

George Pavlidis

Foundations of Photography

A Treatise on the Technical Aspects
of Digital Photography

 Springer

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*To Evrinomi, the beautiful person who has
always been my stable foundation.*

Preface

Any study of photography naturally relates to the study of how one may use light (Greek φως, originally pronounced 'p^hɔ:s', now simplified to 'fos') to write, inscribe, or create images (Greek γράφω pronounced 'γ^{ra}.fo'). fos + γ^{ra}.fo gives φωτογραφώ, the Greek word for *to photograph*. Light has had and continues to have a special impact on humans, in fact in everything that relates to what we perceive as *life*. It is what wakes us up in the morning, what warms us, and what gives us the images of the world around us. It has the power to turn a simple view at the sea into serenity and anticipation, the gaze at the forest into calmness, the glance at the sky and stars into cosmological and existential search, or the look at a loved one into joy.

Recognising the value of light in life, humans throughout history devised ways of capturing the images created by light, while, at the same time, wondering and exploring the very nature of this magical element, sometimes using science, sometimes using logic and philosophy, and sometimes relying on feeling and superstition. What is certain is that light is a key element of the universe that is our home, exists regardless of our perception of it, and even plays a defining role in relationships within the universe.

In science, many attempts have been made to explain the nature of light, which sometimes led to theories about the particle nature, the wave nature, or the electromagnetic nature of light. The first to support a *particle theory of light* was a brilliant person called Newton, when in 1675 he (but also other scientists of that era) argued that light was a continuous stream of particles travelling in a straight line from a source, thus, giving a pure particle character to light. Even in the same period but also later, several great scientific minds supported a *wave theory of light*, attributing to it exclusively a wave nature, like the waves on the water surface. Among them were Robert Hooke (1660), Christiaan Huygens (1678), Leonhard Euler (1746), Tomas Young (early 1800), Augustin-Jean Fresnel (1817), and Simeon Denis Poisson (1820s). With the development of electromagnetic theory, scientists such as Michael Faraday (1845), James Clerk Maxwell (1862, 1873), and Heinrich Hertz paved the way towards an *electromagnetic theory of light*. With the advent of Einstein's theory of special relativity in 1905, the idea of a *dual nature of light* was first introduced, which solved the paradox of the constant speed of light, creating, in this process,

another ‘paradox’ that space and time are somewhat more ‘exotic’ parameters of the universe. At the same time, the light appeared to play an even more important role, since first appeared as the connecting element between energy and mass, through the famous Einstein simplified equation $E = mc^2$. In addition, the acceptance of the dual nature of light provided an ‘elegant’ interpretation of the paradox of the photo-electric effect, the release of electrons from a surface when light falls upon it. In fact, it was this interpretation for which Einstein was awarded the Nobel Prize. This view was supported by scientists such as Max Planck (in 1900) with the interpretation of black body radiation, which reinforced a *quantum theory of light* (photons) that backed the dual nature while paving the way for the advent of quantum mechanics and quantum electrodynamics. Even to those not particularly fond of mathematics and science, the names of the aforementioned scientists sound particularly familiar and show the importance given by humans in the understanding of light, highlighting its uniqueness in the universe.

One might say that the study of light within subjects like photography is more related to its wave nature. As a wave, light corresponds to the known and mapped spectrum of electromagnetic radiation, since it is a ‘carrier’ of energy in the universe. Apparently, the part of this spectrum that relates to photography is only a small one, the one called the ‘visible spectrum’, that is, those frequencies (or wavelengths) that are detected by the human eye. These frequencies are higher than microwaves, which are used in communication and some other technologies useful for heating, and are located between the areas defined by infrared and ultraviolet radiation. In addition, one of the characteristic properties of light that plays an important role in the study of issues related to photography is that of *refraction*. Refraction is the phenomenon, in which, when light passes through different media (e.g. from air to water, or through a lens), a change in its velocity occurs, which is expressed by a change of direction of propagation. In addition, there is also the phenomenon of *chromatic dispersion*, in which short wavelengths (violet light) are refracted (bent) more than long wavelengths (red) and this is why the well-known ‘light spectrum’ appears when white light passes through a prism, or rainbows appear in the sky.

