



MICHAEL S. TOOMS

# COLOUR REPRODUCTION

in Electronic Imaging Systems

*Photography • Television • Cinematography*



WILEY

# **COLOUR REPRODUCTION IN ELECTRONIC IMAGING SYSTEMS**

**PHOTOGRAPHY, TELEVISION,  
CINEMATOGRAPHY**

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# Preface

Many excellent books are available which deal in one way or another with image reproduction, either generically for example across photography or television, or in a more specialist manner for a particular technology such as digital television. Invariably colour is discussed as an integral part of the reproduction process, often as an adjunct to the technology of the media being covered. However, few books leave the reader who is specifically interested in the *reproduction of colour* entirely happy that the colour reproduction process has been fully understood at a fundamental level.

Often the more obscure elements of colorimetry are glossed over, which is fine for those who require only a superficial understanding in this area but is frustrating for those who need to understand fully the derivation and interpretation of the various chromaticity diagrams in use. In contrast, the aim of this book is to cover comprehensively the complete process of colour reproduction from capturing the scene to rendering the final image, whether it be in the form of a display or a print. Emphasis is placed on the analysis and processing of the colour components, rather than the technology associated with generating and conveying the components representing the original image from the camera to the point where the image is rendered.

Nevertheless, aspects of colorimetry, such as the derivation of the CIE<sup>1</sup> x,y chromaticity diagram, for example, are fundamentally quite mathematical. So in order not to detract from the flow of the text, the development of the subject is described in a heuristic manner and the supporting mathematics are constrained to the appendices for those who wish to grasp the complete picture at a deeper fundamental level.

The material for this book evolved initially from notes used to support the 'Television Image Formation, Analysis and Reproduction' lecture given by the author in a series of annual engineering lectures for the Royal Television Society (RTS) and subsequently developed into a chapter for the planned RTS book on television engineering. He was also able to build upon the material used more recently in a presentation to the Image Science Section of The Royal Photographic Society on colour management as a means of achieving accurate colour reproduction in photography. As a member of the Society of Motion Picture and Television Engineers (SMPTE), he has watched with interest his colleagues driving the evolution of international standards for colour reproduction in digital cinematography and has drawn upon this material for the part dealing with this topic; this step completed the transformation of the three major picture media systems: television, photography and cinematography to electronic-based systems.

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<sup>1</sup> Commission Internationale de l'Eclairage or International Commission on Illumination, the international body responsible for specifying the measurement of colour.

In recent years, electronic image reproduction has made tremendous strides not only in television, to embrace digital, high definition and 3D television, but also by expanding into photography and latterly into 'digital cinema', where digital cameras have virtually replaced film at the shooting stage and digital large screen projectors have become the norm in most cinemas. Despite these advances, the fidelity of colour reproduction continues to have limitations and there remain enticing approaches to extending the range of colours which may be reproduced as described in the book.

The book sets out to provide an in-depth analysis of colour, its measurement and its reproduction at a fundamental level before going on to provide a comprehensive coverage of its application in uniquely different ways to television, photography and cinematography, respectively.

The application of colour reproduction theory to practical systems is addressed from a historical perspective, since the application of electronics to each media system has always been built on the technology developed for digitising the previous media. Much of the groundwork of applying the then relatively new understanding and standardisation of colour analysis and measurement of the 1930s, through the work of the CIE, was brought to bear by the members of the National Television System Committee (NTSC) of the United States in the early 1950s, when the first practical colour television system was introduced. The European television systems (Phase Alternating Line (PAL) and Sequential Colour with Memory (SECAM)) which followed in the 1960s were essentially based upon the same colour fundamentals. However, they differed from the earlier system in that they evolved methods of encoding the colour signals for transmission that were less prone to the effects of the distortions apparent in the electronic systems of the day, which in its early days had given the NTSC system a poor reputation.

In electronic terms, these pioneer colour television systems reigned supreme for some 40 years before developments in technology in the 1980/90s gave rise to the possibility of adopting a new world-wide standard for television which included a tightening up of the standards associated with the specifications for colour reproduction. Some would claim the opportunity was missed at that time to introduce standards which would embrace developments in colour reproduction which had already been foreseen, and are now waiting on the side-lines for the opportunity to come to the fore.

