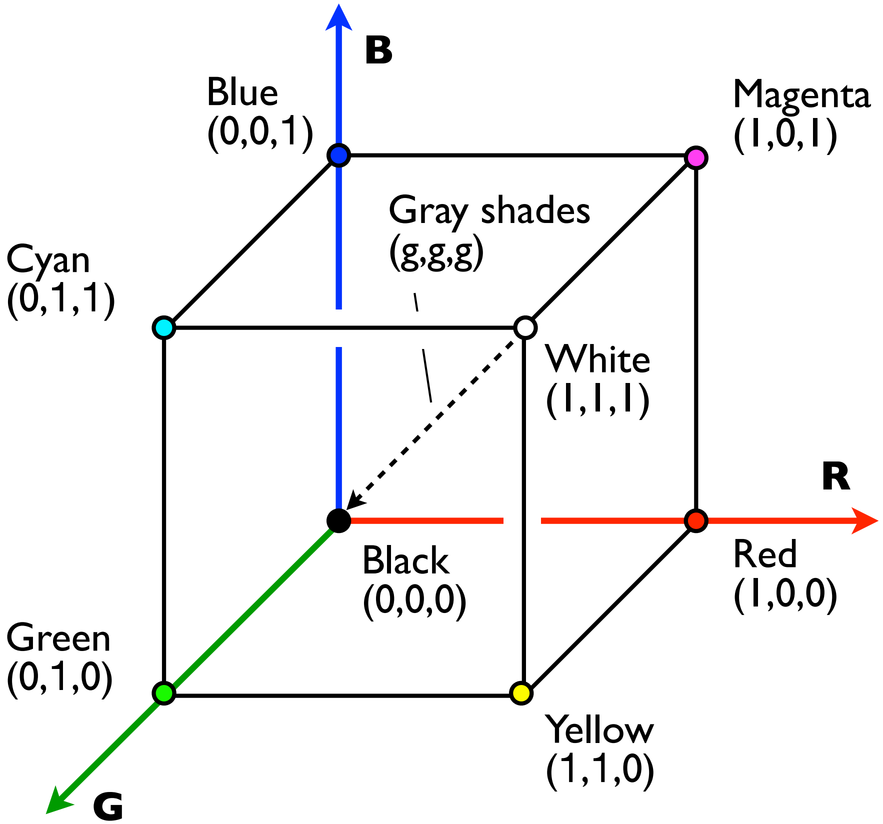
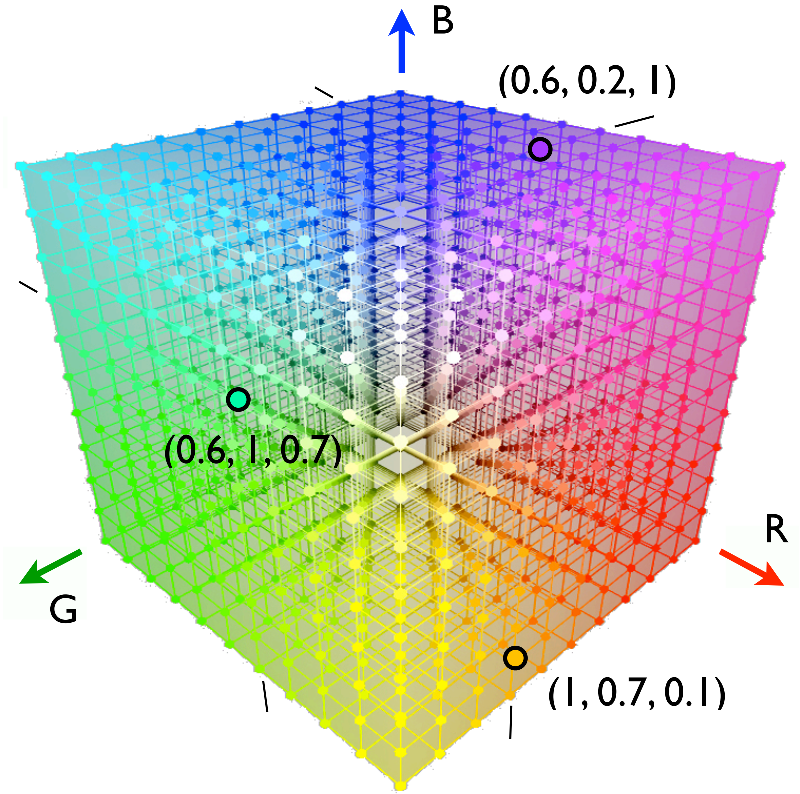
12. Optical data storage

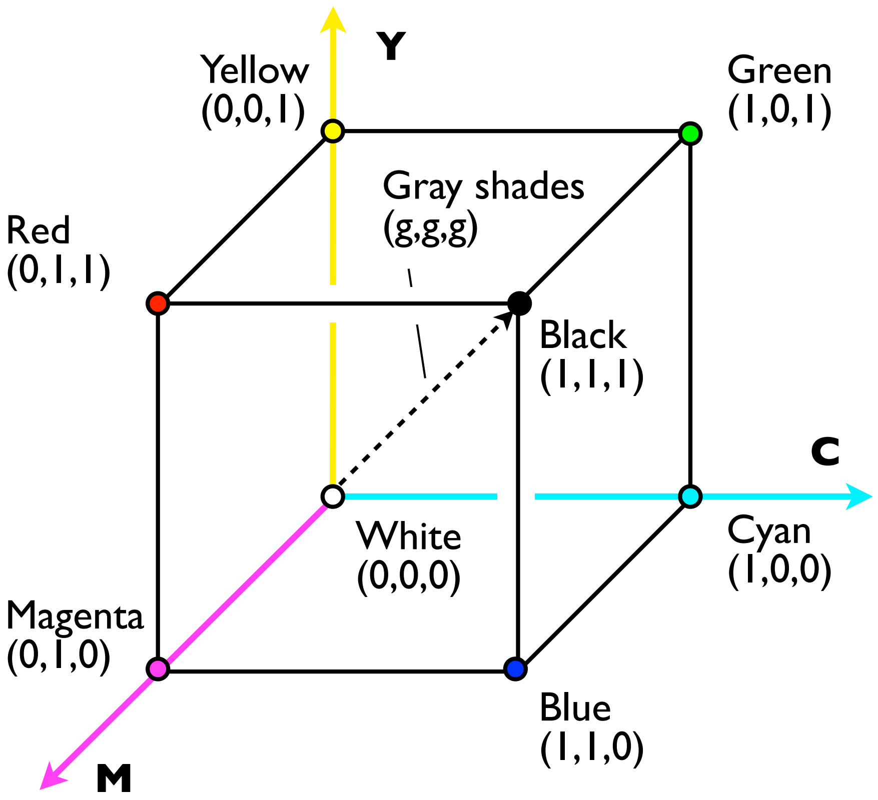
RGB additive color model

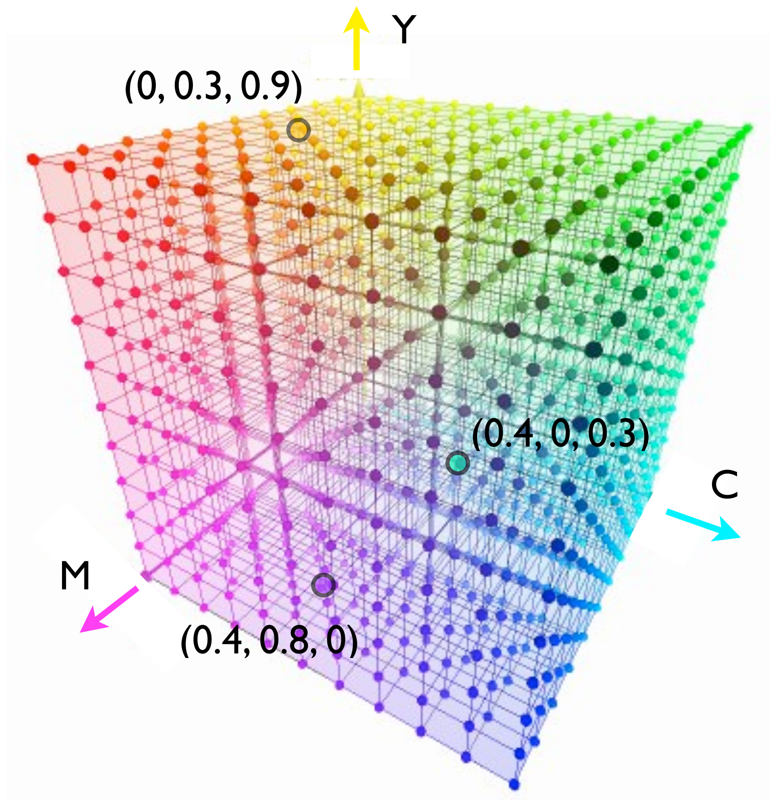




The RGB color model converts the additive color mixing system into a digital system, in which any color is represented by a point in a color tridimensional space and thus by a three coordinates vector. The coordinates are composed of the respective proportions of the primary light colors (Red, Green, Blue). The RGB model is often used by software as it requires no conversion in order to display colors on a computer screen.

