What is colour?

Eliminativism: The view that either (a) colours as we perceive them do not exist in nature, that is, there is no room for them in our scientific ontologies (error theory); or (b) while there is colour, nonetheless the particular colours that we see—the reds, greens, blues—do not exist in nature.

Note that the problem of deciding whether to dispense with colour as a whole depends upon whether our beliefs about colour are true. This is complex question which depends upon the “fit” between the folk understanding of colour and the scientific understanding of colour. Here there many options from complete elimination (there can be no scientific theory of colours just as there is no scientific theory of witches) to reduction (in which each colour term maps neatly onto some term in the scientific theory).

Dispositionalism: To be coloured to have a disposition to cause, under standard conditions, in the standard observers, a perception of colour.

Thus to be red is to be the sort of thing that, under standard conditions, causes the standard observer to see the property of redness.

Hilbert and Byrne call this “psychological dispostionalism” because the coloured objects have a disposition to causes psychological states of a certain kind.

Primitivism. Colours are physical properties, but properties that are irreducible to any other physical properties. A number of epistemic theses usually go along with this view, namely that colours have just the properties that we perceive them to have, and that we know everything that there is to know about colour, in virtue of perceiving them (the thesis of transparency).

Physicalism. Physicalism is the view that colours are some physical properties or other, usually scientifically respectable properties. Brands of physicalism vary depending upon the kinds of properties chosen.

1) **The *causal grounds* of dispositions**. The microphysical properties that give rise to the reflectance and absorption of specific wavelengths of light.

2) **Relational properties.** Colours are defined as a certain kind of relational property. Ecological relationalism equates the colours wit relations between the environment and the observer.

3) **Reflectance Realism**: Colours are the surface spectral reflectances of objects—the disposition of an object to reflect a certain percentage of each wavelength of light.

Hilbert and Bryne on Ecological Theories: The example of the SUV cupholder. There is a co-evolution of the cup shape and the cup-holder. Because a type of cup is shaped a certain way, cup-holders are made in a certain shape; and because there are now cup-holders, cups are manufactured in shapes that best fit the cup-holder. However, perhaps some innovations in cup-design (say for lack of spillage) are then made. The cup-holders must then be modified to hold the new better-safer-drier cup design. And so on.

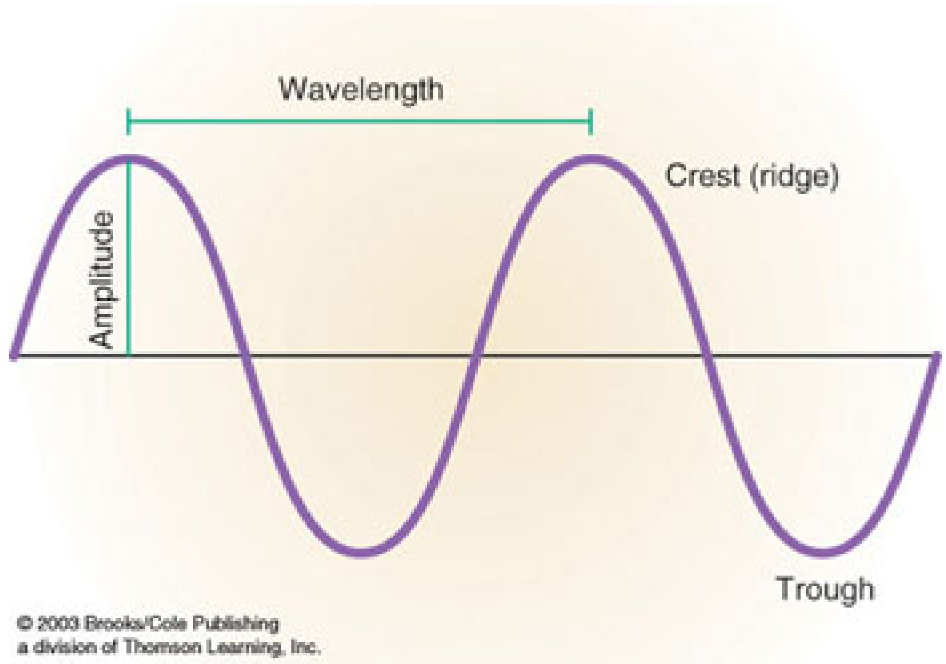
"The cup-holders therefore 'co-evolve' with the shapes of cups. But this obviously does not show much of anything about the nature of shapes; in particular it doesn't show that shapes are non-physical properties."

Causes of Colour

What makes the ruby red? Why is the emerald green? On the most superficial level these questions can be given simple answers. When white light passes through a ruby, it emerges with a disproportionate share of longer wavelengths, which the eye recognizes as red. Light passing through an emerald acquires a different distribution of wavelengths, which are perceived as green. This explanation of color is correct as far as it goes, but it is hardly satisfying. What is missing is some understanding of how matter alters the composition of the light it transmits or reflects. Ruby and emerald both derive their color from the same impurity element: Why then do they differ so dramatically in color? What gives rise to the fine gradations in spectral emphasis that constitute the colors of materials?

It turns out that the ultimate causes of color are remarkably diverse. An informal classification I shall adopt here has some 14 categories of causes, and some of the categories embrace several related phenomena. With one exception, however, the mechanisms have an element in common: the colors come about through the interaction of light waves with electrons. Such interactions have been a central preoccupation of physics in the 20th century, and so it is no surprise that explanations of color invoke a number of fundamental physical theories. Indeed, color is a visible (and even conspicuous) manifestation of some of the subtle effects that determine the structure of matter.

Kurt Nassau 1980 ‘The Causes of Color’


