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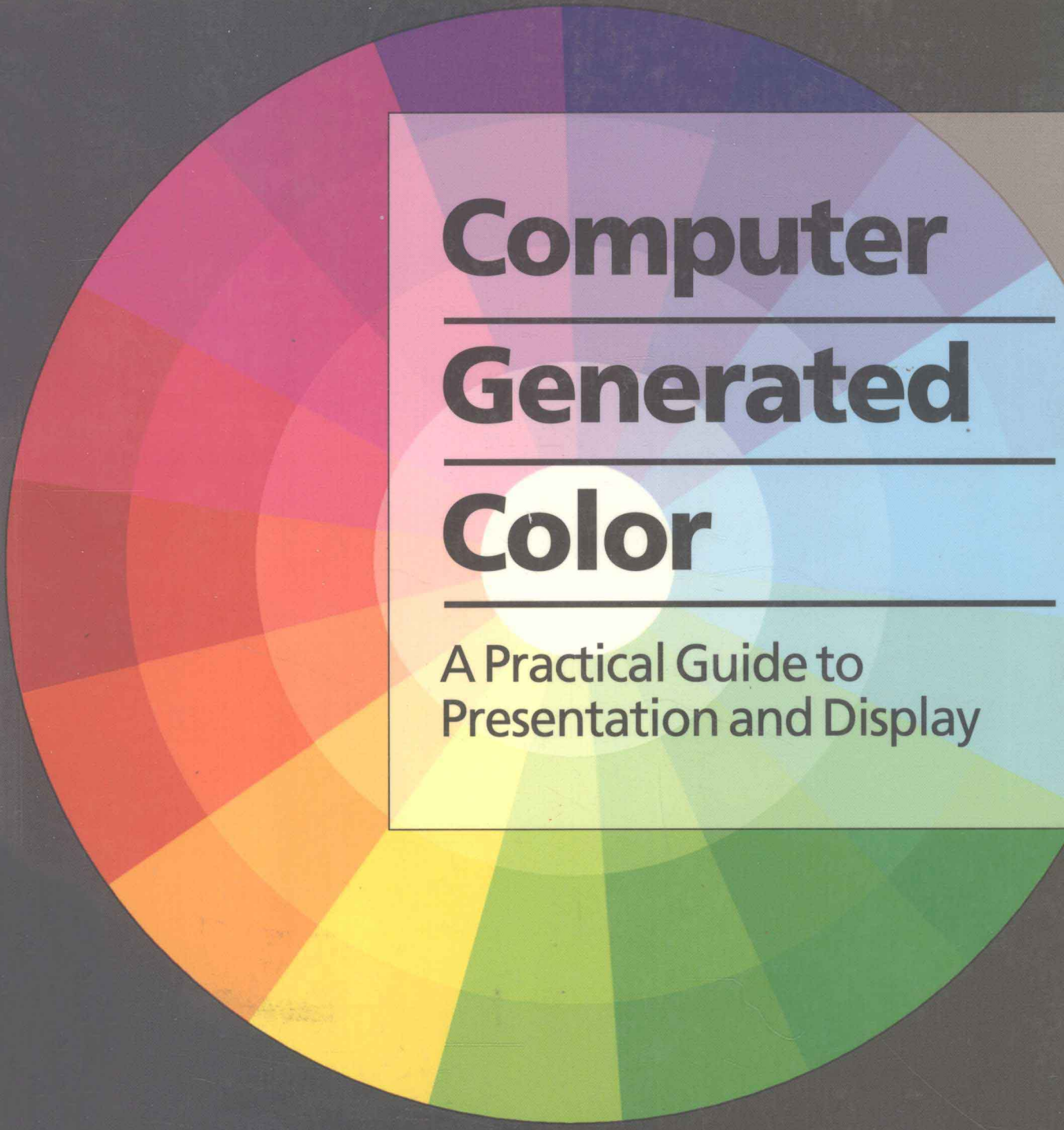

# Computer Generated Color

## A Practical Guide to Presentation and Display

Richard Jackson, Lindsay MacDonald and Ken Freeman

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**Richard Jackson**
**Lindsay MacDonald**
**Ken Freeman**

*Foreword by*
**Robert W. G. Hunt**

JOHN WILEY & SONS
Chichester • New York • Brisbane • Toronto • Singapore

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Baffins Lane, Chichester,
West Sussex PO19 1UD, England
*National* Chichester (0243) 779777
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Queensland 4064, Australia

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Rexdale, Ontario M9W 1L1, Canada

