H50: Types of Coloured Materials

Introduction

The visual appearance of the surface of an object depends on the way the light energy that is incident on the surface interacts with the material. Light is a form of electromagnetic energy, the same form of energy as television or radio signals. Electromagnetic energy has the form of an oscillating magnetic and electric wave that travels in straight lines at speeds of order 286,000 miles per second. The frequency of oscillation determines the wavelength of the radiation, the higher the frequency of oscillation then the shorter the wavelength.

Light is the term used for radiation in the band of wavelengths that are visible to the human eye. Each wavelength in the visible range triggers a different response from the receptors in the eye and appears to have a different colour. White is the sensation given by light that contains a blend of wavelengths from all parts of the visible spectrum. Isaac Newton in Cambridge in 1666 was the first to show that white sunlight is a combination of light of all the basic colours.

The human eye responds to electromagnetic radiation over a very limited range of wavelengths. The range, for a person with normal colour vision, is from 380nm to 730nm, where nm stands for nanometre and is a thousand millionth of a metre (10^{-9} m). For most practical purposes the range of sensitivity of the eye can be taken as from 400nm to 700nm, as illustrated in Figure 1. The associations between the wavelength bands and the colour names are only approximate since the colours merge smoothly from one band to another.

The light that is entering the eye gives rise to the sensation of colour. The sensation of colour is the interpretation by the brain of the signals coming from the eyes.

Some materials appear coloured because they create light by the conversion of energy in another form into light. These materials are classed as “self luminous”, a colour television screen and the lamps in the room are examples of this type, and both convert electrical energy into light.

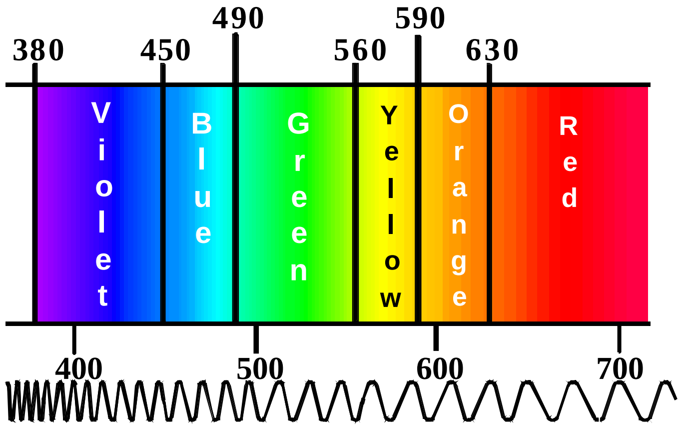


Figure 1: Colour names against wavelength (nm).

It is clear, just by looking around, that the majority of coloured objects can be classed as “reflective” or “surface colours”. They appear coloured because of the interaction of the light shining onto their surfaces with the atoms and molecules within the surface region. The majority of materials produced by the coating industry are surface colours.

Colour by reflection

The selective absorption of wavelengths from white light is probably the most common way of creating colour. The white light shone onto a plain white surface is reflected evenly across the spectrum to cause a balanced set of visual signals to be passed from the eye to the brain. This is interpreted as “White”.

In a coloured material, the pigments or dyes that are present absorb some of the wavelengths from the incident light, often converting the absorbed light into heat energy. The remaining wavelengths are reflected back by the background or by any highly scattering “white” pigments that may be present.

To appear coloured, a material should absorb light from wavelengths within one, or at most two of the bands shown in Figure 2. If the material does not absorb light in any of the bands then it will appear white. If it absorbs wavelengths spread evenly through all three of the bands then it will appear grey or black.

