Computer Graphics

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Eötvös Loránd University
Faculty of Informatics

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Introduction and contact details

- Lecturer: Ágoston Sipos
- E-mail: `siposagoston@inf.elte.hu`
- Room: TBD
- Consultation: after a discussion by email
- Information on the Canvas

Lecture

- Subject codes: IP-24fKVSZGE, IPM-22AUTCGE
- Prerequisite on Bsc: Computer Graphics Practice (weak, IP-24fKVSZGG, IPM-22AUTCGG)
- Linear Algebra!
- Option for recommended grade via two exams during the semester:
  1. First: halfway through; second: at the end
  2. 50%-50% theoretical and practical tasks
- In examination period: one exam from the whole, and one resit exam.
- Website: `https://cg.inf.elte.hu`
- During the semester, information will be sent out in a Neptun message and uploaded to Canvas

Recommended literature

Recommended literature:

1. *Andrew Glassner* I recommend his free book to those interested: `http://realtimerendering.com/Principles_of_Digital_Image_Synthesis_v1.0.1.pdf`
2. If you want to work more seriously with graphics later on, you should get to know these:
   - *Akenine-Möller, Haines, Hoffman*: Real-Time Rendering (3rd edition)
   - *Pharr, Humphreys, Hanrahan*: Physically Based Rendering (From Theory to Implementation)

Practice

- Subject code: IP-24fKVSZGG, IPM-22AUTCGG
- Weak prerequisite for BSc
- Prerequisites: basic math, linear algebra (IP-18fMATAG), imperative programming (IP-18fIMPROGEG)
- Coordinator: Ágoston Sipos
  - Email: `siposagoston@inf.elte.hu`
  - Everyone should write to <u>their own teacher</u> for practice
- Grading:
  - During semester one small assignment
  - 3-hour long computer exam

What is computer graphics?

- Applied field of science where you *must* produce tangible results or at least visible

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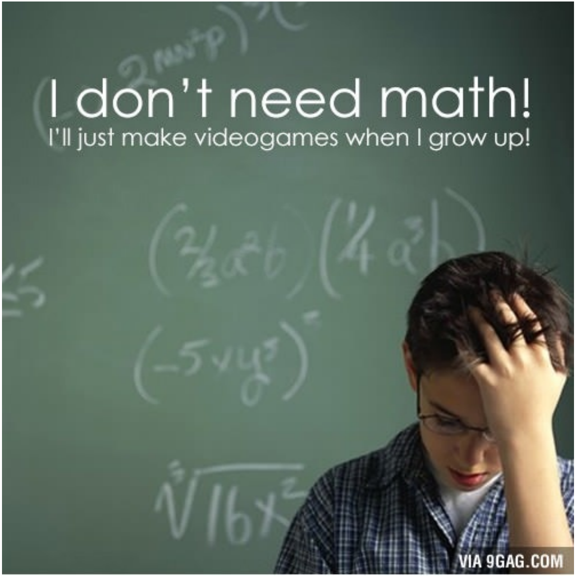
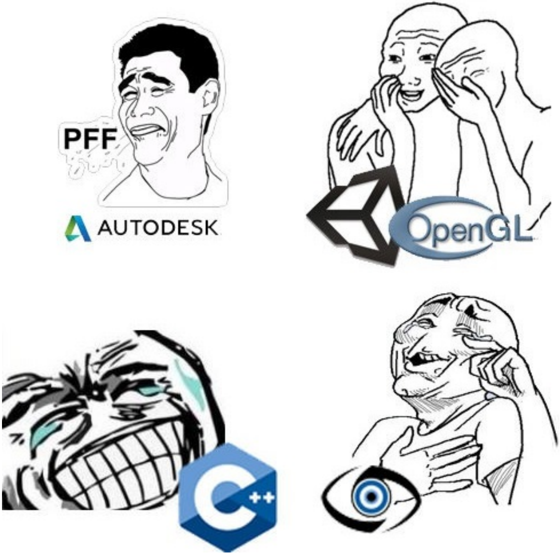
What is computer graphics?

- Applied field of science where you *must* produce tangible results or at least visible
- This means that a strong theoretical background is necessary to understand the description of the problem to be solved
- Knowing the formulas is not enough


I don’t need math!
I’ll just make videogames when I grow up!
VIA 9GAG.COM


PFF
AUTODESK
OpenGL

$$L_o(\mathbf{x},\omega) = L_e(\mathbf{x},\omega) + \int_\Omega f_r(\mathbf{x},\omega',\omega)L_i(\mathbf{x},\omega')(\omega'\cdot\mathbf{n})d\omega$$

Computer Graphics

- **Computer graphics** is a branch of computer science.
- Task: visual material
  - generation
  - analysis
  - processing