Inspired by how biological systems, like the human visual system, detect light and form images, humans have a long history of trying to capture light and permanently imprint images using special techniques, devices, and equipment. This history has its roots in ancient times when early thinkers got an idea of what a dark room (camera obscura) might be, even during times when it was impossible to create one. During the later scientific revolution, chemistry has been put to the task, with many great contributions that ultimately made it possible to permanently imprint full-colour images on various media and surfaces. In the following years, the technology to create photographs switched from a chemistry to an electro-mechanical application, which, eventually, enabled smaller devices with better results and wider applicability. A significant step was made during the twentieth-century digital revolution, carrying along the imaging technology. Significant advancements in digital systems made it possible for high-quality imaging with smaller and smaller devices, at massive scales with enhanced sharing capabilities.

It seems that *the art and science of photography* has been the subject of numerous studies and there is a vast relevant literature. Worldwide, photography matured to a state-of-the-art technical and artistic level around the twentieth century, and in the twenty-first century, it walked boldly into the digital realm. One could easily find several curricula that support the study of photography and there is a vast amount of online courses on photography, primarily focusing on its artistic form. This treatise departs from that treatment and studies photography as a highly scientific and technical subject so that it may be of actual utility to those interested in the principles and the inner workings of the apparatuses, providing, thus, an understanding of why images and photographs are created the way they are, what the limitations may be, and which configurations may result into which outcomes and why.

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George Pavlidis

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Acronyms

A	Aperture Priority
AE	Automatic Exposure
AE-L	Automatic Exposure Lock
AF	Autofocus
AF-A	Area Autofocus
AF-C	Continuous Autofocus
AFS	Silent Autofocus
AF-S	Single Autofocus
AV	Aperture Priority
B	Bulb
B&W	Black and White
BIF	Bird in Flight
CF	Compact Flash memory card
CFast	Compact Flash memory card with faster Serial ATA bus
CFexpress	XQF form factor memory card that utilises NVMe storage
CMYK	Cyan, Magenta, Yellow Black
CSC	Compact System Camera
CWB	Custom White Balance
DNG	Digital Negative Graphic
DOF	Depth of Field
DPI	Dots per Inch
DSLR	Digital Single Lens Reflex
DVI	Digital Visual Interface
DX	Crop Sensor Format
EC	Exposure Compensation
ED	Extra Low Dispersion Glass
EF	Canon Full Frame Sensor Format Lenses
EF	Electronic Focus
EF-S	Canon Crop Sensor Format Lenses
ETTL	Expose to the Left
ETTR	Expose to the Right

EV	Exposure Value
EVF	Electronic Viewfinder
EXIF	Exchangeable Image File Format
FF	Full Frame
FOV	Field of View
FPS	Frames per Second
Full HD	Full High Definition
FX	Full Frame Format
GB	Gigabyte
GIF	Graphics Interchange Format
HDMI	High Definition Multimedia Interface
HDR	High Dynamic Range
HFD	Hyperfocal Distance
HSM	Hyper Sonic Motor for Sigma
HSS	High Speed Sync
IF	Internal Focusing
IPTC	International Press Telecommunications Council
IQ	Image Quality
IR	Infrared
IS	Image Stabilisation
ISO	International Standards Organisation
JPG or JPEG	Joint Photographic Experts Group
KB	Kilobyte
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LR	Adobe Lightroom
LTE	Long Time Exposure
M	Manual
MB	Megabyte
MF	Manual Focus
microSD	Small form factor Secure Digital memory card
microSDHC	Small form factor Secure Digital High Capacity memory card
microSDXC	Small form factor Secure Digital Extended Capacity memory card
MLU	Mirror Lock-up
MP	Megapixels
MS	Memory Stick
MUP	Mirror Lock-up
ND Filters	Neutral Density Filters
NR	Noise Reduction
OCF	Off Camera Flash
OCR	Optical Character Recognition
OEM	Original Equipment Manufacturer
OOC	Out of Camera
OOF	Out of Focus
OS	Optical Stabilisation or Operating System