CMY subtractive color model





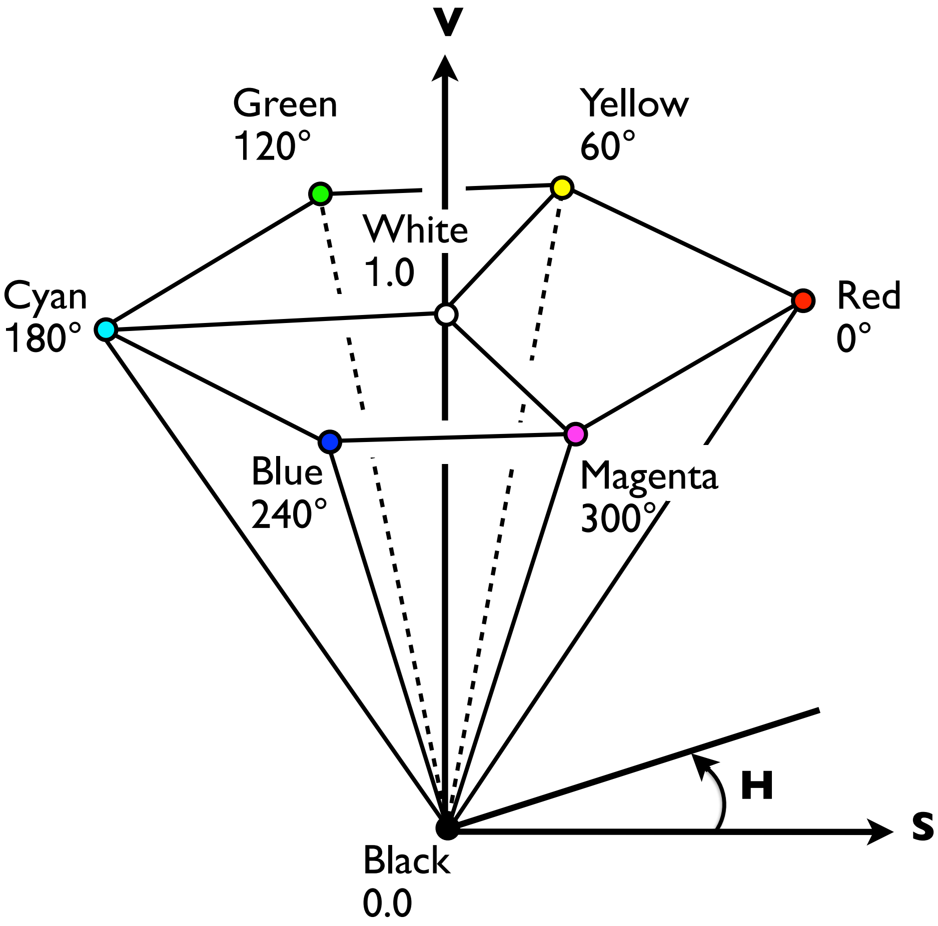
The CMY color model corresponds to the subtractive color mixing system. The coordinates of a point in this color space are composed of the respective proportions of the primary filter colors (Cyan, Magenta, Yellow). The CMY model is used whenever a colored document is printed. The conversion RGB and CMY models can be written as follows:

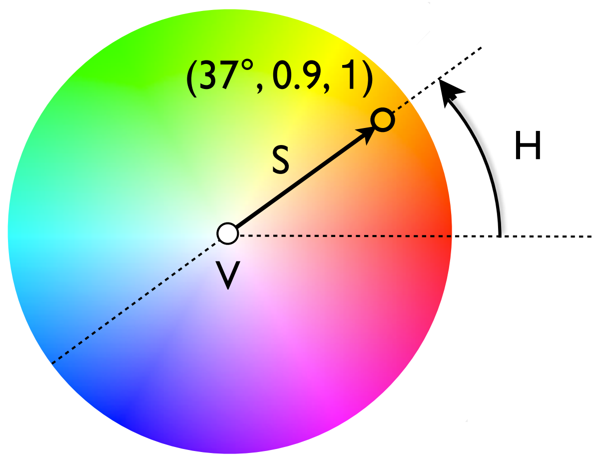
$$\begin{pmatrix} C \\ M \\ Y \end{pmatrix} = \begin{pmatrix} W \\ W \\ W \end{pmatrix} - \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

For the orange point, for example:

$$\begin{pmatrix} C \\ M \\ Y \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} - \begin{pmatrix} 1 \\ 0.7 \\ 0.1 \end{pmatrix} = \begin{pmatrix} 0 \\ 0.3 \\ 0.9 \end{pmatrix}$$