Image manipulation

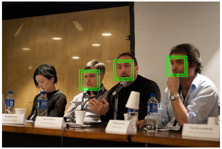
Brandon Christopher Warren, flickr

Image processing and analysis

- Image processing

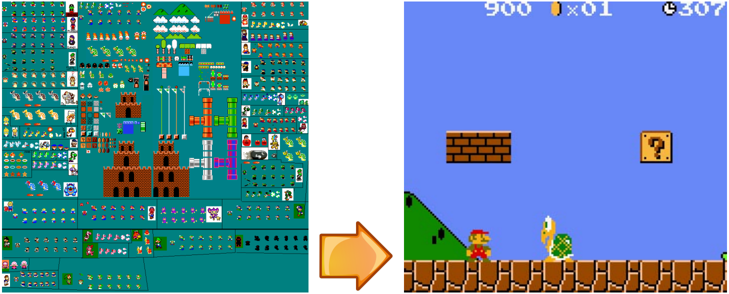


- Image analysis



Beatrice Murch and OpenCV

2D: Model → Image



3D: Model $\rightarrow$ Image

Tools of computer graphics

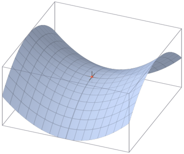
- In this lecture we take a look at how we produce images
- For this, we need to be able to
  - store the virtual world we want to display on the computer (**representation**),
  - display the representation (**image synthesis**),
  - And the displaying must be done on appropriate devices (**displays**).

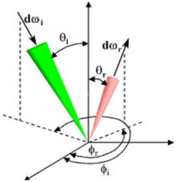
Image synthesis

Questions:

- How do we represent the world? – Modelling
  - This semester: geometric models, light–surface interaction – mathematical and physical models
  - MSc: Mathematical foundations of computer graphics
  - MSc: Surface and body modeling
  - Comp. Elective: 3D modelling with Maya
- How to calculate the image? – Algorithms
  - This semester: ray tracing and incremental rendering
  - Comp. Elective, MSc: Advanced Computer Graphics
- How do we display it? – Devices
  - In this lecture, a brief overview

Modelling





- Geometrical models
- Optical models
- Textures
- *all can be generated, measured, photographed, etc.*

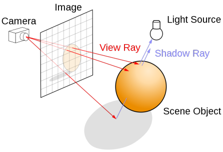
Algorithms

Approaches

- Ray tracing
- Incremental image synthesis

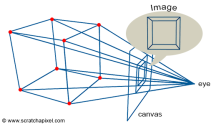
Light phenomena

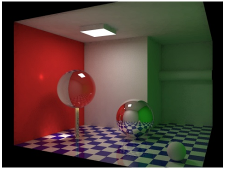
- Reflection, refraction
- Shadows
- Global Illumination
- Volumetric phenomena



Henrik, Wikipedia


CryEngine2





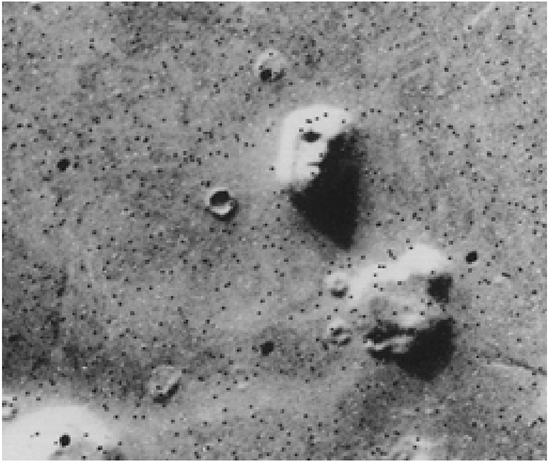

Gilles Tran, Oyonale.com


BlendELF.com

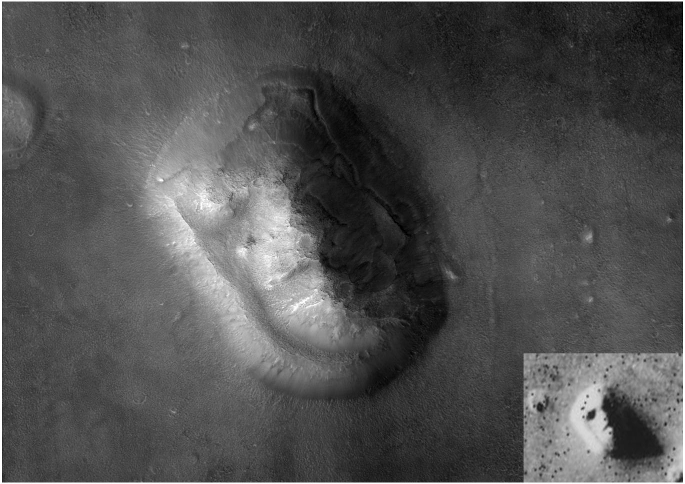
Motivation

- An image is most often created with two main goals:
  - Creating an image for the computer: in this case, you don't need to deal with actually displaying it, you only need to provide a description (where, what color it is)
  - Creating an image for a human: the image must be displayed $\rightarrow$ for this, you need to be aware of certain basic properties of human vision, so that the information you want to convey undergoes as little distortion as possible
- We will deal with the latter; the human vision depends on many factors, even the current state of lights and shadows themselves are influential factors