John Wiley & Sons (SEA) Pte Ltd, 37 Jalan Pemimpin #05-04,
Block B, Union Industrial Building, Singapore 2057

***Library of Congress Cataloging-in-Publication Data***

Jackson, Richard, 1931–
Computer generated colour : a practical guide to presentation and display / Richard Jackson, Lindsay MacDonald, Ken Freeman.
p. cm.
Includes bibliographical references and index.
ISBN 0 471 93599 9—ISBN 0 471 93378 3 (pbk.)
1. Color computer graphics. I. MacDonald, L.W. (Lindsay W.), 1950– . II. Freeman, Ken, 1931– . III. Title.
T385.J33 1993
006.6—dc20 93-32955
CIP

***British Library Cataloguing in Publication Data***

A catalogue record for this book is available from the British Library

ISBN 0 471 93599 9; 0 471 93378 3 (pbk)

Typeset from authors' disks in 10/12pt Palatino by Text Processing Department,
John Wiley & Son Ltd, Chichester

Printed in Great Britain by Bath Press Colourbooks, Glasgow

# Foreword

Colour has revolutionised photography, television, and printing. As befits a creation of the present times, the computer has been quick to follow suit. Colour is replacing monochrome in software packages, in display devices, and in desktop publishing facilities.

But the very speed with which the revolution has taken place in the computer world has produced many challenges. Colour is, in one sense, so easy to produce that programmers can be overwhelmed by its abundance; and, after an initial honeymoon period when everything coloured is exciting, the factors that have to be understood in order to succeed in producing effective colour can seem very complicated. There is clearly, therefore, value in a book that deals with these topics.

*Computer Generated Colour* tackles this task in the context of the responses of the visual system to the variety of factors that affect colour appearance. It then goes on to describe methods of ordering colours into a systematic framework Descriptions of hardware for displaying the images and software for producing them then leads to the heart of the book which is a detailed discussion of the do's and don'ts of good colour design for computer output. Finally the complicated relationship between display colour and print colour is considered, with descriptions of practical methods of coping with the transformations necessary to transfer between these media. Each section is profusely illustrated with diagrams, and the style is both clear and succinct throughout.

A welcome, but, for a technical book, very unusual, feature is the use of so much colour. Many double page spreads are in colour, and many of the points being made are therefore fully illustrated. This results in what will undoubtedly prove to be a very useful book also being a real pleasure to read!

**Robert W. G. Hunt**

# Preface

This book was born out of frustration! The authors have been concerned with the generation, display and evaluation of coloured images for most of their working lives. Because human vision is highly sensitive to colour, and human understanding of images can be greatly enhanced by their colour content, we saw the advent of cheap and readily accessible computer generated colour images as a necessary and highly welcome step forward. The reality has been more than a little disappointing. All too often, illegible coloured text is displayed on overbearing coloured backgrounds, garish graphs and charts defy interpretation, and brightly coloured icons vie with each other, screaming for the viewer's attention. The medium is fine—but what price the message?

Over the past few years we have been working (along with many other researchers in industry, teaching and standards institutes) to propagate a more sensible and informed approach to the design of electronically coloured images, and to establish clear and easily implemented guidelines for the successful use of colour in information displays. Our collective experience with lectures, tutorials and short papers pointed to the clear need for a book that gives concise advice on the colour options available to designers, programmers and computer users—be they novices or professionals—who want to achieve effective results.

Of course, this is not the only book available in this field. What is special about this one? First, there is lots of colour! To appreciate how colour is perceived and how it affects the data, it is of enormous help to see plenty of coloured examples. Half the pages of this book are colour pages and much thought has been given to putting over essential design points in visual form. Secondly, the information is specially accessible to the reader. We have deliberately not written an academic 'tome' and it is not necessary to read the book linearly from start to finish in order to understand the content. Open the book at any page and you

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come to a self-contained two-page section which deals with a specific topic. Where the colour availability has called for figures illustrating a topic to be carried over to an (immediately) adjacent page, we have tried to make each of the two spreads readable in its own right. This structure has resulted in the need for concise and direct writing which is not broken up by references. For those who want to explore a given topic further, we have included a Further Reading list at the end of each chapter, with notes on the content of the items listed.

The central theme of the book is encapsulated in chapters 5 ('Designing Coloured Text') and 6 ('Colour in Graphics and Visualisation'). These deal directly with the basic application of colour to data screens. Here is where we enunciate our own particular set of 'golden rules' and give pointers to the newly-emerging ISO standards on this topic.

