Interaction of light and materials

ver. 20191201

Properties of light

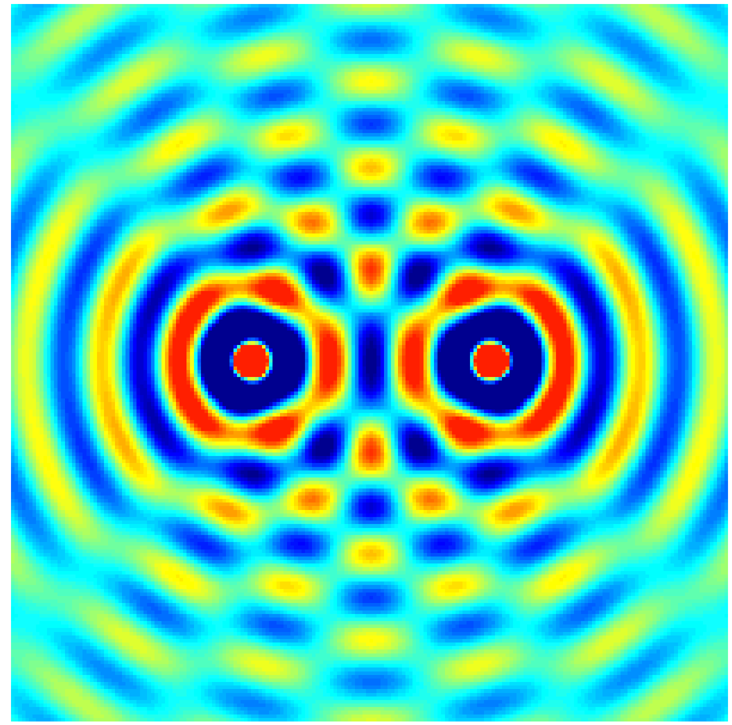
- Light is electromagnetic radiation.
- Wave–particle duality.

By Ibrahim Iujaz from Rep. Of Maldives

Light behaves as wave

A principal certainty of being wave is the production of interference patterns.

Interference of waves from two dot-like sources.



By Oleg Alexandrov - self-made with MATLAB, Public Domain, https://commons.wikimedia.org/w/index.php?curid=3380145

Properties of light as wave

Speed of light (c): not constant, depends on the medium!
highest speed in vacuum: c_0 = 2,99792458·10^8 m/s

Wavelenght (λ): the length of one period of the electromagnetic wave

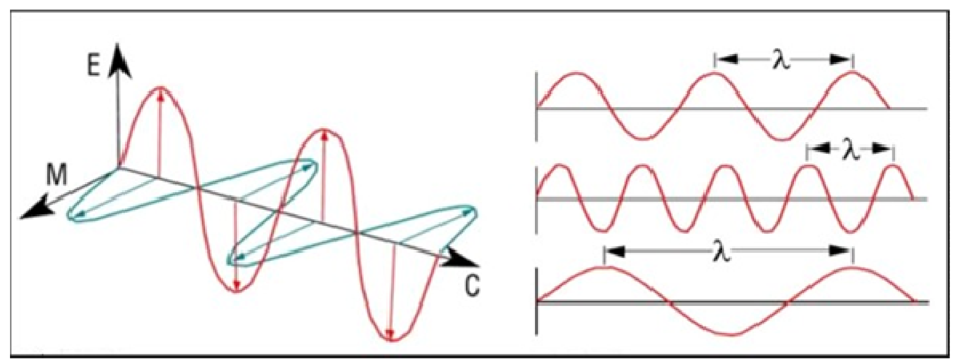
Frequency (ν): the number of waves that pass a point in space divided by the time interval

Wave number ($\tilde{\nu}$): number of wavelengths divided by the distance

Not independent quantities!

$$c = \lambda \cdot \nu$$

$$\tilde{\nu} = 1/\lambda$$



www.tankonyvtar.hu FOI101.png

Properties of light as wave

Problem: Give the wavelengh and wavenumber of the light if its frequency is $4.84 \cdot 10^{14}$ Hz!

Answer: $\lambda = c_0 / \nu = 2.998 \cdot 10^{8}$ m/s / $4.84 \cdot 10^{14}$ Hz = $6.1942 \cdot 10^{-7}$ m = 619.42 nm

$\underline{\lambda = 619 \text{ nm}}$

Note that Hz = 1/s!

$\tilde{\nu} = 1/\lambda = 1/\ 6.1942 \cdot 10^{-7}$ m = $1.64 \cdot 10^{6}$ m^{-1}

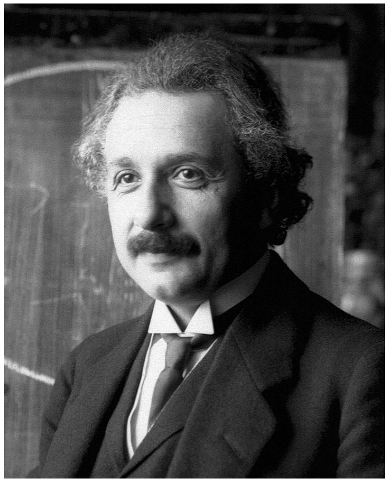
Albert Einstein

Einstein won a Nobel prize in physics in 1921.

„for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect."

NOT for the Theory of relativity!

What was supposed to be more important than the Theory of relativity hundred years ago?



Albert Einstein
1879-1955
German physicist

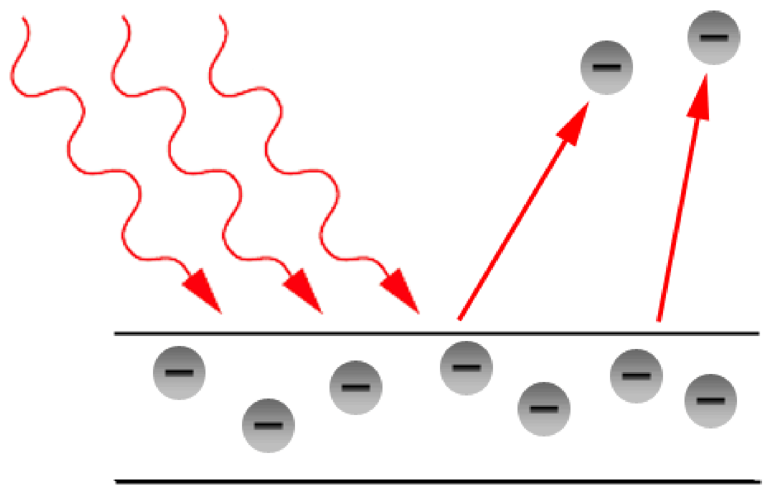
The photoelectric effect – light behaves as particle

Photoelectric effect: metal electrodes exposed to light sparks more readily, emits electrons.