HSV color model

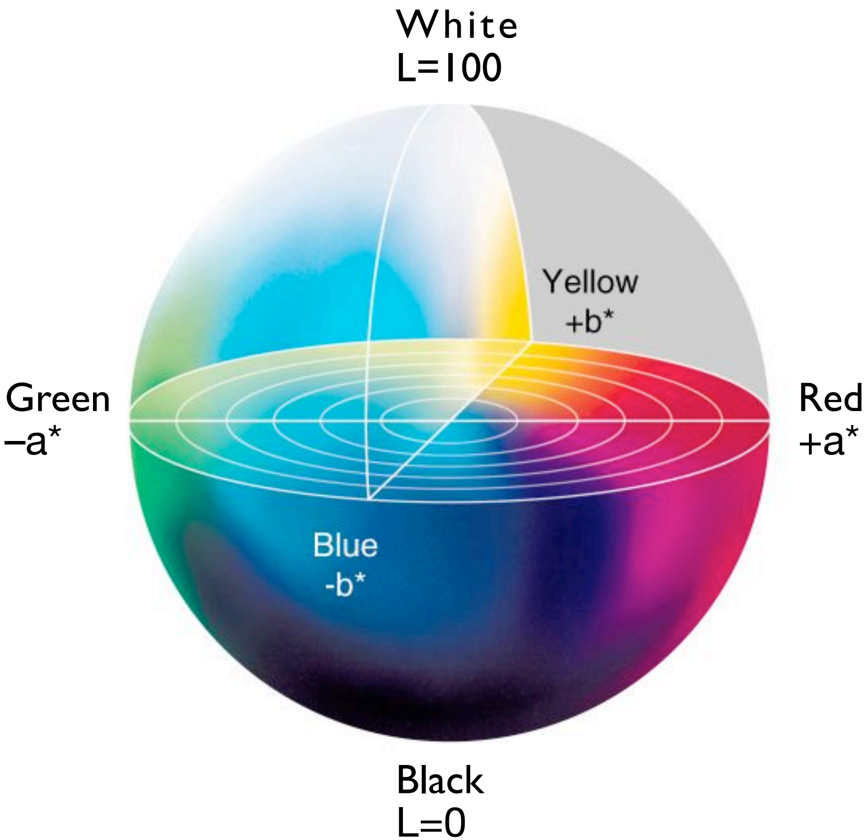


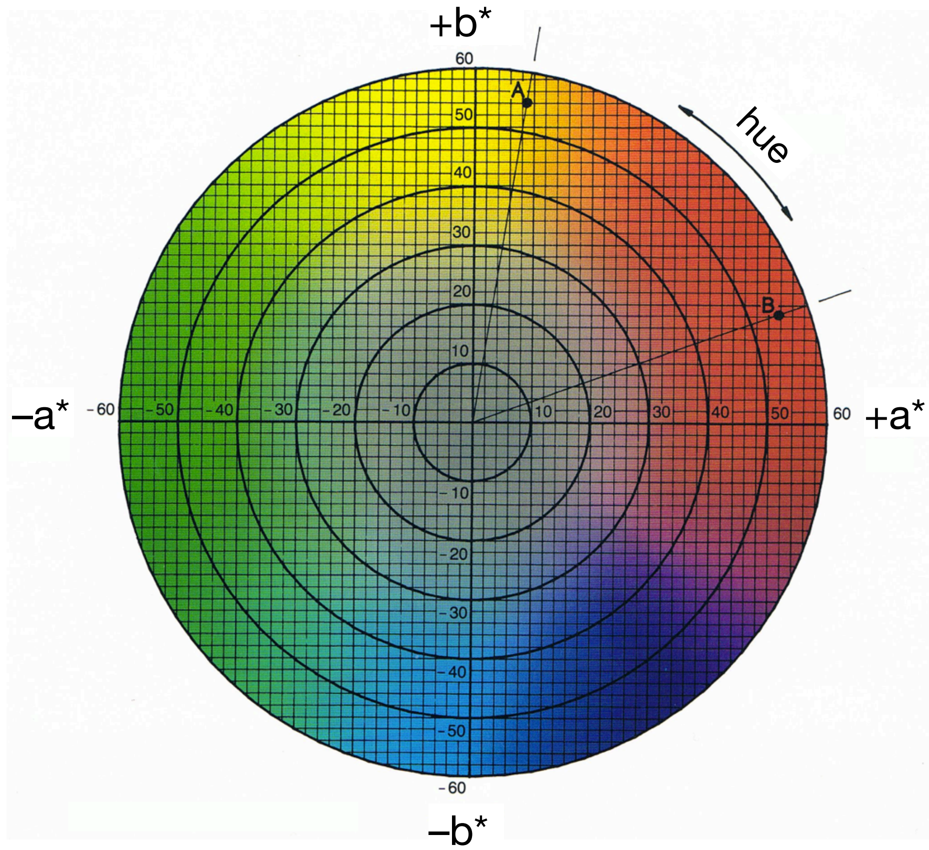


Hue is given in polar coordinate. The Saturation is the radius from the V-axis and describes the vividness of the color. The Value along the V-axis describes the brightness.

Compared to the RGB and CMY, the HSV color model has the advantage that the colors correspond more closely to our subjective description. It is, therefore, easier to make a specific color selection. This color model uses three parameters: Hue, Saturation, and Value. By projecting the RGB unit cube along the diagonal from white (1,1,1) to black (0,0,0), we get the basic hexagon of the HSV pyramid.

LAB color model

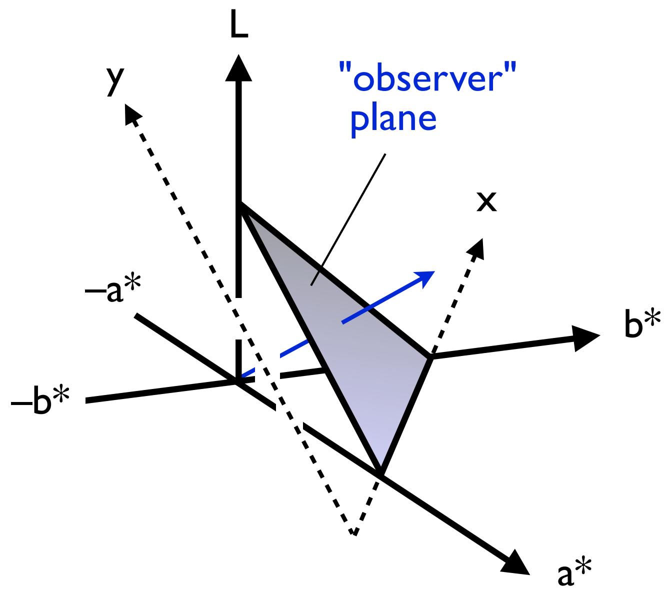


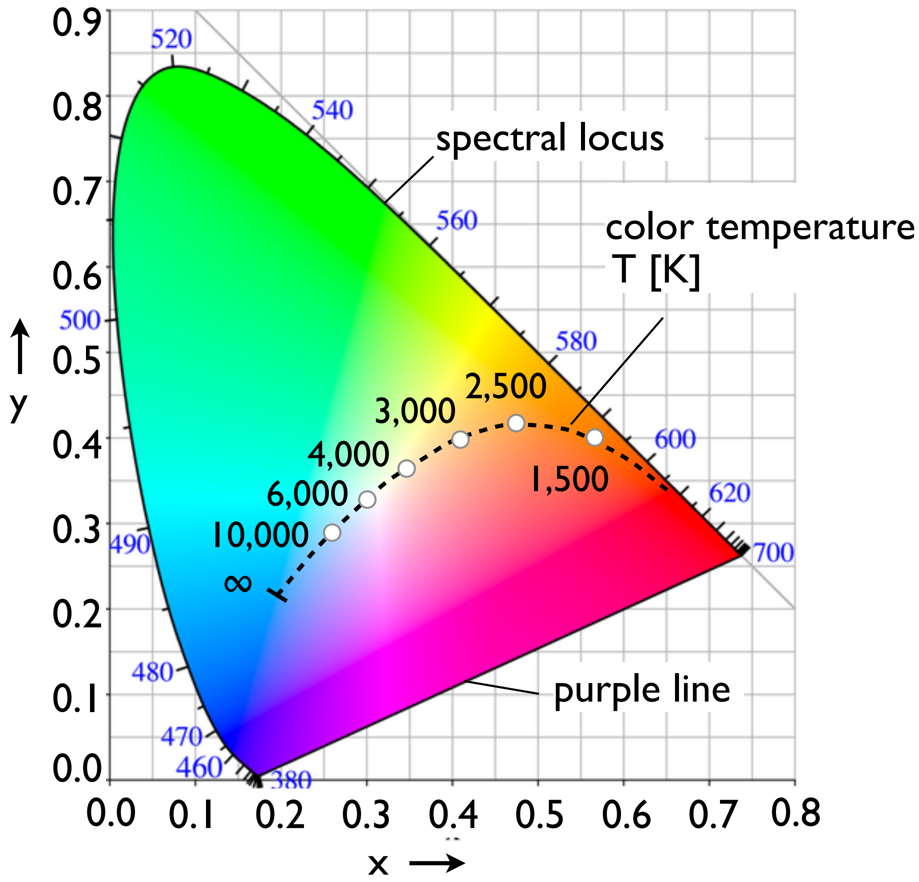


LAB color model is commonly used in graphic arts and in the textile industry. Originally proposed by the "*Commission Internationale de l'Eclairage*" (CIE), it is also referred to *CIELAB* model. It uses L, a*, b* coordinates. L is the Lightness contrast, similar to the brightness Value of the HSV model, except that L values scales from 0 (black) to 100 (white). Hue and Saturation polar coordinates of the HSV model are here converted into cartesian coordinates a*, b*, which values vary from –100 to +100. The color space can then be represented by an ideal sphere.

Chromaticity diagram

A convenient way of visually representing all colors in a two-dimensional space is the use of a cut view of the La*b* sphere along an *observer plane* described by L = a* = b*. The obtained figure is called *chromaticity diagram* (CIE 1931). This 2-D space has two axes *x* and *y*.