Those who wish to become adept at colour screen design, however, also need to know something of the basics of Light And Vision (chapter 1) and of human Colour Response and Modelling (chapter 2). Equally important is knowledge of the capabilities and limitations of Colour Displays (chapter 3) and of the systems for Generating the Image (chapter 4). These four chapters provide the foundations upon which the colour design criteria must be based.

Finally, we turn, in chapter 7, to one of the most important new topics in this field. A great deal of computer output turns up as ink on paper. Increasingly this is in colour. Although the main thrust of the book is aimed at the results achievable on self-luminous monitor displays, we have managed, at a late stage, to include notes on the basic differences between monitor and printer colour and on the sometimes exasperating task of successfully translating graphical designs originated on monitor screens into printed images.

Of course, the book itself is realised in print. This means that there have to be differences between our illustrations and what you would actually see on a monitor. To cope with this we are also producing a Compact Disc (CD-I/Photo CD) which will enable our readers to see key figures on a monitor and to compare these with the printed version. We wish you many happy hours of colour design!

# Acknowledgements

A book concerned with the perception of colour, its creation and display by computer hardware and software and, above all, with advice and examples regarding effective use of colour in computer-generated images has inevitably made use of many sources of illustrative diagrams and photographs and, as far as possible, we have acknowledged their origins in the text. However, we wish also to record our indebtedness to several organisations and individuals for more general assistance.

Grateful thanks are due to various parts of the UK Philips organisation, especially Philips Research Laboratories (PRL), Redhill, Surrey, where for several decades two of the authors (KGF and RNJ) were involved in extensive colour display and systems research. Special mention must also be made of Simon Turner of PRL, who with Philips Interactive Media Systems (PIMS) has enabled us to offer readers the innovative option of acquiring high-quality versions of many of our colour diagrams and photographs in the form of a Photo CD, the technology of which is described in the book courtesy of Kodak UK.

Another feature of this book, as explained in Chapter 7, has been the use of computer techniques to prepare directly from our respective computer image data files the colour separation films needed for printing the many colour illustrations. The major contribution to this process by Crosfield Electronics, Hemel Hempstead (via LMacD) is most gratefully acknowledged.

Our thanks are also due for the support and encouragement of Prof. Bob Spence and the Imperial College of Science, Technology and Medicine, London, where one of us (RNJ) is an Honorary Research Fellow.

Finally, we thank our respective wives for their forbearance during a task which took far longer than any of us imagined at the outset!

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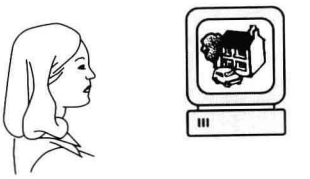
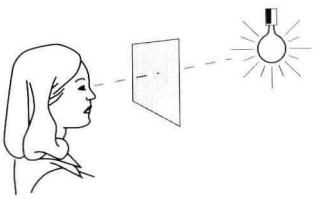
# 1 Light and Vision

In every viewing situation there are at least two elements—a source of light and an observer. Usually there is also a third element, an object that mediates between the source and observer by transmitting or reflecting the light in some way. Without light the world would be dark and mysterious, knowable only through the non-visual senses as the blind person perceives it. Without objects there would be only a void, filled with disembodied sources of light. Without an observer there would be no sensation, no knowing or caring.



**1a** *Illuminant colour, where the observer looks directly at the light source.*

All the phenomena of colour can be described in terms of these three elements, arranged in one of three modes of viewing: observer looking directly at the light source, observer seeing light through a filter, or observer seeing light reflected from an object. The physical characteristics of the illuminant and object determine the nature of the radiation that reaches the observer. But there is nothing in the constitution of the electromagnetic waves themselves that is coloured. Rather it is the intricate and miraculous processing of eye and brain that results in our perception and interpretation of that radiation as colour. Colour is all in the mind!



**1b** *Transmitted colour, where the observer sees the light passing through a filter.*

The first part of this chapter deals with the nature of light, how we measure it and how it interacts with objects. The additive mixing of light from luminous sources such as phosphor displays is contrasted with the subtractive mixing of light caused by the absorption properties of dyes and pigments.

The second part of the chapter deals with human colour vision, how we gather, detect and make sense of the light that reaches us. Starting with the anatomy of the eye and progressing through the responses of the retinal photoreceptors and their neural interconnections, we find a complex and fascinating system. From an understanding of vision we can learn many lessons for how best to use colour in displays.