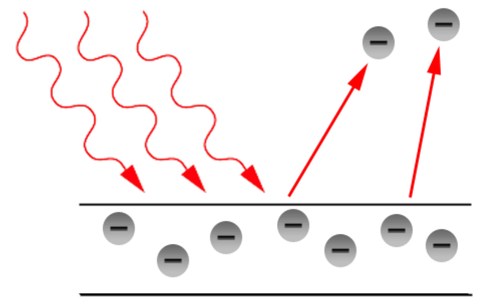
Red light does not produce electrons even if the light intensity is strong.

Blue, ultraviolet light produces electrons even if the light intensity is weak. More intensive light produced more electrons.

Not only the light intensity is impoertant, but the wavelength / frequency of light!



The photoelectric effect
The expalanation

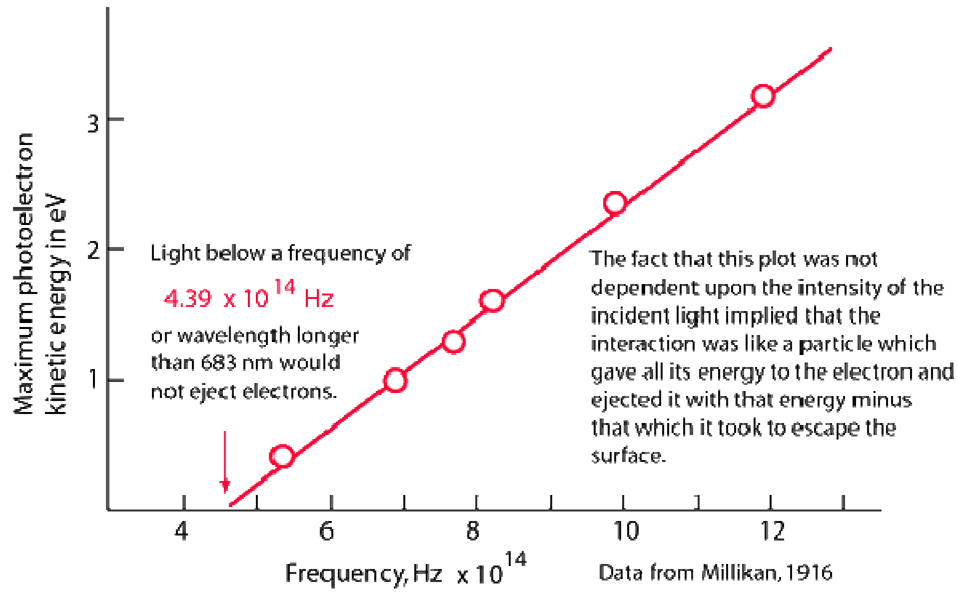


Light consists packets (quanta) having fixed energy at certain frequencies.

One such light quantum must have a certain minimum frequency (energy) before it can liberate an electron.

This minimum energy is called photoelectric work. If the photon has more energy (higher frequency) the surplus energy is converted to the kinetic energy of the electron.

Everything can be explained well assuming a particle, the light quantum called **photon**.



http://hyperphysics.phy-astr.gsu.edu/hbase/imgmod/pelec4.png

Properties of light

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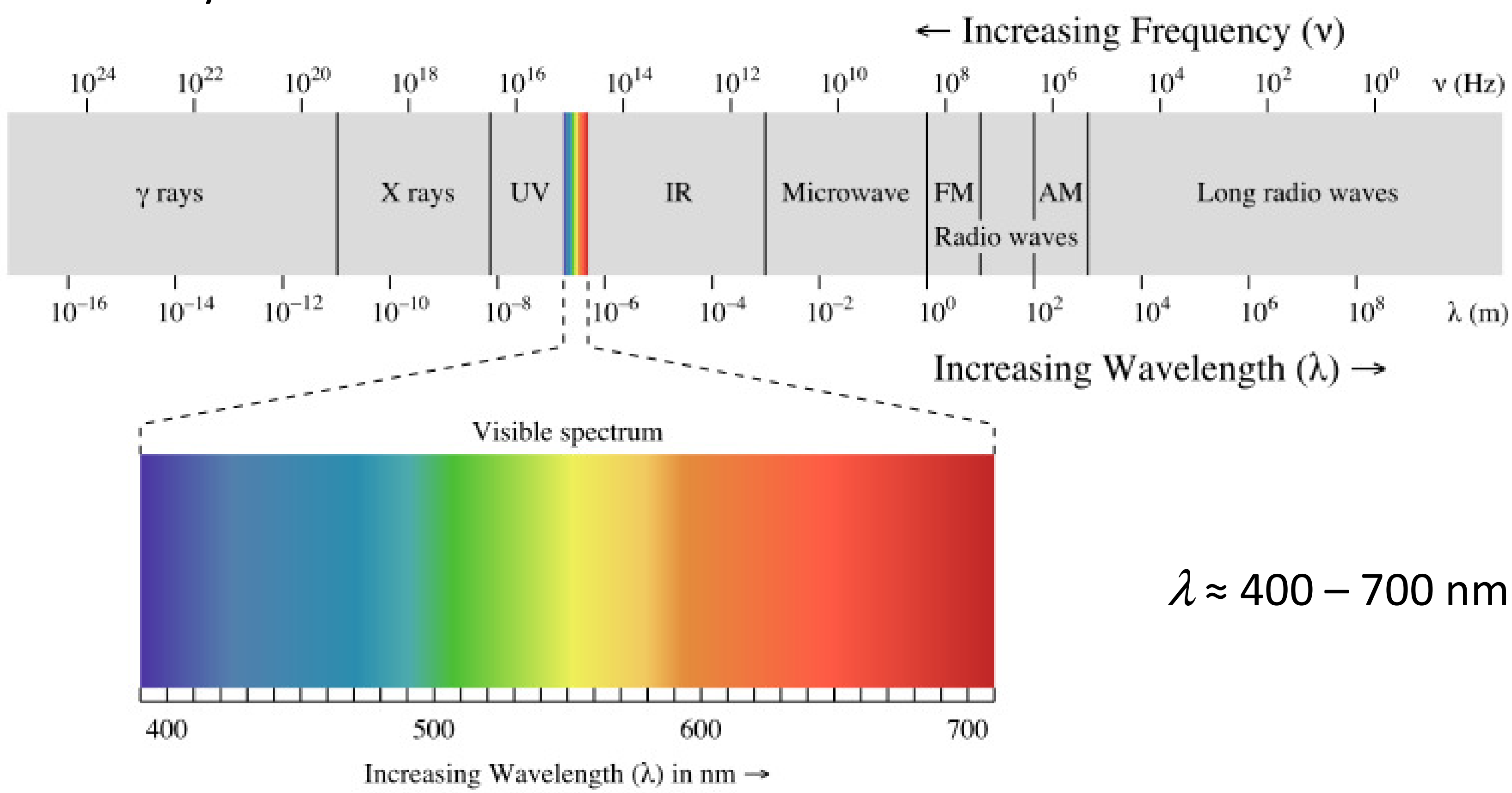
Not independent quantities! $c = \lambda \cdot \nu$

