TOPICS

- Recap of PHYS110 *- 1 lecture*
- **Physical Optics** *- 4 lectures*

  EM spectrum and colour
  Light sources
  Interference and diffraction
  Polarization

- Lens Aberrations *- 3 lectures*

  Spherical aberrations
  Coma, astigmatism, field curvature, distortion
  Chromatic aberrations

- Instrumental Optics *- 4 lectures*

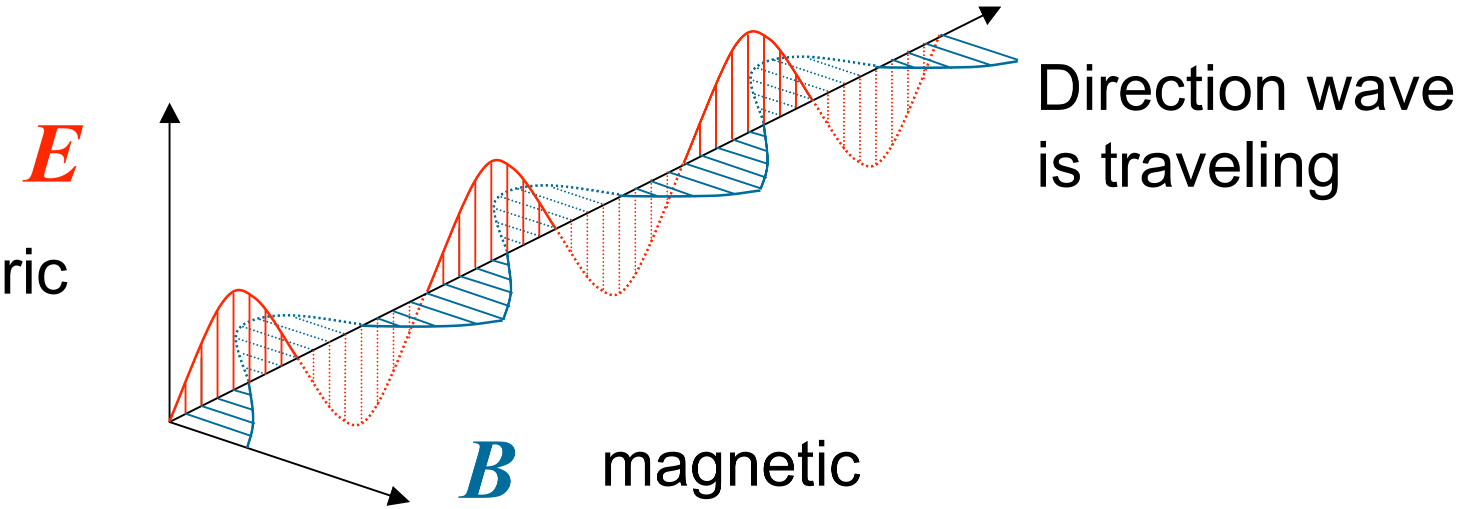
  Telescope, microscope
  Stops, eyepieces
  Instruments for the anterior eye
  Instruments for the posterior eye

Lecture 2

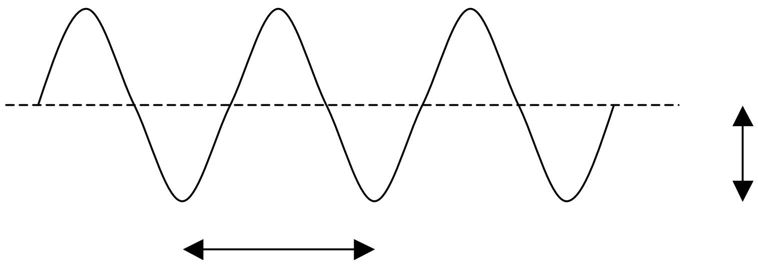
- Electromagnetic spectrum and colour
  - properties of light
  - the electromagnetic spectrum
  - continuous and line spectra
  - additive colour mixing
  - subtractive colour mixing

EM waves

- Light is a transverse wave - like waves on a string
  - In contrast, sound is a longitudinal wave
- The associated electric and magnetic fields, E and B are perpendicular to the direction the wave is travelling and to each other