Wavelength
Crest (ridge)
Amplitude
Trough
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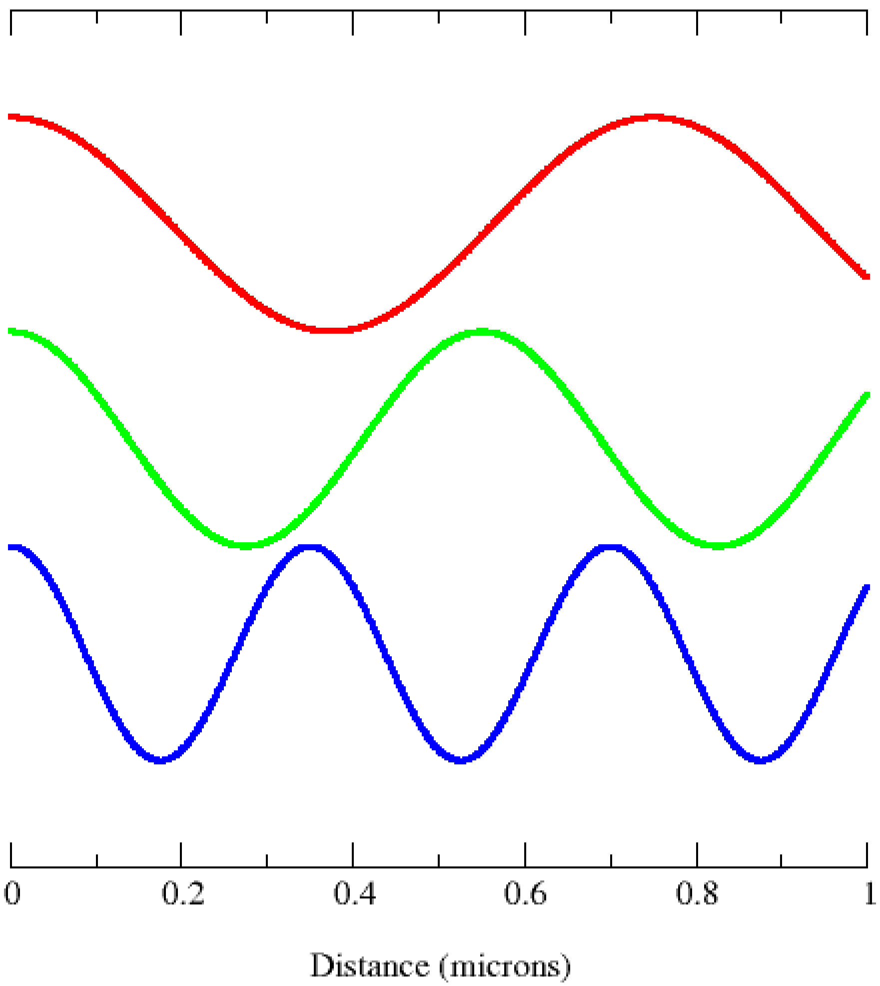
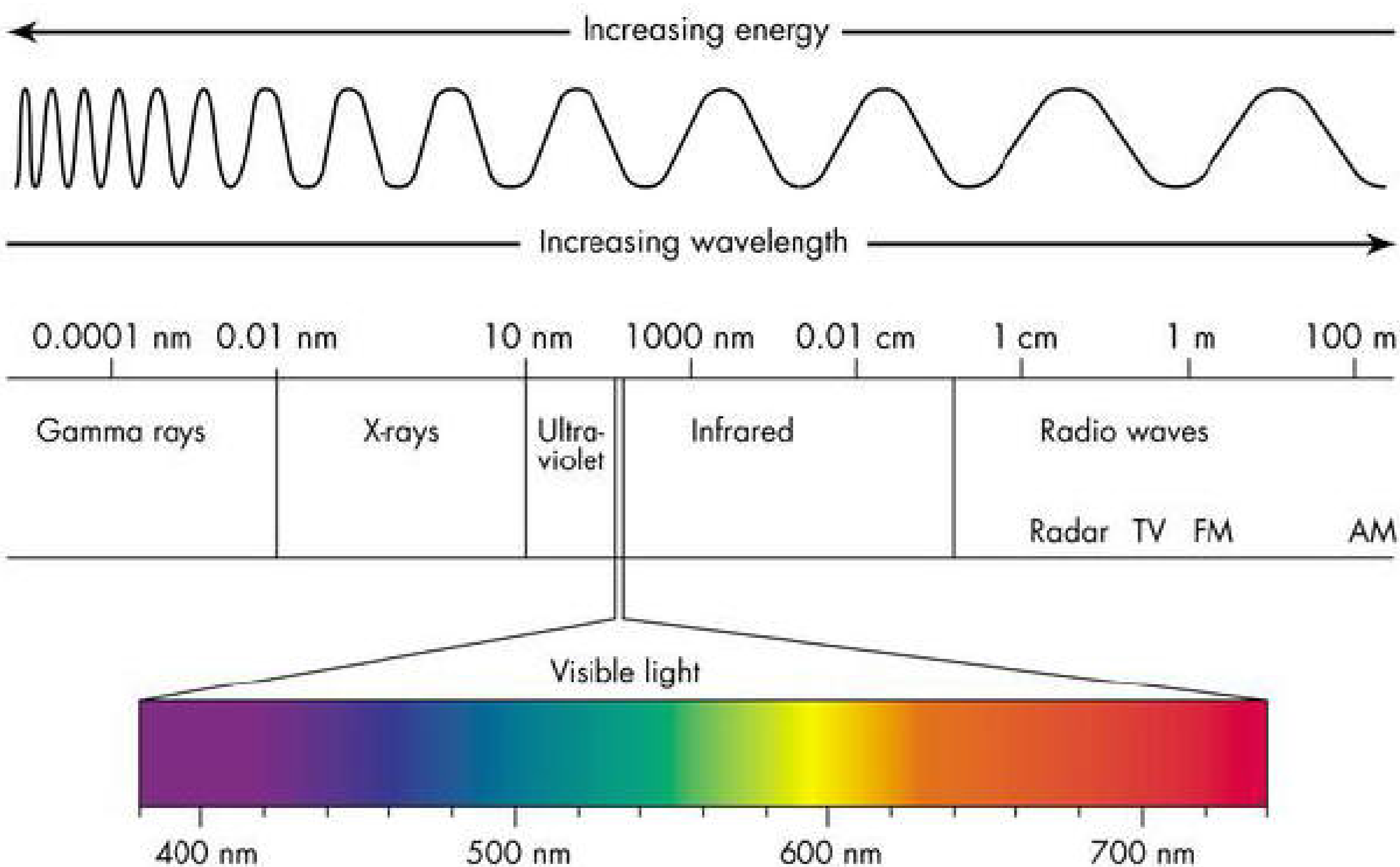
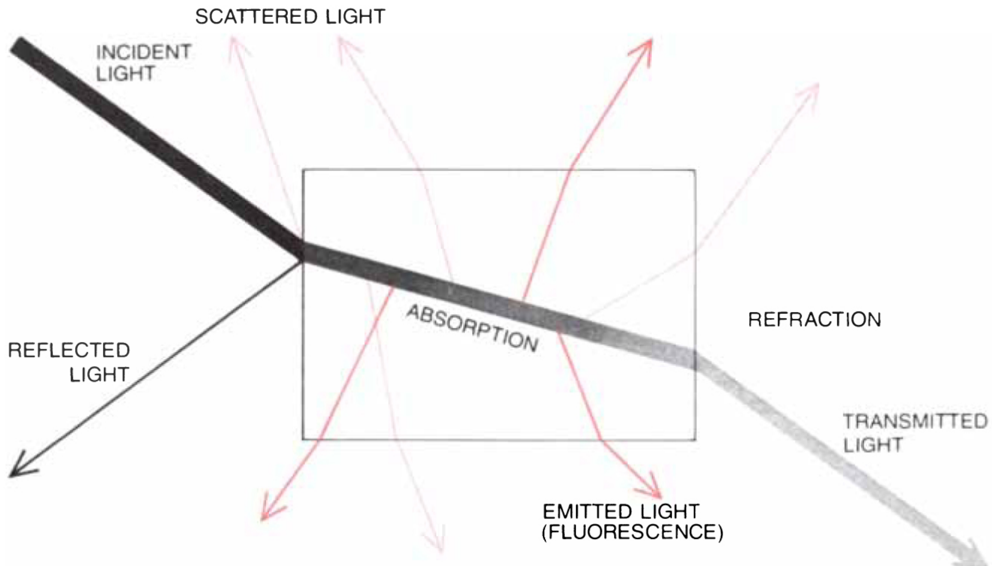

0
0.2
0.4
0.6
0.8
1
Distance (microns)

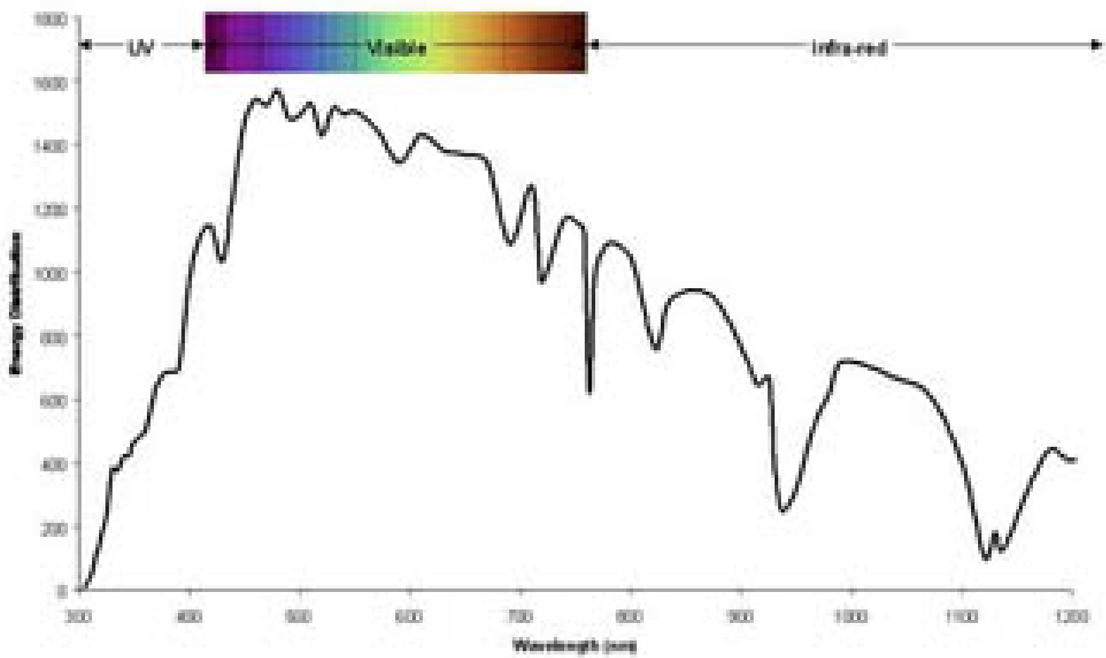


Increasing energy
Increasing wavelength
0.0001 nm
0.01 nm
10 nm
1000 nm
0.01 cm
1 cm
1 m
100 m
Gamma rays
X-rays
Ultra-
violet
Infrared
Radio waves
Radar
TV
FM
AM
Visible light
400 nm
500 nm
600 nm
700 nm

When light meets with some medium or other what happens therein is an *interaction. The net effect will be a function of the properties of the light and the properties of the medium or material.*

