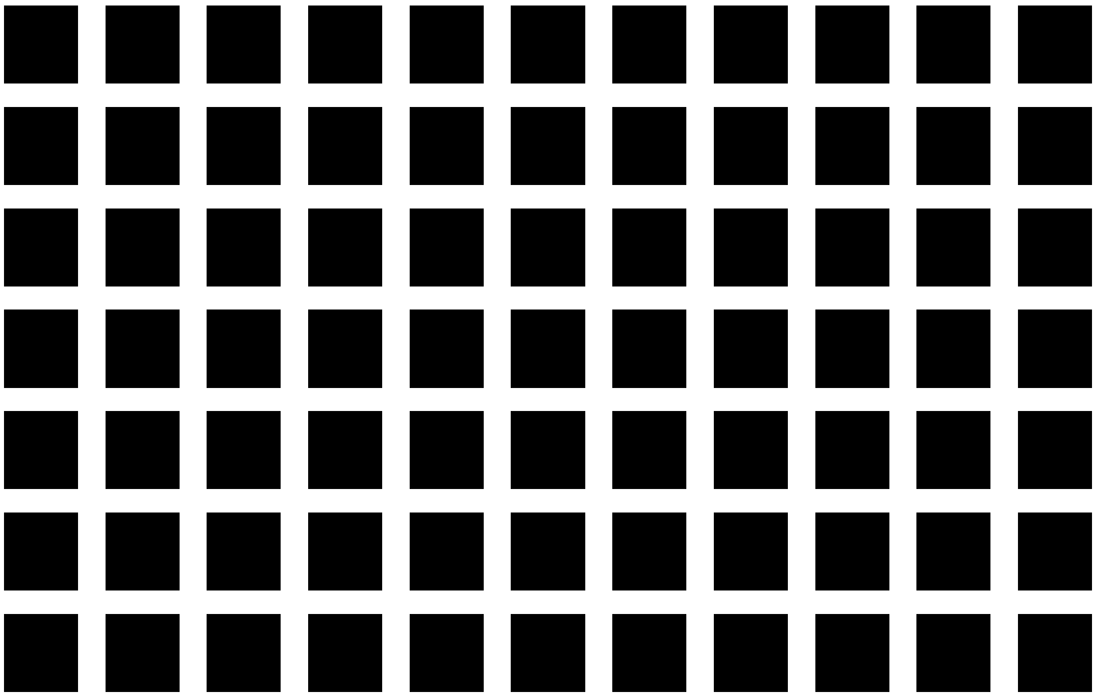
# Contrast Vision

- Lightness constancy is partly achieved by **perceiving contrast** rather than luminance
  - Neural mechanism: **Lateral inhibition**
  - **Receptive field** with center/surround structure



# Contrast Illusions

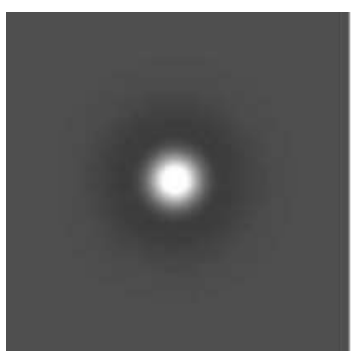
- **Hermann grid**
  - Lateral inhibition stronger in the periphery (try to stare directly at one of the spots at the intersection between grid lines)