Wave properties

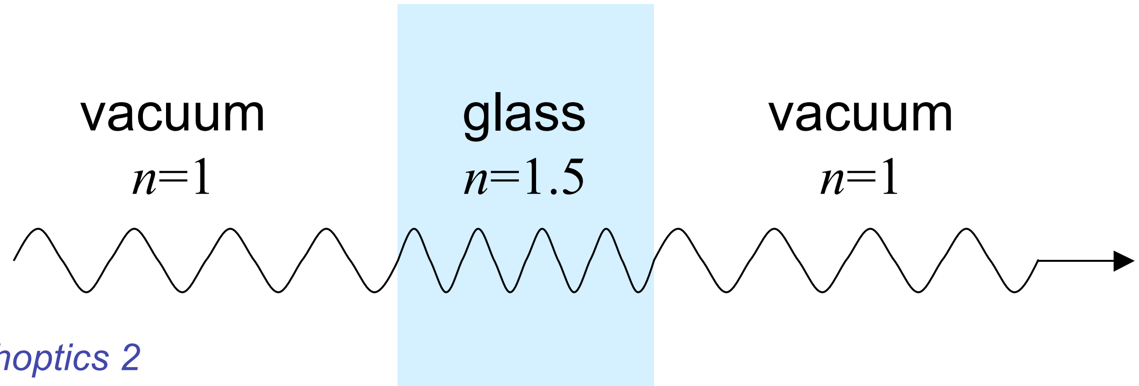


amplitude, A
determines the brightness

wavelength, λ
determines the colour

Speed and frequency of light

- In vacuum, light travels at c=300,000 km/s, independent of the colour
- In a medium with refractive index n, the speed of light is $v=c/n$
- The wavelength becomes correspondingly smaller: $l_{\mathrm{medium}}=l_{\mathrm{vacuum}}/n$
  - The wavelength of light referred to is by default the wavelength in vacuum



Frequency of light

- The speed v, wavelength λ, and frequency f of light are related: $f = v/\lambda$
- The frequency is independent of the medium
  - In a medium with refractive index n, both v and λ decrease by a factor n, so $f = v/\lambda$ stays the same

Example:

Red light with a wavelength of 600nm (in vacuum) has a frequency of

$$f = \frac{c}{\lambda} = \frac{3\times10^{8}\,\text{ms}^{-1}}{600\times10^{-9}\,\text{m}} = 5\times10^{14}\,\text{Hz}$$

Quantisation of light

- Light comes in units of energy called **photons**
- Short wavelengths carry more energy per photon than long wavelengths
- The energy of a photon is calculated as $E=hf$ or $E=hc/\lambda$
- The energy of a photon is independent of the medium
- h is called Planck's constant
- $h = 6.626\times10^{-34}\text{Js}$

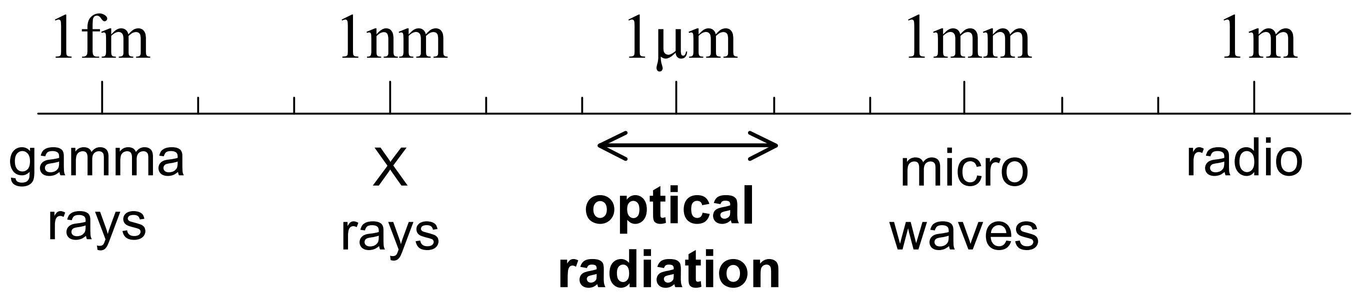
Example:

Red light with a wavelength of 600nm has an energy per photon of

$$E = \frac{hc}{\lambda} = \frac{6.626\times10^{-34}\,\text{Js}\times3\times10^{8}\,\text{ms}^{-1}}{600\times10^{-9}\,\text{m}} = 3.3\times10^{-19}\,\text{J}$$

EM spectrum

- Covers enormous range of wavelengths:



