Computer Graphics

Felix Heide

Princeton University

COS 426, Spring 2021

Overview

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

Administrative Stuff

- Instructors
  - Prof: Felix Heide
  - TAs: Darby Haller, Ethan Tseng, Zheng Shi
  - Lab TAs: Catherine Yu, Joanna Kuo, Julian Knodt, Sahan Paliskara
- Book
  - *Computer Graphics with OpenGL, 4th Ed,*
    Hearn, Baker, and Carithers,
    Prentice Hall, 2010. ISBN: 978-0136053583
- Enrollment
  - If you are not enrolled, see me after class.
- Web page
  - www.cs.princeton.edu/courses/archive/spring21/cos426/

cs.princeton.edu/courses/archive/spring21/cos426/

COS 426

OVERVIEW MATERIALS ASSIGNMENTS EXERCISES GALLERY LINKS

COS 426: Computer Graphics

Spring 2021

Syllabus

Description

Computer graphics is the intersection of computer science, geometry, physics, and art. This course will study topics in this broad and remarkable field, with an emphasis on practical methods and applications. In particular, the course will provide an extensive introduction to image processing, modeling, rendering, and computer animation. The goal of this course is to equip students with the various tools and techniques they need to build large 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 research (physics, biology, chemistry, engineering, and other disciplines), etc.

Topics include: color theory, sampling, image processing, image compositing, mesh representations, mesh processing, parametric curves and surfaces,

Contents

Coursework

- Exam (15%)
  - Virtual (March 11)
- Programming Assignments (60%)
  - Assignment #1: Image Processing
  - Assignment #2: Modeling
  - Assignment #3: Ray Tracer
  - Assignment #4: Rasterizer
  - Assignment #5: Animation
- Final Project (20%)
  - Your choice! (due Dean's Date)
- Participation (5%)

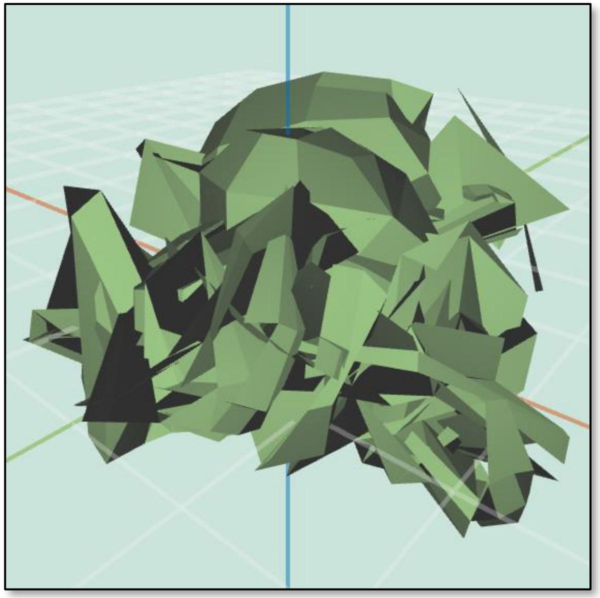
Programming Assignments

- When?
  - Roughly every 2-3 weeks
- How?
  - Javascript
  - 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

- 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

- Piazza (www.piazza.com)
  - View announcements
  - Post questions to the class
  - Answer other students questions
  - Set up for everyone enrolled as of today
  - Use this instead of email to instructors/TAs (can send private messages)

Precepts

- When and Where
  - Wed **OR** Thu 7:30-8:20
  - Attend either as you prefer – they will be equivalent
  - Over Zoom
- Attendance
  - Topics vary, so attend the ones that help you
  - This week: getting up to speed in Javascript

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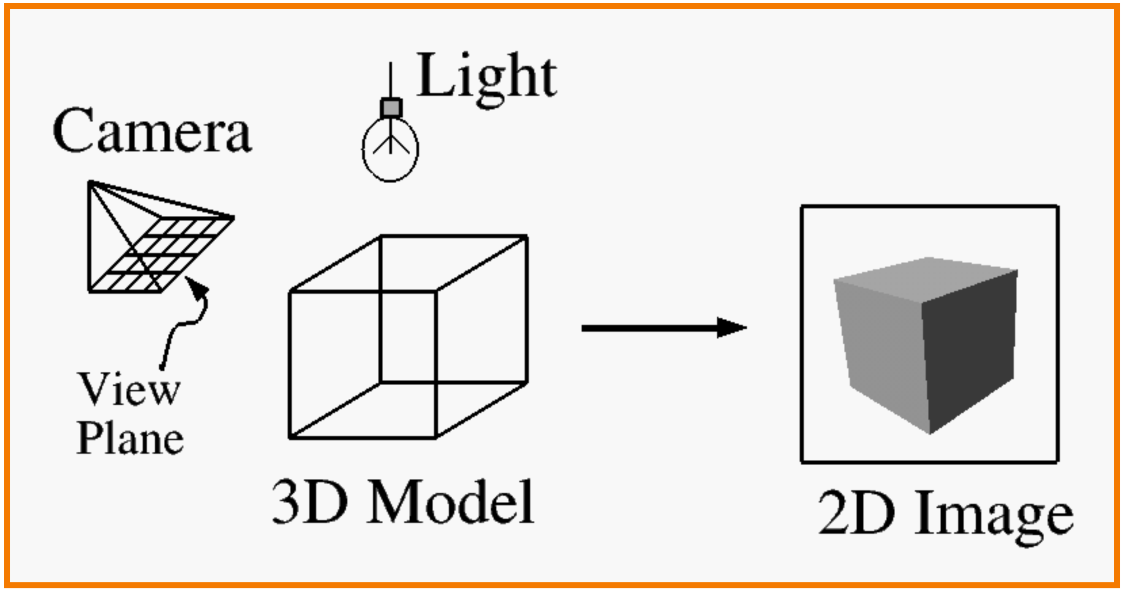
Introduction

- 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

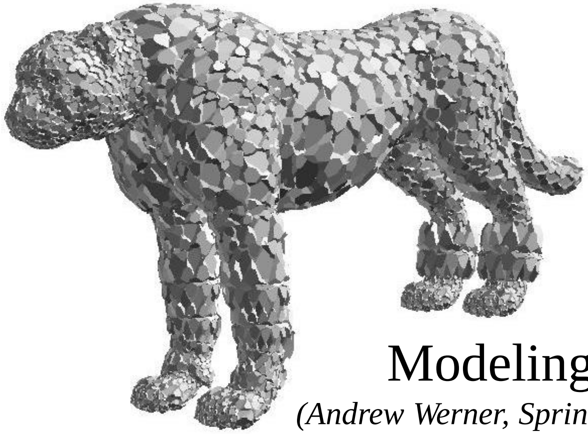
II. Modeling

III. Rendering

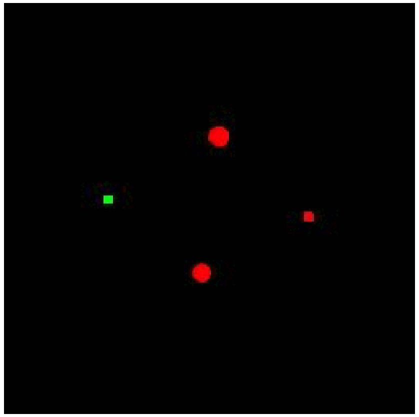
IV. Animation

Image Processing
(Rusty Coleman, CS426, Fall99)

Rendering
(David Paulk, CS426, Spr2015)



Modeling
(Andrew Werner, Spring 2014)



Animation
(Riley Thomasson, Spring 2014)

Part I: Imaging

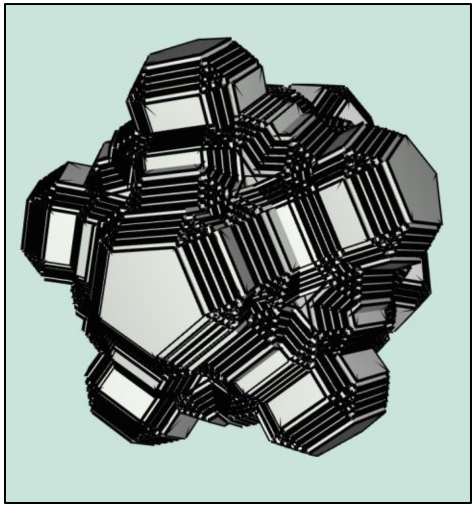
- Image Basics
  - Definition
  - Color models
- Image Representation
  - Sampling
  - Reconstruction
  - Quantization & Aliasing
- Image Processing
  - Filtering
  - Warping
  - Composition
  - Morphing

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



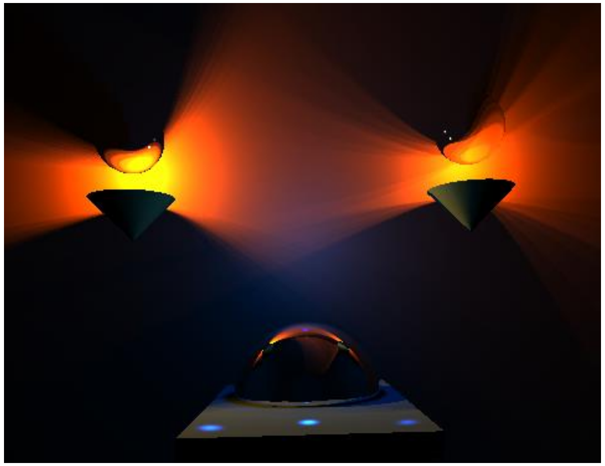
(John Whelchel, CS 426, Spr2015)

(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

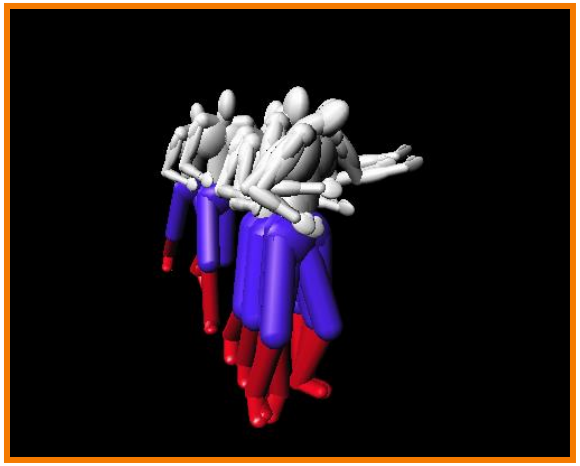
Pixel Shading
(Final Fantasy, Square Pictures)



Global Illumination
(Diana Liao, CS 426, Spr15)

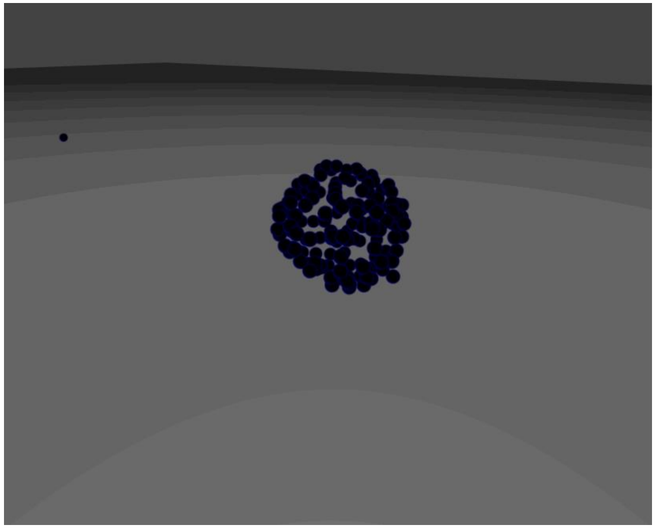
Part IV: Animation

- 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

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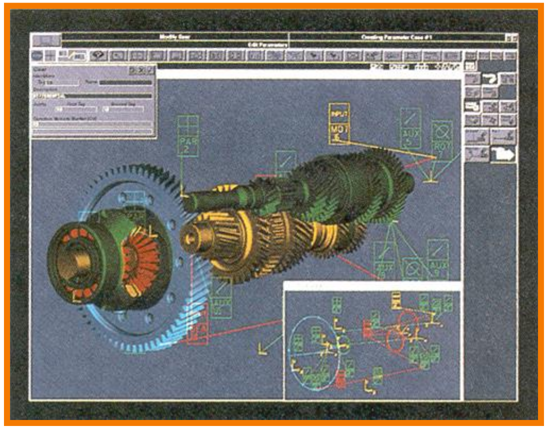
Los Angeles Airport
(Bill Jepson, UCLA)