**1c** *Reflected colour, where the observer sees the light reflected from an object.*

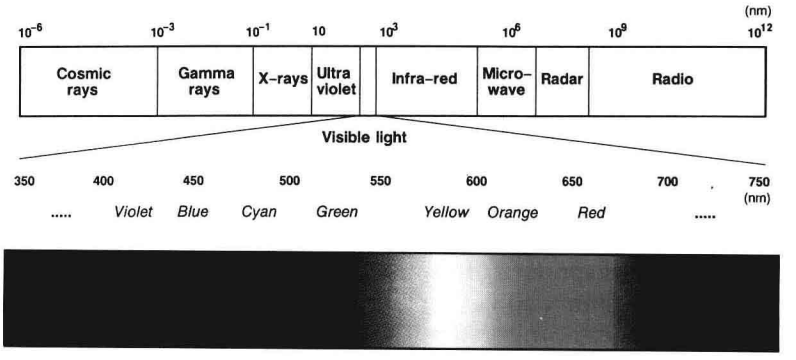
# Light and the Spectrum

**2a** *The rainbow is the most impressive natural manifestation of the refraction of white light into the spectrum. (Photo courtesy Sonia Halliday Photographs.)*

Light is the visible form of electromagnetic radiation. It travels in straight lines through a vacuum at slightly less than 300,000 kilometres per second, in an undulating wave-like motion. Through media such as air or water or glass, however, its velocity is reduced in proportion to the refractive index of the medium. James Clerk Maxwell showed that the wave properties of light could be described in terms of a model in which the electric and magnetic fields traverse perpendicular to each other and to the direction of motion.

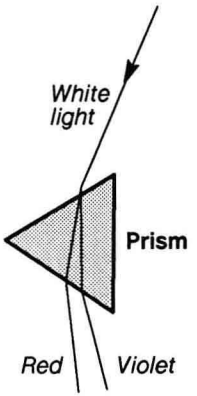
Electromagnetic radiation covers the entire range of wavelengths from fractions of a picometre to thousands of kilometres. What determines the wavelength is the vibrational energy of the radiating element. When an electron makes a transition from a higher to a lower energy level in an atom or molecule, for example, it emits a quantum of energy that is propagated as an electromagnetic wave. Such radiation would typically be in the X-ray, ultraviolet or visible region. Gamma rays arise from state changes within the atomic nucleus itself, where binding energies are higher; whereas infrared radiation arises from state changes within whole molecules, which are more loosely bound. Microwave and radio waves arise from the resonance of a macroscopic physical element such as an aerial.

In the middle of the electromagnetic spectrum lies the narrow range of wavelengths visible to the human eye, from about 380 to 760 nanometres; one octave out of some fifty that can be detected by other means. The shortest visible wavelengths appear violet and progress through blue, green, yellow and orange to red at the longest visible wavelengths, in the familiar spectral colour sequence seen in the rainbow.




**2b** *Visible light comprises a narrow range of wavelengths just below one micron ($10^{-6}$ metre) and is only a small part of the electromagnetic spectrum.*

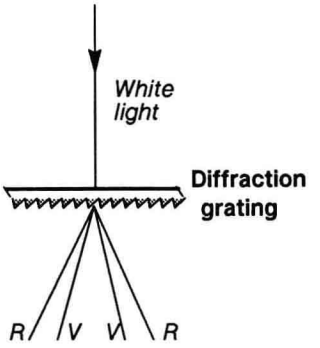
Much of our understanding of the spectrum derives from the work of Isaac Newton, who became interested in colour when grinding optical lenses for telescopes and attempting to correct for the chromatic aberration that caused coloured fringes in his images. In 1666 he performed the famous optical experiments in his room at Trinity College, Cambridge, showing that white light could be decomposed into its constituent colours by means of refraction through a glass prism. He determined that the effective refractive power of the glass varied according to the position of the colour in the sequence, with red deviating least in angle and blue the most, and he coined the term 'spectrum' to describe the ghostly quality of the effect.




**3a** *White light falling on the surface of a prism is dispersed according to its wavelength to form a spectrum, with short wavelengths (violet) being deflected most and long wavelengths (red) least.*

Newton demonstrated that if one colour were separated out from the spectrum, for example by restricting the light to pass through a narrow slit, then it could not be further changed in character by means of a second prism. He further demonstrated that by passing all the colours of the spectrum through a second prism the rays could be recombined into white light that was equivalent in every way to the original white light. From these observations he deduced that white light is a composite of different kinds of basic and indivisible rays (which we now know to be the different electromagnetic wavelengths).