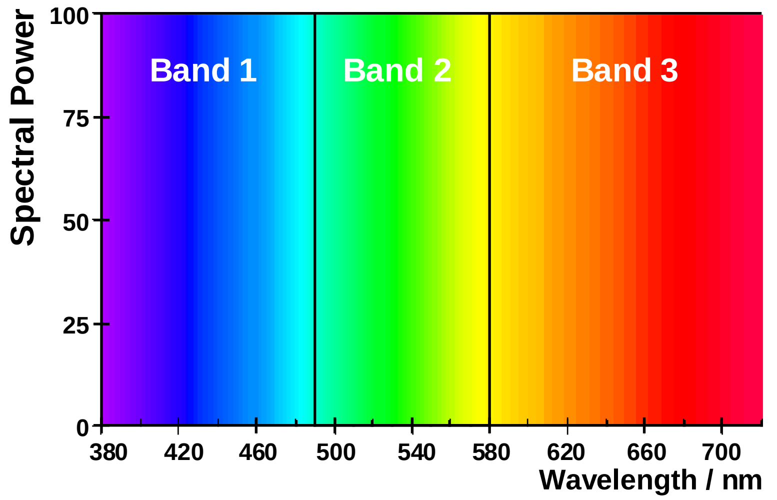


Figure 2: A coloured material will absorb light from one, or at most two wavelength bands.

A red object appears red because the light with wavelengths in the blue band (1) and green band (2) are absorbed by the material and only the wavelengths in the red band (3) are reflected into the eye. Table 1 shows the reflected colour observed for each combination of band absorbed or reflected.

Table 1: The band of light that is absorbed or reflected and the associated surface colour.

Colour	Band 1	Band 2	Band 3
White	Reflected	Reflected	Reflected
Black	Absorbed	Absorbed	Absorbed
Yellow	Absorbed	Reflected	Reflected
Magenta	Reflected	Absorbed	Reflected

Colour	Band 1	Band 2	Band 3
Cyan	Reflected	Reflected	Absorbed
Blue	Reflected	Absorbed	Absorbed
Green	Absorbed	Reflected	Absorbed
Red	Absorbed	Absorbed	Reflected

Types of coloured material

It is possible to identify three different types of coloured materials based on the way in which light absorbing and scattering components are distributed within the surface regions of the material. Table 2 gives the definition of the three types together with some common examples.

Table 2: Three types of optical system

Optical systems	Common Examples
Homgeneous systems Materials where the light incident on the surface interacts with only one type of material. The composition and structure of the material are the same throughout the surface region.	Conventional paints Opaque plastics Dyed textile fabrics and garments
Layered systems Materials where the light incident on the surface interacts with two or more layers of different optical properties. The composition and structure of the material within each layer is the same throughout that layer.	Printing on non-absorbent substrates such as carton board, metal foil and plastic laminated board. Lacquer coatings on wood, metal and other surfaces. Two-coat and three-coat automotive paint systems. Plastic films, photographic prints and transparencies.
Heterogeneous systems Materials where the light incident on the surface interacts with a material whose composition and structure changes with the depth below the surface.	Printing on absorbent substrates such as newsprint. Pigment printing on textile fabrics. Stained wood.

In the next section, each type of material is introduced in turn and the different types of interaction of the light with the surface regions are described.

Homogenous, opaque, materials

Pigmented materials

A pigmented material can be regarded as a two-phase system, a continuous phase and a disperse phase. In paints, plastics and printing inks, the continuous phase is usually a polymeric binder material together with any additive materials dissolved in the binder. The disperse phase, also known as the discontinuous phase, includes all particulate materials, whether they are pigments, fillers or other types of additive.