Gear Shaft Design
(Intergraph Corporation)

Boeing 777 Airplane
(Boeing Corporation)

Applications

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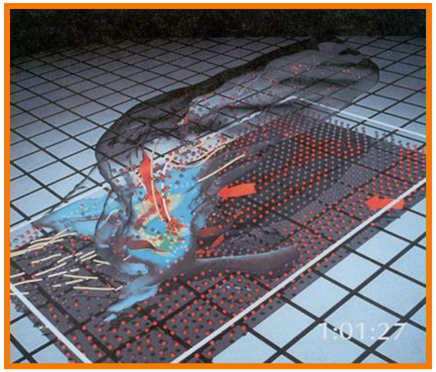
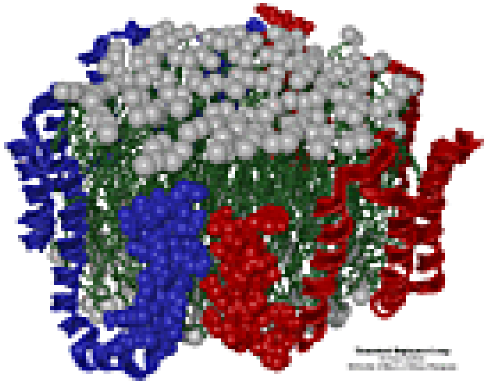
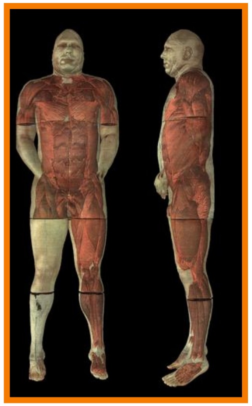


Airflow Inside a Thunderstorm
(Bob Wilhelmson, University of Illinois at Urbana-Champaign)



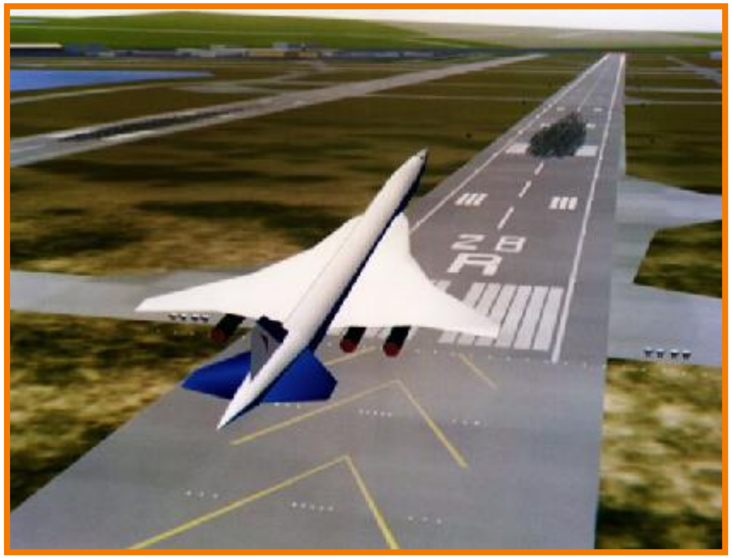
Apo A-1
(Theoretical Biophysics Group, University of Illinois at Urbana-Champaign)



Visible Human
(National Library of Medicine)

Applications

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



Early Flight Simulation
(NASA)

Applications

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

Forum of Trajan
(Bill Jepson, UCLA)

Human Skeleton
(SGI)

Applications

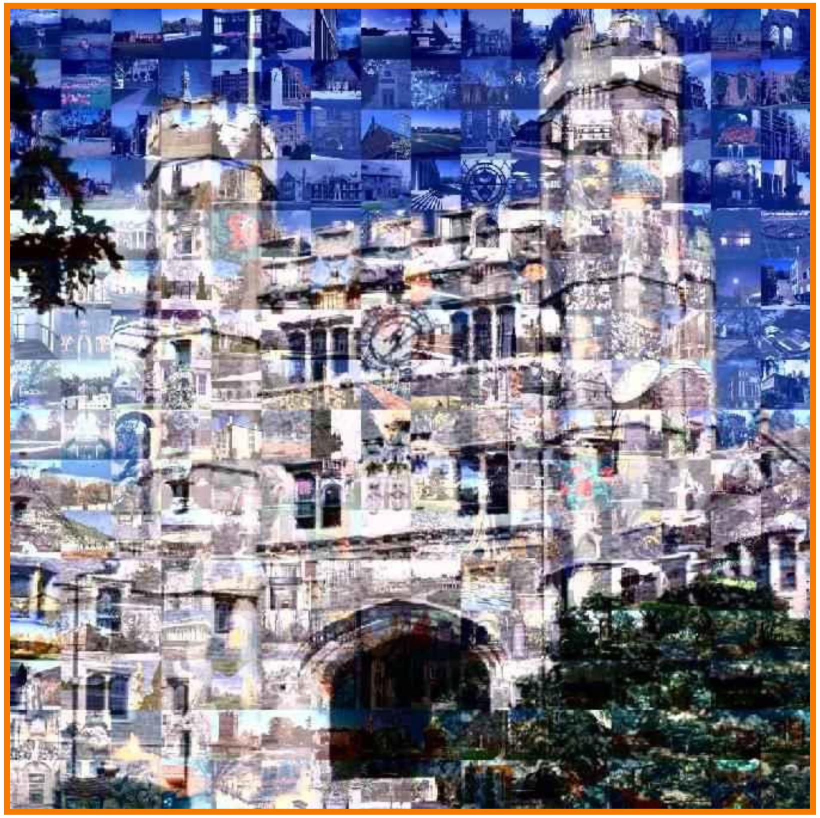
- Entertainment
- Computer-aided design
- Scientific visualization
- Training
- Education
- **E-commerce**
- Computer art

Virtual Stores
(Matterport)

Applications

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

➔ **Computer art**



Blair Arch
(Marissa Range '98)

Overview

- Administrative stuff
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- Imaging
  - Let’s get started …

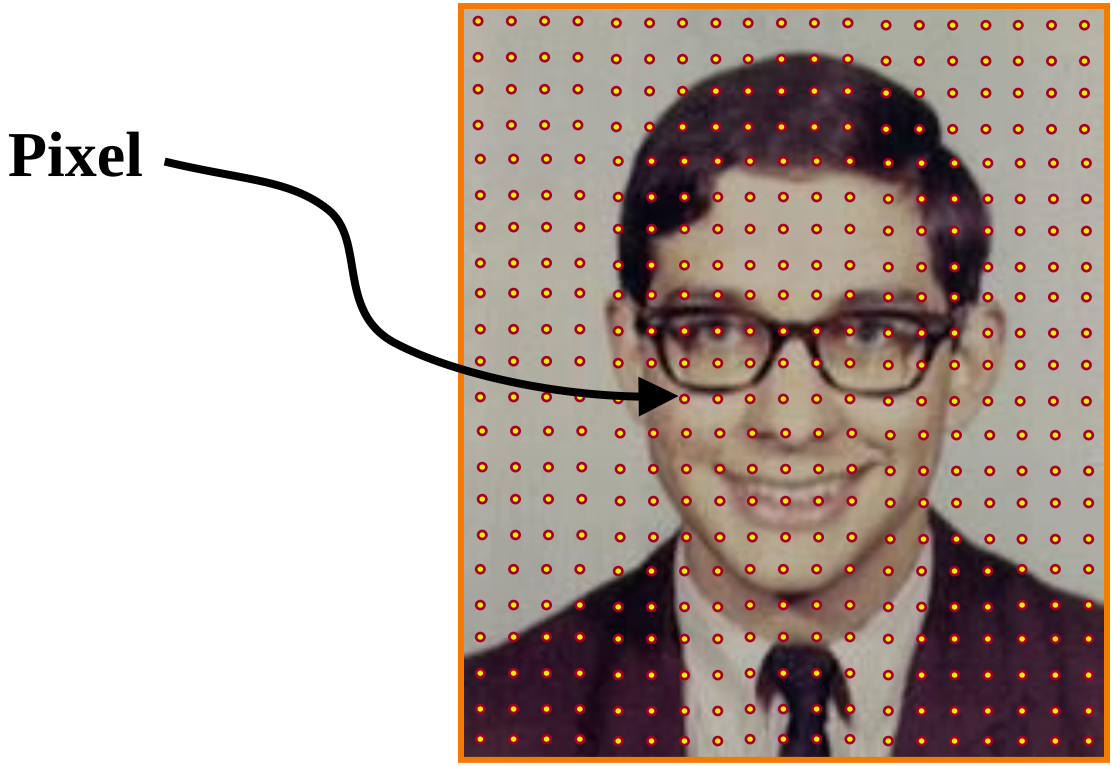
What is an Image?

What is an Image?

An image is a 2D rectilinear array of pixels

Digital image

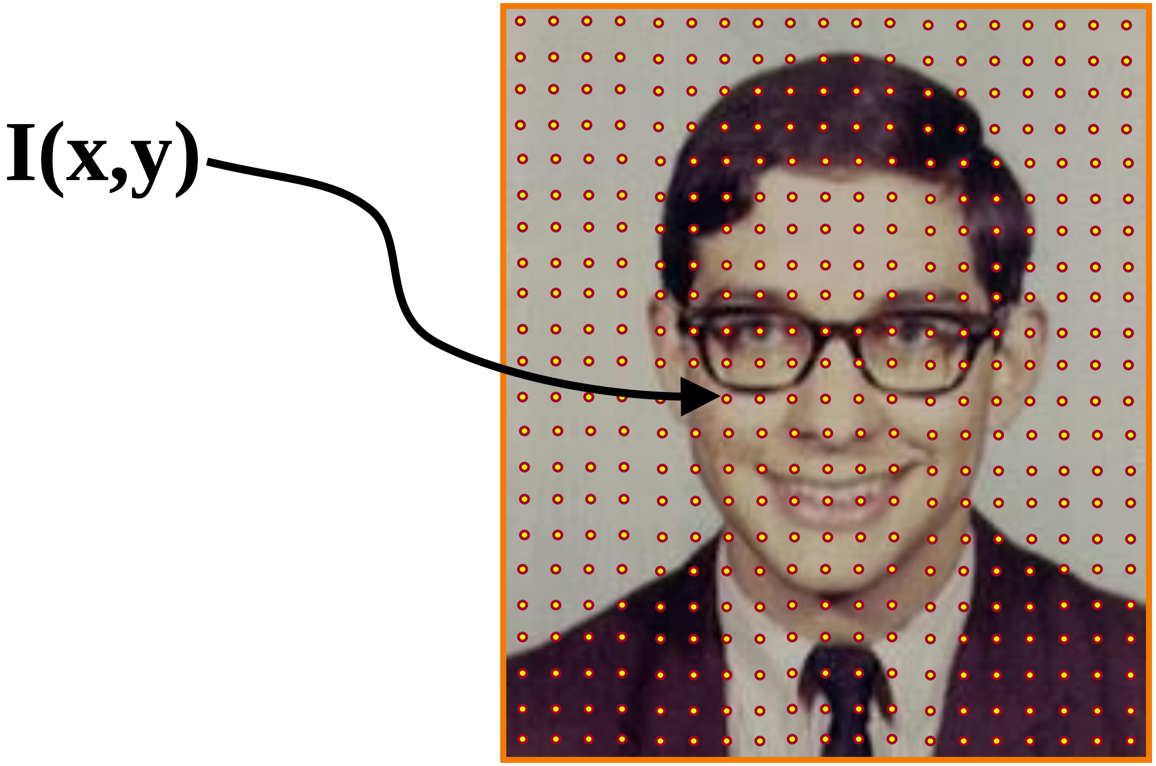
What is a Pixel?



