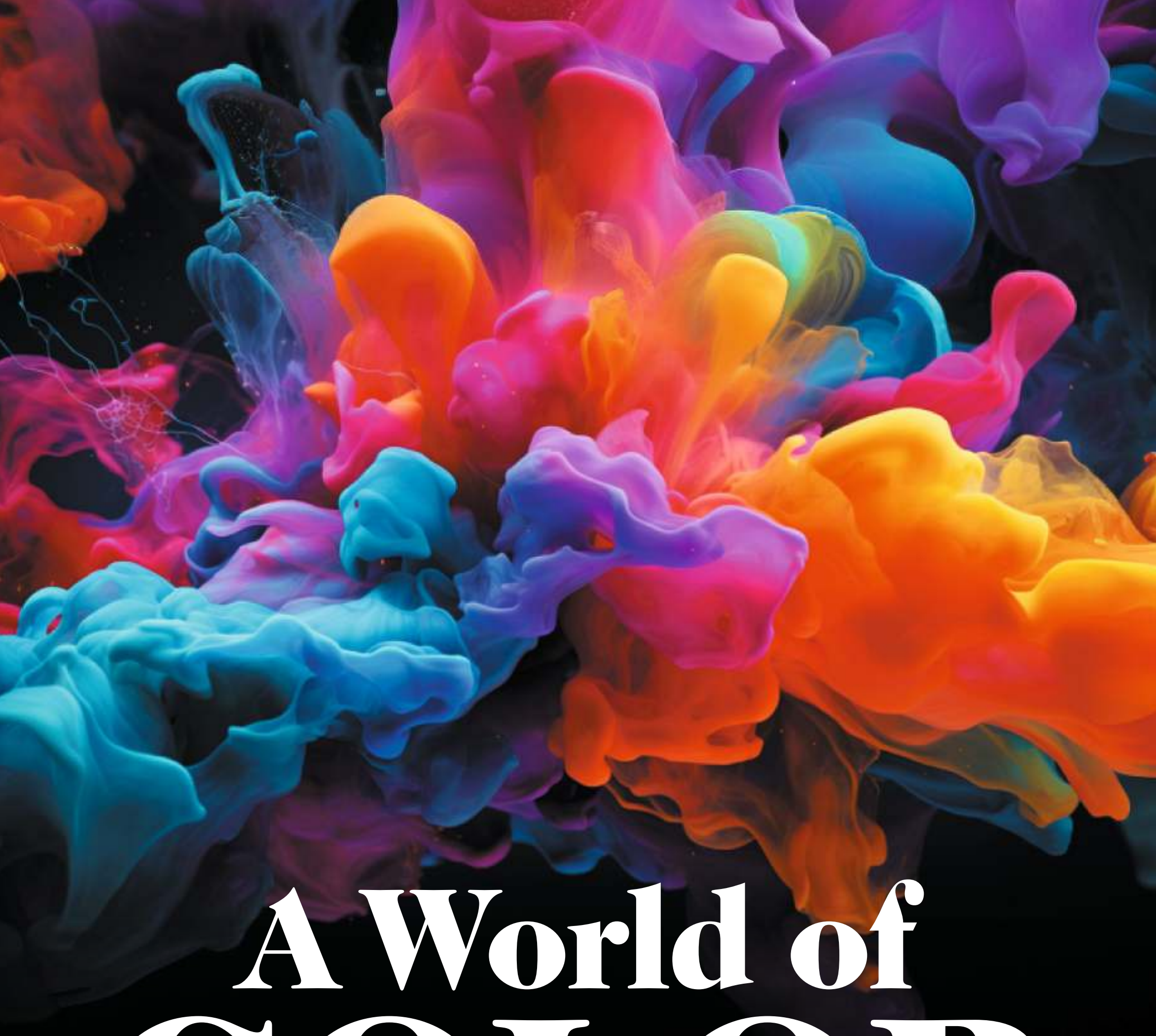


A World of COLOR

The Science of Color in Everyday Life

David Cann

Springer

Copernicus Books

Sparking Curiosity and Explaining the World

Drawing inspiration from their Renaissance namesake, Copernicus books revolve around scientific curiosity and discovery. Authored by experts from around the world, our books strive to break down barriers and make scientific knowledge more accessible to the public, tackling modern concepts and technologies in a nontechnical and engaging way. Copernicus books are always written with the lay reader in mind, offering introductory forays into different fields to show how the world of science is transforming our daily lives. From astronomy to medicine, business to biology, you will find herein an enriching collection of literature that answers your questions and inspires you to ask even more.

David Cann

A World of Color

The Science of Color in Everyday Life

Springer

David Cann
Oregon State University
Corvallis, OR, USA

ISSN 2731-8982 ISSN 2731-8990 (electronic)
Copernicus Books
ISBN 978-3-031-97370-3 ISBN 978-3-031-97371-0 (eBook)
https://doi.org/10.1007/978-3-031-97371-0

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2025

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

If disposing of this product, please recycle the paper.

To my family. Without their love, support, and inspiration this would not be possible.

Preface

This book came about from a course I've taught for the Honors College at Oregon State University since 2020. The course is taught in a "colloquium" format with a goal of guiding students through a subject that lets you see the world from a different perspective through lectures, reading material, and lots of discussion. Most of the colloquium courses taught by my colleagues are focused on topics in the liberal arts and humanities, but I think color is a unique subject for a course of this type. Color is a critical aspect of our everyday lives, both subjectively and emotionally. As the book describes, the origins of color are often linked to invisible processes that yield insights about the universe around us. With a little knowledge about the physical and chemical mechanisms behind the colors we observe, we see the world a little differently. It is my hope that this book serves this purpose for the reader.

The subject of color is probably one of the broadest topics in science in that it spans multiple disciplines from physics to chemistry to geology to biology to engineering and even human anatomy. As a material scientist, my 30+ years of research and teaching experience provides a useful frame of reference for writing this book. While a lot of the topics are outside my expertise, the overarching philosophy of materials science is focused on structure-property relationships. That is, how does the particular arrangement of atoms and molecules in material influence the properties were observe. This vantage point is extremely useful in discussing the many color mechanisms in this book. There is a nearly infinite amount of detail for each color mechanism, but the most interesting part is merely the linkage between the color we observe and atomic or microscopic structure of the material. The goal is not to be a textbook on color mechanisms, but a field guide for the reader that explains what goes on behind the scenes in our colorful world.

Since I've spent my entire life as an academic, I often find it hard to gloss over details because often times the details matter. However, in writing a science book aimed at the general public, inserting countless caveats and qualifying statements into the narrative would result in boring the reader beyond all hope. Thus, in this book I will aim to stay true to the goal of explaining the fundamental scientific concepts without disrupting the flow. For that I am indebted to my editor and many colleagues that have helped me put this together.

I am also indebted to Dr. Kurt Nassau who authored the book *The Physics and Chemistry of Color: The Fifteen Causes of Color*. This is an incredibly unique book that was one of the primary motivations for this book. From his bibliography from the Gemological Institute of America, Dr. Nassau was a research chemist and minerologist at AT&T Bell Labs for 30 years, retiring as Distinguished Research Scientist in 1989. His book is an impressive encyclopedia of color that discusses the origins of color in great technical depth. It is a hidden gem that many of my material scientist colleagues hold in very high regard. After reading my book, his book is an excellent reference for greater level of detail into the physics, chemistry, and biology.

Corvallis, USA David Cann

Acknowledgements There are so many people to acknowledge I don't know where to start! First off, I have to acknowledge someone I've never met. Kurt Nassau's book *The Physics and Chemistry of Color* is truly the inspiration for this book. I found this gem early in my academic career and it has served as an invaluable resource in helping me understand color mechanisms in materials. The chapters on color mechanisms in minerals was incredibly useful for undergraduate and graduate materials science classes, and the entire book effectively served as a template for this book. Nassau's book is truly an impressive achievement in that it covers every conceivable color mechanism in an amazing level of detail. You will also note that his book is listed as a reference for most of the chapters in this book because it is a great place for the reader to go if they want more detailed information on the topics in this book.

I am also indebted to my wonderful colleagues at Oregon State University that served as guest speakers for my Honors colloquium class *A World of Color*. Their knowledge and passion helped broaden my appreciation for color. Dr. Christopher Marshall shared his infectious enthusiasm for the colorful world of insects with my class. I loved his captivating stories of collecting bugs in the Amazon rainforest and learning about the impressive abilities of the humble beetle. Anna Fidler showed us around her art studio and helped us understand the nature of color through the eyes of an artist. Dr. Vince Remcho showed my class how color can be used for chemical analysis using your smart phone. Marianne Dickson's joy was palpable when she demonstrated how to color fabrics with natural dyes from flowers, barks, and even insects. Dr. Luanne Rolly explained the wonders of ink jet printing—which is truly one of the most amazing engineering achievements of our age. Last, but not least, Dr. Brian Bay helped us understand what happens behind the lens when images are rendered on our computer screens and in our brains. I am incredibly thankful to have such gifted and generous colleagues at Oregon State University.

I am fortunate to have great friends that have supported me along the way. First and foremost, my friend and colleague Dr. Bill Warnes helped proof the entire manuscript (though don't blame him for any errors that crept into the final text!). His attention to detail and timely feedback helped make this book the best it can be. Thanks also go to my old friend David Bartlett for his help with reading one of the final drafts. My friend and fellow editor Dr. Grant Norton provided sage advice to me on how to get started with writing a book like this. I can highly recommend his excellent books *A History of Modern Materials* and *Ten Materials That Shaped Our World*. I would also like to thank Dr. Katie Burke who helped in the early stages of writing. Her guidance and input really helped me with style and storytelling. I would also like to thank Bruce Mulholland for his help compiling important data on fluorescence which appears in the book. Finally, but most importantly, I am truly grateful to my wife Ilene Cann. Her sharp eye and “right-brain” viewpoint helped me rewrite some of the critical sections of text to be more meaningful to a broader range of readers.

To all, thank you from the bottom of my heart.

Competing Interests The author has no competing interests to declare that are relevant to the content of this manuscript.

Contents

About the Author

David Cann grew up in the suburbs of Washington, D.C., but moved to Oregon in 2005 to join Oregon State University as Professor of Materials Science. He has spent more than 30 years as a researcher working on ceramic materials for electronic applications. He taught a colloquium course on the physics and chemistry of color for OSU's Honors College which catalyzed his interest in color. More importantly, color is everywhere in his life outside of work. As an avid hiker, his life is filled with colorful wildflowers, vibrant landscapes, minerals, and wildlife in the Coastal and Cascade mountain ranges near his home. His curiosity fed the desire to learn more about the science behind the colorful outdoor universe.

The inspiration for this book came about from reading Carl Sagan's book *The Demon-haunted World: Science as a Candle in the Dark*. In the book, Sagan focuses on the primal feeling of "awe" people have when contemplating science and nature. He advocates the point of view that science education is most impactful when it connects to that sense of awe. Color naturally fits into this paradigm. We see it, we experience it, and we even feel it. The purpose of this book is to magnify the sense of wonder by connecting color to the natural world through the exploration of scientific principles.

The author lives in Oregon with his wife, two sons, a dog, and a mischievous cat. When not working, writing, or hiking, he enjoys spending time with the family, cooking, sports, and board games.

1

The Nature of Color

Color is beauty. Color is emotion. Color is life.

Every facet of the world we experience is enriched by color. When we first open our eyes at dawn, we are met with warm hues that gently arouse our senses. Throughout the day, as we make our way through the world color guides us, informs us, warns us, and stimulates our senses. The photoreceptors in our eyes are well matched to the spectral output of our sun and their functionality has evolved over the years to help us survive. Color tells us when to stop at an intersection, when something is safe to eat, and whether we should go see a doctor about that mole on my arm. Color might give us a hint about which section you should sit in at a contentious sporting event, and color can tell us whether a gathering of people is a wedding or a funeral. Beyond the physical appearance of color, its primary importance in our lives is reflected in many aspects of the human experience. We describe political processes using color, with green parties aligned with environmental movements around the world, red is historically associated with the international socialism movement, and recently the United States has been subdivided into blue and red states. Even our emotional states are described by color, with angry reds, cowardly yellows, envious greens, and moody blues. These emotions can be intertwined with the colors of our physical environment. Our moods are linked to the colors in our homes, with warm colors like beige and cream, and cool colors like teal and grey. Color is obviously central to many expressions of art, from the bold primary colors of Mondrian, to Picasso's blue period, to Seurat's mixing of colors through the pointillism technique. Colors are often expressed in music, from Dylan's *Tangled Up in Blue*, Prince's *Purple Rain*, REM's *Orange Crush,* and Coldplay's *Yellow*. Of

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_1

course, there's even an entire genre of music described by color, namely the blues. In short, color is an intrinsic part of our very existence.

These were the thoughts that crossed my mind as I headed off on a hiking trail close to my home here in Western Oregon. Marys Peak is a 4000 foot imposing landmark and it's the highest peak along the length of the coastal mountain range in Oregon. It's been an important part of my life ever since I moved to Oregon, for camping, hiking, stargazing, and sometimes as a place to avoid the heat of the valley where I live. I've been in academia in one form or another for most of my life and hiking is a welcome release from the pressures, the deadlines, and the stress. One day while mulling over these thoughts while on a hike I was stunned by a field of electric blue wildflowers. Here in Oregon, in the springtime you can often find beautiful blue larkspur and camas flowers near mountain streams. They're only around for a few weeks but the breathtaking colors can be overwhelming. I wondered about the origins of those vibrant colors—not just with the flowers but everything in the outdoor world around me.

This was the moment I came up with the concept for this book. The idea had been mulling around in my brain since I had read one of Carl Sagan's last books, *Science as a Candle in the Dark: The Demon Haunted World* [1]. In the book, Sagan thoughtfully describes the basic sense of awe that we all feel when we come face to face with the wonders of nature. A beautiful waterfall, a towering mountain peak, a rainbow, a meteor… at our core we feel an almost primal sense of wonderment at the sight of nature's most striking features. Sagan felt it was important for science educators to use that basic human curiosity as a launching point to bring science into the story. The sense of awe we feel is magnified with a contemplative explanation of the science behind the scenes. Sagan said it is important to not get bogged down into tedious mathematics and complex theories, but to tell the story of the science in a manner which explains the engine of science. The most important concept is that there is an explanation for these fascinating natural phenomena. It is not magic, but is something entirely knowable. Certainly, the gory details might only be known to specialists, but for any subject there is an accessible scientific explanation that anyone can understand.

This idea led me on a personal quest to learn everything I could about the science behind the colors in the world around me. Walking up the mountain, there is so much to see if you open your eyes to the kaleidoscope of colors in our world, and so much to learn about where those colors come from. Along the way, we will learn that color is not just a decoration. In fact, the origins of color will reveal hidden secrets about the natural world. The green color of plants tells us about the living chemical engine that drives its growth. The red color of blood tells us about the life sustaining oxygen carried in our cells. There's a secret world behind what we can see with our eyes and color gives us a hint about the inner workings of the natural world. The aim of this book is to introduce readers to this secret world, through an understanding of the physical, chemical, and biological mechanisms that underpin the observation of color. We'll explore and explain the colorful world that I see while I hike to the top of Marys Peak.

Unlike many physical phenomena (like mass, mechanical strength, electrical conductivity, etc.), color originates from many, many different mechanisms. This book aims to guide readers to a basic understanding of what happens behind the scenes when we see color. This process starts when light begins its journey millions of miles away at our sun. The light travels through space and enters Earth's atmosphere where it interacts with an object, for example a pumpkin. Finally, those light rays reflect off the pumpkin, travel through the air, and end their journey at the photoreceptors at the back of our eyes where they are converted into electrical signals which is then interpreted by our brains.

As a phenomenon, color is quite unique in that it is not objective but incredibly subjective. In contrast, mass and most physical properties are largely objective. If I measure the mass of an object, for example the pumpkin we discussed before, it will be the same no matter how it is measured, or who conducts the actual measurement. We could even measure the mass of the pumpkin on Mars, and while the weight would be different (because gravity is weaker on Mars), the measured mass will be exactly the same.

What is true for mass is **not** true for color for a variety of reasons. In fact, color is fundamentally different. Color is something that our brain assigns to an object based on the nature of the light rays that enter our eyes. This book is heavily indebted to and greatly inspired by the work of Kurt Nassau in his book *The Physics and Chemistry of Color: The Fifteen Causes of Color* [2]. His book beautifully describes three different ways to conceptualize the color of an object. The first approach focuses on defining color as an abstract and declarative **property** of an object. For example, we may simply state that "the pumpkin is orange." A second approach is more focused on the characteristic of light rays emanating from the pumpkin. As we shall see, visible light is a form of electromagnetic radiation and each color has a characteristic wavelength associated with it. For example, blue light has a wavelength around 475 nm, yellow light is around 580 nm, and red light is around 700 nm. It is possible then to describe a color on the basis of the **light rays** that are reflected off of the object. There are certainly objects that generate light on their own (hot filaments, fluorescent objects, etc.) but most objects reflect (or scatter) light that originates from some other source. The source could be the sun, a flashlight, or a streetlight. The light from this source interacts with the object and the color of the object is determined by the nature of the waves that reflect off of the object. This allows us to express this second definition of color as "the light rays reflected off the pumpkin have a wavelength of 590 nm which is attributed to the color orange."

The third definition as expressed by Nassau is more nuanced and really represents the unique and complex nature of color. It can be expressed as "the brain interprets the light that reflects off of the pumpkin and enters your eye as the color orange." The subjectivity and complexity come into play when colors mix. We all remember that we learned in kindergarten that when you mix yellow paint with red paint the result is the color orange. In fact, if we mix equal amounts of red light (with a wavelength of 700 nm) and yellow light (with a wavelength of 580 nm), our eyes will interpret this mixture of light as orange. Thus, in this scenario we "see" orange even though there are **no** light rays entering our eyes that have a wavelength associated with the color orange (590 nm). In fact, as we will soon learn there are an infinite number of ways we could combine light consisting of different colors to create the appearance of orange and our eyes could not discern the difference.

At this point I think it is useful to contrast the behavior of mixing wavelengths of light to the phenomena of sound. Recall that musical notes can be described as waves, with a wavelength and a frequency just like light waves. The note *A* corresponds to a frequency of 440 Hz and has a wavelength of 78.4 cm. When we hit the *A* key on a piano, sound waves emanate from the piano wire and our ears hear a sound that corresponds to this wavelength. Similarly, the note *C* has a frequency of 523 Hz and has a wavelength of 65.9 cm. When we hit the *C* key, we hear the sound at a higher pitch compared to *A*. When we hit the *A* and *C* key on the piano at the same time, our ears hear both notes simultaneously as a chord. Note that this is different than the behavior of light. When red and yellow light waves are combined, we no longer "see" red and yellow light but instead observe orange light. With sound, when we combine waves originating from *A* and *C* keys on the piano we do not hear the note *B*—instead we perceive *A* and *C* together in harmony. Part of this difference is explained by the difference between the operating principles of the photoreceptors in our eyes and the tympanic membrane in our ears. However, it is also a unique characteristic of the nature of color. It is not objective, but in reality, our brains receive the input from the photoreceptors in our eyes and interpret this input as a color. Remembering our example of the pumpkin, we restate this third and most nuanced definition of color as “the brain interprets the light that reflects off of the pumpkin and enters your eye as the color orange.”

Throughout this book we will largely focus on the physical and chemical mechanisms related to the interaction between light rays and objects, but recalling that third definition of color it is important to recognize that you cannot fully understand the nature of color without appreciating the role that the brain plays. Our brains require a great deal of resources to function, including 20% of the total oxygen usage and 25% of the total glucose [3]. While the brain performs many vital functions, the visual system is one of the most energy intensive systems. Thus, our brains have no doubt evolved to efficiently and effectively process and interpret the input data from our optical nerves. The brain renders this data into a spectacular color image that allows us the ability to create and admire great works of art, to stand in awe of the beauty of nature, but most of all it helps us survive.

Let’s keep this in mind as we hit the trail and look for color! (Fig. 1.1).

Fig. 1.1 Hitting the trail!

References and Further Reading

1. Sagan, Carl. 1995. *The demon-haunted world: Science as a candle in the dark*. Random House.
2. The essence of color is discussed in Chapter 1 in Nassau, Kurt. 2001. *The physics and chemistry of color: The fifteen causes of color*. Wiley.
3. Wong-Riley, M.T. 2010. Energy metabolism of the visual system. *Eye Brain* 2: 99–116. https://doi.org/10.2147/EB.S9078. Epub 22 July 2010

2

The Nature of Light

Before we get too far along on the trail, to explain the details of color we first need to understand some of the fundamentals of light. There's a bit of math, but it's mostly there to simply show the relationship between things. The "Marvel origin story" of color starts with electromagnetic radiation. Electromagnetic radiation is the means by which energy is transmitted over distance. This could be short distances such as the infrared radiation felt as heat coming off of a campfire and warming my hands or the light from the headlights on my Toyota Corolla reflecting off a deer on a dark country road. Electromagnetic radiation also travels large distances such as radio waves transmitted from an AM radio station which can travel hundreds of miles, to the red light emanating from the star Betelgeuse in the constellation Orion, which can carry energy from that star to my eyes on a cold winter night a staggering distance of about 700 light years, which is more than 4,000,000,000,000,000 miles.

Electromagnetic radiation is usually described in terms of a wave, and all waves share some fundamental characteristics. The first is frequency (f), which describes how many cycles a wave completes in one second. Frequency is usually denoted by the unit Hertz (Hz). Thus, a frequency of 440 Hz means that the wave completes 440 cycles in one second. The musical note A has as frequency of 440 Hz. In addition to frequency, waves are also described by their wavelength, which is the length of one cycle of the wave, usually expressed as the Greek letter lambda (λ) in units of meters. Frequency and wavelength are inversely proportional to each other, such that high frequency waves have short wavelengths, and low frequency waves have long wavelengths.

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_2

Another fundamental characteristic of electromagnetic radiation is the velocity (v) of the wave, measured in terms of meters per second (m/s). In a vacuum, electromagnetic radiation travels at the speed of light (c) which is approximately 300,000,000 m/s. When not in a vacuum, radiation tends to travel at speeds pretty close to that number though sometimes the differences are important which we will discuss later on. For all waves (sound waves, water waves, radio waves, etc.), frequency, wavelength, and velocity are all related via this simple equation:

$$v = f\lambda$$

For electromagnetic radiation, this velocity is the speed of light c. If the velocity is constant, this equation clearly shows the inverse relationship between f and λ, where if f is large, λ must be small, and vice versa.

Frequency, wavelength and velocity all describe the wave properties of electromagnetic radiation, however we must also take into account the particle-like properties. All quantum objects can be simultaneously described as being both a wave and a particle, and for electromagnetic radiation the particle is called a photon. If we think of an electrical current, there is a certain amount of electrical charge that flows through a wire and the electron is the primary particle that carries that charge. The more current (the more Amps), the more electrons that are flowing in the circuit. A similar analogy can be made for electromagnetic radiation, where energy is the quantity that flows and the primary particle that delivers that energy is the photon. The energy (E) of each individual photon is described by Planck's Law, which is:

$$E = hf$$

where E is the energy of the photon (usually measured in Joules or electron Volts), f is the frequency in Hz (the same frequency as defined for the wave in the previous equation), and h is Planck's constant, which has the value of 6.62×10^{-34} Joules per Hz (or Joules-seconds). This simple equation shows that the higher the frequency, the higher the energy of the radiation.

With these two simple equations we can describe the electromagnetic spectrum. At the bottom of the energy scale are radio waves (low frequencies, and very long wavelengths of meters, centimeters, etc. At higher energies and frequencies, we encounter infrared radiation with wavelengths on the order of 1000 nm, where a nanometer (nm) is one billionth of a meter or 1×10^{-9} m. At even higher energies and frequencies, we have the visible spectrum where color resides. For the purposes of this book, we will define the wavelengths of the visible spectrum as spanning from 400 nm (where violet resides) to

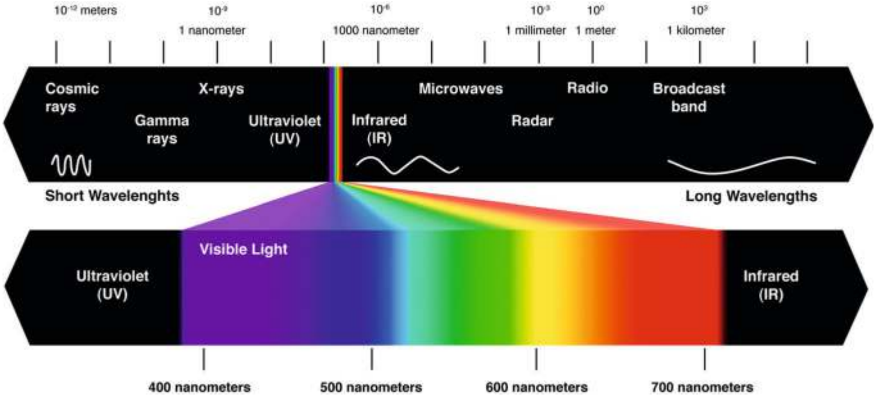


Fig. 2.1 The electromagnetic spectrum. The left side is high energy with short wavelengths, the right side is low energy with long wavelengths. Visible light is in the middle, with violet light on one end with the highest energy and the shortest wavelengths and red light with the lowest energy and the longest wavelengths. *Credit* Xryaa

700 nm (where red resides). To place this into context, at 400–700 nm, the wavelength of visible light is much larger than the size of an atom and simple molecules like water or ethanol (atoms are around 0.1 nm, molecules are closer to 1 nm). Visible light is typically smaller than most dust particles which are usually around 1000 nm or larger (though it really depends on the type of dust). Red blood cells are about ten times larger at around 6000–8000 nm, and the diameter of a human hair is around 50,000 nm. Thus, the wavelength of visible light sits in between atoms and molecules, and larger stuff like dust particles and everything else in the world as we know it.

Ultraviolet radiation exists at energies above the visible spectrum, which corresponds to wavelengths approaching 100 nm. Ultraviolet light carries a lot of energy which is why it damages objects left out in the sun including our skin. At even higher energies, we find x-rays (where $\lambda \approx 0.1$ nm) and at the highest energies we find gamma radiation. These forms of radiation are highly energetic and can do even more damage which is the reason why nuclear contamination is so dangerous (Fig. 2.1).

Thus, the electromagnetic spectrum encompasses a great deal of phenomena. Remember, it is the mechanism by which energy moves from one place to another. The higher the energy, the shorter the wavelength. Focusing in on the visible spectrum which ranges from 400 to 700 nm, we observe the “spectral colors” across this range. At one end, violet light has the shortest wavelength (~ 400 nm) and thus the highest energy, and at the other end we observe red light (~ 700 nm) with the longest wavelength and

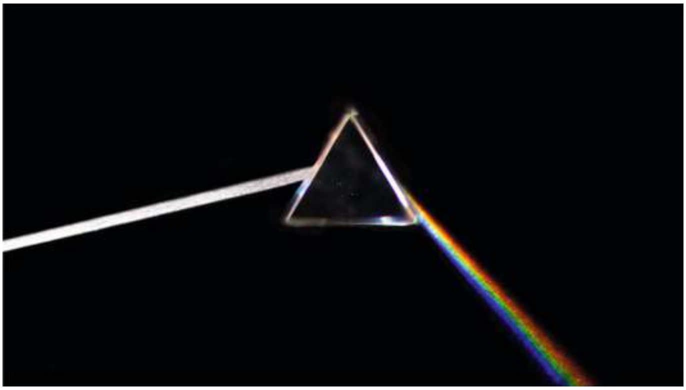


Fig. 2.2 This is a recreation of Pink Floyd's Dark Side of the Moon album cover. It was ingeniously created by Mara Maxwell to show the real effect of white light passing through a prism

lowest energy. In between these extremes, we find the other spectral colors. Next to violet we observe indigo light, then blue light, then green light, then yellow, orange and then at the end of the visible spectrum we observe red. You might remember this sequence from high-school physics from the mnemonic ROYGBIV (Fig. 2.2).

Speaking of high school physics, you might remember that we can observe these spectral colors by shining light through a prism. If you don't remember that, you might remember the cover of Pink Floyd's album Dark side of the Moon (Fig. 2.2). Then again, it's possible you don't remember high school physics precisely because you were too busy listening to Pink Floyd. Anyway, we'll explain the details of how this works later on because it plays a critical role in the stunning colors we see in rainbows and diamond rings. However, briefly, this comes about due to two phenomena: refraction and dispersion. When light enters an object such as this prism, it changes direction due to the interaction of the light wave and the electrical charges in the object. The specific angle depends upon the refractive index of the object (usually denoted by the symbol n). For some materials, the value of the refractive index depends on the wavelength of light, which means each color refracts at a slightly different angle. This is the reason why the prism "converts" white light into the spectral colors we see in the figure below. Basically, white light (which consists of all colors balanced together such that it appears white) enters the prism, and then each color (with their own unique wavelengths) bends at a different angle.

One thing you might have noticed is that while much of the color we see in this world can be described by these spectral colors (Red–Orange–Yellow–Green–Blue–Violet), there are of course other colors. We see that on our hike through the woods in wildflowers of magenta, purple, and pink. These are called "non-spectral" colors which do not appear in this prism experiment. Instead, they appear through *combinations* of spectral colors. To be more precise about defining colors, we'll have to use a semi-quantitative scheme that will allow us to define a color. We'll cover this in the next chapter!

Reference and Further Reading

1. For additional information on the fundamentals of color, see Williamson, S.J., and H.Z. Cummins. 1983. *Light and color in nature and art*. Wiley.

3

Chromaticity

We now know the scientific origins of color in terms of electromagnetic radiation, but as we take in the beauty of the wildflowers along the path of the hiking trail, we notice variations in color. The brilliant blue of the larkspur is clearly distinct from the deep blue of the camas (Fig. 3.1). While from an aesthetic standpoint it's probably not important to scientifically quantify the difference between these two blue colors, the concept is important in understanding the nature of color. The concept itself is called chromaticity and it is essentially the objective quantification of a color.

In this chapter we'll explore ways in which one can define a color precisely. This is obviously important if you're working at a print shop and a customer wants to print a poster in a particular shade of blue. Of course, it's not that easy. As we will learn, not everyone's photoreceptors function in the same way, so what might look like one particular shade of blue to one person might look different to a person with some form of color vision defect. And of course, that shade of blue on the poster might look different depending on the time of day and the type of interior lighting being used. That's why paint stores hand out paint chips so you can more accurately get an idea what the color looks like on that wall in your home.

In some ways I am ill-suited to write this chapter. A trip to the hardware store with my wife to pick out paints can be frustrating for her. While she can differentiate and analyze the suitability of hundreds of shades of paint chips for our kitchen I see only "green", "darker green", and "brown." She'll ask me what I think about one out of a hundred paint chips that appear exactly the same to me and all I can say is "it looks nice!" I am not color *blind*, I think I'm just color *dumb*.

