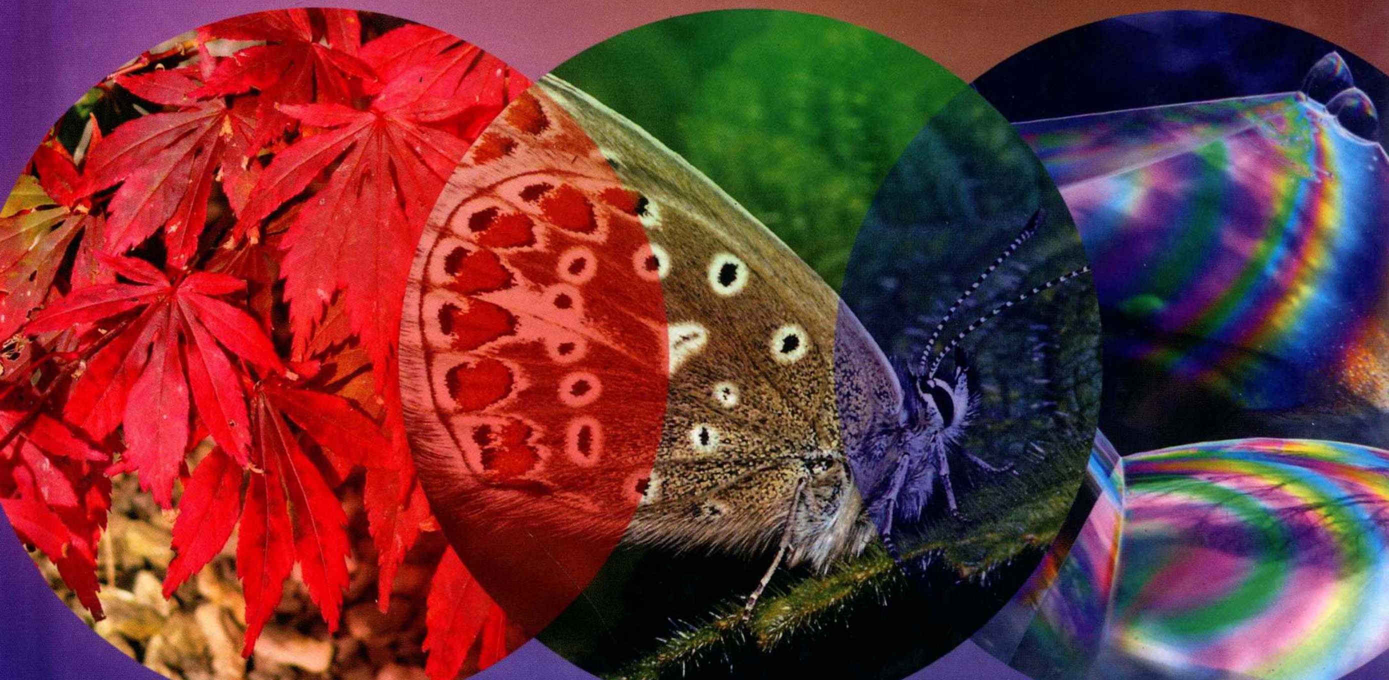
SECOND EDITION

COLOUR

AND THE OPTICAL PROPERTIES OF MATERIALS



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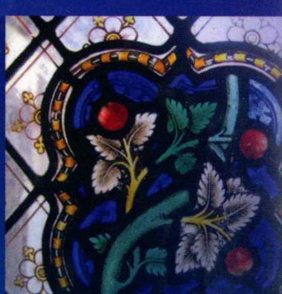

Colour and the Optical Properties of Materials

An Exploration of the Relationship Between Light, the Optical Properties of Materials and Colour

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To Anne, for her continued help and support

Preface

This book is concerned with colour. It is not primarily a textbook on optics, but focuses attention upon the ways that colour can be produced and how these ways govern device applications. However it is not possible to discuss colour without reference to numerous optical properties, so these, too, are explained throughout the text. Colour, though, remains the dominant theme.

When writing about colour and colour production from a scientific point of view one is beset by a number of language conflicts, arising from the historical importance of the subject. Much of this confusion is due to the fact that the terminology has arisen gradually, as a result of historical experiences that scientists of the day found difficult to understand and interpret. Thus, diffraction, scattering, reflection and refraction can all be considered to be scattering of photons, and the variety of terms in use only confuses the modern reader. Indeed, the nature of light itself leads to problems. Is it a series of waves or a spray of bullet-like photons? A light wave can apparently pass through holes in a metal foil that are far smaller than its wavelength. How can this be? Is the light, instead, a series of photons that can do this, and if so, how big is a photon?