Digital image

What is a Pixel?

Sample of a function at a position

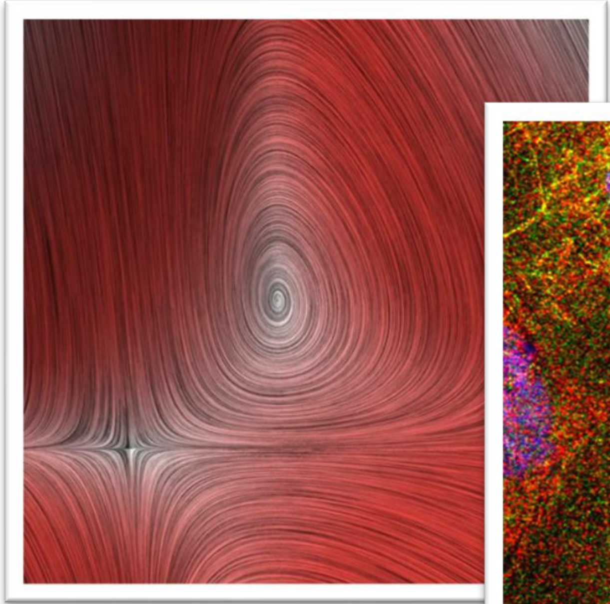


Digital image

What Function?

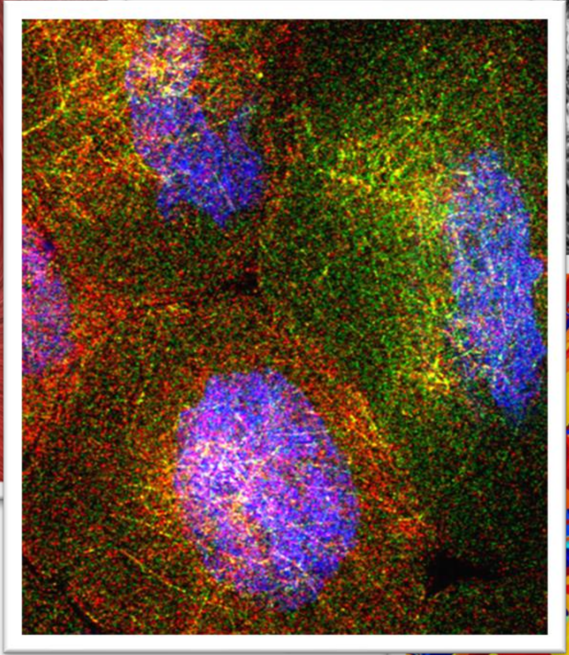
What Function?

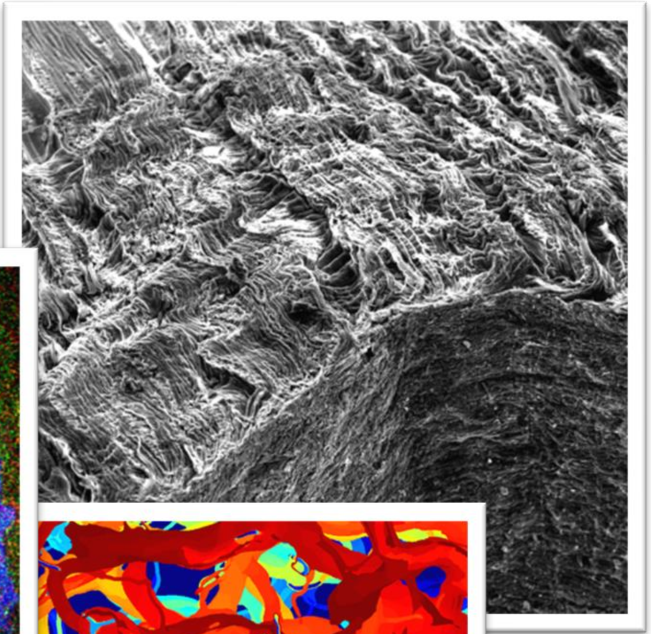
Could be any function …



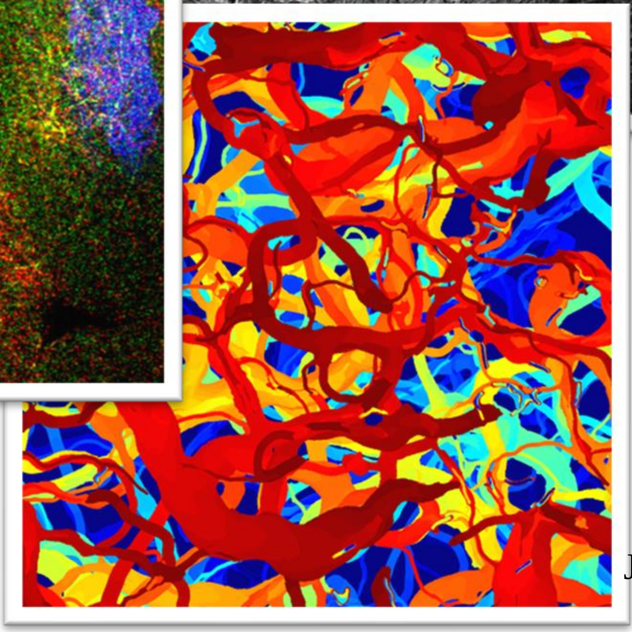
Mitchell A. Nahmias
Paul R. Prucnal

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





Michael Kosk



Mingzhai Sun
Joshua Shaevitz

Art of Science
(Friend Center hallway)

What Function?

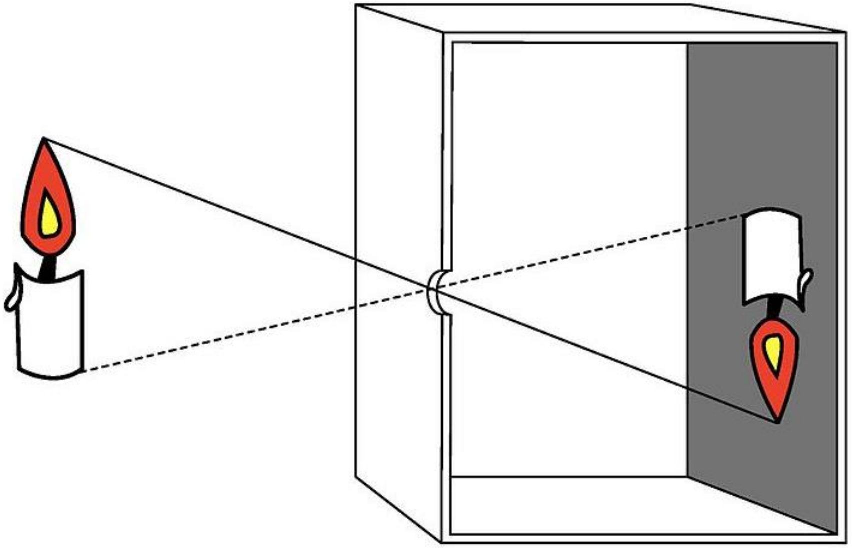
What about photographic images?

I(x,y)?

Digital photograph

Plenoptic Function

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

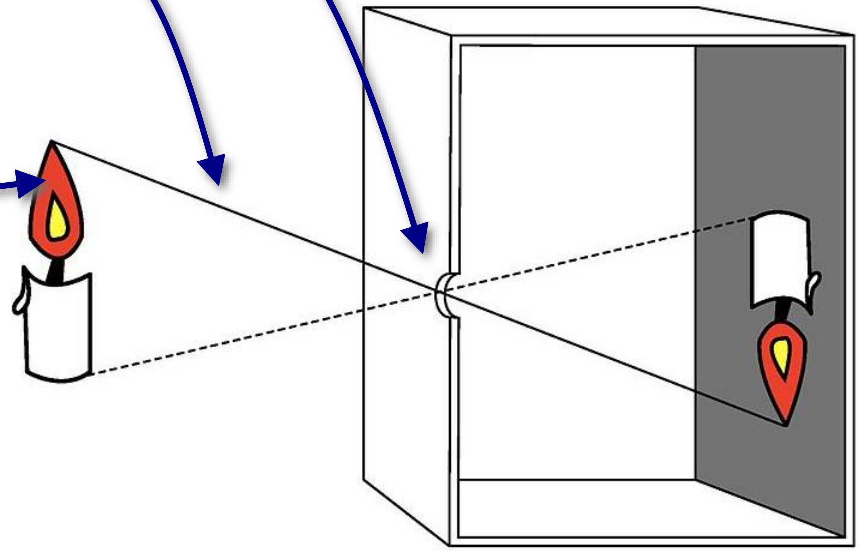


Carlo Benini

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)



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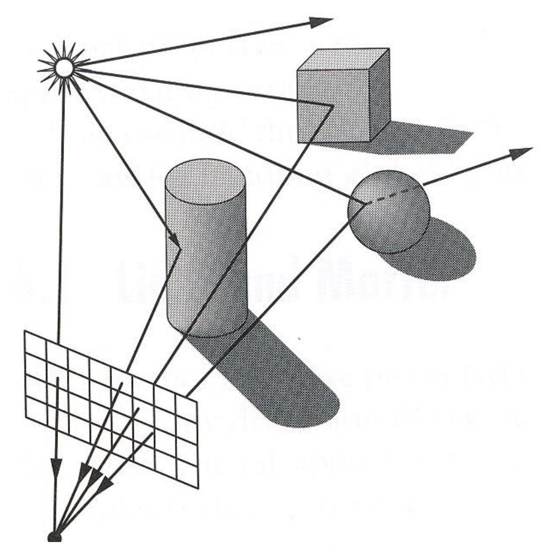
Photographic Images

An idealized photographic image contains a 2D array of samples of the 7D plenoptic function

- at a particular camera viewpoint,
- for 2D array of directions,
- at a certain time,
- at certain frequencies