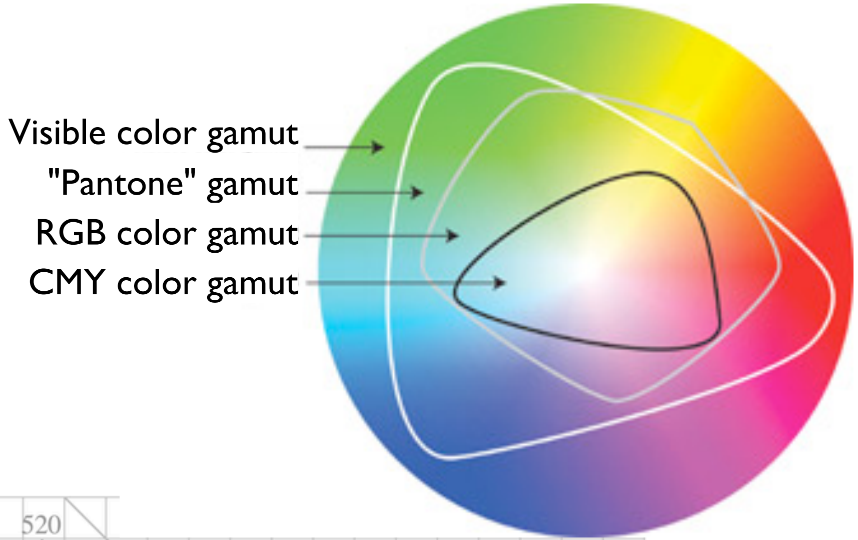


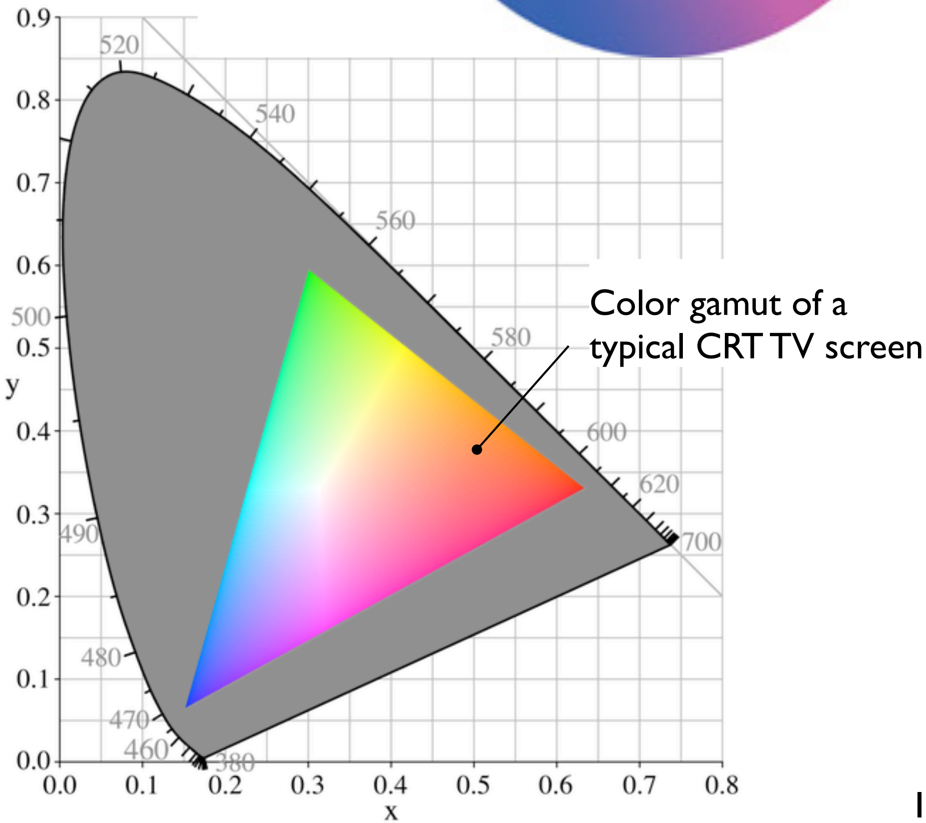
The curved line in this diagram shows where the colours of the spectrum lie and is called *spectral locus*; the wavelengths are indicated in nanometres along the curve. The straight line on the bottom connects the chromaticity co-ordinates of extreme red and blue, called *purple boundary*. The area enclosed by the spectrum locus and the purple boundary cover the domain of all visible colours.

Practical color space and gamut

The three primary colors are not available in practice as pure colors, but are dirtied by a certain proportion of the other primary colors. The result is that it is not possible to create pure white (in the additive color model) or pure black (in the subtractive model). The number of color shades that can be displayed or printed in practice with a three color system is limited to a color *gamut* smaller than the ideal color space seen by the human eye.

The use of additional primitive colors allow in certain cases to extend the color gamut. Printing uses an additional blac<u>K</u> ink (CMY<u>K</u> quadrichromy). Textile printing is even more demanding and often employs an additional orange dye and two more blue dyes and, thus, a total of 6 primitive colors (hexachromy).





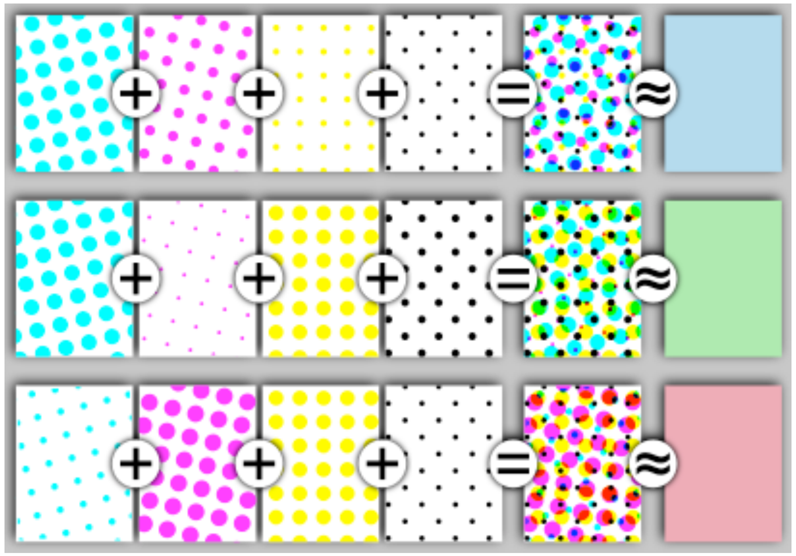
Numerical color processing

In theory it is possible to create every shade using the RGB or CMY color models. How many colors can be represented with these models depends on the number of different graduations possible for each primary color.

To produce >16 Mio different color shades, as in recent graphics cards, 256 graduations of each of the three primary colors are needed. This means 3 x 8 bits = 24 bits are necessary for each color shade. The number of bits used to represent the color of a single pixel in an image is called the color depth.

When the number of available graduations is not sufficient, as in most printers, a halftoning technique has to be used to simulate light color shades, obviously at the detriment of spatial resolution.

Number of bit / primary color	Number of graduations Red	Green	Blue	Number of colors
1	2	2	2	8
2	4	4	4	64
3	8	8	8	512
4	16	16	16	4,096
5	32	32	32	32,768
6	64	64	64	262,144
7	128	128	128	2,097,152
8	256	256	256	16,777,216

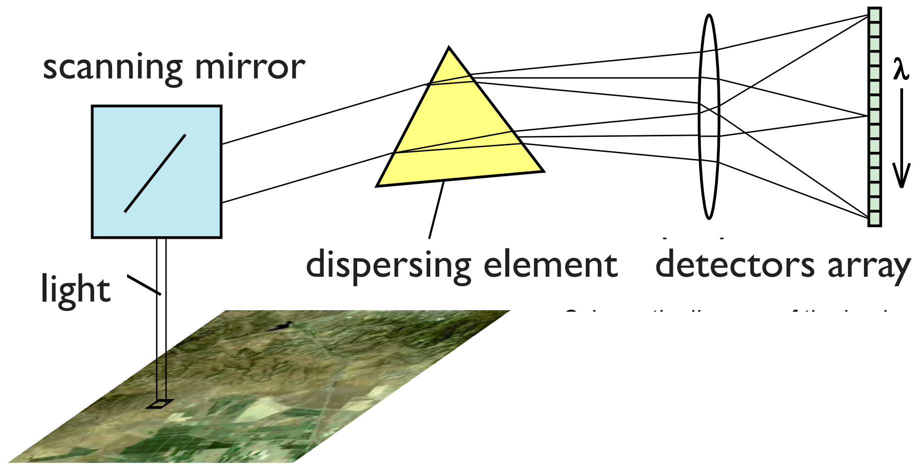


Examples of color halftoning with CMYK (Cyan, Magenta, Yellow, blacK) separations.