Cydonia – 1978



Cydonia – 2001 VS 1978

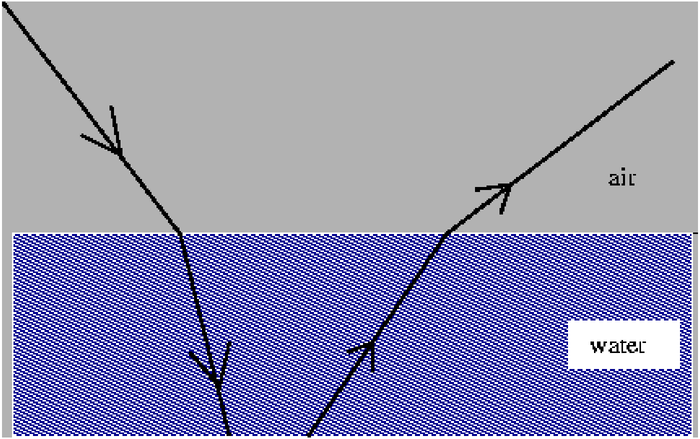


Link to the history of the face on Mars

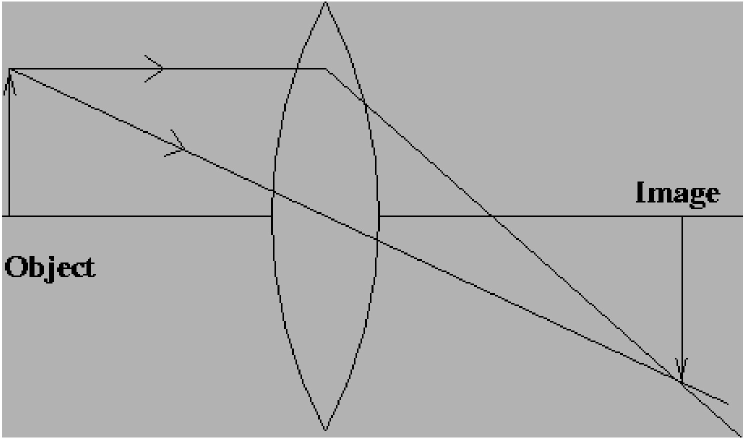
Our goal

- With image synthesis, our goal is to tell what color the display should be at given location
- Therefore, it is important to be able to give both an abstract and a concrete description

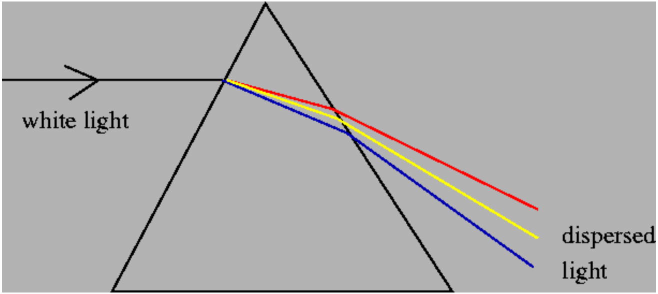
Properties of light – refraction



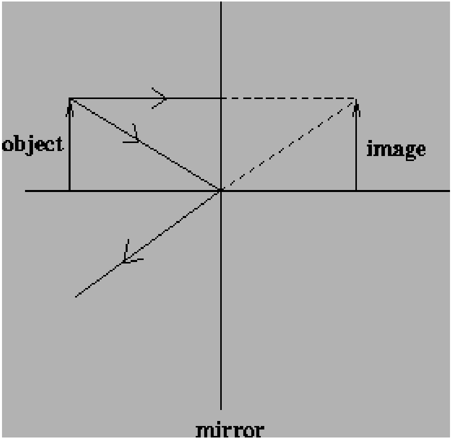
Properties of light – refraction



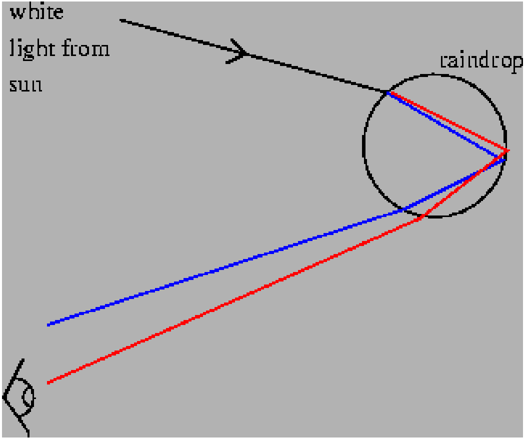
Properties of light – refraction with a prism



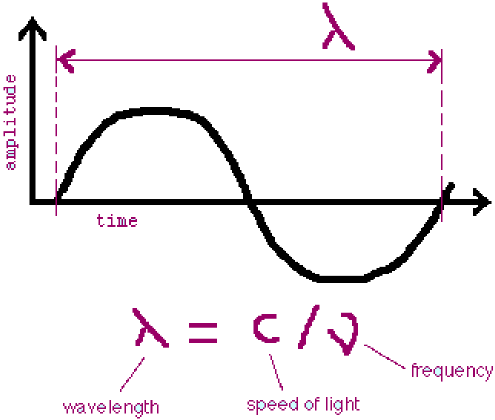
Properties of light – reflection



Properties of light – rainbow

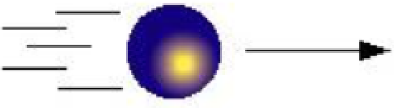


Properties of light – wave?