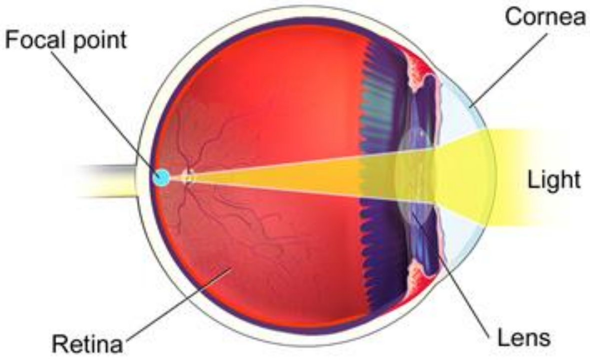


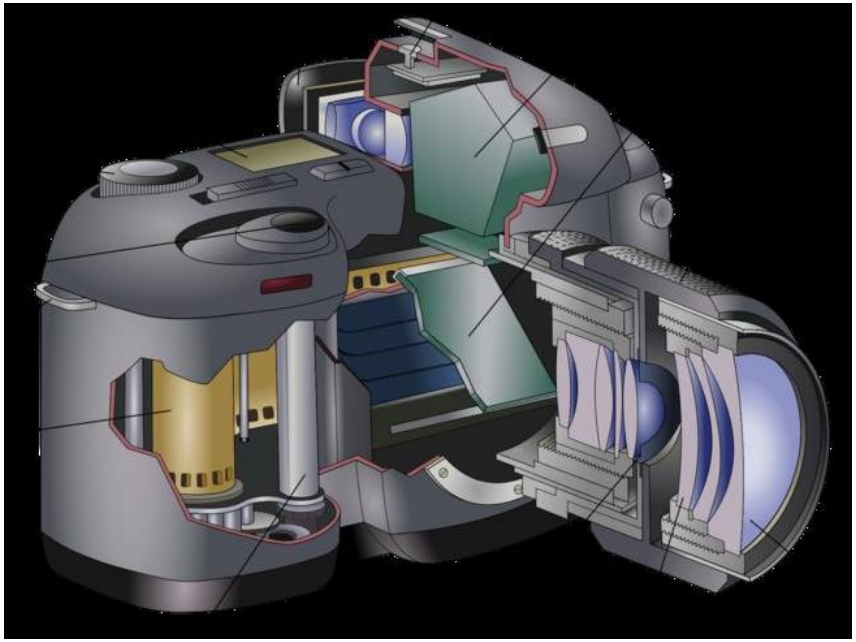
Camera viewpoint

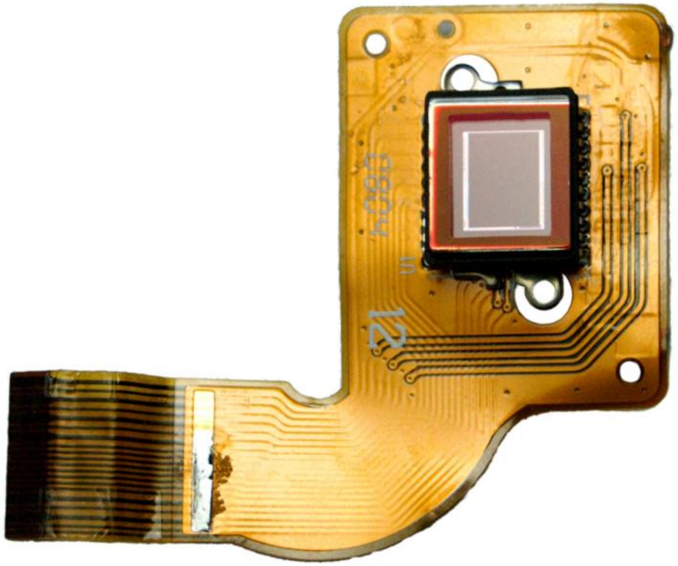
Photographic Images

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

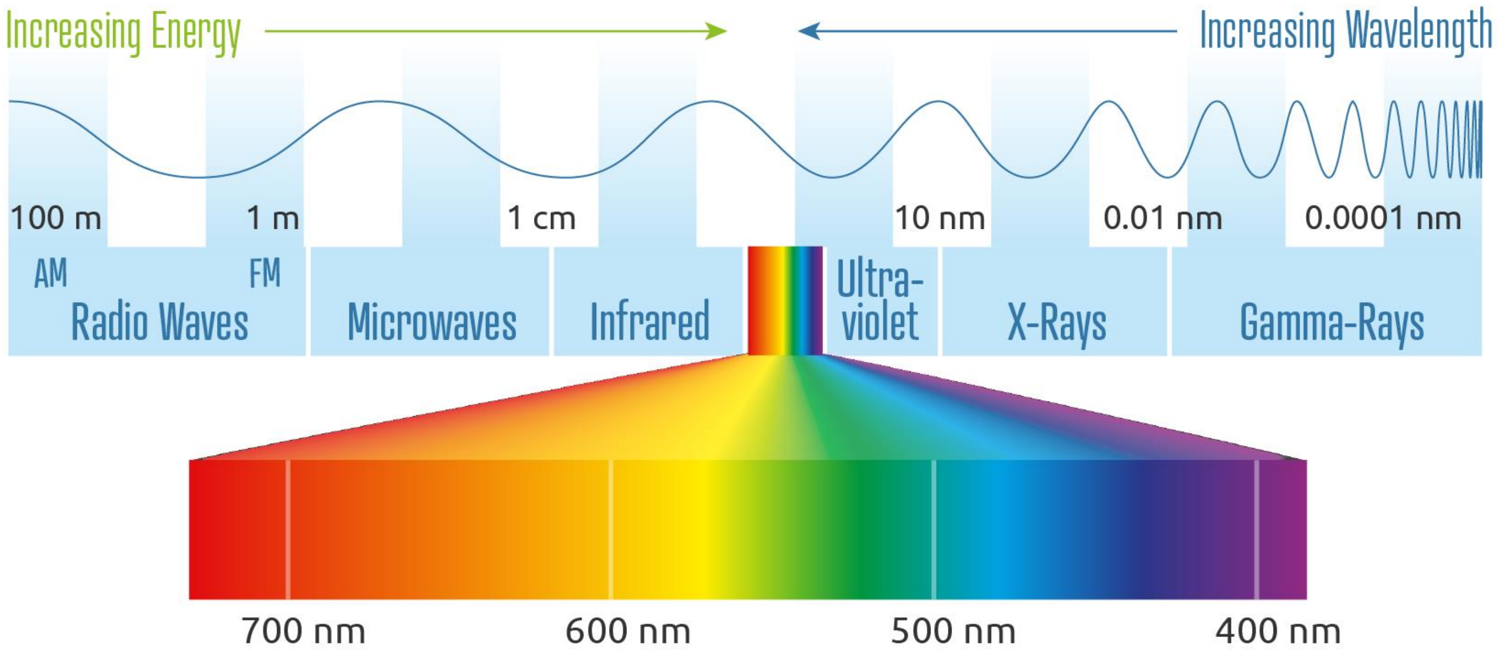
What Frequencies / Wavelengths?

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

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

Electromagnetic Spectrum

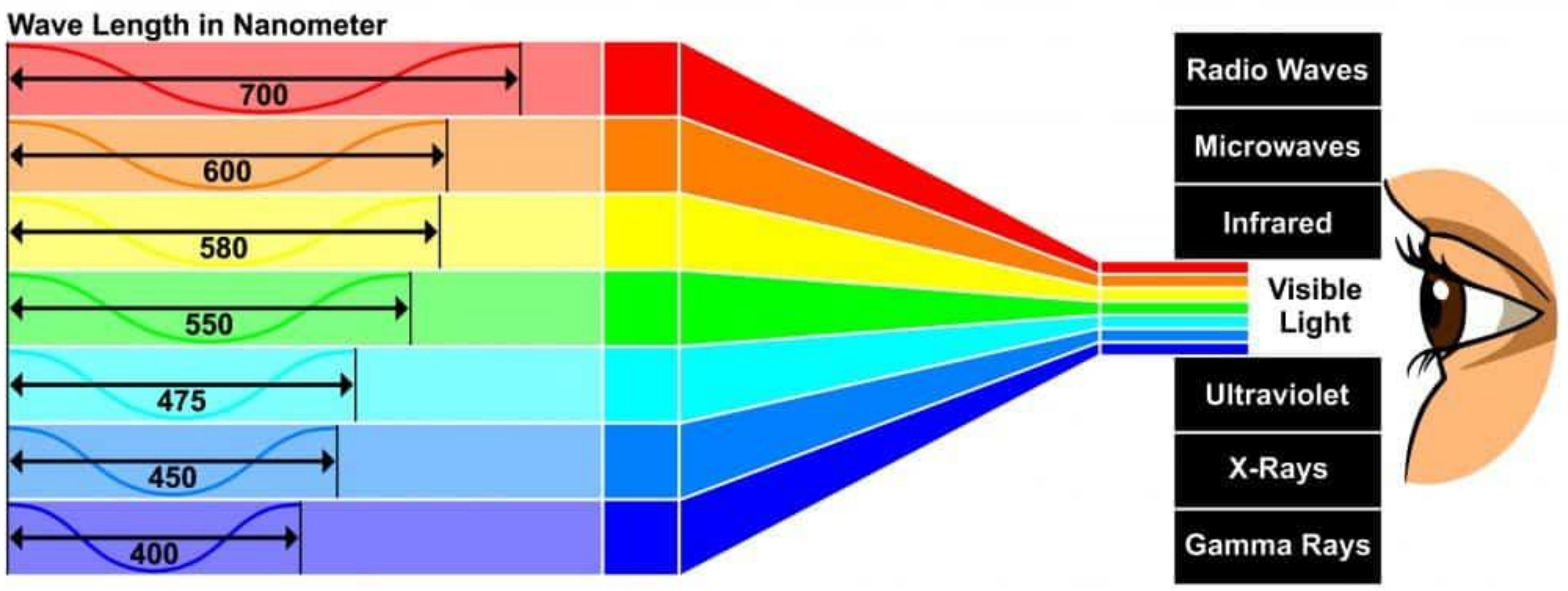
- Visible light frequencies range between ...
  - Red = 4.3 x 10^{14} hertz (700nm)
  - Violet = 7.5 x 10^{14} hertz (400nm)



Figures 15.1 from H&B

Electromagnetic Spectrum

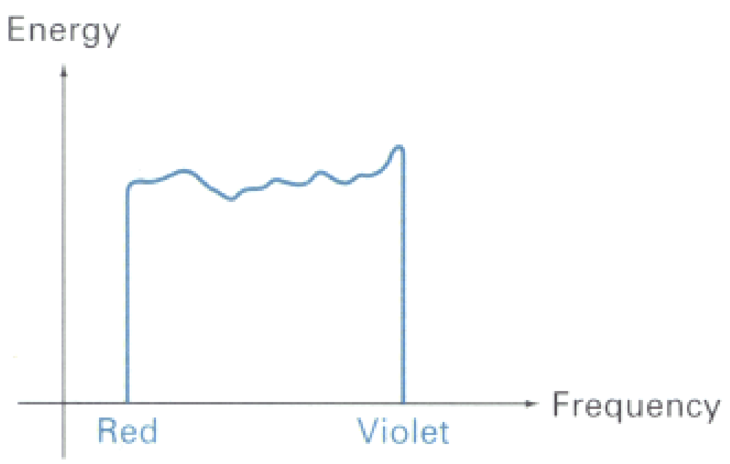
- Visible light frequencies range between ...
  - Red = 4.3×10^{14} hertz (700nm)



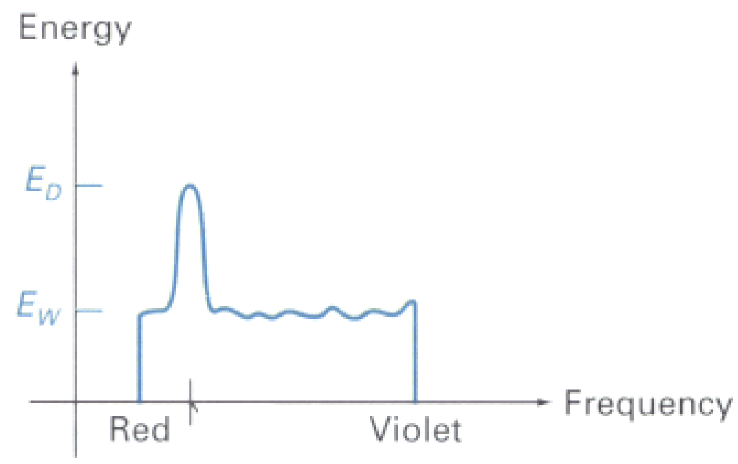
Figures 15.1 from H&B

Color

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



White Light



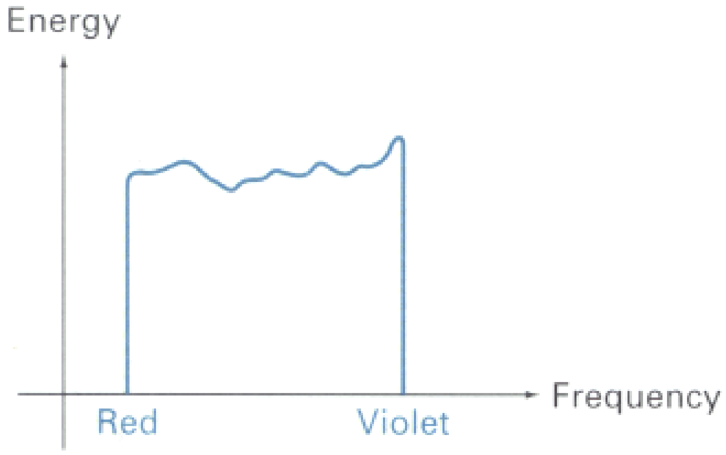
Orange Light

Figures 15.3-4 from H&B

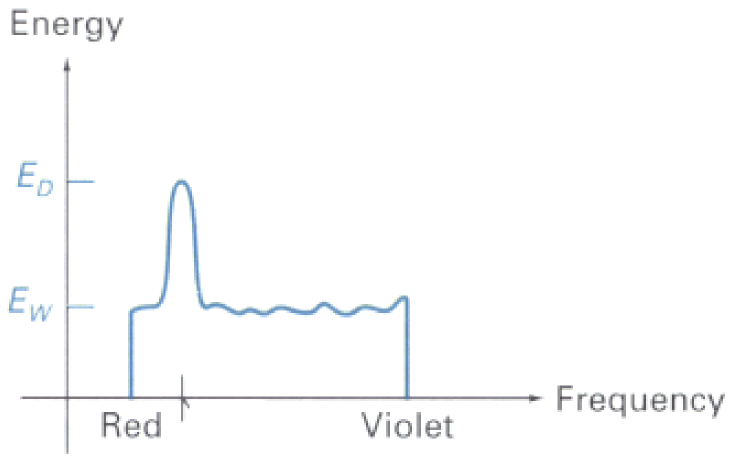
Color

How do we represent a color in a computer?