Other similar difficulties exist. A decaying and glowing fungus exhibiting bioluminescence does not produce light by the same mechanism as a light-emitting diode (LED) using electroluminescence, although both are termed luminescence. The termination '-chromic' suffers from the same lack of precision. Thermochromic molecules may or may not exhibit colour changes by the same mechanism as electrochromic thin films. The names do not supply any information about this. The units used in the measurement of light are equally confusing. This is because absolute measurements of energy, radiometric units, do not correspond to visual perception, measured in photometric units.

Many of these questions are resolved in this book, particularly with respect to light and colour. The explanations are taken at as simple a level that will allow an appreciation of the topic.

The book falls into three recognizable sections. Chapter 1 is introductory and covers ideas of light as rays, waves or photons. The emission and absorption of radiation is described, as is the difference in light from an incandescent source and light from a laser. Vision and the perception of colour (physiology or psychology), and related aspects are described in outline, as is the technical measurement of colour. These are specialist topics, and the information here is designed only to cover the need of subsequent chapters. Finally, the way in which light can interact with a material is summarized, as a prologue to later chapters.

Chapters 2–6 explain optical phenomena mostly in terms of light waves. Colour is generated when light waves comprising all colours (white light) are subdivided physically into a series of smaller wavelength ranges (i.e. colours). Traditional divisions of the topic are retained, although there is little to choose, theoretically, between labelling a process scattering, diffraction or reflection. Because of this, there is sometimes an ambiguity as to where a particular topic should be placed. For example, fibre Bragg gratings might be treated as multiple reflectors or as diffraction arrays. Mie scattering can be regarded as diffraction. The layout adopted here is one that fits best with the explanations involved.

Chapters 7–10 require a photon explanation to account for colour production. Fundamentally, the absorption and emission of light from atoms, ions and molecules forms the central theme, and for this a quantum mechanical approach is needed. Many of these processes are widely exploited in displays. Although these are technologically complex and require considerable engineering skills in production, the way in which they produce colour is always based upon recognisable physical and chemical principles. Because of this, displays are introduced throughout the text in terms of the appropriate colour-generating mechanism, rather than as a separate section.

The topics covered encroach upon physics, chemistry, biology, materials science and engineering and many aspects of these intertwined subject areas are touched upon. Students of all of these disciplines should find this book of relevance to some of their studies or interests. Readers who need more information can turn to the Further Reading sections at the end of each chapter. These include selected references to the original literature or substantial reviews and will allow them to take matters further. In addition, the website (www.wiley.com/go/tilley_colour) that accompanies this book contains exercises and numerical problems which have been provided to illustrate and reinforce the concepts presented in the text. All readers are encouraged to attempt them. There are also introductory questions that appear at the start of each chapter which are designed to stimulate interest. The answers to these are found in the Chapter itself. In addition, the answers to these introductory questions and all the other exercises and problems are to be found on the accompanying website.

Unfortunately, some important light-related topics have been omitted. These include the important biological topics of photoperiodism in animals and plants and photosynthesis. Although colour is of importance in these topics, the specialist knowledge here is biological rather than optical, and information in this field is best reserved for biological texts.

It is a pleasure to acknowledge the considerable help and encouragement received in the preparation of this edition. The editorial staff of John Wiley & Sons have always given both assistance and encouragement in the venture. I am indebted to Professor D. J. Brown, University of California, Irvine, USA; Mr A. Dulley, West Glamorgan Archive Service, Swansea, Wales; Dr A. Eddington, Dr J. A. Findlay; Professor I. C. Freestone, University of Cardiff, Wales; Spectrum Technologies plc, Bridgend, Wales; Dr M. Sugdon, De La Rue Group; Dr R. D. Tilley, Victoria University of Wellington, New Zealand; Professor X. Zhang, University of California, Berkeley, USA; Dr P. Vukusic, University of Exeter, England; Dr G. I. N. Waterhouse, University of Auckland, New Zealand. All of them readily provided photographic material. To all of these I express my sincere thanks. Allan Coughlin gave encouragement and advice, and the members of staff of the Trevithick Library, University of Cardiff, Wales, were indefatigable in answering my obscure queries.

Finally, my thanks, as always, are due to my wife Anne, who tolerated my hours reading or sat in front of a computer without complaint, and made it possible to complete this work.

Richard J. D. Tilley
South Glamorgan
May 2010

Contents

1

Light and Colour

- **What is colour?**
- **Why do hot objects become red or white hot?**
- **How do e-books produce 'printed' words?**

1.1 Colour and Light

Colour is defined as the subjective appearance of light as detected by the eye. It is necessary, therefore, to look initially at how light is regarded. In fact, light has been a puzzle from earliest times and remains so today. In elementary optics, light can usefully be considered to consist of light *rays*. These can be thought of as extremely fine beams that travel in straight lines from the light source and thence, ultimately, to the eye. The majority of optical instruments can be constructed within the framework of this idea. However, the ray concept breaks down when the behaviour of light is critically tested, and the performance of optical instruments, as distinct from their construction, cannot be explained in terms of light rays. Moreover, colour is not conveniently defined in this way. For this, more complex ideas are needed.