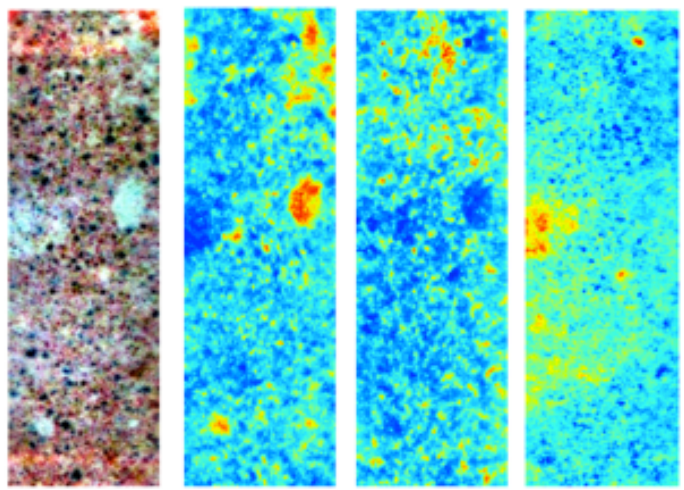
Spectral imaging

A spectral camera is a combination of an imaging spectrograph and an area monochrome camera. It works as a line scan camera, and provides full, contiguous spectral information for each pixel. Spectral resolution can range from ca. 2 nm to 20 nm. Spectral imaging typically allows for recording pictures with the equivalent of 20 to 200 primary colors over the visible domain and can even extend to the near UV and mid-IR (hyperspectral imaging).

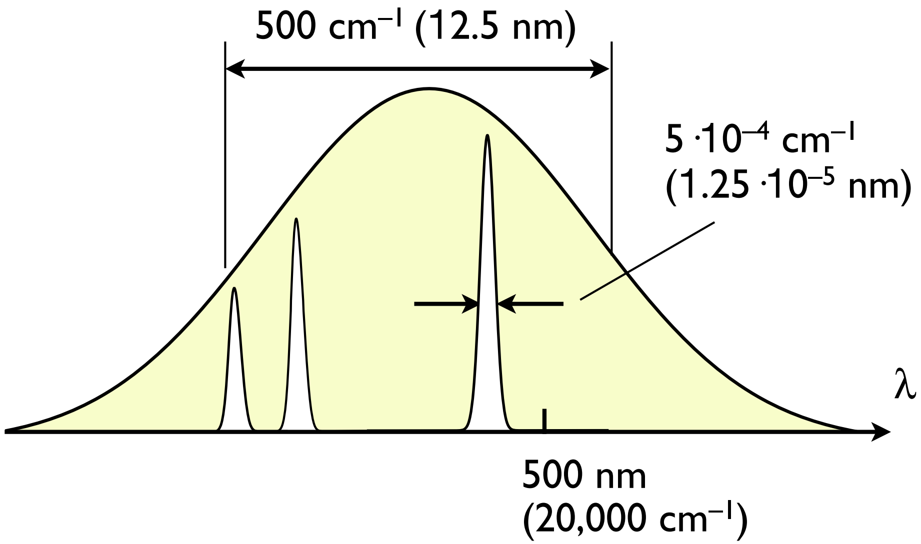
Since spectra obtained for an area on a picture can be matched with electronic spectra of chemical compounds (spectral fingerprints), spectral imaging allows for remote chemical analysis in a number of applications, such as for instance astro-nomy, surveillance, mining and geology, ecology, biology, and forensic science.

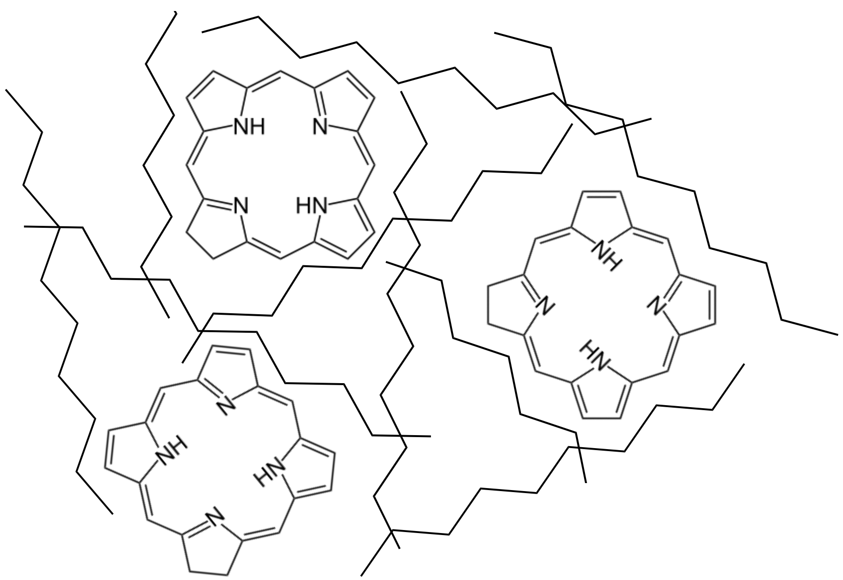


Schematic diagram of an imaging spectro-meter. Some sensors use multiple detector arrays to measure hundreds of narrow wavelength bands.



Homogeneous vs. inhomogeneous line width





The spectrum of a typical organic molecule in a host matrix at $T \leq 4$ K is schematized here on the left. The absorption profile of an individual molecule is fundamentally determined by the uncertainty principle. For a fluorescence lifetime of τ = 10 ns, the value of the *homogeneous* width of the absorption line is expected to be 0.0005 cm^{-1} or 15 MHz.

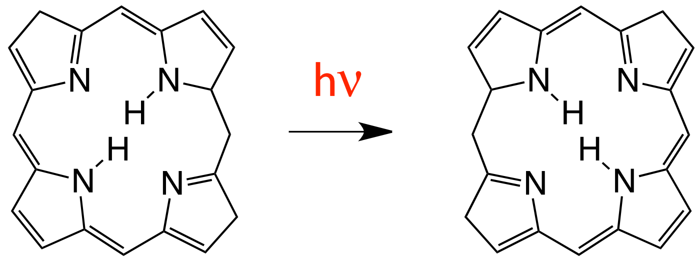
All molecules in the matrix, however, have slightly different environment, producing an inhomogeneous band broadening. The width of the vibrationless $S_1 \leftarrow S_0$ transition is typically 500 cm^{-1} (15'000 GHz). Thus, ratios of the inhomogeneous/homogeneous width of up to 10^6 can result.

Spectral hole burning

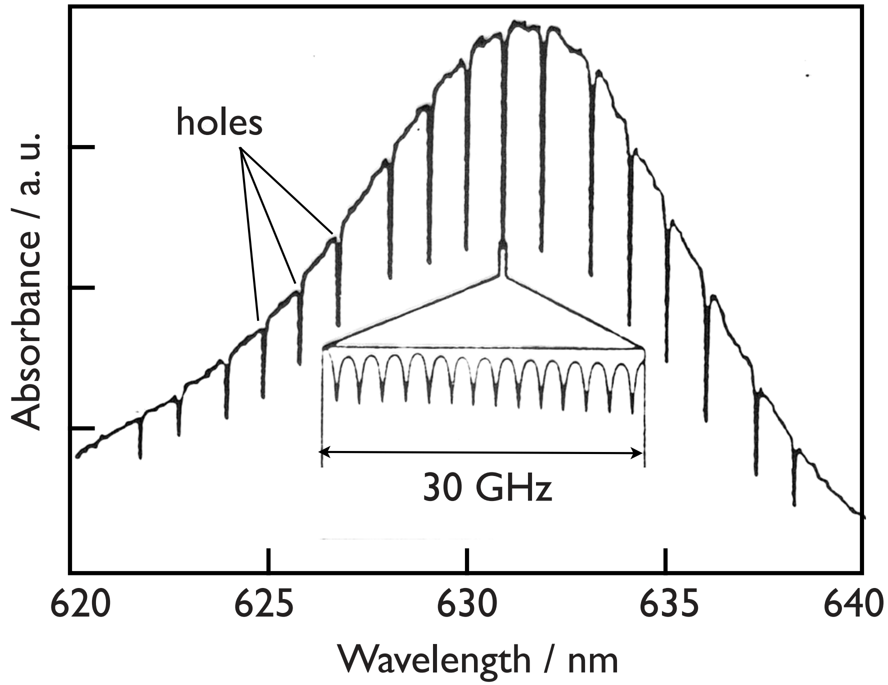
Spectral hole burning is the frequency-selective bleaching of the absorption spectrum of a material, which leads to an increased transmission (a "spectral hole") at the selected frequency.