- Must store a finite amount of data to represent magnitudes for infinite number of frequencies



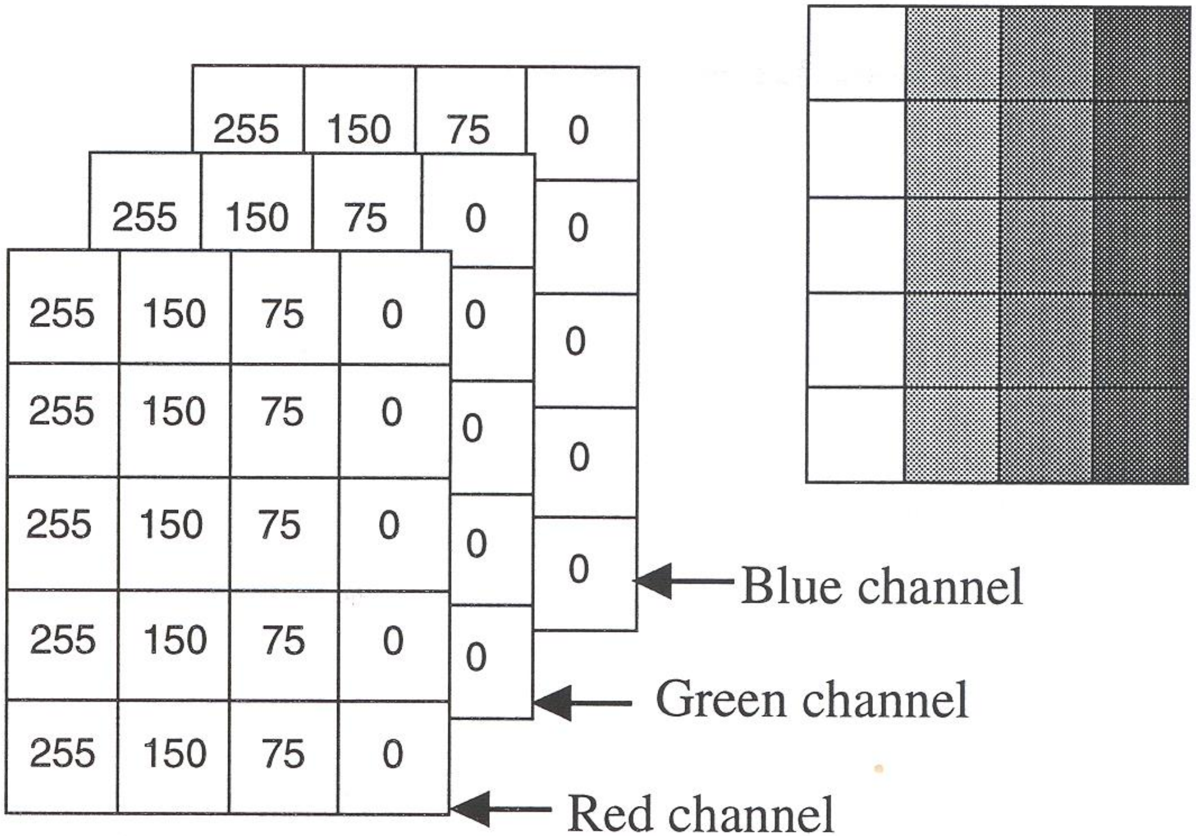
White Light



Orange Light

Figures 15.3-4 from H&B

Color Frame Buffer

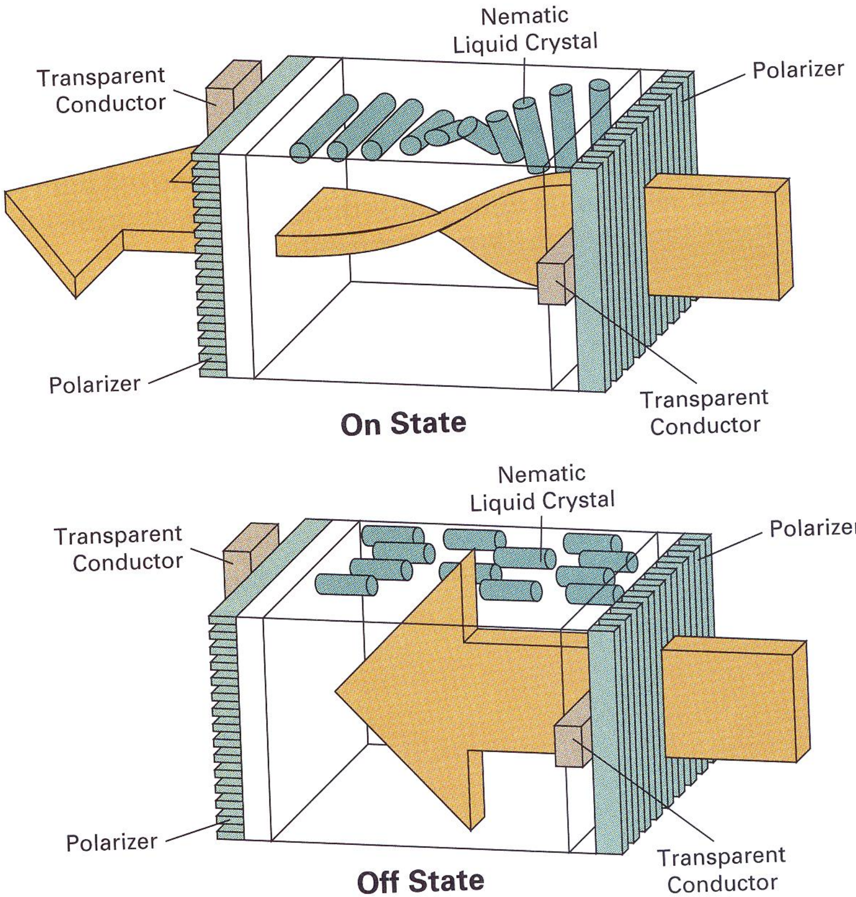


Frame Buffer Display

- Video display devices
  - Liquid Crystal Display (LCD)
  - Plasma panels
  - 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:

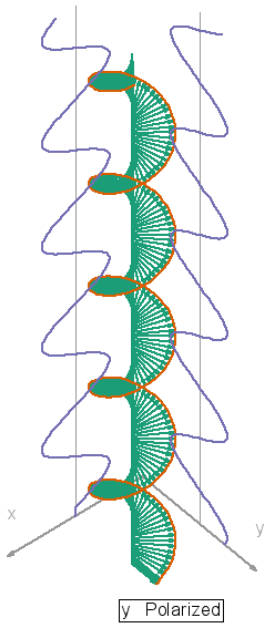
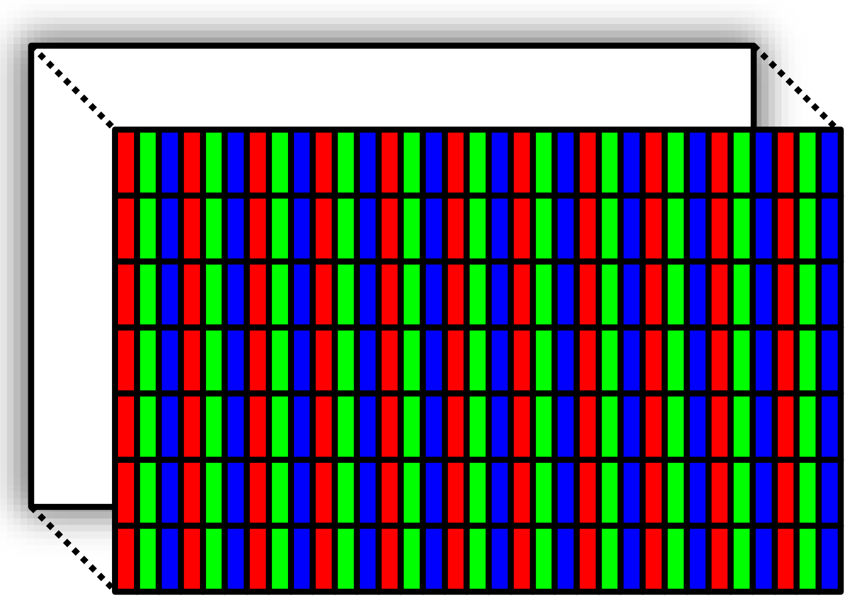


Figure 2.16 from H&B

Frame Buffer Display

LCD up close

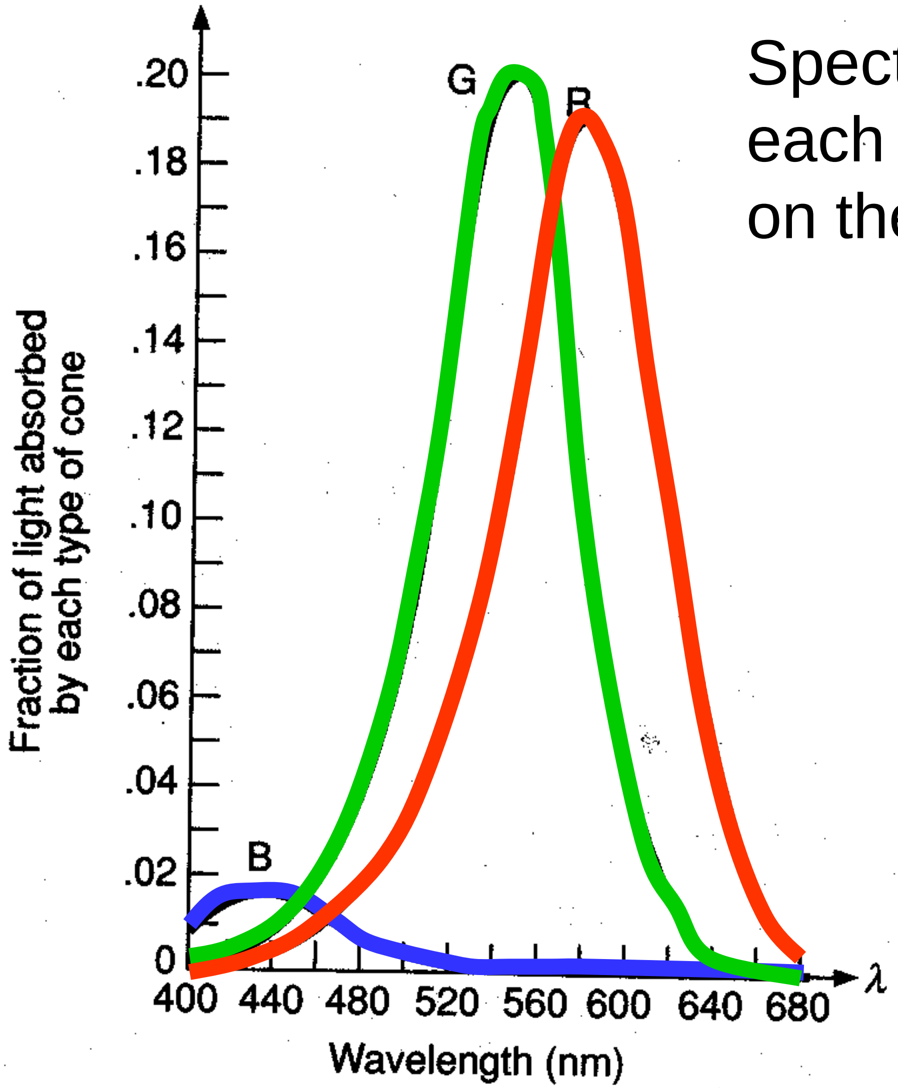


Colors are interleaved

Color

Why red, green, and blue (RGB)?