OVF	Optical Viewfinder
OZ	Optical Zoom
P	Programmed Autoexposure
PNG	Portable Network Graphics
PP	Post Processing
PPI	Pixels per Inch
PQ	Picture Quality
PS	Adobe Photoshop
PSE	Adobe Photoshop Elements
RGB	Red, Green, Blue
SD	Secure Digital memory card
SDHC	Secure Digital High Capacity memory card
SDXC	Secure Digital Extended Capacity memory card
SLR	Single Lens Reflex (same as DSLR, but referring only to film cameras)
SP or S	Shutter Priority
sRGB	Standard RGB Colour Space
SS	Shutter Speed
SWM	Silent Wave Motor
TB	Terabyte
TC	Teleconverter
TIFF or TIF	Tagged Image File Format
TLR	Twin Lens Reflex
TOG	Pho<tog>rapher
TTL	Through the Lens metering
TV	Time Value (usually in shutter priority mode)
USB	Universal Serial Bus
USM	Ultra Sonic Motor
UWA	Ultra Wide-angle
VR	Vibration Reduction
WA	Wide-angle
WB	White Balance
XQD	XQD memory card based on the fast PCI Express interface

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Chapter 1

From Vision to Photography



—Οὐ μὲν οὖν ἐστὶν ἡ ὄψις, τοῦτ' ἐστὶν ὁρατόν, ὁρατὸν δ' ἐστὶ χροῶμά τε καὶ ὁ λόγος μὲν ἐστὶν εἰπεῖν, ἀνώνυμον ... τὸ γὰρ ὁρατόν ἐστι χροῶμα, τοῦτο δ' ἐστὶ τὸ ἐπὶ τοῦ καθ' αὐτὸ ὁρατοῦ καθ' αὐτὸ δὲ οὐ τῷ λόγῳ, ἀλλ' ὅτι ἐν ἑαυτῷ ἔχει τὸ αἴτιον τοῦ εἶναι ὁρατόν.^a

Aristotle, On the soul

^a The object, whose sense is the view, is the visible. Visible is the colour, and the one that we can explain with the mind, but it does not have the same name....The visible is therefore the colour; and this, exists (on the surface), on the perceptible itself, which is per se visible not by word, but because it has in itself its cause to be visible.

Abstract Among the most important senses that humans use to experience the material world is vision. Vision gives rise to visual perception that is considered to be crucial for our understanding of the environment. As such, vision and visual perception have been the target of research for many of humanity's great minds throughout the ages. Understanding of the workings of vision, as well as of the workings of nature, gave rise to technologies that mimic and sometimes supersede the human capacities in vision. This chapter serves as an introduction to this treatise by providing a background on how vision works and how we came to develop the theory and techniques to be able to capture permanent images on various media.

1.1 Introduction

Humans perceive the world using a variety of senses. Of paramount importance among them is the sense of light,¹ which provides the input data for visual sensation and thereby spatial and spectral perception. This is commonly called the *visuospatial perception* or simply *visual perception*. Visual perception is, apparently, closely linked to the interpretation of sensed visual stimuli. What is called the human vision, can be viewed as the sensorial input to the complex process of visual perception.

It is by the eye alone that we know the countless shining worlds that fill immeasurable space, the distant landscapes of our earth, with all the varieties of sunlight that reveal them, the wealth of form and colour among flowers, the strong and happy life that moves in animals. Next to the loss of life itself, that of eyesight is the heaviest.

stated *Hermann Ludwig Ferdinand von Helmholtz* in the opening of his 1868 lecture on the *Recent progress of the theory of vision* (von Helmholtz, 1885).

Perception of the world based on visual stimuli, being a cognitive function of significant importance, has been a subject of substantial inquiries since the dawn of modern thinking, seeded by the ancient Greek philosophers, like *Alcmaeon of Croton* (6th–5th century BCE), *Empedocles* (5th century BCE), *Democritus* (5th–4th century BCE), *Plato* (5th–4th century BCE) and *Aristotle* (4th century BCE), who also cites the work of others. A common conceptualisation of the era (with exceptions, of course) was that *light emanates from the eyes* and was connected with notions of the basic elements of being. A first *Greek colour theory*² is described by Benson (2000); this is a theory largely influenced by a common conceptualisation of that era for a four-colour system based on *white, yellow, red, black*, indeed influenced by the notion of the four basic elements in nature (fire, earth, air, water, possibly in corresponding order).