Energy: $E = h \cdot \nu$

where h is the Planck's constant
($6.62607004 \cdot 10^{-34}$ m^2kg/s)

The electromagnetic spectum

The **visible** spectrum is a narrow portion of the electromagnetic spectrum that is visible to the human eye.



$\lambda \approx 400 - 700$ nm

The visible spectrum

The **visible** spectrum is a narrow portion of the electromagnetic spectrum that is visible to the human eye.

There are no strict bounds.

Animals may see wider rages than humans.

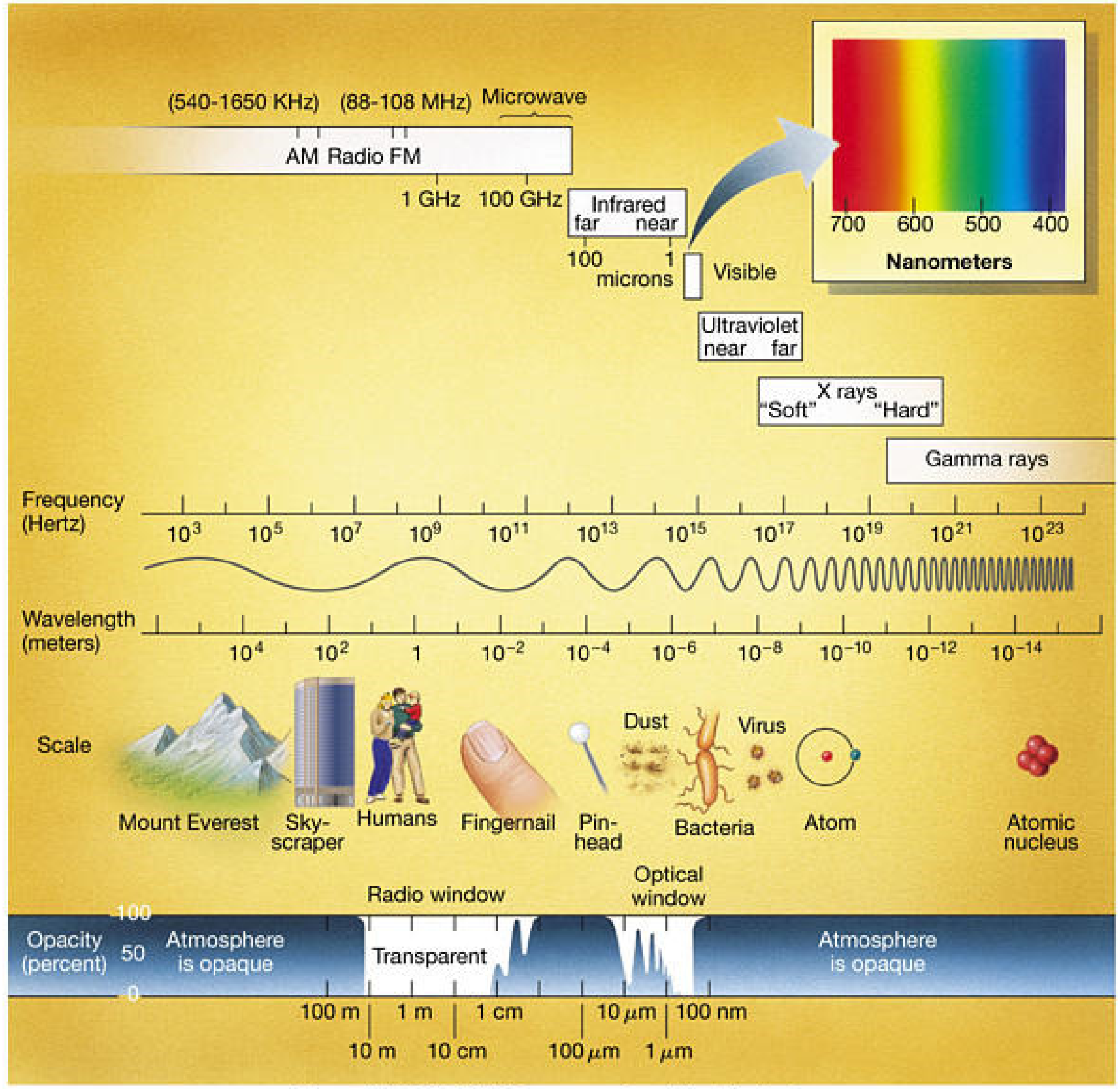
See e.g.:
Taking a Bird's-Eye View…in the UV: Recent studies reveal a surprising new picture of how birds see the world
Jay Withgott
BioScience, Volume 50, Issue 10, October 2000, Pages 854–859,
10.1641/0006-3568(2000)050[0854:TABSEV]2.0.CO;2

Why this range?

Earth's atmosphere partially or totally **blocks some wavelengths** of electromagnetic radiation, but it is **mostly transparent for the visible light and the radio waves** (called optical and radio windows).

The wavelenght of the **radio waves** is **too long** for the everyday observations (order of 1 m).

→The optical windows is used by nature.