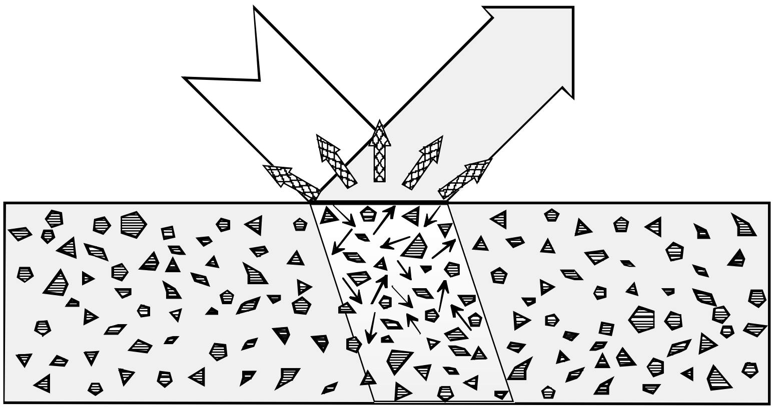


Figure 3: Interactions of a light beam at the surface and within an opaque, pigmented material

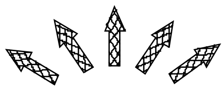
Figure 3 is a schematic diagram of the surface region of an opaque, pigmented material. It has been drawn in an idealised way to show the different types of interaction that can occur between a light beam and the various components of the material.

When a material contains a large amount of pigment, or a coating layer is thick enough, none of the incident light will penetrate through the material or the coating layer. The spectrum of the light reflected from an opaque layer is determined by the absorption and the scattering properties of the components in the material and does not change with the thickness of the material. Another property of an opaque material is that the addition of a transparent, colourless diluent to the material will not change its appearance.

Figure 3 shows two types of interaction that take place between the incident light energy and the material.

- Partial reflection at the air to coating boundary
- Absorption and scattering by the pigment particles within the layer.

These are discussed in more detail in the following sections.



<u>*Light reflected from within the material*</u>

The light passing through the boundary interacts, through scattering and absorption, with the pigment particles. If the absorption occurs within a selected band of wavelengths in the visible spectrum then the transmitted light and the reflected light will be coloured.

Figure 4 illustrates the paths that photons might take in an opaque, pigmented material. The figure was obtained by a computer program that simulates the interactions of an incident light beam with a layer composed of a clear medium, a white pigment and a coloured tinter pigment.

Photons are “fired” at the top surface of the layer and when the photon encounters a particle, a random number generator is used to decide whether the photon is absorbed or scattered by the particle.

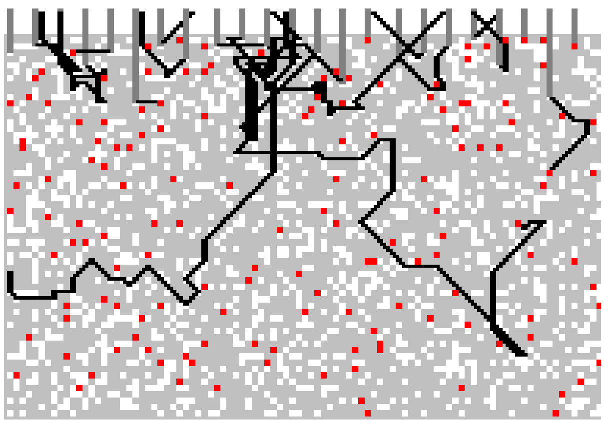


Figure 4: Simulated photon paths, opaque layer

The figure shows the paths obtained when 30 photons were fired at the layer. The conditions of the simulation and the result obtained are shown in Table 3.

Table 3: Conditions for the computer simulation of light interacting with an opaque layer

Material	% PVC
White	25
Tinter	5
Medium	70

Parameter	% Value
Reflection	50
Transmission	0
Absorption	50

For a conventionally pigmented material, the direction of the light transmitted back through the material to air will be spread over a range of angles. If we exclude the viewing angle that coincides with the specularly reflected (mirror like) light, then the colour impression of the surface is the same, to a good approximation, at all viewing angles. The exception is at glancing or oblique angles of viewing and skilled colourists will often tilt pairs of panels to compare the colour at both the face and glancing angles of viewing.

Dyed textile fabrics

A dyed textile fabric is a single-phase system consisting of the woven or knitted yarn only. Figure 5 is a depiction of a fabric woven from yarn consisting of tri-lobal fibres twisted together. The interweaving of the yarns along their length gives mechanical continuity, both across and through the fabric.