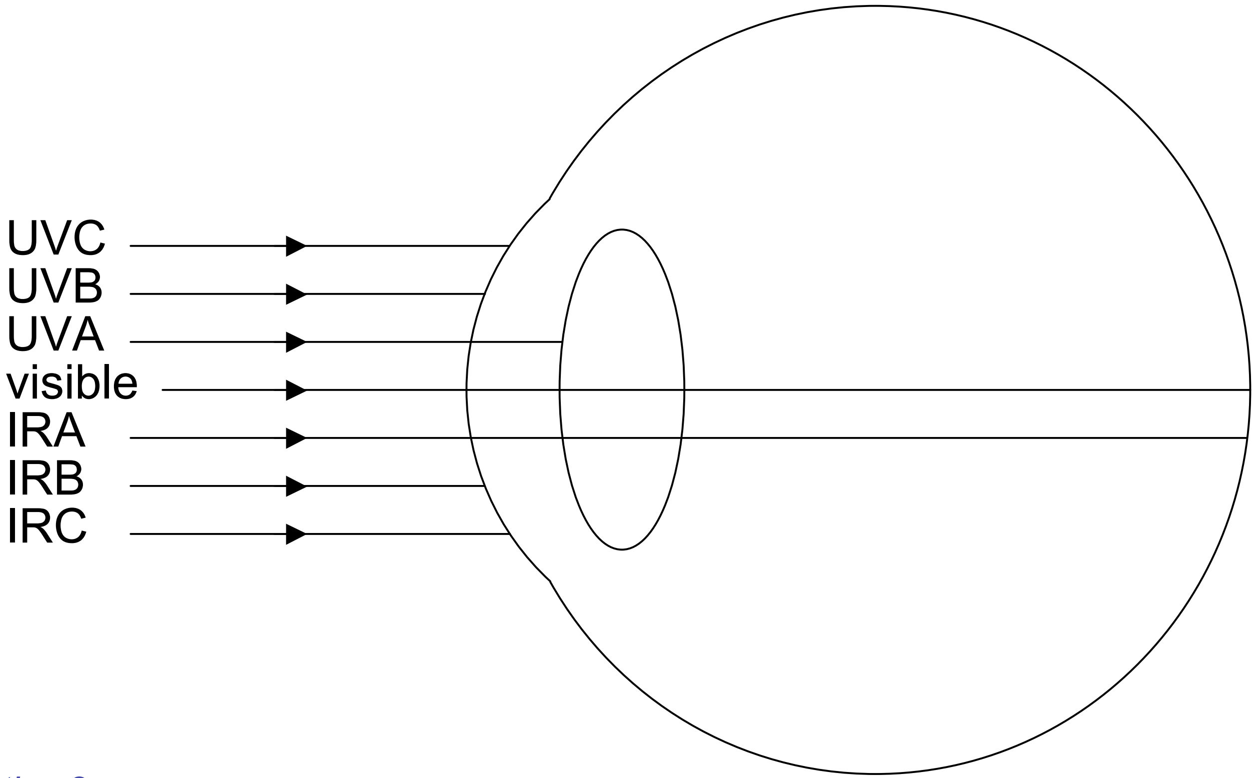
- In this course we only consider optical radiation, covering 200nm – 10μm.

Optical radiation

- Subdivided into 7 bands:
  - Ultraviolet C: 200 - 280 nm
  - Ultraviolet B: 280 - 315 nm
  - Ultraviolet A: 315 - 400 nm
  - **Visible light**: 400 - 780 nm
  - Infrared A: 780 - 1400 nm
  - Infrared B: 1400 - 3000 nm
  - Infrared C: 3000 - 10000 nm
- Ultraviolet radiation is invisible but can damage tissue by breaking molecular bonds
- Infrared radiation is invisible but intense IR radiation can damage tissue by heating

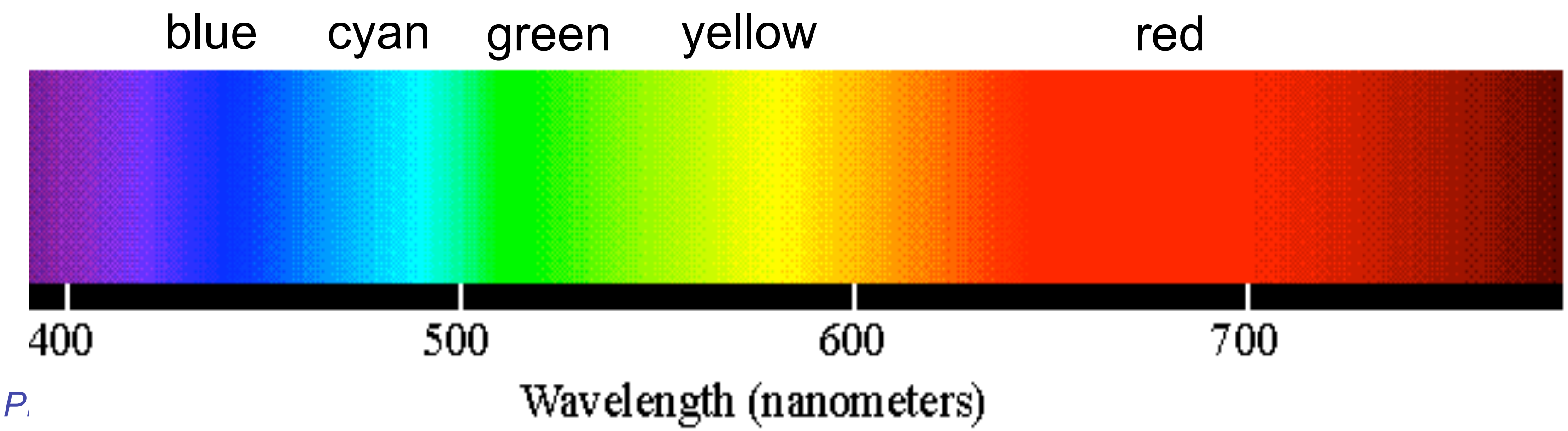
Absorption in the eye

- The cornea absorbs the very short (UVC, UVB) and very long (IRB, IRC) wavelengths
- The lens absorbs UVA
- Visible light and IRA radiation reach the retina