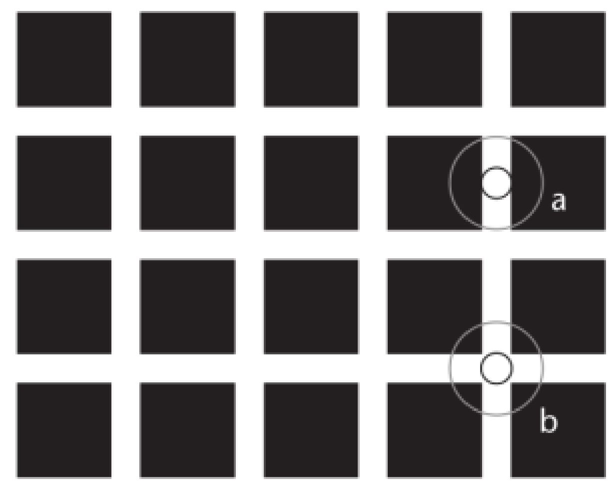


# Contrast Vision: Mathematical Model

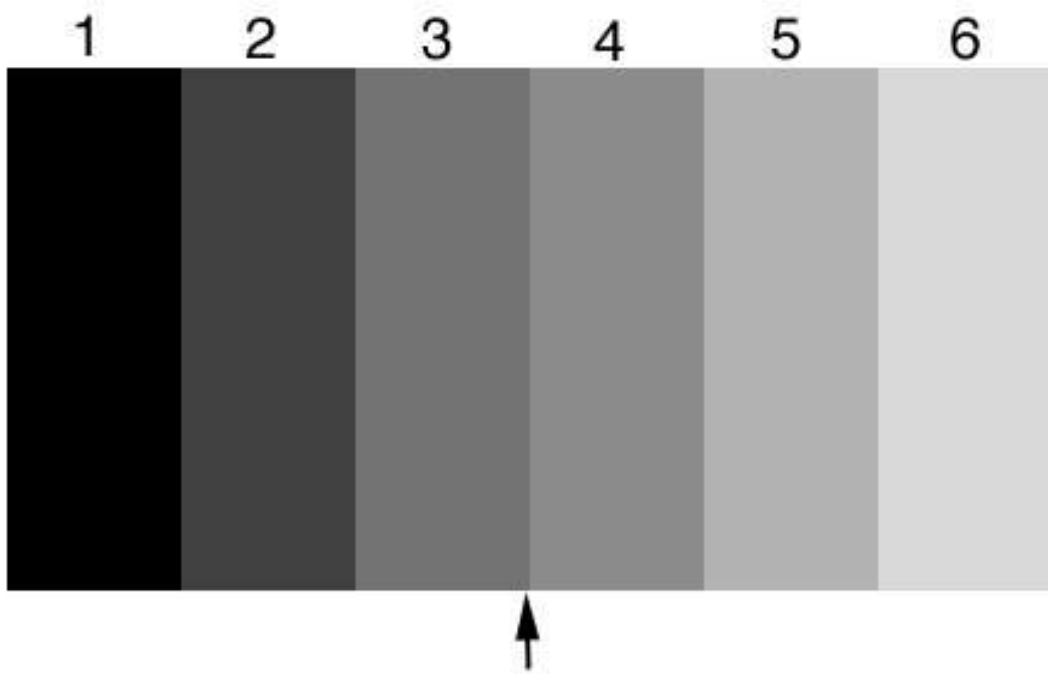
- We can approximate the perceived local contrast by convolving an image with a **“Difference of Gaussians” (DoG)**:

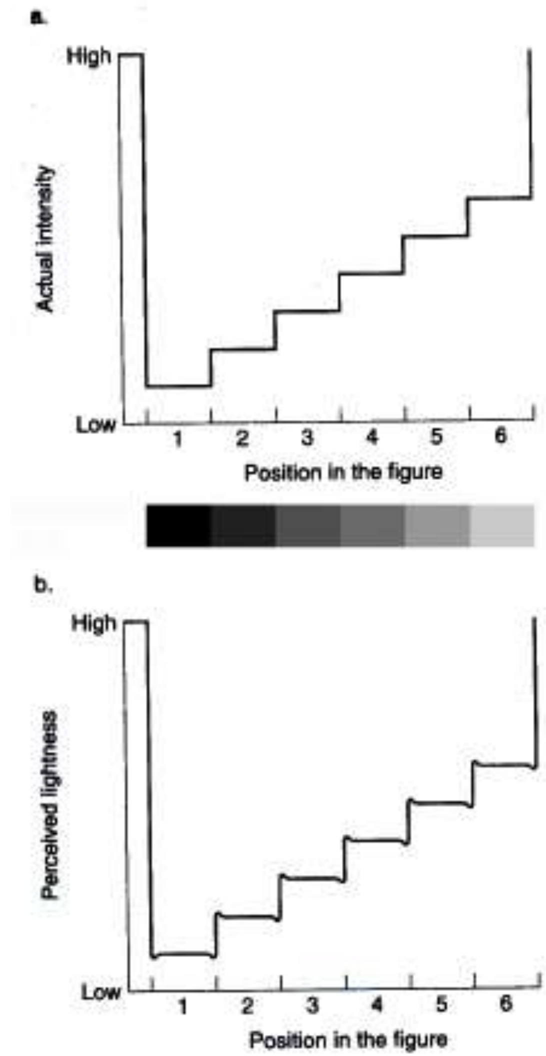
$$f(x) = \alpha_1 e^{-\left(\frac{x}{w_1}\right)^2} - \alpha_2 e^{-\left(\frac{x}{w_2}\right)^2} \quad (w_1 < w_2)$$