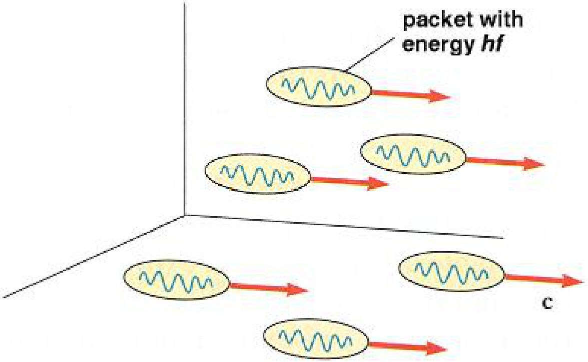
Properties of light – particle?

$$E = hf$$

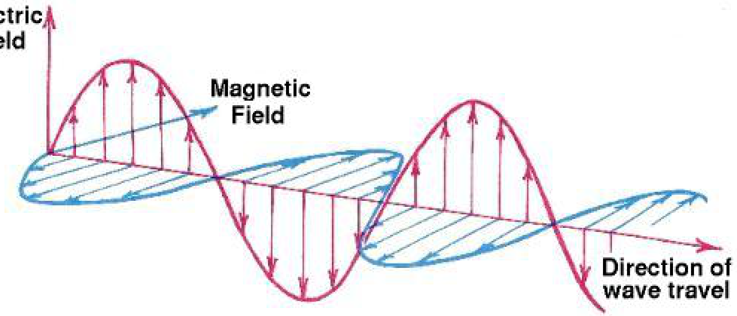


$$h = 6.63 \times 10^{-34}\ \text{Joules}\cdot\text{sec}$$

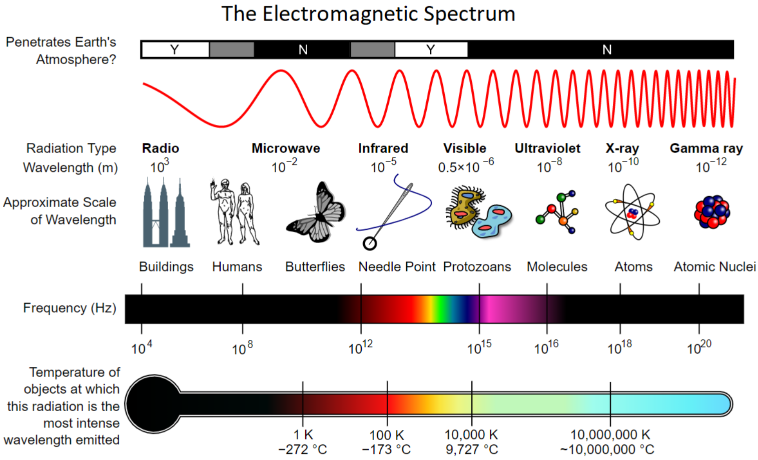
Properties of light – photons



Properties of light – light is electromagnetic radiation



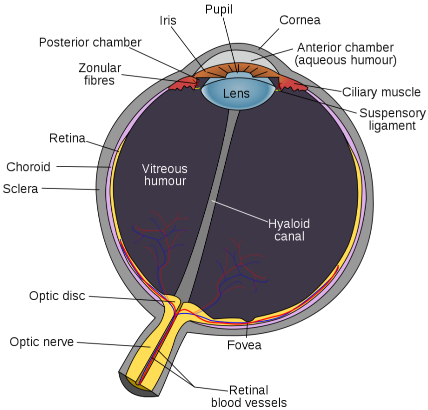
Electromagnetic radiation



Vision

- It has both physiological and psychological aspects
- The eye and the brain are involved

The structure of the human eye



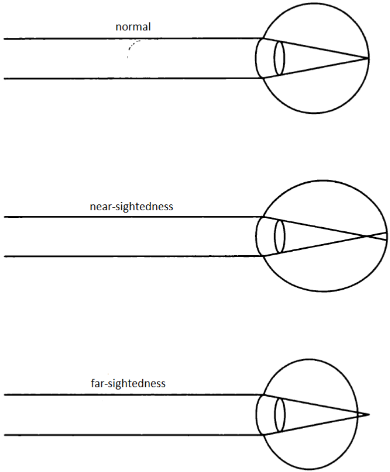
The path of light in the eye

- The light is refracted on the cornea and enters the eye – it is essentially a light-collecting lens
- The iris reduces (filters) the amount of light entering the eye, and the pupil functions as an aperture
- the eye lens is the second collecting lens; focuses the incoming light rays onto the retina (in the „healthy" eye)

The dioptre of the eye

- In total, the different parts of the eye are approx. $+60$, $+80$D (dioptre) – this means a focal length of 16-12.5mm
- The average human eye is 24mm long from the cornea to the retina – to focus on the macula you need approx. 42D
- The remaining optical power in the eye is needed to compensate for imperfections in the shape of the eye and for focusing on very close and very far objects.