Interaction of light and materials

- Fundamental processes which can happen when light interacts with materials:
  - Reflection – light does not penetrate in the material, but comes back from the surface
  - Transmission - light goes through the material without loss of energy at a given angle
  - Scattering – light penetrates in the material, but comes out at different angles
  - Absorption – light enters and gives its energy to the material

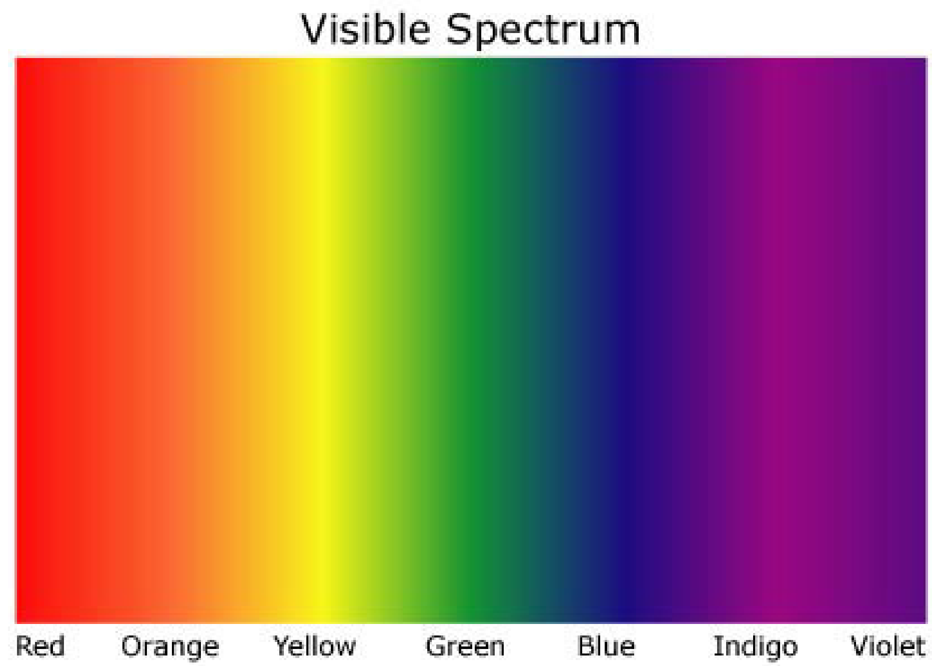
Dispersion of light by prism

http://www.thenakedscientists.com/forum/index.php?action=dlattach;topic=24878.0;attach=9410

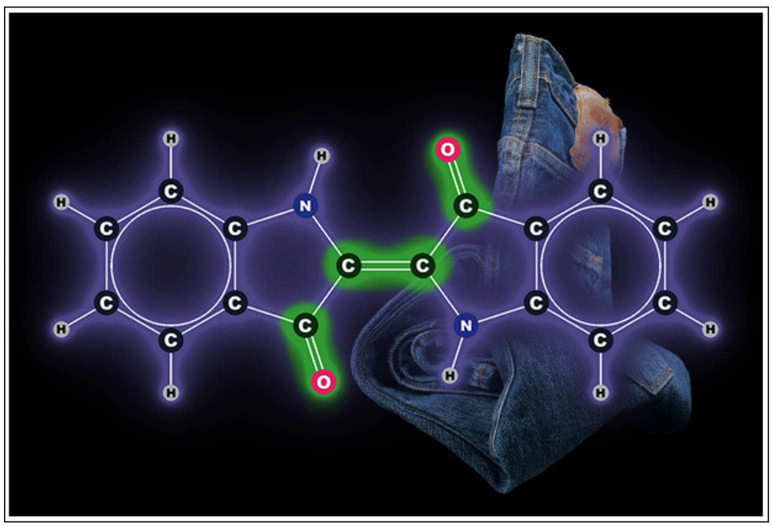
The color of materials

Things do not have color by themselves, only when light hits them, we can see colors.
Remember, your surroundings appear greyish or downright black when you're in the dark.

We can see a spectral range of the visible light as color:



http://flyeschool.com/sites/flyeschool/files/images/art_terms/spectrum.jpg



The organic molecule (2,2'-Bis(2,3-dihydro-3-oxoindolyliden)) causes the blue-indigo color of the jeans.
https://www.zmescience.com/science/physics/what-gives-colour/

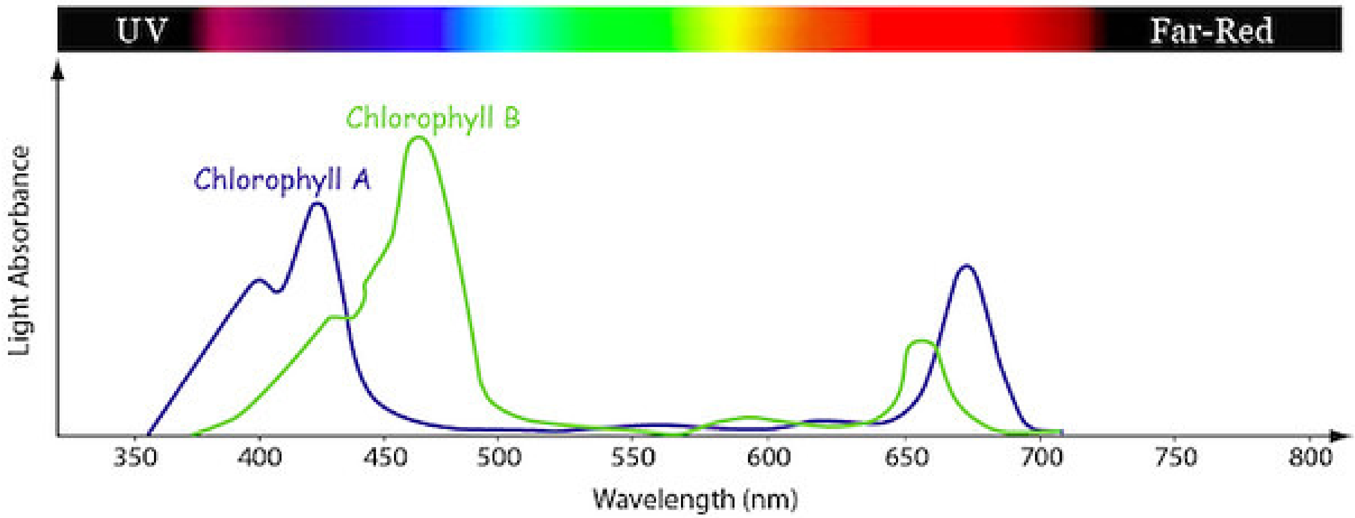
The color of materials

If something is **opaque** the color depends on the **light reflected**.

The color you can see is the mix of the **reflected colors**.