Two basic requirements, that must be met for the observation of this phenomenon, are: a) The spectrum is inhomogeneously broadened and b) the material undergoes upon light absorption a modification which changes its absorption spectrum. Typical materials include dye molecules dissolved in suitable host matrices and the frequency selective irradiation is usually realized by a narrow band laser.

Up to 10^6 spectral holes can be "drilled" in a inhomogeneously broadened absorption band envelope. This means that each adressable pixel of the material (typically a few squared microns) could in principle carry the information corresponding to one million colors with a depth of one bit.



Photochemical tautomerization of chlorin dye



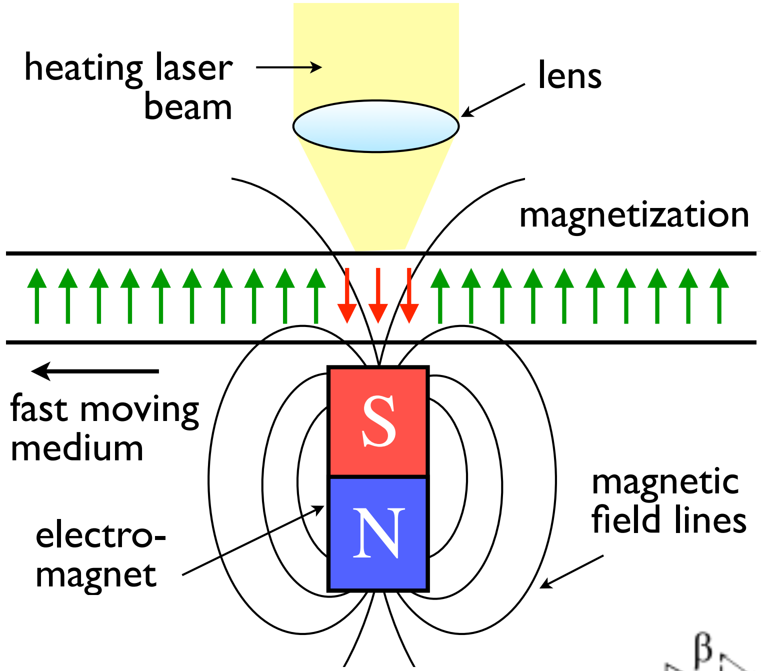
Spectral hole-burning. Holes burnt into the inhomogeneously broadened band are shown as recorded with low and high wavelength resolution techniques.

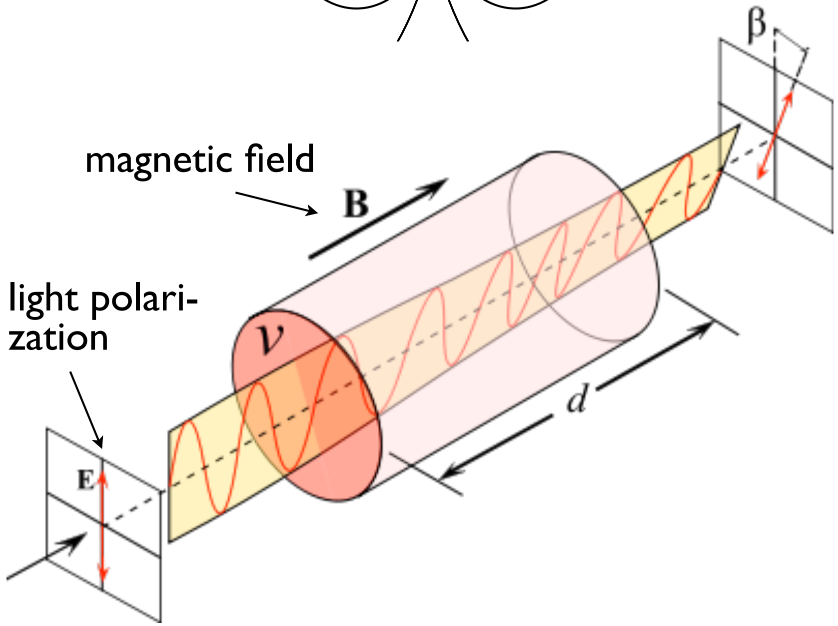
Comparison of various data storage systems

Storage system	Storage density [Mb cm^{-2}]	Bit size [µm]	Storage capacity [MB]	Access time [ms]
Printed page	$4.5 \cdot 10^{-5}$	$2 \cdot 10^{3}$	0.02	$1 \cdot 10^{4}$
Solid state device (NAND)	$2 \cdot 10^{6}$	$7 \cdot 10^{-3}$	$2.6 \cdot 10^{5}$	$1- 4 \cdot 10^{-2}$
AgX color 24x36 mm negative	10	3	11	
Floppy disk	0.2 - 10	5	1.44 - 200	10 - 100
Magnetic hard disk	$7 \cdot 10^{4}$	0.28	10^{6} / plate	8
Magneto-optic disk (MOD)	$7 \cdot 10^{2}$	0.4	650 - $9.2 \cdot 10^{3}$	10
CD-ROM	58	1.6	650	110 - 170
DVD, DVD+RW	400	0.49	$4.7 \cdot 10^{3}$ / side	80 - 220
Blu-Ray® Disk (BD)	$3 \cdot 10^{3}$	0.18	$5.6 \cdot 10^{4}$ / side	100 - 250
Holographic versatile disk (HVD)	$3.3 \cdot 10^{5}$	10^{-2}	$3.9 \cdot 10^{6}$	2

Magneto-Optical Disk (MOD)

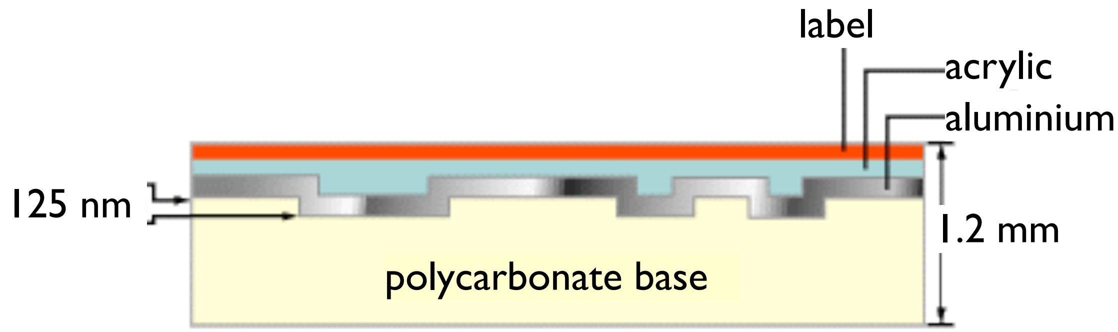
All commercially available MO disks are based on an amorphous terbium-iron-cobalt [$Tb_2(Fe_9Co)_8$] magnetic alloy. This ferromagnetic material is sealed beneath a plastic coating. During recording, an IR diode laser beam is focused on the surface of the alloy and heats the material up to the Curie point (typically T_C = 180°C), at which the material becomes paramagnetic. This allows an electromagnet positioned on the opposite side of the disk to change the local magnetic polarization. The latter is retained when temperature drops. During reading, the laser power is decreased to a level unable to heat the material significantly. According to the magnetic state of the surface, the reflected laser light varies due to the magneto-optic Kerr effect (MOKE) that causes the rotation of the direction of linear polarization of light upon reflection from the surface of a magnetic medium.