The first testable theory of the nature of light was put forward by Newton (in 1704) in his book *Optics*, in which it was suggested that light was composed of small particles or 'corpuscles'. This idea was supported on philosophical grounds by Descartes. Huygens, a contemporary, thought that light was wavelike, a point of view also supported by Hooke. Young provided strong evidence for the wave theory of light by demonstrating the interference of light beams (1803). Shortly afterwards, Fresnell and Arago explained the polarisation of light in terms of transverse light waves. However, none of these explanations was able to refute the particle hypothesis completely. Nevertheless, the wave versus particle theories differed in one fundamental aspect that could be tested. When light enters water it is refracted (Chapter 2). In terms of corpuscles, this implied a speeding up of the light in water relative to air. The wave theory demanded that the light should move more slowly in water than in air. The experiments were complicated by the enormous speed of light, which was known to be about

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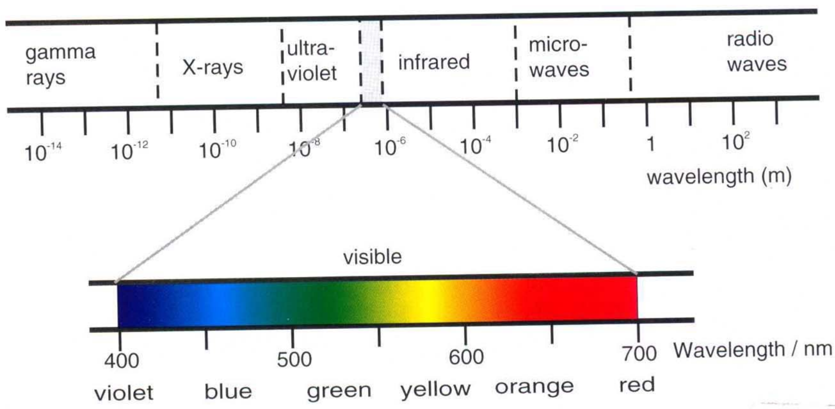

Figure 1.1 ***The electromagnetic spectrum. Historically, different regions have been given different names. The boundaries between each region are not sharply defined but grade into one another. The visible spectrum occupies only a small part of the total spectrum***

3×10^8 m s^{-1}, and it was not until April 1850 that Foucault first proved that light moved slower in water than in air, and seemingly killed the corpuscular theory then and there. Confirmation of the result by Fizeau a few months later removed all doubt.

Over the years the wave theory became entrenched and was strengthened by the theoretical work of physicists such as Fresnel, who first explained interference and diffraction (Chapter 6) using wave theory. Polarisation (Chapter 4) is similarly explained on the assumption that light is a wave. The wave theory of light undoubtedly reached its peak when Maxwell developed his theory of electromagnetic radiation and showed that light was only a small part of an *electromagnetic spectrum*. Light was then imagined as an electromagnetic wave (Figure 1.1). Maxwell's theory was confirmed experimentally by Hertz, whose experiments led directly to radio.

The problem for the wave theory was that waves had to exist in something, and the 'something' was hard to pin down. It became called the *luminiferous aether* and had the remarkable properties of pervading all space, being of very small (or even zero) density and having extremely high rigidity. Attempts to measure the velocity of the Earth relative to the luminiferous aether, the so-called aether drift, by Michelson and Morley, before the end of the nineteenth century, proved negative. The difficulty was removed by Einstein's theory of relativity, and for a time it appeared that a theory of light as electromagnetic waves would finally explain all optical phenomena.

This proved a false hope, and the corpuscular theory of light was revived early in the twentieth century, principally by Einstein. Since 1895, it had been observed that when ultraviolet light was used to illuminate the surfaces of certain metals, negative particles, later identified as electrons, were emitted. The details of the experimental results were completely at odds with the wave theory. The electrons, called *photoelectrons*, were only observed if the frequency of the radiation exceeded a certain minimum value, which varied from one material to another. The kinetic energy of the photoelectrons was linearly proportional to the frequency of the illumination. The number of photoelectrons emitted increased as the intensity[1] of the light increased, but their energy remained constant for any particular light source. Very dim illumination still produced small numbers of photoelectrons with the appropriate energy.

[1] The imprecise expression 'intensity' has largely been replaced in the optical literature by well-defined terms such as irradiance (Appendix 1.1). The term intensity is retained here (in a qualitative way to designate the amount of light) because of the historical context.