The green color of leaves comes that chlorophyll absorbes violet, blue and red, therefore mainly green is reflected from the surface.

https://ak8.picdn.net/shutterstock/videos/9747008/thumb/11.jpg



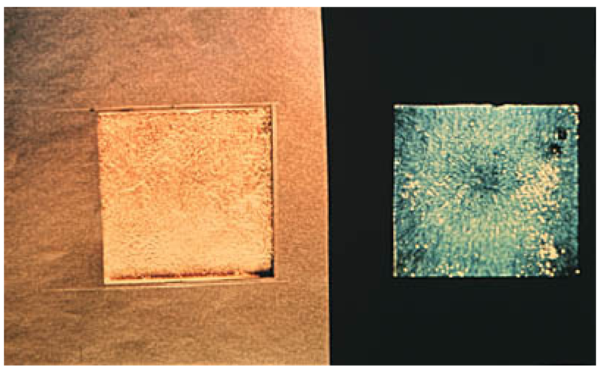
https://live.staticflickr.com/8280/29979758460_937d88fd59_z.jpg

The color of materials

If something is **transparent** the color depends on the **light transmitted**.

The color you can see is the mix of the **transmitted colors**.

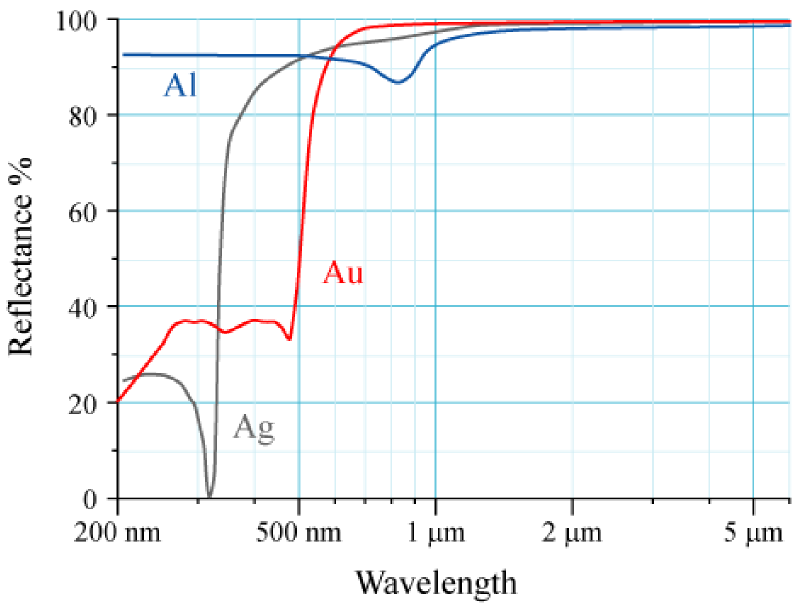
Gold metal looks orangish when it is solid, opaque metal, but if it is a very thin foil, as thin as light can transmitted through it has bluish color. The these colors are complementary colors.



https://www.mozaweb.hu/course/feny/jpg/feny419.jpg

Gold is metallic gold color in reflected light.

Gold is metallic blue color in transmitted light.



By DrBob, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1729695

450 nm - 500 nm: blue

What kind of color is the black?

Black is the darkest color, the result of the absence or complete absorption of visible light. (*Wikipedia*)

So black surfaces absorb all kind of light. By theory. In practice:

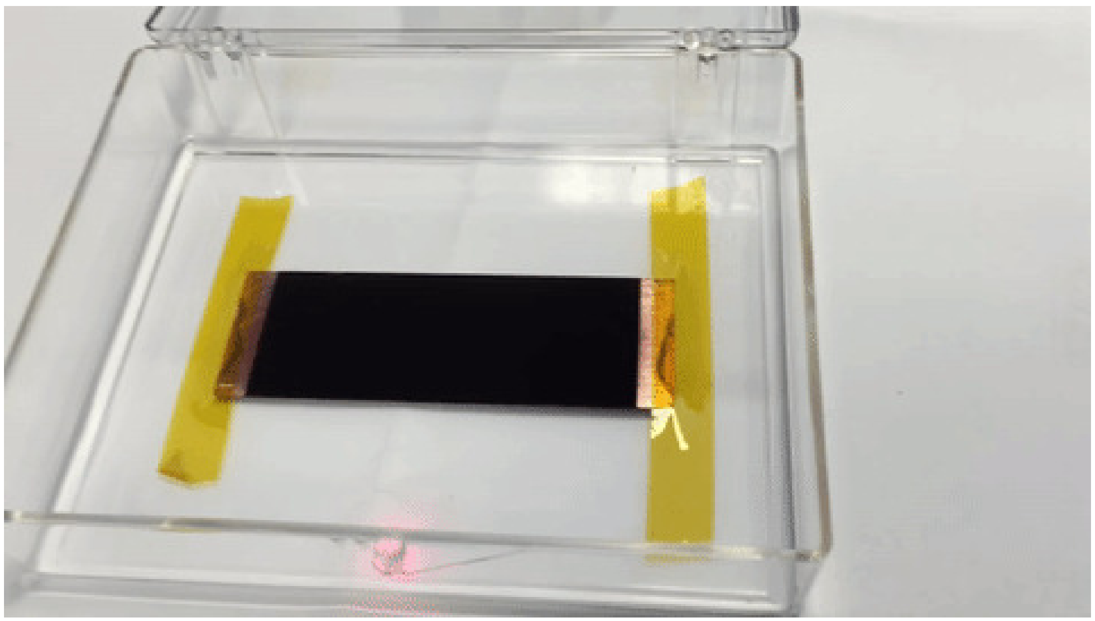
http://www.gunandcamera.com/wp-content/uploads/2015/01/thermometer-laser-pointer1-300x200.jpg

What is really black? The Vantablack!

http://www.surreynanosystems.com/ **Vantablack**

This material is made of carbon nanotubes and **absorbes 99,96% of the incident light!**

You can not see even the bright dot of a laser!