The path of light in the eye



Light receptors

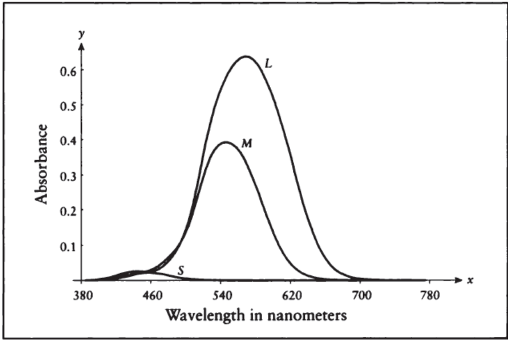
- There are two types of light sensing neurons in the retina:
  - *Rod:* they are sensitive to lower intensity light, capable of differentiating between light and dark, and have a lower resolution
  - *Cone:* neurons that require a stronger light stimulus, they are responsible for colored and detailed vision, they are ten times less sensitivee as the rods
- They are sensitve to only a certain band of the electromagnetic spectrum
- In practice, we calculate with the wavelengths between 380-780 nanometers (1 nanometer $= 1$ nm $= 10^{-9}$ m), this is the *visual band*

Photoreceptors

- When light hits a photoreceptor, a chemical reaction starts, resulting in a neural signal being sent to the brain, called *photopigment*
- Individual photoreceptors react (are sensitive) to different wavelengths of light to a different degree:
  - *Rods:* depending on the wavelength, the magnitude of the response to the same intensity of light can be described by a bell-curve-like curve – roughly corresponding to human vision at night
  - *Cones:* there are three types of them (denoted by S, M, L); each of them gives a maximum reaction at different wavelengths, and gradually less at different wavelengths
- Photopigments only record the fact of detection: an exact wavelength is not transmitted to the brain! (Spatial and frequency resolution trade-off)

Photoreceptors – Cones

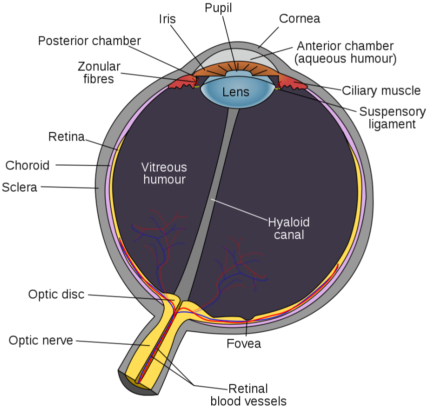
- There are three types of cones in the eye:
  - S cone: The most sensitive to light around 420 nm (blue)
  - M cone: The most sensitive to light around 530 nm (green)
  - L cone: The most sensitive to light around 560 nm (red)



Photoreceptors – Cones

- If a cone is 30% sensitive to a given wavelength, it means that it will absorb the light component of that wavelength 3 times out of 10 and send a signal to the brain
- The signals from the receptors are transmitted to the brain by the optic nerve
- The connection point of the optic nerve to the eyeball is the blind spot, there are no cones or rods here
- The macula, which is the place of sharp vision located to the side of the blind spot, in its center fovea, where only cones are found (150,000 cones per mm, but: for a hawk, 1 million at the densest part)
- Moving outwards from the fovea, cones become rarer and are replaced by rods

The structure of the human eye



Proof of blind spot

Photoreceptor signal

- A neural signal from a single photon lasts a few ms
- The effect of each new incoming photon is added to the previous one
- $\rightarrow$ The signal delivered by the receptor is essentially a temporal average, a low-pass filter, the cut-off frequency depends on the lighting conditions

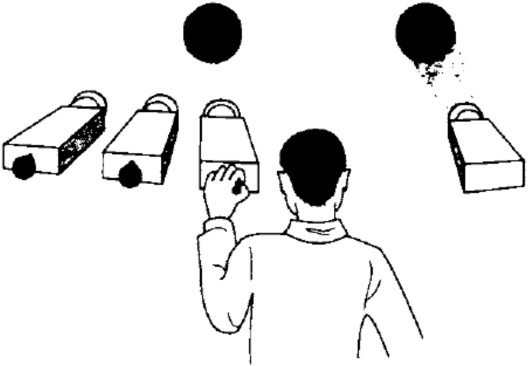
Photoreceptor signal

- A slowly flashing light is perceived as individual flashes
- However, if the time between the flashes is getting smaller and smaller, then the signals emitted by the photoreceptors are "congested" (they reach the *Critical flicker frequency*) $\rightarrow$ and we perceive it as a continuous light
- The above are true for a series of images: under CFF, flashing images are treated as separate elements, after crossing the treshold we perceive it as a contionious image stream. This is what the animation is based on
- Flicker rate depends on many factors (backlight, size of displayed image, etc.)
- Under ideal conditions, roughly 60Hz (for bees it's 300Hz)

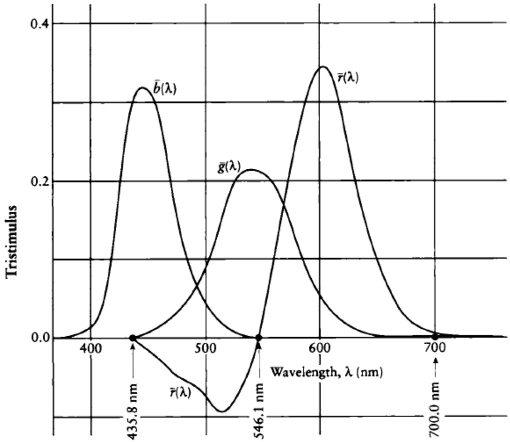
CIE

- International Commission on Illumination, 1931.: how could one give a "standard" description of how a person perceives colors
- One of the results of the experiments was that any color can be produced as a mixture of three colors (here: by projecting colored lights onto each other). (the same color can be created with different combinations of different colors! These are the metamers.)
- $\rightarrow$ Any perceived color can be coded with a number triple, *tristimulus* value