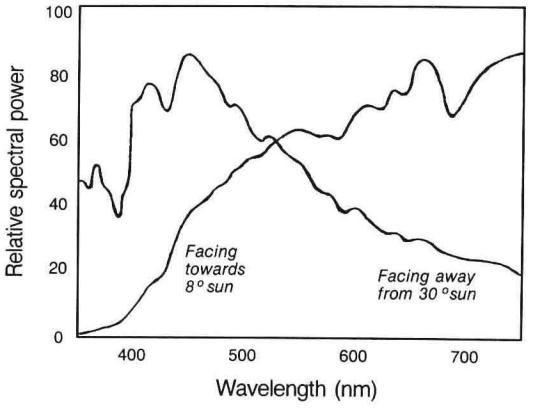
The prism has been superseded in modern colour measuring instruments by the diffraction grating, which consists of a large number of close evenly spaced parallel slits, ruled on glass or metal. The points of peak energy of incident light waves, spreading out by diffraction from each slit, will reinforce or cancel their neighbours depending on their relative phase, resulting in the formation of a series of bright spectra without the distortion caused by a prism.




**3b** *If white light is incident normally on a diffraction grating, several spectra are formed on either side of the normal. Short wavelengths (violet) are deflected less than long wavelengths (red), the opposite situation to a prism.*

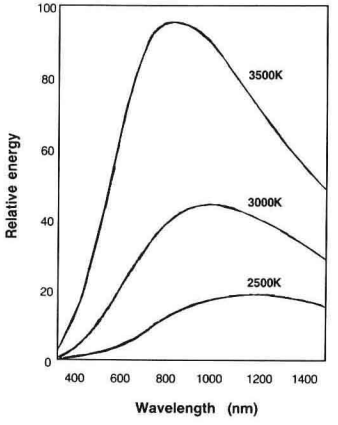
# Energy Distributions and Sources of Light

Because light has a wave nature its energy can be spread throughout the range of visible wavelengths and beyond. Sources of light range from monochromatic, which concentrate all their energy at a single wavelength, to equi-energy white lights, which have equal energies at all wavelengths. Most common light sources lie somewhere between these two extremes, with varying energy at different wavelengths. Graphically this is represented by plotting power (= energy per unit time) as a function of wavelength, called the spectral power distribution (SPD) curve.




**4a** *The spectral power distributions for two samples of daylight, one bluish and one reddish. (Reproduced by permission from Hunt, 'Reproduction of Colour')*

The world's predominant source of light is the sun. Although it is the one that most influences our lives, it is also the most variable and hence most difficult to characterise. Daylight, the sun's light that reaches us at the earth's surface, is extremely variable. Its colour depends on the time of day and year, latitude, degree of cloud cover, atmospheric conditions and direction of viewing. Even when viewed from outer space, beyond the influence of all these terrestrial factors, its energy output fluctuates according to various solar cycles. Thus, although the spectral power distribution curve of sunlight is reasonably smooth, it is far from constant.




**4b** *The spectral power distributions of three blackbody radiators with colour temperatures of 2500K, 3000K and 3500K.*

Planckian radiators (also known as blackbody radiators) form an important class of light sources, the most familiar being the tungsten filament light bulbs used in domestic lamps. When heated these begin to emit infrared radiation, and as the temperature rises the peak energy shifts to shorter wavelengths with the colour sequence red-orange-yellow-white-blue. The SPD of the radiant energy as a function of wavelength is defined by Planck's radiation law and the total radiated energy (the area under the curve) varies as the fourth power of temperature. The colour of

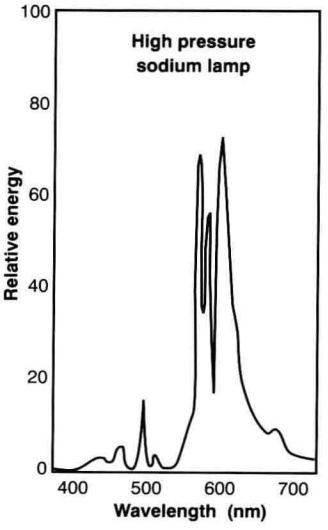
the emitted light of an ideal Planckian radiator can therefore be defined precisely by just one parameter, its absolute temperature in Kelvin. The colour of a non-Planckian light source is frequently defined by correlation with the nearest equivalent Planckian radiator temperature.