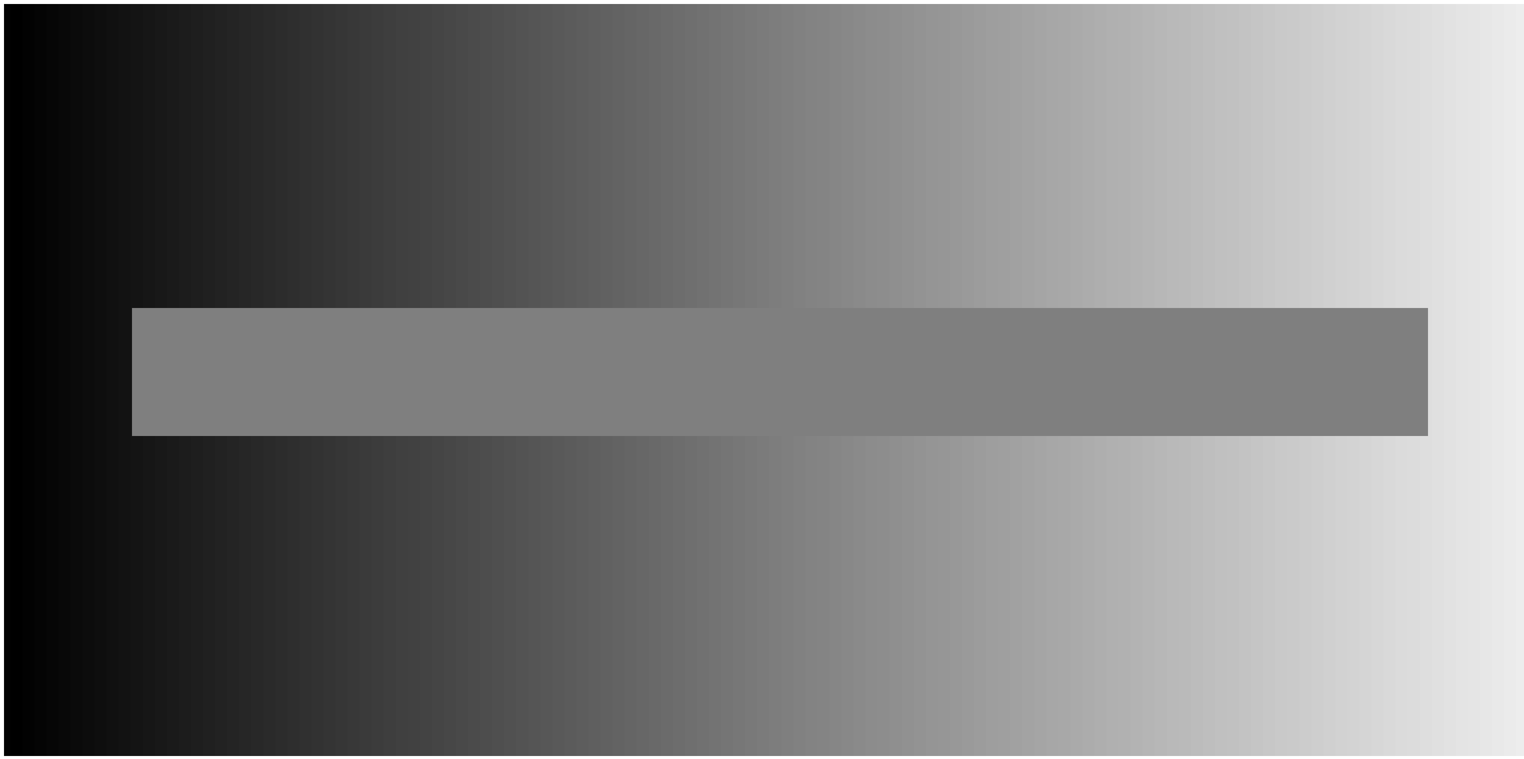


# Mach Bands


1
2
3
4
5
6

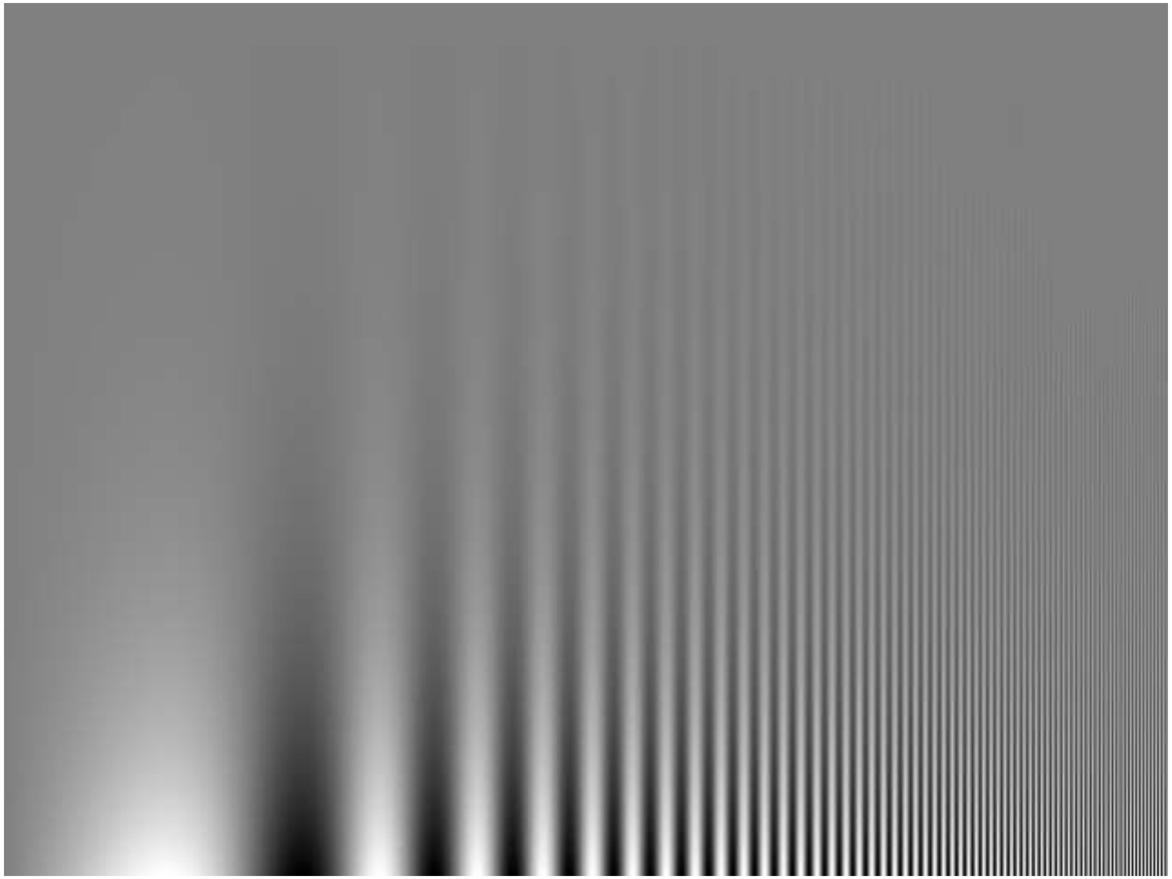

a.
High
Low
Actual intensity
1
2
3
4
5
6
Position in the figure
b.
High
Low
Perceived lightness
1
2
3
4
5
6
Position in the figure