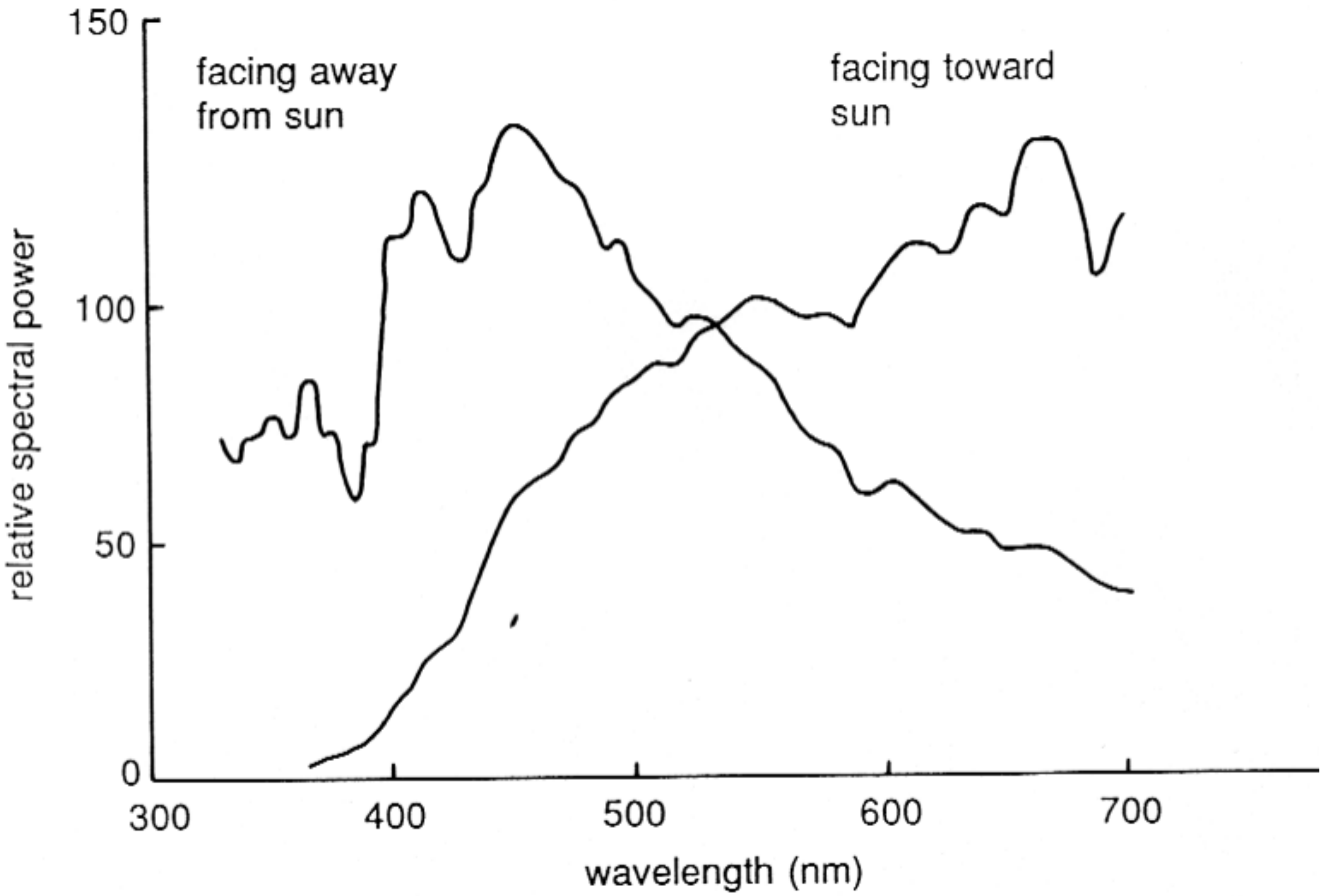


INTERACTIONS OF LIGHT with condensed matter include reflection, refraction, scattering and absorption; some absorbed light can also be reemitted (usually at a longer wavelength) as fluorescence. The effects of each of these processes can vary with wavelength and so can give rise to color. For example, the preferential absorption of short wavelengths and reflection or transmission of long ones makes an object appear yellow, orange or red. In general condensed matter absorbs broad and essentially continuous bands of wavelengths rather than discrete lines.



Although sunlight has a roughly even distribution of energy over the visible range, nonetheless natural light comes in varying SPD’s depending upon the lattitude, the time of day, the direction of the viewer, the particles in the atmosphere, and the filtering effects of the natural environment.

Artificial light sources add to that complexity, for they often have highly selective SPDs.



150
100
50
0
relative spectral power
facing away
from sun
facing toward
sun
300
400
500
600
700
wavelength (nm)

Spectra From Common Sources of Visible Light

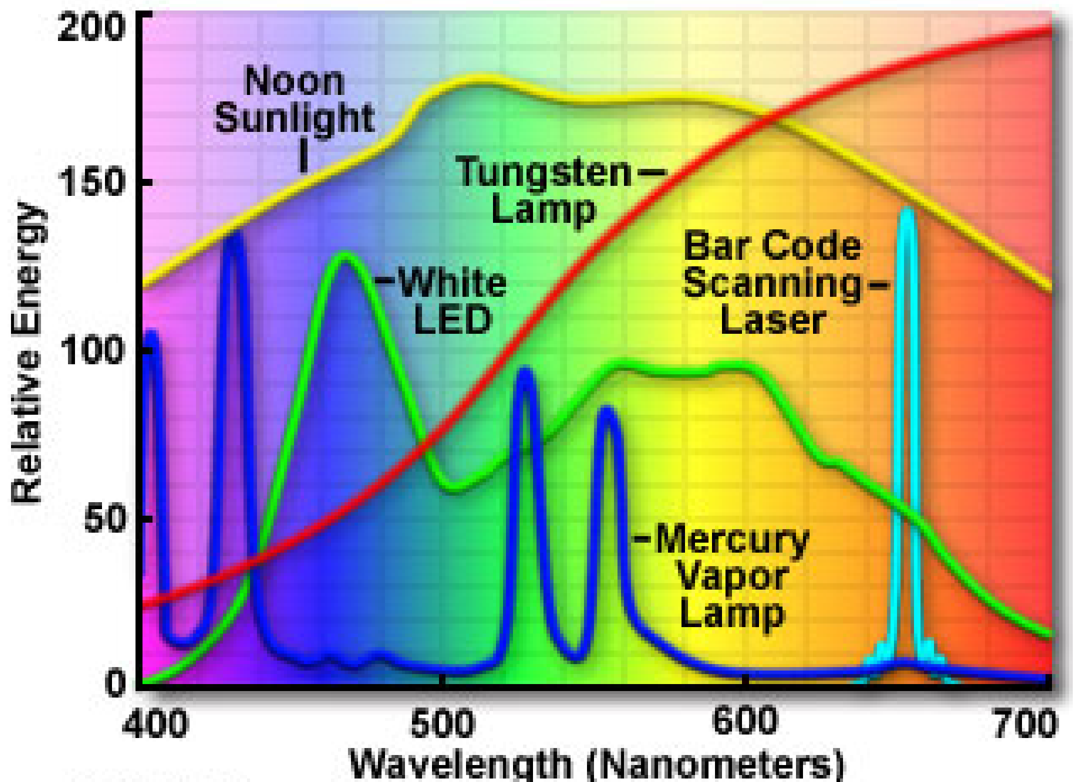
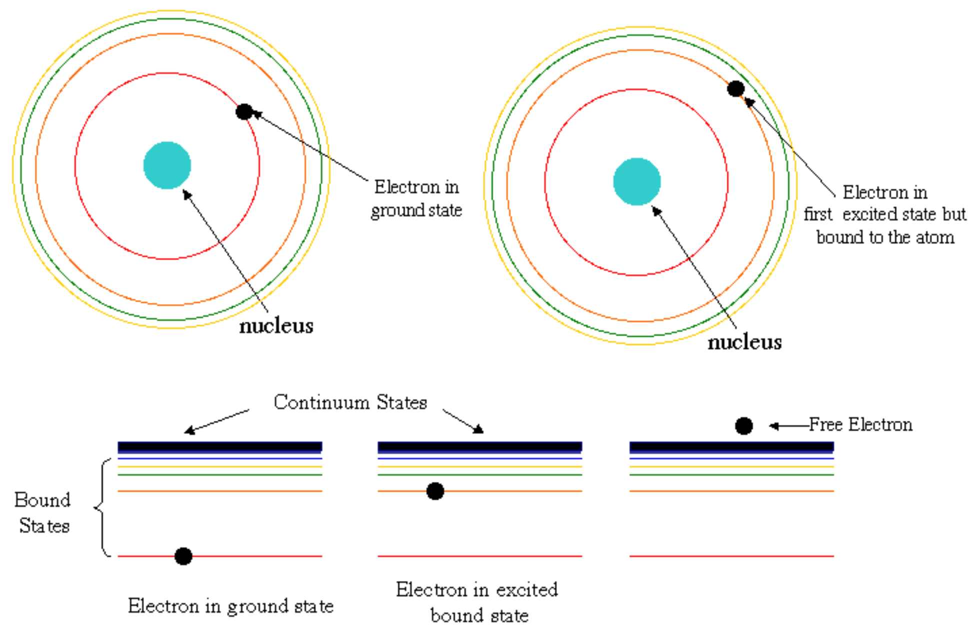


Figure 3

What determines whether light is absorbed by the matter or whether it will be re-emitted (reflected) or transmitted? The “rules’ differ, depending upon what sort of matter the light with which the light interacts, for this determines how and it what way light will be abosrbed or emitted.