Although the initial approaches were based on a false hypothesis that light is a type of fire emanating from the eyes, the philosophers were not afraid to walk the paths of logic to approach the more elusive phenomenon of perception. Plato's allegory of the cave highlights a pervasive theory of visuospatial perception with significant philosophical and scientific implications; *perception of the world around consists of reflections of that world within*, in a complex synthetic process in the brain, based upon stimuli captured by the sense of vision. The pervasive self-world problem arises from this theory that is summarised in not knowing *how a brain is able to distinguish itself from the world it creates* (Plato, 2014; Lehar, 2005). Interesting contributions to

¹ The word *light* most probably originates in the ancient Greek λευκός (/lef'kos/), meaning *white*. Although the word for white might have been transformed to become the word for light, the original Greek word for light is φῶς (/fos/), probably from the word φάος (/fa.os/), which originates in the Proto-Indo-European root **b^heh₂* (shine).

² It is suggested that the word *colour* comes from the Latin *colōs* which transformed to *color* from the proto-Indo-European **ker-* (cover, conceal, save). Greeks used the word χρῶμα (/k'riouma/), in English *chroma*, from the proto-Indo-European root **g^hrēw-* (grind, rub). The original meaning of the origins show that the words used to describe colour seem to relate to the covering or the roughness of a surface.

the understanding of the propagation of light was made by the *Heron of Alexandria*,³ who in his work *Catoptrica* (or *Catoptrics*) studied light reflection on mirrors and proposed an (extremely) early *principle of least time*, by which light follows the path of least time (most time-efficient possible path); this principle reappeared around the year 1000 and more formally in the 1660s. In his own words,⁴

Ἐπειδὴ γὰρ τοῦτο ὡμολογημένον ἐστὶ παρὰ πᾶσιν, ὅτι οὐδὲν μάτην ἐργάζεται ἡ φύσις οὐδὲ ματαιοπονεῖ, ἐὰν μὴ δώσωμεν πρὸς ἴσας γωνίας γίνεσθαι τὴν ἀνάκλισιν, πρὸς ἀνίσους ματαιοπονεῖ ἡ φύσις, καὶ ἀντὶ τοῦ διὰ βραχείας περιόδου φθάσαι τὸ ὁρώμενον τὴν ὅψιν, διὰ μακρᾶς περιόδου τοῦτο φανήσεται καταλαμβάνουσα. εὗρε-
θησονται γὰρ αἱ τὰς ἀνίσους γωνίας περιέχουσαι εὐθείαι, αἵτινες ἀπὸ τῆς ὀψews [περιέχουσαι] φερομένας πρὸς τὸ κάτοπτρον κάκειθεν πρὸς τὸ ὁρώμενον, μείζονες οὔσαι τῶν τὰς ἴσας γωνίας περιεχουσῶν εὐθειῶν. καὶ ὅτι τοῦτο ἀληθές, δῆλον ἐν-
τεῦθεν.

Alcmaeon of Croton (6th–5th century BCE) is considered among the first to perform dissection and to showcase the nature of the eyes, which led him to propose that the eyes are connected with water and fire, and that vision depends on brilliance and transparency. He also proposed that the brain is the centre to which all the senses are connected (Diels and Kranz, 1903).⁵ *Parmenides of Elea* (c.540–470 BCE), in his poem-like work *On Nature* presented two views of reality, the objective world of absolute truths (or *on the intelligible*) and the subjective world of human sensation (δόξα or *on the perceptible*). Everything that humans perceive as true is false, and thus, visual perception is, basically, an illusion and there is no such thing as colour. *Empedocles of Acragas* (495–430 BCE) was a pioneer in colour theory. In Diels and Kranz (1903), where parts of his most important work *On Nature* are included, one may find a poem counting about two thousand verses (Ierodiakonou, 2005). He accepted a world consisting of four roots, fire, water, earth and air. Of those roots, fire is white and water is black. His idea was that all colours are the result of combinations of white and black, as compact arrangements of tiny dots of black and white. In Theophrastus' *On Sensation*, Empedocles explains the way the sense of vision works, using his peculiar grating (pore) theory of senses, in which vision is based on white (fire) and black (water) sensing pores next to each other. *Protagoras of Abdera* (c.490–420 BCE), was a controversial individual, who Plato cites in saying the famous quote⁶

³ Heron (or Hero) of Alexandria was an engineering genius of ancient times. There are significantly conflicting opinions about the period he lived, which is vaguely somewhere between 250 BCE and 275 CE, while most sources identify it as somewhere between 10 and 80 CE. His ingenuity can be easily understood in his work on *Pneumatica* and *Automata* in Schmidt (1899). He has been referenced as the Leonardo Da Vinci of Alexandria.