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_3

Fig. 3.1 One of the most colorful features of Spring in Western Oregon is the emergence of beautiful larkspur flowers

There are many different schemes that are used to define a particular color. Each scheme has advantages and disadvantages and most of them are customized for a specific purpose. For example, quantifying a specific color reproducibly and reliably is important in defining the color of paints, reproducibility in printing, or matching colors in electronic displays. For our purposes we'll stick to one of the very first schemes because it is relatively simple to define a color and it also helps to graphically illustrate the interactions between colors when they are mixed. It is called the CIE 1931 chromaticity diagram. The CIE stands for *Commission Internationale de l'éclairage*, which was formed in France in 1931 for the purpose of creating a systematic basis for defining colors.

The diagram (Figs. 3.2 and 3.3) shows a curved arc where the spectral colors are located on the exterior of the arc. On the outside of the arc the wavelengths are shown for the spectral colors from approximately 400 nm for violet and with increased wavelength going clockwise up to 700 nm for the color red. Also note the energy of the light is also listed in terms of electron volts (eV). We mentioned this in the last chapter as a fundamental property of light. The electron volt is a useful unit of measure for describing the energy of really small objects like electrons or photons of light. Red light has the lowest energy (around 1.8 eV) and then going counter-clockwise around the diagram we get to violet light has the most energy (around 3 eV). While the colors on the outside are the "spectral" colors, inside the diagram we find the

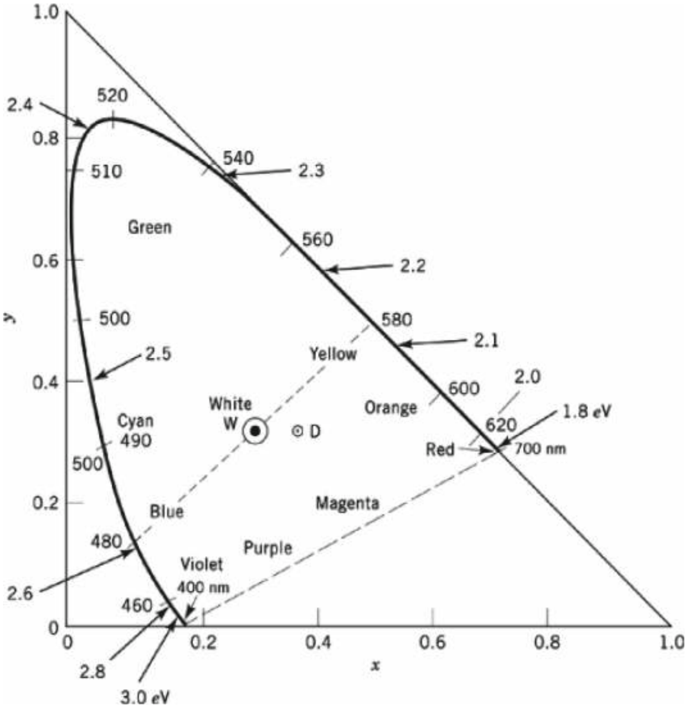


Fig. 3.2 This is the CIE diagram which graphically portrays colors in an xy plane. The colors on the curved arc are the spectral colors, going clockwise from violet at the bottom all the way around to red on the right. The diagram lists the wavelengths of those colors (in nm) and also includes the energy of each color (in electron volts (eV)). Adapted from Nassau, The Physics and Chemistry of Color (Wiley, New York, 1983)

"non-spectral" colors. These are colors which cannot be observed through separating white light using a prism. This includes lots of colors my wife can name with great precision. I can name colors like magenta, pink, but there are lots of other colors I can't name because I don't have the vocabulary. Also note that in the middle of the diagram there is a point denoted with a W. This is the location of white. Another point, denoted with a D is the location of "standard daylight." As we know, the light from our sun has a yellow character so it is not purely white. Black is not on this diagram, but it is defined as an object that has zero transparency and zero reflectivity. The absence of any light scattering or being emitting from that object results in the appearance of the color black.

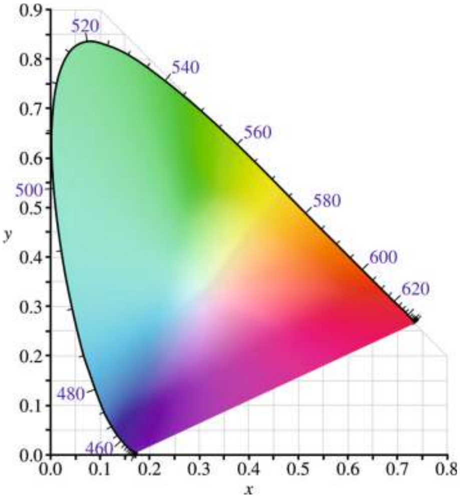


Fig. 3.3 Another depiction of the CIE diagram showing the distribution of colors across the diagram. *Credit* BenRG

The quantification of specific colors comes from the x- and y-axes, with numbers ranging from 0 to 1. That means we can define a color on this diagram with 2 numbers, for example one particular shade of red can be defined at x = 0.7, y = 0.3. There is one more dimension, called "luminous intensity" which is often denoted with the symbol Y. It can be thought of as the "3rd dimension" on this diagram which relates to the intensity of the color. With this CIE 1931 scheme, any color can be defined with 3 numbers, xyY.

One of the most useful parts of this diagram is that it is possible to predict the effects of mixing colors through a simple graphical extrapolation. Let's look at a line connecting spectral blue (at around 480 nm) and spectral yellow (at around 580 nm). Note that the line crosses the W point denoting white. If we start at blue on the edge of the diagram and march towards point W, the blue color becomes more and more pale as we approach W. The spectral blue color on the outside arc can be called "saturated" and as we approach point W the blue color becomes "unsaturated." Eventually at point W all traces of the original blue color are gone and the observed color is pure white. If we continue on this line we would observe "unsaturated" yellow, and continuing on the yellow color would become more prominent until reaching the end of the line where we would obtain "saturated" yellow. Thus, blue and yellow are considered to be "complimentary colors," which means if they are added in appropriate amounts the resultant color is white. We can see other complimentary colors which straddle the W point on the diagram, such as Orange and Cyan, and also Purple and Green.

While complimentary colors can be used to create the appearance of white, the CIE diagram allows us to accurately predict any resultant color that arises from combining two or more colors. This is specifically called "additive mixing." It works through the lever rule, where you determine the resultant color based on the relative intensities of the individual component colors. Figure 3.4 illustrates three different means of creating a particular shade of unsaturated orange such as for a pumpkin. On the left, we can create that orange through a combination of white and spectral orange. The lever rule applies here which means that the resultant color depends upon the relative intensities of the white and orange components. To achieve the specific unsaturated orange color indicated by the X in the diagram, we combine a greater proportion of the spectral orange color in combination with a lower intensity of white. The middle diagram indicates another method of creating the same orange color by combining a deep red color and cyan. Again, to create the resultant color at the X mark, a much greater intensity of red is needed compared to cyan since the point X is much closer to the red part of the diagram. The diagram on the right indicates the resultant orange color which is observed from the combination of three colors, red, green and blue. The lever rule indicates the location of the resultant combined color based upon the intensities of the red, green and blue components. With the right amounts, we can obtain precisely the same orange color as the previous cases. Later on in this book, we will revisit this phenomenon as this is how color displays such as LED televisions and smart phones generate millions of colors from just three colors.

Going back to our discussion of the philosophical nature of color, remember the most nuanced definition of color with reference to the observation of a pumpkin was "*the brain interprets the light that reflects off of the pumpkin and enters your eye as the color orange.*" This could arise from a combination of rays including spectral orange and white, which additively combine such that our brains observe the resultant color as orange. Or, it could be that light rays of red and cyan enter our eyes, and even though this is a very different input, our brains observe the resultant color as orange. Or, our eyes could be bombarded with light rays of blue, green and red, with the same interpretation of orange. In fact, there are infinite possible combinations of light rays that would result in the same interpretation of an unsaturated orange color. With just our eyes, there's no way to know which of these scenarios is causing our brains to observe the color orange. We would

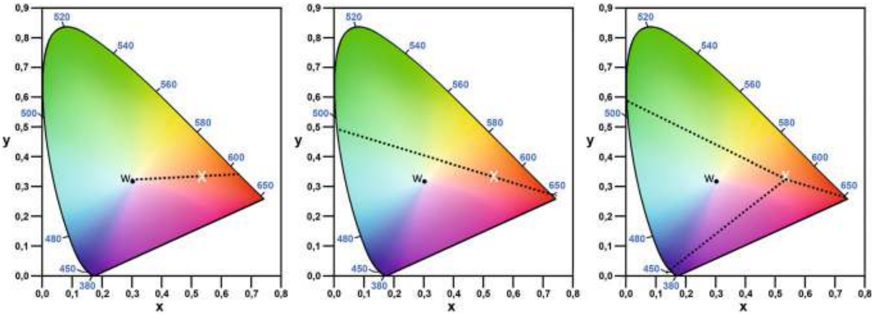


Fig. 3.4 Point X indicates a particular shade of orange. The three diagrams show three possible combinations of colors, in appropriate amounts, that could create the same shade of orange through additive mixing. The left diagram shows a combination of reddish-orange and white (at point W). The center diagram shows a combination of light green and deep red. The right diagram shows a combination of three colors, green, blue and deep red. *Credit* BenRG

need specialized equipment to understand what components are combining to create the observed orange color. For example, an instrument called a spectrophotometer measures the intensity of light as a function of wavelength. As we will learn in an upcoming chapter, our eyes have some primitive capability for differentiating different wavelengths of incoming light, but this information is discarded and our brains compress and simplify the incoming data as the observation of a single color. Why? Well, remember our brain is an incredibly energy intensive organ and the processing of vision is one of the most energy intensive processes that the brain is responsible for. I assume encoding the full spectral information for each color pixel in our field of vision is well beyond what is needed for our survival. We'll look at color vision in the animal and insect species and it is pretty clear that each organism develops the vision and color perception it needs for survival and nothing more.

What we have described to this point is the phenomenon called *simultaneous additive mixing*. That is, we can predict the resultant color from the simultaneous input of different rays of light of different colors that enter our eyes at the same time. There are two other types of additive mixing that we encounter. Another related phenomenon is *temporal additive mixing*. A classic example of this is a spinning color wheel. If we paint a circular wheel with complimentary colors on opposite sides of the wheel, when the wheel spins the resultant color will be white. Essentially, when the wheel spins fast enough so that our eyes cannot visualize the rotation, the two colors combine additively to appear white. Traditional movies shot on film typically have 24 frames per second which is fast enough that our eyes cannot see the individual frames. Thus, there is a minimum rotation speed for the spinning color wheel to appear white. Of course, it doesn't just work with complimentary colors—you can create any color by simply creating a color wheel with different component colors. The relative amounts of the component colors on the wheel will determine the resultant color just as we demonstrated from the CIE diagram.

Another type of additive mixing is *spatial additive mixing*. With this phenomenon, individual points of color are spaced close enough so that our eyes cannot distinguish the individual points. Instead, we observe additive mixing of those colors to create a resultant color. In art, this technique is called pointillism and the example shown in Fig. 3.5 is a piece by Georges Seurat called *A Sunday on La Grande Jatte* (1884). From a distance, the painting shows vibrant colors depicting a beautiful scene by the water. We see children at play, women in uncomfortable dresses holding up parasols, and men lounging around. However, as seen in the 1986 film *Ferris Buellers' Day Off*, upon closer inspection (Fig. 3.6) Cameron stares deeply into the painting to see the individual dots of color which contribute to the observed color through additive mixing. From Cameron's facial expression, he probably sees a lot more than that. Maybe he sees the meaning of pointillism as a metaphor for the tiny unperceivable elements behind the scenes that contribute to our perception of an object. We'll see this as a common theme in this book where the color we observe is an indication of things going on at the microscopic level like photosynthetic energy conversion, or oxygenation of blood. Creating colors through additive mixing is just one way a swath of colors can be created. In the next chapter, we'll discuss subtractive mixing which as the name indicates involves creating color by removing parts of the visible spectrum.

Fig. 3.5 A Sunday on La Grande Jatte by Georges Seurat (Art Institute of Chicago)

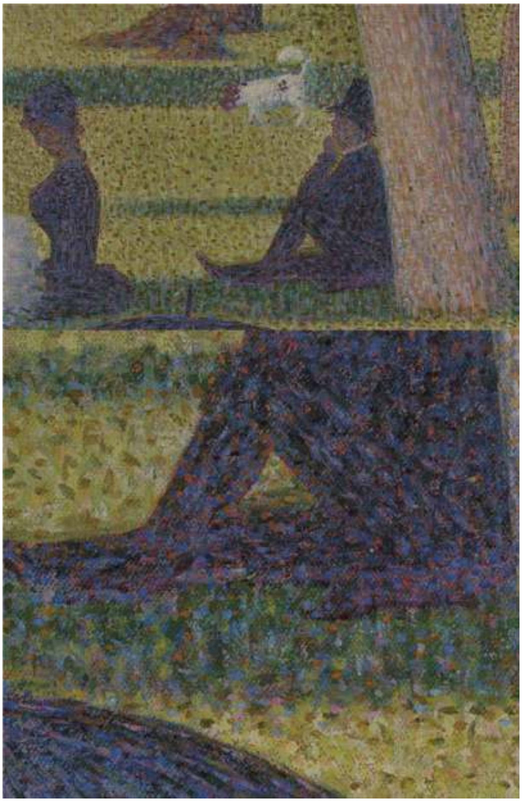


Fig. 3.6 Close up of A Sunday on La Grande Jatte (Art Institute of Chicago) showing the individual points of color that is fundamental to the pointillism technique

References and Further Reading

1. The basics of color and additive mixing is discussed in Chapter 1 in Nassau, Kurt. 2001. *The physics and chemistry of color: The fifteen causes of color*. Wiley.
2. The Art Institute of Chicago has a wonderful website with lots of information on the art in their collection.
3. Williamson, S.J., and H.Z. Cummins. 1983. *Light and color in nature and art*. Wiley.

4

Color by Subtraction

Where I live, on many hiking trails you can't count on reliable cell service. While smart phones and GPS are great, I tend to always carry a map with me in case I get lost. Glancing at the trail map, it's another source of color with shades of green representing elevation and colorful lines for the different trails. The colors I see are the result of a different mechanism than what we discussed in the previous chapter. The mixing of colors using the CIE diagram as we have described in the previous chapter is called *additive mixing*. In contrast there is a related phenomenon called *subtractive mixing*. While additive mixing is highly predictable, subtractive mixing is much less predictable. It really depends upon the details of the color spectrum. This is particularly important for pigments such as those used in paints. It's also the mechanism for the colorful ink printed in the figure of this book in your hands.

Subtractive mixing works by removing a segment of the visible spectrum. White light appears white to our eyes because all of the spectral colors are in balance. We'll look at the mechanisms later, but basically there are physical or chemical processes that effectively *absorb* part of the visible spectrum (which removes light over a range of wavelengths), leaving the rest of the visible spectrum untouched. Let's consider one of the complimentary pairs we discussed previously—blue and yellow. A yellow pigment creates the appearance of yellow because it preferentially absorbs blue light. When blue light is removed from the spectrum the resultant color we observe is yellow. Conversely, if a pigment preferentially absorbs yellow light the resultant color would appear blue. It works like that with any complimentary pair. If a pigment absorbs violet light, it will appear green. And a pigment that absorbs green light will appear violet, and so on.

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_4

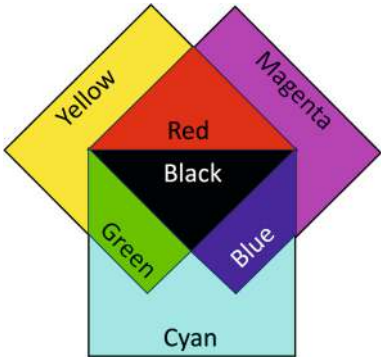


Fig. 4.1 Schematic of subtractive mixing. Each color (cyan, yellow, and magenta) is characterized by a section of the color spectrum that has been removed. Thus, when all three colors are combined the net result is black

With additive mixing, when you combine complimentary colors, the resultant color is white. With subtractive mixing, if we were to combine violet and green, for example, the resultant color is black (since the combined pigments absorb the entire visible spectrum). This is the basis for printing processes that utilize cyan, magenta, and yellow inks. Since most of the time we print on a white sheet of paper, black is added as a color and given the symbol K in so-called CMYK printing. This is widely used on ink-jet printing and other printing processes, where specific combinations of these colors can be used to create millions of colors (Fig. 4.1).

However, subtractive mixing isn't as predictable as additive mixing and the apparent resultant color ultimately depends on the specific spectral information. This is nicely demonstrated in Fig. 4.2 which is taken from an example in Nassau's book [1]. Consider first the example on the left. One particular pigment (A) absorbs all wavelengths below 540 nm which results in an apparent yellow color. Another pigment (C) absorbs all wavelengths up to 575 nm, which results in an apparent orange color. What happens when these pigments are combined through subtractive mixing? We effectively overlap both spectra together (shown in D) such that in this case all wavelengths below 575 nm would be absorbed, resulting in an apparent orange color. Thus, the mixing of this orange pigment (A) and this yellow pigment (C) results in an apparent orange color (D). In the example on the right, we use a different yellow pigment (B), one that absorbs light over most of the visible spectrum, only allowing light over a narrow range of wavelengths centered near 575–585 nm. If we combine this yellow pigment with the orange pigment in the previous example (C), when the two pigments combine the

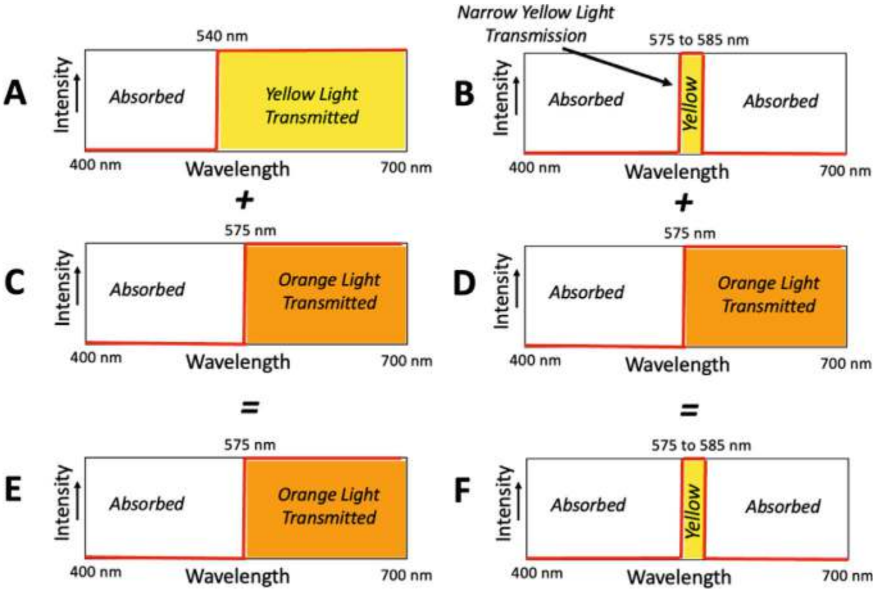


Fig. 4.2 This schematic shows the complexity of subtractive mixing due to the absorption of certain wavelengths. In the example on the left, yellow light (A) mixed with orange light (C) results in yellow light. In the example on the right, a different yellow light (B) mixed with orange light (D) results in orange light (F). Thus, with subtractive mixing, the resultant colors really depend upon the details of which wavelengths are being absorbed. Adapted from Nassau, The Physics and Chemistry of Color (Wiley, New York, 1983)

overlapped spectra results in only the narrow yellow band (E). Thus, the addition of this new yellow pigment (B) and the orange pigment (C) resulted in an apparent yellow color (E). Thus, in the first case yellow + orange = orange, and in the second case yellow + orange = yellow. This demonstration aims to show that the resultant colors that arise from subtractive mixing really depends upon the details of the absorption spectra which you can't know unless you have some special equipment like a spectrophotometer.

It is also useful to remember that the addition of pigments reduces the overall brightness since segments of the visible spectrum are being absorbed due to the pigments themselves. With additive mixing this is not the case since the overall intensity of two or more colors is combined. Figure 4.3 demonstrates this effect as it shows three examples of complimentary colors printed into narrow lines with decreasing width [2]. When the lines are spaced close enough that the individual colors cannot be differentiated, the resultant color appears as gray. This is because the complimentary colors absorb light over the majority of the visible spectrum, reducing the brightness. The absorption isn't perfect, otherwise it would appear black.

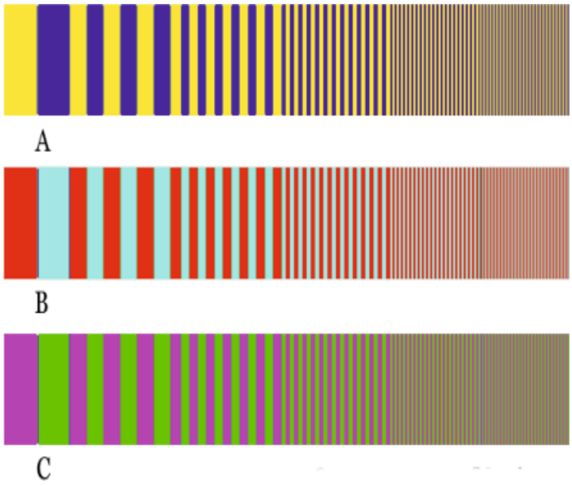


Fig. 4.3 This schematic shows three examples of complimentary colors printed into narrow lines with shrinking widths. When the lines are relatively thick the colors can be differentiated, but when the lines are spaced close together the individual colors cannot be differentiated and the resultant color appears as gray. Reproduced with permission by Dr. David J. C. Briggs from the website The Dimensions of Colour (http://www.huevaluechroma.com/)

This process is the fundamental basis for CMYK color printing. You've probably noticed that your color printer uses 4 ink cartridges corresponding to the colors cyan, magenta, yellow, and black. Combinations of these inks can result in the creation of millions of colors, which is defined as the "gamut." It's essentially the effective area in the CIE diagram that defines the range of colors which can be achieved through the mixing of these individual inks. The example at right shows the separate prints for the cyan, magenta, yellow and black inks, which combine to create the overall color image shown in Fig. 4.4.

At this point, we have a means of defining specific colors using the CIE diagram, we have an understanding of what happens when we mix colors, either through additive mixing or subtractive mixing. The next step is to discuss where magic happens—in the photoreceptors located at the back of our eyes!

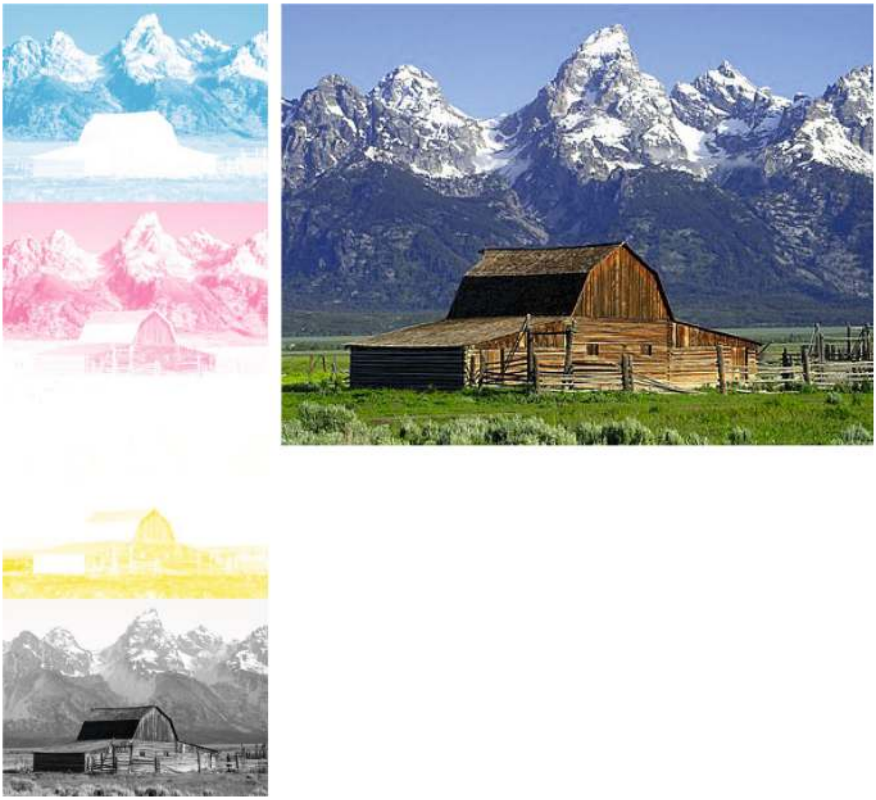


Fig. 4.4 Example of a color image of the Teton range broken into four separate colors, cyan (C), magenta (M), yellow (Y), and black (K) (also known as CMYK). *Credit* Jon Sullivan, PD Photo. PD Photo—Public Domain

References and Further Reading

1. Subtractive color mixing is discussed in Chapter 1 in Nassau, Kurt. 2001. *The physics and chemistry of color: The fifteen causes of color*. Wiley.
2. For more information on color, Dr. David J. C. Briggs has a wonderful website with valuable information about color at http://www.huevaluechroma.com/.

5

Seeing Color

Walking along the trail, it's easy to get lost in thought. Out in the natural world I'm blissfully disconnected from emails and phone calls. There are no prompts for upcoming Zoom meetings or deadlines or grading papers. Instead, my attention is drawn to the colorful world around me. It's easy to forget what it means to "see" an object, like a delicate purple fairy slipper that gracefully appears along the hiking trail in the Spring. However, to understand the true origins of that purple color we have to expand the scope of our environment to see the big picture (Fig. 5.1).

When we observe the color of an object, we're at the tail end of a very long chain of events that culminates with the signal sent to our brains from the photoreceptors in our eyes. Let's consider *all* the steps in that chain. First, nuclear reactions in the sun generate heat which sends energy in the form of electromagnetic radiation on an eight-minute journey of over 94 million miles to Earth. When it arrives, it interacts with the Earth's atmosphere (especially at dawn and dusk) and the light finally reaches the object we are gazing at. That light then interacts with the object, some of the light is absorbed, and some of the light is reflected along a path that has a trajectory to our eyes. On its path to our eyes, it may still interact with the atmosphere, but when it finally reaches us the light ray ends its life by being absorbed in a light sensitive molecule in the sensors in our retina. The electrical signal generated from that interaction is interpreted in our brains as a color. To this point, we've described the characteristics of electromagnetic radiation as it relates to color, namely wavelength. Throughout this book, we'll describe all the other parts of this chain of events, but in this chapter, we will briefly discuss the last step where visible light interacts with our eyes.

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_5

Fig. 5.1 An incredible find—a delicate fairy slipper!

On a fundamental level, there are two overarching principles that relate to what we understand about the observation of color. First, recall that light (*specifically electromagnetic radiation*) is a manifestation of energy. Second, atoms and molecules interact with light in a myriad of ways that use that energy in different ways. In this sense, the interaction of light and matter is basically an expression of the First Law of Thermodynamics, that energy is conserved.

The basic functionality that underpins our ability to sense light and color is a molecule that is sensitive to light. Over the course of this book, we'll see lots of examples of this where a molecule absorbs energy via a photon within a stream of light and converts that energy into some other form of energy. The basic idea is as follows. All objects including molecules (for example the water molecule H_2O) have energy. Molecules express that energy through various ways, including kinetic energy (the energy of motion), rotational energy (the energy of rotation), vibrational energy (the energy of vibration), or some other form of energy (chemical, etc.). If we think of a baseball as a model for a molecule, the kinetic energy would be the speed of the baseball travelling to home plate. A high velocity fastball would represent a large kinetic energy, and a low velocity changeup would represent a small kinetic energy. Rotational energy would be analogous to the spin of the baseball. A knuckleball has very little spin and hence very little rotational energy. In contrast, a curve ball has a great deal of rotational energy which, when air interacts with the seams on the baseball, results in the lateral motion of the baseball—thus making it difficult for the batter to hit. When molecules absorb light, the energy they gain from the light is converted into an increase the velocity or an increase in the rotation or vibrational energy of the molecule.

All forms of life that have some form of vision utilize a special type of light-sensitive molecule that converts light (via a photon) into an electrical signal. In organisms with highly advanced vision, that electrical signal then gets "processed" to generate a full color image. In simpler organisms, that electrical signal might just indicate the change from light to dark. One such photosensitive molecule that is present in mammalian eyes is called rhodopsin, also known as visual purple. Photosensitive molecules are present in many organisms and they play critical roles in their survival. Later we will discuss the process of photosynthesis which creates chemical energy from light, but plants also have photosensitive molecules that help direct the growth of the plant in order to aim the growth of leaves in the direction of the sun. There's even a fungus (formal name Pilobolus, but its awesome informal name is "dung thrower") that has a primitive form of vision that allows it to aim its spores at the brightest object in its field of view (usually the sun) [1].

In researching this chapter, it became clear that there is a broad spectrum of vision-related phenomena in the natural world. I searched the internet and I couldn't find a robust definition of the word "vision." I found a seemingly endless list of insufferable Ted talks with the keyword vision. I also found lots of dictionary definitions that relate vision to the act of "seeing" which seems like circular logic to me. If you think of "vision" as the detection of light to stimulate some kind of action or response, plants clearly have vision because they use the detection of light to guide their actions (which direction to grow, when to flower, etc.). While I wouldn't call this "imaging" since the plant is not creating an image, it is responding to an external stimulus (i.e. light). It is just a simpler version of what we do with the photoreceptors in our more complex eyes.

Going beyond the plant kingdom, you can find an organ that functions somewhat like the human eye in three phyla, namely vertebrates, mollusks, and arthropods. Vertebrates include mammals such as ourselves, but other creatures that have backbones including reptiles, birds, fish, and amphibians. Mollusks that have eyes include octopi, snails, and cockles. Arthropods with eyes are found in insects, arachnids, and crustaceans. In mollusks like chitons and bivalves, the eye is not used for imaging or color analysis. Similar to the case of plants, it merely senses a change from light and dark to detect the shadow of a predator [2]. However, within the mollusk phylum, cephalopods such as squid and octopi are predators which require a more advanced form of vision to effectively hunt their prey. In fact, squid and octopi have eyes that have a structure that looks similar to vertebrate eyes. Octopi are able to use camouflage which implies they have color vision, however the mechanism is not fully understood since they only have one type of photoreceptor [3]. This is confusing because as we shall see we achieve color vision through the use of multiple photoreceptors that are tuned to different wavelengths across the visible spectrum which allows us to differentiate colors.