https://media.giphy.com/media/Ae9DkvzPCiReo/giphy.gif

The blackest car of the world was released in 2019: BMW X6 Vantablack

https://techworld.hu/wp-content/uploads/2019/08/bmw-x6-vantablack.jpg

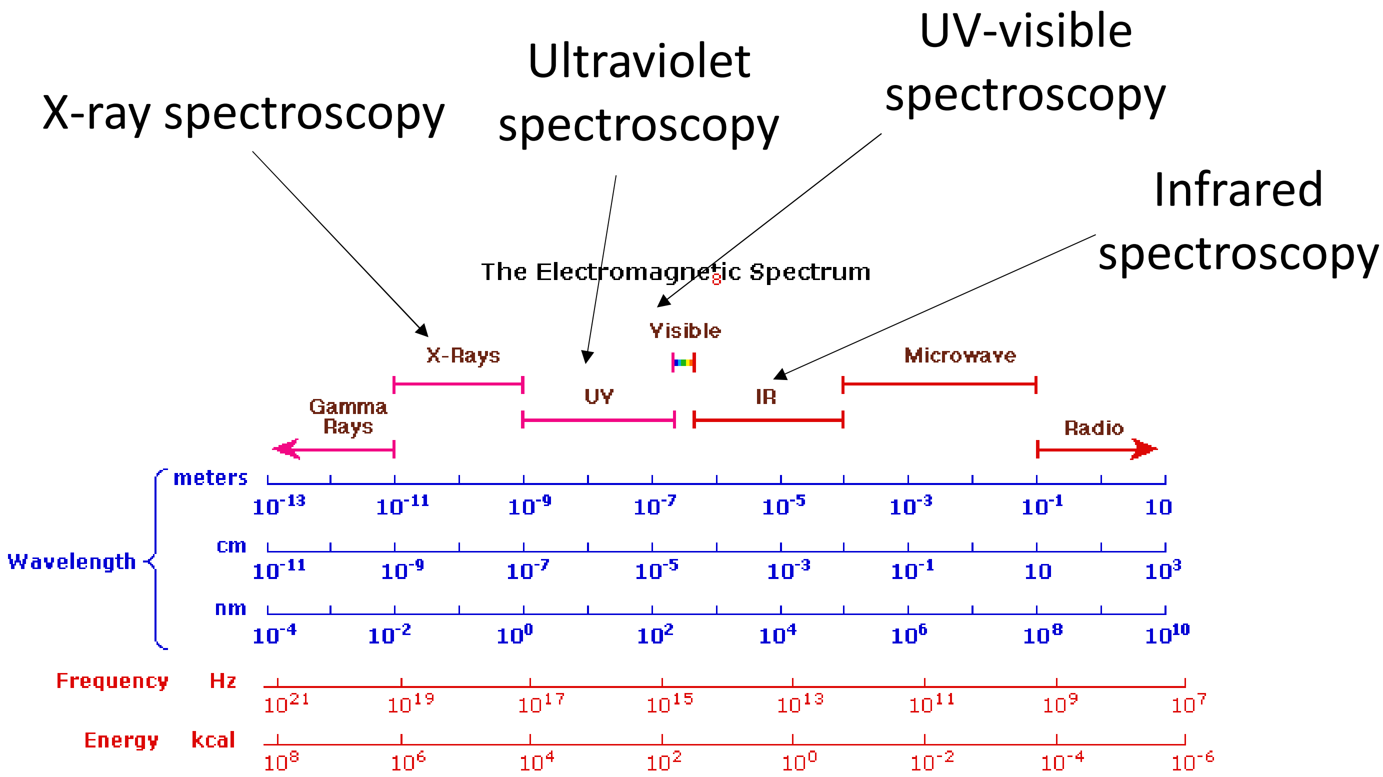
Spectroscopy

Spectroscopy is the quantitative study of the interaction between matter and electromagnetic radiation.

Can be characterized by

- the range of the electromagnetic radiation
- the nature of the interaction
- type of material

Spectroscopy
by the range of the electromagnetic radiation



Spectroscopy
by the nature of interaction

- **Absorption spectroscopy**: energy is absorbed by the material
- **Emission spectroscopy**: energy is release as electromagnetic radiation
- **Elastic scattering and reflection spectrosopy**: the incident radiation is reflecred or scattered without change of energy
- **Inelastic scattering spectroscopy**: the incident radiation is scattered while its energy changes
- **Coherent or resonance spectroscopy**: the electromagnetic radioation causes resonance

Spectroscopy
by the type of material

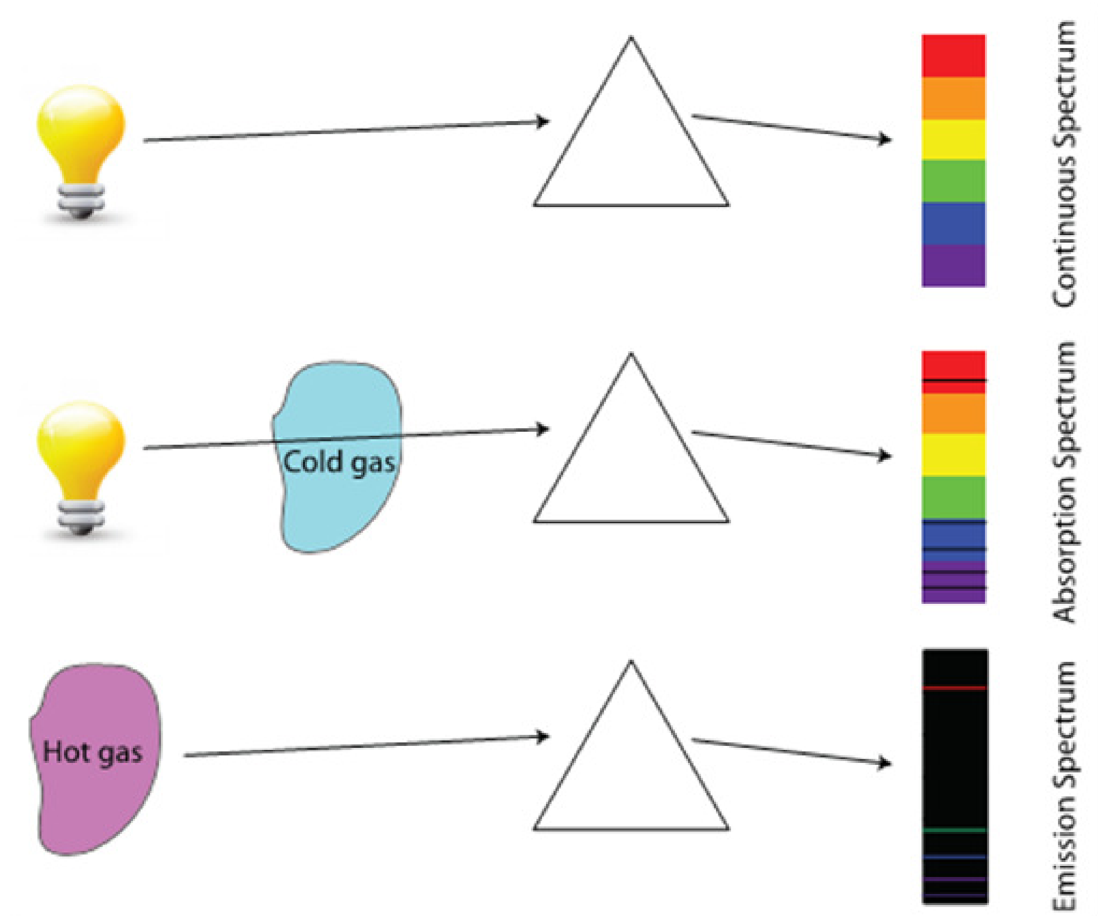
- Atomic spectroscopy
- Molecule spectroscopy
- Crystal spectroscopy
- Nuclei spectroscopy

