COS426

Computer Graphics

Fall 2022

PRINCETON UNIVERSITY

Overview

- Administrative stuff
  - People, times, places, etc.
- Syllabus
  - What will I learn in this course?
- Imaging
  - Getting started …

Administrative Stuff

- Instructors
  - Prof: Szymon Rusinkiewicz
  - TAs: Yuting Yang, Yuanqiao Lin, Guðni Nathan Gunnarsson
- Book
  - *Computer Graphics with OpenGL, 4th Ed,*
    Hearn, Baker, and Carithers,
    Prentice Hall, 2010. ISBN: 978-0136053583
- Web page
  - www.cs.princeton.edu/~cos426
- Discussion
  - Ed (linked from web page, or from Canvas)

COS 426: Computer Graphics

Fall 2022

60 FPS (33-60)

Syllabus

Description

Computer graphics lies at the intersection of computer science, geometry, physics, and art. This course provides an introduction to the field, with an emphasis on practical methods and applications in image processing, modeling, rendering, and computer animation. The goal of this course is to equip students with the tools and techniques they need to build projects with significant graphical components; this includes applications for realizing artistic visions (art and architecture), user interaction (UI/UX development), entertainment products (video games, CGI, animations, and augmented reality), visualizations and academic

Contents

Coursework

- Exam (15%)
  - During class hours (in person or online, TBA): Oct 13
- Programming Assignments (60%)
  - Assignment #0: JS Paint (warmup)
  - Assignment #1: Image Processing
  - Assignment #2: Modeling
  - Assignment #3: Ray Tracer
  - Assignment #4: Rasterizer
  - Assignment #5: Animation
- Final Project (20%)
  - Interactive game (completed in groups of 3-4): due Dean's Date
- Participation (5%)

Programming Assignments

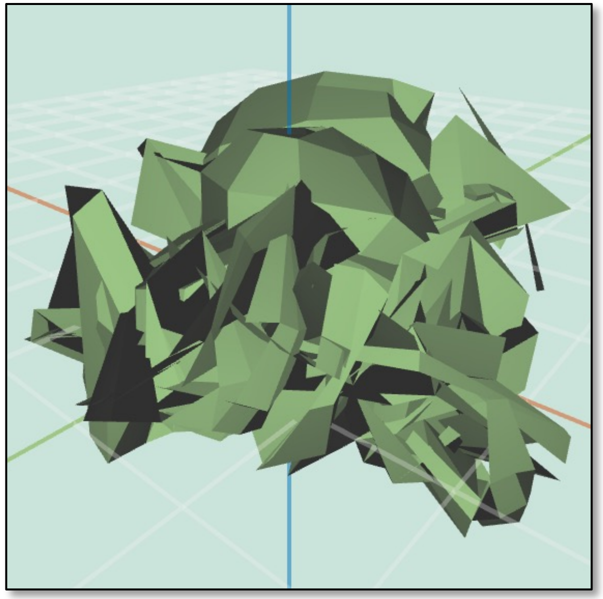
- When?
  - Roughly every 2-3 weeks
- How?
  - Javascript (precept this week)
  - Some OpenGL (WebGL, GLSL)
- What?
  - Basic feature lists
  - Extra credit lists
  - Art contest

Art and Simulation Contest

- Everybody should submit entries!
  - 1 point for submitting
  - 2 points for winning

Cool Images/Videos

(Jad Bechara, CS 426, Spring 2018)



Bloopers

(Reed Tantiviramanond, CS 426, Spr15)

Characters for web banner

Collaboration Policy – See Website

- Overview:
  - You must type your own code, but may work in pairs
  - You must reference your resources
  - See policy on course web, and ask when in doubt
- It's OK to …
  - Talk with other students about ideas, approaches, etc.
  - Get ideas from information in books, wikipedia, etc.
  - Use "support" code provided with our assignments
- It's NOT OK to …
  - Share your code digitally (e.g. post on web, email)
  - Copy code directly from another student
  - Leverage code acquired from other sources

Questions / Discussion

- Ed (edstem.org, log in through Canvas)
  - View announcements
  - Post questions to the class
  - Answer other students' questions
  - Is set up for everyone enrolled as of today
  - Use this instead of email to instructors
    (can send private messages)

Precepts

- When and Where
  - Thu 7:30 - 8:20 pm, Friend 111
  - Fri 10:00 - 10:50 am, Friend 111
  - Fri 11:00 - 11:50 am, Friend 111
  - Attend your own precept if you can, but if unable then attend another precept
- Topics
  - Usually centered around assignments
  - This week: getting up to speed in Javascript

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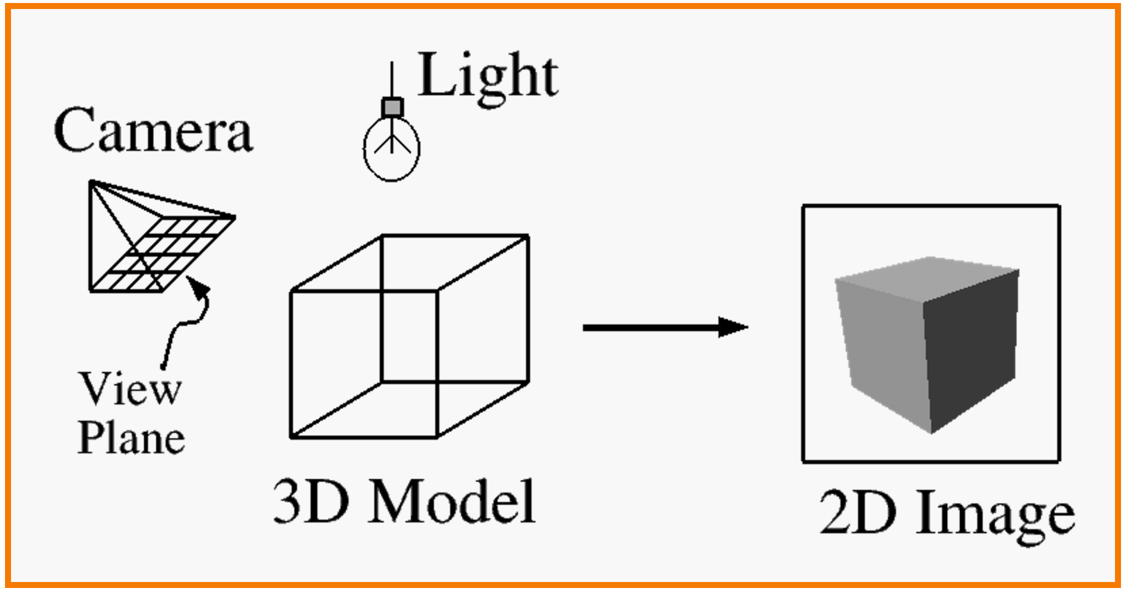
Introduction

- What is computer graphics?
  - Imaging = *representing 2D images*
  - Modeling = *representing 3D objects*
  - Rendering = *constructing 2D images from 3D models*
  - Animation = *simulating changes over time*



Syllabus

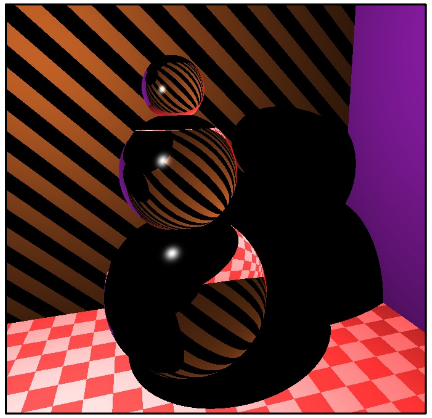
I. Imaging

II. Modeling

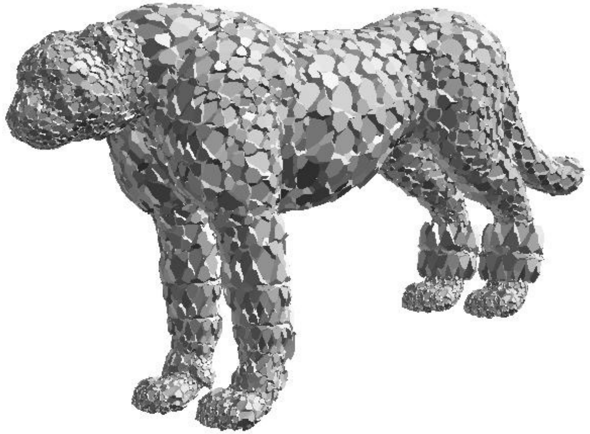
III. Rendering

IV. Animation

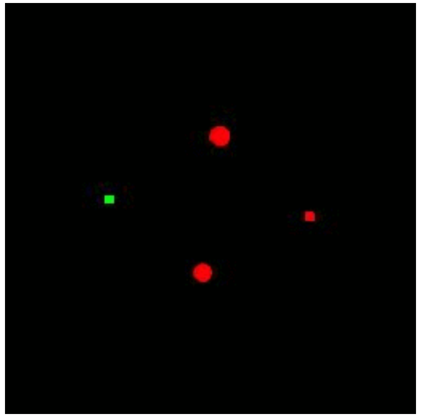
Image Processing
(Rusty Coleman, CS426, Fall99)



Rendering
(David Paulk, CS426, Spr2015)



Modeling
(Andrew Werner, Spring 2014)



Animation
(Riley Thomasson, Spring 2014)

Part I: Imaging

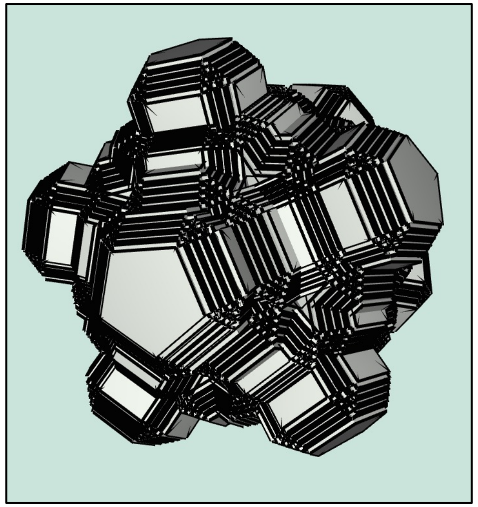
- Image Basics
  - Definition
  - Color models
- Image Representation
  - Sampling
  - Reconstruction
  - Quantization & Aliasing
- Image Processing
  - Filtering
  - Warping
  - Composition
  - Morphing

Image Composition
(Michael Bostock, CS426, Fall99)

Image Morphing
(Reilly Bova, CS426 Fall 2018)

Part II: Modeling

- Representations of geometry
  - Curves: splines
  - Surfaces: meshes, splines, subdivision
  - Solids: voxels, CSG, BSP
- Procedural modeling
  - Sweeps
  - Fractals
  - Grammars



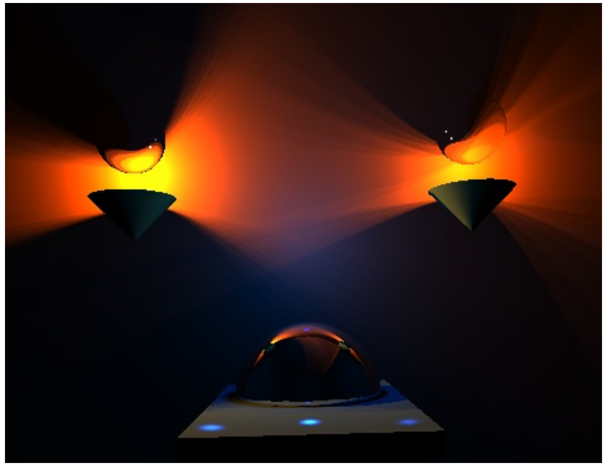
(John Whelchel,
CS 426, Spr2015)

(Brendan Chou, Spring 2014)

Part III: Rendering

- 3D Rendering Pipeline
  - Modeling transformations
  - Viewing transformations
  - Hidden surface removal
  - Illumination, shading, and textures
  - Scan conversion, clipping
  - Hierarchical scene graphics
  - OpenGL
- Global illumination
  - Ray tracing
  - Radiosity

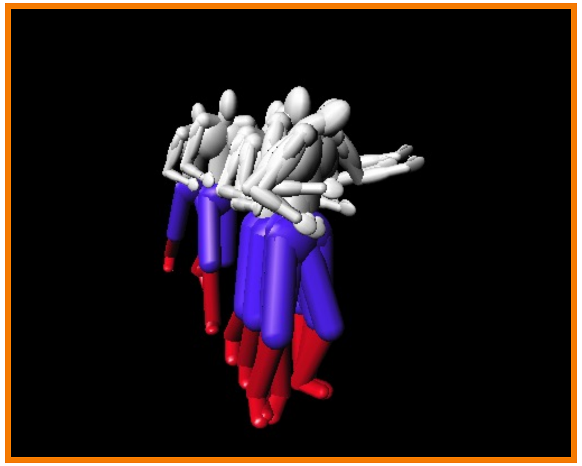
Pixel Shading
(Final Fantasy, Square Pictures)



Global Illumination
(Diana Liao, CS 426, Spr15)

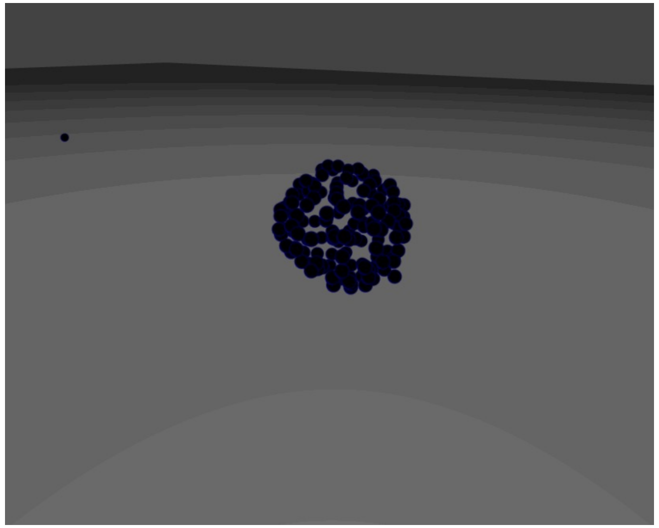
Part IV: Animation

- Keyframing
  - Kinematics
  - Articulated figures
- Motion capture
  - Capture
  - Warping
- Dynamics
  - Physically-based simulations
  - Particle systems
- Behaviors
  - Planning, learning, etc.