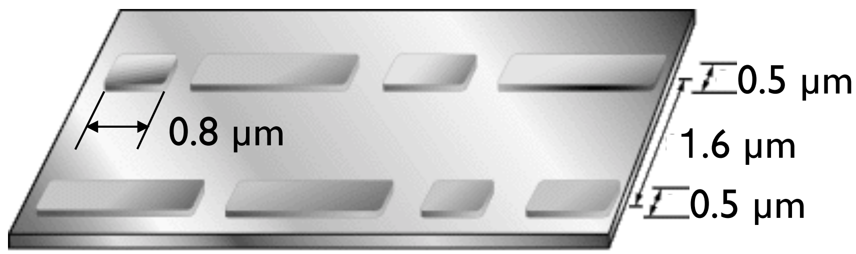


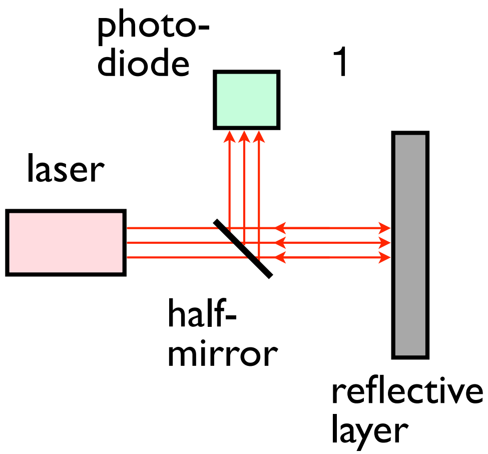


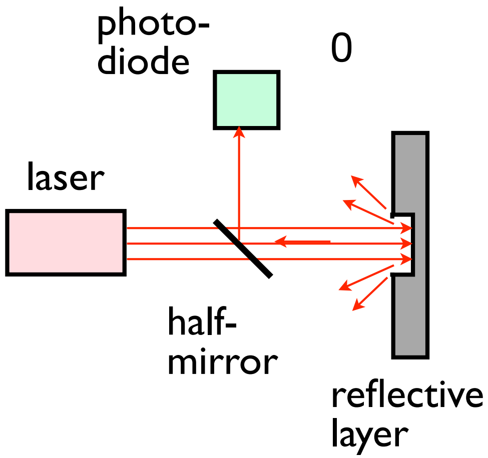
magneto-optical Kerr (Faraday) effect

Compact Disk (CD-ROM)





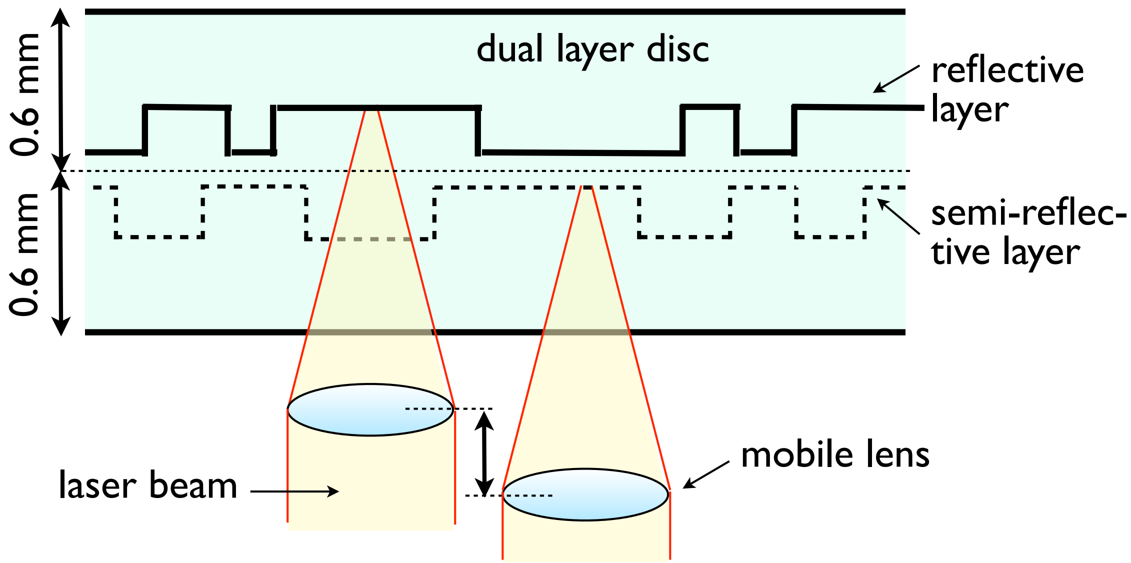




Compact disks are made of a 1.2 mm-thick disk of polycarbonate, with a thin layer of aluminium as a reflective surface. The most common size of CD-ROM disc is 120 mm in diameter. Data is stored on the disc as a series of microscopic indentations. A NIR laser (λ= 780 nm) is shone onto the reflective surface to read the pattern of pits and lands. Because the depth of the pits is approximately $\lambda/4$ to $\lambda/6$, the reflected beam's phase is shifted in relation to the incoming beam, causing destructive interference and reducing the reflected beam's intensity. This pattern of changing intensity of the reflected beam is converted into binary data.

Digital Versatile Disks (DVD, Blu-ray® BD)

Feature	CD-ROM	DVD	Blu-ray®
Diameter / thickness (mm)	120 / 1.2	120 / 1.2	120 / 1.2
Sides	1	1 or 2	1
Layers per side	1	1 or 2	2
Capacity (GB)	0.7	4.7 - 17	50
Track pitch (μm)	1.6	0.74	0.32
Minimum pit length (μm)	0.83	0.44	0.14
Linear scan velocity (m/s)	1.3	3.5	4
Laser wavelength (nm)	780	635 or 650	405



DVD uses 650 nm wavelength laser diode light as opposed to 780 nm for CD. This permits a smaller pit to be etched on the media surface compared to CDs (0.74 μm for DVD versus 1.6 μm for CD), allowing in part for a DVD's increased storage capacity.

A dual-layer disk employs a second physical layer within the disc itself. The drive with dual-layer capability accesses the second layer by shining the laser through the first semi-transparent layer.

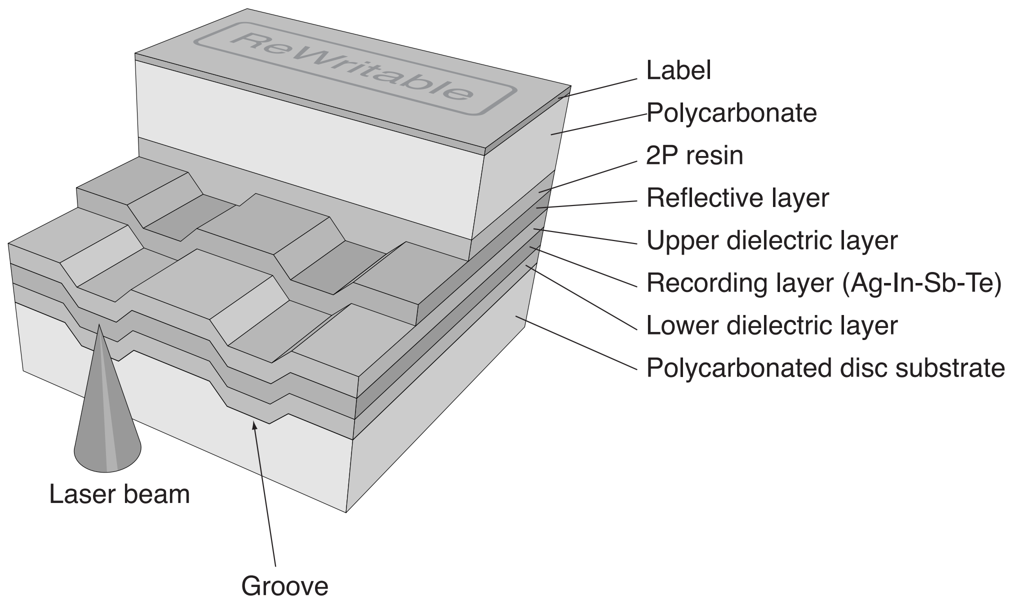
In comparison, Blu-ray® disk, the successor to the DVD format, uses a wavelength of 405 nm, and one dual-layer disc has a 50 GB storage capacity.