Interaction with different spectral regions

- **Radio**: Collective oscillation of charge carriers in bulk material (plasma oscillation, e.g. the oscillation of the electrons in an antenna).
- **Microwave through far infrared**: Plasma oscillation, molecular rotation.
- **Near infrared**: Molecular vibration, plasma oscillation (in metals only).
- **Visible**: Molecular electron excitation, plasma oscillations (in metals only).
- **Ultraviolet**: Excitation of molecular and atomic valence electrons, including ejection of the electrons (photoelectric effect).
- **X-rays**: Excitation and ejection of core atomic electrons, Compton scattering (for low atomic numbers).
- **Gamma rays**: Energetic ejection of core electrons in heavy elements, Compton scattering (for all atomic numbers), excitation of atomic nuclei, including dissociation of nuclei.
- **High-energy gamma rays**: Creation of particle-antiparticle pairs. At very high energies, a single photon can create a shower of high-energy particles and antiparticles upon interaction with matter.

Note: the electromagnetic spectrum is continous and the involved intractions overlap between the neighbouring regions.

Absorption vs. emission spectroscopy



Continous spectrum:
contains continous range of frequencies

Line spectrum:
contains only discrete frequencies

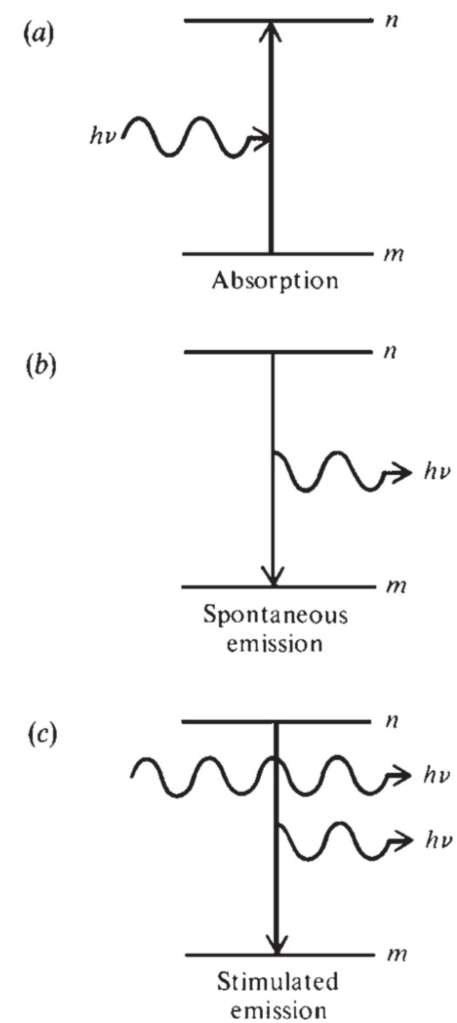
http://aplusphysics.com/wordpress/regents/wp-content/uploads/2011/05/image_thumb10.png

Background of the absorption / emission spectroscopies

Absorption: the material is exposed to light and the stationary state m changes to a higher energy stationary state n and
$\Delta E = E_n - E_m = h\nu$

Spontaneous emission: the stationary state n changes to a lower energy stationary state n while a photon is emitted with energy $h\nu = E_n - E_m$

Stimulated emission: the material is exposed to light and the stationary state n changes to a lower energy stationary state n while a photon is emitted with the same energy $h\nu = E_n - E_m$