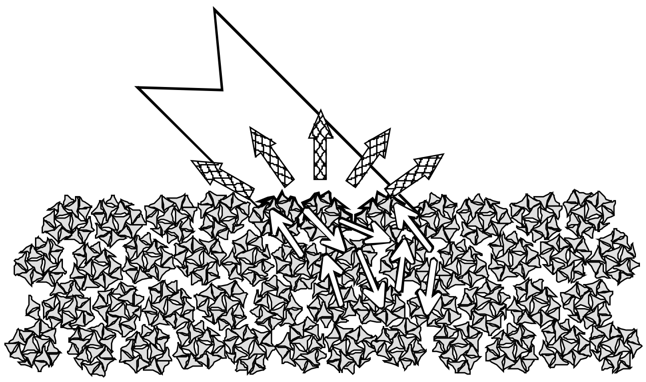
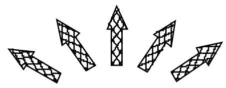


Figure 5: Interactions of a light beam at the surface and within an opaque, textile material

The cross-sectional view through the fabric suggests that there is no continuous phase. However, in optical terms, a textile material is a two-phase system.

The continuous phase is formed by the air and the discontinuous phase is formed by the textile fibres.



Light reflected from within the fabric

The light passing through the boundary is scattered within the fabric at the internal air to fibre boundaries. The refractive index difference between the air (refractive index 1.00) and the polymeric fibre (refractive index of order 1.50) means that the air gaps act as scattering centres.

Light travelling within the textile fibres will interact with the dye molecules. If light absorption occurs within a selected band of wavelengths in the visible spectrum then the transmitted/reflected light will be coloured.

Wet or damp material

If the air gaps are filled with a material with a refractive index nearer to that of the fibre, then the scattering is reduced and the fabric becomes darker and more transparent. This used to be a cause of embarrassment to wearers of pure white swimming costumes made from synthetic fabrics. Water has a refractive index of 1.33; much closer to the index of the fibre, the consequent reduction in scattering when the costume became wet meant that the fabric became virtually transparent. The same effect occurs when some types of T-shirt become wet.

The problem of the wet transparency of synthetic fabrics can be overcome by incorporating a very fine dispersion of a light scattering pigment into the polymer fibre during spinning. Light is scattered within the fibres as well as at the air to fibre boundaries.

Homogeneous semi-transparent materials

Many printed and coated surfaces are a semi-transparent layer over an opaque substrate. The coating material is usually composed of a dispersion of pigment and filler particles embedded in a continuous medium. Some of the particles in the coating scatter the light into different directions and, if the layer is coloured, some of the particles absorb the light.

Figure 6 is a schematic diagram of the surface region of an object that has been coated with a layer of a conventionally pigmented material. It has been drawn in an idealised way to show the different types of interaction that can occur between a light beam and the various components of the material.

The incident light energy is partially reflected at the air to coating boundary.

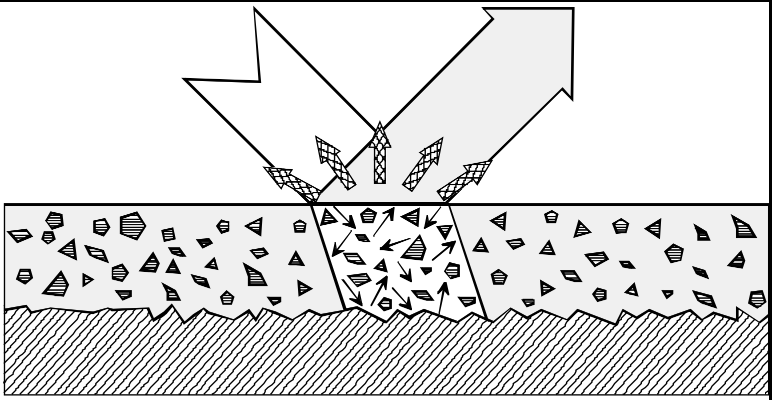


Figure 6: Interactions of a light beam with surface covered with a pigmented coating layer