Dancing Guy
(Jon Beyer, CS426, Spr05)

Particle system
(Drew Wallace, Spring 2015)



Applications

- **Entertainment**
- Computer-aided design
- Scientific visualization
- Training
- Education
- E-commerce
- Computer art

Geri's Game
(Pixar Animation Studios)

Applications

- Entertainment
- **Computer-aided design**
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- Training
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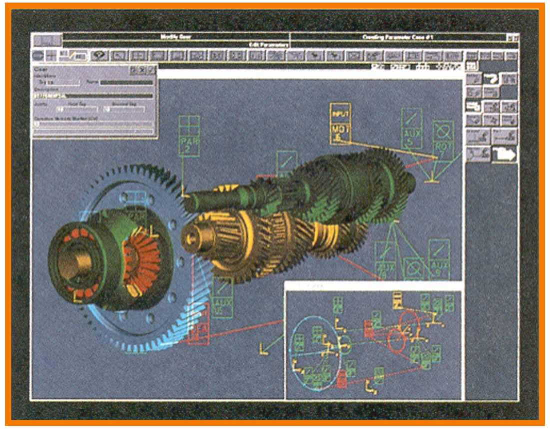
Los Angeles Airport
(Bill Jepson, UCLA)



Gear Shaft Design
(Intergraph Corporation)

Boeing 777 Airplane
(Boeing Corporation)

Applications

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- **Scientific visualization**
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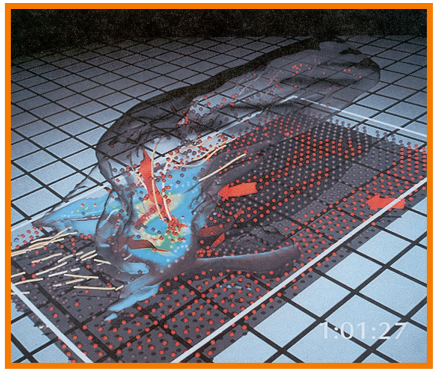
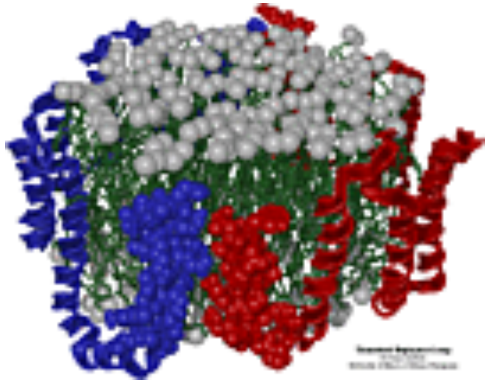
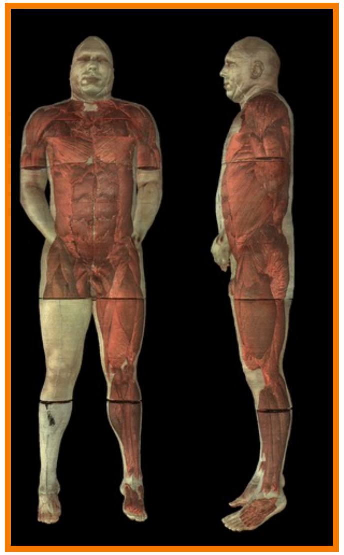


Airflow Inside a Thunderstorm
(Bob Wilhelmson,
University of Illinois at Urbana-Champaign)



Apo A-1
(Theoretical Biophysics Group,
University of Illinois at Urbana-Champaign)



Visible Human
(National Library of Medicine)

Applications

- Entertainment
- Computer-aided design
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- **Training**
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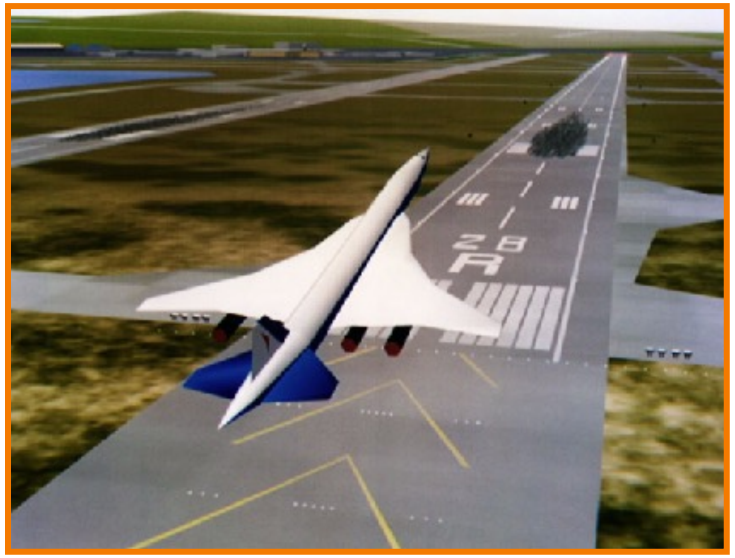
- Computer art



Early Flight Simulation
(NASA)

Applications

- Entertainment
- Computer-aided design
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- Training
- **Education**
- E-commerce
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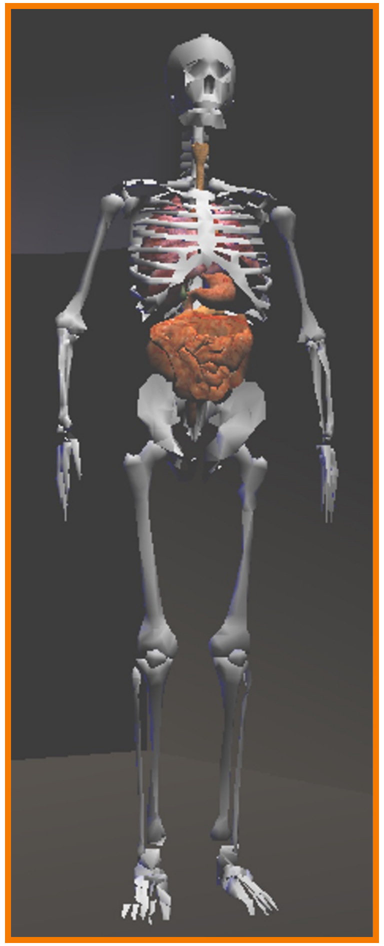
Forum of Trajan
(Bill Jepson, UCLA)



Human Skeleton
(SGI)

Applications

- Entertainment
- Computer-aided design
- Scientific visualization
- Training
- Education
- **E-commerce**
- Computer art

Virtual Stores
(Matterport)

Applications

- Entertainment
- Computer-aided design
- Scientific visualization
- Training
- Education
- E-commerce
- **Computer art**

Blair Arch
(Marissa Range '98)

Overview

- Administrative stuff
  - People, times, places, etc.
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  - What will I learn in this course?

➢ Imaging
  - Let’s get started … (Yes, this WILL be on the exam!)

What is an Image?

What is an Image?

- An image is a 2D rectilinear array of pixels

Digital image

What is a Pixel?

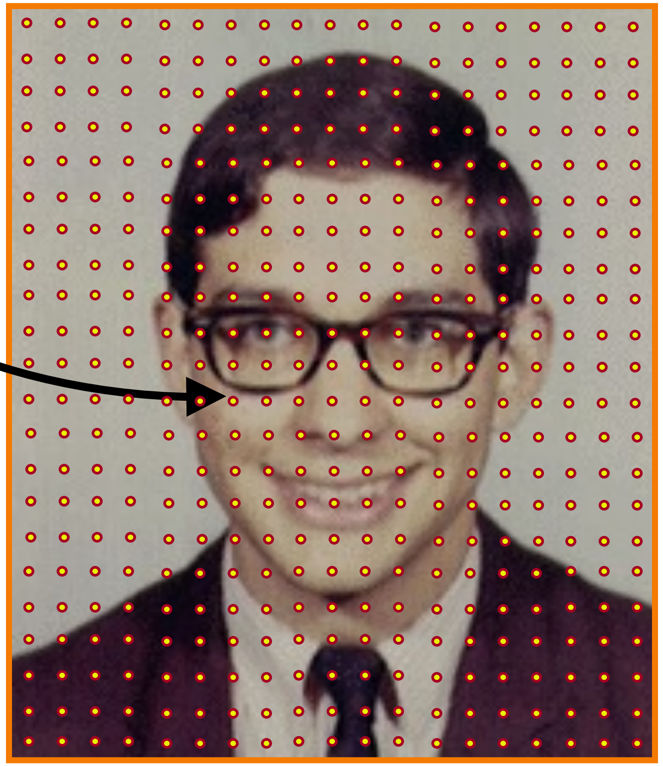
Pixel

Digital image

What is a Pixel?

- **Sample** of a function at a position

I(x,y)



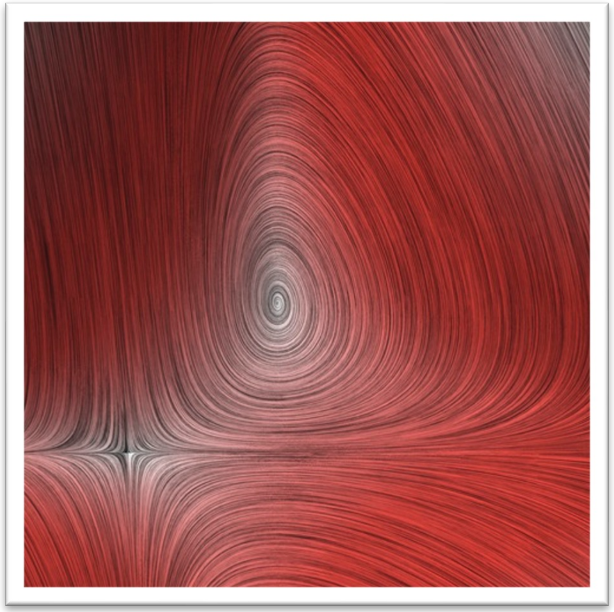
Digital image

What Function?

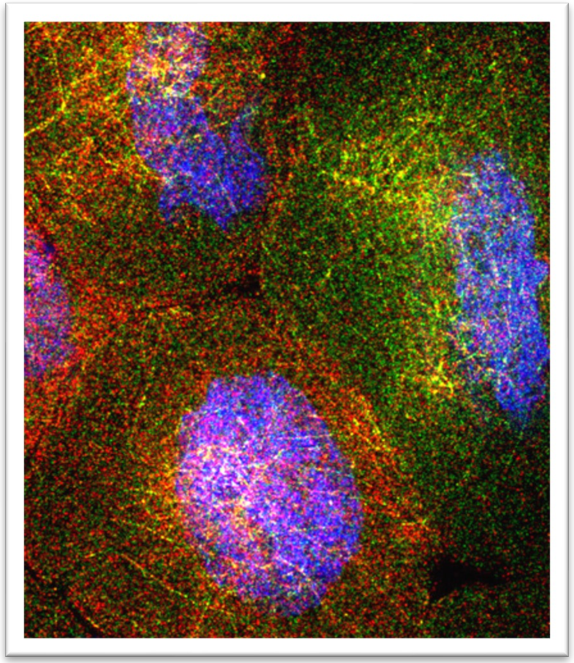
What Function?