Within the arthropod phylum, there are many forms of vision that incorporate functionalities that help them survive. Some have simple eyes like ourselves, while others have compound eyes which feature an array of miniature eyes called ommatidia. Lobsters utilize compound eyes that are designed to enable vision in dark, mirky waters at the bottom of the ocean. Mantis shrimp have perhaps the most advanced color vision capabilities amongst all organisms. These predators have a total of twelve different types of photoreceptors which help them operate and hunt their prey in the complex and colorful coral reef environment [4]. In contrast, humans only have four photoreceptors. Many insects have compound eyes which are more useful at tracking the trajectory of flying predators or prey. Most insects only have two photoreceptors, one in the green/yellow region around 550 nm and the other is active in the blue to ultraviolet range. However, honeybees, bumblebees and diurnal butterflies have true color vision with three photoreceptors that operate at wavelengths for ultraviolet, blue, and yellow light [5, 6].

As you recall from our discussion earlier, vision (and especially color vision) is an extremely energy intensive process which requires a great deal of glucose and oxygen and thus it taxes the computational capabilities of the nervous system. Thus, for an organism to survive, the capabilities of the vision system have to be perfectly optimized for survival. A mollusk with an eye that possesses full color imaging would require too much energy and would not significantly improve the organisms' survival. Along these lines, it is reasonable to postulate that compound eyes are the most energy efficient solution to the needs for many insects that rely on avoiding predators for their survival.

Focusing now on human vision, we see a schematic of the human eye in Fig. 5.2. Ignoring the functions of the cornea, iris and lens, the incoming light rays focus on the retina located on the back of the eye. We humans have two types of photoreceptors, rods and cones. Both achieve their function through the use of the previously mentioned molecule rhodopsin which converts light into an electrical signal. Overall, the human eye has 120 million rods and about 6 million cones which come in three types, covering three different wavelengths [7]. For reference, a state-of-the-art digital camera has around 50 megapixels, which means it has 50 million photoreceptors. Of course, they

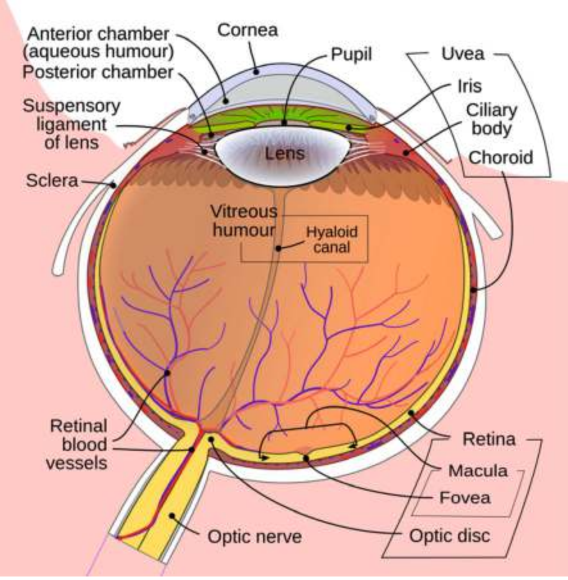


Fig. 5.2 Schematic of the human eye. The rod and cone sensors are located at the back of the eye within the retina. *Credit* Rhcastilhos and Jmarchn

don't operate in the same way and thus comparing rods and cones to pixels is like comparing apples-to-oranges. Nonetheless, we will soon have digital cameras which have capabilities comparable to the human eye. Each rod and cone photoreceptor absorbs the incoming photon, and the energy from that photon is converted into an electrical signal. Each rod and cone is electrically connected to the axon, which is a fibrous structure connected to the optic nerve. The optic nerve transmits the electrical signal to the brain where the information is rendered into an image. From that long journey starting at the sun, I can now "see" the purple fairy slipper I hold in my hands.

But where does the perception of color come from? The key is the spectral response of the individual photoreceptors, the rods and cones. Figure 5.3 shows the sensitivity of the rods and cones as a function of wavelength. At the low wavelength end (400 nm), the color corresponds to violet and on the high wavelength end (700 nm) the color corresponds to red. Looking first at rods, note they come in only one type and you can clearly see they are much more sensitive than the cones. This means where there is limited light (for example at night), only rods can function effectively since the cones require a greater amount of light input. Note also that since there is only one type of rod sensor, there is no ability to sense color. The absorption of a photon of light by a rhodopsin molecule within the rod sends a singular signal along the optic nerve without any information about wavelength (and therefore color).

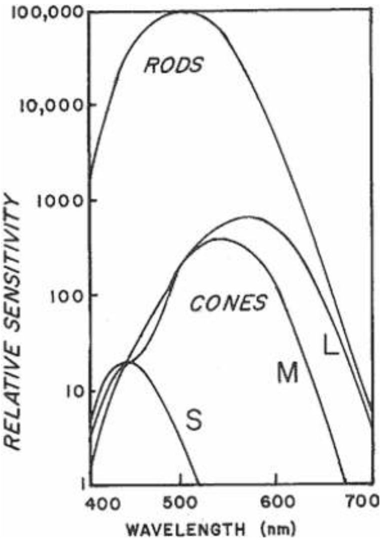


Fig. 5.3 Sensitivity of rod and cone sensors as a function of wavelength. There are three different cone sensors covering different wavelength ranges corresponding to different colors, where S = short wavelengths (blue), M = medium wavelengths (green), and L = long wavelengths (red). Adapted from Fig. 1.16 in Nassau, The Physics and Chemistry of Color (Wiley, New York, 1983)

We know this because in low light conditions we cannot perceive any color. At night, or with dim lighting indoors, with only these rods functioning a bright red rose appears to our eyes with features defined by black, gray, and white colors. In fact, the vision of nocturnal mammals is dominated by rods since cones are not useful under the low lighting conditions at night [8].

When light is more abundant, the cones in our eyes begin to work. Just as with the rods, a photon is absorbed which sends a signal to the brain. However, most people have three types of cones that each absorb light at different wavelengths which enables the ability to determine the color of an object. As shown in the figure, the three cone subtypes are labeled as S, M, and L which corresponds to cones that are sensitive to light at short, medium, and long wavelengths. These wavelengths roughly correspond to blue for the S cone, green for the M cone, and red for the L cone. The electrical input from these three sensors is conveyed to the brain with information about the relative intensities of these three separate wavelengths (i.e. colors). Through the magic of the inner workings of our brain, it synthesizes these three inputs and interprets a resultant color. Recalling the CIE diagram we discussed in Chap. 3, the three independent inputs (from the S, M, and L cones) quantify the intensity of light at three different colors. Through a triangulation process, the brain can integrate this input to “see” a multitude of colors based upon the relative intensities of the three different cones.

We noted that the rod sensors are much more sensitive which means they dominate under low levels of light. It’s also interesting to note that each of the three types of cones have different maximum sensitivities as well. Notice that the sensitivity of the S cone (which detects blue light) is much less than the M and L cones (which detect green and red light, respectively). This means our eyes are much less sensitive to blue light, which means it requires an abundance of light to perceive the color blue. This is easy to demonstrate if you have a light switch with a dimmer. Turn the lights off and stare at an object in the room, while slowly increasing the intensity of the light. You’ll notice that as the intensity of light increases, the color of the object changes. The overall color will shift towards increased blue tones. It’s definitely subtle, but if you have a dimmable light switch in a room, stare at an object carefully while increasing the light intensity and you will definitely see it. This is called the Bezold-Brücke effect. Essentially what’s happening is under low levels of light the S (i.e. blue sensitive) cones in our eyes are inactive and thus the color of the object is dominated from the signal from our M and L cones which is sensitive to the green-to-red side of the spectrum [8].

Of course, not everyone is born with a set of three different cones that function like those shown in the figure. About one in twelve men and about one in 200 women have some type of color vision deficiency or color blindness [9]. The most common form of color blindness occurs when the sensitivity of the M and L cones overlap so that it becomes impossible to discriminate between the colors red and green. It’s a good idea to keep this in mind if you’re creating images or plots to make sure they can be understood by people with color vision deficiency. Thankfully, there are lots of great websites that have suggested color palettes that work for most if not all types of color vision impairment. On some sites, you can upload your image and have it converted into a form that simulates what it would look like under different types of color blindness. Considering that the goal of a making a plot or schematic is to communicate an idea, making sure the color scheme works for everyone is an important consideration.

So, at this point, we know how what color is and we know how to define a particular color using wavelength or using the CIE diagram. We know how we humans see colors when a photon of light is absorbed by the molecule rhodopsin which is present in the rods and cones in the retina. The rods and cones convert the light into a complex electrical signal which is synthesized by the brain into the perception of a particular color. Thinking of the fairy slipper, where did that color come from in the first place? Color is everywhere.

It is created in the night sky above us in the red, white, and blue stars many light years away from Earth, and color is created in the tiny microscopic pixels of light in the display on the laptop I am typing into right now. The rest of this book will explore the myriad of ways in which color is created in our world.

References and Further Reading

1. This incredible story about the Pilobolus fungus is nicely explained on this website: https://weirdandwonderfulwildmushrooms.blogspot.com/2014/10/hat-throwers-pilobilus.html.
2. Serb, J. M., and D. J. Eernisse. 2008. Charting evolution's trajectory: Using molluscan eye diversity to understand parallel and convergent evolution. *Evo Edu Outreach* 1: 439–447.
3. Summary of color vision in octopi: https://carnegiemnh.org/octopus-mystery-how-do-they-see-color/.
4. Graydon, O. 2009. An eye for inspiration. *Nature Photon* 3: 668. https://doi.org/10.1038/nphoton.2009.211.
5. Warrant Eric, J. 2017. The remarkable visual capacities of nocturnal insects: Vision at the limits with small eyes and tiny brains. *Philosophical Transactions of the Royal Society B: Biological Sciences* 372: 20160063.
6. Arikawa, K. 2017. The eyes and vision of butterflies. *Journal of Physiology* 595: 5457–5464. https://doi.org/10.1113/JP273917.
7. The anatomy and perception of color in the human eye is discussed in Chapters 1 and 14 in Nassau, Kurt. 2001. *The physics and chemistry of color: The fifteen causes of color*. Wiley.
8. This is a wonderful website that summarizes nocturnal vision in mammals: https://archives.evergreen.edu/webpages/curricular/2011-2012/m2o1112/web/nocturnal_mammals.html.
9. Gordon, N. 1998. Colour blindness. *Public Health* 112 (2): 81–84.

6

Color from Heat

To understand the origins of color we needed to learn the basics. Not just the physics of color, but also a little bit about how we “see” color. With that out of the way, we can now begin our hike in earnest. Our goal is to take in the color in the world around us and learn about where it all comes from.

Fumbling around in the pre-dawn hours at our campsite, we see the world in colorless gray since only the rods in our eyes are active. The outlines of the trees and pebbles and soil at our feet are all outlined in shades of gray. The only color we see emanates from the smoldering embers in the fire pit. The reddish-orange remnants of the fire give off a warm glow that breaks through the monotonous gray surrounding us. This is the first color we see and this is the first color mechanism that we will discuss.

This first color phenomenon is called incandescence. In short, this is color that originates solely from the temperature of an object. We saw that with the glowing embers, but we also observe this every day when the sun rises. Basically, hot objects emit light.

It turns out all objects emit electromagnetic radiation depending on their temperature. This is called blackbody radiation and there are two important equations that describe how it works. The first is called Stefan’s Law [1]:

$$E = \varepsilon \sigma T^4$$

In this equation, E is the total energy emitted, ε is called the emissivity (which varies from 0 to 1), σ is the Stefan–Boltzman constant, and T is the temperature (in Kelvin). Basically, this equation describes how much energy is emitted depending upon the temperature. Most importantly, it shows that as

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_6

the temperature increases, there is a very significant increase in the amount of energy emitted. Thus, objects at room temperature emit some radiation but not a lot (remember room temperature is 25 °C or 300 Kelvin). However, as the temperature increases this becomes very significant since the temperature term rises to the fourth power. As objects get hotter, they emit more and more radiation.

The other important equation that relates to color is Wien's Law which is the following [1]:

$$\lambda_{max}(\mu\text{m}) = \frac{2987}{T}$$

This equation describes the relationship between the wavelength (λ) of the emitted radiation of an object as a function of temperature (T) of the object. It shows that the maximum wavelength of the radiation (in units of μm (λ_{max} (μm)) decreases as the temperature increases. Objects emit energy over a broad range of wavelengths but the term λ_{max} (μm) essentially describes the wavelength of maximum intensity. The equation demonstrates that as things get hotter (i.e. T increases), the λ_{max} (μm) term decreases which means objects will emit radiation at shorter and shorter wavelengths.

Let's look at some examples. Right now, you and I are at 37 °C (i.e. body temperature) which corresponds to 310 K. Wien's Law tells us that we are emitting radiation at a wavelength of around 10 μm. Recall 1 μm equals 1000 nm, and since the visible spectrum is from 400 to 700 nm, that means that radiation at 10 μm (or 10,000 nm) is deep into the infrared part of the spectrum. We can't see it since our eyes are only sensitive to visible wavelengths but it's there. There are specialized infrared cameras that are sensitive to infrared radiation which are used for military applications and hunters use them too (since animals also emit infrared radiation). I have also seen infrared cameras used on late night TV to search for sasquatch but that's the subject of a different book.

Figure 6.1 shows how the peak intensity of radiation shifts to lower and lower wavelengths (indicated by λ_{max} in the figure and in Wien's equation above). Note also that the total amount of radiation (the area under the curve) increases significantly as the temperature increases. This is the result of the Stefan-Boltzmann equation where the total amount of energy emitted increases as the temperature increases. It is also important to note how broad the peak is. While Wien's Law tells us there the maximum occurs, an object will give off a good bit of radiation at higher and lower wavelengths.

We can understand a good example of this sort of color mechanism when we go back to the example of the glowing embers in our campfire. A well-built

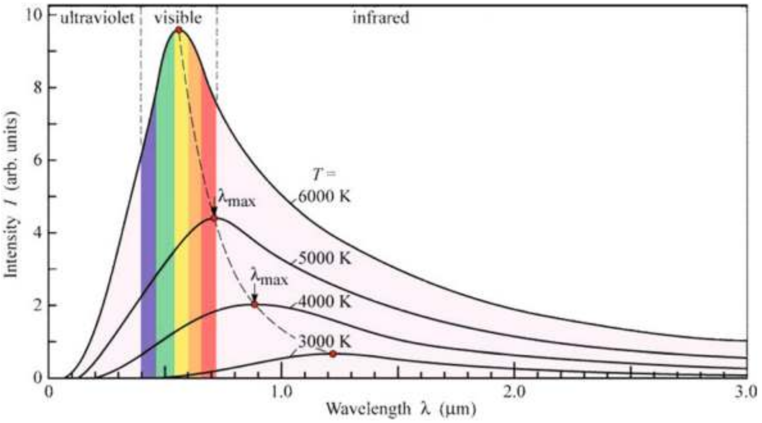


Fig. 6.1 Blackbody radiation as a function of temperature where the visible spectrum is highlighted. As the temperature increases, the radiation output shifts to lower temperatures. *Credit* CC-BY 4.0; OpenStax

campfire can get as hot as 600 °C depending on how big it is and how well insulated it is. At 600 °C (which is 873 K), Wien's Law tells us the peak in emission should occur around 3 μm which is in the infrared. Of course, while we can't see infrared radiation, we certainly can feel it while standing near the campfire. However, even after the fire is completely out, we can see visible light emitting from the hot embers and the smoldering logs. Where does the visible light come from? It's because while the maximum peak in radiation occurs at 3 μm (again from Wien's Law), as Fig. 6.2 shows the peak is pretty broad and there is a small amount of radiation at shorter wavelengths which overlaps with the upper edge of the visible spectrum. Remember, for visible light, red is the longest wavelength (around 700 nm). Thus, for an object at room temperature all of the radiation is in the infrared with nothing in the visible spectrum. However, when an object heats up, the curve shifts to the left (to lower wavelengths) and the emitted radiation slowly creeps towards the visible spectrum. At some point (maybe around 500 °C or so depending on how dark it is) the leading edge of the emission curve just barely breaks into the deep red end of the visible spectrum. We notice this when one of our cones detects the red light (specifically the L cone which detects long wavelength radiation). You've no doubt observed this when an object heats up and it glows red. This is especially easy to see at night when the glow is easy to see against the dark background.

What happens if the object gets hotter? The relationship between the temperature of an object and its apparent color is the key to incandescence. As an object heats up Wien's Law tells us that it starts to emit and lower and

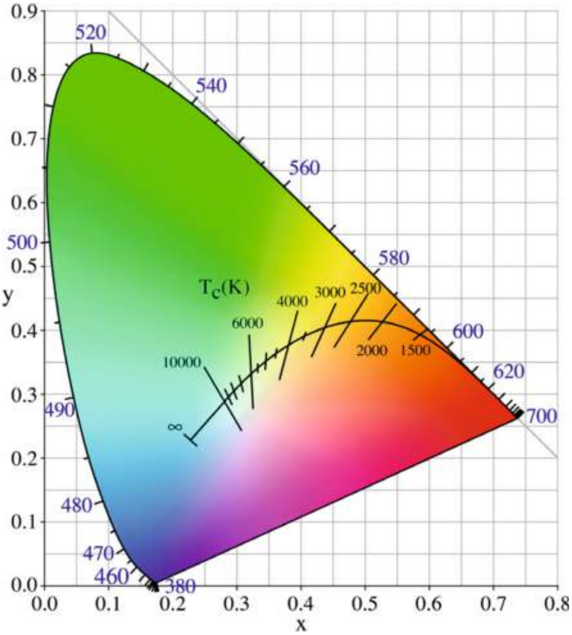


Fig. 6.2 CIE diagram showing the location of the maximum intensity as a function of temperature. As the temperature increases the color shifts from red to yellow to white to blue-white. *Credit* en:User:PAR

lower wavelengths as the temperature increases (seen as shifting to the left in the figure). This means objects will first start to glow red like embers in the fireplace. As the temperature increases the emissions will shift to lower wavelengths and the object will start to take on an orange color. Hotter still, the object will appear yellow. Interestingly, as the object gets even hotter, it's color becomes white, not green. That's because while it is certainly emitting green radiation, it is still emitting red, orange and yellow radiation at the same time—as well as some blue as well. With additive mixing, this balance of colors results in the appearance of the color white. If the temperature increases further, Wien's Law indicates that the peak of the emission curve shifts further to blue wavelengths. This means all colors are being emitted, but there is an abundance of blue light being emitted as compared to the other colors which results in the appearance of a blue-white color. We can clearly see the progression of this color sequence and the corresponding temperatures on the CIE diagram in the figure.

As we leave camp and start on our hike the brilliant morning sun shines onto the trail. The sun itself is another great example of incandescence as it emits light because it is a hot object. The sun is hot because at its core there are nuclear reactions which give off an enormous amount of energy. The light from our sun arises from the hot surface of the sun which is at a temperature of about 5700 °C. If we plug in that temperature into Wien's Law it tells us to expect the peak intensity of the radiation at 500 nm, which is right smack in the visible spectrum. It's kind of an interesting coincidence that the maximum sensitivity of our rod photoreceptors is also at the same wavelength of 500 nm. Of course, it's probably not a coincidence since the photoreceptors in our eyes probably evolved over time to match the spectral output of the sun. Sea creatures that live in the oceans live in very different lighting conditions depending on the depth and their photoreceptors are optimized for those specific environments.

The wavelengths of light emitted by the sun are pretty evenly balanced across the visible spectrum, so the sum total is effectively white. This is located on the CIE diagram in the center near the white point. A useful point in the diagram is sometimes denoted as D65 which corresponds to "standard daylight". It's used to simulate daylight when assessing how objects would appear when illuminated by sun light.

Of course, the actual color of the sun depends on atmospheric conditions, the angle of the sun with respect to the horizon, and other factors. We know the apparent color of our sun on a clear day is not white but yellow, but that's not due to the temperature of the sun. Rather it is due to the interaction with the atmosphere which we will describe later on in this book.

While our sun is at around 6000 °C, if you look in the night sky you can see stars with a range of colors. These colors are indicators of the temperature of the star. The red giant Betelgeuse in the constellation Orion is a cool 3000 °C, whereas one of the brightest stars in the sky Vega is a pure white star at a temperature of 10,000 °C. Even hotter, in the Orion nebula near Betelgeuse is Rigel which on a clear night appears as a blue white star with a temperature of 40,000 °C. Figure 6.3 shows the difference in the spectra for blue, yellow and red stars [2].

There are lots of other examples of color and light derived from incandescence. Even the most primitive example of light—a burning candle—derives much of its light from incandescence. A combustion reaction provides energy which heats up the gas and soot sounding the flame. The temperatures in the outer part of the flame reach 1200–1400 °C which results in the characteristic yellow color of candlelight. The candles replacement for indoor lighting is the incandescent light bulb invented by Thomas Edison in 1878 [3]. It uses electricity to heat up a tungsten filament to temperatures as high as 2500 °C, which explains the "warm" orange-yellow light. We've become quite accustomed to the nature of this light so that even LED-based lights are designed to mimic this orange-yellow character. One of the reasons incandescent lights

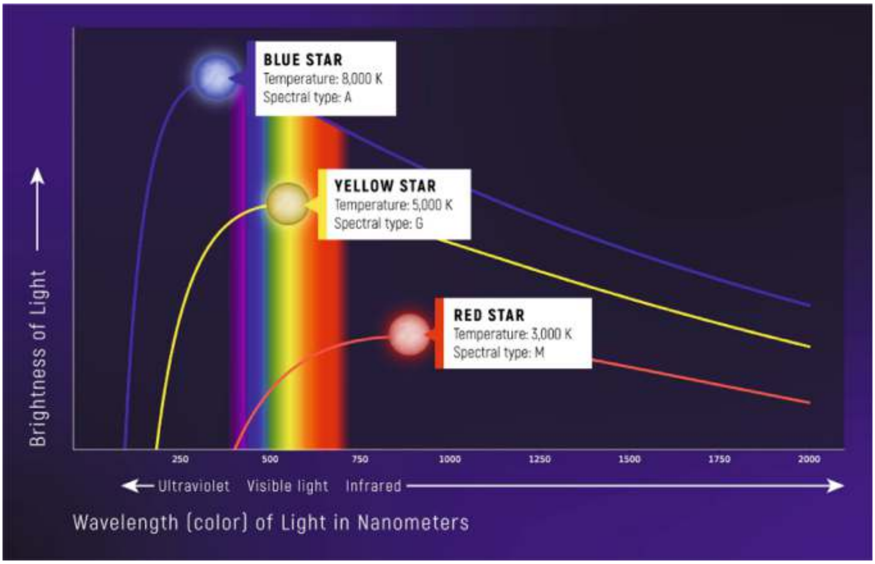


Fig. 6.3 Examples of blackbody radiation for stars at different temperatures resulting in different colors. *Credit* NASA, ESA, CSA, Leah Hustak (STScI), Andi James (STScI)

are less common is because, as a light source, they are pretty inefficient. This is quite obvious from the shape of the emission spectra shown in the figure. At these high temperatures, a great deal of light is emitted throughout the visible spectrum, but as you can see the peak is broad and outputs a significant amount of radiation into the infrared. Thus, much of the electrical energy that goes into heating the tungsten filament is emitted as infrared light.

Since incandescence operates on the fundamental principle that the temperature of an object determines the color of light that it emits, it is also possible to use this principle in reverse. We can use the color of an object to determine its temperature. Early blacksmiths used this concept in mastering the craft of forging and working with metals like bronze and in particular iron. At around 600 °C, iron begins to give off a faint red/brown glow and as it heats up it turns to red, and then orange, and then at 1300 °C it emits yellow light. The processing of iron is extremely sensitive to temperature and a skilled blacksmith can use these colors to make the highest quality part.

These days there are more sophisticated ways to determine the temperature of an object. However, one approach still uses color as the primary means of determining the temperature. The instrument is called a pyrometer, and while there are numerous variations the main operating principle is the same. The instrument measures the spectral output of an object to determine its temperature. In essence, it uses Wien's Law to determine temperature by measuring the wavelength of light emitted by an object. During the pandemic you probably encountered this instrument when going through airport security, or maybe when you were checking into a hospital. The hand-held device was usually pointed at your forehead and it measured the infrared radiation that you were emitting which can be used to determine if you had a fever.

In essence, incandescence is fundamental to life on Earth since it is the origin of light in our world. The light emanating from the sun starts out as white light, but we will see it turn into vibrant colors as it interacts with objects in our world. As we continue on the trail the rising sun brings color into our world. Let's find out what's behind these colors that we see.

References and Further Reading

1. Color from incandescence is discussed in Chapter 2 in Nassau, Kurt. 2001. *The physics and chemistry of color: The fifteen causes of color*. Wiley.
2. Morrison, Ian. 2008. *Introduction to astronomy and cosmology*. Wiley.
3. This is a wonderful review of the history of the light bulb: https://www.optica-opn.org/home/articles/volume_19/issue_9/features/a_brief_history_of_lighting/

7

Color from Atoms

One of the fascinating aspects of color is that it is often a reflection of the chemistry of an object. On my hike up the mountain, the colors I see are the result of the how light interacts with the atoms in the object.

Throughout this book we will see numerous examples of color arising from the interaction between light and atoms. The key principle is the concept of an electronic transition. This involves an electron changing from a high energy state E_2 (but still bound to the atom) to a lower energy state E_1. When it does so, it emits a photon with energy equal to the difference in energy between those two states ($E_2–E_1$). Generally, the low energy state is called the ground state and it represents the lowest possible energy state for the electron. This is the most common configuration for the electrons bound to the atom. The high energy state is called the excited state whereby one of the electrons is elevated to a high energy state.

Remember from fundamental chemistry, electrons are bound to the atom and they exist in quantum states which correspond to atomic orbitals. There are four types of states (or orbitals), s, p, d, and f, arranged into shells, and every atom has a unique configuration of electrons in those states. Let's take sodium (Na) as an example. It is the 11th element in the periodic table thus it has 11 electrons. The "ground state" configuration of those electrons is described by the following:

$$1s^2 2s^2 2p^6 3s^1$$

Here the first number corresponds to the shell (1st, 2nd, and 3rd shell), the letter corresponds to the orbital type (s and p), and the superscript refers to

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_7

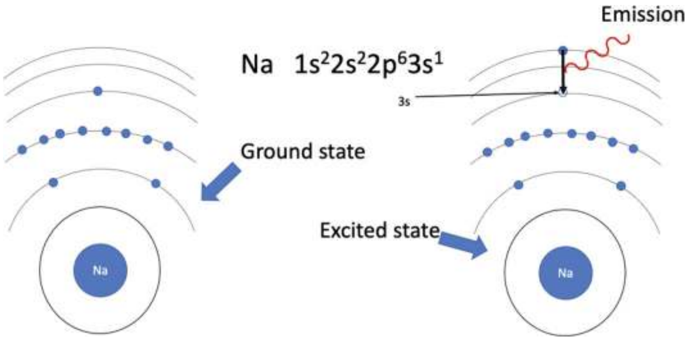


Fig. 7.1 Schematic of the structure of a sodium atom. The diagram on the left shows the electrons in the lowest energy configuration (i.e. the ground state). The diagram on the right shows one of the outer electrons in an high energy (i.e. excited) state. When that electron relaxes back to it's ground state a photon is emitted

the number of electrons in each of those states. There's lots of rules about how many electrons can be in each state and other details, but for the moment let's simply focus on the last electron located in the 3s state. As shown in Fig. 7.1, it is the outermost electron for Na and is located farthest from the nucleus. Let's assume this electron which starts in the ground state E_1 (i.e. the lowest energy state), but then it gains energy from somewhere and uses that energy to elevate to some higher energy state E_2. This would place the Na atom in an excited state. This is a highly unstable configuration and in a short period of time that electron will relax back down to its ground state (the 3s state). When it does so, it will emit a photon at an energy equal to the difference between the excited state and the ground state, that is $E_2–E_1$. Remember the wavelength of a photon can be related to energy and thus the wavelength of this light would be given by the equation:

$$\lambda = \frac{hc}{(E_2 - E_1)}$$

For the specific case of Na, it turns out it's a little more complicated and there are two possible excited states at almost the same energy that results in two emissions at 2.103 eV and 2.105 eV (Fig. 7.2). The wavelength corresponding to those energies is close to 589 nm which is right in the middle of the color yellow [1].

You've probably seen this kind of light in the form of sodium vapor lamps. They are commonly used as a light source for parking lots and along highways. They tend to be pretty efficient, but they can cause confusion in a parking lot if you're trying to find your car. Remember the color of an object

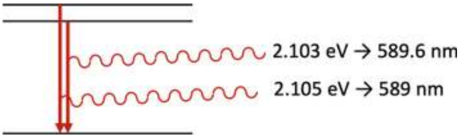


Fig. 7.2 Energy level diagram for sodium showing two excited states. When electrons in those states relax back to the ground state yellow light is emitted at a wavelength close to 589 nm

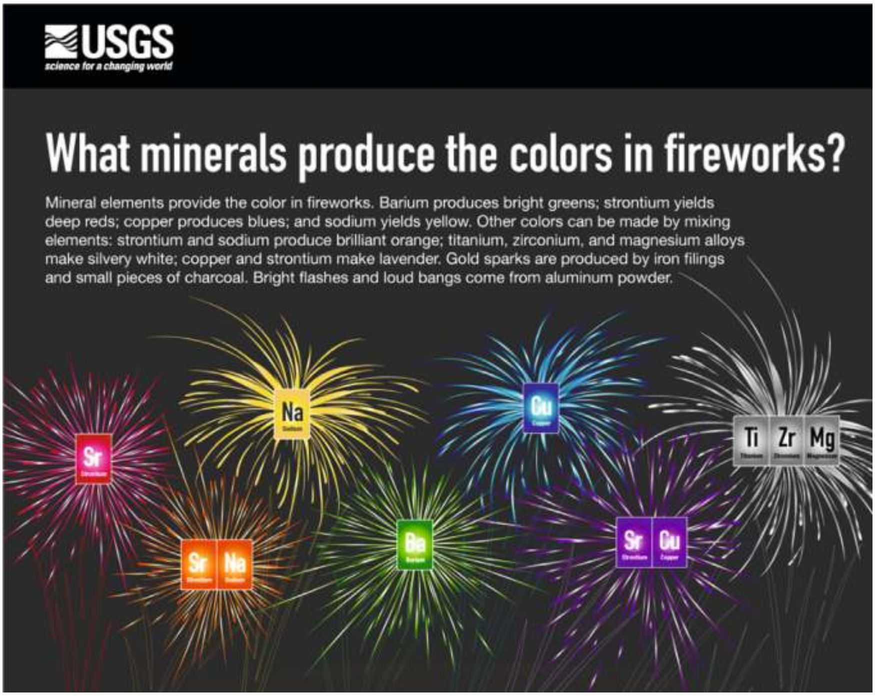
as we observe depends upon the light that hits the object which then enters our eyes. Usually, the light the hits the object is white light (from sunlight or some other white source). With sodium vapor lamps, it is pure yellow light that hits the object, which drastically changes the apparent color to our eyes.

In addition to energy efficiency, the other main benefit of sodium lighting is the fact that it helps minimize light pollution. Since the emission is limited to just one wavelength (589 nm) it can easily be filtered out. This is invaluable to astronomers since it allows telescopes to effectively subtract terrestrial light pollution from their images of deep space objects.