# Simultaneous Contrast



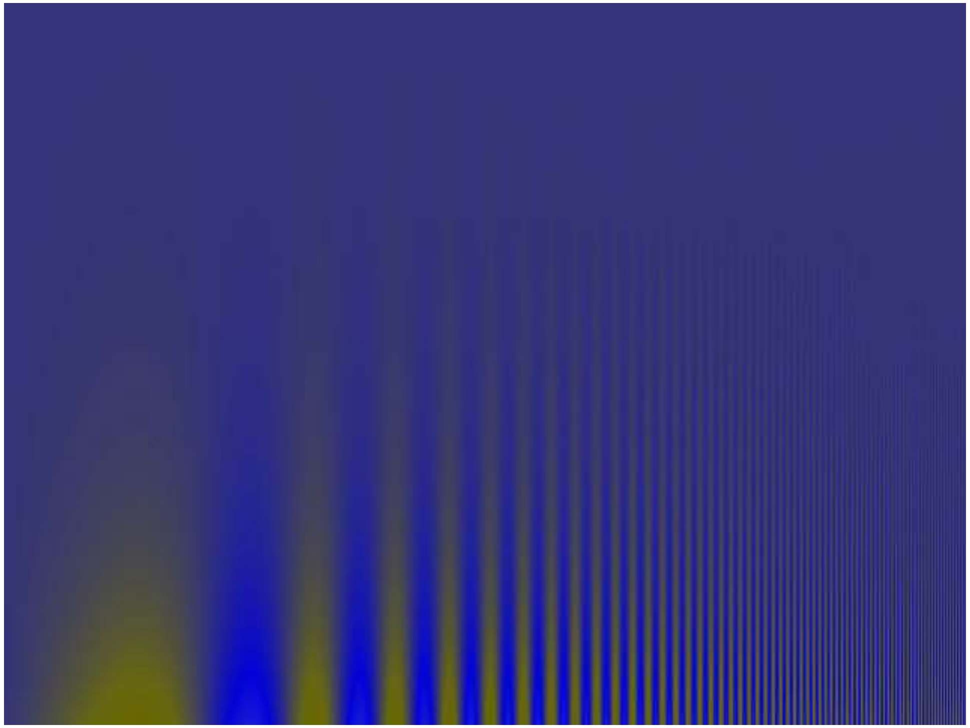
# Contrast Sensitivity

- The **Campbell-Robson Contrast Sensitivity Function** reflects our higher contrast sensitivity at medium spatial frequencies