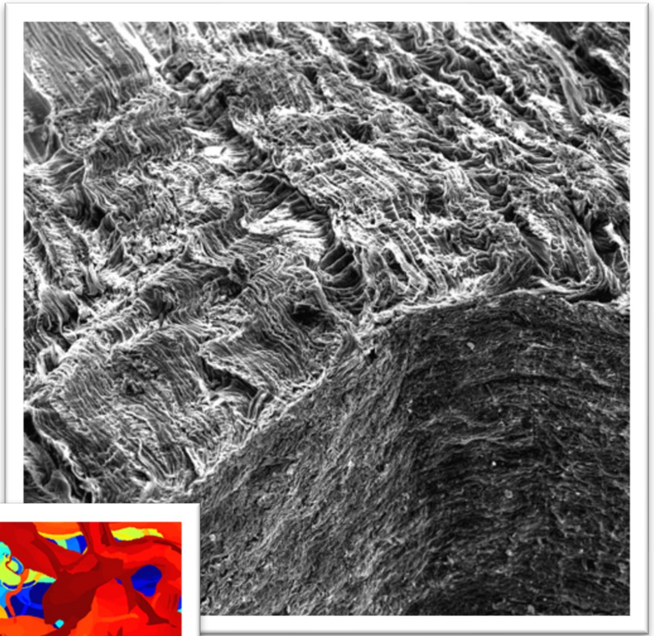
- Could be any function …

Shawn C. Little
Kristina S. Sinsimer
Elizabeth R. Gavis

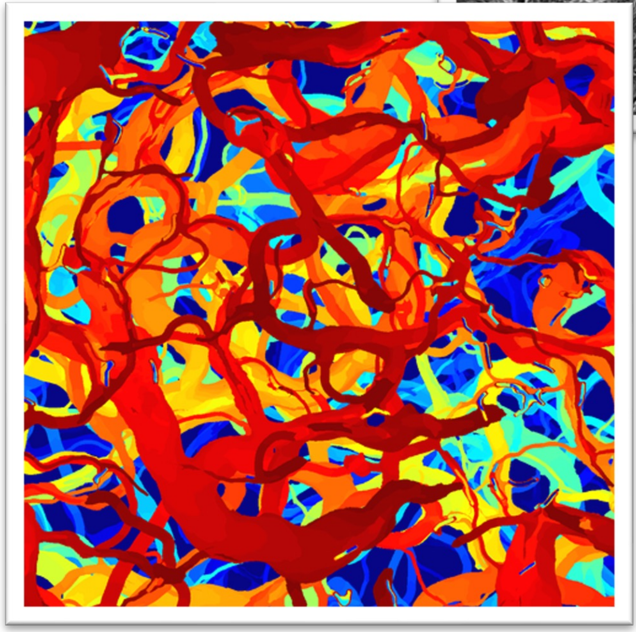


Mitchell A. Nahmias
Paul R. Prucnal





Michael
Kosk



Mingzhai Sun
Joshua Shaevitz

Art of Science
(Friend Center hallway)

What Function?

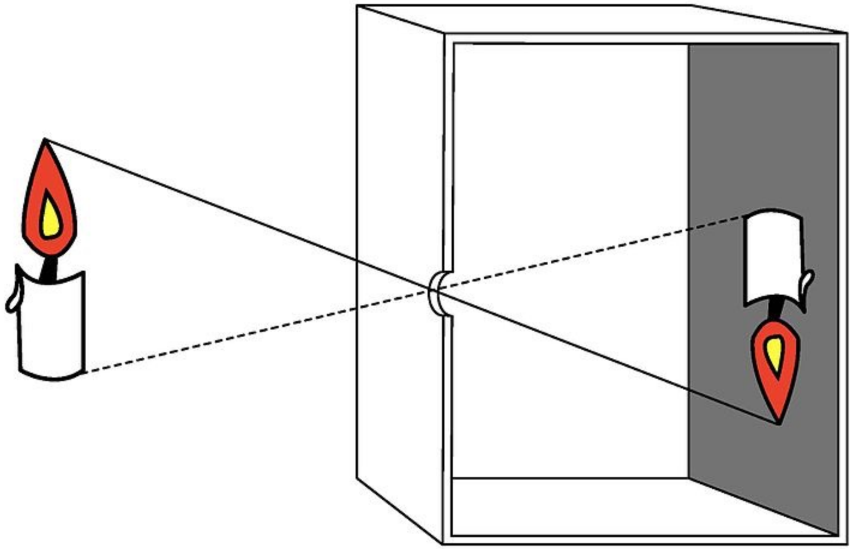
- What about photographic images?

I(x,y)?

Digital photograph

Plenoptic Function

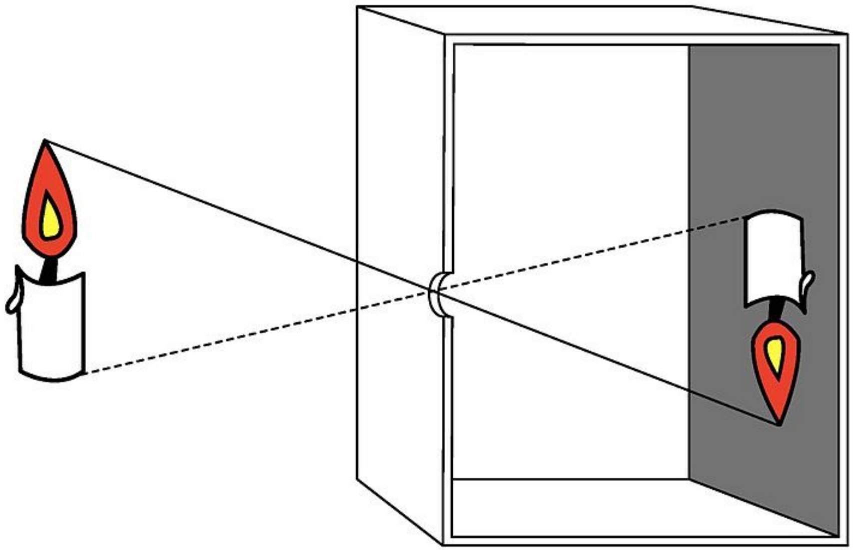
- Each pixel of a photographic image is a function of *radiance* arriving at a sensor



Carlo Benini

Plenoptic Function

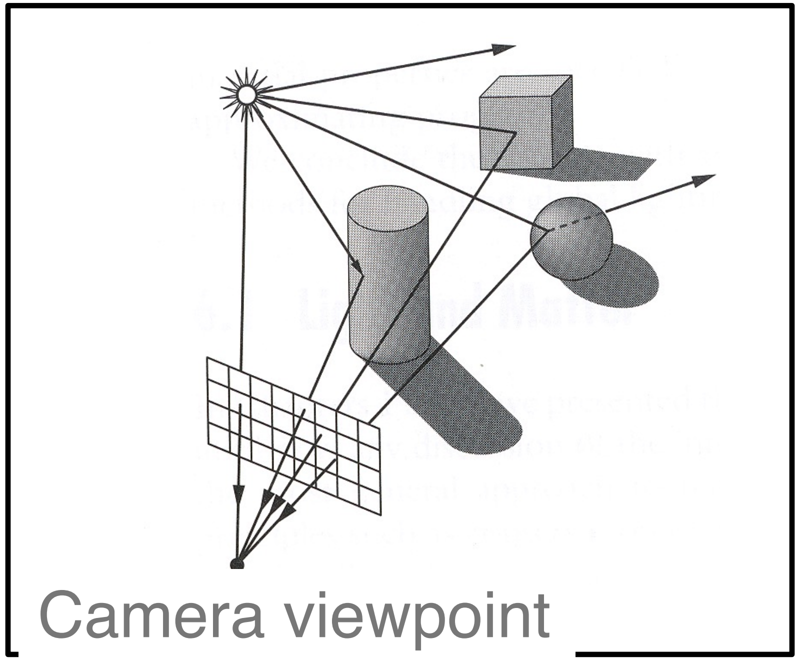
- The 7D plenoptic function $L(x,y,z,\theta,\phi,t,\lambda)$ describes the radiance arriving …
  - at any position (x,y,z),
  - in any direction (θ,ϕ),
  - at any time (t),
  - at any frequency (λ)



Carlo Benini

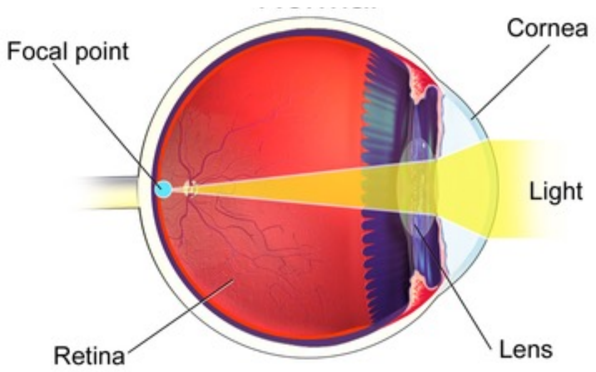
Photographic Images

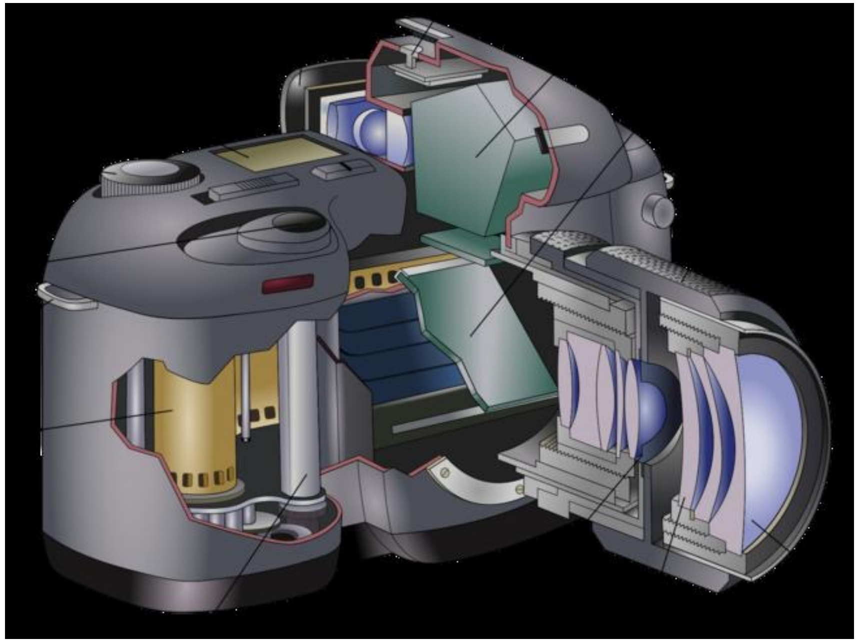
- An idealized photographic image contains a 2D array of samples of the 7D plenoptic function
  - at a particular camera viewpoint,
  - for a 2D array of directions,
  - at a certain time,
  - at certain frequencies

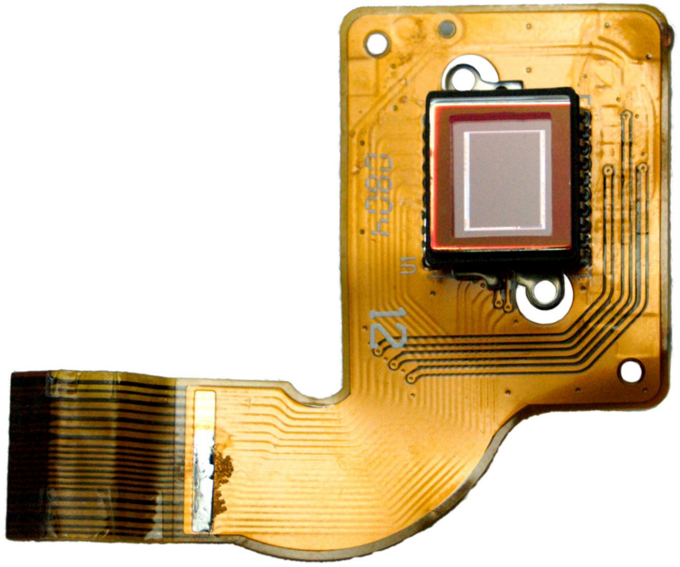


Photographic Images

- In practice, can't measure plenoptic function directly
  - Photoreceptors in eye
  - Film in a traditional camera
  - CCD cells in digital camera