While sodium creates yellow light, the actual color depends upon the atom. For example, barium emits a green color, copper is blue, and zinc is kind of an aquamarine color. Basically, the atomic structure (the number of protons and electrons) determines the energy of the excited states and the equation above converts that into the wavelength of light which determines the color. This is the phenomena behind the colors we see in fireworks where combinations of elements (usually in the form of salts) results in the colorful displays we see on the fourth of July (Fig. 7.3) [2].

The key to this color mechanism is to excite electrons into high energy states, so that when they relax back down to the ground state they give off light. Fireworks use high temperatures to elevate electrons into excited states but another way to make this happen is to use electricity. If we fill up a gas tube with an inert gas and then apply a very large voltage, the electrons in the atoms in the gas will be excited just like at high temperatures. Then, when they relax back down to the ground state they emit light of a specific wavelength and color depending on the atom in the gas You've seen this before, and in fact I see it right now in the Pabst Blue Ribbon neon sign in the window of the dive bar I am sitting in as I type these words into my laptop. The color depends upon the gas, and we commonly use neon for red/pink light, argon for blue light, and helium for yellow light. Other colors are also possible with coatings and other designs.

There's one last example of this mechanism and it's hard to believe it has anything in common with a beer sign at a dive bar (though I do love Pabst).



What minerals produce the colors in fireworks?

Mineral elements provide the color in fireworks. Barium produces bright greens; strontium yields deep reds; copper produces blues; and sodium yields yellow. Other colors can be made by mixing elements: strontium and sodium produce brilliant orange; titanium, zirconium, and magnesium alloys make silvery white; copper and strontium make lavender. Gold sparks are produced by iron filings and small pieces of charcoal. Bright flashes and loud bangs come from aluminum powder.

Fig. 7.3 The color of fireworks depends upon the chemistry of the components in the flame. Here's a diagram from the US Geological Survey that shows some examples

In this case, instead of temperature or high voltage as a means of creating excited electrons, this mechanism uses solar wind. In addition to sunlight emanating from our sun, there is also a constant stream of charged particles bombarding our planet. Most of it gets redirected by the Earth's atmosphere and magnetic field, but near the north and south pole the solar wind interacts with the atoms located around 100 to 1000 km way up in the upper atmosphere. In much the same way as the neon sign, electrons in molecular nitrogen (N_2) and oxygen (O_2) are excited into high energy states. When the electrons relax back down to the ground state they give off characteristic pink light (for nitrogen) and green light (for oxygen) that we called auroras or northern lights. You don't have to be near the poles to see it and I've never seen it where I live in Oregon but my son Ian has. Here's a picture he took while he was staying above the Arctic circle in Finland showing the characteristics green emission from excited oxygen molecules (Fig. 7.4).

It's hard to imagine that the colors we see in aurorae, neon beer signs, and yellow parking lot lights have a common origin. All of these examples of color are derived from an electronic transition that arises from an electron

Fig. 7.4 Aurora borealis over the city of Rovaniemi, Finland. Photo credit: Ian Cann

being elevated into an excited state and then dropping down to the ground state. The energy of this transition (E_2–E_1) determines the wavelength of light that is emitted which therefore determines the color. It is important to note that it is also possible for this electronic transition to happen in reverse (Fig. 7.5). That is, if we shine white light onto the atom (in the form of a gas, for example), the atom will absorb only the specific wavelengths of light that perfectly match up with the specific energy levels for that atom, E_2–E_1. The white light passing through this gas will be modified with "missing" wavelengths of light that were absorbed by the atoms in the gas.

When we discussed incandescent light, we noted that the color of an object could be related to it's temperature. The converse was also true, that we could determine the temperature of an object if we measured the color or wavelength of light being emitted. This duality can also be applied to electronic transitions. The color of light emitted (or absorbed) by an atom is specific to each atom. It's like a fingerprint that can be used to link color to the chemical composition of an object. This is one of the fundamental techniques used in chemical analysis (for example atomic emission spectroscopy). There are

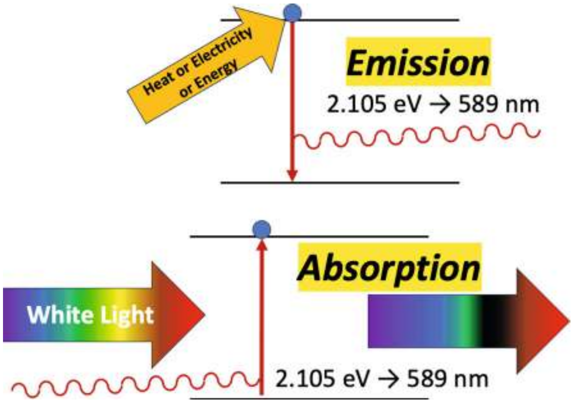


Fig. 7.5 The diagram at top shows emission, where an electron in a high energy state relaxes down to a lower energy state and emits a photon of a specific color. The bottom diagram shows white light incident on an atom. Light of specific wavelength of absorbed which excites an electron from the ground state to an excited state. The removal of that wavelength results in changing white light into colored light

many variations on the details, but it is an invaluable method to identify an unknown object.

Say for example you find some suspicious white powder and you're not sure if it is salt, talcum powder, or plutonium. The first step is to dissolve it into a solvent (like water for example), and then it is sprayed into an open flame. The high temperature of the flame will cause electrons in the atoms to become excited into high energy states. When they relax back down to the ground state the atoms will emit light at specific wavelengths depending upon the atom. The emitted light is captured by a detector which measures the intensity of light as a function of wavelength. From this data we can determine which elements are present since sodium and chlorine (for salt), magnesium, silicon and oxygen (for talc), and plutonium will all have unique emission wavelengths. With proper calibration, it is also possible to determine the amount of the atoms which are present because the intensity of the emitted light depends upon the total amount. For example, table salt is mostly made up of sodium and chlorine in a one-to-one ratio, but iodine is often added. We could use atomic emission spectroscopy to determine how much iodine was present in the salt by measuring the intensity of the emission wavelengths coming from the iodine atoms. As you can imagine this is an incredibly useful tool for chemists. Most universities have a number of them and you'll also find them in forensics labs which we all know from watching CSI are operated by incredibly attractive laboratory scientists.

This same concept works on an even grander scale—the universe! With special instrumentation on telescopes we can analyze the light emitted from a celestial object to see emissions at specific wavelengths that tells us which atoms are present in that object. It also works through absorption. If a star passes behind some dust cloud or nebula we can see evidence of the absorptions that have been subtracted from the light output of the star. The wavelengths that are absorbed can be traced to atoms that are present in the dust cloud. In fact, this relationship between the wavelength and the atom is responsible for much of our current understanding of the state of the universe.

In 1929, Edwin Hubble observed characteristic absorption peaks for hydrogen in distant galaxies [3]. He noticed that while the absorption peaks fit the profile for the hydrogen atom they weren't at the same wavelengths as you would measure for hydrogen on Earth. For the objects he was studying, all of them had absorption peaks that were shifted to longer wavelengths compared to where they should be—called a redshift since they were shifted in the direction towards red light. This shift in wavelength was attributed to the Doppler effect, whereby an object which is travelling away from an observer experiences an increase in wavelength or a decrease in wavelength if the object is travelling towards the observer. You have no doubt observed this with ambulance sirens, where the pitch rises or falls depending up the direction of the ambulance. Hubble made an astonishing discovery when he noticed that the amount of red shift was directly related to the distance to the galaxy. That is, objects close to Earth exhibited a small red shift whereas objects that were far away exhibited a large redshift. This shows that the universe is expanding and the rate at which objects are receding depends upon the distance (this is known as Hubble's Law). Thus the simple relationship between the energy levels in an atom and the corresponding wavelength of light results in the color of many objects as well as an insight into the nature of the universe.

References and Further Readings

1. 2001. Color from gas excitations is discussed in Chapter 3 in Kurt Nassau. *The Physics and Chemistry of Color: The Fifteen Causes of Color*, Wiley.
2. The US Geological Survey has a nice summary of the chemistry of the color of fireworks: https://www.usgs.gov/media/images/what-minerals-produce-colors-fireworks.

3. Here is a nice summary from NASA on the Hubble's discovery: https://science.nasa.gov/mission/hubble/science/science-behind-the-discoveries/hubble-cosmological-redshift/.

8

Color from Fluorescence and Phosphorescence

The previous chapter described color originating from electronic transitions whereby electrons change states within an atom. The energy difference between the states (i.e. E_2–E_1, the excited state E_2 and the ground state E_1) determines the wavelength of the light that is emitted according to this equation:

$$\lambda = \frac{hc}{(E_2 - E_1)}\lambda = \frac{hc}{(E_2 - E_1)}$$

If we think more generally about the energy of an atom or a molecule, there are other ways they can exhibit excited states. Imagine the molecular form of iodine, I_2, consisting of two iodine atoms bonded together. The two atoms have a chemical bond which acts like a spring, with a spring constant and the oscillation of the atoms stretching and compressing the chemical bond is a form of *vibrational energy*. In a simple system like this, this two-atom molecule will have vibrational frequency proportional to the spring constant divided by the mass of the two iodine atoms. If we give energy to the molecule, it will increase the vibration frequency. A molecule like I_2 can also exhibit *rotational energy*, which is pretty much self-explanatory.

Thus, with molecules there are multiple ways in which they could exhibit excited states. They have electronic states (which relate to electrons accessing higher energy orbitals), but they also have vibrational and rotational states [1]. Therefore, if energy is given to a molecule it has many options for expressing that energy as shown in Fig. 8.1.

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_8

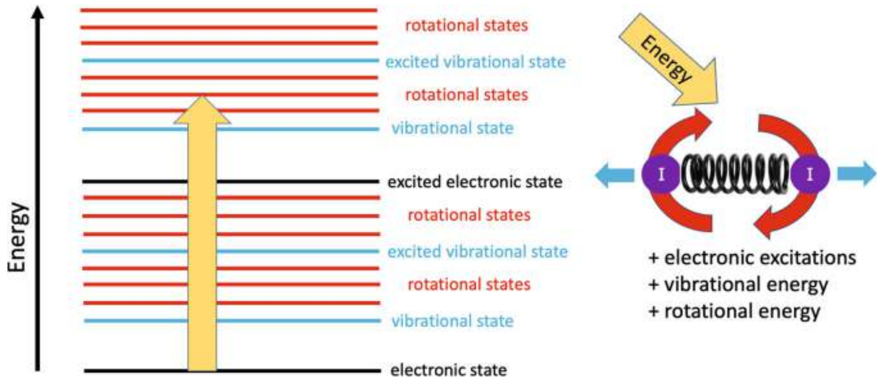


Fig. 8.1 Energy diagram for a molecule (e.g. I_2). The ground state is at the bottom and the molecule can be excited into higher energy states through vibration (blue states) or rotation (red states)

The vertical axis is energy (like our previous diagrams) but it now shows all the different options for the energy states of a molecule like iodine. The black lines correspond to electronic states which represents electrons jumping into higher energy orbitals. The blue lines represent vibrational states of the iodine molecule where the frequency of the vibration increases as the energy increases. Lastly, the red lines represent the rotational energy of the molecule, where at higher energies the molecule rotates at higher speeds.

You'll notice there are a lot more states than we had for a simple sodium atom. The addition of vibrational and rotational states means the molecule has a lot more options to absorb energy. It also means that instead of specific narrow wavelengths for electronic transitions in atoms like sodium, instead we tend to see broad absorptions over a range of wavelengths (because there are so many more states clustered together by adding in vibrational and rotational states).

We see this phenomenon in the color of some of these diatomic elements. For example, iodine absorbs over a wide range of wavelengths spread over infrared, red, orange, yellow and green due to these states. With all these colors absorbed, the apparent color of iodine is violet which is where it gets its name since in Greek "iodes" means purple. The other diatomic elements in the same column of the periodic table exhibit colors for similar reasons, including a reddish-brown color for bromine, and a pale green for chlorine.

While the molecule iodine isn't a particularly important part of the color story, it is useful as a starting point to introduce more important color mechanisms like fluorescence and phosphorescence. All of the previous examples of energy transitions we have discussed are relatively simple. That is, an electron is excited into a higher energy state (by absorbing a photon, for example) and

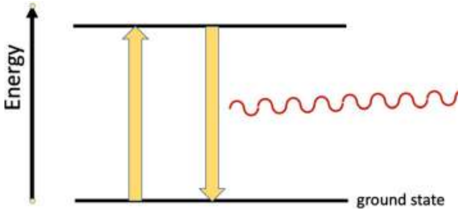


Fig. 8.2 Schematic showing an electron being excited into a high energy state, and then dropping down to the ground state. When the electron drops into the ground state it emits a photon

then it immediately drops back down to the ground state and emits a photon (Fig. 8.2). This is the simplest case where all of the energy input from the incident photon (let's call it A) goes into exciting the electron up to the high energy state. Then, when the electron drops back down to the ground state the energy of the photon that is emitted is that same energy A, and it happens instantaneously.

With fluorescence, there is one extra step in this process [1]. It starts off the same, in that the molecule absorbs a photon of energy A, which excited the molecule to a higher energy state (represented by an electron in a higher energy orbital, and/or vibrational state, and/or rotational state). However, in the next step the molecules loses a portion of that energy (defined by the energy NR) through a process called *non-radiative transfer*. Basically, the molecule gives off that energy by transferring it to its surroundings through vibrations, or rotations, or some other form of energy which is not electromagnetic energy. It does this in a very short period of time—less than 10^{-8} s. After this *non-radiative transfer* step, the molecule then drops back down to the ground state and emits a photon of energy F. A schematic of this process is shown in Fig. 8.3.

Note that in terms of the energy balance, now the input energy is A, and the output energy is split between NR and F, so that:

$$A = NR + F$$

In a sense, the fluorescent molecule absorbs light of energy A and emits light of energy F, where F is less than A. Since energy and wavelength are related, that means that a fluorescent material will absorb light at a higher wavelength and then emit light at a lower wavelength.

Phosphorescence is similar to fluorescence except the non-radiative transfer step is very slow [1]. In some cases, it takes a long time (relatively speaking) for molecules to change their vibrational and/or rotational state and thus the

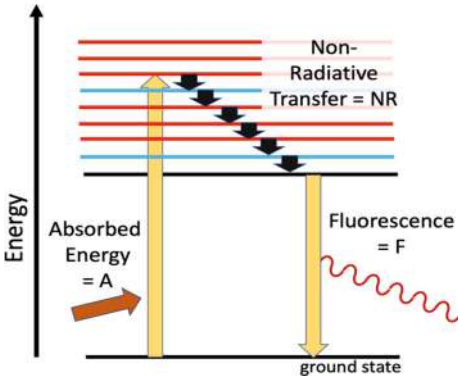


Fig. 8.3 Schematic showing the mechanism of fluorescence. First, an electron absorbs energy A which elevates it into a high energy state. Next, the electron then loses some energy through vibrations or rotations (i.e. non-radiative transfer, NR). Lastly, the electron drops back down to the ground state and emits a photon of energy F

non-radiative transfer step could take on the order of seconds instead of a billionth of a second for fluorescence. This is shown in the schematic in Fig. 8.4. The energy balance is essentially the same where P is the energy of the emitted phosphorescent photon:

$$A = NR + P$$

There are many, many examples of fluorescence and phosphorescence in nature and in fact one could write a whole book on just this topic alone. The schematics I've shown in this book are really simple and in real examples of minerals or molecules it can get quite complicated, especially for complex biomolecules and crystals.

Fluorescence is present in many minerals, including aragonite, calcite, and amber. You've no doubt seen this in mineral exhibits in science museums where mineral specimens are illuminated by invisible ultraviolet light and they emit colorful visible light of many different colors (Fig. 8.5). Remember with fluorescence, the input light (A) has to be higher energy which is why ultraviolet light is used. Some of that energy is lost to non-radiative transfer (NR) and then the mineral emits lower energy light which ends up in the visible spectrum with a color that depends upon the details of the mineral.

Fluorescence is common in organisms and in particular it has been studied extensively in fish and other underwater creatures which has been nicely summarized in a recent review by Marie-Lyne Macel [2]. Fluorescence serves a variety of purposes that help with survival in the underwater environment.

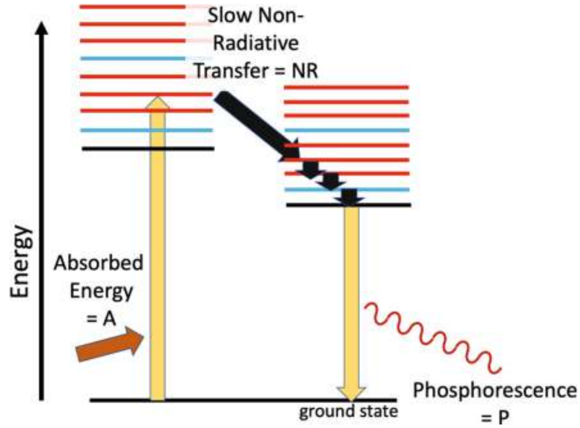


Fig. 8.4 Schematic showing the mechanism of phosphorescence. First, an electron absorbs energy A which elevates it into a high energy state. Next, the electron then slowly loses some energy through vibrations or rotations (i.e. non-radiative transfer, NR). Lastly, the electron drops back down to the ground state and emits a photon of energy P. The key difference here is the non-radiative transfer step is very slow. The result is that with phosphorescence, light will be emitted long after the energy is absorbed

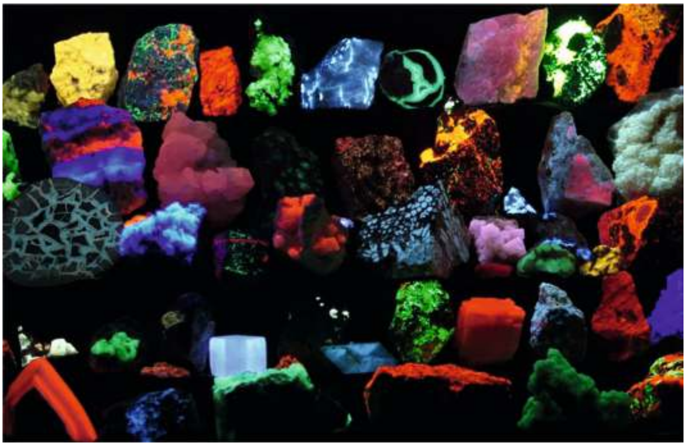


Fig. 8.5 Examples of color emission from fluorescence minerals. Here the specimens are being illuminated with ultraviolet light and then re-emitting light at lower energies in a variety of colors. *Credit* Hannes Grobe/AWI

As we shall see in the next chapter, at a certain water depth red, orange, and yellow colors are removed from sunlight and some fish do not have photoreceptors for these colors. Therefore, fluorescence allows blue light which is present at these depths to be converted to these colors (since blue light is higher energy than red, orange and yellow). This allow fish with these fluorescent colors to find prey without being seen, or find a mate, or use it for camouflage. Some fish use fluorescence to distract prey or predators, perhaps as a means of communication. One common source of fluorescence that is present in many organisms is green fluorescent protein (GFP). While it occurs naturally, it can also be used as a tool in cell and molecular biology as a biomarker to determine if a gene is expressed in a particular organism [3]. It's even been incorporated in laboratory mice where they give off a fluorescent green light.

In addition to fluorescence, some sea creatures also use bioluminescence which is a different phenomenon. In bioluminescence, light is generated via a chemical reaction. The angler fish, which is pretty much the ugliest living thing I have ever seen in my life, uses bioluminescence to light up the end of an appendage like a lure to attract prey [4]. On the terrestrial side, fireflies use bioluminescence to light up summer nights.

We humans also use fluorescence because of its unique characteristics. Hunter orange is a fluorescent dye which absorbs violet, blue, green, and yellow light, and emits fluorescent orange light (see Fig. 8.6). The orange color appears conspicuous because it is significantly more intense than the surrounding colors. We see the same effect in fluorescent pigments and dyes that used in paints and fabrics when high visibility is important for safety (e.g. bike vests or helmets). Fluorescent (or sometimes called neon) colors are sometimes used for intentionally tacky clothing. I was alive in the 80's so I am very familiar with this phenomenon. I worked at a record store at a shopping mall so fluorescent clothing was pretty much the required uniform.

Fluorescence is also used in anti-counterfeit measures for paper currency. When exposed to ultraviolet light, the US twenty-dollar bill fluoresces a green line across the bill (Fig. 8.7). You might have wondered what the cashier at the Circle K was doing after you handed them a crispy twenty to buy that candy bar. You've probably seen them waiving the bill under a UV light to check for the appearance of that green fluorescent stripe to verify its authenticity.

Back on the trail, we continue our way up the mountain. It's mid-morning now and the sun is rising high above the horizon. It's starting to warm up so a quick detour to a mountain stream would be a perfect pit stop. It's also a great opportunity to learn about the color of water.

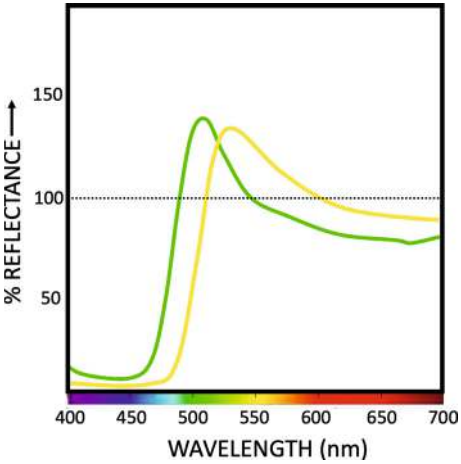


Fig. 8.6 Optical spectra for fluorescent green and yellow. The intensity of the reflected light peaks at values greater than 100% which means it is much brighter than the surroundings. This demonstrates why fluorescent colors stand out. *Credit* Bruce Mulholland [5]

Fig. 8.7 Fluorescent band on US twenty-dollar bill. *Credit* Scott Nazelrod

References and Further Readings

1. 2001. The basics of fluorescence and phosphorescence is discussed in Chapter 4 in Kurt Nassau. *The Physics and Chemistry of Color: The Fifteen Causes of Color*. Wiley.
2. Macel, Marie-Lyne., Filomena Ristoratore, Annamaria Locascio, Antonietta Spagnuolo, Paolo Sordino, and Salvatore D'Aniello. 2020. Sea as a color palette: The ecology and evolution of fluorescence. *Zoological Letters* 6: 9.

3. Hadjantonakis, A. K., and A. Nagy. 2001. The color of mice: In the light of GFP-variant reporters. *Histochemistry and Cell Biology* 115: 49–58.
4. Wikipedia has a nice write up and a selection of images on the world's ugliest species, the Angler Fish: https://en.wikipedia.org/wiki/Anglerfish.
5. Mulholland, B. M. 1997. Introduction to color theory. *Plastics Engineering* 53: 33–35.

9

Color from Water

Back on the trail, we pass a mountain stream. The water sprays over colorful rocks and feeds the flowers alongside the stream. We don't often think of water as having a color. Most of the time it is transparent and any color we perceive is not due to the water molecule (H_2O) but is coming from something in the water (like algae, particulates, etc.). However, there is a subtle mechanism that gives water its blue color under certain circumstances.

The origin of the color mechanism is due to the intrinsic vibrational states of the water molecule. The figure below shows three distinct vibrational modes that are present (Fig. 9.1).

Each mode has a vibrational frequency ν_1, ν_2, and ν_3, which corresponds to wavelengths from 2600 to 6200 nm [1]. This is deep in the infrared, just a bit beyond the visible spectrum. However, these vibrations are waves and like all waves they have overtones. You might have heard overtones in music, where a single key on a piano has a dominating tone (set by the length of the piano wire), but you can hear higher pitched notes which are geometrically related to the principal note. They are much weaker than the principal tone, but you can hear them if you listen carefully. The same phenomenon occurs with these vibrational waves. While the principal frequencies ν_1, ν_2, and ν_3 are not observable in the visible spectrum, these vibrations interact in a myriad of multiples and linear combinations to create a series of vibrations such as $\nu_1 + \nu_2$, $2\,\nu_1 + \nu_3$, $\nu_1 + \nu_2 + \nu_3$, etc. Adding together these waves means these overtones are at higher frequencies, which means lower wavelengths [2]. Figure 9.2 shows the absorption of the water molecule as a function of energy and wavelength. As you can see the dominant absorption occurs in the infrared, but the overtones slip into the visible spectrum

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_9

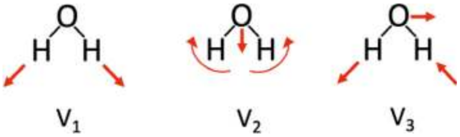


Fig. 9.1 Vibration modes of the water molecule. Each has a specific energy and vibration frequency

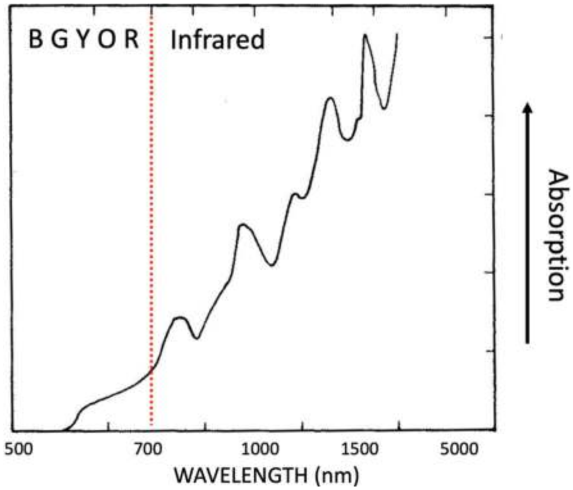


Fig. 9.2 Water absorption spectra for water as a function of wavelength. The primary absorptions are in the infrared, but the absorption peaks creep into the far edge of the visible spectrum in the deep red region. *Adapted* from Figs. 4–9 in Nassau, The Physics and Chemistry of Color, (Wiley, New York, 1983)

on the long wavelength side corresponding to the color red. If we remove red from the spectrum the dominant color is blue! This is the origin of the blue coloration we sometimes see in water.

To really understand this mechanism, we need to clarify a few important points. For one, this absorption in the red is very, very weak. That means we need a large volume of water (with many, many water molecules present) to observe it. It also doesn't help that our S cone that is focused on the blue side of the visible spectrum is the least sensitive cone. If we stare through a glass of water we don't see blue—there just isn't enough absorption to impart an observable blue color. It is also important for all other color mechanisms to be absent. Water often has particulates (from soil, sediment, sand from beaches) and sometimes it is host to organisms like algae or other plant life. The presence of these features in the water dominates the color we observe (brown or green rivers, for examples) and thus the intrinsic blue color is not

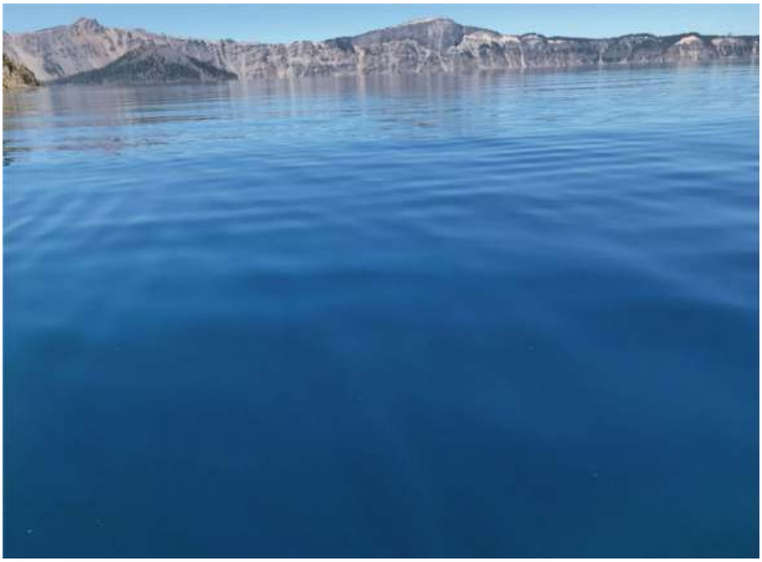


Fig. 9.3 Crater Lake in Oregon as seen from a boat in the middle of the lake. The intense deep blue color surrounding you is overpowering. And, you're in the middle of a giant volcano, which itself is intimidating. Thankfully it is not active!

seen. However, there are places where we see large volumes of highly pure water and one such place is Crater Lake in Oregon. Shown in Fig. 9.3 is a photo taken from a family vacation from the middle of the lake. The lake is 1943 feet deep and it is fed entirely from snow melt inside the caldera yielding some of the clearest blue water in the world. It is also possible to see the blue coloration from satellite images as shown in the NASA image in Fig. 9.4. The shade of blue varies depending upon the depth of the water, which is likely influenced by the white sand at the bottom of the ocean near the shore.

Of course, since the color mechanism comes from the water molecule itself, it is not limited to liquid water. We can also see the intrinsic blue color in solid water in the form of glaciers. There's no blue color in ice cubes because there simply isn't enough volume, but with large glaciers there is a very clear blue color. We don't observe it in loosely packed snow—even if it is a 10 foot high drift of snow—because there is a lot of porosity and the pores scatter light which diminishes the blue coloration. However, glaciers are often densely packed rocks of ice and the blue color comes through clearly in the dense regions (Fig. 9.5).

Fig. 9.4 Deep blue colors seen from the international space station. The colors are related to the depth and also influenced by the color of the ocean floor. *Credit* Image courtesy of the earth science and remote sensing unit, NASA Johnson space center [3]

Fig. 9.5 Blue coloration in a glacier in Antarctica. The little black specks are penguins admiring the deep blue color. *Credit* Sylvia Gaffney

References and Further Readings

1. Yu, C. C., K. Y. Chiang, M. Okuno, et al. 2020. Vibrational couplings and energy transfer pathways of water's bending mode. *Nature Communications* 11: 5977.
2. 2001. Color derived from the water molecule is discussed in Chapter 4 in Kurt Nassau. *The Physics and Chemistry of Color: The Fifteen Causes of Color*. Wiley.
3. This photo from the International Space Station is identified as ISS005-E-13929 and you can find many more incredible photos at the NASA Johnson Space Center website eol.jsc.nasa.gov.

10

Color from Transition Metals

Walking along the trail, the rocks and minerals all around bring color into the world. Where I'm at the colors are fairly subtle, with shades are brown, red, and sometimes green. But we know rocks and minerals can have vibrant colors which is why they are often featured in jewelry. Recall that many of our previous color mechanisms were related to electronic transitions. For sodium, it was a very simple process whereby an electron in an excited state drops down into the ground state and then emits a photon. For fluorescence, it's a similar process except the electron in an excited state spends some time losing energy through non-radiative processes before eventually emitting a photon of lower energy. In this chapter, we'll discuss a very common color mechanism which is unique to transition metals. In fact, a large fraction of the color we see in the mineral world is due to the presence of transition metals either as the main component of the material or even as an impurity.