Human Color Perception

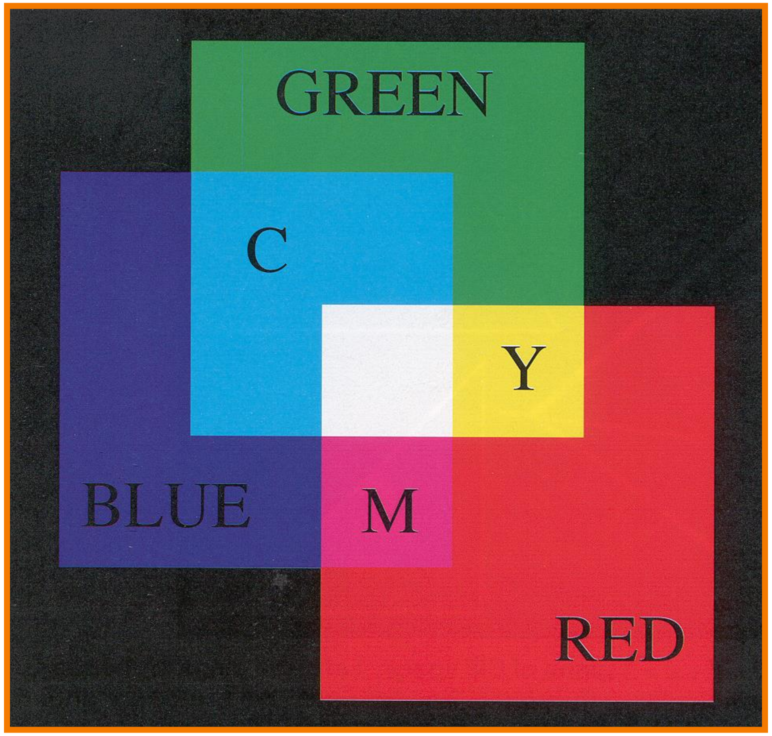


Spectral-response functions of each of the three types of cones on the human retina.

Tristimulus theory of color

Figure 13.18 from FvDFH

RGB Color Model

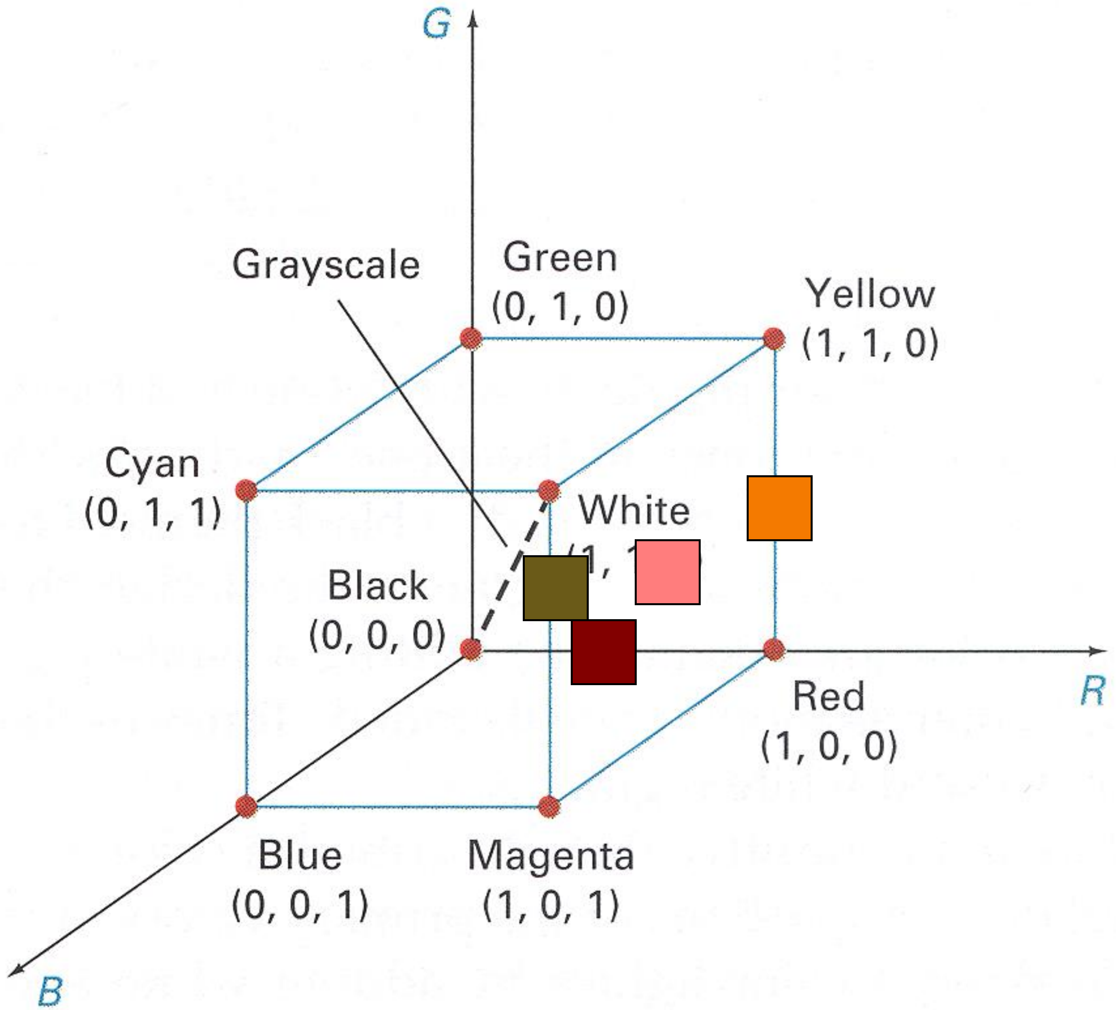


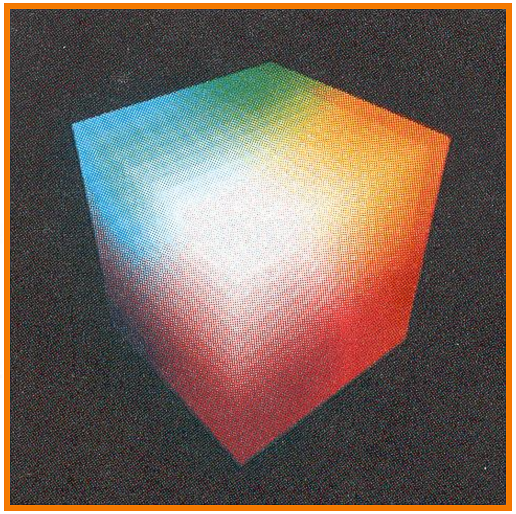
Colors are additive

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





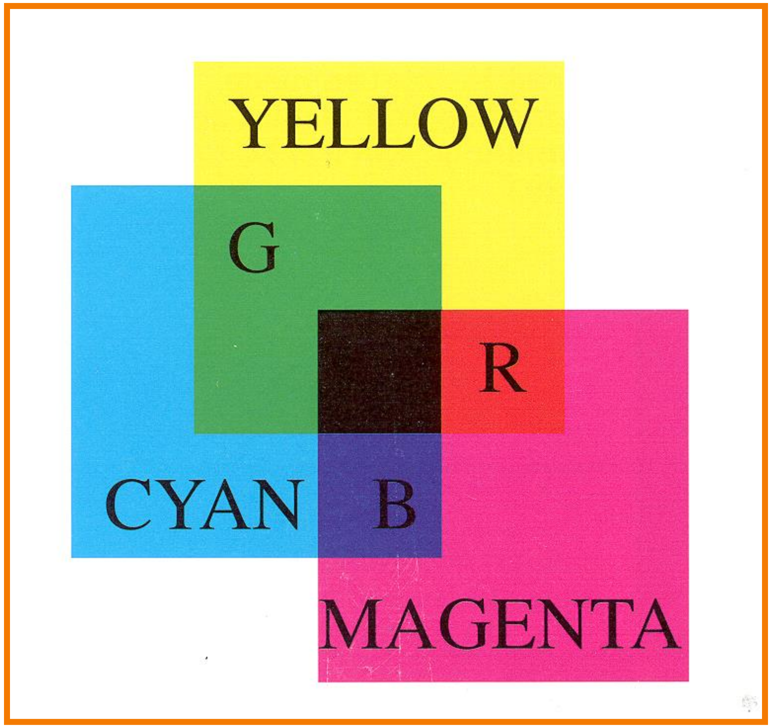
Figures 15.11&15.12 from H&B

Other Color Models

- CMY
- HSV
- XYZ
- La*b*
- 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