For single atoms (in gases)….



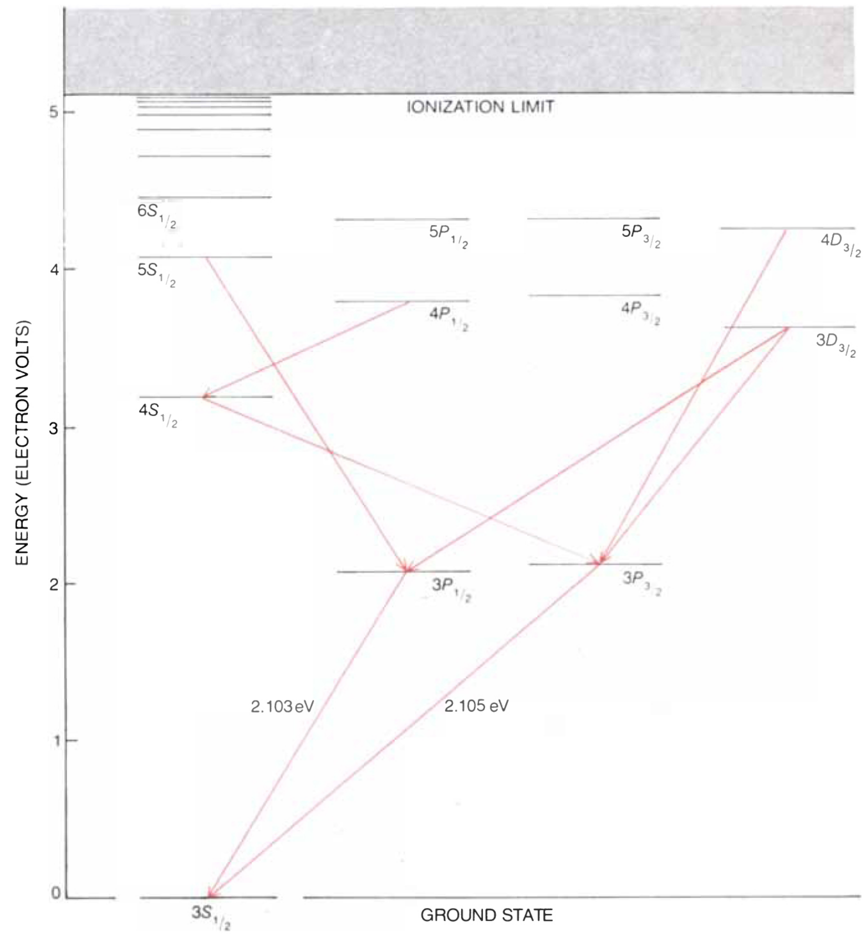
Valence electrons are the primary source of colour for single atoms, as they are the least stable, and require less energy to be “bumped” to a higher level of orbit.

“An important constraint on all interactions of electromagnetic radiation with matter is the quantum-mechanical rule that says atoms can have only certain discrete states, each with a precisely defined energy; intermediate energies are forbidden. Each atom has a lowest possible energy, called the ground state, and a range of excited states of higher energy. The allowed energy states can be likened to the rungs of a ladder, although their spacing is highly irregular. Light or other radiation can be absorbed only if it carries precisely the right amount of energy to promote an atom from one rung to a higher rung. Similarly, when an atom falls from an excited state to a lower-lying one, it must emit radiation that will carry off the difference in energy between the two levels. The energy appears as a photon, or quantum of light, whose frequency and wavelength are determined by the energy difference.”

In other words, an atom, which comes into contact with a wide spectrum light source light sunlight, will absorb only that (or those) wavelength of just the right energy to “bump” the electron up to a higher level of orbit; if the atom then falls back to its ground state, then the atom will emit light of the same wavelength.

Thus if you *heat up* an element, it will eventually emit visible light of certain specific wavelengths, corresponding to the energies required to raise the electron(s) to the ever greater levels of orbit.

If you *add light* to an atom of a particular kind, then the white light will be *depleted*—will loose—only those wavelengths required to increase the orbit of the electron(s). In other words, you *gain* colour by selectively *loosing* wavelengths of the white light which are absorbed by the atom.



LADDER DIAGRAM for the sodium atom defines a spectrum of discrete wavelengths, which are the only ones the atom can emit or absorb. In order to climb to a higher rung the atom must absorb a quantum of radiation whose energy corresponds exactly to the difference in energy between the initial and the final states. On falling to a lower rung the atom emits a quantum with the same energy. Most downward transitions pass through the levels designated $3P_{1/2}$ and $3P_{3/2}$ to the lowest level, or ground state, labeled $3S_{1/2}$. In these transitions quanta are emitted with energies of 2.103 and 2.105 electron volts, in the yellow part of the spectrum, and so a vapor of excited sodium atoms glows bright yellow. In the ladder diagram only the vertical dimension has meaning, but the various series of levels are separated horizontally for clarity.

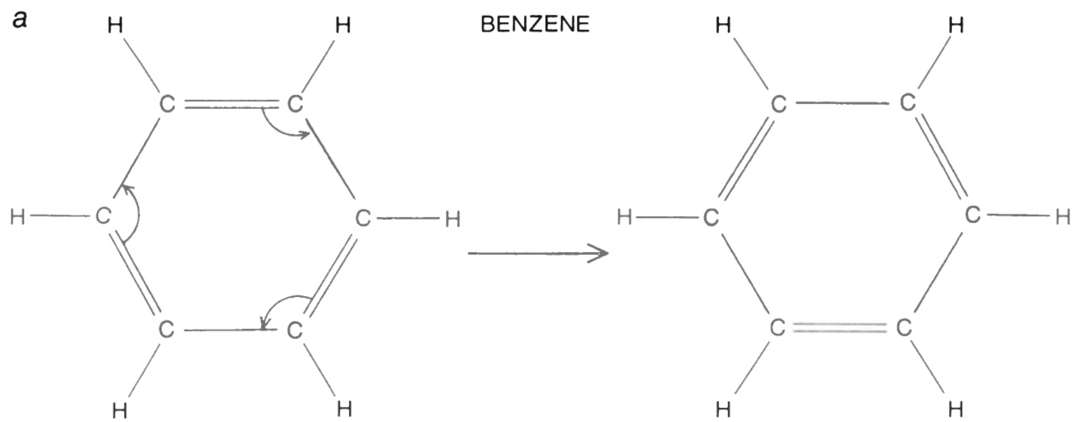
In molecules and solids, the valence electrons are paired in chemical bonds, which require energy in the ultraviolet (high energy) range to break.

“Only electrons in exceptional states remain to give rise to coloration. It is evident, however, that such exceptional states cannot be too rare; if they were, most molecules and solids would be transparent to visible light.”

E.g. Transition metal elements and rare earth metals.

“One set of unusual electronic states appears in the transition-metal elements, such as iron, chromium and copper and in the rare-earth elements. The atoms of metals in the transition series have inner shells that remain only partly filled. These unfilled inner shells hold unpaired electrons, which have excited states that often fall in the visible spectrum. They are responsible for a wide range of intense colors. For example, both ruby and emerald derive their colı or from trace amounts of chromium.”