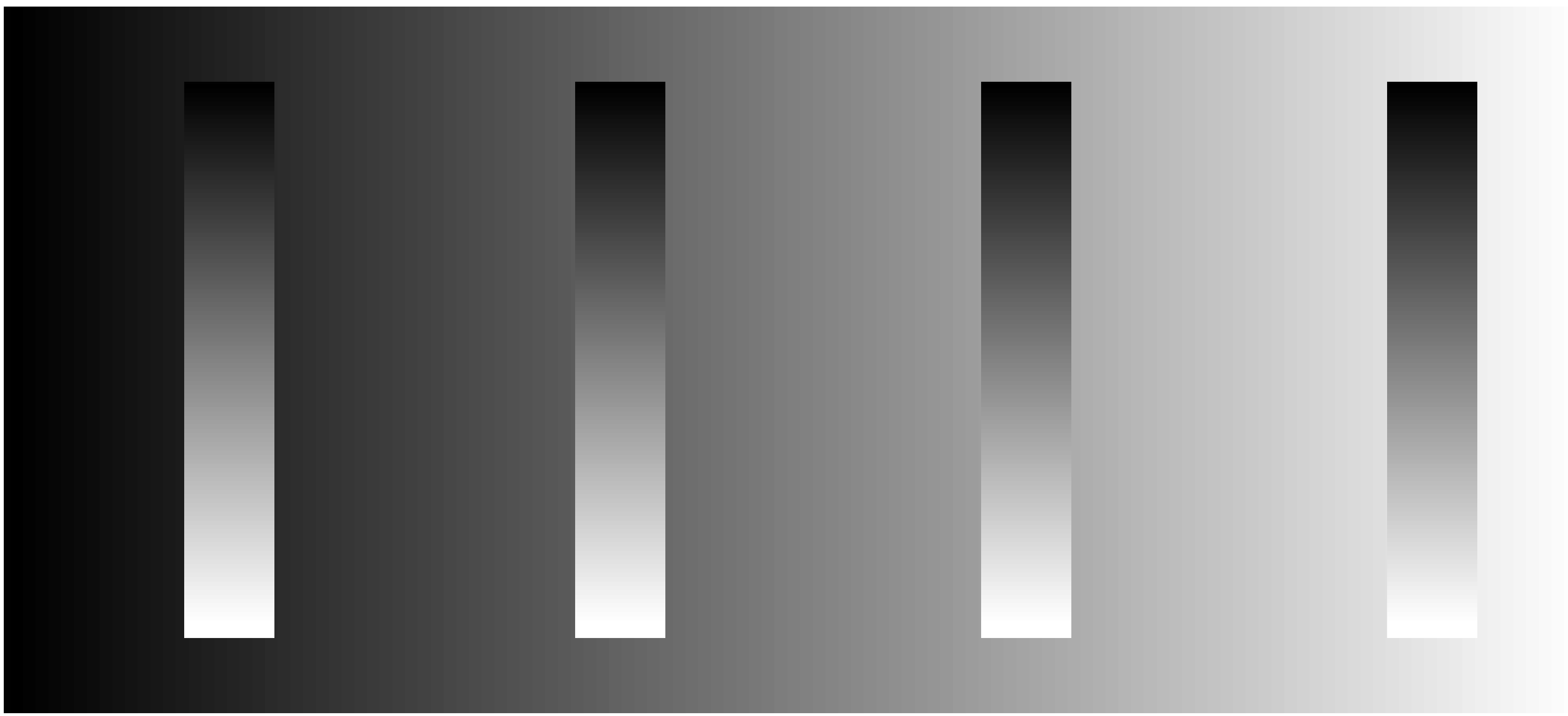
# Color Contrast Sensitivity

- Our sensitivity for **color contrast** is lower than for luminance contrast
  - Exploited in **image compression:** More bits allocated to luminance than to color