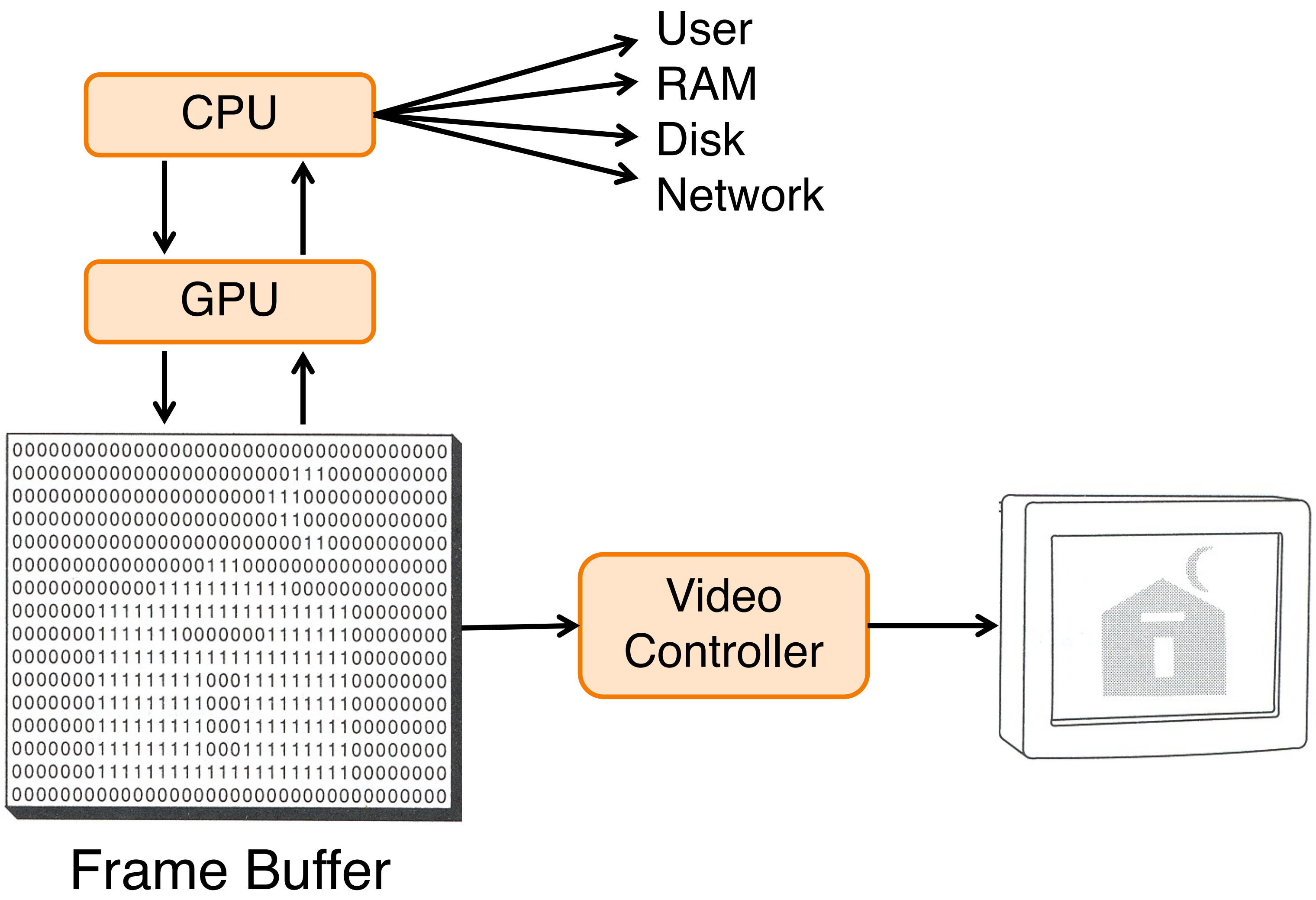
Photographic Images

- Photographic pixels as finite samples of the plenoptic function

$f(x,y,z,\theta,\phi,t,\lambda)$

Digital photograph

How Are Digital Images Stored?



Based on Figure 1.2 from FvDFH

Frame Buffer Limits: Resolution

- Spatial resolution
  - Image has only “Width” x “Height” pixels
- Intensity resolution
  - Each pixel has only “Depth” bits for colors / intensities
- Temporal resolution
  - Screen refreshes images at only “Rate” Hz

Typical Resolutions

	Width x Height	Depth	Rate
Cheap laptop	1366 x 768	24	60
High-end laptop	2560 x 1600	24	60
TV	1920 x 1080	16-ish	60 (interleaved)
Film	3000 x 2000	36	24
Printer	5100 x 6600	1-4	-

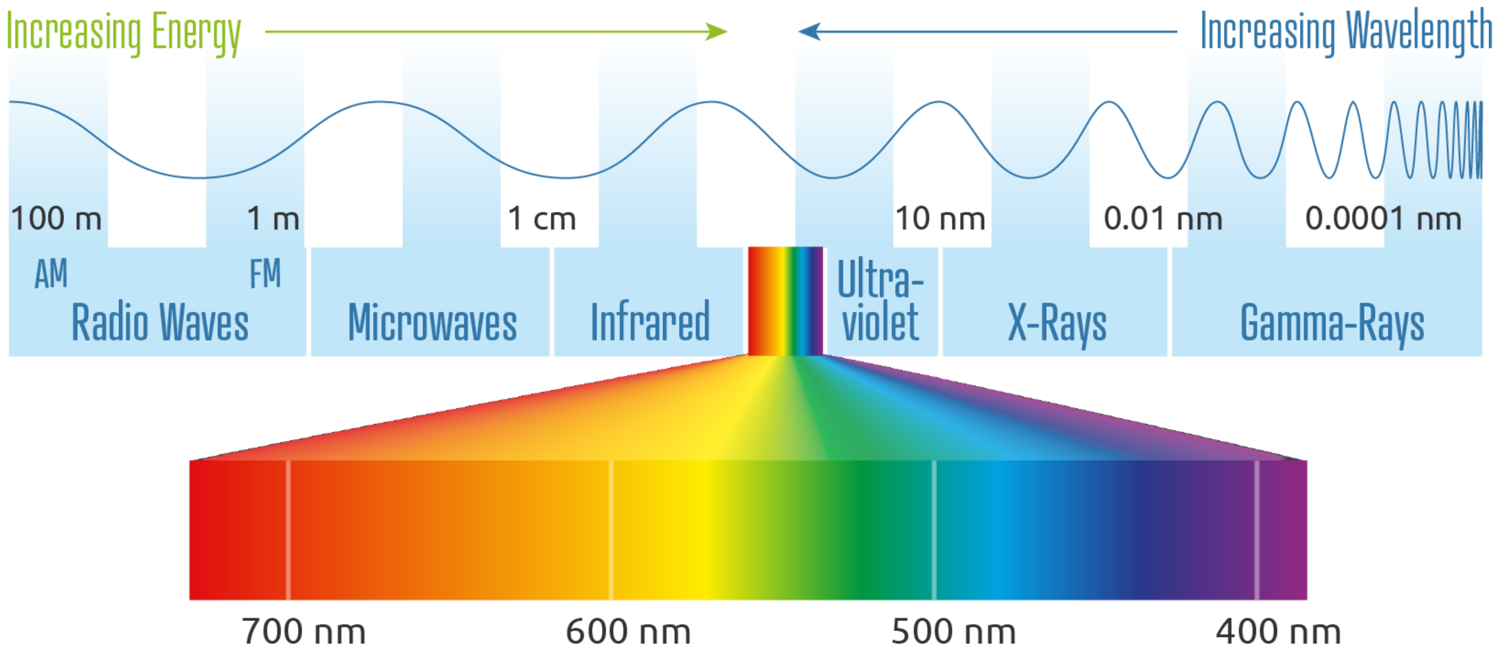
What Frequencies / Wavelengths?

$f(x,y,z,\theta,\phi,t,\lambda)$

Corresponding frequency is: $\dfrac{c}{\lambda}$

Electromagnetic Spectrum

- Visible light frequencies range between ...
  - Red = 4.3×10^{14} hertz (700nm)
  - Violet = 7.5×10^{14} hertz (400nm)



Figures 15.1 from H&B

Electromagnetic Spectrum

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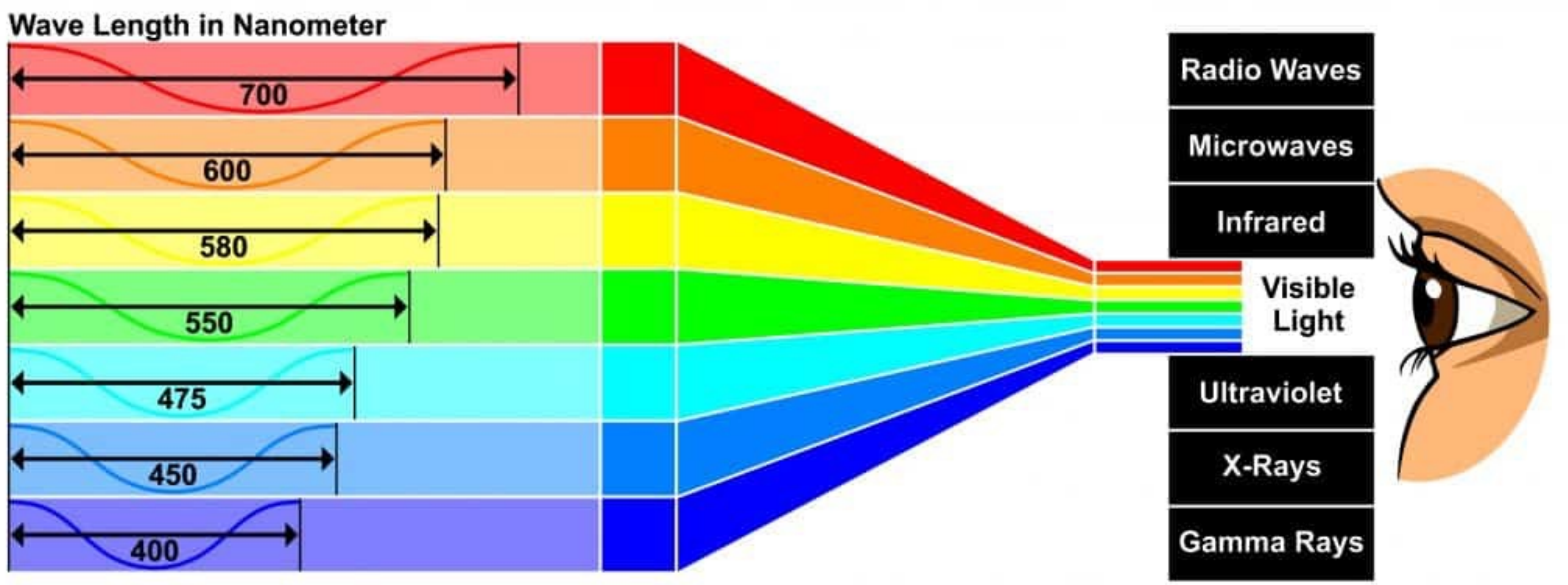
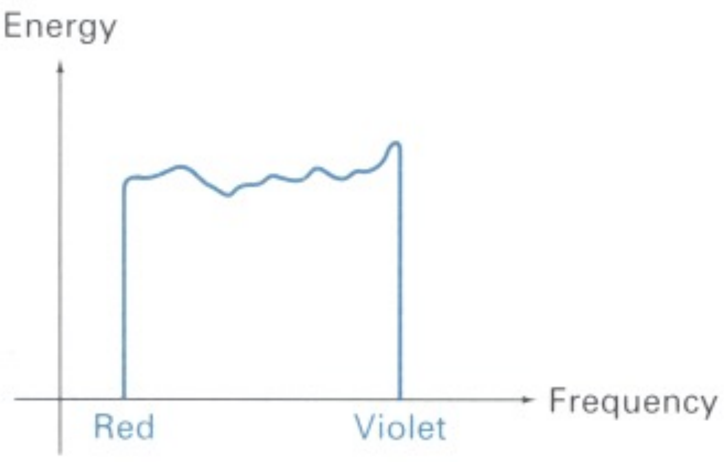