The light that enters the coating layer is scattered and absorbed by the particles suspended in the layer, some light energy will be reflected out of the layer and some transmitted towards the interior of the material. In Figure 6Figure , the opaque substrate material reflects a portion of the light back towards the illuminated surface. There is a series of multiple reflections within the layer, until the light energy is either transmitted back through the coating to air boundary or is absorbed.

The spectrum of the light reflected from the surface depends on a number of factors;

- The partial reflectance at the air/coating boundary.
- The absorption and scattering properties of the coating layer.
- The thickness of the layer.
- The reflectance spectrum of the substrate material.

Figure 7, illustrates the paths that photons might take in a semi-transparent pigmented layer. The simulation was obtained under the same conditions as for the opaque material, except that only one third of the volume of pigment was used.

The illustration shows the paths obtained when 30 photons were fired at the layer. The conditions of the simulation and the result obtained are shown in Table 4

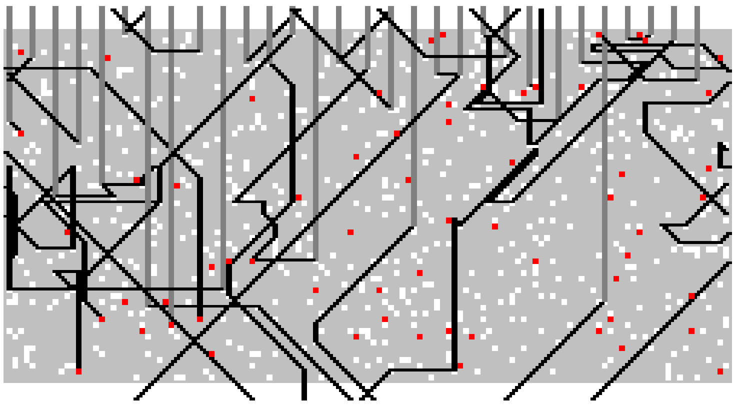


Figure 7: Simulated photon paths, semi-transparent layer

The semi-transparent layer reflects 30% of the incident light, less than an opaque layer of the same material. However, 30% of the incident light penetrates through the semi-transparent layer.

Table 4: Conditions for the computer simulation of light interacting with a semi-transparent layer

Material	% PVC
White	8.33
Tinter	1.67
Medium	90

Parameter	% Value
Reflection	30
Transmission	30
Absorption	40

A coating layer can be fully transparent. For example, a yellow lacquer coated onto a foil-laminated carton board will give an attractive metallic gold appearance. This type of coating absorbs but does not scatter light. The coating is coloured either by the addition of soluble dyes or by transparent forms of pigment particles.

Heterogeneous materials
The third type of system describes the case when the colorants in the coating material are partially or totally absorbed into the surface layers of the substrate. An excellent example is the surface regions of wood that has been treated with a stain. The colorants in a wood stain can be a mixture of dyes dissolved in a carrier solvent or pigments in suspension, or both. On application, the carrier liquid is rapidly adsorbed into the wood surface, transporting the colorants into the pores and channels between the wood fibres.

Two other examples of heterogeneous systems are conventional fountain pen ink written onto paper and newsprint ink printed on newspaper and low-cost magazines. The colorants are held within the surface by physical entrapment and can be rubbed off onto your fingers.

Figure 8 is a schematic diagram of the surface region of an object where the coating material has been absorbed into a fibrous substrate. There is more colorant absorbed in the region adjacent to the surface than in the deeper of the material.

The incident light energy is partially reflected at the air to coating boundary.