Visible light

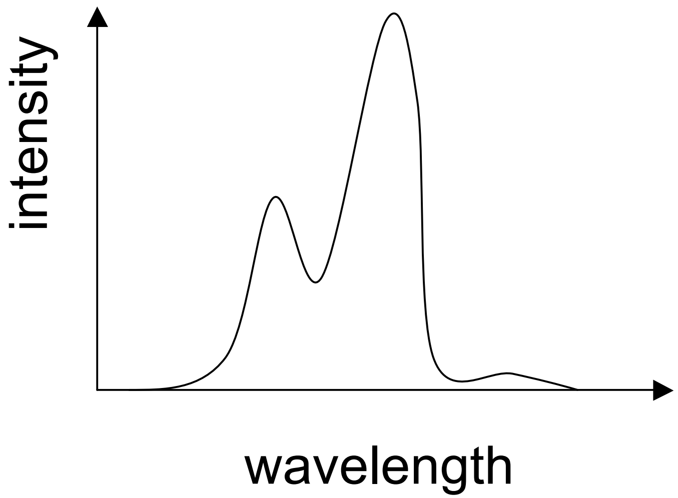
- Blue light has
  - the shortest wavelength
  - the highest frequency
  - the highest energy per photon
- Red light has
  - the largest wavelength
  - the lowest frequency
  - the lowest energy per photon



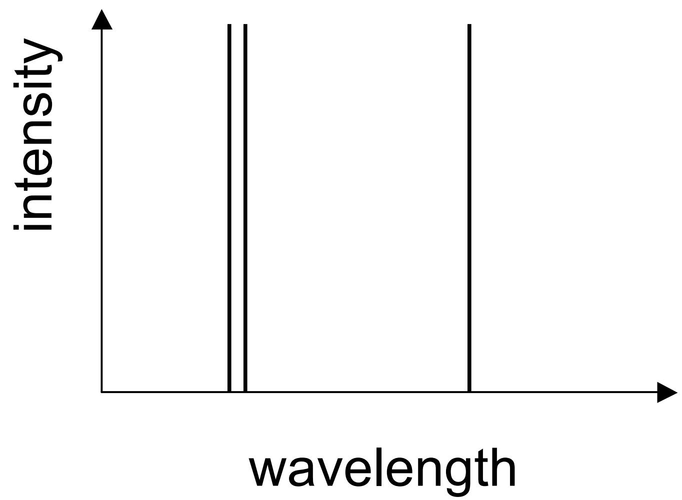
Spectrum of light

- In general, light is a mixture of many wavelengths
- Light is described by its spectrum:

continuous spectrum
all wavelengths in a certain range contribute to the light

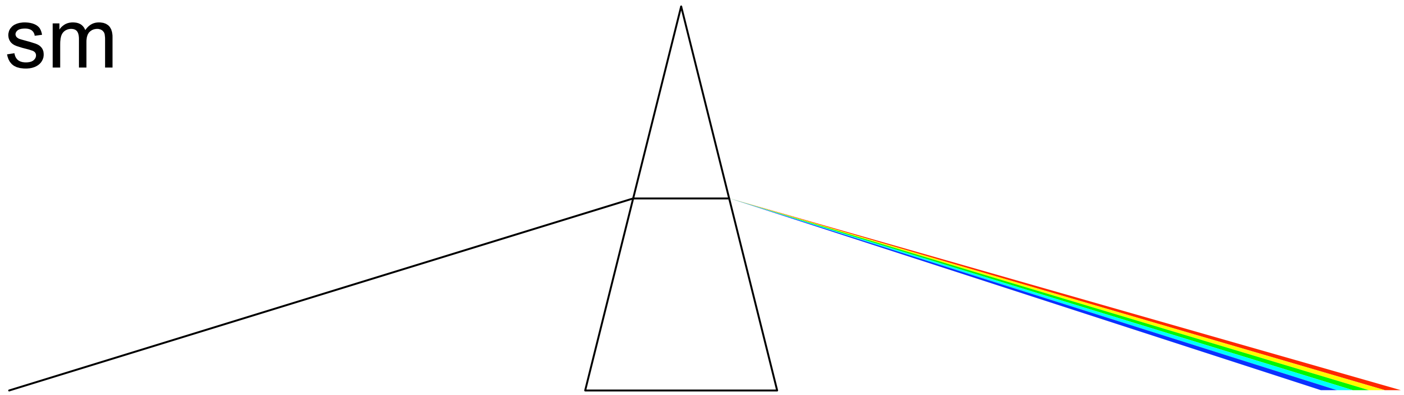


line spectrum
only a small number of wavelengths dominate



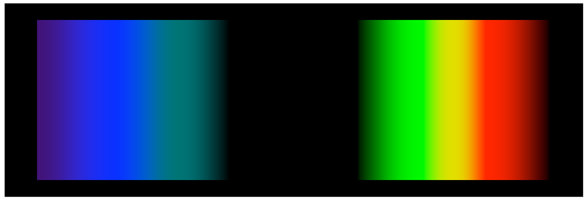
Spectral analysis

- The spectrum of light can be analysed with a spectrometer
- The simplest spectrometer is a prism
- Most materials have a higher refractive index for blue light than for red light
- Blue light thus deviates more than red light in a prism

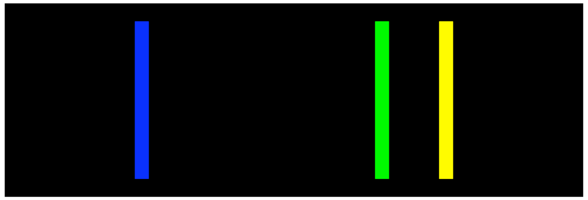


Spectral analysis

Continuous spectrum
seen through spectrometer

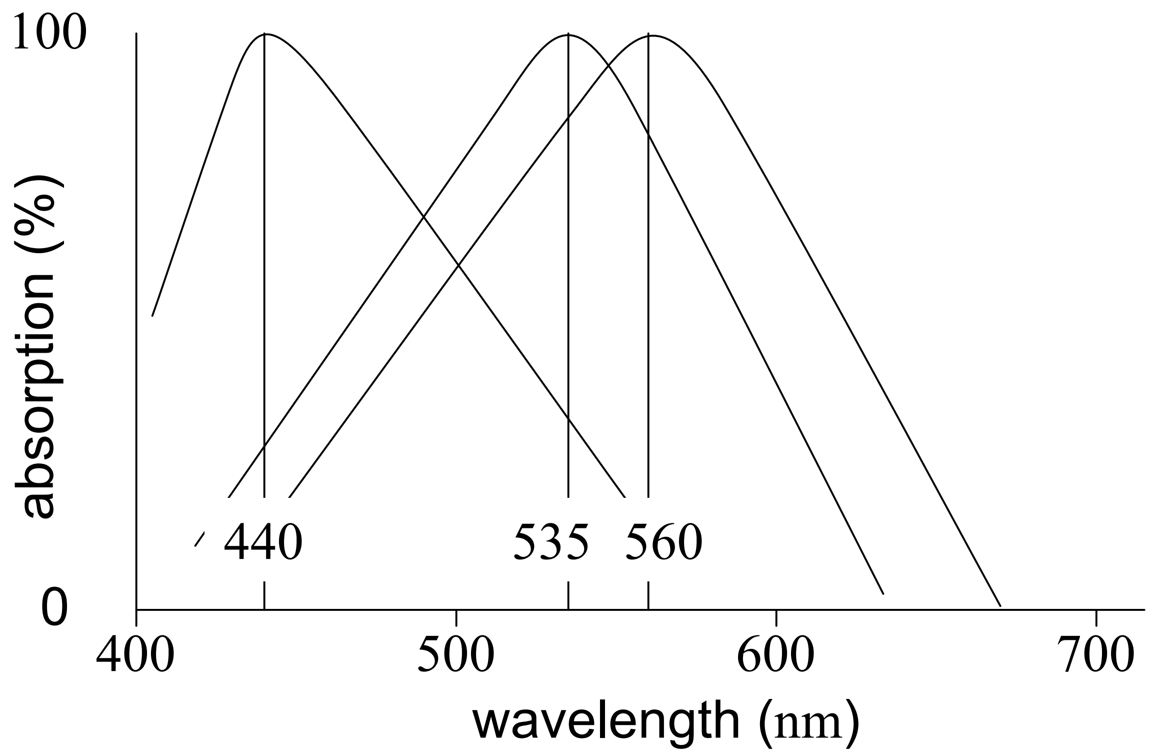


Line spectrum
seen through spectrometer



Spectral sensitivity of the eye

- The eye is a (very poor!) spectrometer
- Has receptors for 3 different parts of the spectrum
- These correspond roughly to red, green and blue.