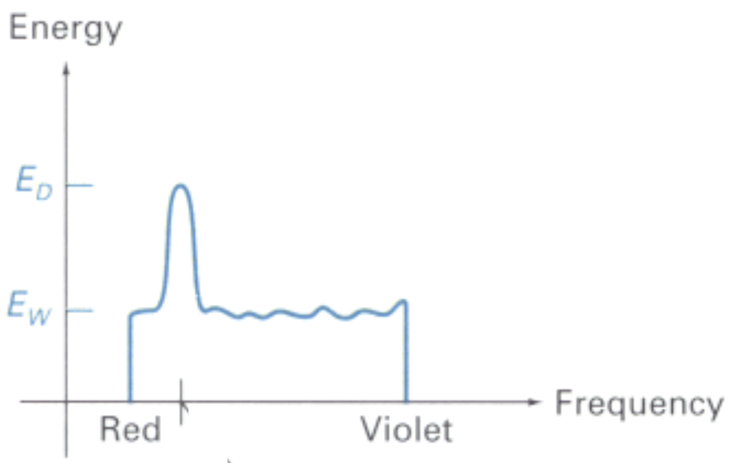
Figures 15.1 from H&B

Color

- The color of light is characterized by its **spectrum**
  - Magnitude of energy at every visible frequency



White Light

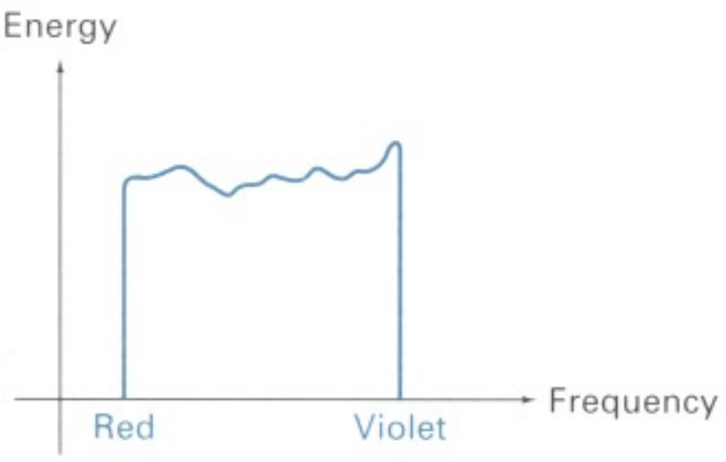


Orange Light

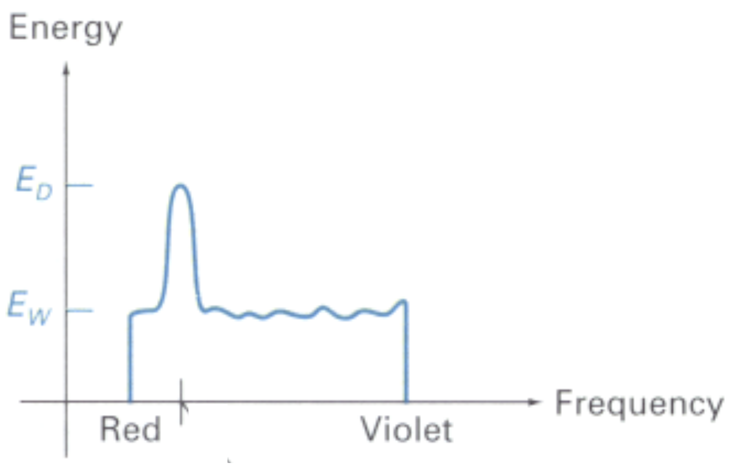
Figures 15.3-4 from H&B

Color

- How do we represent a color in a computer?
  - Must store a finite amount of data to represent magnitudes for infinite number of frequencies



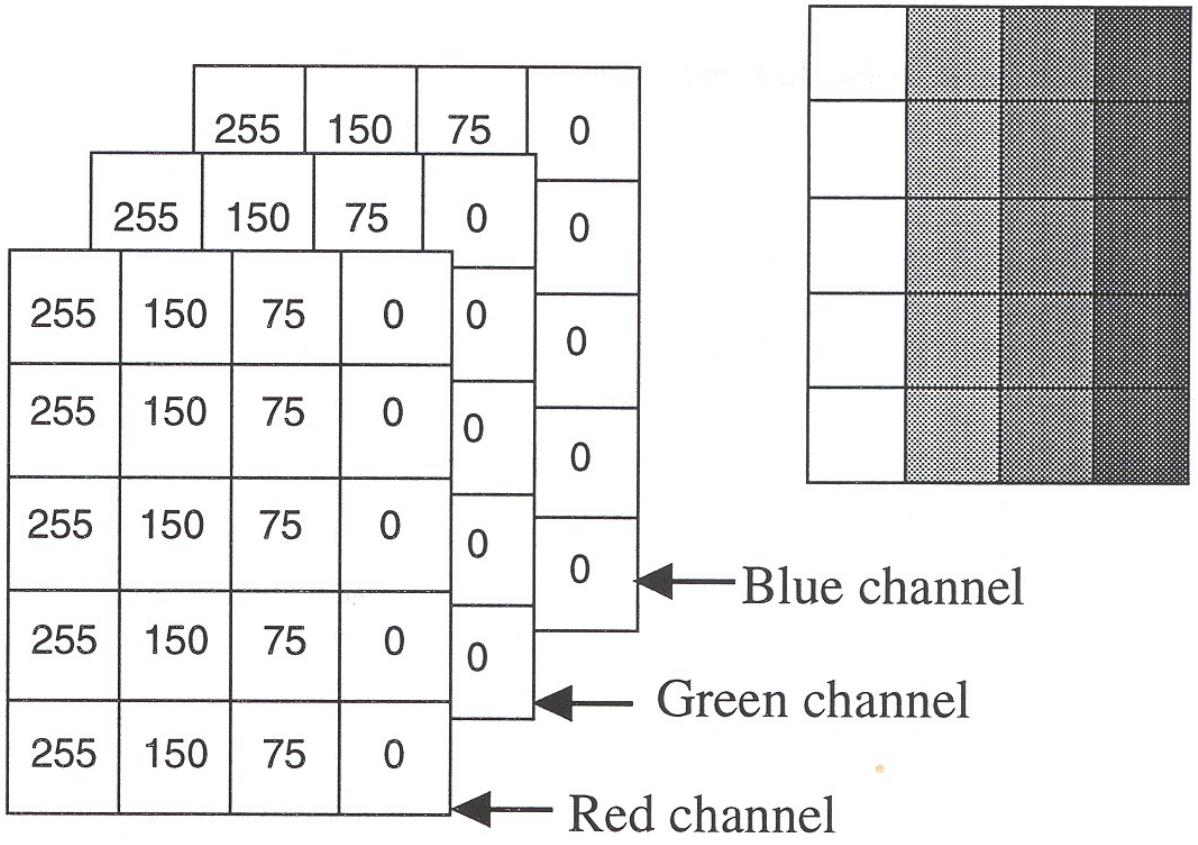
White Light



Orange Light

Figures 15.3-4 from H&B

Color Frame Buffer

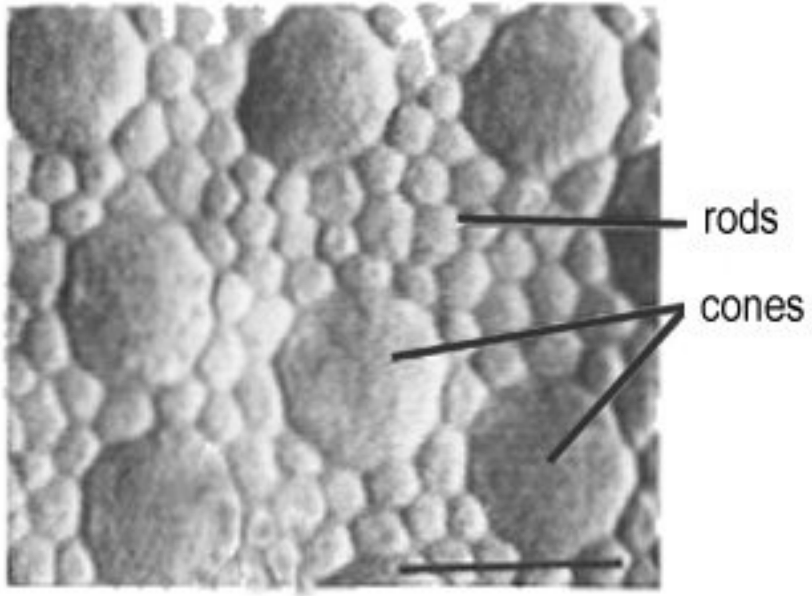


Color

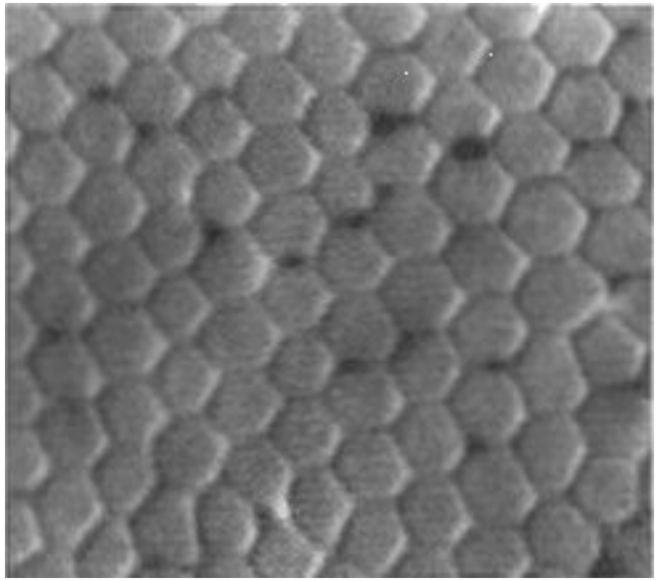
Why red, green, and blue (RGB)?

Modern Understanding of Color

- Two types of receptors: rods and cones



Rods and cones



Cones in *fovea*
(central part of retina)

Human Color Perception

- Spectral-response functions of each of the three types of cones on the human retina

- Tristimulus theory of color

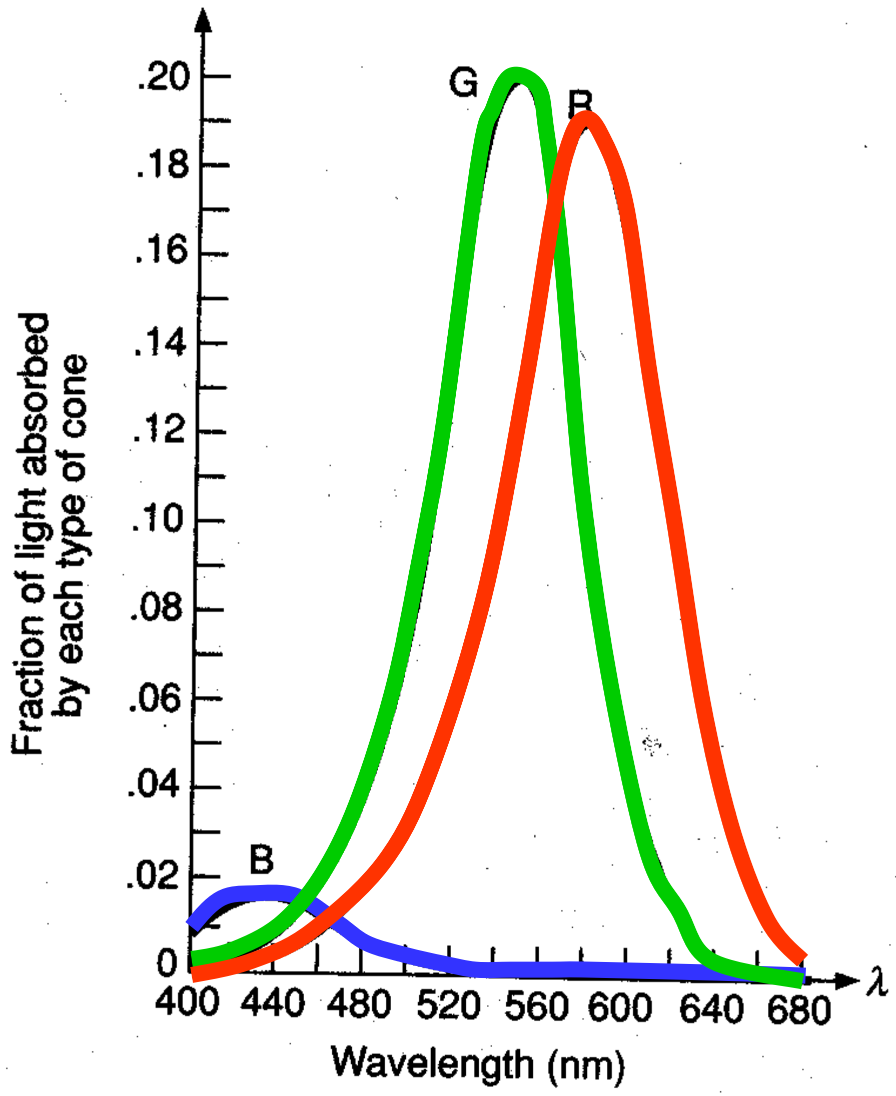
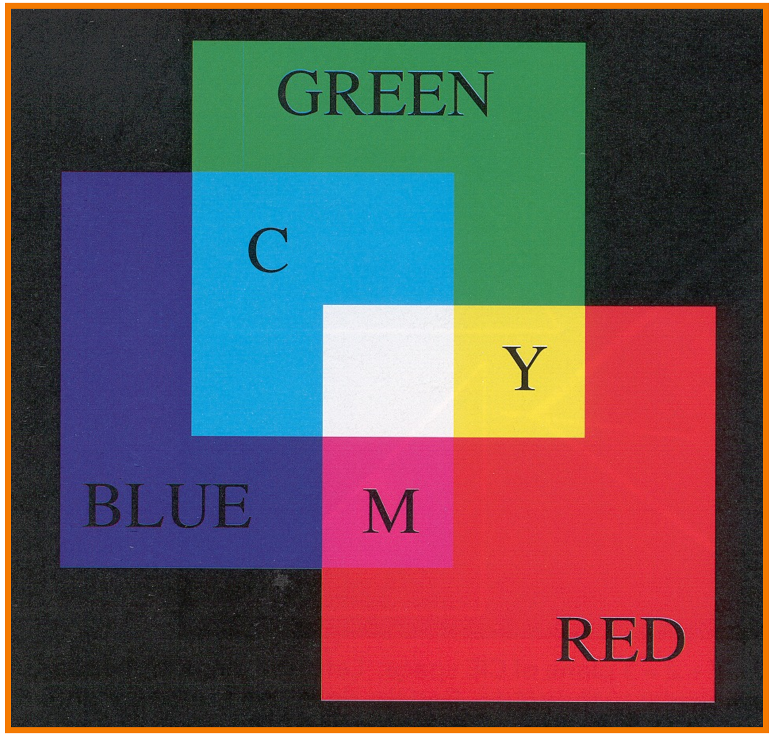