Transition metals are found in the middle of the periodic table and their common characteristic is that they all have partially filled d-orbitals. Let's take chromium as an example. It's a transition metal with the following electronic structure:

$$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^4$$

This means chromium has a total of four d electrons in its outermost 3d state. Focusing on those the 3d states, there are a total of five different d-orbitals (d_{xy}, d_{xz}, d_{yz}, $d_{x2\text{-}y2}$, and d_{z2}) and each holds two electrons. That adds up to a total of ten possible electrons that can be accommodated, so chromium is nearly half-filled with four out of ten electrons residing in the

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_10

3d states. For an isolated atom, all ten 3d states would be at the same energy, but if we place a transition metal like chromium into a crystal it turns out those ten 3d electrons no longer have the same energy. The energy of those states is modified by interactions between the electrons in those 3d orbitals and the environment surrounding the chromium ion in the crystal. In a crystalline mineral, the chromium ion is typically bonded to oxygen ions and the geometric arrangement of those oxygens interacts with the five d-orbitals differently. The net result is that instead of all ten d electrons having the same energy, there is a splitting of those states into two or more different energy levels. This is sometimes called the "crystal field effect," and the energy difference between these states is called the crystal field energy. The stronger the interaction, the greater the crystal field energy.

What is behind this interaction? Basically, it a repulsive interaction between the negatively charged electrons in the d orbital and the negative charge of the oxygen ions. Each of the five d orbitals has their own shape which describes the physical location of the electron (see Fig. 10.1). In a crystal, each transition metal will be bonded to ions (e.g. oxygen ions) in specific arrangements. Figure 10.2 shows a red transition metal (e.g. Cr) bonded to six oxygen ions. The energy of those five d-orbitals is modified depending upon how close the electrons get to negatively charged oxygen ions. If a particular electron orbital brings the electron very close to the oxygen ion, the energy of the electron is raised (it costs energy for the electron to approach the negatively charged oxygen ion). If a particular orbital is located far away from the oxygen, the electron energy is reduced.

Where this is relevant to the story of color is that it turns out the crystal field energy is often right in the range of visible light. Therefore, electronic transitions between these states result in a range of colors depending upon the atom and depending upon the crystal that it is in.

One of the most classic examples occurs with the mineral corundum. The main component in corundum is aluminum oxide (Al_2O_3), which isn't a transition metal and so it doesn't have any d-electrons. Therefore, pure corundum is transparent and colorless. However, mineral specimens found in nature are rarely pure and in fact one common impurity often found in corundum is chromium. Since chromium is a transition metal, it's d orbitals experience the crystal field splitting as shown in the diagram. Instead of all five d orbitals having the same energy (as it would be for an atom), the oxygen ions surrounding the chromium split the d orbitals into two energy levels. As you can see from Fig. 10.3, the d_{xy}, d_{xz}, and d_{yz} orbitals are lower in energy because their orbital lobes are oriented away from the negatively

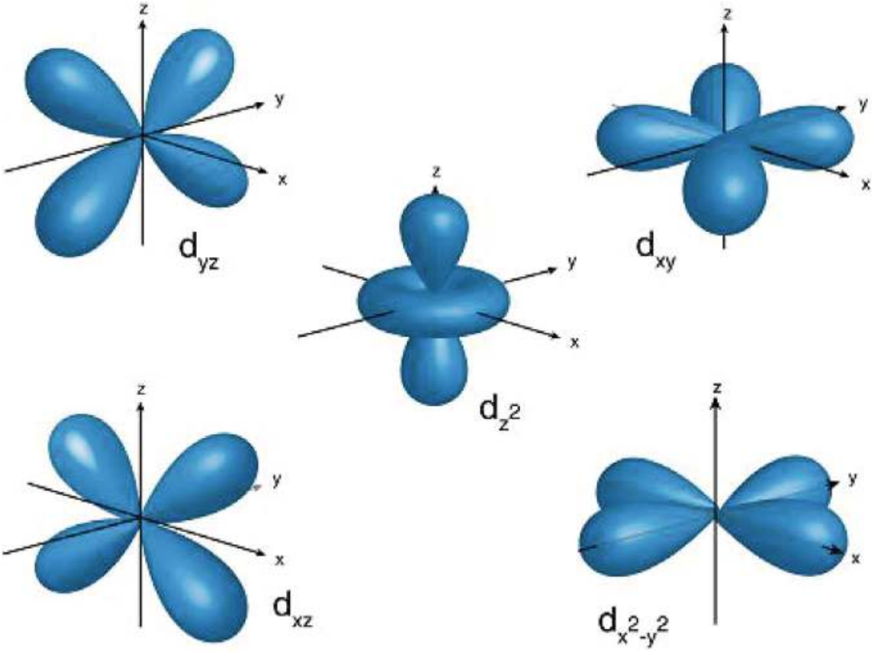


Fig. 10.1 Schematic of the five separate d-orbitals found in transmission metals. *Credit* CK-12 Foundation

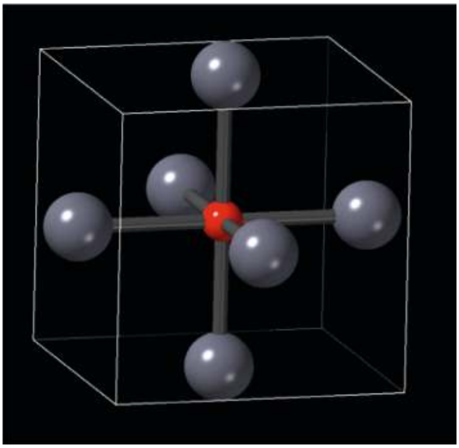


Fig. 10.2 Common arrangement for a transition metal in a solid. The red atom is the transition metal, and the gray atoms are oxygens

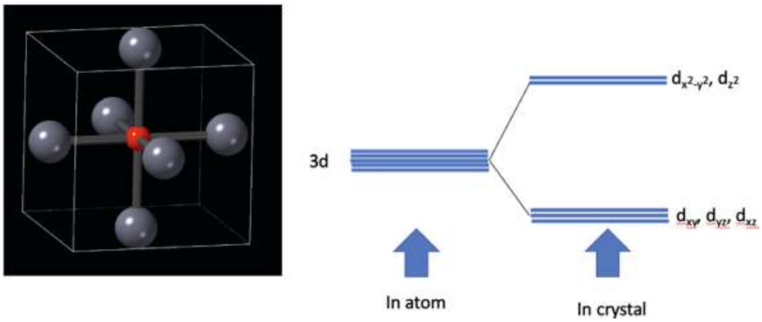


Fig. 10.3 Schematic of the effects of crystal field splitting. In an atom, all five d-orbitals have the same energy but inside of a crystal the energy of the electrons in the d-orbitals changes due to interactions with its surroundings

charged oxygen ions. In contrast, the d_{x2-y2}, and d_{z2} orbitals are directed very close to the oxygen ions and thus these states are at higher energies.

The important part is electrons can be excited into these states, causing absorptions in the visible spectrum. Let's look at this in more detail for chromium in corundum [1]. There are two electronic transitions shown in Fig. 10.4 identified as A_1 and A_2. These are quite similar to the absorptions we've seen before, where the energy of these absorptions are linked to specific wavelengths. When white light shines on this crystal, some of the light will be absorbed by exciting an electron via the electronic transition A_1. The energy of this transition corresponds to the edge of the visible spectrum at wavelengths close to 400 nm. This results in a strong absorption of violet light. In addition, some of the white light will be absorbed via electronic transition A2, which is lower in energy. Lower energy means longer wavelengths, and thus this electronic transition results in the absorption of green light. With violet and green removed from the spectrum, what's left is a strong red transmission and a small amount of blue. This results in gem with a deep red color with hints of blue. We know this as the gemstone ruby (Fig. 10.5). The color comes from the chromium impurity in corundum, and the intensity of the red color depends upon the amount of chromium in the crystal. A similar effect is observed when corundum has the transition metal impurities iron and titanium resulting in a deep blue color we call sapphire.

Chromium is a fairly common element within the Earth's crust and it often substitutes for aluminum in minerals and gems because they are similar in size. Another example is the crystal beryl with the chemical formula $Be_3Al_2Si_6O_{18}$. Since none of the elements in beryl are transition metals, namely beryllium (Be), aluminum (Al), silicon (Si), and oxygen (O), pure beryl is colorless (similar to pure corundum Al_2O_3). However, when

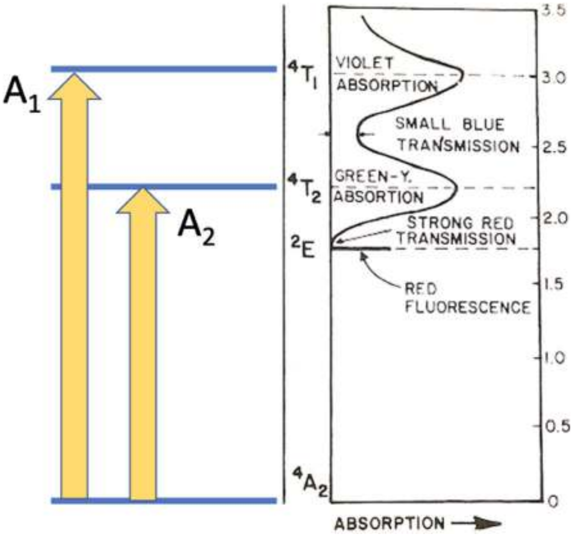


Fig. 10.4 Schematic of the absorption spectra of ruby. With the chromium transition metal there are two strong absorptions in the green and violet. Red light is not absorbed at all, and blue light is only light absorbed. The net result is the deep red color of ruby with a tinge of blue. *Adapted* from Fig. 5–4 in Nassau, The physics and chemistry of color, (Wiley, New York, 1983)

Fig. 10.5 A photo of a ruby crystal with the characteristic ruby red color. *Credit* Rob Lavinsky, iRocks.com

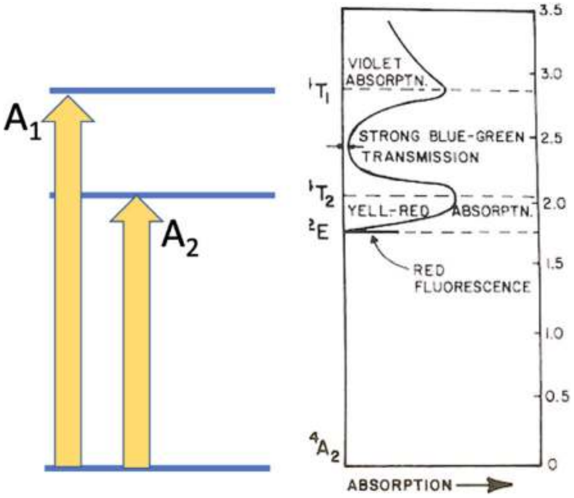


Fig. 10.6 Schematic of the absorption spectra of emerald. The structure is similar to ruby with two characteristic absorptions, however because the environment surrounding the chromium ion is different the energies of the absorptions are different. With emerald there are two strong absorptions in the yellow–red and violet. There is very little absorption in the blue-green region and thus the net result is the deep green color of emerald. *Adapted* from Figs. 5–4 in Nassau, The physics and chemistry of color, (Wiley, New York, 1983)

chromium is present as an impurity it substitutes for aluminum resulting in very similar electronic transitions to ruby. Figure 10.6 shows the same two electronic transitions A_1 and A_2, however the energies are different [1]. The environment surrounding the chromium ion in corundum is not the same as the environment in beryl. The bond lengths and angles are not the same and therefore the energies of A_1 and A_2 are slightly smaller. This causes a shift in the location of the absorptions. Instead of violet and green absorptions for ruby, the primary absorptions are blue–violet and yellow–red. When white light shines on this crystal, the result is a strong blue-green coloration. This explains the color of emerald, where again the intensity of the green color depends upon how much chromium is present in the gemstone (Fig. 10.7).

This is a complicated story as the color depends upon the atom and the environment. For the case of electronic transitions in sodium atoms it was very simple. Sodium atoms in a gas will always give off yellow light at a specific wavelength because they are isolated. With transition metals, the electronic transitions come from d electrons, and the energy of these electrons depends upon their local environment. This explains why the chromium ion in corundum creates a red color, but the same chromium ion in beryl creates a green color. It can be even more complicated when considering iron because

Fig. 10.7 A photo of an emerald crystal with the characteristic deep green color. *Credit* By Géry PARENT

it can take on many different colors. When iron is present in garnet it creates red, in citrine quartz it is yellow, in peridot it is green, and in aquamarine it is blue. The environment surrounding the iron is very different in each of these crystals and that determines the color we see. By environment, I mean what kind of ions the iron atom is bonded to, how many ions it is bonded to, and the angle of those bonds. While this is all incredibly subtle, all of these microscopic factors influence the energy of the d electrons, which determines the colors we observe.

This shows some of the complexity surrounding the origins of the colors we see in minerals. The color comes from the atoms that are present, but a particular atom can create different colors. It's kind of frustrating because as I walk along the trail and see wondrous colors in the rocks and minerals along the mountainside, I can't deduce which atoms are present merely from the color. When I see a red mineral, if I know it is garnet then I can be reasonably certain that iron is present to create that color. But if it is something other than garnet, there's many other mechanisms that may create the observed red color. But how do you know if that red rock is garnet? Minerologists have methods that help identify unknown minerals in the field. One method is to determine the minerals hardness as compared to some reference minerals (diamond is the hardest, talc is the softest). Another technique is to observe how it fractures (or cleaves) measuring the shape and symmetry of the cleaved surfaces. With this information, as well other information such as its luster (shininess) and density, one can identify an unknown mineral in the field [2].

Of course, I don't have these geology field skills and all reddish-brown rocks look the same to me.

So, in the end, it has become complicated. My goal of wanting to understand the origins of color in the physical world around me as I walk along the trail has hit a massive obstacle. Color is not like other physical properties. Iron can create a whole spectrum of colors. It is the same with anthocyanin in flowers, where different subtle atomic-scale arrangements of the structure of the molecule results in different colors. However, it's not always this complicated. We know the origin of lots of color mechanisms with great certainty. The first part of the book where we described atomic emissions (like the sodium vapor lamps), gas excitations (neon lights), and the blue color of water are all more easily understood. It gets more complicated when we consider materials with more complex chemistries like minerals and biological materials. So, we move on!

References and Further Readings

1. 2001. Color arising from the presence of transition metals is discussed in Chapter 5 in Kurt Nassau. *The Physics and Chemistry of Color: The Fifteen Causes of Color*. Wiley.
2. This website helps with identification of rocks and minerals by using a rock key which is basically a bunch of questions about the rock (e.g. Is it shiny? Does it have layers? Etc.) http://www.minsocam.org/msa/collectors_corner/id/rock_key.htm.

11

Color Centers and Quantum Dots

As we walk along the trail, some of the colors we see in the rocks and minerals have a different origin than our previous chapter. While transition metals are one of the most common sources of color in minerals, another mechanism is called a color center. It's also sometimes called an F-center, where the F stands for *farbe* which is German for color. The ultimate source for the color comes from high energy radiation that interacts with the mineral or crystal. The radiation could come in many forms, including high energy x-rays, gamma rays, or ultraviolet rays which we discussed when introducing electromagnetic radiation way back in Chaps. 1 and 2. Here on the surface of the Earth we are constantly being bombarded with radiation coming from the cosmos. Our atmosphere shields most of it, but still some radiation gets through and interacts with gems and minerals. Radiation can also be in the form of high energy particles like alpha particles or beta particles that are the byproduct of radioactivity. In the Earth's crust lots of minerals are radioactive, and over the course of millions or billions of years even weakly radioactive minerals can generate a significant amount of radiation.

The effect of this radiation is to create defects in crystals. To understand this concept, we need to clarify exactly what it means to be crystalline. To do that, let's first define something which is non-crystalline. If we were to take a snapshot of the atoms in a liquid at a single point in time, we would see that they are arranged randomly. If we measured the distance between atoms in a liquid (i.e. the bond length) we would see that while there is an average value, there is a great deal of variation with some short bond distances and some long bond distances. If we measured the bond angles between atoms we would find the same thing—some average value but with variations from

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_11

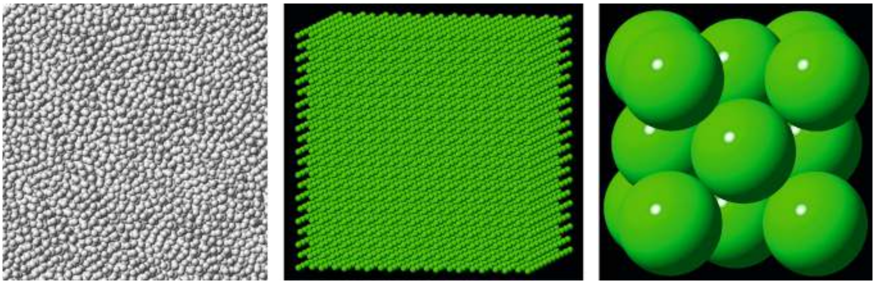


Fig. 11.1 The schematic on the left is an example of a non-crystalline solid with no long-range order. The schematic in the middle shows the crystalline state, where the atoms are arranged into an ordered configuration over long distances. The schematic at the right is a close up showing the specific arrangement characteristic of crystalline copper. Schematic on left adapted from reference [1], Poletaev, G. et al. *Metals*, *13*, 1664 (2023)

atom to atom. In the liquid state atoms are constantly in motion but, in some materials, we can cool the liquid down to freeze-in this random atomic arrangement. This is called the non-crystalline state or the glass state. The most common examples of this state are window glass, the glass on your smart phone, or the glass holding your wine. In this state of matter, the atoms were once liquid but when cooled to room temperature the atoms freeze into place and retain their random or non-crystalline arrangements.

In contrast, in a crystalline material, atoms lock in to precise positions with exact bond distances and bond angles that do not vary from place to place in the crystal. This happens when a liquid crystallizes at the freezing temperature of a substance. The atoms in the liquid fall into place, in specific, regular, periodic positions. The process is shown in Fig. 11.1, where the schematic on the left shows an arrangement of atoms that is non-crystalline. After crystallization, the atoms form the ordered arrangement illustrated in the middle figure. The structure shown is the specific arrangement for copper and the figure on the right is a closeup of the arrangement of the atoms.

Now back to the effects of radiation! There's a lot of things that can happen when high energy radiation hits a crystal like the one shown above. As the radiation interacts with the atoms and electrons in the crystal it violently transfers energy. If the radiation has enough energy it can break the atomic bonds that holds an atom in place and eject it from its equilibrium position. When it does so it creates an empty atomic site—which we call a point defect. In reality there are many ways that radiation can wreak havoc on a crystal, and there's an entire field of science and engineering devoted to studying it and preventing it from happening. Obviously, the components inside a nuclear reactor need to be resilient enough to withstand this radiation. It's also an

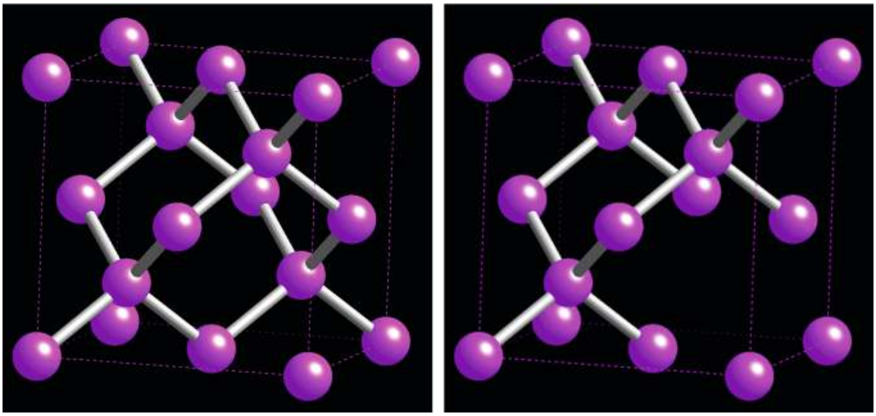


Fig. 11.2 The schematic on the left is the crystalline arrangement for diamond, where carbon atoms take on the specific positions shown in the diagram. The diagram on the right shows a missing carbon atom which acts like an electron trap—also called a color center

important part of the design of satellites, where radiation levels are high due to the thin atmosphere.

Let's focus on the part of this story that relates to color and that is the point defect—an empty atomic site in the crystal. This point defect effectively acts like an electron trap. Like any quantum object, an electron which finds itself trapped here exists in states. The lowest energy state is the ground state, and the electron can be excited into a higher energy state by absorbing a photon. In this sense the defect is not all that different from an atom. Electrons in an atom are bound (or trapped) to the positively charged nucleus and they exist in states, which for atoms we call orbitals (like the d orbitals in the previous chapter). Figure 11.2 shows an example of the diamond crystal structure. On the left is the perfect crystal, and the schematic on the right shows the presence of a point defect.

The color mechanism comes from the interaction of this electron and light. Just as elements like hydrogen or sodium can absorb light causing electrons in the ground state to be excited into a higher energy state, the same applies to these electrons. It turns out the energy difference between the ground state and the excited state is typically between 2 to 3 electron volts, which corresponds to wavelengths in the visible spectrum. This means the electrons in color centers absorb light in part of the visible spectrum which results in the observation of color.

One of the main examples for this color mechanism is found in the mineral fluorite. The presence of trapped electrons in fluorite cause color center absorptions at a wavelength of around 555 nm which corresponds to

Fig. 11.3 Image of a fluorite crystal with a purple color due to the presence of a color center. *Credit* Rob Lavinsky, iRocks.com

yellow [2]. From the CIE diagram, if we remove yellow at 555 nm from the white light the resultant color is purple (as seen in the purple fluorite crystal in the photo in Fig. 11.3). Interestingly, fluorites are incredibly stable and highly tolerant of radiation damage. In fact, some of the oldest minerals in the Earth's crust have crystal structures similar to fluorite with the oldest being dated at more than 1 billion years old [3]. All other minerals that have been subjected to millions and millions of years of radiation, as well as chemical and mechanical weathering, typically break down but fluorites are incredibly resilient. In fact, fluorite is the subject of a great deal of research in the development of materials for nuclear waste immobilization. This unique material is designed to safely store radioactive plutonium for over 10,000 years while being subjected to radiation as part of the radioactive decay process [4]. Fluorite-based materials are well-suited for this task.

We see the effects of color centers in other minerals as well. Quartz (SiO_2) is colorless in its pure form, but when quartz with aluminum impurities is subjected to radiation the result is smoky quartz. The smoky appearance comes from a large number of electronic transitions that cause absorptions across the visible spectrum, resulting in all wavelengths being absorbed—and hence the smoky appearance. The purple color of amethyst is also related to the presence of color centers. From the previous chapter, we know that iron (Fe) impurities in quartz result in the pale-yellow color of citrine. If a citrine crystal is irradiated the resultant color centers impart a purple color.

It is important to note that color centers are metastable—meaning that the crystal is not at equilibrium. Given enough time the crystal will re vert back to its equilibrium state. For example, if a color center in fluorite is created by knocking a fluorine atom out of position, eventually that fluorine atom will find its way back and the color center will disappear (and the color of the crystal will revert back to whatever it was). This can take geologic time scales (thousands or millions of years) or it could be much quicker. It really depends on the crystal.

It turns out the process of enhancing the color of crystals through radiation is used in the gemstone industry. There are many difference sources of radiation that are used to generate the color centers, including cobalt-60, nuclear reactors, and even linear accelerators. Figure 11.4 shows an example of the different colors that diamonds can exhibit through radiation and high-pressure treatments [5]. In addition to diamonds, radiation is sometimes used to enhance the color of topaz, beryl, pearls, amethyst, and tourmaline.

We can observe color effects which are similar to color centers in something called a quantum dot. A quantum dot is an ultra-small crystal typically on the scale of 1 to 10 nm. Since atoms are about 1/10th of a nanometer, that means quantum dots are built from just a few thousand atoms. They work in a similar manner to other phenomena we have seen in that electrons inside the quantum dot exist in states, with a ground state and one or more excited states. If the electron is elevated into the excited state it drops back down to the ground state and in the process a photon of light is emitted. The interesting thing about quantum dots is that the size of the crystal determines the wavelength of light that is emitted. The larger the crystal the longer the wavelength. Figure 11.5 shows an example of the colors emitted by quantum dots of different sizes.

Beyond just the pretty colors, quantum dots can be very useful which was the primary motivation for awarding the 2023 Nobel Prize in chemistry to Bawendi, Brus, and Ekimov. In one approach, it is possible to functionalize the surface of a quantum dot to adhere to a specific surface, for example cancer cells. Since the quantum dots have a specific color based on their size—they can be used to highlight the presence of those cancer cells. Since the quantum dots are so small they are able to pass through many membranes in the body and thus they are well suited for delivering drugs (or radiation). Quantum dots are also in development for display technologies which we will discuss later on in this book.

Fig. 11.4 Diamonds are normally colorless, but the image shows a selection of diamonds in a variety of colors due to irradiation and high-pressure treatments. *Credit* M. Wang et al., journal of spectroscopy, 8153941 (2018) [5]

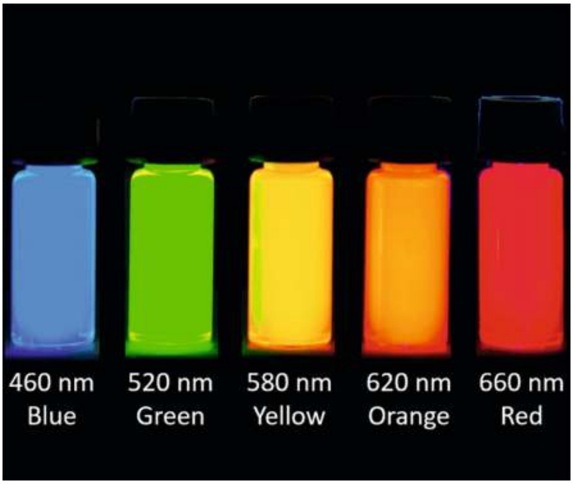


Fig. 11.5 Colorful array of quantum dots. The color depends upon the size of the quantum dot. Image reproduced with permission from Radetec Diagnostics, Melbourne, Australia

References and Further Readings

1. Poletaev, G., Y. Gafner, S. Gafner, Y. Bebikhov, and A. Semenov. 2023. Molecular dynamics study of the devitrification of amorphous copper nanoparticles in vacuum and in a silver shell. *Metals* 13: 1664.
2. 2001. Color centers, also called F centers, are discussed in Chapter 9 in Kurt Nassau. *The Physics and Chemistry of Color: The Fifteen Causes of Color*. Wiley.
3. The geology of the formation of the Earth is pretty complicated, but many of the oldest minerals are similar to fluorites. Here's a detailed review: Morrison, Shaunna, M., Prabhu Anirudh, and Hazen, Robert M. 2023. An evolutionary system of mineralogy, Part VI: Earth's earliest Hadean crust (>4370 Ma). *American Mineralogist* 108(1): 42–58.
4. Here's a recent review of nuclear waste immobilization techniques: Pilania, R.K., and C.L. Dube. 2023. Matrices for radioactive waste immobilization: a review. *Frontiers Materials* 10: 1236470; Anna, Shelyug., and Alexandra Navrotsky. 2021. And here is a discussion of the stability of fluorites for nuclear applications. *ACS Earth Space Chem* 5(3): 703–721.
5. Wang, Meili, Shi, Guanghai, Joe C.C. Yuan, Wen, Han, and Qing, Bai. 2018. Spectroscopic characteristics of treated-color natural diamonds. *Journal of Spectroscopy* 8153941: 10.

12

Color in Nature

Walking through woods in Oregon we're bombarded with green all year round. On the ground, we have thick, waxy green salal leaves. Above our heads are the leaves and needles of fir trees, giant oaks, and even towering redwoods near the coast. In the winter, brilliant green mosses and lichens hang from the tree branches like living curtains. Up to this point in the book we've primarily focused on inorganic sources of color such as minerals, gems, rocks, etc. All non-living things. However, the living world all around us—plants, trees, flowers, fruits, grasses…. brings vibrant colors to our world. These are organic materials (and by organic, I mean that they are primarily carbon-based) and the colors that we see arise from electronic transitions in the molecules they are made from. Just like atoms, color centers, and quantum dots, electrons in organic molecules exist in states—molecular states. Just as before, there is a ground state and multiple excited states. Since organic molecules tend to be more complicated than the simple atoms and compounds we've discussed so far, the detailed nature of these states is pretty complex and outside the scope of this book. But despite that complexity, the mechanisms that create the colors we see are not very different. Just as before, electrons in the ground state absorb light at specific wavelengths to access excited states. The absorption of light at these wavelengths removes certain colors from the visible spectrum which results in the complimentary color. In this chapter, we will introduce three common types of organic molecules that are responsible for many of the colors we see in plants, flowers, and even our foods: carotenoids, anthocyanins, and porphyrins.

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_12

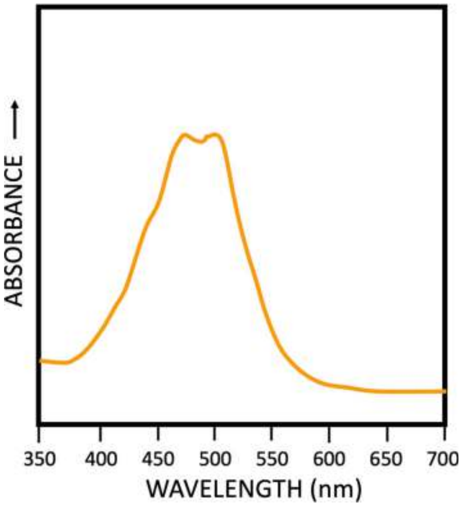


Fig. 12.1 Absorption spectra for orange carotenoid protein, showing the strong absorption in the blue-green region near 400 to 500 nm which results in an apparent orange color. *Credit* Ryan Leverenz and Cheryl Kerfeld [3]

Carotenoids

Carotenoids are organic molecules commonly found in plants and algae. One example is *beta-carotene* which is responsible for the orange color of carrots, pumpkins, and apricots. The absorption spectra for *beta-carotene* is shown in Fig. 12.1. The main absorption occurs around 400–500 nm which effectively removes blue and green from the visible spectrum. The reflected light then appears as the orange color we see in many fruits and vegetables. Some bacteria also produce *beta-carotene*, and the presence of that bacteria in the food supply of flamingos is responsible for the coloration of their feathers. Young flamingos are born with reddish-grey feathers, but as shown in Fig. 12.2, over time the color changes from pink to red based upon their consumption of *beta-carotene* [1]. The molecule *crocin* is another carotenoid which is present in saffron and is responsible for the yellow color. Saffron adds a dark yellow color when added to foods like paella and risotto, and it is also used to dye fabric [2]. We have met the carotenoid compound *rhodopsin* before (also called "visual purple"), as it is the photoactive molecule that is present in our eyes. The absorption of light in by the *rhodopsin* compound in our cones is converted into an electrical signal which is fed into our brains to create a color image.