CIE

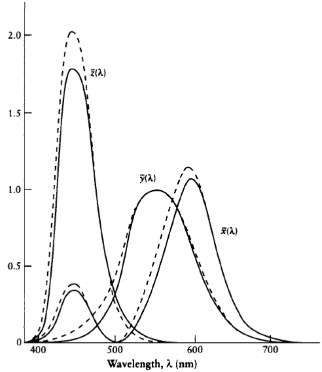


CIE



0.4
0.2
0.0
Tristimulus
$\bar{b}(\lambda)$
$\bar{g}(\lambda)$
$\bar{r}(\lambda)$
$\bar{r}(\lambda)$
400
500
600
700
Wavelength, λ (nm)
435.8 nm
546.1 nm
700.0 nm

CIE



2.0
1.5
1.0
0.5
0
$\bar{z}(\lambda)$
$\bar{y}(\lambda)$
$\bar{x}(\lambda)$
400
500
600
700
Wavelength, λ (nm)

CIE

$$C(\lambda) = X\,\overline{x}(\lambda) + Y\,\overline{y}(\lambda) + Z\,\overline{z}(\lambda)$$

$$X = \int_{\lambda \in \mathcal{R}_\mathcal{V}} C(\lambda)\,\overline{x}(\lambda)\,d\lambda$$

$$Y = \int_{\lambda \in \mathcal{R}_\mathcal{V}} C(\lambda)\,\overline{y}(\lambda)\,d\lambda$$

$$Z = \int_{\lambda \in \mathcal{R}_\mathcal{V}} C(\lambda)\,\overline{z}(\lambda)\,d\lambda$$

Tristimulus value

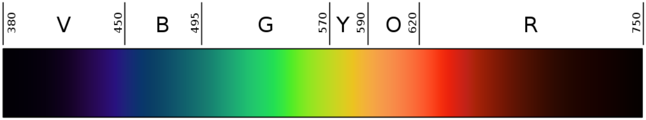
- *Perceived color* $\rightarrow$ *color space*
- A coordinate system with three "independent" base vectors can be selected here.
- Let's choose three sufficiently distant wavelengths, then for each color, specify the mixture of three such *monochromatic* light beams (containing only the given wavelength).
- These will be the *tristimulus coordinates* of the given color

RGB color space

- An additive color model. Let the three selected wavelengths be:

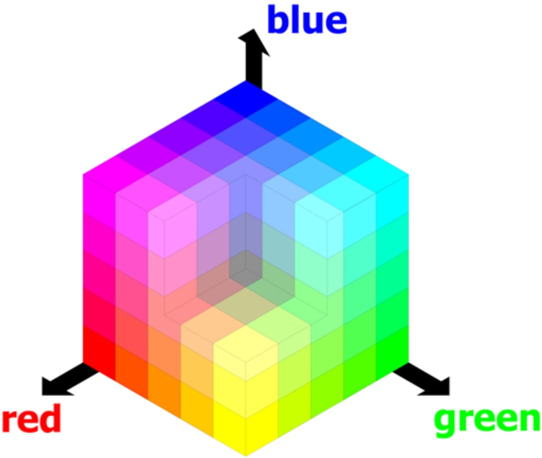
$$\lambda_{red} = 700nm, \lambda_{green} = 561nm, \lambda_{blue} = 436nm$$

- Let λ be a monochromatic light beam



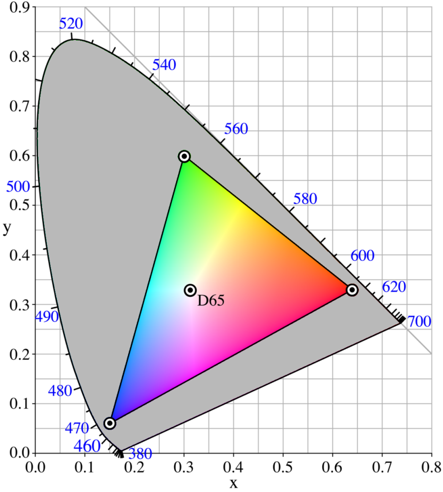
- Then we use the $r(\lambda), g(\lambda), b(\lambda)$ *color matching functions* to get the associated RGB values.
- Can all the colors of the spectrum be represented this way? No.
- Can all colors perceptible to humans be represented this way? No.
- Other color perception quirks: `https://www.youtube.com/watch?v=uYbdx4I7STg`