Chromophores & pi orbitals

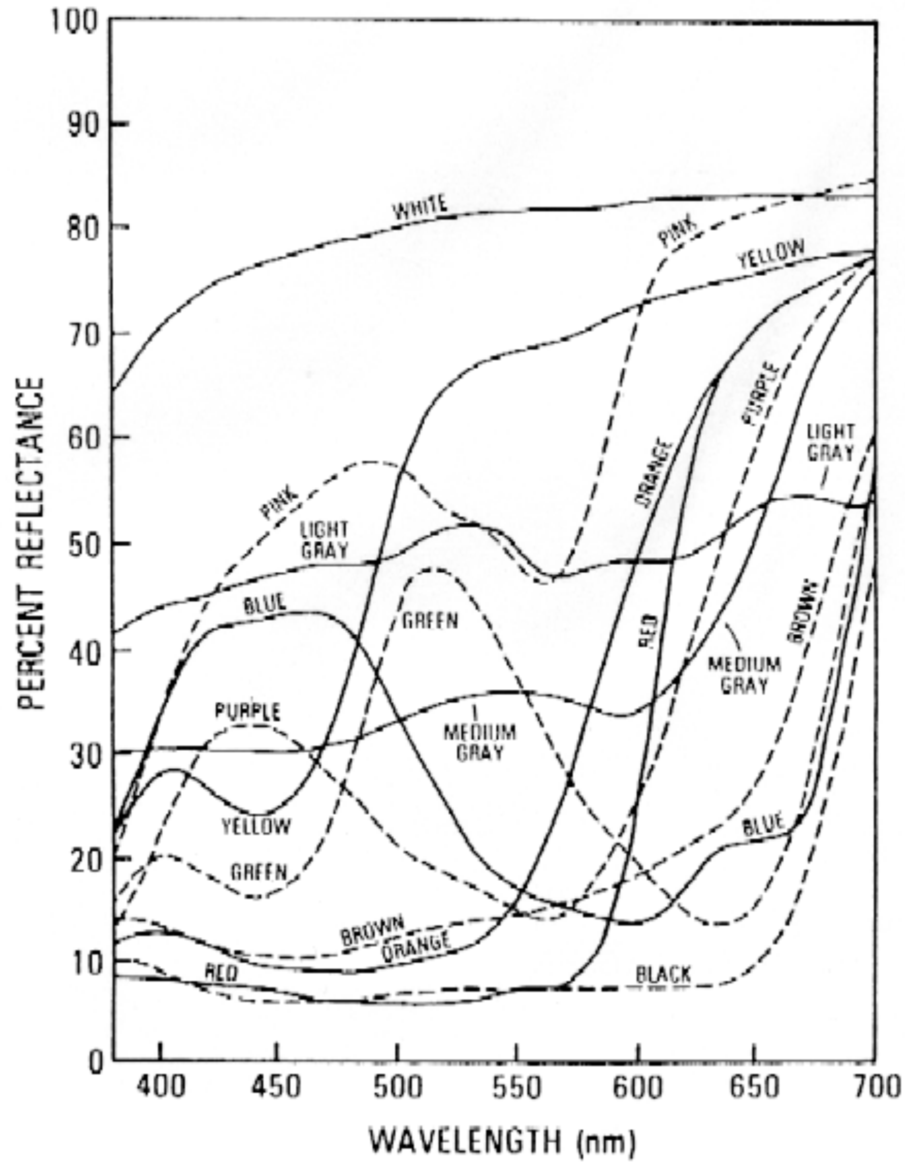


"The two structures defined in this way are equivalent, and there is no basis for choosing between them. Actually the best representation of the structure shows all the atoms connected only by single bonds; the remaining pairs of bonding electrons are distributed over the entire structure in molecular orbitals, which in this instance are called **pi orbitals.**"

In benzene, above, the energy within the ultraviolet range is required for an increase in energy state. But in larger molecules with multiple rings, energy within the visible range is sufficient. These coloured organic molecules are called *chromophores* and account for the colour of organic materials. These are the *pigments* or *dyes*, of which there are over 8000.

The most common cause of colour (for the surfaces of objects): Selective absorption by organic pigments.

While gases have sharply defined emissions of energy (I.e. confined to narrow ranges of the visible spectrum), solids have continuous emissions (i.e. over the entire range of the whole spectrum.)

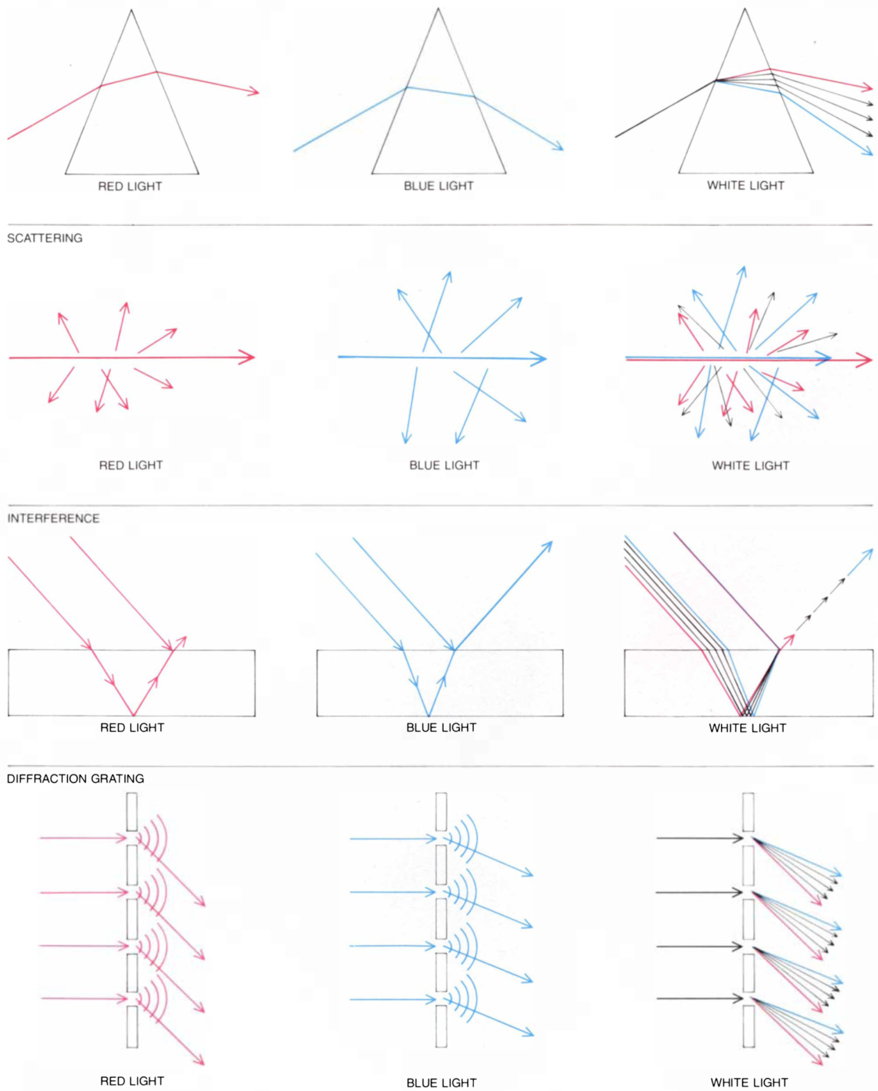


Fluorescence occurs when molecules in an excited state return to their ground state, via a number a number of intermediate orbits, releasing light within the visible range. Note that the light emitted is of a lower wavelength than the light absorbed, given the intermediate states.

E.g. Fabric brighteners, rubies and emeralds.

“As in ruby and emerald, the fluorescent light is emitted when an excited state decays through an intermediate level and the energy of at least one of the intermediate transitions corresponds to a visible wavelength. The fabric brighteners added to some detergents achieve their effect by absorbing ultraviolet radiation in daylight and reemitting a part of the energy as blue light.”

Laws of optics



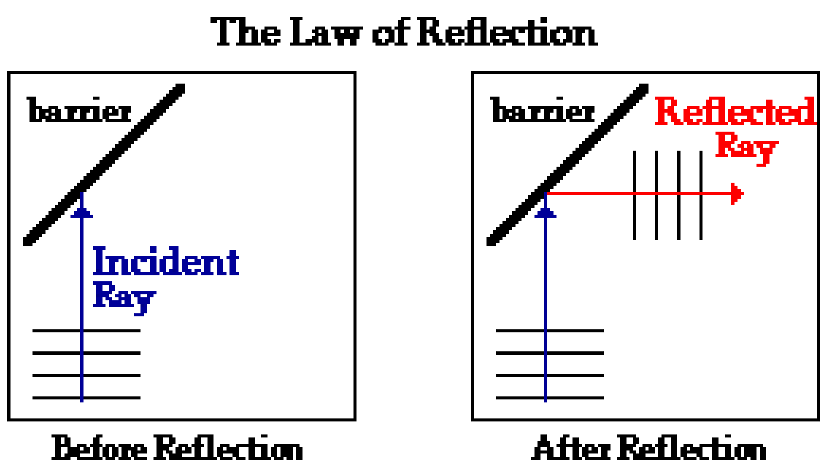
PHYSICAL OPTICS provides the most convenient interpretation of colors generated by several mechanisms that involve a change in the direction of light. The dispersion of white light into its component colors by a transparent prism comes about because short wavelengths are refracted through a larger angle than long wavelengths. In a similar way the scattering of light by small particles is more effective at short wavelengths, so that more blue light is scattered than red. Interference is observed when a light wave is split into two parts that are then brought together again. If the waves are in phase when they recombine, the intensity is enhanced; if they are out of phase, the waves cancel each other. Since the phase difference between the two beams can depend on wavelength, interference can enhance some colors and suppress others. In a diffraction grating light is scattered by many uniformly spaced centers and the resulting multiple wave fronts interfere with one another. Each wavelength is reinforced in one set of directions and canceled in all others, so that white light is dispersed.