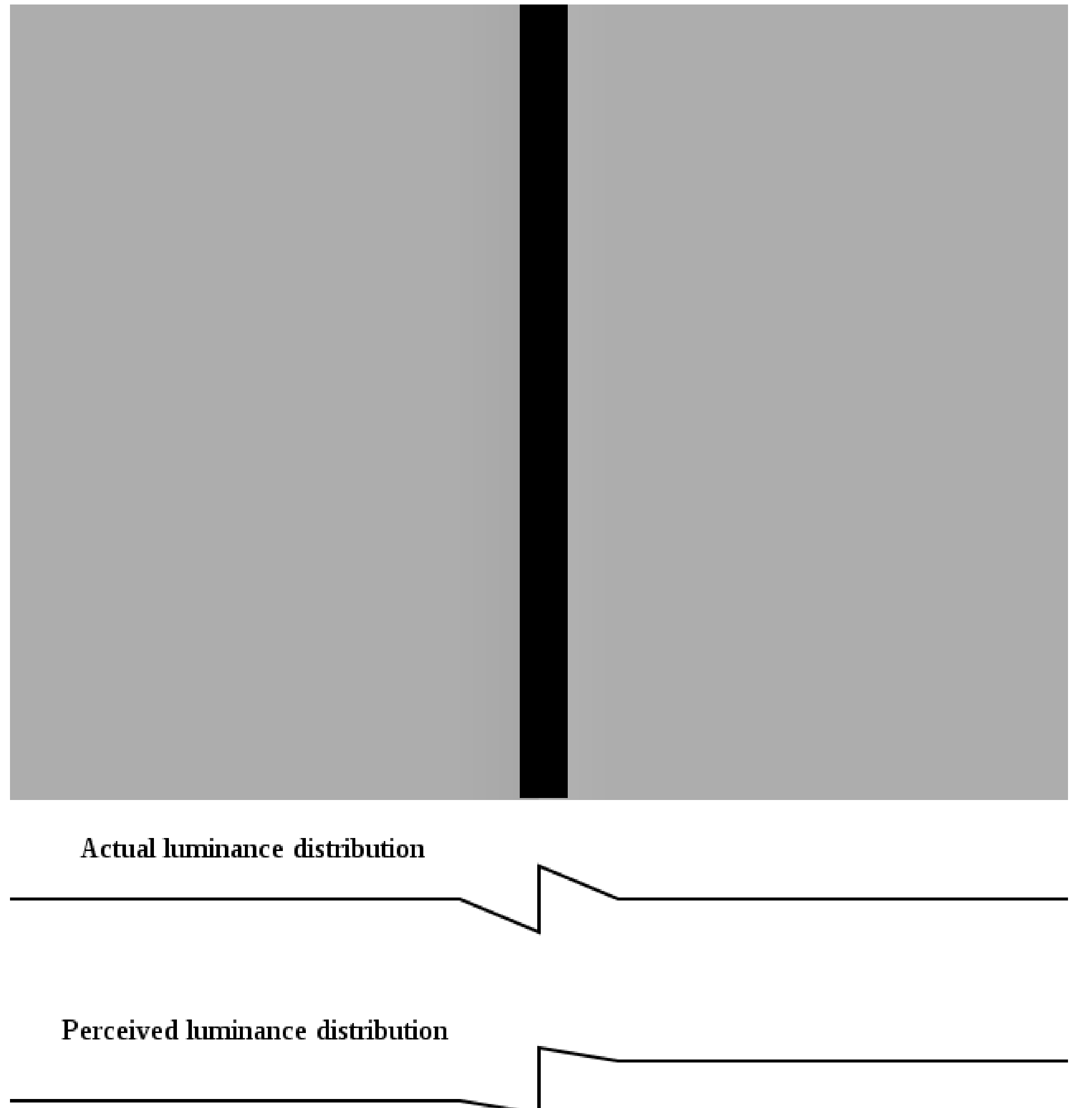
# Contrast Crispening

- Sensitivity for small changes is best around the background intensity



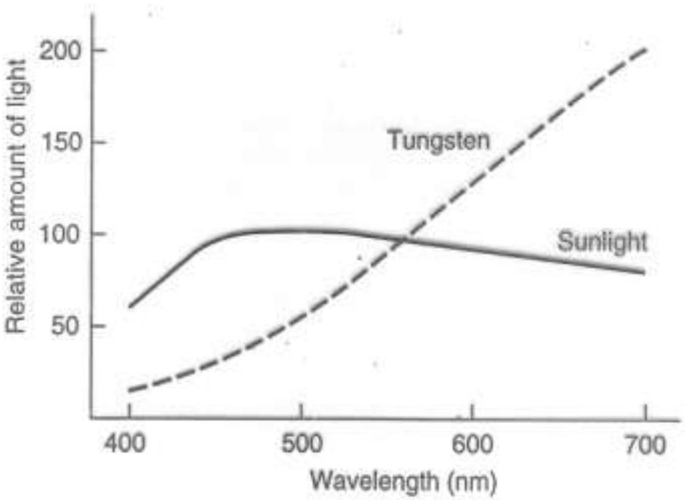
# Cornsweet Illusion

- HVS extrapolates edge information



# Color Constancy

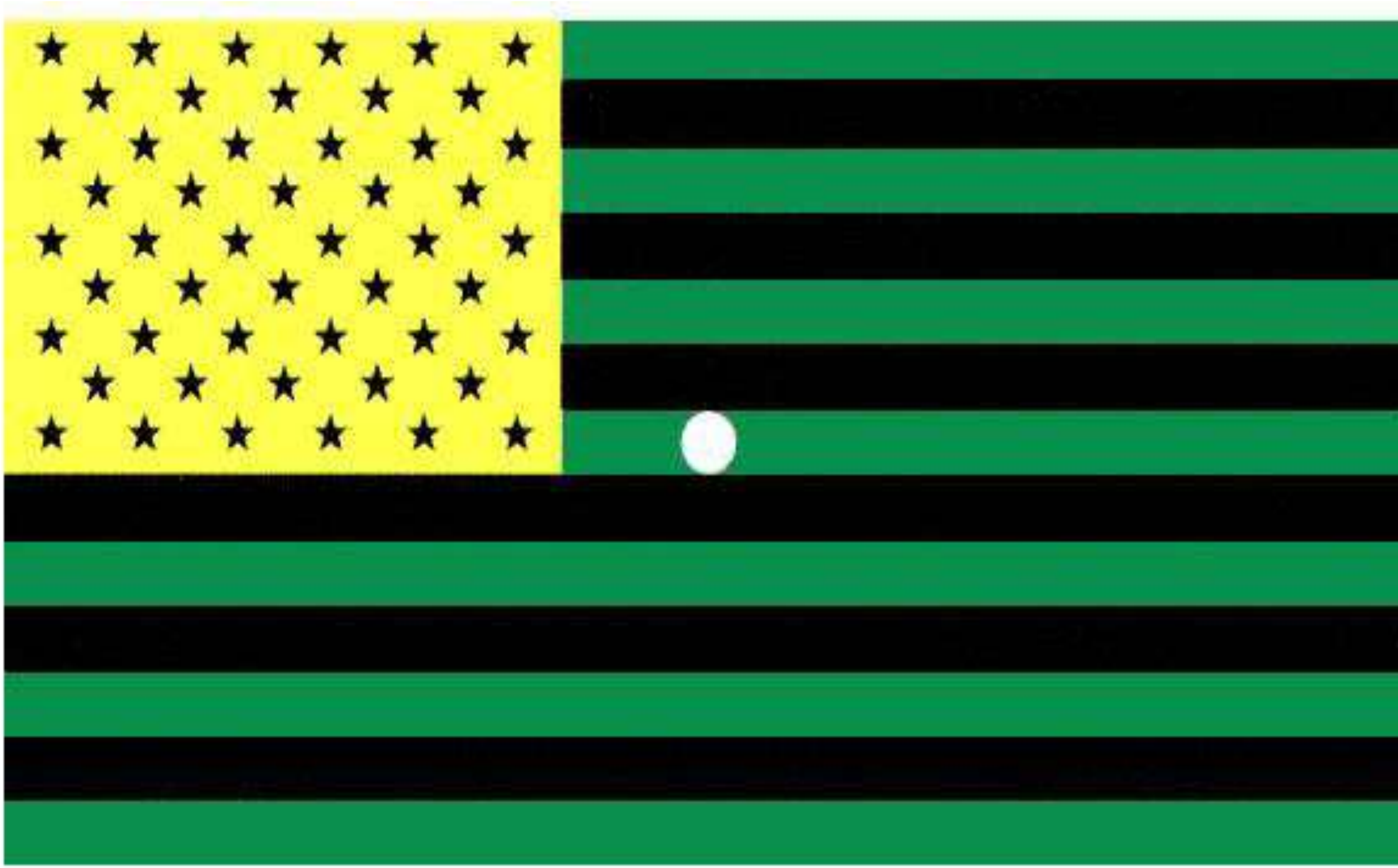
- **Color constancy** is even more complex than lightness constancy
  - Colors are perceived to be relatively stable under a wide range of incident spectra
  - **Color adaptation** and **color contrast** contribute
  - **"Reference white"** in scene might play a role