RGB color cube



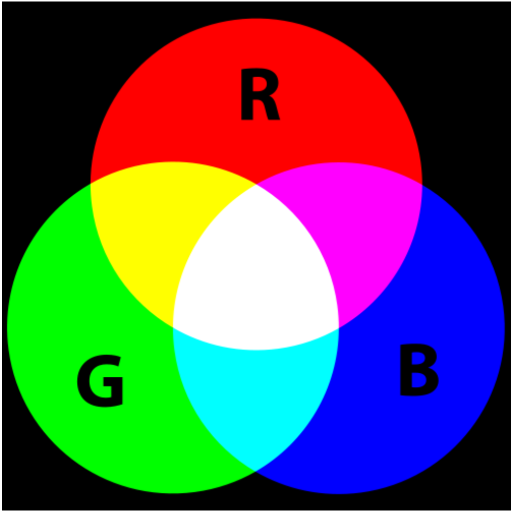
Ethan Hein, flickr

Colors that can be given in RGB



Dicklyon, Wikipedia

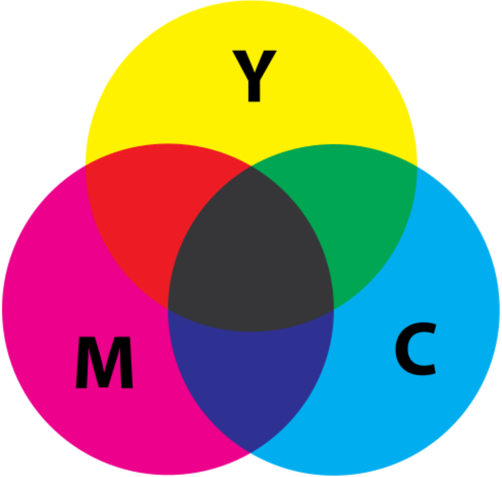
Additive color mixing



CMY(K)

- Let's look at the axes "opposite" the original axes in the RGB cube!
- These are Cyan (C), Magenta (M) and Yellow (Y).
- These three "axes" span the color space in the same way.
- This is used for color printing (there: CMYK – K is black so that you don't have to use the other three cartridges at the same time to print black)

Subtractive color mixing



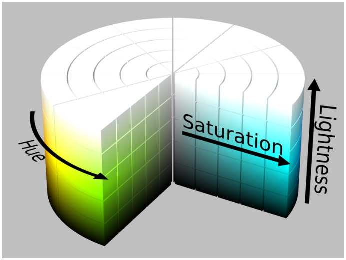
HSL and HSV – motivation

- When we talk about colors, we often use concepts such as *hue*, *saturation*, *lightness* or *darkness*. How can we use these in RGB color space?
- Let's take a color in RGB. Let's find a less bright shade! What is the relationship between components and liveliness?

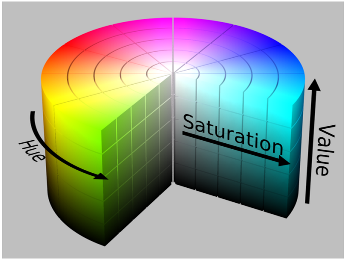
Jacobolus, Wikipedia

HSL and HSV

- Colors are represented using a cylinder, a color value *(Hue)*, a saturation *(Saturation)* and a brightness *(Lightness)* or lightness *(Value)*.



SharkD, Wikipedia

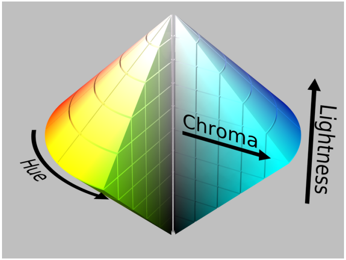


SharkD, Wikipedia

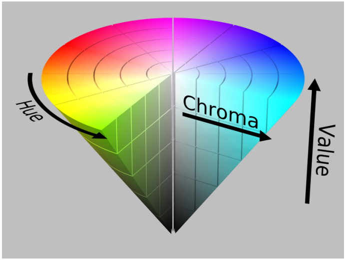
HSL and HSV

- *Hue* (color value) scale:

- Same colors:

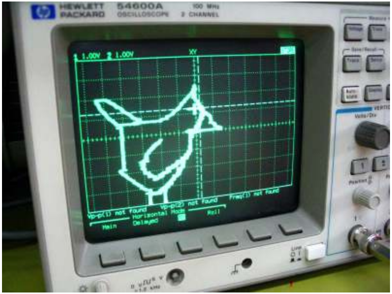


SharkD, Wikipedia

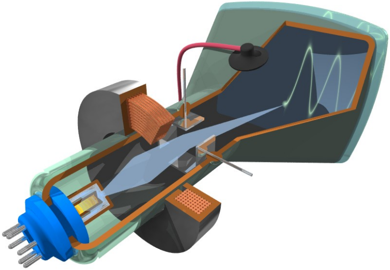


SharkD, Wikipedia

Devices – Oscilloscope



Felix E. Guerrero, flickr

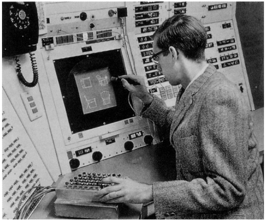


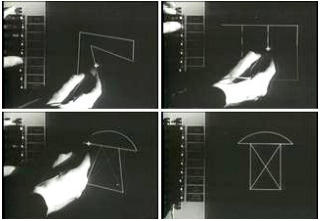
Soren Peo Pedersen, Wikipedia

- The electron gun on the back of the device emits electrons.
- The path of the electron beam is deflected by electromagnets based on the signal.
- The electron beam is bent with electromagnets based on the incoming signal
- Electrons colliding with the phosphor layer at the front of the device emit the light.