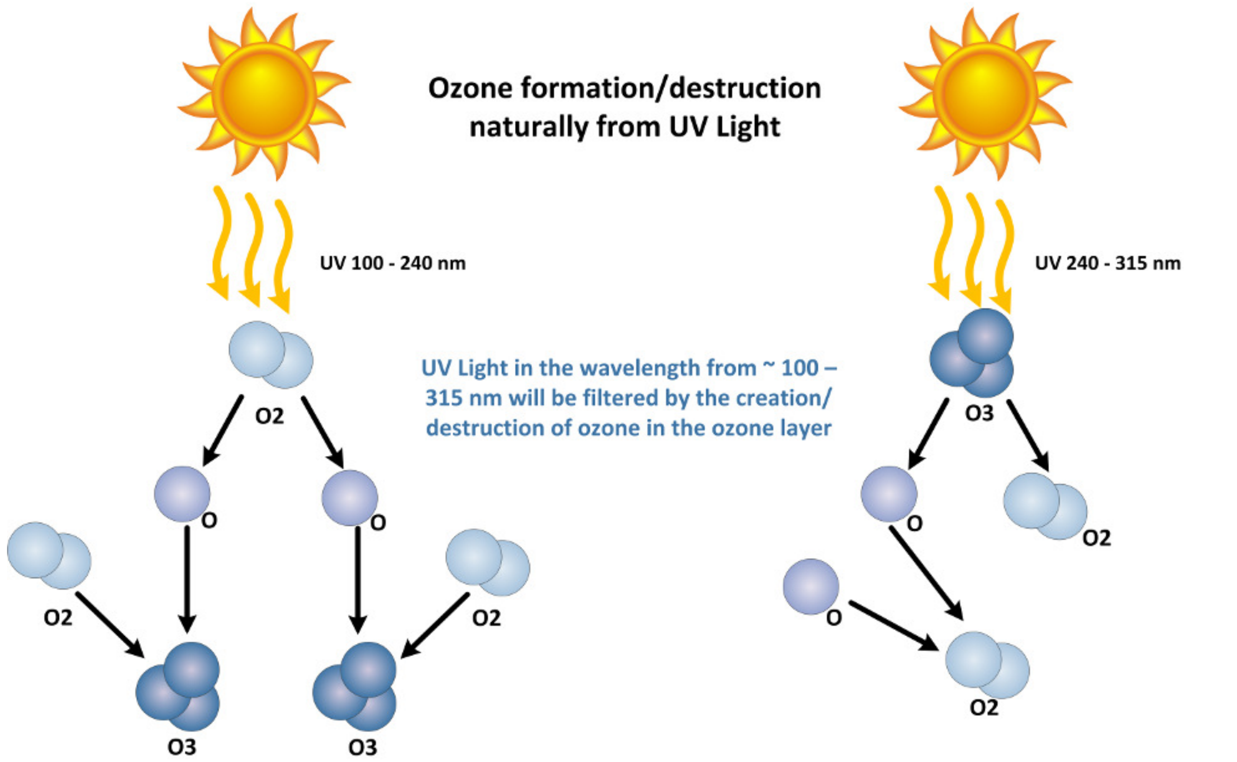


Levine: Physical Chemistry 6th Edition
Fig. 20.3

What may happen here?

- **Stimulated emission travels in the same direction** as the incident radiation beam and so decreases the observed absorption signal.
- **Spontaneous emission is sent out in all directions** and does not affect the measurable signal.
- The **energy** of absorbed radiation is usually **dissipated** by intermolecular collisions to translational, rotational, and vibrational energies of the molecules, thereby increasing the temperature of the sample.
- Some of the absorbed **energy may be radiated by the excited molecules** (fluorescence and phosphorescence), especially in gases (long average time between collisions).
- The absorbed radiation **may lead to a chemical reaction** (e.g. ozone photolysis in the stratosphere).

Ozone formation/destruction in the stratosphere



UV Light below 240 nm will disrupt the bond of the oxygen molecule and form two oxygen atoms. These oxygen atoms will quickly attach to natural oxygen to form Ozone (O3).
Peak ozone generation occurs at 185 nm wavelength of UV light.

UV Light in the 240-315 nm will disrupt the bond of the ozone molecule and convert this ozone back to oxygen.
Peak ozone destruction occurs at 254 nm wavelength of UV light.

Lasers

Laser: “light amplification by stimulated emission of radiation.”

The laser output:

- highly monochromatic
- highly directional
- intense
- coherent (in phase radiation)

May applications in spectroscopy and kinetics!

Working principle:

- produce **population inversion** (nonequilibrium situation with more molecules in an excited state than in a lower energy state)
- **stimulated emission** will **predominate over absorption** and we will get a net amplification of the radiation
- **in phase photons** are produced **travelling in the same direction**

Basic types of lasers

- *solid-state metal-ion laser*: a transparent crystal or glass to which a small amount of an ionic transition-metal or rare-earth compound has been added

  e.g. Nd:YAG laser contains an yttrium aluminum garnet (YAG) crystal ($Y_3Al_5O_{12}$) with impurity Nd^{3+} ions substituting for some $Y^{3+}{}_3$ ions.

- *semiconductor laser* (also called *diode laser*): contains semiconducting solid, typically tiny and works in the infrared

  e.g. GaAs laser (fiber optic communications, barcode readers, laser pointers, CD/DVD/Blu-ray disc reading/recording, laser printing, laser scanning)

- *gas laser*: an electric discharge through the gas leads to population inversion

  e.g. HeNe laser (formerly used in optical scanners such as supermarket bar-code readers)

- *chemical laser*: exothermic chemical reaction produces products in excited vibrational levels

  e.g. Chemical oxygen iodine laser (Fed with gaseous chlorine, molecular iodine, and an aqueous mixture of hydrogen peroxide and potassium hydroxide. The aqueous peroxide solution undergoes chemical reaction with chlorine, producing heat, potassium chloride, and oxygen in excited state, singlet delta oxygen. Spontaneous transition of excited oxygen to the triplet sigma ground state is forbidden giving the excited oxygen a spontaneous lifetime of about 45 minutes. Singlet delta oxygen transfers its energy to the iodine molecules. The excited iodine then undergoes stimulated emission and lases at 1.315 μm. Suitable for laser cutting and drilling.)

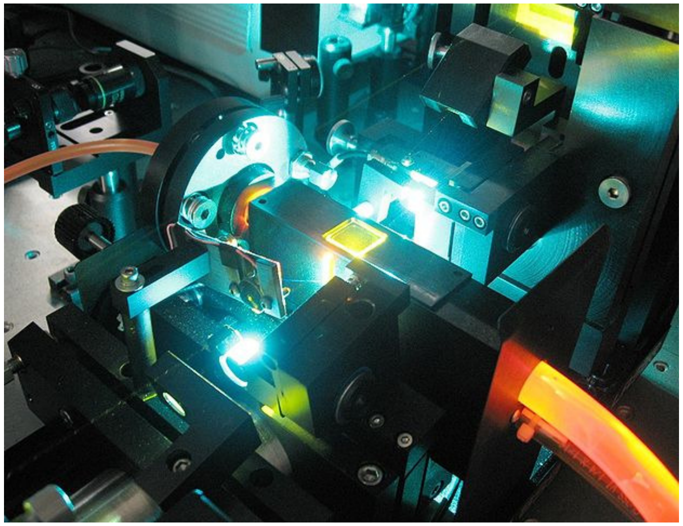
Basic types of lasers

- *excimplex laser*: An exciplex (excited complex) is a species that is formed from two atoms or molecules and that is stable (with respect to dissociation) in an excited electronic state but is unstable in its ground electronic state. When the two atoms or molecules that form such a species are identical, the species is called an excimer (excited dimer).
  e.g. helium, KrF

- *dye laser*: A solution of an organic dye flows through the laser cell, produces continous range of frequencies which is tunable.
  e.g. rhodamine 6G

A table-top continouse wave dye laser based on rhodamine 6G, emitting at 580 nm (yellow).

The emitted laser beam is visible as faint yellow lines between the yellow window (center) and the yellow optics (upper-right), where it reflects down across the image to an unseen mirror, and back into the dye jet from the lower left corner. The orange dye-solution enters the laser from the left and exits to the right, still glowing from triplet phosphorescence, and is pumped by a 514 nm (blue-green) beam from an argon laser. The pump laser can be seen entering the dye jet, beneath the yellow window.



https://en.wikipedia.org/wiki/Dye_laser