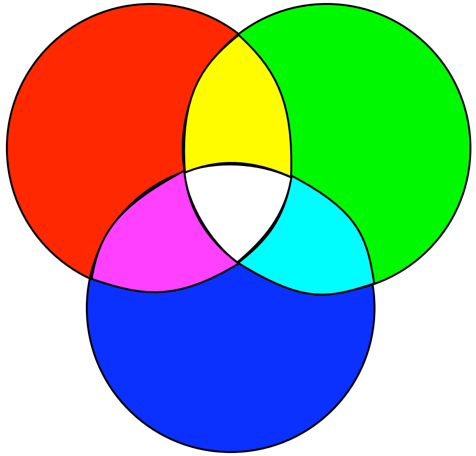
Colours

- Depending on which receptors are stimulated, we interpret colours:

No receptor stimulated:	black
Red receptor stimulated:	red
Green receptor stimulated:	green
Blue receptor stimulated:	blue
Red, green receptor stimulated:	yellow
Red, blue receptor stimulated:	magenta
green, blue receptor stimulated:	cyan
Red, green, blue receptor stimulated:	white

Additive colour mixing

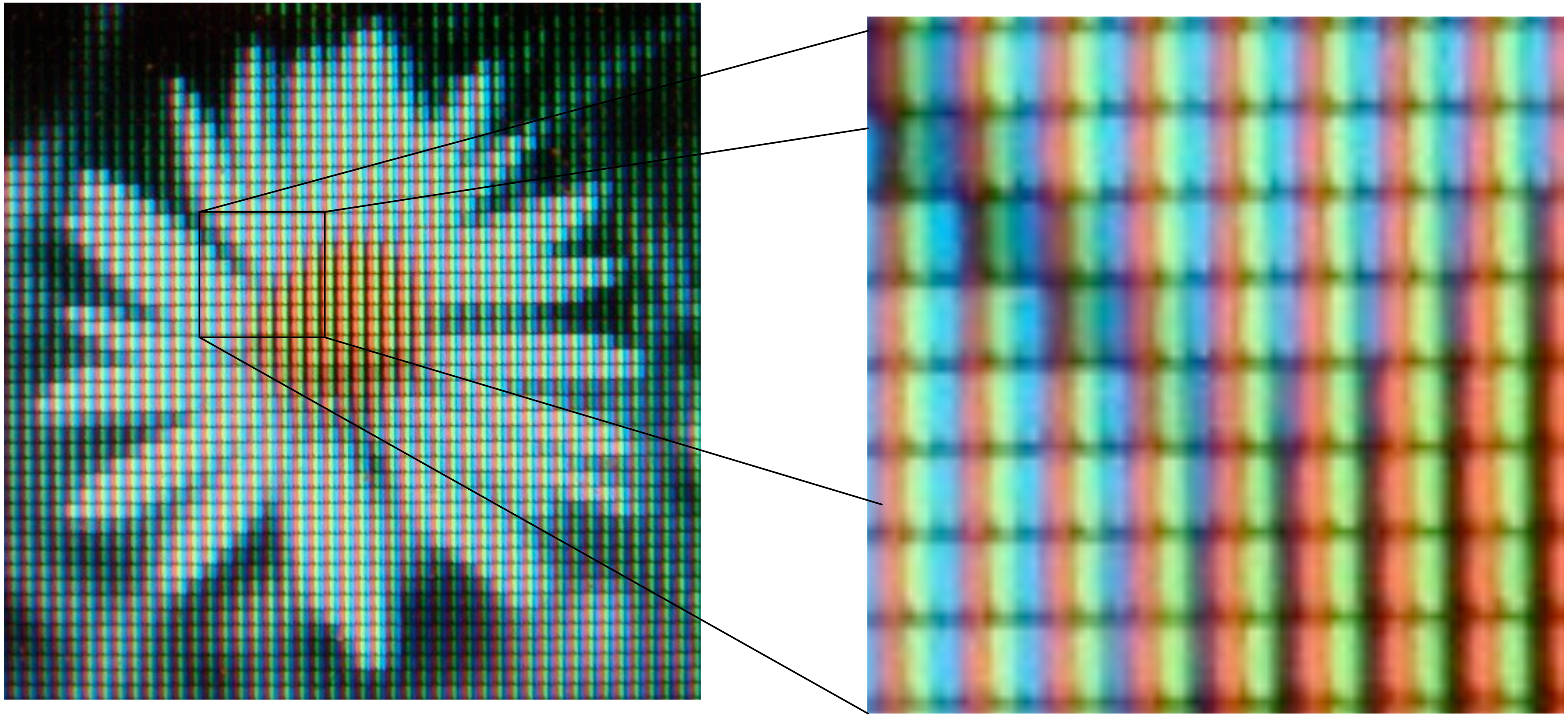
- This leads to the theory of **additive** colour mixing:
- These rules apply to mixing **light**