During broadly the same period of the early 1990s, these developments also saw the evolution of the standardisation of digital video signals, the JPEG digital compression system and cost-effective solid-state image sensors, making practical digital stills cameras available at increasingly affordable prices for general consumer use. Finally in the early 2000s, with the adaptation of specialised television cameras of high resolution for recording sequences for the cinema, and the availability of suitably bright and high-resolution projectors, the way was open in the late 2000s for experts within the cinematographic standards bodies<sup>2</sup> to set the colour specifications for the digital cinema. Part 5 of this book describes that journey in terms of the colour techniques and specifications adopted by each of the three media: television, photography and cinematography.

<sup>2</sup> The Academy of Motion Picture Arts and Sciences, the American Society of Cinematographers, the Digital Cinema Initiatives and the Society of Motion Picture and Television Engineers.



## Acknowledgements

Without the encouragement I have been fortunate enough to receive from so many people, I would not have been in a position to write this book. I am resolved therefore to acknowledge not only those who have assisted me in preparing the book but also those who in one way or another have encouraged my interest and enthusiasm for colour from the beginning, albeit that some are no longer with us.

It was evident to me as a young child that my interest in the exciting range of colours around me went well beyond the norm of those in my circle of family and friends, with the possible exception of my mother who did her best to assist me with the difficult topic of colour naming. I remember well one particular, rather unusual colour that when questioned was told it was 'cerise'.

My formal introduction to colour came whilst serving as a radar technician in the RAF when I selected as a birthday present, John W. Wentworth's book 'Colour Television Engineering'. This was read avidly during the plentiful non-shift time available and became my bible for many years; I am much indebted to the author for dealing so comprehensively and insightfully with colour measurement and its application to reproduction.

Subsequently, when working for EMI at the time of the introduction of their NTSC encoder, I was grateful to its designer, David Kent, for his patient detailed explanations of the workings of each of the several unique circuits of which it was comprised.

I joined ABC Television in the United Kingdom at a time when broadcasters were experimenting with colour television and Michael Cox was leading the work there on the SECAM system. Eventually it became clear that the PAL system developed under the leadership of Dr. Bruch in Germany was to be the likely choice of system for the United Kingdom and at that time I began to work for Mike who taught me a lot as I 'bread-boarded' an experimental PAL encoder whilst he tackled the more difficult decoder.

In preparation for the introduction of a colour television service during this period, I, together with my colleague and friend Ray Knight, attended a post-graduate colour course under Professor Wright at Imperial College London, which turned out to be a milestone event. W. David Wright was one of the two colour scientists who had undertaken the work which led to the CIE standards on the measurement of colour. We were privileged to be able to derive our personal colour matching functions on the Wright colorimeter that had been used to obtain the data for those standards. David Wright's tremendous knowledge of the subject and his enthusiasm for sharing it with his students helped cement in me a lifelong interest in the subject.

The effect on my friend Ray Knight was very similar and since then we have kept in constant touch, sharing our interest in colour from slightly different perspectives. Nevertheless, we have continued to exchange ideas and, as the result of many, many discussions over the years, my knowledge of the subject has been further broadened by his enthusiasm and determination to ensure that we shared a common understanding of the more obscure aspects of the subject. Ray has also written on colour, particularly from the perception of an artist, on picture-matching and colour-mixing. As a result he has produced many excellent diagrams and I am very grateful for his generosity in allowing me to use several of them in this book. It follows from our close association with colour that he was the natural choice to review much of the manuscript as it was written and I am indebted to him for the exhaustive comments he has provided and the discussions that have led to the original material being much improved.

A little later Dr. Boris Townsend, a leading researcher and author on colour television at that time, who was much in demand for membership of international committees and as an invited college lecturer, joined the ABC colour team. His management style was exemplary and he encouraged my interest in colour by insisting that I stood in for him on a number of occasions, both in lecturing and attending European Broadcasting Union (EBU) technical meetings to agree on the chromaticities of primaries to be used in the first European colour television system.

More recently as the idea of writing a manuscript for a book took shape and it became necessary to discuss the finer points of some of the more obscure aspects of colour and to establish the direction in which international media committees were moving in laying the foundations of new system specifications, I called upon the support of several colleagues in the field.