Fig. 12.2 Image showing the differences in color of an adult and young flamingo. Newborn flamingos have grey feathers, but adult flamingos have a diet rich in beta-carotene which turns their feathers pink. *Credit* Steve from Washington, DC, USA

Flavonoids

Another family of organic molecules found in many foods, plants, and flowers are *flavonoids*. Flavonoids perform many important functions in plants, but with regards to color one important member of this family are *anthocyanin* compounds [4]. There are more than 400 *anthocyanins* [5], and their color profile is extremely broad. With minor changes to the molecular structure, a range of colors are possible from pink, to red, to yellow to blue. They are common in red, blue, and purple foods that you see in the market like blueberries, cranberries, raspberries, cherries, eggplants, grapes and cabbage. It is also a common pigment in flowers such as the *spring gentian* shown in the Fig. 12.3 which I took while hiking in the shadow of the Matterhorn in Switzerland. In addition to a range of colors, it is also true that the color of *anthocyanins* can be sensitive to pH which makes them useful as pH indicators [5].

Fig. 12.3 Bright blue spring gentian flowers on the high-altitude slopes of the Matterhorn in Switzerland

Porphyrins

Porphyrins are another class of organic molecules that are commonly found in green plants and vegetables [2]. One example is *chlorophyll*, which has the absorption spectra shown in Fig. 12.4. Two variants of chlorophyll are shown both of which primarily absorb in the blue/violet and red/orange ends of the visible spectrum. With these colors removed due to the presence of *chlorophyll*, the result is the abundant green color we observe in our lawns, gardens, and forests. We've seen lots of examples of electronic transitions where a molecule or atom or crystal absorbs light which leads to the appearance of a color. In the case of *chlorophyll,* there's more to it than just the color green. In addition to creating the greenery around us, the absorption of light is also critical to generating energy for the organism.

In plants, algae, and cyanobacteria, *chlorophyll a* is the primary means for converting light to chemical energy through the photosynthesis process. The light that is absorbed plays a key role in the chemical reaction for photosynthesis shown here:

$$6CO_2 + 6H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2$$

This chemical reaction shows that carbon dioxide (CO_2) and water (H_2O) combines with the energy from the absorbed light and creates two products, a hydrocarbon, for example glucose ($C_6H_{12}O_6$), and oxygen (O_2). The hydrocarbon represents stored chemical energy which can be released through the

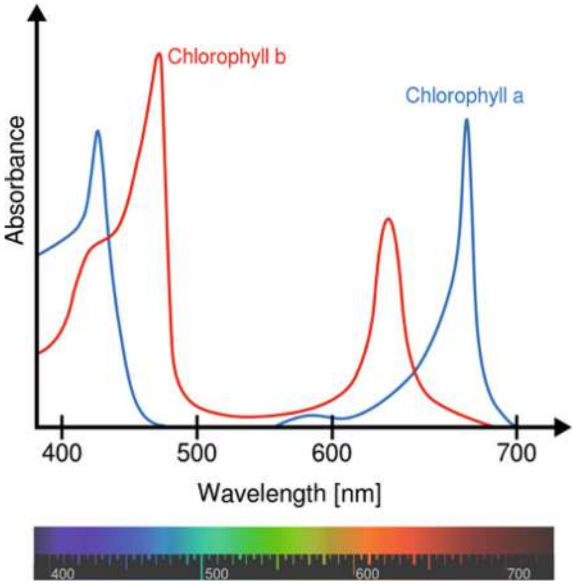


Fig. 12.4 Absorption spectra for two types of chlorophyl, showing the strong absorption in the blue/violet and red/orange ends of the visible spectrum which results in an apparent green color. *Credit* Original: Daniele Pugliesi Vector: M0tty

reverse reaction (called cellular respiration):

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

The energy released through this reaction can be used by the plant for growth and survival.

The leaves of deciduous trees have *chlorophyll, beta-carotene,* and *anthocyanins* and they interact in interesting ways. The absorption of *chlorophyll* dominates during the spring and summer months while the engine of photosynthesis is active in the tree, resulting in green leaves. As the season turns to autumn, the photosynthesis process slows down and eventually the *chlorophyll* breaks down. The color of the leaves gradually becomes dominated by presence of *beta-carotene* and *anthocyanins* resulting in leaves of yellow, orange, and red (Fig. 12.5). In a sense, the color of the leaf is an indication of the energy conversion process going on behind the scenes. When the leaves are green, the plant is actively capturing sunlight and using *chlorophyll* to store energy in hydrocarbons to fuel its growth. As the color of the leaves shift, this indicates the plant is turning off the photosynthesis process until it begins anew in the spring.

Fig. 12.5 The changing color of leaves. As chlorophyl breaks down, the color of the leaves gradually becomes dominated by presence of beta-carotene and anthocyanins resulting in leaves of yellow, orange, and red. *Credit* Tbk1101

Another compound in the porphyrin family is the molecule *heme* [2]. It is a ring-shaped molecule which contains iron, and is found in mammalian blood. The *heme* molecule combines with globin proteins to create *hemoglobin* which plays a critical role in binding and transporting oxygen throughout the bloodstream. The iron in the *heme* molecule binds with oxygen creating *oxyhemoglobin.* It is primarily responsible for the apparent red color of blood because it absorbs blue and green light. (Note: we'll talk about the apparent blue color of veins in a later chapter). Like we've seen before with other color mechanisms, we can use the color of blood as a probe to tell us something about the chemistry. It turns out the intensity of the red color of blood depends upon how much oxygen is present, which is the main operating principle behind the pulse oximeter. You've probably had one of those devices on your finger tip last time you had a physical.

If you think about it, the red color of blood really is primal. It's probably why it is used in signs to get our attention with red traffic lights, stop signs, and emergency exits. Even in the natural world red is often a warning signal—red peppers are spicy, and some red-colored frogs, snakes and mushrooms are poisonous. Interestingly, not all species have the *heme* molecule in their blood—mostly just vertebrates (i.e. animals with a backbone).

There is a lizard in New Guinea with lime green blood called the green tree skink (*Prasinohaema virens*, shown in Fig. 12.6). These lizards have hemoglobin just like us, but there is an abundance of another compound in their blood called *biliverdin* which is the source of the green color. The

Fig. 12.6 Prasinohaema virens, one of the described species of green-blooded lizards from New Guinea. *Credit* Chris Austin, Louisiana State University

overall evolutionary benefit of the green blood is not clear [6]. The presence of *biliverdin* colors everything in the lizard green including skin, tissue even its bones. This would certainly help with camouflage but given that *biliverdin* is toxic it might also help the lizard defend against predators or parasites.

Another example is the horseshoe crab which has blue blood due to the presence of *hemocyanin* which absorbs primarily in the red, resulting in the apparent blue color. It has a similar function to hemoglobin, but instead of iron binding with the oxygen, it uses copper. Apparently, there are elements in this blue blood that have significant health benefits especially in the development of vaccines [7, 8]. It's not cheap either, with a price tag of $60,000 per gallon (Fig. 12.7).

Fig. 12.7 Horseshoe crab blood in a reagent bottle. Photography by Ariane Müller

References and Further Readings

1. Wonderful story about the coloring in flamingos. https://www.bbc.co.uk/newsround/40964645.
2. 2001. Color from organic molecules is discussed in Chapter 6 in Kurt Nassau. *The Physics and Chemistry of Color: The Fifteen Causes of Color*. Wiley.
3. Data on the absorption of light in carotenoid compounds taken from the website from the Kerfeld lab at Michigan State University: https://www.kerfeldlab.org/images.html.
4. Nice summary of flavonoids from the Linus Pauling Institute (with important disclaimer). https://lpi.oregonstate.edu/mic/dietary-factors/phytochemicals/flavonoids. Note: This link leads to a website provided by the Linus Pauling Institute at Oregon State University. David Cann is not affiliated or endorsed by the Linus Pauling Institute or Oregon State University.
5. Kong., Jin-Ming, Lian-Sai, Chia, Ngoh-Khang, Goh, Tet-Fatt, Chia, and R. Brouillard. 2003. For a nice summary of anthocyanins, Analysis and biological activities of anthocyanins. *Phytochemistry* 64(5): 923–933.
6. Zachary B. Rodriguez, Susan L. Perkins, and Christopher C. Austin. 2018. Multiple origins of green blood in New Guinea lizards. *Science and Advanced* 4: eaao5017.

7. Walls, E.A., J. Berkson, and S.A. Smith. 2002. The Horseshoe Crab, *Limulus polyphemus*: 200 million years of existence, 100 years of study. *Reviews in Fisheries Science*, 10(1): 39–73.
8. For more information on conservation efforts for horseshoe crabs, see the Ecological Research & Development Group which has been actively engaged in promoting best practices among LAL/TAL producers regarding the harvesting, bleeding, and release of horseshoe crabs: https://horseshoecrab.org/what-is-an-endotoxin/. In addition, here's a recent paper on the current state of recombinant reagents and their implications for conservation: Glenn Gauvry, USP Chapter <86> Bacterial Endotoxins Test Using Recombinant Reagents: A Step Forward, But Not a Milestone for Horseshoe Crab Conservation. https://www.researchgate.net/publication/384930401_USP_Chapter_86_Bacterial_Endotoxins_Test_Using_Recombinant_Reagents_A_Step_Forward_But_Not_a_Milestone_for_Horseshoe_Crab_Conservation.

13

Color from Refraction

All along my hike, my eyes are drawn to the colors in front of me and at my feet. With a break in the trees ahead of me I can see a glimpse of the horizon. With the sun behind my back, I can see the faint outlines of a rainbow tenderly painting the sky. To this point, pretty much all the color mechanisms we've talked about were similar. Essentially, it worked like this. White light, containing a balanced mixture of the spectral colors, shines onto an object (flower, crystal, blood, anything). An atom or molecule within the object absorbs light at a specific wavelength. The energy from that light could do many different things: excite electrons into high energy states, or cause the molecule to vibrate, or even drive the process of photosynthesis within a plant. The key is that part of the visible spectrum has been removed due to this absorption, and thus the constituent colors contained within the light reflecting off the object is no longer in balance. Thus, we see green leaves, or blue blood, or a red ruby. To understand the rainbow, we'll need to discuss color originating from a very different mechanism—refraction.

We first encountered refraction when we introduced Newton's prism experiment showing that white light is composed of the spectral colors red, orange, yellow, green, blue, and violet. However, we skipped over the part about *why* the prism separates light. We need to explain two terms to understand how this works: refraction and dispersion. In the beginning of this book we described the fundamentals of light as a form of electromagnetic radiation. It has a wavelength (which relates to color) and it has a velocity. The speed of light depends upon the medium that it is travelling through. This is because all electromagnetic radiation has a built-in electric field that travels with the wave. Electric fields interact with all charged particles, and thus the light wave

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_13

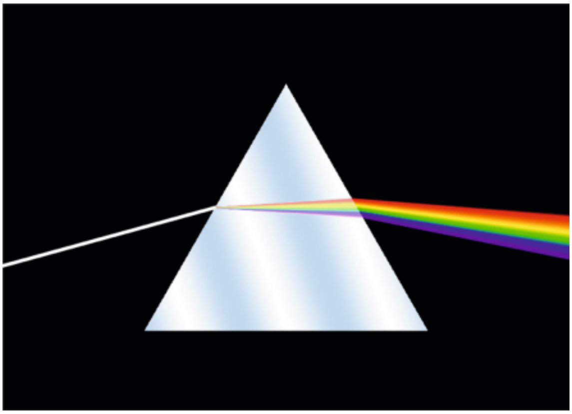


Fig. 13.1 Schematic showing refraction of light in a prism. Each of the colors are bent at different angles resulting in the splitting of white light into the spectral colors. This is called dispersion. *Credit* Wikimedia Commons

slows down when it encounters charges. In a vacuum there's no charges for light to interact with, thus it travels at the maximum speed (at a velocity denoted as $c_0 = 300{,}000{,}000$ m per second). When light enters a solid or a liquid, it interacts with the charged particles that are part of the atoms and molecules; negatively charged electrons and positively charged protons. This slows down the light wave, depending upon how much charge is present in the material (and it also has to do with the chemistry and types of bonds too). The parameter that describes this is the refractive index, usually denoted by the symbol n.

In addition to slowing down the light wave, the refractive index also has another effect. When light enters the material, it changes direction and the refractive index determines the angle. The larger the refractive index, the larger than change in direction. You've probably seen this effect if you've ever put your fingers into an aquarium and seen the distortion. The part of this story which is related to color comes from another effect called dispersion. This is the case when the refractive index depends on wavelength (and therefore color). This means when white light enters a material, each color within the white light will change direction to a different angle. This is the essence of Newton's prism experiment, where light spreads into the prismatic colors due to dispersion (Fig. 13.1). It's also the album cover for the Pink Floyd's Dark Side of the Moon, though I'm not sure what the connection is. We see this effect in glass ornaments (sometimes called "suncatchers") that create tiny rainbows when they are illuminated by the sun. This is also the mechanism for rainbows and diamond fire both of which we will discuss next.

Fig. 13.2 Picture of a rainbow outside my house. While my eyes weren't sensitive enough to see the double rainbow, it shows up clearly in the image

Rainbows

Not all materials exhibit dispersion, but water exhibits a significant amount of dispersion and this is the origin of the colorful rainbows. The geometry of the sun, rain droplets, and observer is important to make this work. The observer stands with their back to the sun. White light from the sun enters raindrops and the dispersion splits light into the prismatic colors. Each color of light then reflects off the droplets back to the observer. Figure 13.2 shows a picture of a rainbow near my house. The observer can see the rainbow spanning an angle between 41° to 43° as shown in Fig. 13.3 [1]. Of course, it doesn't have to be rain, you can also create the same effect with a garden hose or any small droplets of water. In this case you can clearly see a second rainbow outside the primary rainbow. I'm not sure I noticed it with my eyes, but the camera in my smart phone is much more sensitive than my eyes so it shows up clearly in the image. This secondary rainbow occurs when the incoming light has a second reflection inside the droplet of water. The diagram in Fig. 13.4 shows the different geometries of the primary rainbow (on the left) and the secondary rainbow (on the right).

Diamond

Diamond has a high refractive index, which means that when light enters the diamond it will deflect at a large angle. It also exhibits significant dispersion

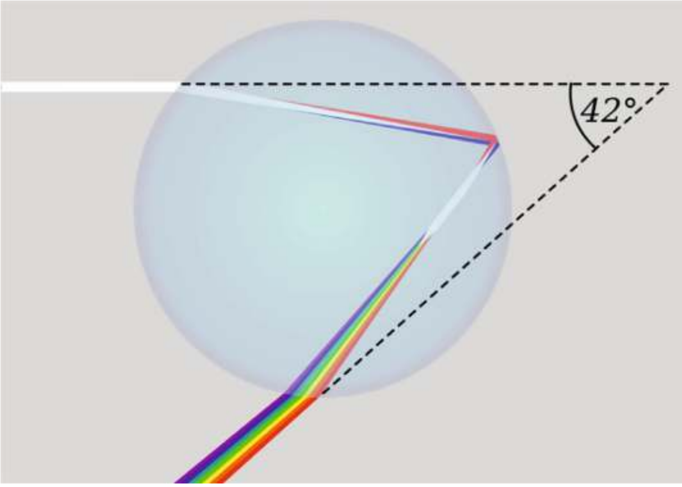


Fig. 13.3 The creation of a rainbow comes about from two processes. First, white light entering a rain droplet and splits into the spectral colors through dispersion. The colored light reflects of the back surface of the droplet and travels back to the observer. *Credit* KES47

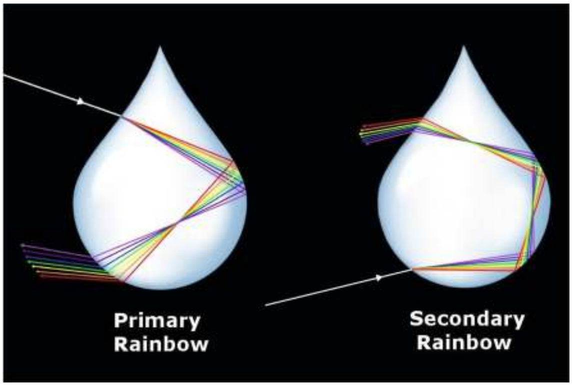


Fig. 13.4 Schematic showing formation of a primary rainbow and the secondary rainbow. *Credit* ScienceABC

which means each color of light deflects at a different angle. You can clearly see these effects when you look at a diamond under white light. White light enters the diamond and when it reflects (one or more times) back to your eyes, because of the dispersion many different colors appear out of different facets of the diamond depending upon the angle of your eye and the face of the diamond. You can also see colors when the diamond is rotated or moved, because when your eye is stationary and the diamond is moving different colors are moving into your field of view. Diamonds are cut into specific

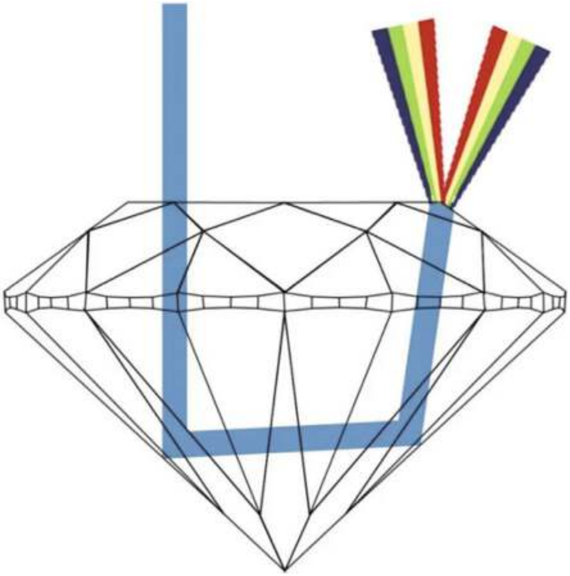


Fig. 13.5 Schematic showing the effect of diamond fire. White light enters the diamond, and the dispersion separates it into spectral colors. After reflecting off the back surfaces of the diamond it travels back to the observer. The colors seen by the observer will depend upon the angle. *Credit* www.PriceScope.com

shapes to maximize these effects. Figure 13.5 shows a specific cut called the modern brilliant cut, which allows for a diamond that reflects light back to the observer through two reflections through multiple facets. Figure 13.6 shows the colors that arise due to the effects of refraction and dispersion. The appearance of color when you rotate a diamond is called the "fire." Maybe this is what Pink Floyd was referring to with the song "Shine on you crazy diamond."

There is an interesting side note about importance of a proper cut in one of the world's most famous diamonds, the Koh-i-noor diamond (Fig. 13.7). This diamond was taken from India by the East India Company and given to Queen Victoria in 1849 (in a story wonderfully told in a book and podcast by Anand and Dalrymple [2]). While the original diamond was enormous (191 metric carats), it was only roughly cut in a way which did not show the fire. It was displayed at the Great Expedition in London in 1851, but received an underwhelming reception by the public. Given its symbolic importance, it was recut to highlight the coloration. While the new cut enabled the colorful diamond fire, the cutting process involved dramatic changes to its size and it lost nearly half its weight. (That must be a metaphor for something!) The image below is a replica of the Koh-i-Noor, but the original diamond is

Fig. 13.6 Example of diamonds showing the effects of dispersion. *Credit* Mario Sarto

Fig. 13.7 Replica of the Koh-i-Noor diamond at Prince of Wales Museum of Western India, Mumbai. *Credit* aiva

currently part of the United Kingdom's collection of crown jewels which can be seen in the Tower of London.

Sadly, I see no diamonds on my hike but I do see something interesting up ahead! Just as I cross the tree line, I approach the summit to observe the vast sky open up in all directions. The colors of the sky, white puffy clouds, deep blue skies, and colorful sunsets await me!

References and Further Reading

1. Color from refraction is discussed in Chapter 10 in Kurt Nassau. 2001. *The Physics and Chemistry of Color: The Fifteen Causes of Color*. Wiley.
2. Dalrymple, William, and Anita Anand. 2016. *Kohinoor: The Story of the World's Most Infamous Diamond*. 1st ed. Juggernaut Publication.

14

Color from Scattering

If we think of the origins of color in our world, most of the color comes from the mechanisms we've talked about previously with atoms and molecules absorbing light in plants, minerals, paints, animals, and textiles. However, there's another common mechanism that colors our skies and many living things such as birds, insects, and even some mammals. This color mechanism is called scattering.

With the previous color mechanisms we discussed, white light shines onto an object—some of that is absorbed by the object (or more specifically, some colors that are part of white light are absorbed). With scattering, the light isn't absorbed but merely redirected (like for example reflection). If all colors are scattered equally, then the object will appear white to our eyes. In clouds, small particles of water and ice scatter all colors of light equally and the result is the appearance of white puffy clouds. However, if the amount of scattering is different for each color (and thus each wavelength of light) then scattering can create the appearance of color.

For really small particles, and by that I mean for particles which are smaller than the wavelength of light (400–700 nm), a type of scattering called Rayleigh scattering dominates. The result is that smaller wavelengths of light are scattered more than long wavelengths which is described by this equation [1]:

$$\%Scattered = \frac{Constant}{\lambda^4}$$

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_14

This is a pretty simple equation where λ represents the wavelength of light. The equation shows that small wavelengths scatter a greater percentage of light. This means that blue light scatters to a much greater degree as compared to red light. We see this effect every time we look up (on a sunny day at least) because of the presence of molecules like nitrogen (N_2) and oxygen (O_2) in our atmosphere. Both these molecules (and most other molecules) are much smaller than the wavelength of light and thus light travelling through our atmosphere follows the above equation for Rayleigh scattering.

The yellow color of the sun can be attributed to this mechanism. Earlier in the book we discussed the origin of the light coming from the sun due to incandescence. Due to its surface temperature of 5600 K, the light leaving the sun has a fairly good balance of spectral colors resulting in mostly white light. When we stare directly at this sun (of course, don't actually do this!), the white light coming from the scorching hot surface of the sun travels through our solar system unchanged. When it enters our atmosphere on the way to our eyes, the light rays are scattered. However, not all colors are scattered equally. Due to Rayleigh scattering, blue light is scattered away from our eyes to a much greater degree than the other colors that make up white light. Thus, the light that enters our eyes is effectively deficient in blue light (Fig. 14.1). From our discussions of color theory, yellow and blue are complimentary colors, so the removal of blue from the balance of colors results in the yellow coloration of the sun. When it is high in the sky (at noon, for example) it takes a short path through the atmosphere and thus the yellow coloring is subtle. However, when the sun is close to the horizon it travels a longer path through the atmosphere which increases the amount of blue scattering which highlights the yellow coloration. When the sun is really close to the horizon, its color shifts to even longer wavelengths as the long path through the atmosphere removes the shorter wavelengths from the spectrum results in the orange or red sunset.

This same effect explains the origin of the blue sky. In this case white light from the sun scatters off of the atmosphere. Just as before, not all colors scatter the same and a preponderance of blue light scatters to our eyes. The blue color really comes out when the air is clean (Fig. 14.3). The photo below shows the author underneath a deep blue sky on top of 13,000 foot Wheeler Peak in eastern Nevada (Fig. 14.2). When pollution and particulates are present in the air, there are other scattering mechanisms at play. These mechanisms tend to scatter all wavelengths more or less equally which dilutes the blue coloration—resulting in gray colored skies.

You can really see the effects of scattering from the atmosphere in photographs taken at high elevations. Figure 14.4 is a photo showing a clear

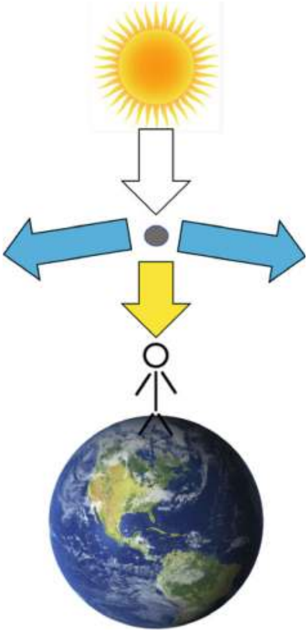


Fig. 14.1 The yellow color of the sun comes from Rayleigh scattering. White light coming from the sun enters our atmosphere. Blue light is preferentially scattered and since yellow is complementary to blue, to the observer, this results in the apparent yellow color of the sun

change in the color as the atmosphere gets thinner and thinner. High above the Earth the sky appears black because there are no molecules to scatter the light coming from the sun. This is also the case on the moon. Since the moon has almost no atmosphere, the sky appears black as seen in the photo in Fig. 14.5.

If skies are blue on Earth and black on the moon, what about Mars? We've sent numerous probes to Mars over the years with sophisticated cameras which have given us amazing photos of the Martian landscape. One interesting finding is that the coloration of the sky is quite variable. Just like on Earth, Rayleigh scattering occurs in the Martian sky but its effects are limited because the atmosphere is much thinner than the Earth's. The air pressure on the surface of Mars is less than one percent of Earth's air pressure and therefore there are significantly fewer gas molecules in the atmosphere to cause scattering. Therefore, in some photos the Martian atmosphere appears "bluish black". While the atmosphere is thin, the Martian skies are often filled with dust. The dust is mostly comprised of iron oxide particles which scatter red light and absorb blue light. Remember, iron is a transition metal and thus it can absorb light through electron transitions into empty d-states. Images

Fig. 14.2 Deep blue skies are seen from atop Wheeler Peak in Great Basin National Park in Nevada

from Mars landers like the one in Fig. 14.6 from NASA's Mars Perseverance Rover reveal "dark yellowish brown" or "butterscotch" colored skies due to these effects [2, 3].

Rayleigh scattering is just one type of scattering mechanism which applies when the wavelength of light is much larger than the object (e.g. a gas molecule). When the objects are comparable to the wavelength of light (e.g. around 1 mm), other scattering mechanisms come into play such as Mie scattering. The details of Mie scattering are much more complex than Rayleigh scattering, but in general these larger particles scatter light of all wavelengths equally. We see the effects of Mie scattering in white puffy clouds. The clouds contain tiny water particles or droplets which are typically between 1 and 100 μm in size. When sunlight hits the cloud, the water particles scatter all wavelengths more or less equally which results in the white appearance as you can see from this photo on top of Mount Washington in NE Oregon (Fig. 14.7).

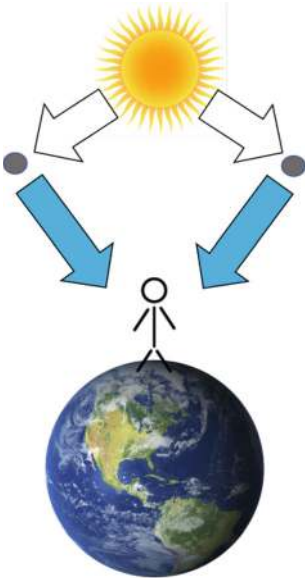


Fig. 14.3 The blue color of the skies comes from Rayleigh scattering. White light coming from the sun enters our atmosphere. Blue light is preferentially scattered by the atmosphere and thus, to the observer, this results in the apparent blue color of the skies

Fig. 14.4 A photo taken from a weather balloon at approximately 100,000 ft above Oregon showing the thin layer of atmosphere. *Credit* Justin Hamel and Chris Thompson

Fig. 14.5 Photo taken from surface of the moon showing black skies, since there is no atmosphere to scatter light. *Credit* By NASA/Bill Anders

Fig. 14.6 Martian skies as captured by a camera on NASA's Mars Perseverance Rover. *Credit* NASA Spirit Mars Exploration Rover (MER-A)

Fig. 14.7 Lots of scattering in this photo. White puffy clouds from atop Mount Washington in Oregon, and scattering from the snow as well!

After taking in the views at the summit, I head back into the woods. Crossing the boundary from the mountain top meadow and back into the woods, life is abundant. In particular, I see butterflies, birds and insects adorned in vibrant colors. Feathers, wings, and exoskeletons exhibit colors using a similar scattering mechanism that we see in the skies. It doesn't come from a pigment or impurities like we've seen before, but the colors come from something called structural coloration.

References and Further Reading

1. Color from scattering is discussed in Chapter 11 in Kurt Nassau. 2001. *The Physics and Chemistry of Color: The Fifteen Causes of Color*. Wiley.
2. NASA has a lot of interesting information on all of the Mars missions here: https://science.nasa.gov/mars/
3. Here's a scientific article on the optics of Martian sunsets: Ehlers, Kurt, Rajan Chakrabarty, and Hans Moosmüller. 2014. Blue moons and Martian sunsets. *Applied Optics* 53: 1808–1819.

15

Color in Biological Systems—Structural Coloration

The colors we see in the sky come about from light scattering in the atmosphere. We observe colors when white light (from the sun) shines on a particle (gas molecule, dust particle, water droplets, etc.) and some wavelengths (i.e. colors) are scattered more than others. If all colors scatter to the same degree—then the object appears white (e.g. a white puffy cloud). The phenomenon is not limited to the atmosphere—it is also very common in biological systems. We see it in the colors of blue Morpho butterfly wings, colorful bird feathers, green lizard skin and countless other examples in nature. It's called structural coloration and it is different than a pigment. A pigment is a substance or a molecule that absorbs light of a certain wavelength (and color) so that we observe the complimentary color. We have countless examples of this—including the chlorophyl molecule that absorbs red light which results in the abundant green color we see in plants. You can tell something is a pigment because if it gets on your hands or clothes the color transfers. The molecules will absorb light no matter where they are located.

In contrast, structural coloration is not due to a specific molecule that absorbs light. The color comes from scattering in a similar way to the colors in the sky. However, instead of light scattering off of particles floating in the air—in structural coloration light scatters off of objects inside a transparent tissue within the skin, wing or feather or an organism. The object that causes the scattering can be anything. One common example is keratin, which is a fibrous protein found in vertebrates (i.e. organisms that have a spine). It's a significant component of hooves, horns, and claws (including your fingernails) but when it forms as a small particle about the size of the wavelength

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_15

of visible light it can be a source of color. Guanine is one of the components of DNA and RNA, but in organisms it can form into small crystals that act as scattering sites to create color. Sometimes the scattering object can be nothing at all—specifically a hole or a bubble. When light travels through a transparent material and encounters an air-filled hole or bubble, light will scatter. If different wavelengths of light scatter at different rates—then the result will be the appearance of a color.

What's behind this concept of scattering? Basically, waves of light will scatter will scatter when they encounter a change in the medium it is travelling through. If we think of a stream of water flowing down a perfectly smooth channel the surface of the water will appear flat like a sheet of glass. If we place a rock in the channel, the rock will disrupt the flow and on the surface of the water we will see bumps and undulations as the water gets redirected around the rock. This is a reasonably close analog to what happens to light when it encounters an obstacle. For visible light, it is the refractive index that determines the degree to which light gets scattered. As you recall from a previous chapter, the refractive index is a measure of the interaction between a light wave and the medium it is travelling in. A material with a high refractive index (i.e. much greater than 1) has a strong interaction. When light enters a material with a high refractive index it slows down significantly and changes direction. In contrast, a material with a refractive index close to 1 interacts weakly with light, meaning it doesn't slow down or change direction very much. The key to scattering is the *change* in refractive index. As shown in Fig. 15.1, when light travels in air (which has a refractive index very close to 1), when it encounters a gas molecule or water droplet, there is a significant change in refractive index which results in scattering. Similarly, when light is travelling through a material with a relatively large refractive index (like keratin) and it encounters an air bubble (with a refractive index of 1) it scatters. Most importantly, when different wavelengths of light scatter to different degrees we observe this as color [1].