Plate II.7 from FvDFH

CMY Color Model

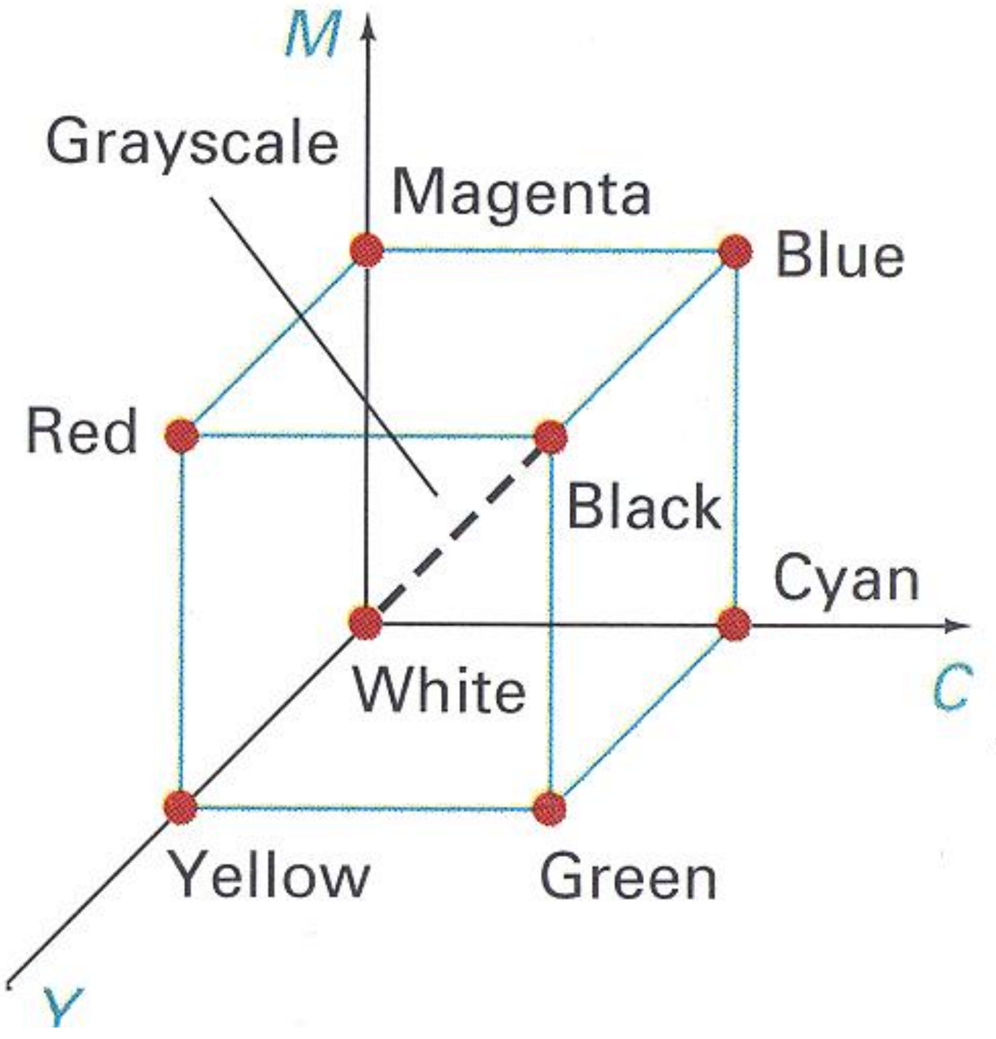
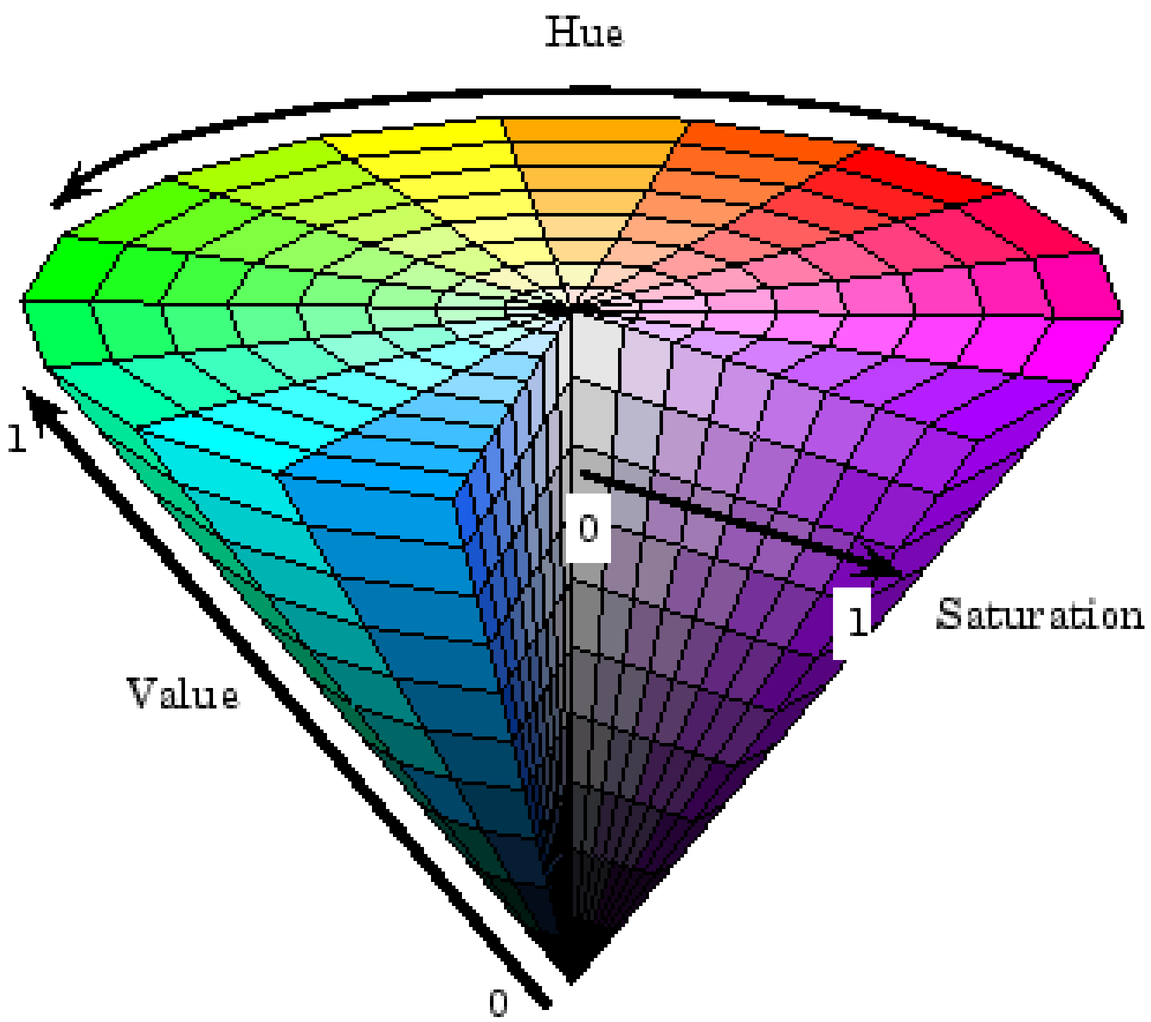


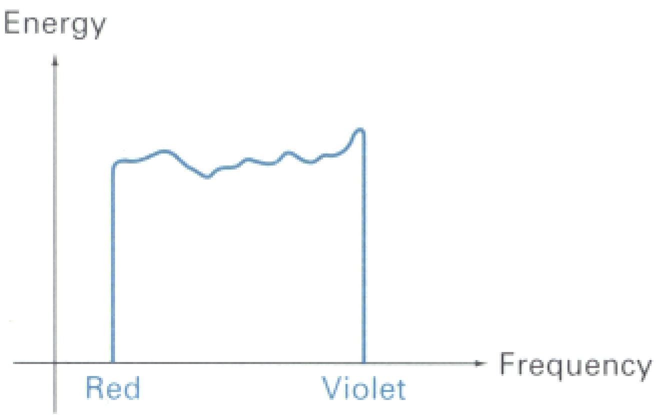
Figure 15.14 from H&B

HSV Color Model

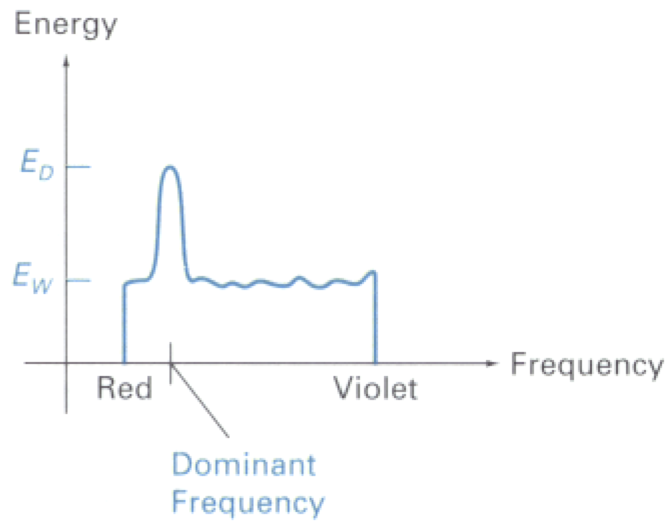


HSV Color Model

- HSV interpretation in terms of color spectrum
  - Hue = dominant frequency (highest peak)
  - Saturation = excitation purity (ratio of highest to rest)
  - Value = luminance (area under curve)



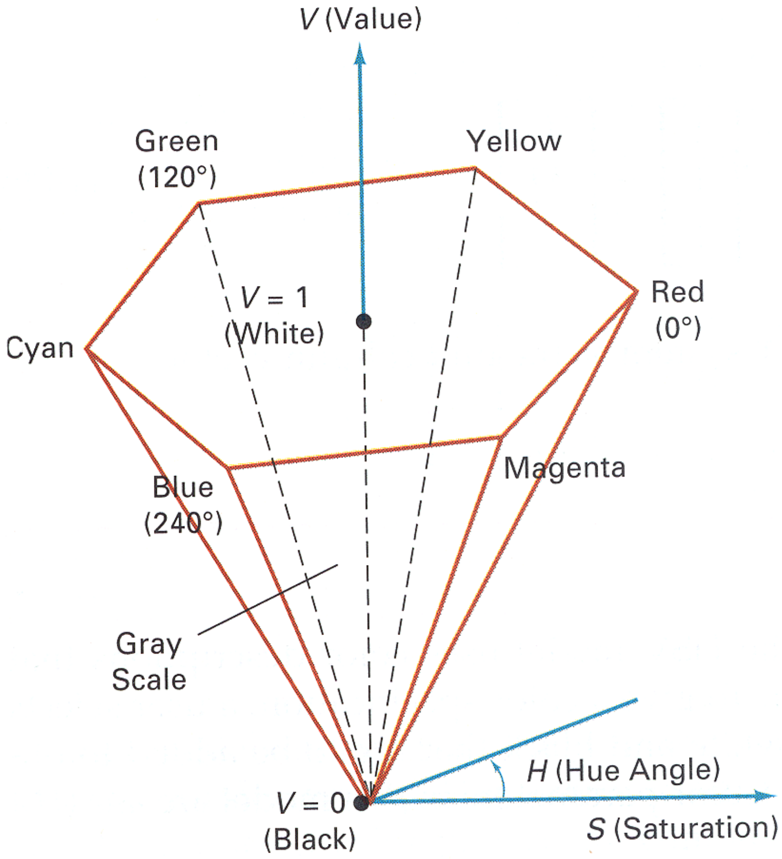
White Light



Orange Light

Figures 15.3-4 from H&B

HSV Color Model



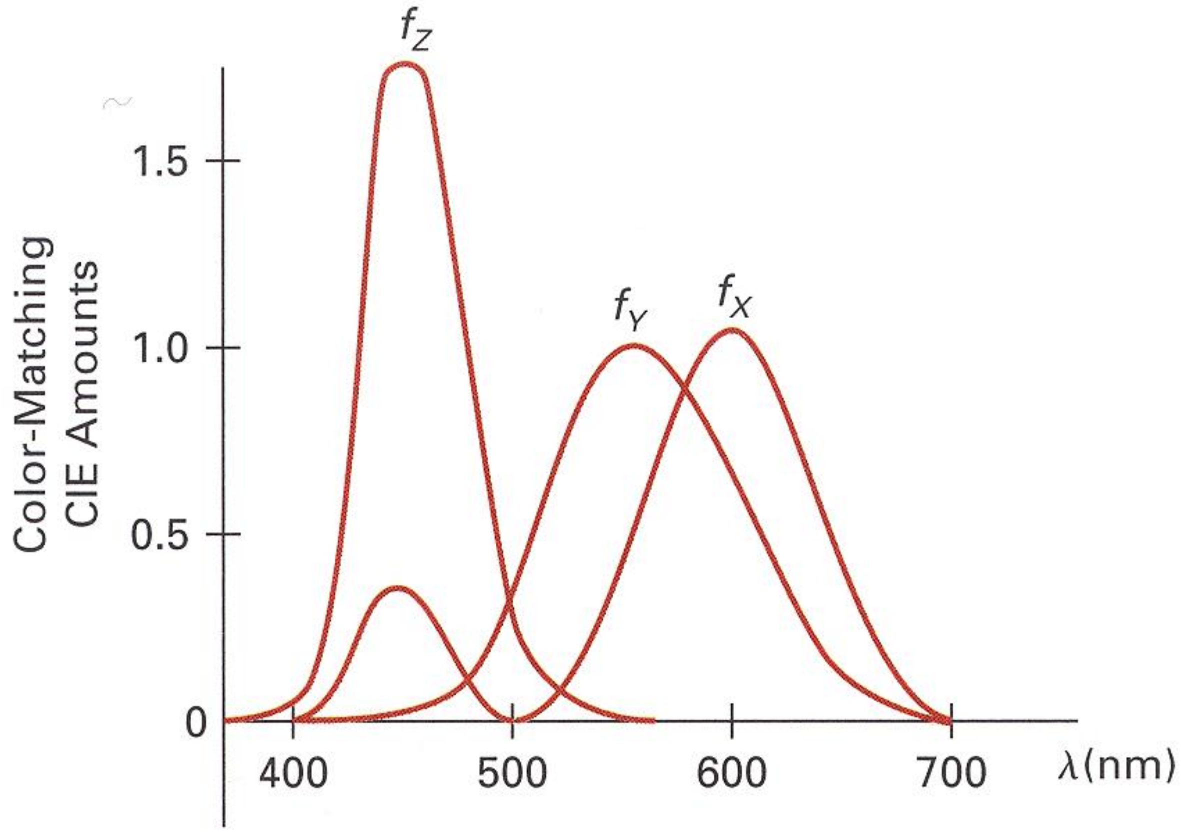
H	S	V	Color
0	1.0	1.0	Red
120	1.0	1.0	Green
240	1.0	1.0	Blue
*	0.0	1.0	White
*	0.0	0.5	Gray
*	*	0.0	Black
60	1.0	1.0	
270	0.5	1.0	
270	0.0	0.7	

Useful for user interfaces
because dimensions are intuitive

Figure 15.16&15.17 from H&B

XYZ Color Model (CIE)