Reflection and Transmission

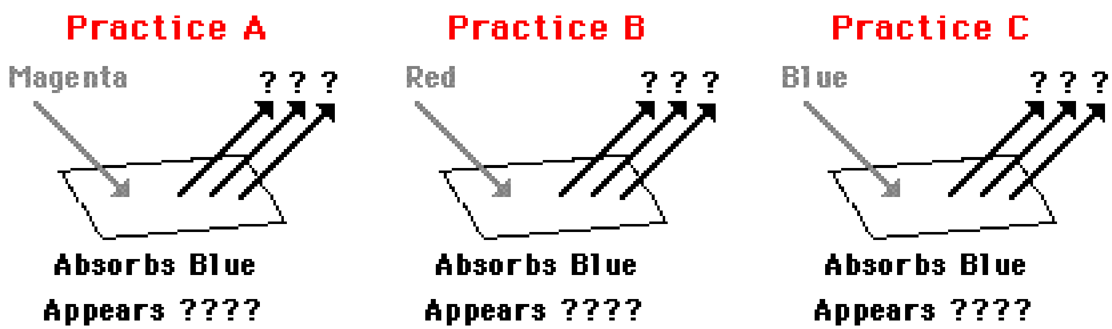
If the frequencies of the light and the electrons of the solid/liquid medium are different, then the light will be reflected or transmitted.

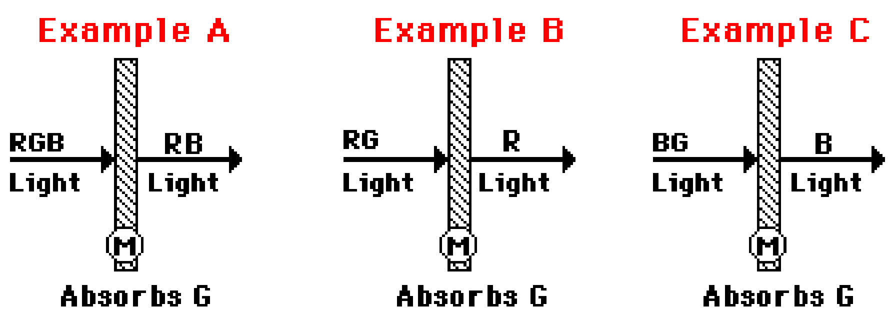
The light is absorbed briefly, the electrons start to vibrate, but instead of increasing their amplitude, they soon cease vibration. If the object is transparent, these small vibrations are passed from atom to atom and the light is re-emitted out the opposite side of the object. This is *transmission*.

If the object is opaque, then the initial vibrations are not passed to neighboring atoms but are immediately *re-emitted* from the surface of the object; this is *reflection*.



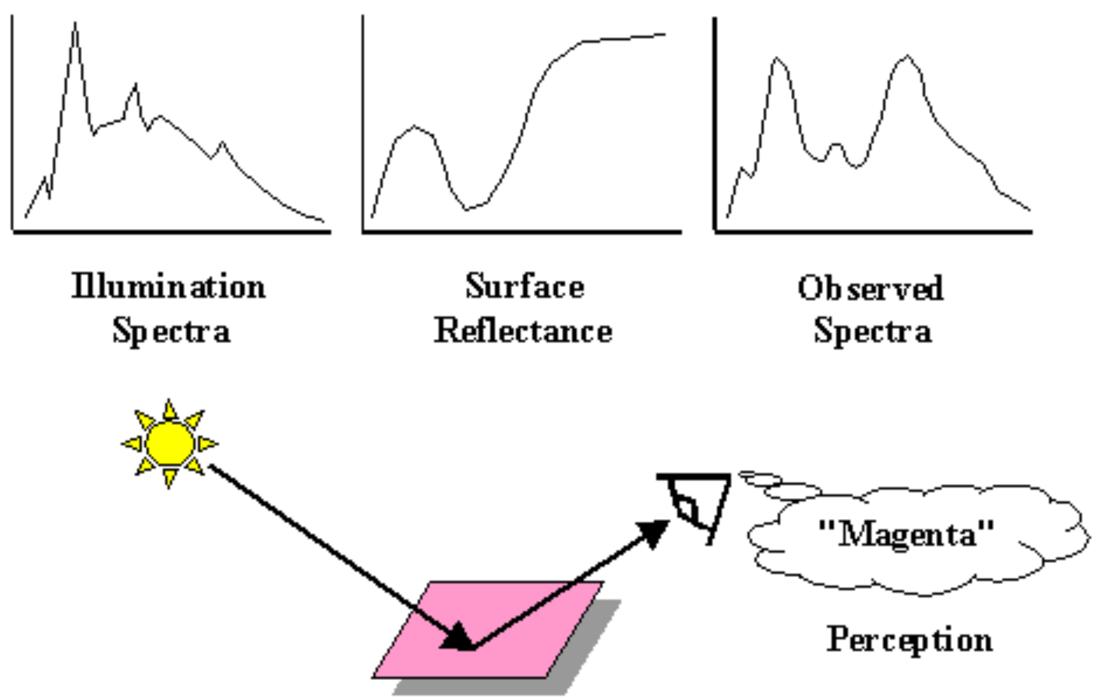
Colour subtraction: absorption and filtering

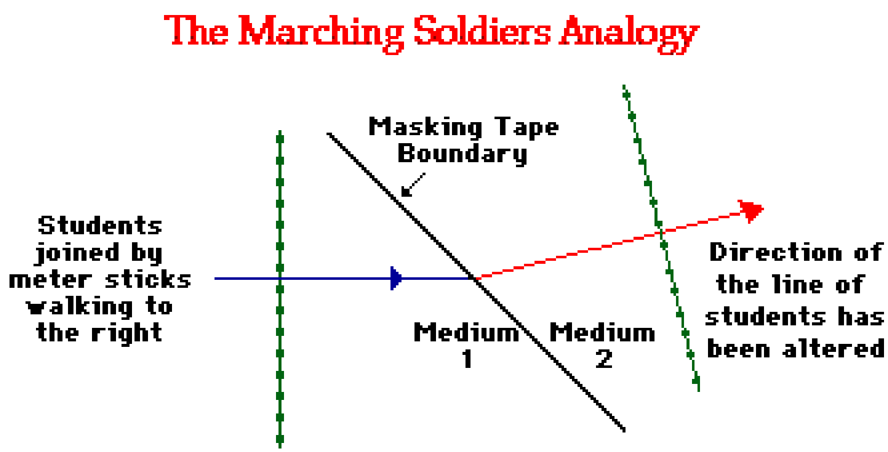


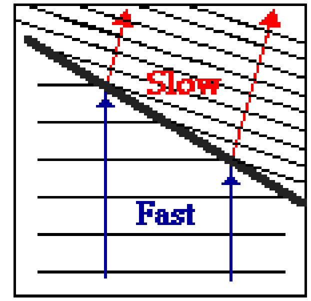


The wavelength composition of the stimulus which reaches your eye depends upon both the SPD (spectral power distribution) of the light source and the SSR (surface spectral reflectance) of the object (given its surface pigmentation).

Thus, in order to see objects as having particular colours, the brain must disambiguate the contributions made by the light source and the surface reflectance of the object.