⁴ The original text was found online at http://www.poesialatina.it/_ns/Greek/testi/Heron/Catoptrica.html (last accessed March 2022).

⁵ The 1903 edition can be found online at <https://archive.org/details/diefragmenteder00krangoog/> (last accessed March 2022).

⁶ This is from Plato's *Theaetetus* and the original text can be found online at <http://www.hellenicaworld.com/Greece/Literature/Platon/gr/Theaititos.html>, *Theaetetus*[152a] (last accessed March 2022).

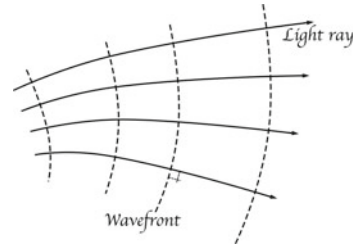
Man is the measure of all things, of those that exist that they do, of those that do not exist that they do not.

Protagoras supported that the sensation triggered by an object to a person is true to that person, whatever *true* may mean to that particular person. *Democritus of Abdera* (c.460–370 BCE) was the world-known pioneer of the atomic theory, by which atoms are the building blocks of everything in the universe. He linked colours with quantities of energy and their shapes, roughness and density. In this theory, colours are like energy signatures of the objects themselves. Vision, as a process, is the result of the pressure of the air between the objects and the eyes. He accepted four primary colours, white, black, red and green. Democritus suggested the subjective nature of human sensation and perception, and that absolute truths through sensual impressions cannot be judged. Either there is no truth, or an objective truth is not accessible. *Plato of Athens* (427–347 BCE), who believed in a world of ideas (universal ideals) deeply contemplated on the nature of perception, in general. He recognised sight as the most important sensation, and supported that it is the result of the coalescence of the stream of fire coming out from the eyes (the stream or ray of sight) and the stream of fire (light) due to the daylight (the sun) (Plato, 2008, 2014; Shorey, 1935a, b; Archer-Hind, 1888). *Aristotle of Stagira* (384–322 BCE), in his treatise *On the soul*—more like *biology* in modern terminology—in Book II, Chap. 7, he defined that whatever is visible is colour and colour is what lies upon whatever is inherently visible. Every colour can set in motion the transparent. Light is the consistency of something transparent being transparent.⁷ Aristotle strongly opposed the ideas of his times that vision begins with light emanating from the eyes. In Aristotle's *Meteorologica*, Book III (Aristotle, 1994; Lee, 1952), he explained the formation of the rainbow and its colourful appearance as a juxtaposition of the main colours, which he named to be red, green and purple.

With a significant temporal gap in the relevant literature between the ancient and the modern times (around 300 BCE to 1400 CE), there seem to be just two persons whose dedication to pure logic and science practically bridged the philosophical approaches of the ancients with the experimental scientific approaches to appear in the following centuries. Somewhere around 1000 CE, in the middle ages, *Abū 'Alī al-Ḥasan ibn al-Ḥasan ibn al-Haytham* (or simply *Alhazen*) (965–1040), who is considered to be one of the most influential figures in science, made a significant contribution to our knowledge of optics and visual perception. Alhazen contradicted the ancient notions of light emanating from the eyes, based on experimentally founded arguments, and supported a model of vision, in which the eyes are used to sense light. He went on and discovered several long-standing theories regarding light, optics and mirrors and provided the first clear explanation of a *camera obscura* and the inverted projection through an aperture, a significant step for photography. In his seven-volume treatise, *Kitāb al-Manāẓir* (*Book of Optics*) Alhazen used the term *Al-Bayt al-Muthlim* (darkroom) to describe it (Alhazen, 1021). Around two centuries later, *Erasmus Ciołek Vitello* (or *Witelo*, c.1270–1285), a German-Polish

⁷ The original text can be found at <https://goo.gl/QGp7QN> (last accessed March 2022).

Fig. 1.1 The dual view of light in Hamilton's geometrical optics



natural philosopher, made a significant contribution to the foundations of colour vision by publishing his *Vitellonis Thuringopoloni opticae libri decem* (*Ten Books of Optics*), in which he brought and extended Alhazen's theories to Europe.