One of the most striking examples of this is found with the color blue seen in many insects, birds and animals. The diagram in Fig. 15.2 shows how it works. White light (containing a balance of all the spectral colors) enters a layer (e.g. keratin, tissue, feather, or skin) which contains particles (or air bubbles) that are of a certain size that preferentially scatter blue light. While blue light scatters in all directions, the rest of the spectrum continues through to a layer of melanin. Melanin is a biomolecule which is present in many organisms and is present in our skin and hair. It's important here because it strongly absorbs all colors across the visible spectrum. The combination of these two layers results in the appearance of the color blue. We see this in blue

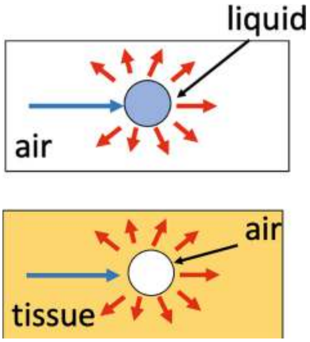


Fig. 15.1 Schematic showing two examples of scattering. At top, it shows incoming light scattering off a liquid droplet suspended in air. At the bottom, light is travelling through some transparent medium and scatters off of an air bubble. In both cases the effect is the same. Light will scatter when it encounters a change in refractive index

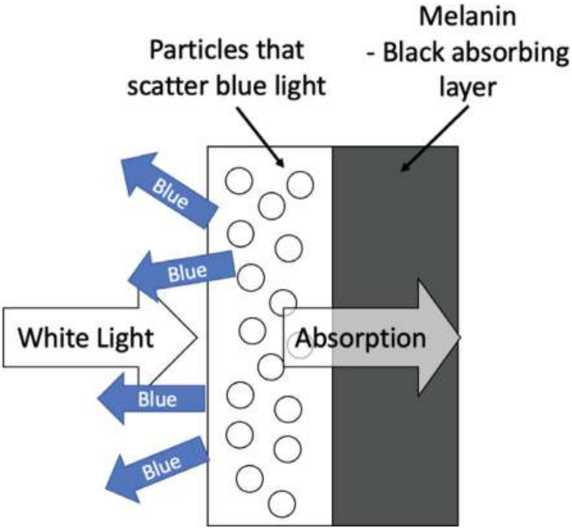


Fig. 15.2 Schematic showing structural coloration that results in the color blue. Incoming white light enters a layer containing particles (or air bubbles) that preferentially scatter blue light in all directions (including back to the observer). The remaining components of white light continue on and are absorbed at the back layer composed of melanin. Thus, white light goes in and everything is absorbed except for blue light which is scattered back to the observer

jay feathers, blue skin in monkeys and turkeys, and blue wings in dragonflies (Figs. 15.2 and 15.3 from reference).

This is what structural coloration is all about. It's not a molecule or substance which is absorbing light, but rather the geometric structure that

Fig. 15.3 Example of structural coloration in the blue wings of a dragonfly. *Credit* Taken from Guillermo-Ferreira et al. [2]

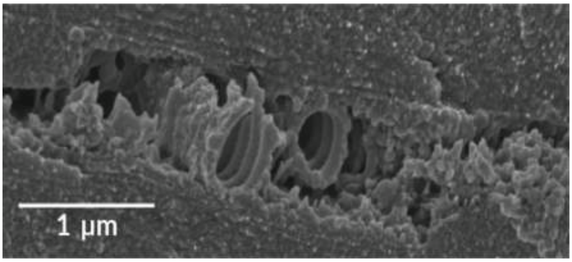


Fig. 15.4 High magnification image of the internal structure of a dragonfly wing showing the tiny air bubbles which preferentially scatter blue light. *Credit* Taken from Guillermo-Ferreira et al. [2]

preferentially scatters light of a certain color. For example, the blue dragonfly wings shown in the picture below are the result of tiny air bubbles within the wing which is made from chitin (Fig. 15.4) [2].

The color of the wings of a blue jay has a similar structure (Fig. 15.5). The wings are made from keratin and the structure is "sponge-like" with pores that reflect light depending on the size of the pores [3]. The feather shown in Fig. 15.6 has colors that vary from white to light blue, to dark blue. The structure of the spongy layer in the feather determines the color that is observed.

Other colors are possible with a more complex layered structure [1]. Imagine a layer with particles that scatter blue light, a layer that scatters yellow light, and in the back a melanin layer which absorbs all colors (Fig. 15.7). In this case white light goes in, and blue and yellow light would be scattered back to the observer. Additive mixing of blue and yellow light results in the appearance of green such as you might see in a lizard or frog (Fig. 15.8).

The color of turkey skin is derived from the spacing of collagen fibers within the epidermis (Fig. 15.9). Interestingly, the turkey can change the

Fig. 15.5 Image of a blue jay (*Garrulus glandarius*) with multicolored wings. Taken from Parnell et al. [3]

Fig. 15.6 Photograph of the feather of the jay *Garrulus glandarius* with colored stripes ranging from white to light blue to dark blue to black. Taken from Parnell et al. [3]

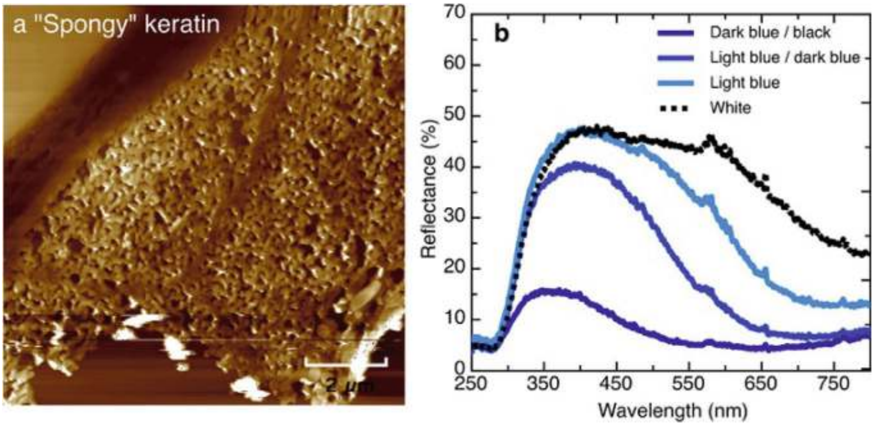


Fig. 15.7 Close up of the structure of the feather showing the internal pores which scatter light to create the different colors. The plot on the right shows the reflectance spectra for the different regions resulting in the different colors. Taken from Parnell et al. [3]

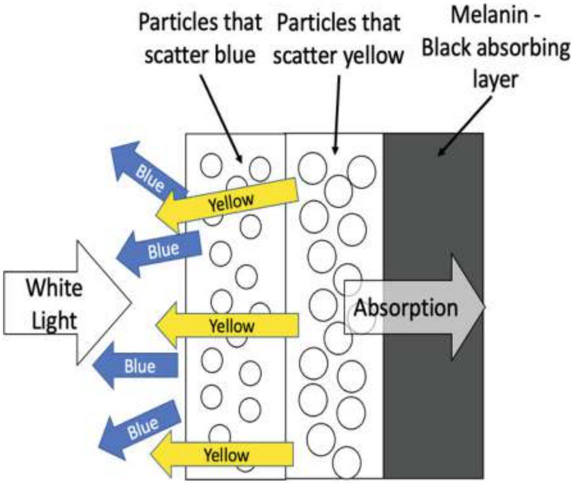


Fig. 15.8 Similar to the previous diagram, this schematic shows a multilayer structure which results in a green coloration. Incoming white light first interacts with a layer containing particles (or air bubbles) that preferentially scatter blue light in all directions (including back to the observer). The remaining components of white light continue on and enter a layer with larger particles (or air bubbles) that preferentially scatter yellow light. The remaining light is absorbed at the melanin layer in the back. Thus, white light goes in and everything is absorbed except for blue and yellow light which is scattered back to the observer creating the appearance of green light

Fig. 15.9 Lizard showing green coloration due to scattering. C0 Public Domain

color of the skin by controlling blood flow within the epidermis which changes the distance between the collagen fibers [4]. The key here is that color comes from scattering, and the scattering occurs when white light encounters a change in refractive index which could be a fiber (like the turkey), a particle, or an air bubble or pore (like bird feathers). Rather than a molecule which acts like a pigment that absorbs light (like chlorophyl), with structural coloration color is directly built into the basic geometry or structure of the skin or feather or wing. This explains why the colors from a bird feather or dragonfly wing don't transfer or stain your hands, and they can't be used as a pigment to dye fabrics (Fig. 15.10).

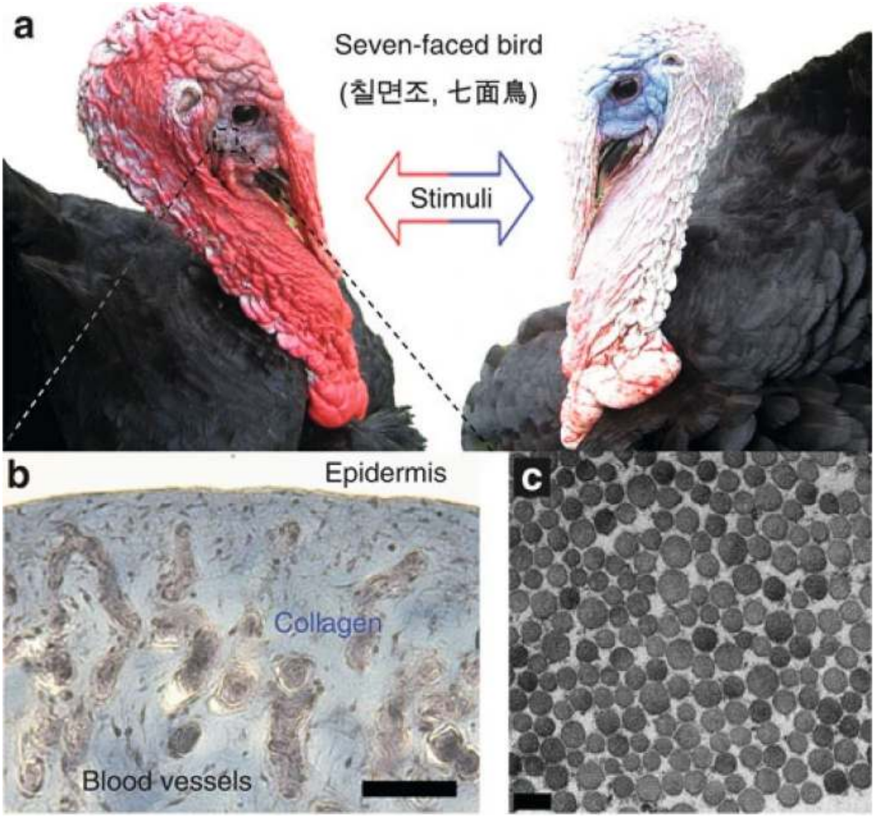


Fig. 15.10 The color of turkey skin changes depending upon the spacing of collagen fibers within its epidermis. The turkey can change the color by controlling the blood flow into the epidermis, which changes the spacing between the fibers. *Credit* Oh et al. [4]

References and Further Reading

1. Scattering induced color is discussed in Chapter 11 and biological coloration is discussed in Chapter 13 in Kurt Nassau. 2001. *The Physics and Chemistry of Color: The Fifteen Causes of Color*. Wiley.
2. Guillermo-Ferreira, Rhainer, Esther Appel, Paulina Urban, Pitágoras C. Bispo, and Stanislav N. Gorb. 2017. The unusual tracheal system within the wing membrane of a dragonfly *Biology Letters* 13: 20160960.
3. Parnell, A., A. Washington, O. Mykhaylyk, et al. 2015. Spatially modulated structural colour in bird feathers. *Science and Reports* 5: 18317.
4. Oh, J. W., W. J. Chung, K. Heo, et al. 2014. Biomimetic virus-based colourimetric sensors. *Nature Communications* 5: 3043.

16

Color from Interference

To this point we've discussed color originating from pigments and scattering, but color can also appear when light waves interact through interference. The interaction that we're talking about refers to the "phase" of the light waves. When waves of light (or any kind of wave) are "in-phase," the peaks and troughs of the two waves line up perfectly (Fig. 16.1). The intensity of the two waves add together which means the intensity of the combined wave is increased. This is called constructive interference. For waves of light, that means the brightness of the light increases, or for sound waves that would be mean the sound would be louder. In contrast, if the peaks and troughs of two waves do not line up, the intensity of the combined wave can be reduced or if they are "out-of-phase" the intensity is perfectly cancelled out (Fig. 16.2). The net result would be the absence of light (i.e. black) or for sound waves it would be the lack of sound (which is basically how noise cancelling headphones work). This is called destructive interference.

But how does this lead to the appearance of color? We need to combine this effect with the concept of refraction. Let's consider a monochromatic wave of light incident on an object. The term monochromatic means that the light ray is made up of just a single wavelength. White light has a combination of wavelengths, so monochromatic light would be just one color.

Let's consider two rays of light hitting a transparent object as shown in Fig. 16.3 [1]. The dotted lines represent the peaks of the wave, and you can assume the troughs of the wave would be halfway between the dotted lines. As shown in the diagram light ray #1 reflects off the surface of the object at point C. Light ray #2 enters the object at point A, and based on it's refractive index the light ray will change direction, will slow down, and will change it's

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_16

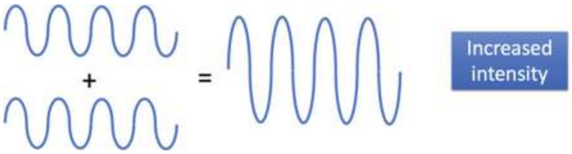


Fig. 16.1 The combination of two waves which are in-phase results in *constructive* interference, which means the intensity of the two waves are added together

Fig. 16.2 The combination of two waves which are out-of-phase results in *destructive* interference, which means the intensity of the two waves subtract to zero

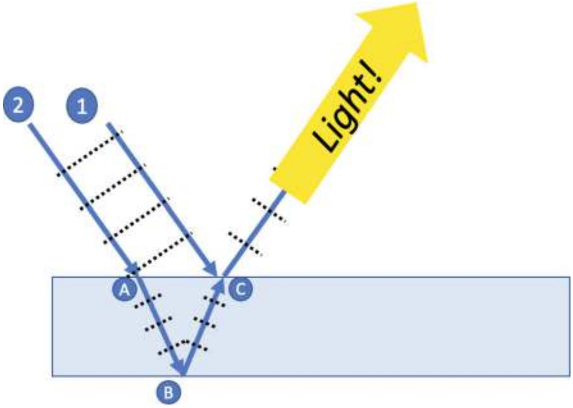


Fig. 16.3 Schematic showing the basic geometry of interference. Light wave #1 is incident on the material and reflects to the observer. The dotted lines indicate the phase of the light wave (e.g. it's peak). Light wave #2 enters the material at point A and changes direction due to refraction. Light wave #2 continues until it reflects off the back surface at B, travels to the front and then leaves the material where it combines with light wave #1 at point C. Comparing light waves #1 and #2, light wave #2 has travelled an additional path length of ABC. If that path length is an integral number of wavelengths, then light wave #1 and #2 will be in-phase (resulting in constructive interference). This would result in a high intensity peak. If, instead, the path length ABC results in the light waves being out of phase the result is destructive interference (or darkness)

wavelength (λ). It then reflects off the back of the object at point B and then combines with ray #1 at point C.

Here's where interference comes into play. Basically, the two rays combine at point C and based on the intensity of the light depends on whether they are in-phase or out-of-phase. The determining factor is the path length taken by ray #2 indicated by the route from point A to B to C. Let's call that path length the distance X. Light ray #2 will be in-phase when it combines with light ray #1 if the path length X is an exact multiple of the wavelength. We could express this mathematically as:

$$X = n\lambda \text{ for in-phase}$$

where X is the path length (A–B–C), λ is the wavelength of the wave, and n is an integer (n = 1, 2, 3, etc.). Basically, while travelling through the object from point A to B to C, ray #2 will go through a series of peaks and troughs and if the above equation is satisfied the peaks and troughs of the wave will line up perfectly with ray #1. This means rays #1 and #2 will combine "in-phase" resulting in constructive interference. Since the waves combine, an observer would see light reflecting off of the surface of the object.

In contrast, if the path length taken by ray #2 is not a multiple of the wavelength of the ray, the result will be destructive interference. If the path length X is described by the equation below, the two waves will be perfectly out-of-phase.

$$X = \left(n + {}^{1}/_{2}\right)\lambda \quad \text{for out-of-phase}$$

Basically, ray #2 travels through the object and when it joins ray #1 at point C, it's peaks are lined up with ray #1's troughs and it's troughs are lined up with ray #1's peaks. The net result is perfect cancellation of the two waves, resulting in no intensity. To the observer, it would appear that light entered the object but no light is detected on the reflection (i.e. it is dark).

Now let's consider the case where the object has a varying thickness—like a wedge (Fig. 16.4). In this case the path length taken by ray #2 would be different depending on the thickness of the object. The result would be a repeating pattern of constructive and destructive interference along the length of the wedge. To an observer this would be seen as a repeated pattern of light and dark such as shown in the figure. Figure 16.5 shows interference lines that arise when light from a yellow laser (with wavelength of 589 nm) illuminates two glass disks stacked on top of each other. The two glass disks are nearly perfectly flat, but when stacked there is a small air gap in the shape of a wedge similar to the diagram. The different path lengths through the air gap results in the light and dark lines shown in the figure.

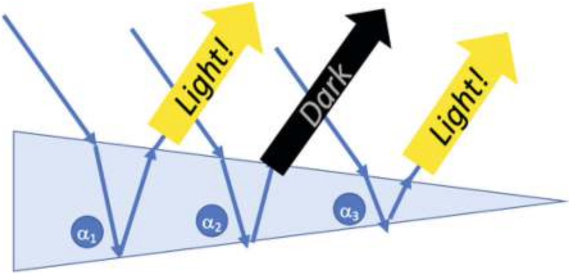


Fig. 16.4 Schematic showing an example of monochromatic light incident on a thin wedge. Since the thickness of the wedge varies along the length, the path length of the light ray travelling inside the wedge will vary. Path lengths with constructive interference will show up as regions of bright light, and path lengths with destructive interference will show up as dark regions

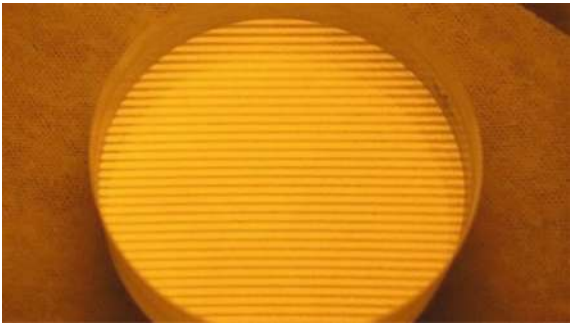


Fig. 16.5 Diagram showing interference effects when yellow light shines through an wedge-shaped air gap between two glass plates. The air gap is in the shape of a wedge leading to alternating light and dark regions, which indicate regions of constructive and destructive interference. *Credit* By Zaereth—Own work

But how does this result in the appearance of color? Consider this same experiment, but this time instead of a single wavelength of light let's shine white light on the object (Fig. 16.6). Just as before, all the spectral colors contained in white light will enter the object and change direction due to refraction. For us to see light when the light rays combine (at point C), the two rays need to be in-phase to have constructive interference. This depends upon the path length X and the wavelength λ. But, each color within white light has a different wavelength. This means that each color of light will be in-phase at a different angle. You've seen this with the rainbow-like colors in oil-slicks or with colorful patterns in bubbles. What you're seeing is result of white light entering the bubble or oil slick, and then the specific colors are observable because the light rays travelled a path length that resulted in

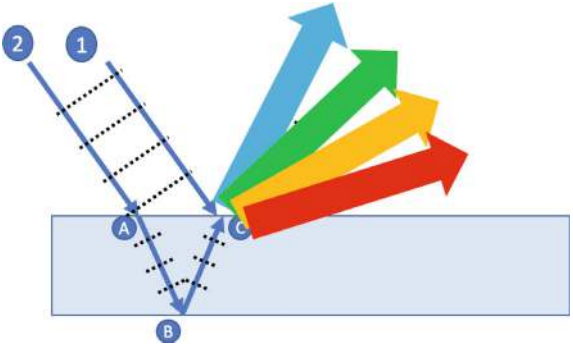


Fig. 16.6 When white light enters an object, interference will occur at different angles because each color of light has a different wavelength and thus constructive interference will occur at different path lengths. There is also the consideration of the effects of dispersion where each color of light will diffract at a different angle

constructive interference. The specific colors you see depend upon the wavelength of each color and the thickness of the bubble or oil layer. You can also see this in transparent insect wings which will show colors based on the thickness of the wing [2].

This phenomena is also apparent in the recent US twenty dollar bill. The design of the paper note includes a feature in the number 20 in the lower right corner called color-shifting ink. If you look carefully at the number 20, it changes color depending upon the viewing angle [3]. It comes about because there is a layered structure in the paper that causes interference effects to appear. That's another mechanism used to help prevent counterfeiting. Figures 16.7, 16.8 and 16.9 are common examples of color derived from interference effects.

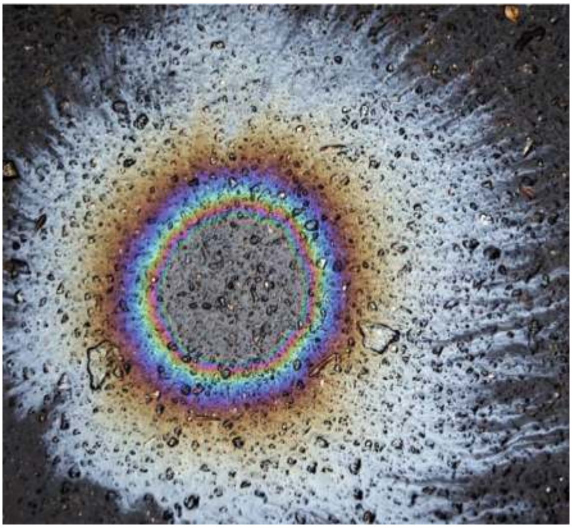


Fig. 16.7 Image of an oil slick, showing the effects of interference. *Credit* Aniskov

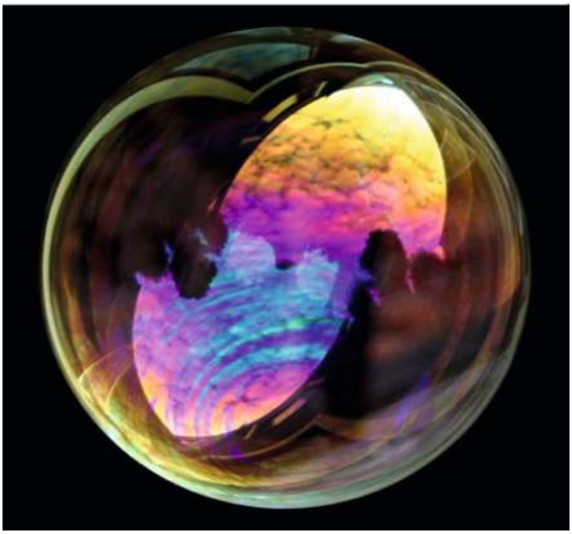


Fig. 16.8 Image of a soap bubble, showing the effects of interference. *Credit* Brocken Inaglory

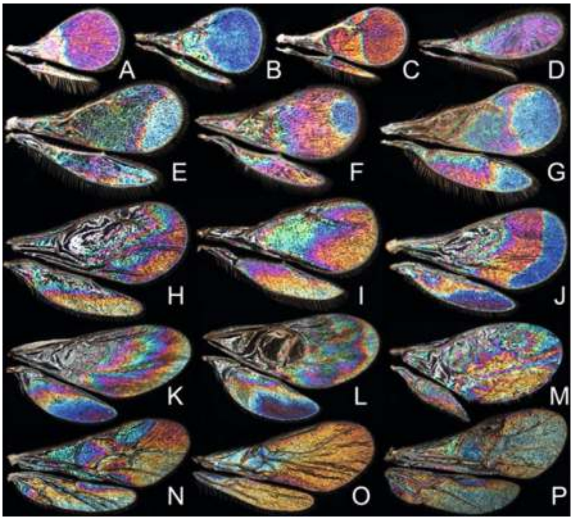


Fig. 16.9 Interference effects seen in insect wings. The wings are transparent with varying thickness so depending upon the viewing angle different colors can be seen across the wings. *Credit* Shevtsova et al. [2]

References and Further Reading

1. Color from interference is discussed in Chapter 12 in Kurt Nassau. 2001. *The Physics and Chemistry of Color: The Fifteen Causes of Color*. Wiley.
2. Shevtsova, E., C. Hansson, D. H. Janzen, and J. Kjærandsen. 2011. Stable structural color patterns displayed on transparent insect wings. *Proceedings of the National Academy of Sciences of the United States of America* 108 (2): 668–673. https://doi.org/10.1073/pnas.1017393108.
3. The US treasury department has a cool explanation of all the anti-counterfeiting features on the $20 bill here: https://www.uscurrency.gov/denominations/20

17

Diffraction: The Color of Hummingbirds, Chameleons, and Opals

The previous chapter discussed the effects of interference in a simple "one-layer" system like an oil slick on water or in looking through a soap bubble. We see color because light of a certain wavelength travels through the layer and back at a precise path length that enables constructive interference (i.e. in-phase). Thus, at that one viewing angle we just see one color—all other colors (with different wavelengths) do not meet the geometric conditions for constructive interference (in-phase). If we look at a different angle (by moving our eyes, or moving the object) different colors will come in-phase. This phenomenon is called iridescence—the changing in the apparent color of an object as the viewing angle changes [1].

We see this effect in systems with much greater complexity in both biology and minerology. Instead of a single layer, there might be multiple layers, or instead of layers it might be a regular array of particles. With these more complicated systems, when electromagnetic radiation (such as light) interacts with these structures, we usually describe it by the term diffraction. Despite a different name it's largely the same story. In Fig. 17.1, light ray #2 enters the object (this time depicted as an array of spheres) and there is a specific angle where the waves #1 and #2 are in-phase and constructive interference occurs. The critical characteristics for this system are the wavelength of light (which determines the color) and the spacing of the layers (or size of the particles).

We see this iridescence in the feathers of hummingbirds. In the Fig. 17.2, the feathers of an Anna's hummingbird change color as the bird rotates its head. With the change in viewing angle different wavelengths and different colors become in-phase.

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_17

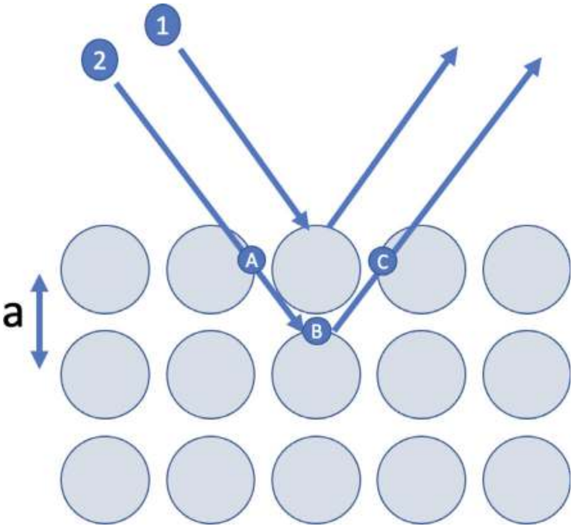


Fig. 17.1 Schematic of diffraction phenomena for an array of identical spheres. Similar to the effects of interference in a film described in the previous chapter (see Fig. 16.3), in this case light rays #1 and #2 will be in phase if the path length A–B–C equals an integral number of wavelengths. Here, instead of the thickness, the path length is determined by the size and/or spacing of spheres (indicated by the parameter "a")

Fig. 17.2 Hummingbird exhibiting iridescence with the color depending upon the observation angle. *Photo credit* Mick Thompson

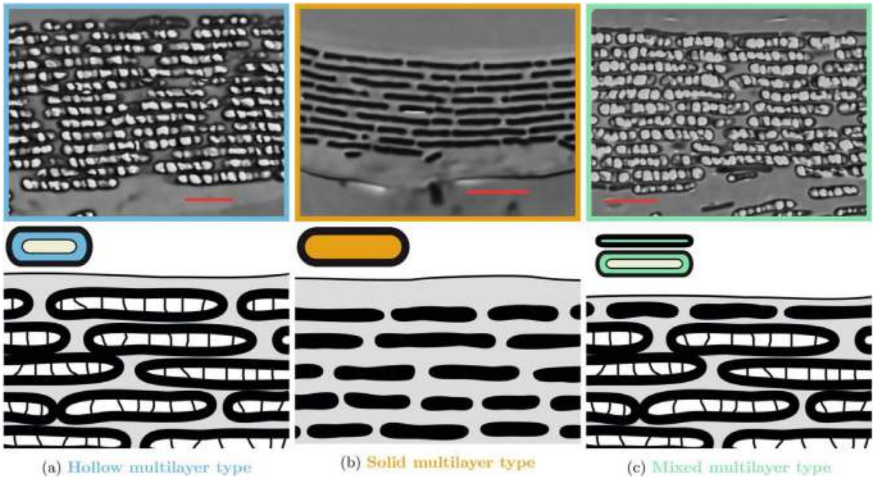


Fig. 17.3 Internal structure of the hummingbird feathers with nanometer scale features that create the iridescence effect. The structure is made up from nanometer-sized melanin platelets or rods, which can be hollow or solid, surrounded by a matrix of keratin. The spacing between the layers determines the wavelength and respective colors that appear depending upon the viewing angle. *Credit* Gruson et al. [2]

The iridescence comes from a microscopic multilayer structure in the feathers. The structure is made up from nanometer-sized melanin platelets or rods, which can be hollow or solid, surrounded by a matrix of keratin (Fig. 17.3). The spacing between the layers determines the wavelength and respective colors that appear depending upon the viewing angle [2]. We have hummingbirds in our back yard or on the trail in Oregon and they are amazing to see. The colors in their feathers pop in and out as they dip their beaks in and out of our feeder.