Red light	+ green light	= yellow light
Red light	+ blue light	= magenta light
Green light	+ blue light	= cyan light
Yellow light	+ blue light	= white light
Magenta light	+ green light	= white light
Cyan light	+ red light	= white light

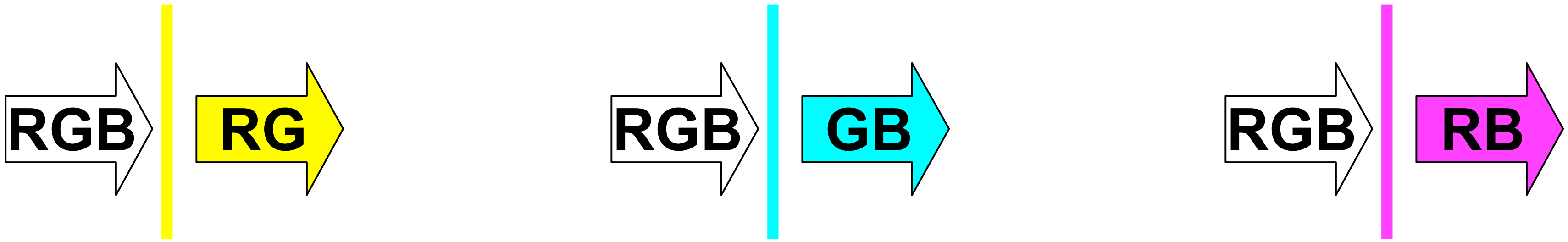
Example: television screen

- From close by, a television screen has a red, green and blue segment for each pixel.
- When seen from far away, the 3 segments mix into one colour, following the rules of additive colour mixing



Coloured filters

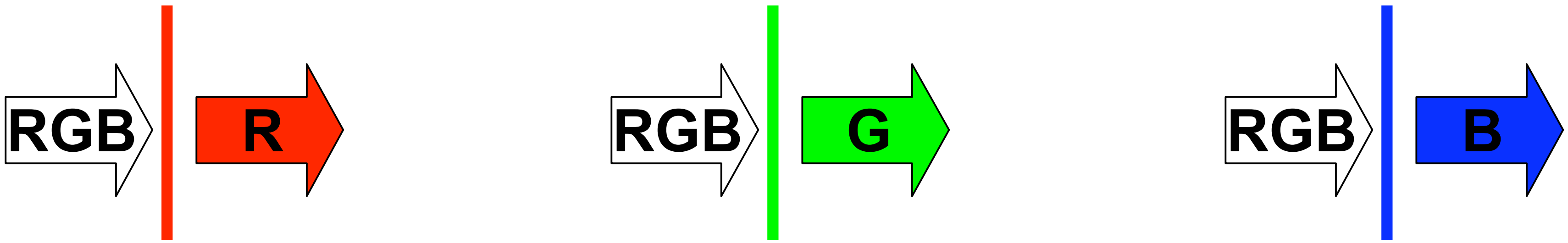
- If white (R+G+B) light passes through a yellow filter, the blue component will be absorbed. What's left is yellow light (R+G)



A yellow filter absorbs blue

A cyan filter absorbs red

A magenta filter absorbs green

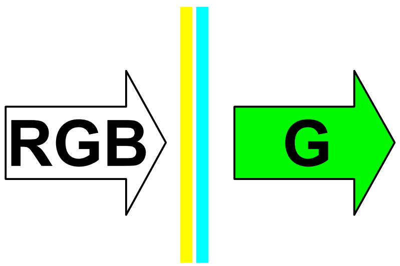


A red filter absorbs green and blue

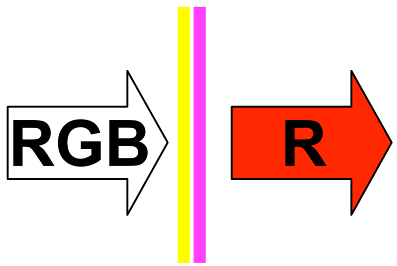
A green filter absorbs red and blue

A blue filter absorbs red and green

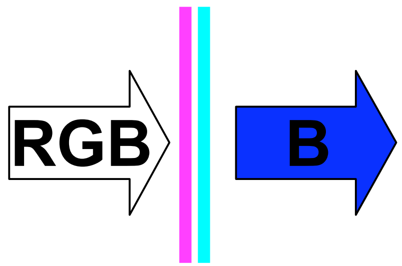
Combining filters



A yellow and cyan filter absorb blue and red. Combined, they appear green



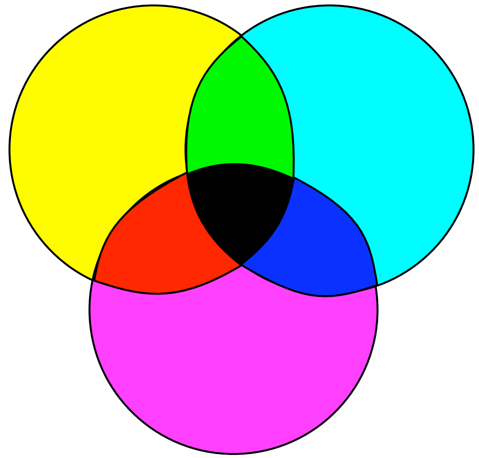
A yellow and magenta filter absorb blue and green. Combined, they appear red