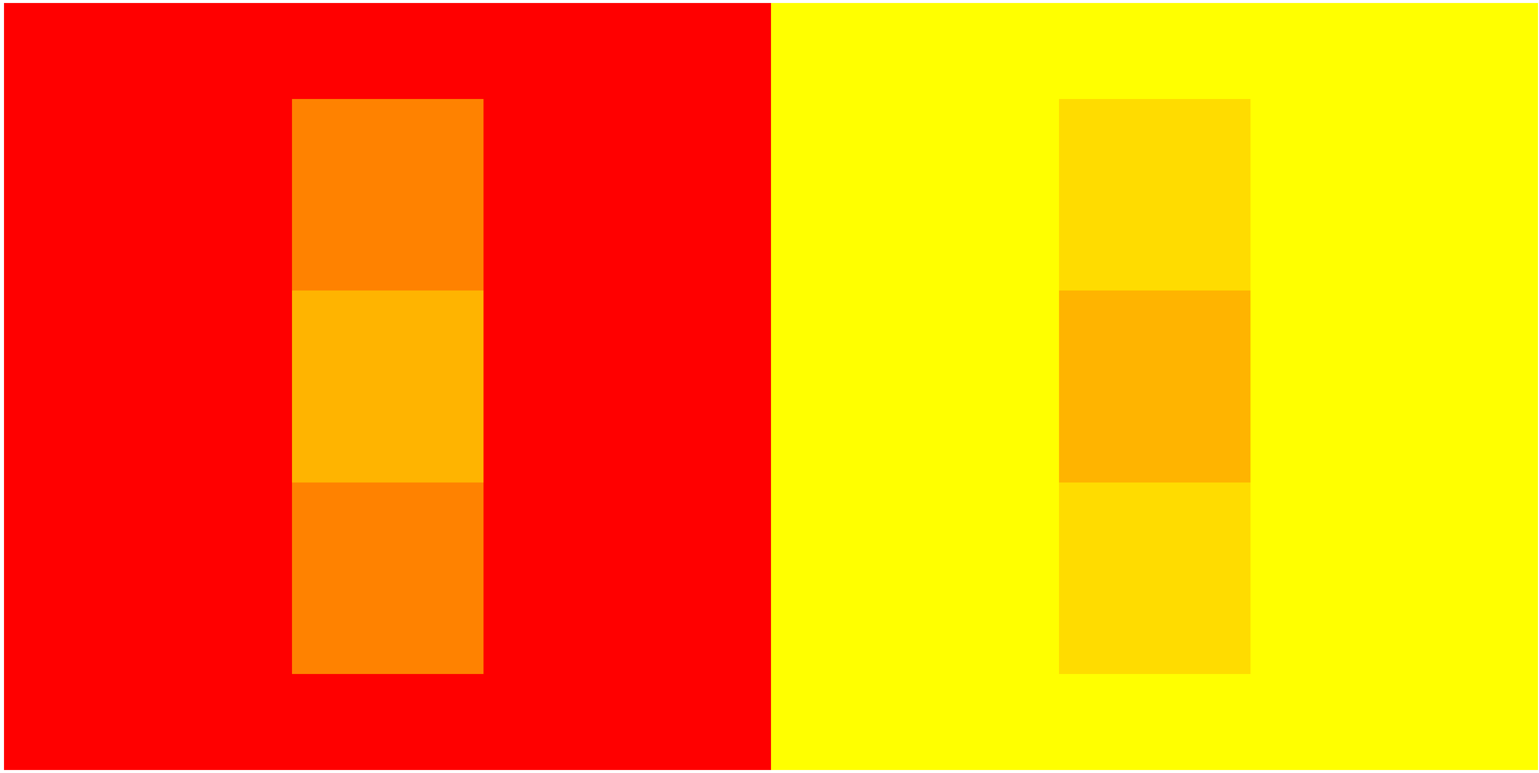


White balance in photography

# Color Adaptation



# Color Contrast



Source: www.psy.ritsumei.ac.jp/~akitaoka/shikisai2005.html

# How Would You Call This Slides's Background Color?

# How Would You Call This Slides's Background Color?

# Brown

- Dark shades of yellow / yellowish orange are perceived as **brown**
  - Opposed to dark shades of red / green / blue
  - Brown is not part of the spectrum, but perceived as a distinct color
  - Perception of brown requires presence of other colors (e.g., white) for reference

- **Important for visualization:**
  - When encoding class membership using color, dark and light shades of yellow and orange might not be recognized as belonging together

# Summary: Color Perception

- **Color perception** is…
  - a highly complex and subjective process
  - trichromatic, recoded to black/white, red/green, yellow/blue
- **Luminance** is…
  - most important for recognizing shapes etc.
  - perceived logarithmically (brightness)
- **Lightness** and **color constancy** are achieved…
  - by adaptation and contrast perception
  - using high-level information (shape, illumination etc.)
- **Visualization should not assume that human visual system performs objective measurements**