Michael Pointer, a colour scientist internationally recognised for his work on the extent of the gamut of surface colours, has been invaluable with regard to CIE matters. In particular, referring me to papers on the history and technical detail of pertinent decisions in the evolution of colour measurement standard procedures, making CIE data available, sharing extensive worksheets on colour rendering indices, and taking the trouble to enter into email discussions on a range of topics. By sheer coincidence, he was also appointed as a reviewer of this book and I am much indebted for his suggestions both in clarifying my explanations and drawing to my attention lapses in English grammar.

David Bancroft has been particularly helpful in keeping me up-to-date with current thinking in the international committees which formulate specifications on such topics as the chromaticity of primaries for future television systems, the means of dealing with colour gamut mapping, and the parameters associated with the characterisation of standard monitors for picture matching in television vision control rooms.

Alan Roberts and John Emmett, who have recently jointly undertaken much work on colour rendering indices, which led to a new EBU recommendation on the topic, were very generous in allowing me free access to their work and giving permission to use it in this book. Alan also provided me with a wide range of measured spectral power distributions of light sources, which generously supplements the critical 'Illuminants' data sheet in the accompanying Colour Reproduction Workbook. John Emmett also kindly undertook the measurement of the spectral reflectance of a range of colour surfaces used as examples in the book.

Ionnasis N. Galidakis has an extensive website accommodating a comprehensive range of charts illustrating the spectral power distributions of various elements in their excited state and has given permission for these to be used freely within the book.

Seo Young Choi, who was prepared to enter into an email discussion with a total stranger on the finer points of specifying the scaling factors for colour difference signals in the constant luminance system variant of the UHDTV system, helped me resolve why a particular approach had been taken.

Mike Reed kindly provided me with access to his photographic workstation in order to extend the range of inkjet printer samples available for the chapter describing printers.

Scott Matthews also provided me with access to his professional photographic workstation and took part in detailed discussion and experiments on establishing the perceived contrast ranges of rendered images under different lighting and monitor set-up conditions.

Mick Vincent, a colourist at The Mill, gave me much of his time and expertise in describing the reality of using colour management procedures in a post-production grading environment.

Daniele Siragusano of Filmlight showed me the practicality of using a wide range of colour transform options in current post production systems and we discussed at length the pros and cons of adopting various specific procedures in the grading operation.

My friend, Frank Bateson, acted as a non-specialist reader on much of the manuscript and offered invaluable advice on text which I had thought was self-evident in its explanation but which he showed clearly was not the case.

Special thanks are due to my friend and colleague Bert White, who joined the ABC Television team on the same day as I, and has reviewed both the manuscript, chapter by chapter, and the worksheets included in the workbook which partners this book. He provided a wealth of feedback to improve the readability of the text and encouraged me to complete the work when other issues were pressing upon my time.

Finally of course, special thanks are also due to my wife Pamela who, for what seems an age, has borne with much patience a husband who, whilst buried in the work of the manuscript for hours on end, has, as she has put it, 'switched off' from all her attempts at conversation. In addition, she has had to endure many lonely periods when couples would normally be sharing a relaxing pastime whilst I caught up with a stage in the manuscript.

Michael Tooms  
February 2015



# About the Companion Website

This book is accompanied by a companion website:

[www.wiley.com/go/toomscolour](http://www.wiley.com/go/toomscolour)

This website includes:

- The Colour Reproduction Workbook of some 50 worksheets, including:
  - colour data sheets
  - derivation of chromaticity and camera spectral sensitivity plots from selectable primary chromaticities
  - calculation of illuminant rendering indices from spectral power distributions
  - calculation of matrix coefficients for transforming signal values to those of different system primaries
  - calculation of fidelity of performance of particular colour reproduction systems
- Guide to the Colour Reproduction Workbook (also available in this book as Appendix J)
- JPEG files containing images pertaining to references in the book, including:
  - colour bars
  - grey scale charts to establish perceived contrast range under different environmental conditions
- Guide to using the JPEG files

# Introductions

## The Book

This book is aimed at both the serious practitioners in the fields of photography, television engineering and cinematography, and those amateurs who have the enthusiasm to learn more of the reproduction medium which they enjoy as a hobby.

In essence the requirements of colour image reproduction may be simply stated, we need to:

- First understand what colour is,
- Determine a means of measuring it,
- Capture and measure the value of the colours in a scene,
- Establish the most efficient and precise way we can transfer those measurements to the device which creates and displays the reproduced image,
- Control the image creating device with signal components levels representing the measurements we originally made.