| | |
|---|---|
| **Domestic tungsten lamp** | **2800K** |
| **Office fluorescent lamp** | **3500K** |
| **Graphic arts print viewing** | **5000K** |
| **Carbon arc projection lamp** | **5400K** |
| **Broadcast television** | **6500K** |
| **North-facing daylight** | **7500K** |
| **Computer graphics monitor** | **9300K** |

*The correlated colour temperatures of some common light sources. Lower temperatures are warmer (more yellow) whereas higher temperatures are cooler (more blue). Note that standard computer graphics monitors are normally setup to be very blue.*

Light can also be generated by the transitions of electrons between discrete energy levels in the atoms of a gas excited by an electric current. When electrons return from a higher to a lower energy state they emit radiation at a specific wavelength. The summation of such transitions results in discontinuous narrow energy bands appearing as spikes in the illuminant's spectral power distribution. Simple gas discharge lamps such as neon or low-pressure sodium may be nearly monochromatic. Fluorescent lamps make use of this principle by using the energy output of a mixture of halogen gases to stimulate a coating of phosphors on the tube. Cathode ray tubes employ 'phosphor' materials such as zinc sulphide or rare earth oxysulphides which emit light when excited by a beam of high-energy electrons.

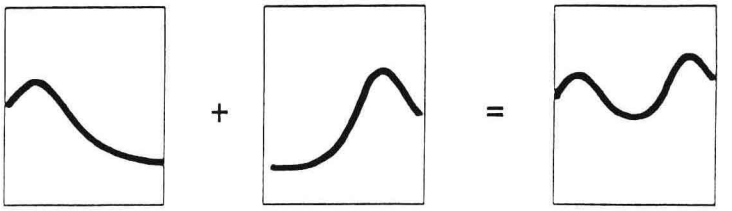
The instrument used for measuring spectral power distributions is a spectroradiometer, that is a meter for radiant energy across the spectrum. This relies on a monochromator (literally, a single colour selector) to separate the incoming radiation into small wavelength intervals, ranging from 20 nm for a coarse measurement down to 1 nm or even finer for a precision instrument. The monochromator forms a spectrum of the incoming radiation by means of a prism or diffraction grating and extracts the desired wavelength interval through a narrow slit. By scanning across the full wavelength range the overall energy distribution can be determined. A reference illuminant of known spectral distribution, traceable back to a national standard source, is essential for accurate calibration because the instrument works by determining the ratio at each wavelength interval between the known (reference) and unknown (test) illuminants.




**5a** *Much of the energy of a high-pressure sodium lamp is concentrated in a few narrow spikes. (After Hunt)*

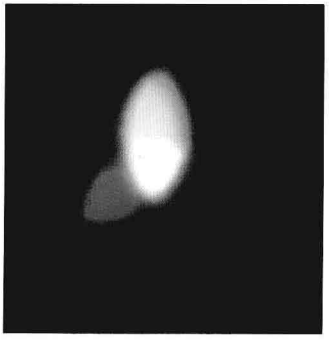
# Additive Mixing of Lights

When two or more lights are mixed, the result is a simple additive combination of the sources. The combined spectral power distribution is obtained by adding the power from each source at each wavelength interval. For example, if a blue light, with a power peak at short wavelengths, is mixed with a red light, with a peak at long wavelengths, the result will be a purple light with a double peak as shown below.




**6a** *Red and blue lights mix additively to give purple*

Newton's experiments showed that white light can be represented as the sum of its constituent spectral components (pp 2–3). Over a hundred years later, in 1801, Thomas Young demonstrated that by overlapping three primary lights having the 'principal colours' of red, green and blue-violet he could obtain the secondary colours of yellow, cyan and magenta (see illustration). He found, moreover, that by adjusting the relative intensities of the red, green and blue-violet lights in the mixture he could match any of the spectral hues, an observation that has important implications for understanding the nature of colour vision (pp 16–17). In each segment of the overlapping circles the observer sees the sum of the incident lights as a different colour. This is surprising because if two musical tones, each of a single wavelength, are played together we hear them as a chord, either concordant or discordant depending on their relative pitch. Yet in the additive mixture of two monochromatic colours, such as red and green to form yellow, we may see a third resultant colour that does not resemble either of its components.



**6b** *Young's demonstration of three overlapping coloured lights.*

Another way of producing additive colour is by spinning discs. When coloured regions on a disc are spun fast enough they appear to fuse together into a new colour which is the visual average of the constituent colours. During the 1850s James Clerk

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