Figure 13.18 from FvDFH

RGB Color Model

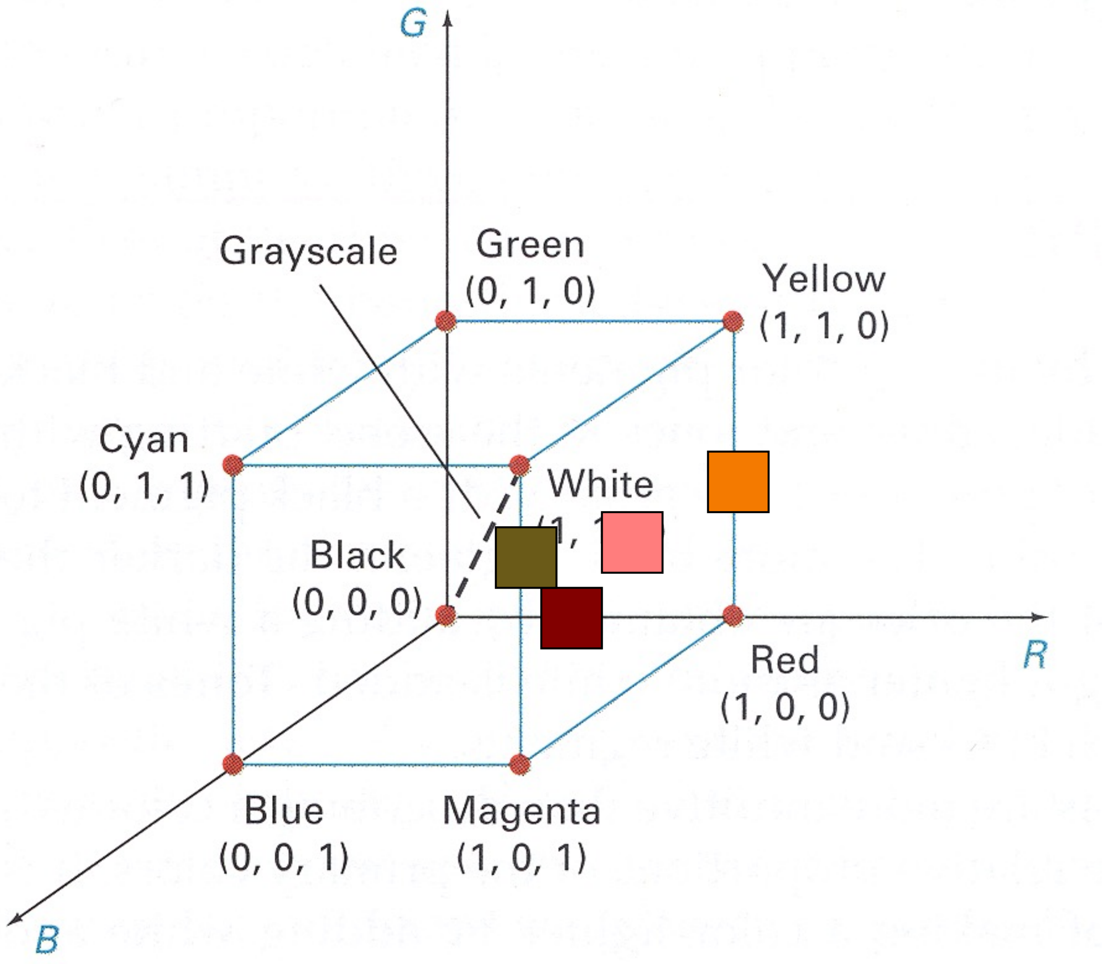


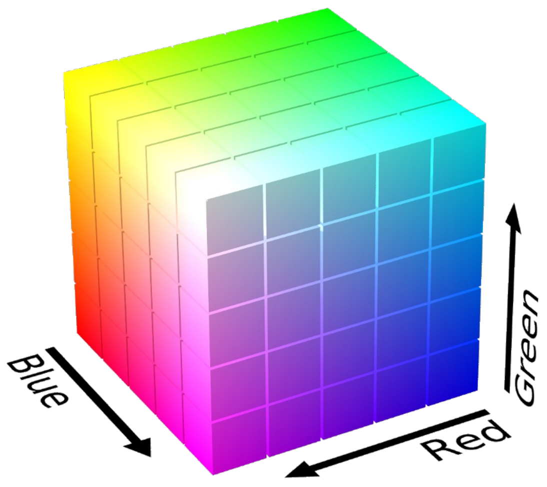
Colors are additive

R	G	B	Color
0.0	0.0	0.0	Black
1.0	0.0	0.0	Red
0.0	1.0	0.0	Green
0.0	0.0	1.0	Blue
1.0	1.0	0.0	Yellow
1.0	0.0	1.0	Magenta
0.0	1.0	1.0	Cyan
1.0	1.0	1.0	White
0.5	0.0	0.0	
1.0	0.5	0.5	
1.0	0.5	0.0	
0.5	0.3	0.1	

Plate II.3 from FvDFH

RGB Color Cube





H&B

RGB Spectral Colors

- Amounts of RGB primaries needed to display spectral colors

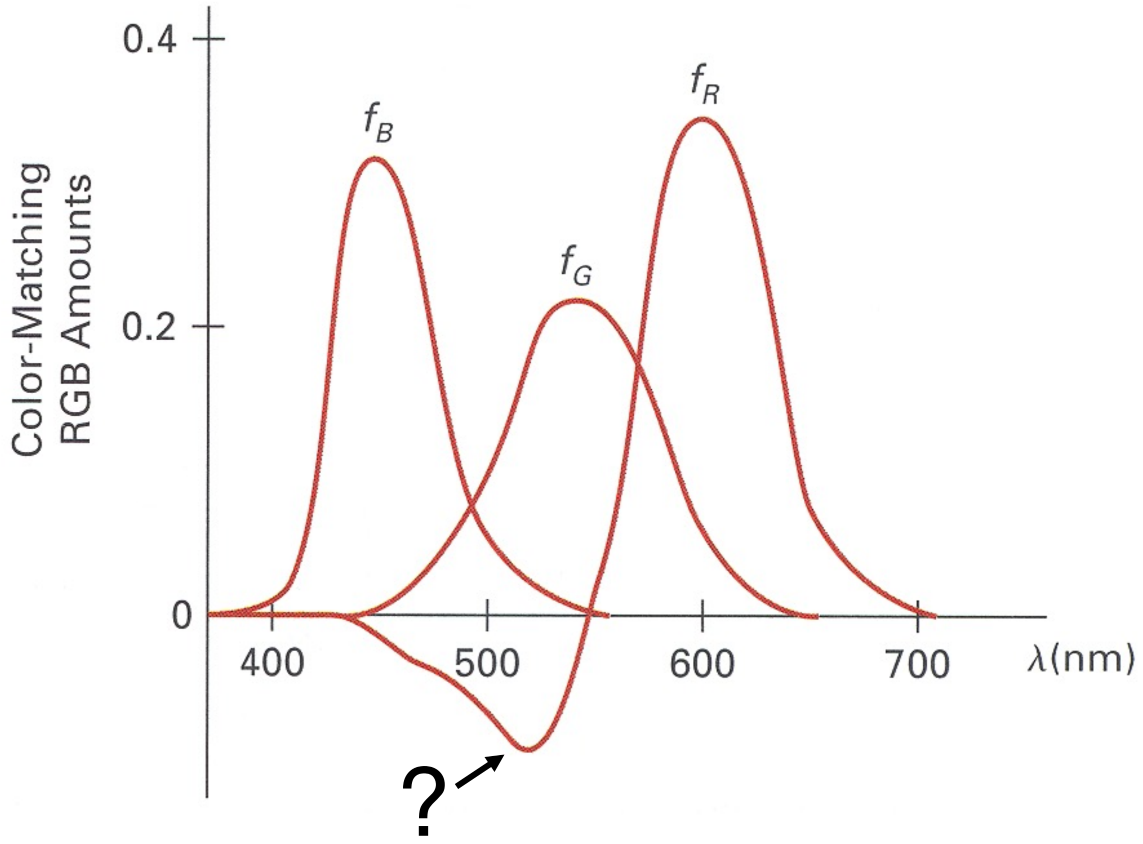


Figure 15.5 from H&B

XYZ Color Model (CIE)

- Linear transform of RGB
  - All colors can be composed of non-negative amounts of XYZ

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.412452 & 0.357580 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