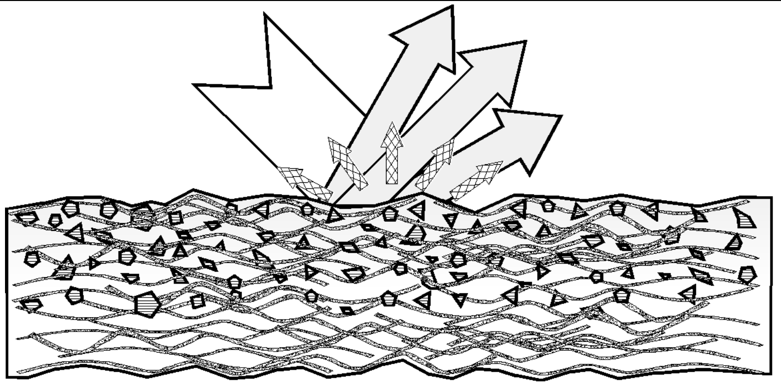


Figure 8: Interactions of a light beam with surface adsorbed pigmented coating layer

The air to coating surface that is shown in Figure 8 is irregular, consequently the boundary reflected light would be spread over a range of angles

The light that passes through the air-to-coating surface is scattered and absorbed by the substrate and by the colorants. Some of the light energy will be reflected out of the layer and some transmitted deeper into the material. A portion of the light energy is reflected from the interior back towards the illuminated surface. There is a series of multiple reflections within the surface region, until the light energy is either transmitted back through the coating to air boundary or is absorbed.

The spectrum of the light reflected from the surface depends on a number of factors;
- The partial reflectance at the air/coating boundary.
- The absorption and scattering properties of the coating material.
- The amount of coating material applied per unit area of surface.
- The depth of penetration of the coating material into the substrate.
- The reflectance spectrum of the substrate material.

Partial reflection of light at a boundary
An air to coating boundary
The difference between the value of the refractive index of air and that of the coating material causes part of the incident light energy to be reflected at the air to coating boundary. It will be shown in a later section that the effect of the boundary reflectance needs to be taken into account in numerical calculations of the total power reflected by the surface. The effect is accounted for by the **Saunderson correction equation**.

Glossy surfaces
For a perfectly smooth surface, the boundary reflected beam makes the same angle with the normal to the surface as that made by the incident beam. This is identical to the way in which a mirror will reflect a beam of light and, for this reason, boundary reflection is also known as specular (mirror-like) reflection. The spectrum of the boundary reflected light is virtually the same as that as the incident beam, so if the incident beam is white light then so is the boundary reflected light. An observer

viewing such a surface will see, at certain viewing angles, reflected images of the surroundings. This gives rise to the visual impression of gloss.

Matt surfaces

The boundary reflectance is present for a rough surface, however the range of angles that the surface presents to an incident beam causes the boundary reflected light to be spread over a wide range of angles. The boundary reflected light is so diffuse that the observer cannot make out images of the surroundings. Consequently, the visual impression is that of a matt surface.

An air to textile boundary

The dye molecules are located within the textile fibres, therefore light has to pass through an air to fibre boundary before it can interact with the dye. The effective boundary is the perimeter of the fibres at the illuminated surface of the material, this is shown in magnification in Figure 9. The boundary outline, for most textile materials, is very convoluted, consequently the boundary reflects light into all possible directions.

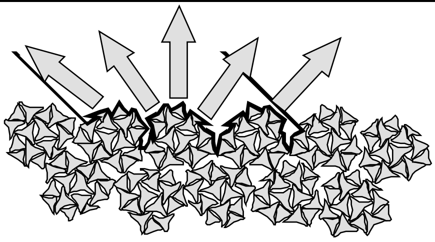


Figure 9: Partial reflection at the air to fabric boundary

The boundary reflected light blends in with the light reflected from the body of the fabric. The boundary reflectance needs to be taken into account in numerical calculations of the total power reflected by the surface. The effect is accounted for by the **Pineo correction equation**.