Laser structuring: CD-R, CD-RW, DVD-R, DVD+RW

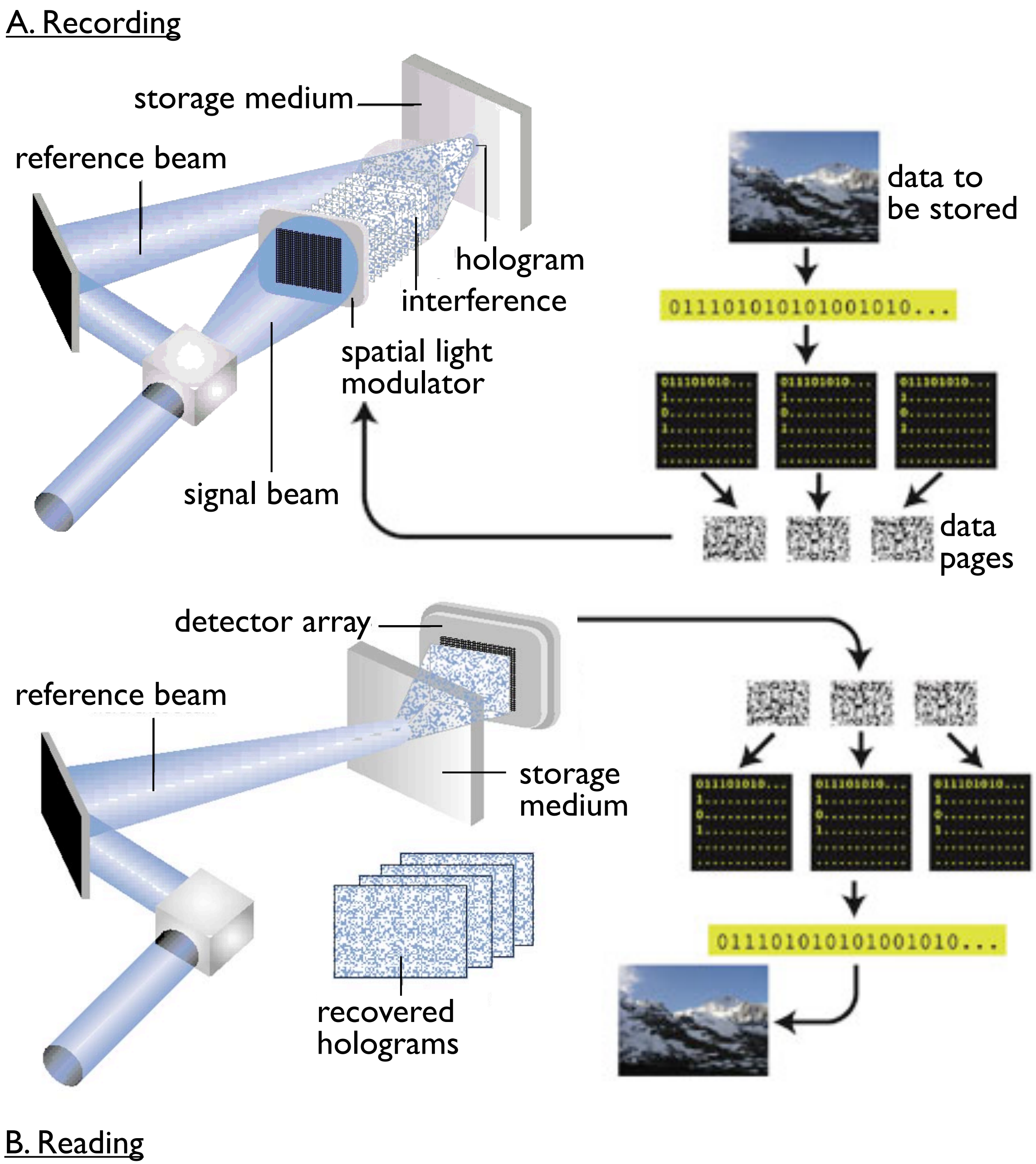
Data writing, erasing and re-writing can be achieved by photo-thermal phase change of an absorbing medium. In its original state, the recording layer of a recordable disk is polycrystalline. During writing, a focused laser beam (~10 mW) selectively heats areas of the phase-change material above the melting temperature (500-700°C). Then, if cooled sufficiently quickly, the liquid state is quenched and an amorphous state is obtained. If the phase-change layer is annealed below the melting temperature but above the crystallization temperature (200°C) for a sufficient time (~5 mW laser beam), the atoms revert back to an ordered state, i.e. the crystalline state.

The amorphous and crystalline states have different refractive indexes, and can therefore be optically distinguished (read laser beam <1 mW). In the DVD+RW system, the amorphous state has a lower reflectance than the crystalline state.

The phase-change medium consists of a grooved polycarbonate substrate, onto which a stack (usually four layers) is sputtered. The phase-change (recording) layer is sandwiched between dielectric- or absorbing dye layers. A commonly used phase-change material is Ag-In-Sb-Te alloy.



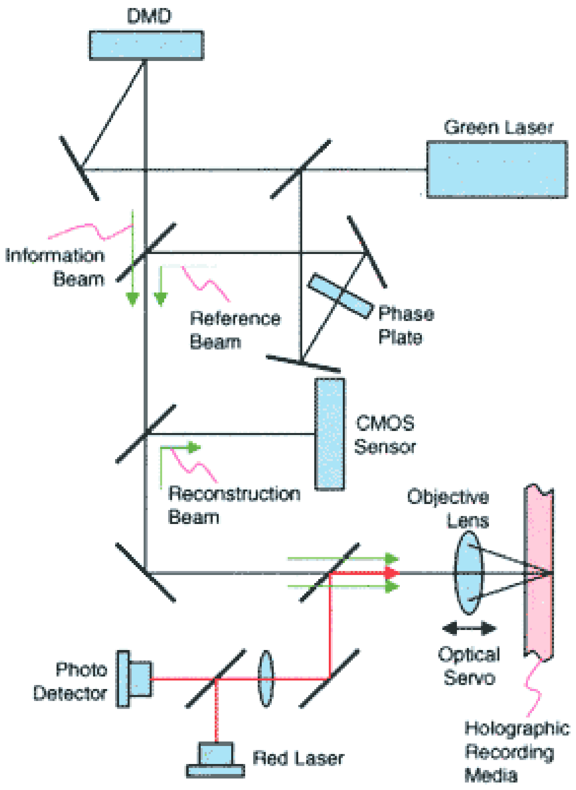
Digital holographic data storage

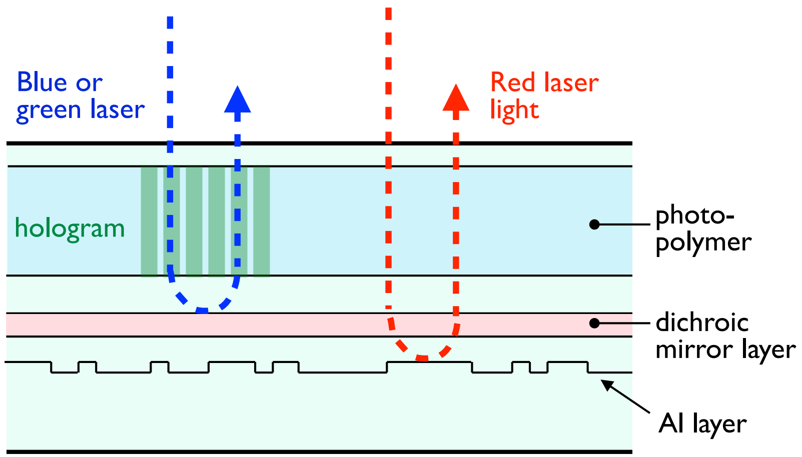


Holographic recording technology records digital data in the form of laser interference fringes in the volume of a storage medium, rather than on its surface. By varying the angle between both inter-ferring laser beams, up to 10^6 holograms can be created in the same piece of polymer, enabling holographic versatile disks (HVD) the same size as today's DVDs to store as much as one terabyte of data (200 times the capacity of a single layer DVD), with a transfer speed of one gigabyte per second (40 times the speed of DVD).

Associated with high-resolution spectral hole burning, holographic recording is seen as the future of data mass storage.

Holographic versatile disk (HVD)





HVD is an optical disk technology developed recently that can store the same amount of information as 20-200 Blu-ray® disks. It employs collinear holography within a photopolymer recording layer rather than a dual-beam system. Reading is achieved with a blue and a red laser beams. The blue laser reads data encoded as laser interference fringes from the recording layer. A red laser is used as the reference beam to read servo information from a regular CD-style aluminium layer near the bottom.

Servo information is used to monitor the position of the read head over the disc, similar to the head, track, and sector information on a conventional hard disk drive. On a CD or DVD this servo information is interspersed amongst the data.

Although HVD standards were published in 2007, no company has released an HVD and the related drive in the public yet.