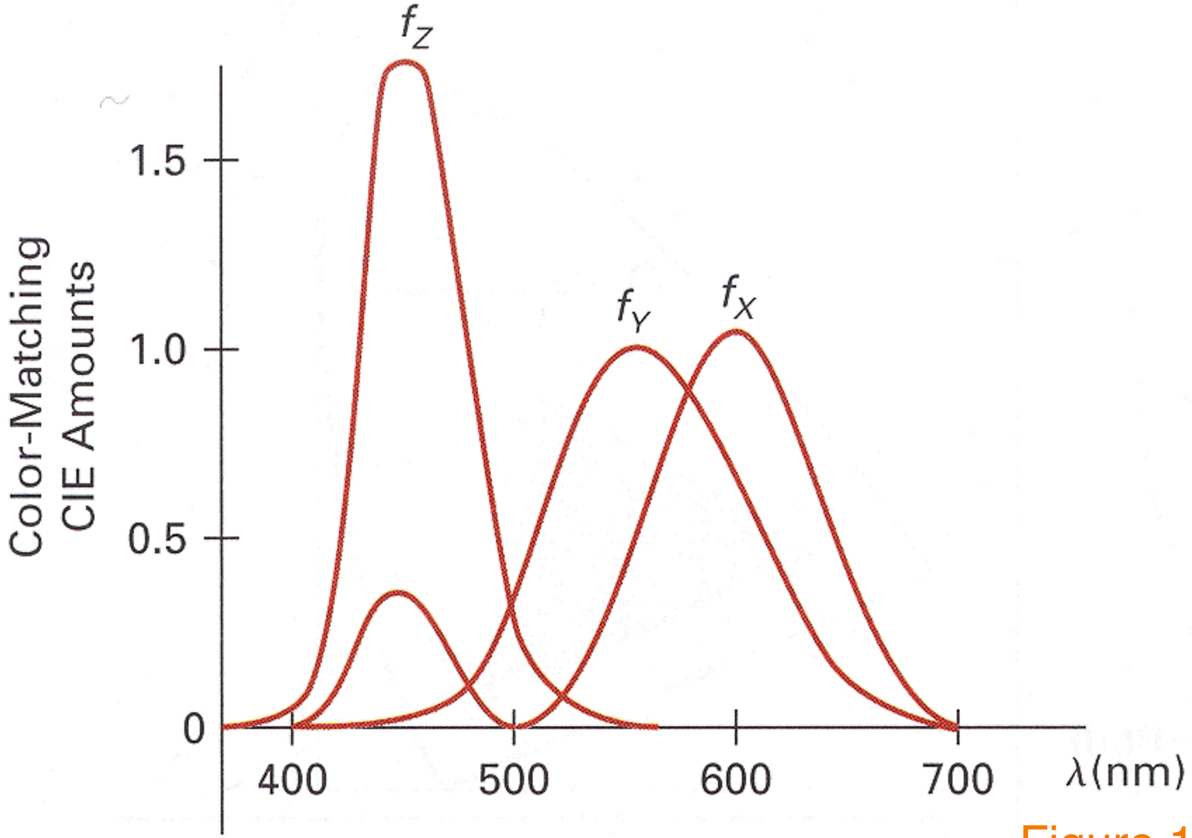
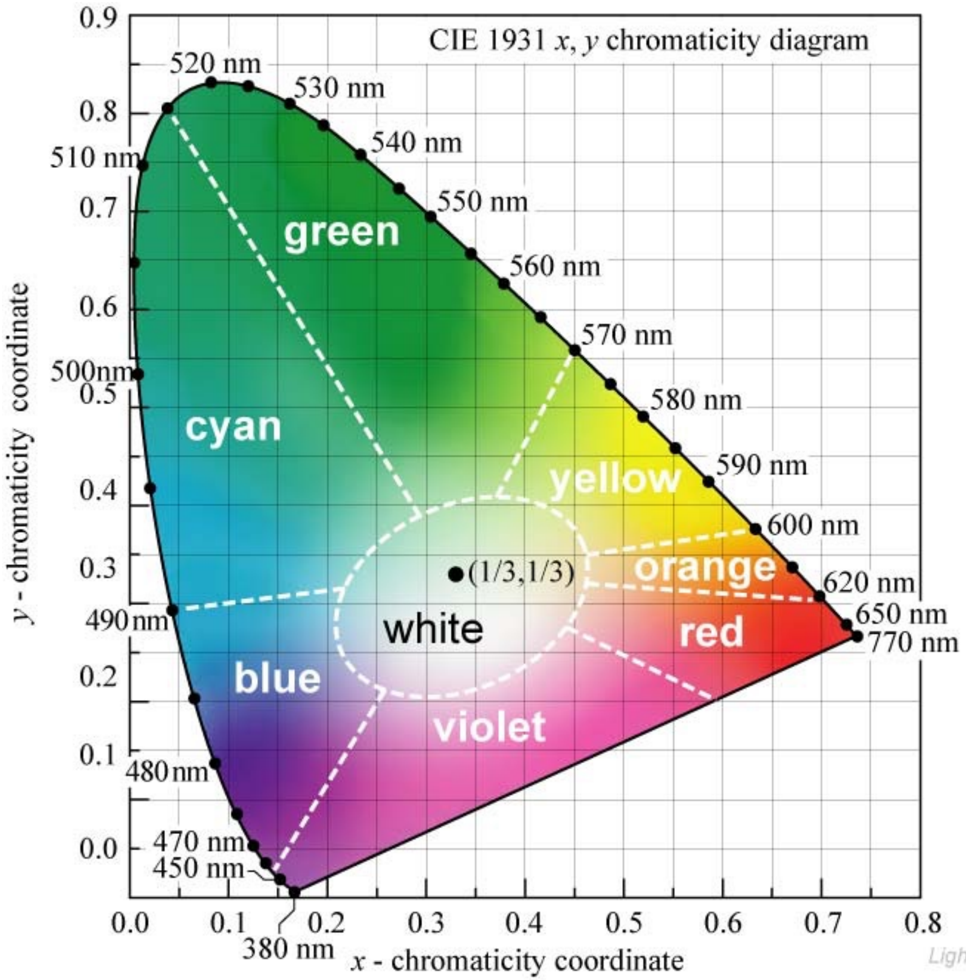


Figure 15.6 from H&B

CIE Chromaticity Diagram

- Normalized amounts of X and Y for colors in visible spectrum



chromaticity diagram. Monochromatic colors are located on the perimeter. Color saturation decreases towards the center of the diagram. White light is located in the center. Also shown are the regions of distinct colors. The equal-energy point is located at the center and has the coordinates $(x, y) = (1/3, 1/3)$.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

RGB Color Gamut

- Color gamut (range of colors) of a typical RGB computer display

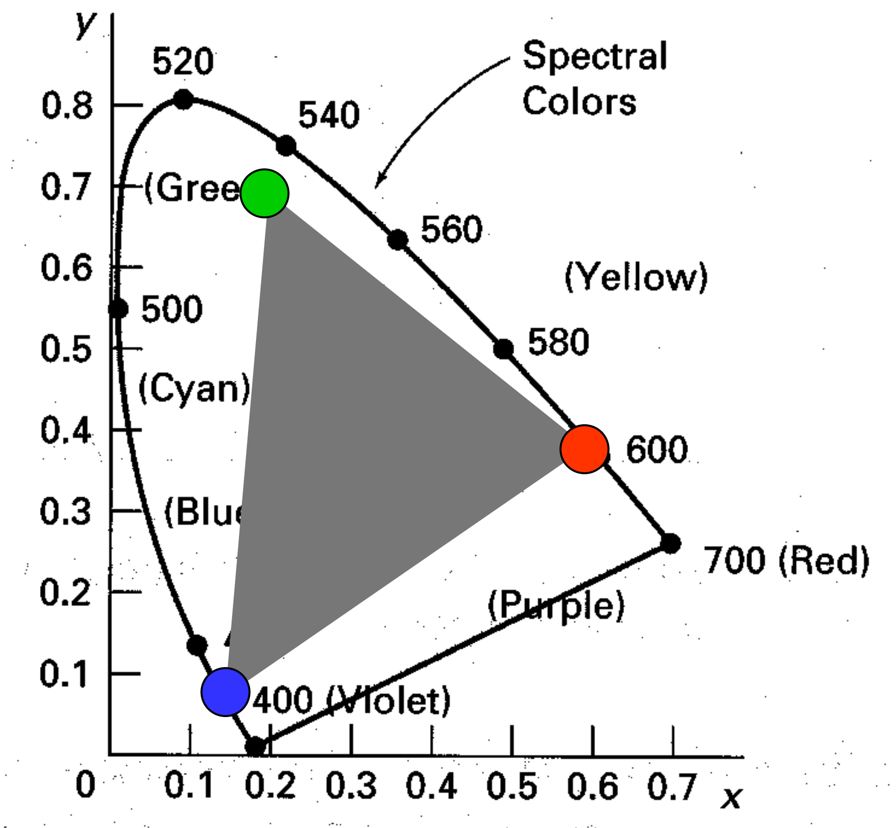


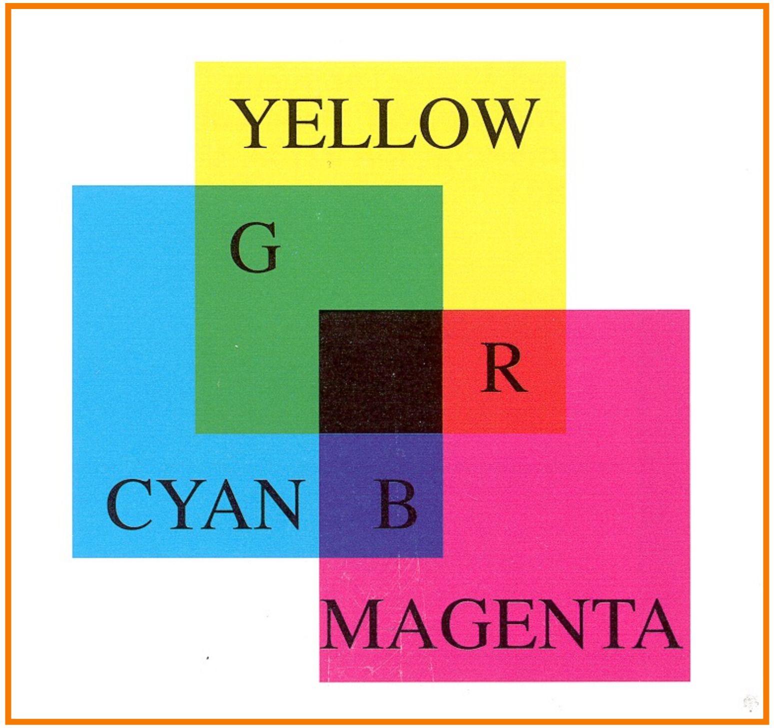
Figure 15.13 from H&B

Other Color Models

- CMY
- HSV
- CIELAB
- Others

Different color models are useful for different purposes

CMY Color Model



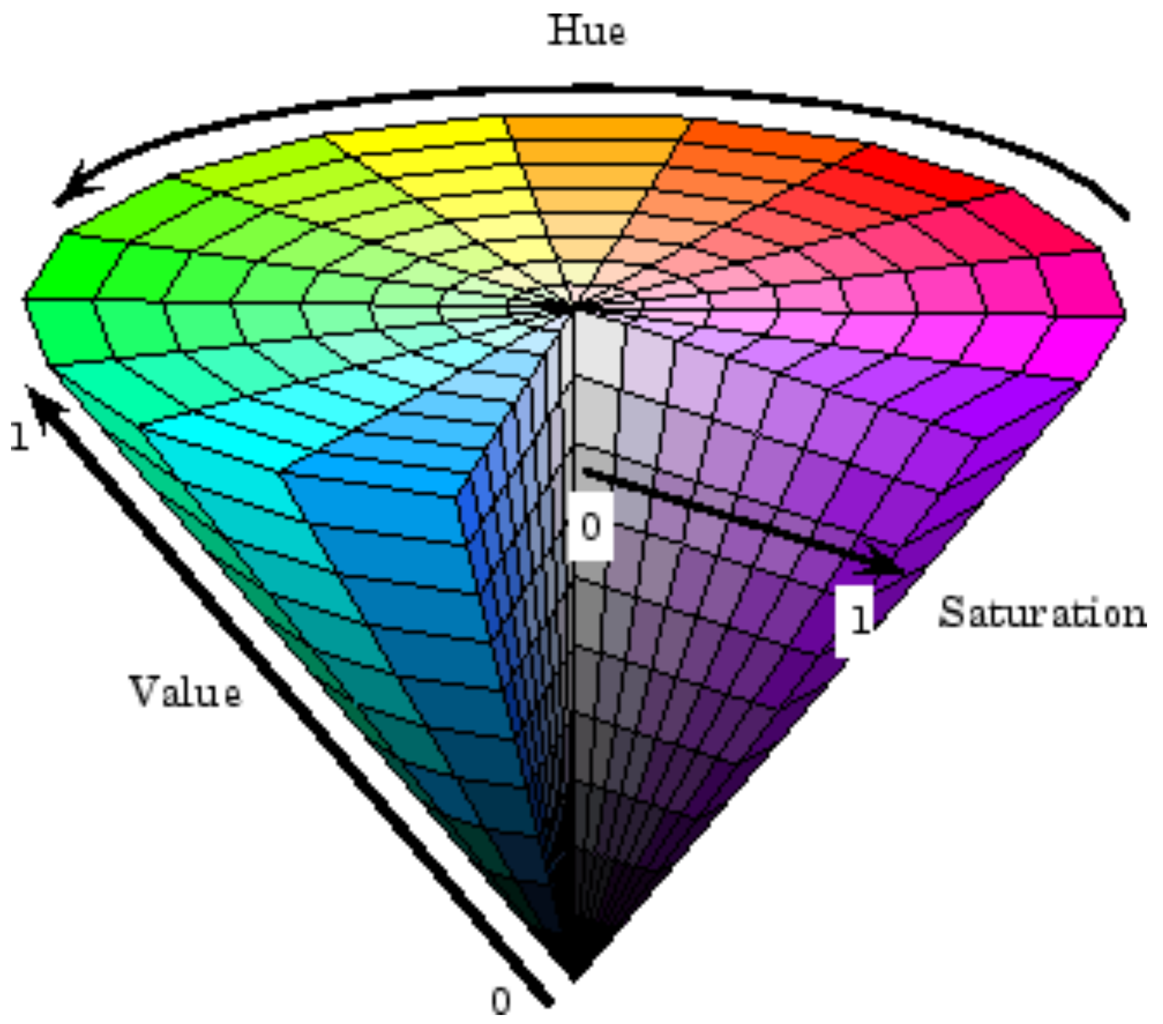
C	M	Y	Color
0.0	0.0	0.0	White
1.0	0.0	0.0	Cyan
0.0	1.0	0.0	Magenta
0.0	0.0	1.0	Yellow
1.0	1.0	0.0	Blue
1.0	0.0	1.0	Green
0.0	1.0	1.0	Red
1.0	1.0	1.0	Black
0.5	0.0	0.0	
1.0	0.5	0.5	
1.0	0.5	0.0	