A magenta and cyan filter absorb green and red. Combined, they appear blue

Subtractive colour mixing

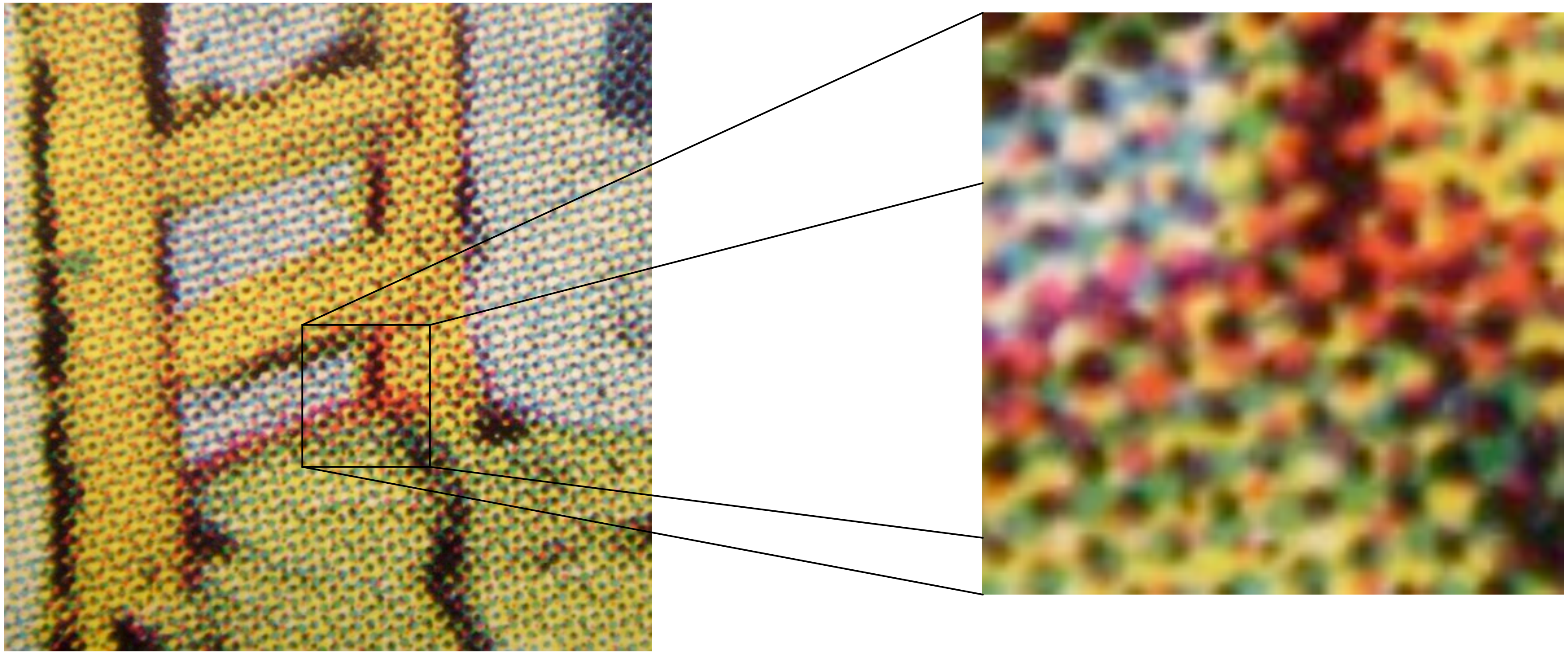
- This is called of **subtractive** colour mixing:
- The rules apply to mixing **filters** or **ink**



Yellow ink	+ cyan ink	= green ink
Yellow ink	+ magenta ink	= red ink
Cyan ink	+ magenta ink	= blue ink
Yellow ink	+ blue ink	= black ink
Magenta ink	+ green ink	= black ink
Cyan ink	+ red ink	= black ink

Example: printed colour pictures

- To print colour pictures, three rasters of ink are used: yellow, magenta, cyan.
- In practice, black is added as a fourth ink to achieve deeper shades of black.



Blue skies, red sunsets

- Sunlight is scattered by the molecules in the air
- Short wavelengths are scattered more than long wavelengths
- Blue is scattered throughout the sky
- Red light arrives in a straight line from the sun