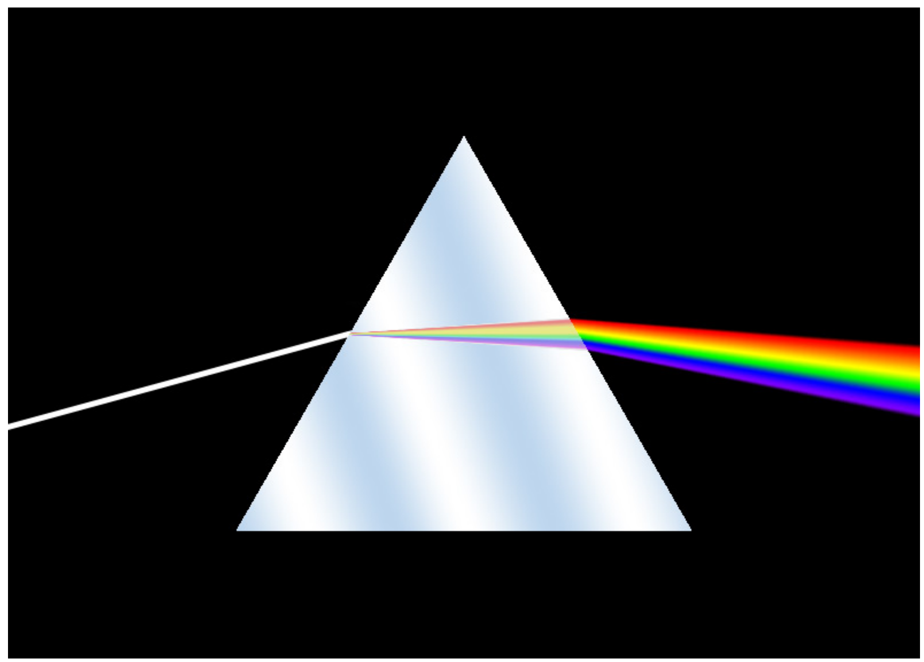




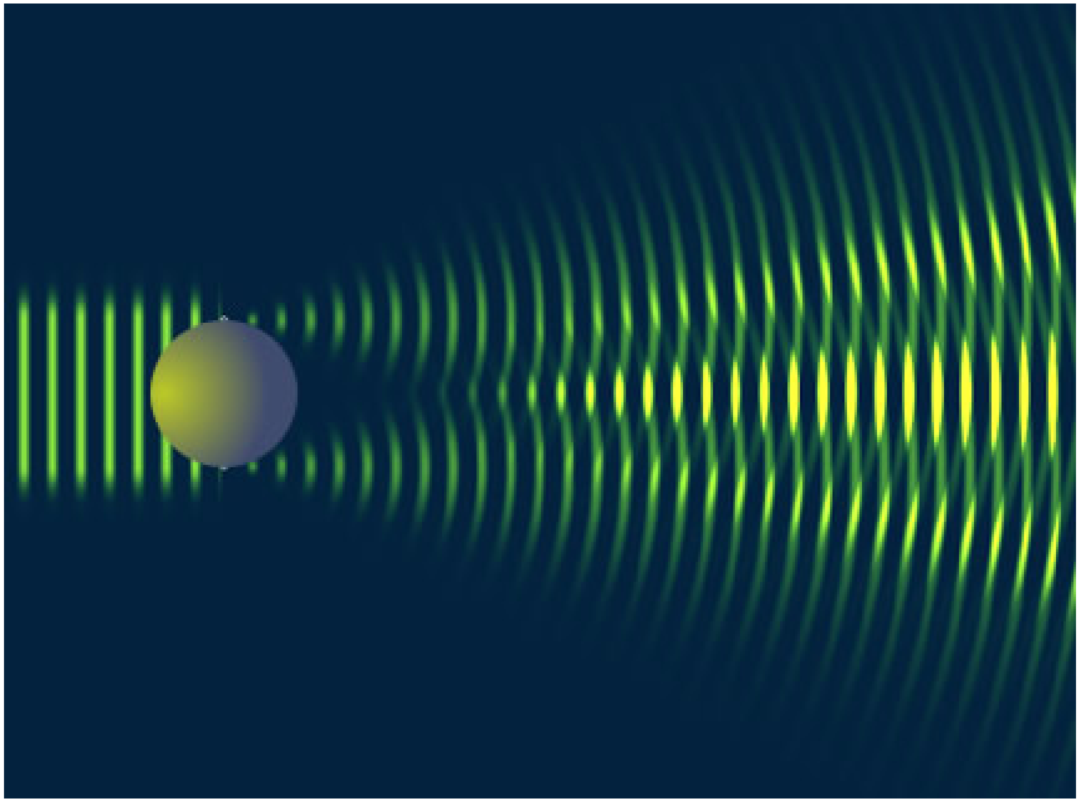


The refractive behavior of light reveals that light is very wave-like.

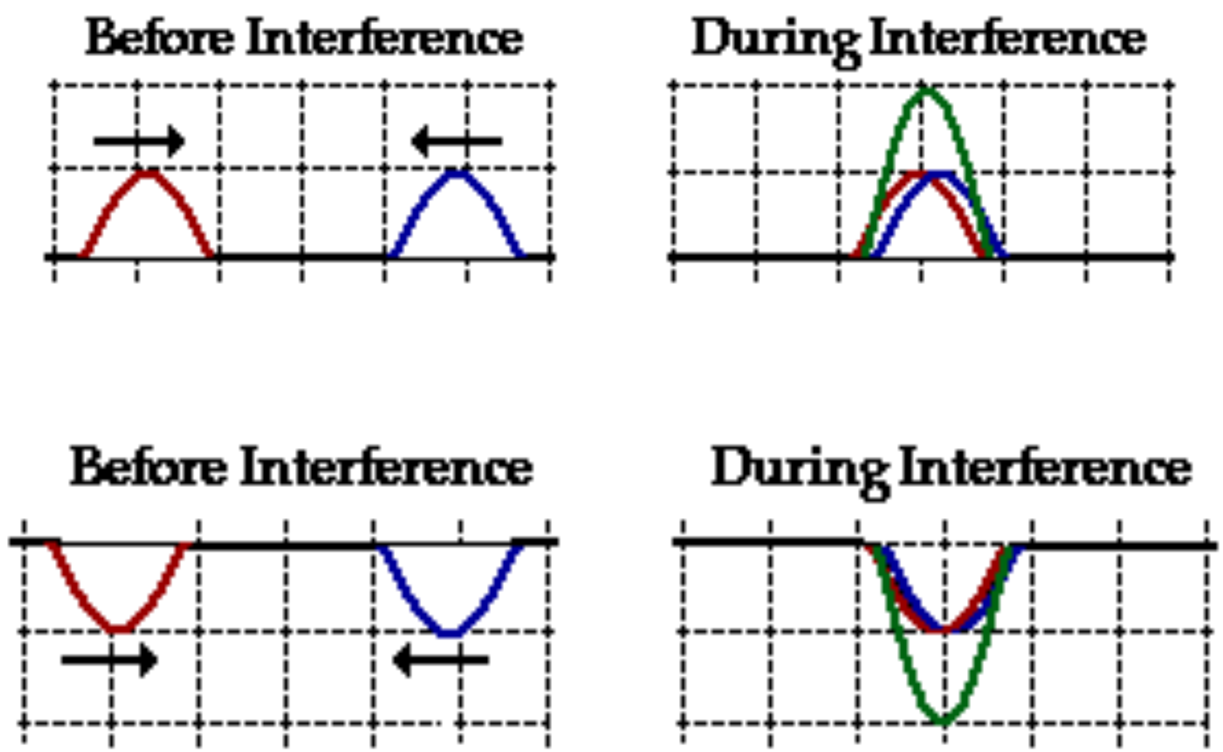
Refraction: When a wavefront crosses the boundary between two media, the velocity of the wavefront will change. If it hits the boundary at an oblique angle, then the direction of the wavefront undergoes a sudden change; the path is "bent", and this bending is wavelength selective.