- Useful for printers because colors are *subtractive*
- Add blacK ink – CMYK

Plate II.7 from FvDFH

HSV Color Model

- Intended for ease of color picking

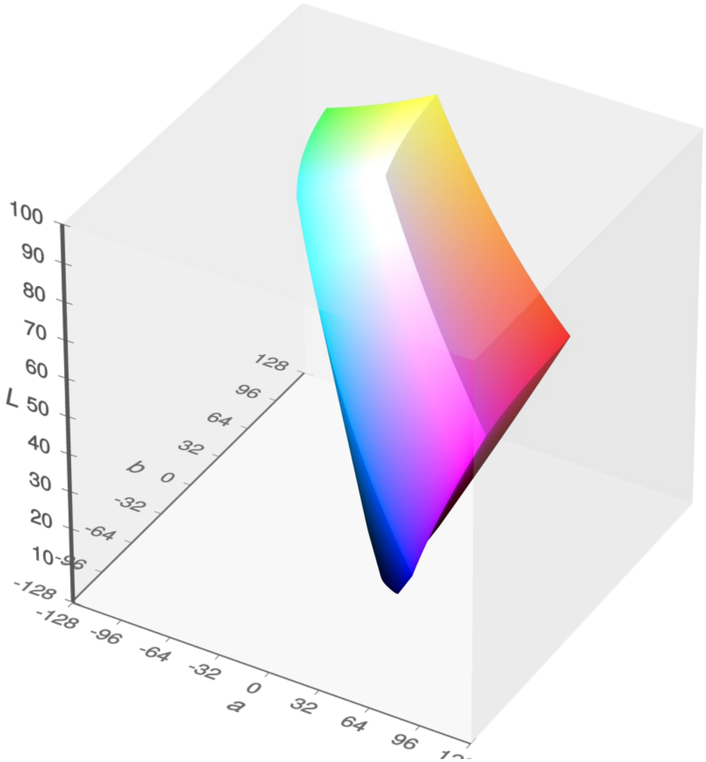


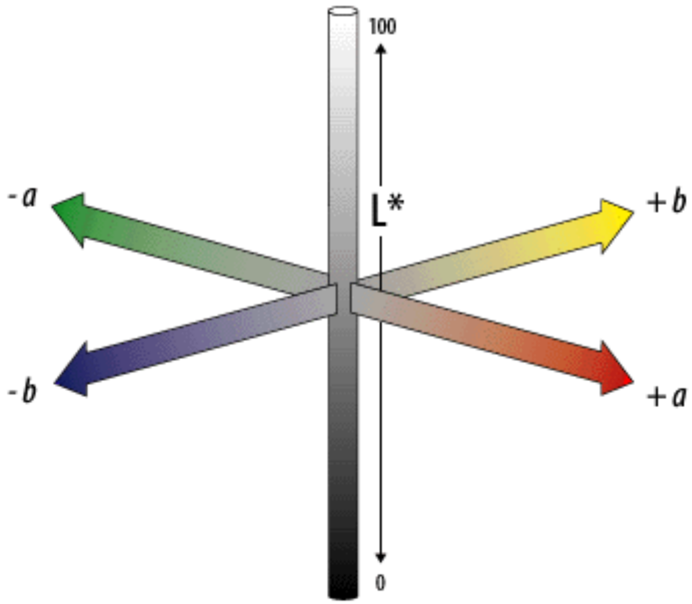
CIELAB Color Model

- Non-linear transform of XYZ based on human perception

$$L^\star = 116 f\left(\frac{Y}{Y_n}\right) - 16$$
$$a^\star = 500\left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right)$$
$$b^\star = 200\left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right)$$

$$f(t) = \begin{cases} \sqrt[3]{t} & \text{if } t > \delta^3 \\ \frac{t}{3\delta^2} + \frac{4}{29} & \text{otherwise} \end{cases}$$
$$\delta = \frac{6}{29}$$
$$X_n = 95.047, \quad Y_n = 100.000, \quad Z_n = 108.883$$





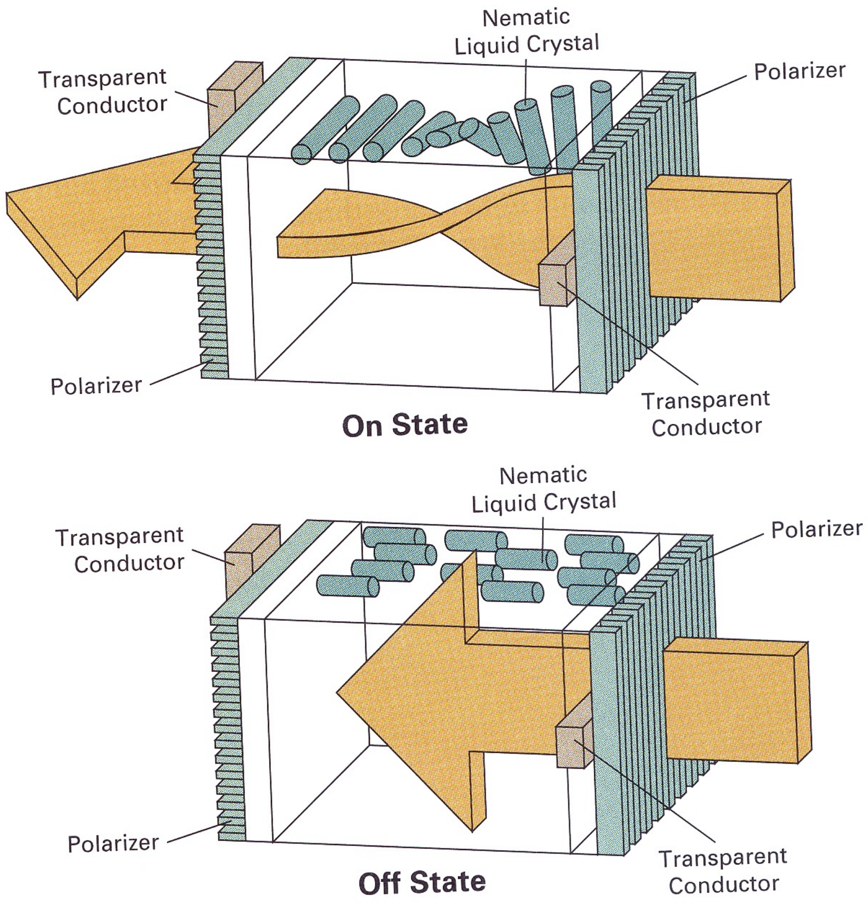
Useful for measuring perceptual differences between colors

Frame Buffer Display

- Video display devices
  - Liquid Crystal Display (LCD)
  - Thin-film electroluminescent displays
  - Light-emitting diodes (LED)
- Hard-copy devices
  - Ink-jet printer
  - Laser printer
  - Film recorder
  - Electrostatic printer
  - Pen plotter

Frame Buffer Display

- Example: liquid crystal display (LCD)



Polarization
:

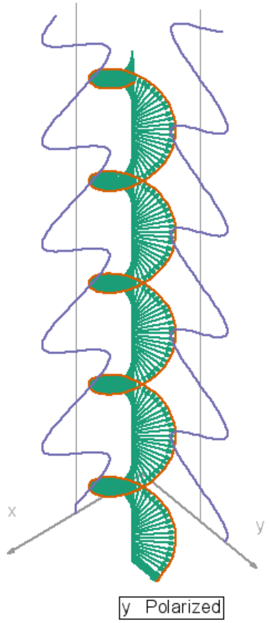
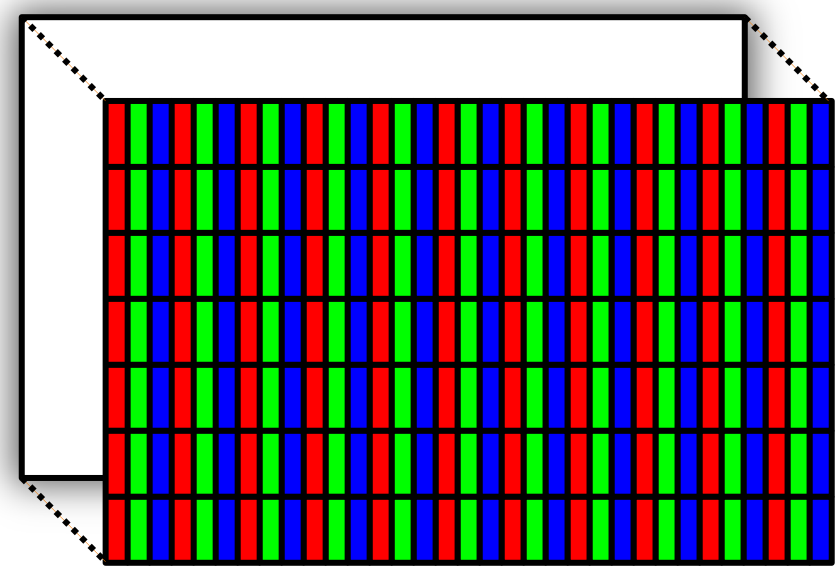


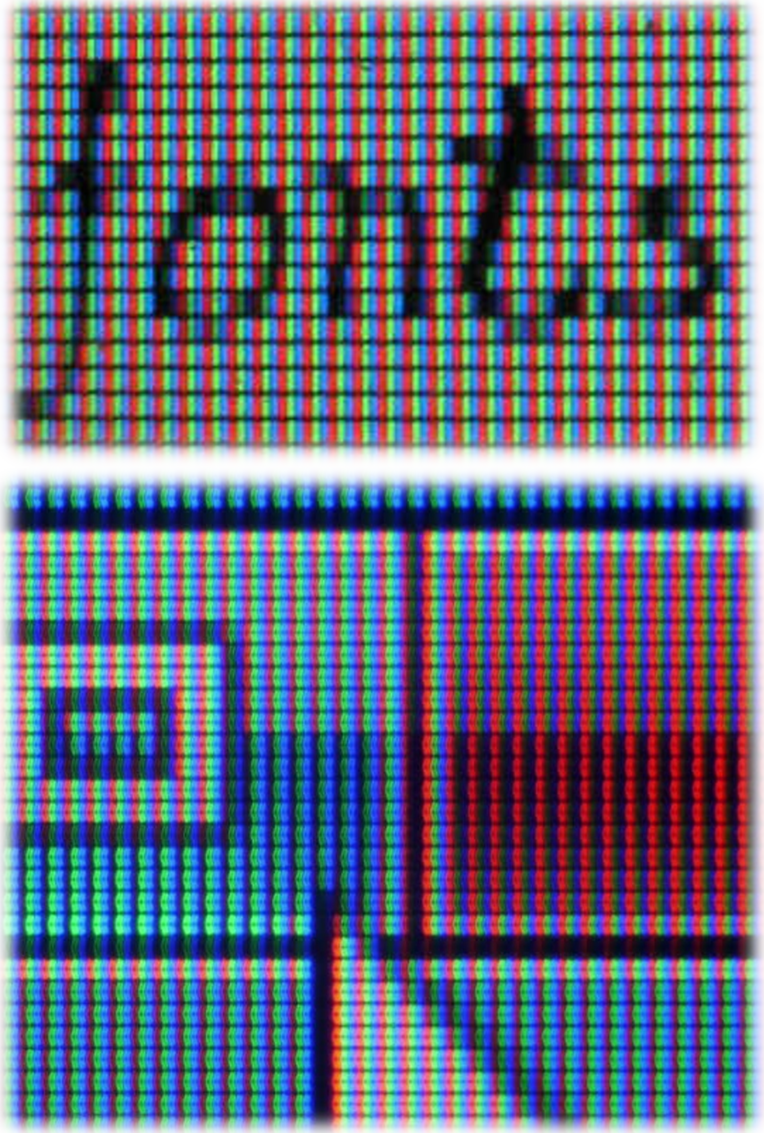
Figure 2.16 from H&B

Frame Buffer Display

- LCD up close



- Pixels with finite area (rectangles)
- Colors are interleaved



Summary

- Images
  - Pixels are samples
  - Photographs sample plenoptic function
- Colors
  - Tristimulus theory of color
  - Different color models for different devices, uses, etc.
  - RGB model is common due to human perception
  - CIE Chromaticity Diagram
- Next time
  - Image processing!