Devices – Sketchpad

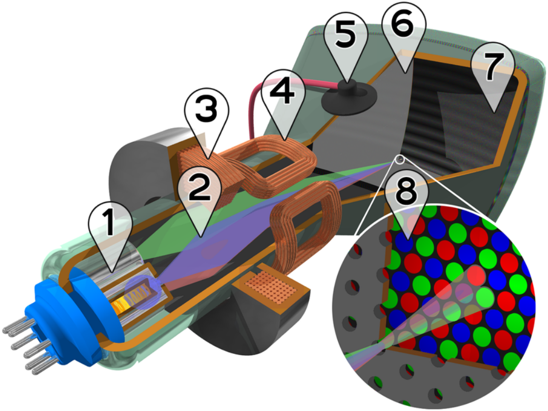
Sutherland – Sketchpad, 1963 (link)





- the ancestor of CAD applications
- 1024x1024 display
- it could be controlled with a light pen + 40 buttons
- introduced constraint-based drawing: parallel, perpendicular, etc.

Devices – CRT monitor

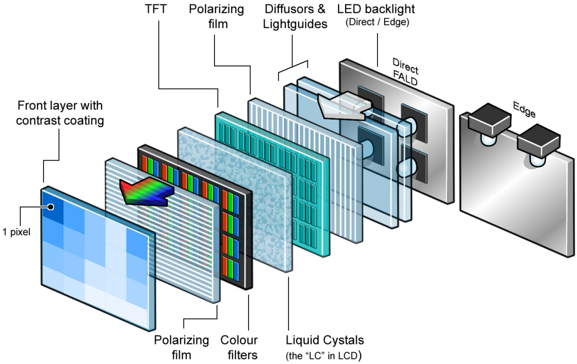


Soren Peo Pedersen, Wikipedia

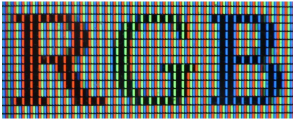
Devices – CRT monitor

- Its ancestor is the oscilloscope – same operation principle.
- The electron beam scans the screen line by line several times per second.
- The power of the beam determines brightness – it changes continuously during scanning.
- Colors: three electron guns, due to the difference in the angle of incidence, they reach the area with the appropriate color filter.
- Slow motion (link)

Devices – LCD monitor



flatpanelshd.com

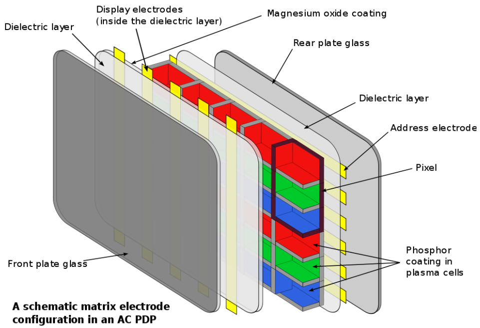


Luís Flávio Loureiro dos Santos, Wikipedia

Devices – LCD monitor

- White backlight
- First, the light passes through a polarizing filter
- Next comes the eponymous liquid crystal layer, it has a property of rotating the light's polarisation with different degrees based on the voltage
- Colors: each color filter receives light of a different polarization.
- Finally, the light passes through the polar filter, which is perpendicular to the previous one, thus controlling the amount of outgoing light.

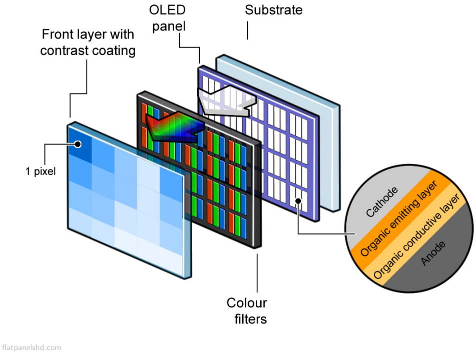
Devices – Plasma Display



Wikipedia

- Each pixel emits its own light.
- The pixels contain a noble gas that lights up under voltage, on a similar principle to the neon tubes.

Devices – OLED



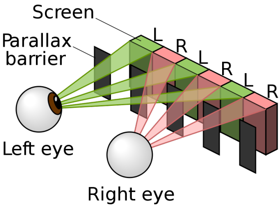
- Each pixel emits its own light.

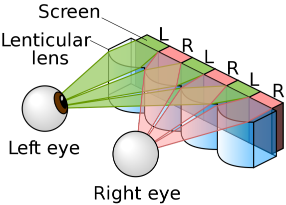
Devices – 3D displays

- *Stereoscopy*
  The two eyes see different image, there is no movement parallax
  - *Head Mounted Display*
  - *Shutter glasses*
  - Glasses with polarized lenses
- *Autostereoscopy*
  It does not require a separate device from the user
  - *Parallax barrier*
  - *Lenticular lens*

Devices – 3D displays

Parallax and Lenticular





Marvin Raaijmakers, Wikipedia

and more...

- Printers
- 3D printers
- Plotters
- Mini LED displays
- Projectors
- ...

Raster graphics

Doink, vecteezy.com

Raster graphics

- The smallest unit of the image is the pixel, which represents a color.
- We store the pixels in some $N \times M$ array.
- When zooming in/out we only change the size of the pixels

Vector graphics

Doink, vecteezy.com

Vector graphics

- The image is made up of elements which can be described mathematically: curves, plane figures
- Different properties are assigned to them: color, fill, line thickness.
- The line is indeed straight, the curves remain curved under any magnification.