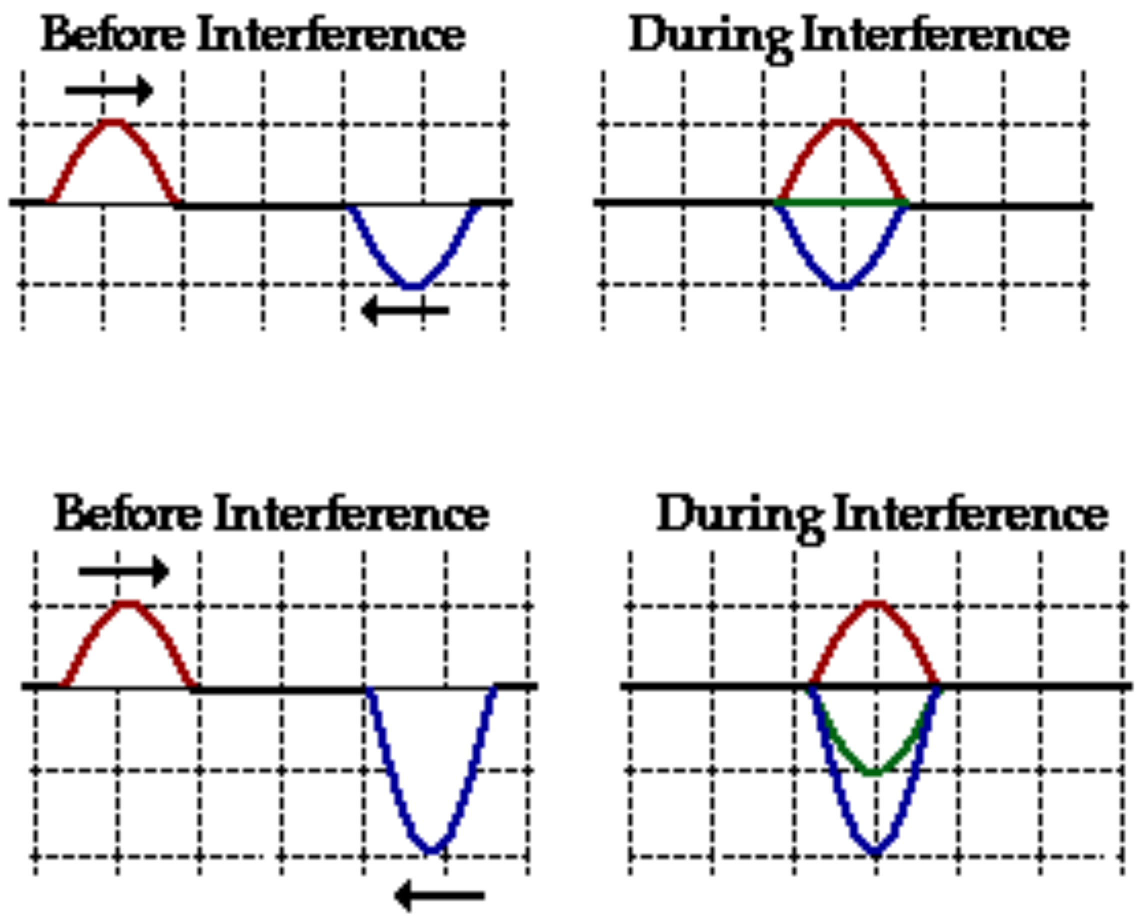
Diffraction: A change in direction of waves as they pass through an opening or around a barrier in their path. Diffraction of and by itself does not result in colour; rather diffraction results in interference of the resulting wavefronts and this produces or changes the predominant wavelength.



Constructive Interference

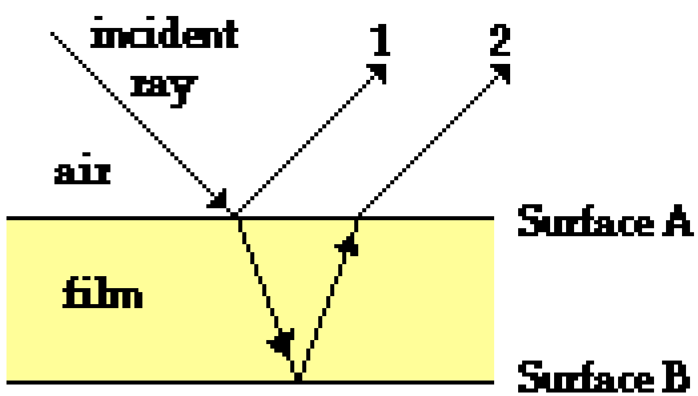


Destructive Interference



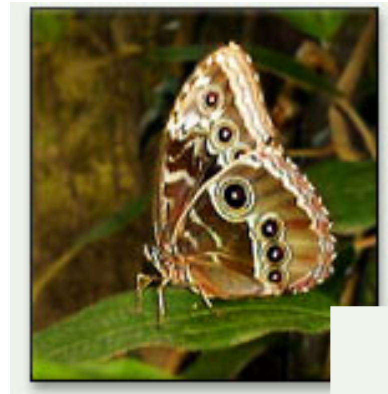
In nature, separation of “white light” often occurs as a result of a number of different boundary behaviors that occur, one after the other, and end up causing constructive inference — hence the “creation” of a new predominant wavelength.

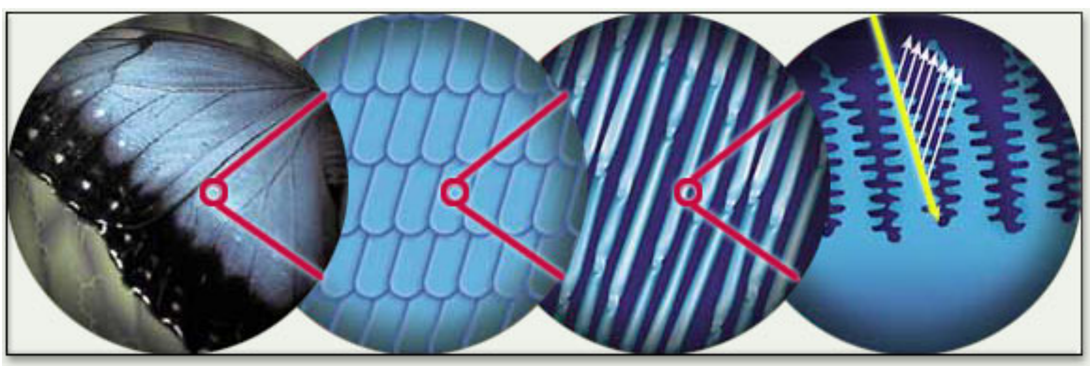
Example: an oil slick



Top

Underside






Scale: 1 µm

ELECTRONIC TRANSITIONS IN FREE ATOMS AND IONS; VIBRATIONAL TRANSITIONS IN MOLECULES	ELECTRONIC EXCITATIONS	INCANDESCENCE, FLAMES, ARCS, SPARKS, LIGHTNING, GAS DISCHARGES, SOME LASERS.
	VIBRATIONS	BLUE-GREEN TINT OF PURE WATER AND ICE.
CRYSTAL-FIELD COLORS	TRANSITION-METAL COMPOUNDS	TURQUOISE, MOST PIGMENTS, SOME LASERS, SOME PHOSPHORS, SOME FLUORESCENT MATERIALS.
	TRANSITION-METAL IMPURITIES	RUBY, EMERALD, RED SANDSTONE, SOME LASERS, SOME FLUORESCENCE.
	COLOR CENTERS	AMETHYST, SMOKY QUARTZ, DESERT-AMETHYST GLASS, SOME FLUORESCENCE.
TRANSITIONS BETWEEN MOLECULAR ORBITALS	CHARGE TRANSFER	BLUE SAPPHIRE, MAGNETITE.
	CONJUGATED BONDS	ORGANIC DYES, MOST PLANT AND ANIMAL COLORS, LAPIS LAZULI, FIREFLIES, DYE LASERS, SOME FLUORESCENCE.
TRANSITIONS IN MATERIALS HAVING ENERGY BANDS	METALLIC CONDUCTORS	COPPER, SILVER, GOLD, IRON, BRASS.
	PURE SEMICONDUCTORS	SILICON, GALENA, CINNABAR, DIAMOND.
	DOPED SEMICONDUCTORS	BLUE DIAMOND, YELLOW DIAMOND, LIGHT-EMITTING DIODES, SEMICONDUCTOR LASERS, SOME PHOSPHORS.
GEOMETRICAL AND PHYSICAL OPTICS	DISPERSIVE REFRACTION	THE RAINBOW, "FIRE" IN GEMSTONES, CHROMATIC ABERRATION.
	SCATTERING	BLUE OF THE SKY, RED OF SUNSETS, MOONSTONE, STAR SAPPHIRE.
	INTERFERENCE	OIL FILM ON WATER, LENS COATINGS, SOME INSECT COLORS.
	DIFFRACTION GRATING	OPAL, LIQUID CRYSTALS, SOME INSECT COLORS

CAUSES OF COLOR are classified in 14 categories of five broad types. All but one of the color-causing mechanisms (vibrations of the atoms in molecules) can be traced to changes in the state of the electrons in matter. Electronic transitions are the most important causes of color because the energy needed to excite an electron commonly falls in the range that corresponds to visible wavelengths of light.

We see colour when one wavelength (or rather one narrow range of the spectrum) becomes predominant — when there is more of one wavelength than another.

There are two basic ways for this to happen if you start with a light source which has an equal distribution of power across the visible spectrum:

1. You could *take away* some wavelengths, leaving one range predominant. This happens whenever a medium absorbs (and hence reflects light) selectively, hence this is *subtractive* colour. (Think PAINT)

2. You could could ADD light with a certain wavelength, thus creating a predominant wavelength. When psychophysicists test for colour vision, by combining lights of various wavelengths, this is *additive* colour. (Think LIGHT)