Relating composition to colour

The structures and light paths shown in the figures illustrate the complexity of the surface regions of coloured materials. In particular, examine the figures to obtain an impression of the range of possible paths that light beams, or photons, might take within these types of materials.

Lambert Bougeur law for non-scattering materials

The Lambert Bougeur law applies to a collimated beam of light passing through a fixed thickness of material, as illustrated in Figure 10.

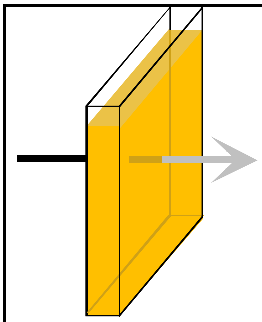


Figure 10: Optical cell

The law describes the change in the intensity (I) of a beam of light (dI) as it travels a short distance (dX) within an absorbing material.

Equation 1 $dI = -I \cdot \varepsilon \cdot dX$

Where ε is the constant of proportionality. Integration of *Equation 1* gives the intensity of light $I(X)$ transmitted through a cell of thickness X.

Equation 2 $I(X) = I_0 e^{-\varepsilon X}$

Where I_0 is the intensity of the incident light. The same form of equation can also be used for the transmission of a collimated beam of light through materials that weakly scatter light, provided the amount of light that is scattered is low, less than 10%.

The Lambert Bougeur law cannot be used to determine the amount of light transmitted or reflected by the coloured materials that both absorb and scatter light. This is because instead of the light travelling a single distance X, scattering creates a range of distances as illustrated by the light paths shown in Figures 4 and 7. Some of the paths are extremely short, the light beam or photon being directly reflected back by a scattering particle very near to the surface, other paths are many times longer and very erratic in direction. There is no direct way to determine the value of X, the path length in *Equation 2,* for every possible path the light beams might take.

Schuster-Kubelka-Munk theory for materials that absorb and scatter light

In the later sections, the Schuster-Kubelka-Munk theory is used to relate the reflectance of a material to its composition. Rather than trying to determine what happens to individual beams of light, the theory considers the net flow of energy, known as an energy flux. The theory is central to a number of national and international standards for characterising the properties of coloured materials. It is also the basis of many of the algorithms used in some types of computer based formulation prediction systems. In order to develop explanations for the influence of the composition of a material on its colour, it is necessary to define the terms intensity, power and flux.

Light intensity, power and energy flux

Intensity

The intensity of a light beam is the time average of the amount of energy per second, which crosses unit area perpendicular to the direction of flow. The units of intensity are Watts per square metre (W m^{-2}). Intensity is a vector quantity, since the definition includes a direction.

Power

Power refers to a total amount of light energy per second, irrespective of direction. For example, if we want to define the power of the light emitted by a filament lamp, we would imagine a spherical surface surrounding the bulb, as illustrated in Figure 10. To determine the power, the intensities of all of the light beams crossing the surface of the sphere are added together.

Power has units of Watts and is a scalar quantity

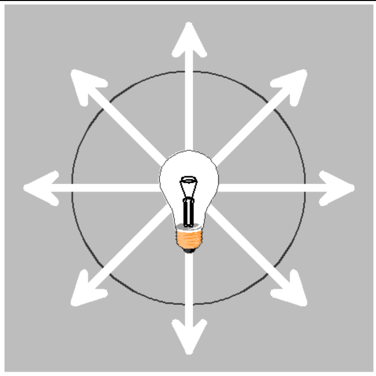


Figure 10: Power radiated by a lamp

Flux

A flux of light energy is the amount of energy travelling within a specified range of directions. The Schuster-Kubelka-Munk theory divides the light travelling within the material into two fluxes.

- One flux includes all the light travelling in directions that have a net movement towards the illuminated surface, often called the "**up flux**".
- The other flux includes all the light travelling in directions that have a net movement away from the illuminated surface, often called the "**down flux**".

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