As the original structure laid out for this book took shape, it became clear that the subject matter associated with each chapter fell naturally into groups broadly reflecting the requirements listed above. These groups became the five parts of the book.

It also became evident that each part would benefit from its own introduction; thus rather than writing a general introduction at the beginning of the book to cover all the material in one step, it was decided to emphasise this natural grouping by writing an introduction to each part. These introductions describe the range of the topics covered and the approach adopted in addressing the material it contains.

Thus the five parts of the book are:

Part 1 Colour – Perception, Characteristics and Definition

Part 2 The Measurement and Generation of Colour

Part 3 The Concepts of Colour Reproduction

Part 4 The Fundamentals of Colour Reproduction

Part 5 The Practicalities of Colour Reproduction in:

Part 5A Television,

Part 5B Photography and

Part 5C Digital Cinematography

A more detailed indication of the material contained in each part is provided by reference to the Contents page, where the titles of the chapters and the sections comprising each chapter are listed. As an alternative, turning to the page containing the part heading will provide access to the introduction to that part.

This book is specifically about colour and its reproduction in photography, television and cinematography using electronics rather than film as the technology of implementation. Each of these media areas is highly technical in its own right, and there are good books available which describe every aspect of these individual technologies; thus, the material in this book is of necessity restricted specifically to the colour technology required of each of these media, which often tends to be only casually dealt with in more generic books. Only where an understanding of the associated technology would be helpful in clarifying the colour concepts in a particular area is the technology then described in very general terms.

The aim of this book is to ensure that it is easily read and understood by the widest range of readers, from those with only a passing understanding of physics and mathematics to those with a more specialised knowledge in these areas who wish for a deeper understanding of the subject. In consequence, I have relied on appendices to provide the depth the latter may require in order that these detailed explanations do not get in the way of the flow of the material.

In order to support the text and the numerous charts which appear in the book, a good deal of calculation was required in the form of worksheets and it seemed that it would greatly extend the usefulness of the book to make these worksheets available to those readers wishing to understand the underlying mathematics. Thus, 'The Colour Reproduction Workbook' is introduced in more detail below.

In researching material to support this book, it became evident that amongst much erroneous material on the World Wide Web there is also much which is excellent, and occasionally, in order to avoid 'reinventing the wheel', I have, where appropriate, included such material with due reference as to its source. I have also received much support from friends and colleagues who are active in the field of colour and reproduction and have welcomed the opportunity to note their contributions with appropriate references.

## **The Colour Reproduction Workbook**

With very few exceptions, all the charts and supporting calculations appearing in the book are derived from worksheets produced by the author. These worksheets have been compiled into an Excel workbook and provide an invaluable resource to those readers who have the need or the interest to explore further the examples provided in the narrative of the book. Many of the worksheets contain icons controlling macros, which when activated will replace one set of data in a calculation with a different set, enabling a wide range of 'what if' questions which may arise in the mind of the reader to be answered. The dedicated data worksheets, which contain a very wide range of basic colorimetric data, provide the reader with the option of copying specific data into the example worksheet to meet their needs, or indeed enter new data, direct into the worksheets.

Each worksheet follows the numbering sequence of its associated chapter, more than one sheet being provided when necessary with an (a) or (b) suffix in order to avoid as far as possible the production of unwieldy spreadsheets. At the top left of the worksheet is a brief description of its functionality.

As the theme of colour reproduction is developed in the book, the supporting calculations become more extensive until the point is reached where a number of worksheets have evolved which effectively become simple mathematical models with accompanying performance charts which describe the whole or large sections of the reproduction process. These worksheets are particularly invaluable in exploring how different parameters can affect the performance of the colour reproduction process.

The workbook is accompanied by the 'Guide to the Colour Reproduction Workbook' which describes its structure and, for the more extensive worksheets, supplements the brief description provided at the top of each worksheet with a section which provides a description of its layout and how to operate the macros.

The Colour Reproduction Workbook and its associated 'Guide to the Colour Reproduction Workbook' may be downloaded from the companion website to this book at [www.wiley.com/go/toomscolour](http://www.wiley.com/go/toomscolour).

In addition the 'Guide to the Reproduction Workbook' appears as Appendix J to this book.



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