The key to diffraction is the relationship between the spacing of the layers or particles and the wavelength of light that creates the color. Some animals can change the spacing of these features, which has the effect of changing their apparent color. This is the mechanism that chameleons use to change color in response to a stimuli. The images shown in Fig. 17.4 is taken from a wonderful paper by Teyssier et al. [5] which shows an example of a male chameleon from Madagascar called the panther chameleon (*Furcifer pardalis*). The image on the left shows his coloration while relaxed, whereas the figure on the right shows the dramatic change in color when excited. When I first saw this paper, the first question I had wasn't about the science behind the color. Rather, I wanted to know why was this lizard so pissed off? How does one excite a lizard? Is there a standard method? Sometimes the experimental

Fig. 17.4 Example of color change from green when relaxed to red when excited in the panther chameleon. *Credit* Modified from Fig. 1 in Teyssier et al. [5]

method sections of papers like these are fun to read, but in this case in Teyssier's paper it only said "the animal was engaged in a male–male combat." I would have liked to have a lot more detail about this. I pictured something like a lizard-sized Roman coliseum with gladiator lizards battling it out. Are you not entertained? Or maybe it's a chameleon fight club, where the first rule of chameleon fight club is to not talk about chameleon fight club.

Anyway, for these panther chameleons the color mechanism is derived from an array of microscopic crystals of guanine in a matrix of cytoplasm [5]. The scattering comes about because there is a large difference in refractive index between guanine and cytoplasm. The image in Fig. 17.6 shows microscopic images of the crystals in the relaxed and excited state, where the white crystals are guanine. The white scale bar is 200 nm, so these features are smaller than the wavelength of light (400–700 nm). As you can see the spacing between the crystals is much greater in the excited state. The lizards are able to change the spacing of these crystals, which changes the geometry for different wavelengths of light diffracting off the crystals. The result is a shift in color from green to reddish orange. The CIE diagram in Fig. 17.5 shows the color path for the chameleons from the relaxed state to the excited state. This process occurs relatively quickly (the paper by Teyssier et al. says it takes a few minutes) and the process is reversible (Fig. 17.6).

This same basic effect is present in the mineral world in the unique appearance of opals [1]. Natural opals appear in many forms, some milky white with iridescent characteristics, while others show brilliant colors of red, pink,

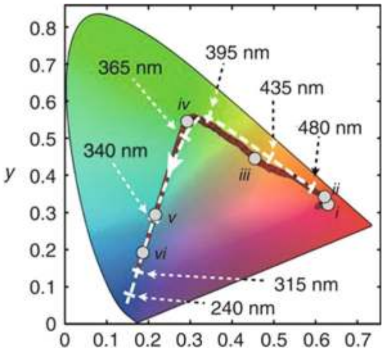


Fig. 17.5 The change in color is linked to changes in the spacing between guanine crystals in the skin. The CIE diagram tracks the shift from red to green as the spacing (listed in nm) between the crystals change as the chameleon relaxes after being excited. *Credit* Modified from Fig. 1 in Teyssier et al. [5]

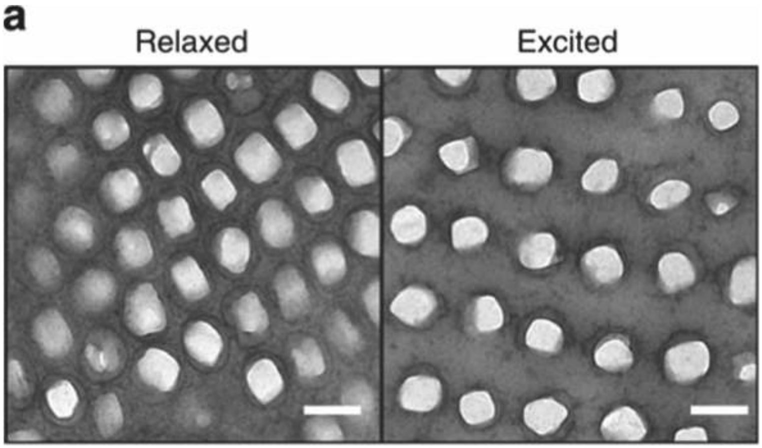


Fig. 17.6 Arrangement of the guanine crystals in the panther chameleon when relaxed (on the left) and excited (on the right). The change in spacing changes the color of light which is preferentially scattered from green in the relaxed state to red in the excited state. *Credit* Modified from Fig. 2 in Teyssier et al. [5]

orange, blue, or black. The microscopic structure of the opal looks like the schematic at the beginning of this chapter with silica (SiO_2) spheres packed into an ordered array within a matrix of air. It's not actually pure silica, but hydrated silica that has absorbed typically 5 to 10 weight percent water. The image in Fig. 17.7 is an example of the mineral opal (*This is sample CIT-6377, an opal from Australia, acquired in 1956*) and the image in Fig. 17.8 is synthetic opal. (Silica strongly absorbs water which is why you'll often find a

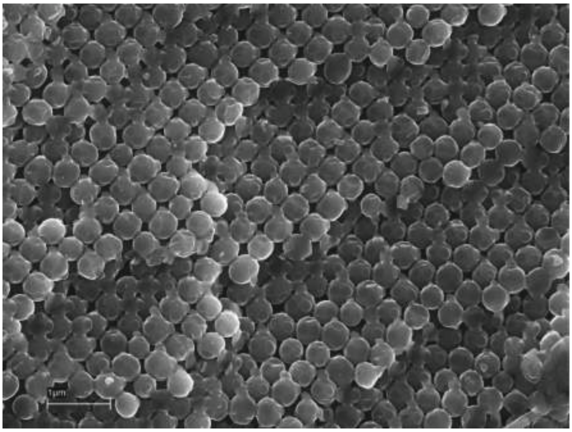


Fig. 17.7 Arrangement of silica spheres in the mineral opal. The size of the spheres determines the color that is preferentially scattered. *Photo Credit* Chi Ma, Caltech

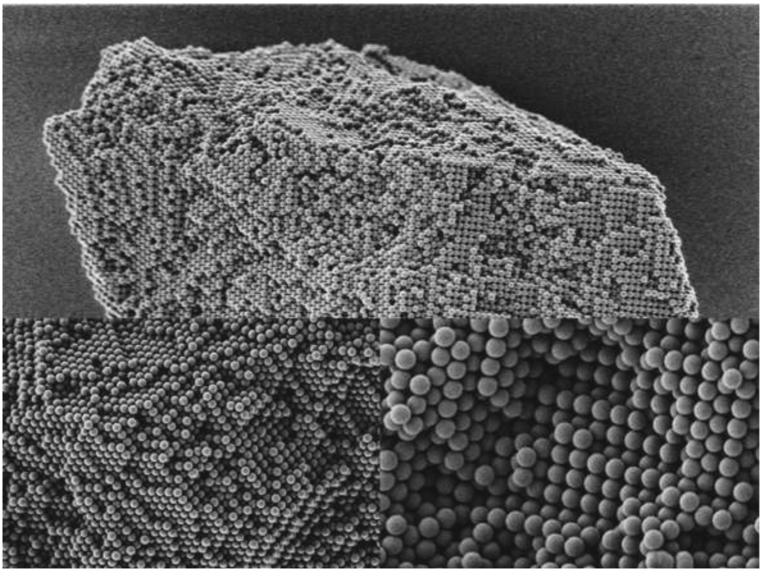


Fig. 17.8 Image shows the arrangement of silica spheres in a synthetic specimen of opal. *Credit* Roy Goldberg at pinfire.de

packet of silica beads in your packaged food or sensitive electronics with the instructions DO NOT EAT!).

The color effect in opals works like the other examples we've discussed. White light the enters the opal and diffracts due to the ordered arrangement of the silica spheres. The colors which are observed is determined by the size of the spheres. This is similar to a multilayer system where the spacing between the layers determines the colors that are observed. The figure shows a microscopic image of a synthetic opal consisting of hydrated silica spheres that are around 400 nm.

The unusual structure of opals is the result of some interesting chemistry. There are basically two different ways that opals form. The first method involves the interaction between silica and water. Silica is the most common constituent in the Earth's crust, and the opals form in cracks and crevices where silica and water are present for very long time periods. As water slowly evaporates (over literally millions of years) the silica (or silica hydrate) precipitates out of the water into microscopic spheres. This is not unlike the process of growing sugar crystals (i.e. rock candy) out of a solution of sugar and water. If the conditions are stable over very long time scales, the microspheres form into a highly ordered arrangement with a uniform size. This form of opal is called precious opal and it is characterized by a brilliant play of color. Just like with our previous examples of diffraction phenomena, the size of the sphere determines the color. Small spheres will result in short wavelength colors like blue and green, and larger spheres will result in yellow, orange or red opals [6]. If the arrangement of spheres is not well ordered (probably due to changes in temperature or pressure during the precipitation process) the result is common opal which lacks color but has a pearly, milky white luster. Amazingly, Australia is home to 95 percent of the worlds precious opals. This is because it was home to an inland sea that was rich in silica-based sands, which provided the starting materials for the formation of opals.

It is also thought that opal can derive from or be aided by biological processes. In particular, over long time periods microbes present in silica-based rocks can secrete acids that dissolve the silica which then creates the conditions necessary for opals to form. In particular, opals are sometimes known to form in the unique microbe-rich environment surrounding hydrothermal vents on the sea floor. What makes this particularly interesting is the recent discovery of opals on Mars (*e.g.* Squyres et al. 2004; Bibring et al. 2005; Poulet et al. 2005 [7]). The NASA rover Curiosity found evidence of opals beneath the surface of the Gale Crater, in an area which would provide protection from the hazardous environment on the surface. Accessing water on Mars is important for future exploration and eventual human colonization of the planet. Given the critical role that water plays in the formation of opals, finding opals on the surface of Mars implies the presence of water in the Martian past. There's even the possibility that this could lead to evidence of microbial life on Mars given the link between opal and microbes [8].

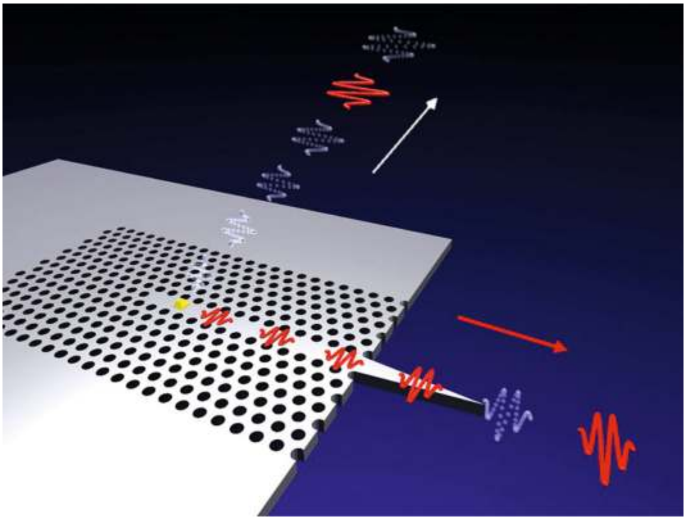


Fig. 17.9 Schematic showing the control of light using a photonic crystal. *Credit* Arcari et al. [9]

Manmade or synthetic opals are also increasingly important area of research development materials for high-speed computing and communication. Electrons can only go so fast and ultimately light is the fastest method of transmitting information which is where synthetic opals play a role. Numerous researchers have developed laboratory-scale methods to fabricate ordered arrays of particles designed to capture and direct light similar to how wires and conduits transport electrons. The device is called a photonic crystal, and while the details are complicated, it still operates on the same principals we've been discussing [9]. The ordered arrangement of particles (or sometimes voids) interacts with light of a specific wavelength through diffraction. In this manner you can create channels and barriers and all sorts of devices for controlling light (Fig. 17.9).

With all this talk of colors due to scattering in feathers, and colors in oil slicks and opals due to interference and diffraction, I've lost track of time and stumbled my way back down the mountain and back to my car. Leaving the natural world behind, I do see some of the same color mechanisms as before. There's pigments in the paint of my car and in the interior fabric and dashboard. It's an old car, so there's also green algae growing in the crevices. One thing that is different is some of the colors I see come from electronic displays. The phone in my hand, the color display showing the speed I'm driving, fuel level in the gas tank, and the radio station I'm listening to. The colors we see here have a different mechanism than what we've seen before.

References and Further Reading

1. Diffraction and opals are discussed in Chapter 12 in Kurt Nassau. 2001. *The Physics and Chemistry of Color: The Fifteen Causes of Color*. Wiley.
2. Gruson, Hugo, Marianne Elias, Christine Andraud, Chakib Djediat, Serge Berthier, Claire Doutrelant, and Doris Gomez. 2019. Hummingbird iridescence: an unsuspected structural diversity influences colouration at multiple scales. bioRxiv 699744. https://doi.org/10.1101/699744
3. Here's a nice summary of iridescence in hummingbirds: https://www.allaboutbirds.org/news/what-is-the-essence-of-iridescence-ask-a-hummingbird/#
4. Here's a wonderful review of iridescence in animals, with a focus on the functionality: Doucet, Stéphanie M., and Melissa G. Meadows. 2009. Iridescence: a functional perspective. *Journal of the Royal Society Interface* 6: 6S115–S132.
5. Teyssier, J., S. Saenko, D. van der Marel, et al. 2015. Photonic crystals cause active colour change in chameleons. *Nature Communications* 6: 6368.
6. The Gemological Institute of America has a nice summary of the colors of opals. https://www.gia.edu/opal-description
7. Here are some recent findings of opals on Mars: (1) Squyres, S. W. et al. 2008. Detection of silica-rich deposits on mars. *Science* 320: 1063. (2) Bibring, P. et al. 2005. Mars surface diversity as revealed by the OMEGA/mars express observations. *Science* 307: 1576–1581. (3) Poulet, F., J. P. Bibring, J. Mustard et al. 2005. Phyllosilicates on mars and implications for early Martian climate. *Nature* 438: 623–627.
8. The National History Museum in the UK discusses the link between life on Mars and Opals: https://www.nhm.ac.uk/discover/news/2015/july/opals-on-mars-could-hold-record-ancient-life.html
9. Arcari, M., et al. 2014. Near-unity coupling efficiency of a quantum emitter to a photonic crystal waveguide. *Physical Review Letters* 113: 093603.

18

Color from Displays

To this point all the colors we've discussed have been "natural" colors. Colors that appear in the sky, in the Earth, in living things, both plants and animals, and even on other planets. However, these days a lot of the colors we see come from the electronic devices in our hands and in our homes. Whether it is a smart phone, a television, a tablet, a smart watch, or the screens in our electronic cars, the common feature in that all these devices effectively convert electrical energy into light—light that can contain millions of colors. In writing this chapter, I'm reminded of the dozens of books sitting on the bookshelf in my office that are hopefully out of date when it comes to electronic devices. The pace of technology evolution is truly mind blowing. In the middle class house I grew up in, we had one color television (not HD, not cable, not satellite, just a TV) and a handful of old black-and-white televisions in various states of disrepair. My father was an electrical engineer, so no electronic device in our house ever got thrown away. While our family was a little unusual, it was not uncommon for people to have television sets for more than 10 years. There were electronics stores (like Radio Shack) that sold spare parts (like transistor tubes and capacitors) so devices could stay in service a long time. When I went off to grad school I inherited the old color TV and was crushed when one day after almost 20 years of service it stopped working. Things changed dramatically with the advent of display technologies in the late 1990's and early 2000's. It became cheaper to manufacture televisions, easier to incorporate color, and the technology was easily scalable to making large televisions. This led to televisions appearing in homes all around the world, and with that an explosion of color. Soon that expanded to other electronic devices such as laptops with color displays,

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_18

smart phones, tablets, and color displays in our automobiles. The pace of change was even more dramatic. The latest study I can find says the average life expectancy of a television is four to six years. That's not when the actual device becomes non-functional, but it's the time period when the device is typically replaced for a new television that is faster, bigger, more colorful, and with additional features. Obviously, this incredible computational power along with the colorful display of information at our fingertips has changed our species forever. There are things we can do now that are enabled by these devices that we could not imagine just 10 to 20 years ago. I now hike with a smart phone that has a color topographical map that tracks my GPS location. I take full-color photos of the sky, the flowers, the leaves, the birds, the mountains in the distance and rocks beneath my feet. With an app on my phone I can identify the plants, insects, and animals that I encounter (even the scat!). It will almost certainly be the case that we will be capable of things 10 to 20 years from now that we cannot even conceive of right now.

Of course, assuming you haven't been living in a cave you probably know all this because you've lived through this. I review this story for a simple reason. The pace of change in this field is so rapid that, again looking back at those antiquated books on my bookshelf, much of what I describe in this chapter is likely to be obsolete by the time you finish reading this chapter. Therefore, I'm not going to go into great detail on specific display technologies and instead I'll focus on the fundamentals on how electricity is converted into millions of colors of light. I'm sure some of it will still be out of date by the time you read this book, but hopefully the fundamentals will still apply.

The fundamental concept I refer to is the conversion of electrical energy into light. In this case the electrical energy either comes from a battery (as with our phones, laptops or tablets), or an electrical outlet for televisions and desktop computers. In previous chapters, we discussed the origins of the *emission* of colored light. This process involves an electron in a high energy state (i.e. an excited state) which drops down to a lower energy (or ground) state. Due to conservation of energy, the electron gives off a photon of light and the color of that light depends on the energy. The key is that energy from somewhere elevates the electron into the excited state that starts the whole process.

With fluorescence and phosphorescence (for example fluorescent minerals) electrons are excited into high energy states by ultraviolet light. With incandescence (for example hot coals in the fireplace or stars in the sky), high temperature excites electrons into high energy states. With northern lights, electrons are excited into high energy states by the solar wind. Light emission in electronic devices works on a similar principle, but it is *electrical*

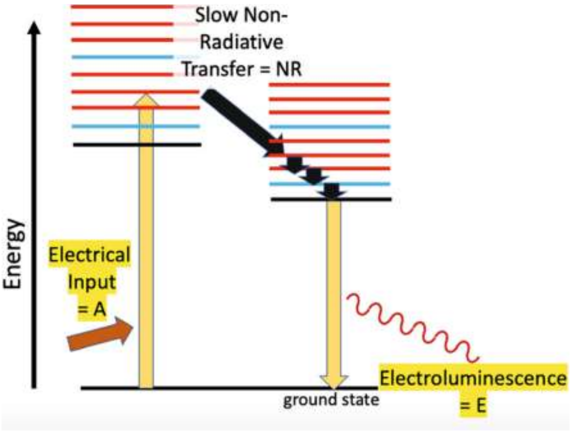


Fig. 18.1 Schematic showing electroluminescence. Overall, it is similar to fluorescence but instead of exciting electrons into high energy states with light, electricity is used. The energy input (from a battery or power supply) excites electrons into high energy states. Some energy is lost due to slow non-radiative transfer, and the light is emitted as electrons drop back down to the ground state

energy that elevates electrons into high energy states. As those electrons relax back down to the ground state, they give off light which we see as a specific color depending upon the energy. In this chapter we will briefly discuss three common means of creating colored light, namely electroluminescent displays, liquid crystal displays (LCD),and light emitting displays (LED). The materials, the structure, and the fabrication techniques will no doubt evolve rapidly over the next decade, but we can draw upon the basic principles we've already discussed to learn how they work.

Electroluminescent devices are probably the simplest display technology. It operates through a similar mechanism to fluorescence and phosphorescence. The only difference is electricity is used to excite electrons into high energy states (Fig. 18.1). Some energy is lost due to non-radiative transfer (which you remember involves atoms or molecules losing energy through vibrations or rotations), and then the electron drops back down to the ground state. In the process it emits a photon and the energy of the photon determines the wavelength and color of light that is emitted.

The structure of the device is quite simple—it's just a layer of the electroluminescent material (probably deposited on a piece of glass or silicon wafer) which is connected to the battery. This is used to light up watch faces, or instrumentation in automobiles, and other niche applications. It's simple enough that it can be used in lots of different functional forms. One recent paper by Shi et al. [2] demonstrated that electroluminescent material could be incorporated directly into a textile along with other electrical components. The result is a smart fabric where your clothing becomes the display. Figure 18.2 taken from the paper shows a number of examples of how display technology integrated into clothing could work. There's a motorcycle jacket with navigation, a businessman's blazer for sending texts, and shirts that can be used to communicate messages. It even includes examples of clothing that displays real-time biometric data. I will let you draw your own conclusions with these examples, but I can think of nefarious purposes for each.

Liquid crystal displays (LCD) are a relatively mature technology that started in the 1960's and have gradually grown in functionality and scale. The original Hewlett Packard calculators used LCD devices to display the numbers. (As a side note, I despised the counter-intuitive logic those calculators used!). In modern LCD color displays, a white light shines from the back of the display towards the observer (called a backlight). The white light shines

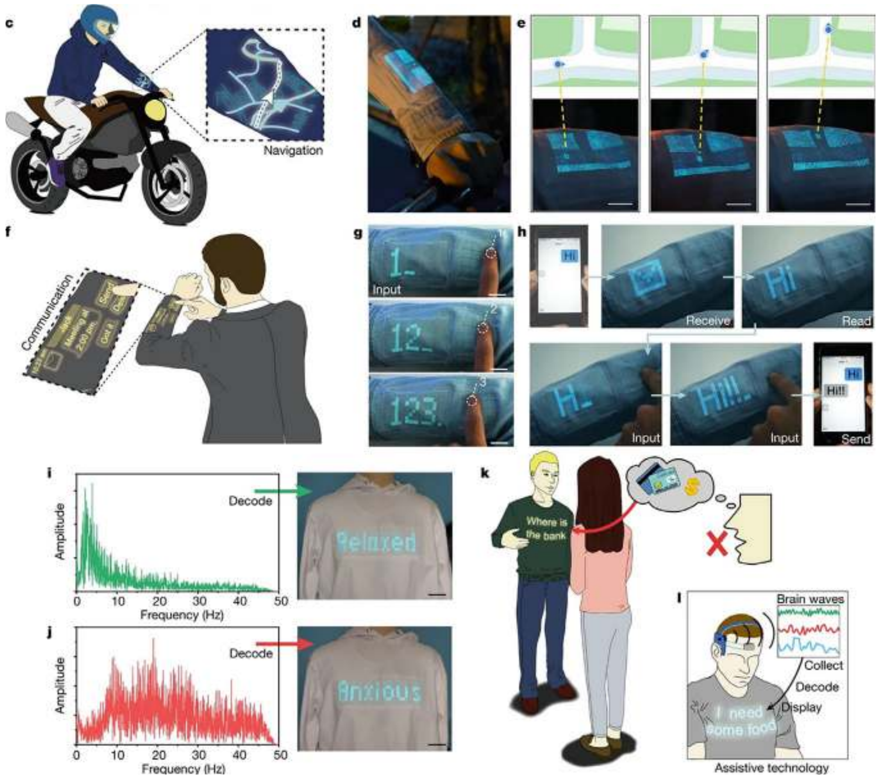


Fig. 18.2 Displays are everywhere now. This article by Xiang Shi shows numerous examples of displays directly integrated into clothing. *Credit* Figure adapted from Shi et al. [2]

through a layer containing liquid crystal. The liquid crystal layer consists of a collection of long skinny molecules that essentially have two conformations. They can switch between these two states when an electrical voltage is applied. In one state the liquid crystal layer allows the light to pass through, and in the other state it blocks the light. In essence it acts like a voltage-controlled light switch. To display colors, the white light passing through the LCD layer passes through a color filter. It blocks all colors except for one color, usually red, green and blue. To get thousands or millions of colors, the red, blue, and green light is mixed in the correct intensities as shown in Fig. 18.3. The color mixing laws we met long ago will dictate the color that we see. Of course, the size of the red, green, and blue pixels are much smaller than we can see with the naked eye unless we are standing close to the television screen with a magnifying glass. Nonetheless, the three colors travel independently through the air to arrive at the cone photoreceptors in our eyes. Our brain interprets the light input as a color based on the relative intensities of the red, green, and blue signals not unlike how we understand the CIE diagram.

Display devices based on light emitting diode (LED) technology have become dominant because they have a number of significant advantages. The original materials used for LEDs were based on semiconductors like silicon or gallium nitride. More recent devices use organic materials (organic meaning carbon-based not, organic in the nutritional sense) and are often referred to as OLEDs (for organic light emitting diodes). Similar to the relationship between the color of atomic emission and the element, each LED material

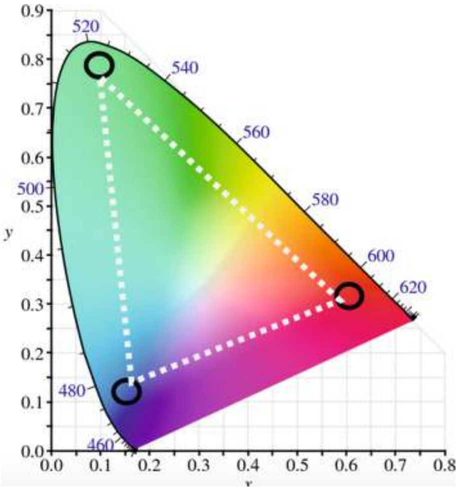


Fig. 18.3 Modification of the CIE diagram showing the three constituent colors (red, green, blue or RGB) from which millions of colors can be created across the diagram. *Credit* BenRG

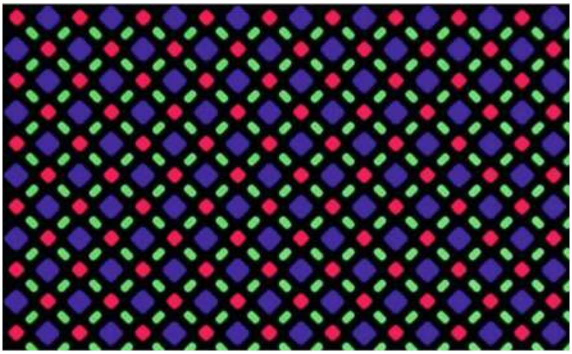


Fig. 18.4 Close up of the red, green, and blue LED pixels in a 2024-era smart phone. Millions of colors can be created by controlling the intensity of light from these three colored pixels. *Credit* DisplayMate Technologies

emits light of a specific wavelength and specific color. The precise mechanism is more complicated that our previous examples, but in essence electrical energy (from the battery or electrical outlet) excites electrons into high energy states and when the electrons relax back down to the ground state light is emitted. Each material emits light at a wavelength that is determined by its chemistry and structure. For example, the semiconductor InGaN (indium gallium nitride) emits blue light, while AlGaInP (aluminum gallium indium phosphide) emits red light. In the design of a display, LED materials are used to create the three base colors, namely red, green and blue. The intensity of each color can be controlled independently, and additive mixing determines the color that we observe with our eyes. In a typical 2024-era smart phone, each sub-pixel is around 10 μm in size and there are more than 1 million sub-pixels of each color. The image in Fig. 18.4 shows the arrangement of the subpixels in a modern iPhone display.

The beauty of LED displays is the ability to scale them to any dimension. While there are plenty of uses of LEDs for small scale or handheld displays (watches, laptops, automobile instrumentation), LEDs can also be used to build large-scale displays. At the time of writing this book, the world's largest display is the Sphere in Las Vegas, Nevada. It contains more than 1 million individual LEDs spaced eight inches apart over a spherical surface of approximately 580,000 square feet (Fig. 18.5).

From larger-than-life color displays to handheld color displays at our fingertips, manmade color has become a significant part of our lives. We've pretty much covered every type of color that we see in our world. In the last chapter, we'll explore what it all means.

Fig. 18.5 The worlds' largest LED display is the Las Vegas Sphere with 1 million individual LEDs spread out over 580,000 square feet. *Credit* Y2kcrazyjoker4

References and Further Reading

1. Color display technologies are discussed in Chapter 14 in Kurt Nassau. 2001. *The Physics and Chemistry of Color: The Fifteen Causes of Color*. Wiley. It's somewhat obsolete, but by the time you read this chapter so is this book!
2. Shi, X., Y. Zuo, P. Zhai, et al. 2021. Large-area display textiles integrated with functional systems. *Nature* 591: 240–245.

19

The Meaning of Color

Throughout the course of this book, we've explored the myriad ways that color appears in our lives. All along my hike, everywhere I look there is color. In the deep blue sky above my head, the colorful rocks beneath my feet, and living green all around me. But what does it all mean?

The physics tells us the cold hard facts about color. We know light is a form of energy, the energy of light depends upon its wavelength, and each wavelength corresponds to one the spectral colors that we perceive from blue to red. However, there's much more to it than that. The most important concept to understand is that the perception of color truly occurs within our heads. Throughout this book we've discussed the dramatic sequence of events that leads to our observation of color. Light emanates from the sun, travels through the solar system and after eight minutes it enters our atmosphere. Sunlight hits an object in our field of vision, and interacts with the object before the light rays ultimately reflect back to our eyes. Based on the spectral characteristics of that light (that is the mix of wavelengths that are present in that packet of light), a series of rods and cone sensors in our retina will register and a series of electrical signals will be sent to our brains so that it can construct a colorful image. This is where the magic happens.

Let's focus on the color part of this story. The brain takes that input and based on which wavelengths are present (or absent), it interprets the collection of light rays as a specific color. Recall that the color orange could be represented by a ray of light with the wavelength of about 600 nm. Or it could be a combination of light rays that add together, like red and yellow rays in the appropriate amounts. In fact, there is an infinite number of possible combinations that would result in our brains interpreting the color

D. Cann, *A World of Color*, Copernicus Books,
https://doi.org/10.1007/978-3-031-97371-0_19

as orange. We use these combinations in display devices to create the whole spectrum from just three colors. For example, we can create thousands of shades of orange from the combination of red, green and blue lights in our smart phone screens. It works in painting as well, where the use of the pointillism technique in art results in a similar effect. Tiny dots of paint, too small for our eyes to resolve individually, combine into the vibrant colors of a painting.

Since the perception of color occurs within us, I think it quite natural that it merges with everything else in our sense of awareness. Clearly, the color of an object in our field of vision supports our other senses. We know the color of an object informs us if it is safe to touch. The color of insects and reptiles can indicate if they should be left alone. An object that is glowing red is too hot to touch. The color of peppers can indicate how spicy they taste (but not always). Even from person to person, the color of our faces can communicate our feelings and intentions.

While on my hike there is striking natural beauty in so many colorful things that we see. However, the inherent beauty of these colors just scratches the surface. All along the journey we've taken in this book, we've learned that the color of an object is just a hint about what goes on behind the scenes. Thus, there's an inherent mystery in the origin of color. I started out on this quest to understand the origins of color as we perceive it on our lives. However, as with many things we directly experience in our lives, something we directly perceive is a really culmination of many unseen factors. This makes color a complicated subject to discuss, but I think it is a good example of the "awe" that Carl Sagan refers to in his writings about science. When we are in awe at the sight of a beautiful sunset we are privileged to stand at the end of long chain of events that created that color. Powerful rainbows created by sunlit water droplets in the misty spray of a waterfall, molecular pigments in stunningly intricate patterns adorn flowers that beckon bees to pollinate them, vibrant green leaves atop tall gravity-defying trees that are natural engines converting sunlight into chemical energy, and colorful, ancient rocks that tell a story of their violent formation. Now, I've come to the end of my journey. I've gained a greater appreciation with the understanding that each color we see in nature tells a story of awe and wonder that is hidden in the science. All we have to do is open our eyes…