Figure 15.6 from H&B

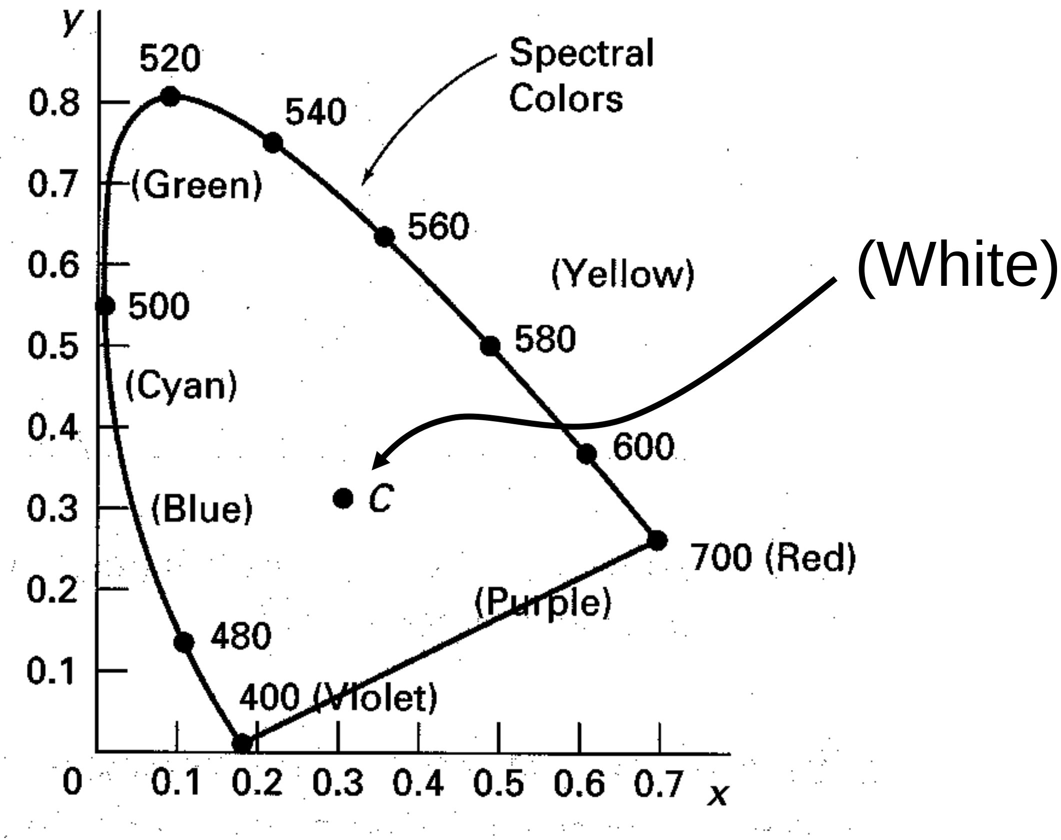


Derived from perceptual experiments

All spectra that map to same XYZ give same visual sensation

XYZ Color Model (CIE)

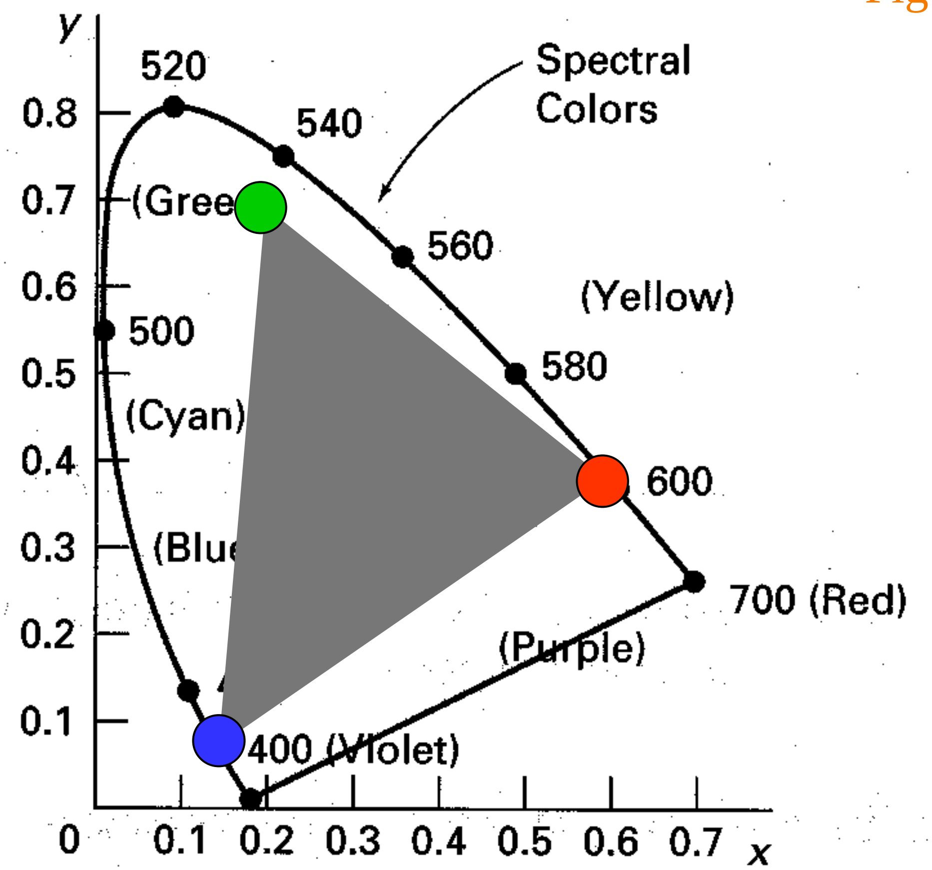
Figure 15.7 from H&B



Normalized amounts of X and Y for colors in visible spectrum

XYZ Color Model (CIE)

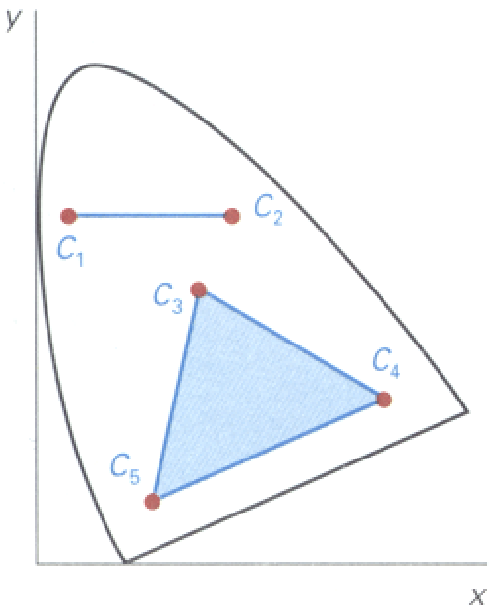
Figure 15.13 from H&B



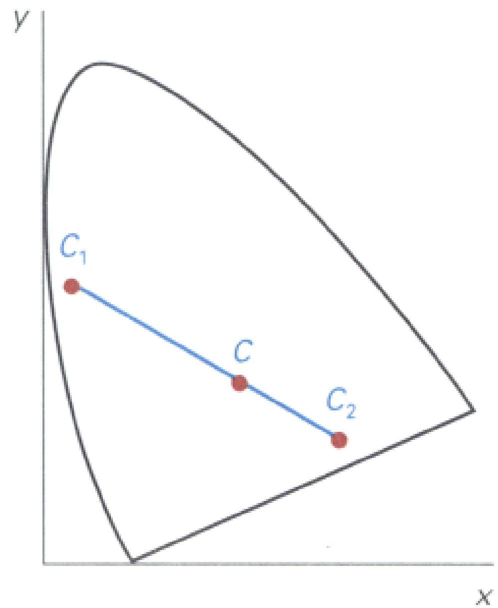
Useful for reasoning about coverage of color gamuts

XYZ Color Model (CIE)

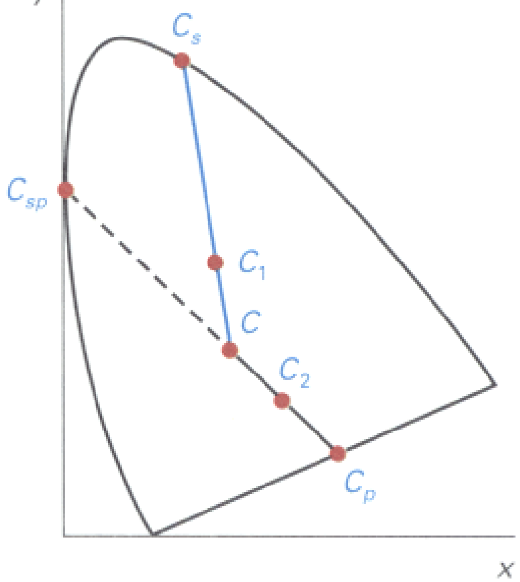
Figures 15.8-10 from H&B



Compare
Color
Gamuts



Identify
Complementary
Colors

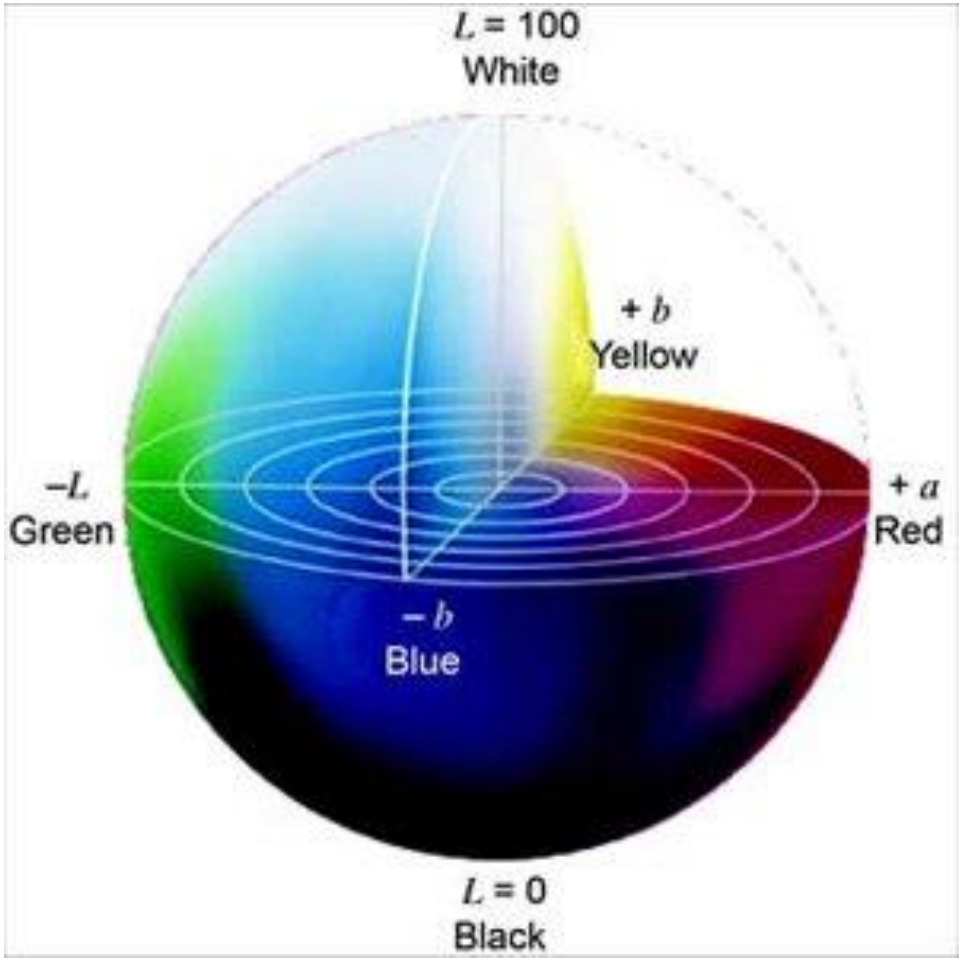


Determine
Dominant Wavelength
and Purity

Useful for characterizing perceptual qualities of colors

La*b* Color Model

Non-linear compression of XYZ color space based on perception



Useful for measuring perceptual differences between colors

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!