Modern understanding and definition of the nature of light, vision and colour visual perception has a history that was written by some of the most prominent scientists, among which are *Isaac Newton* (1642–1726), *George Palmer* (c.1746–1826), *Thomas Young* (1773–1829), *Hermann Günter Grassmann* (1809–1877), *Hermann Ludwig Ferdinand von Helmholtz* (1821–1894) and *James Clerk Maxwell* (1831–1879). Some of the most eminent scientists that engaged with the description of the nature of light and human vision, like *Christiaan Huygens* (1629–1695), *Robert Hooke* (1635–1703), *Leonhard Euler* (1707–1783), *Simeon Denis Poisson* (1781–1840) and *Augustin-Jean Fresnel* (1788–1827), contradicted Newton's *particle theory of light* and supported a *wave theory of light*. Other scientists and great thinkers, like *Michael Faraday* (1791–1867), *James Clerk Maxwell* (1831–1879) and *Heinrich Hertz* (1857–1894) shifted the attention towards an *electromagnetic theory of light*. Around 1830 *William Rowan Hamilton* (1805–1865), an Irish mathematician, the 'father' of quaternions, presented his theory of Geometrical Optics in a set of lengthy papers, including the *Theory of Systems of Rays* (Hamilton, 1828) and the subsequent *Three Supplements* (Hamilton, 1830a, b, 1831), in which he was able to bridge the two different views for light (wave and particle) and provided quantitative evidence on how to expect each of the two natures to arise. He showed that *the rate of change of the refractive index in space in relation to the wavelength of the light wave* is the decisive factor of how light manifests itself: if the rate of change is on the scale of a wavelength then the wave nature of light is observed, whereas if the change is rather smooth the particle nature of light is revealed (Fig. 1.1).

Although Hamilton's work combined the incompatible views of light (a bit in favour of the wave theory) within the realm of classical physics, it was *Max Karl Ernst Ludwig Planck* (1858–1947) that restaged the particle theory of light when he developed the theory of the quanta in his work to explain the black body radiation, giving rise to quantum physics, in which light consists of a stream of discrete particles carrying a fixed amount of energy. *Albert Einstein* (1879–1955) seemed to have fully restated the particle theory of light in his description of the photoelectric effect and its consequences. In addition, *Niels Henrik David Bohr's* (1885–1962) work on quantum physics resulted in the empirical formula for the visible spectral lines of the hydrogen atom developed by *Johann Jakob Balmer* (1825–1898) and boosted even

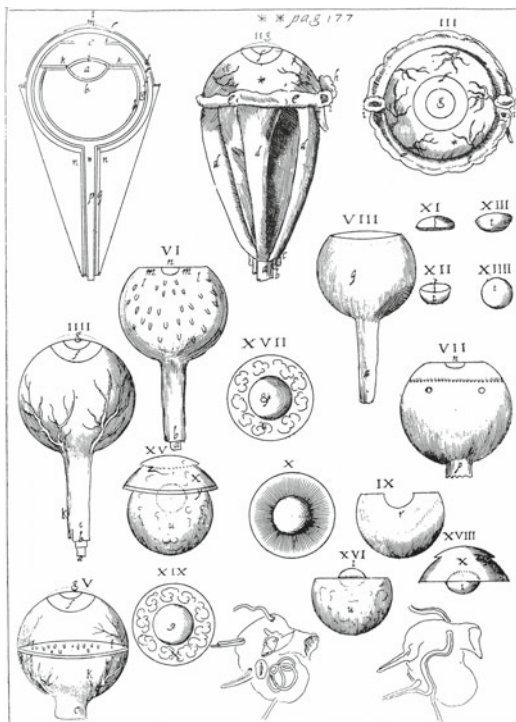
further the idea of light beams being collections of discrete particles. The picture changed completely around 1909 when *Sir Geoffrey Ingram Taylor* (1886–1975) showed that interference of light produced fringes (interference patterns) even with extremely weak light sources, counting less than one photon in the apparatus at any time (Taylor, 1909). It was made clear that there is, actually, a *dual nature of light*, a *wave-particle duality* as it is called. *Paul Adrien Maurice Dirac* (1902–1984) offered a way out of this situation, by supporting a *true dual nature* for light, based on his quantum mechanical approach to Maxwell's electromagnetic theory. In the quantum field theory that emerged complete wave-particle duality was fundamental. After the work by *Erwin Rudolf Josef Alexander Schrödinger* (1887–1961) and the development of his *wave function*, light can be regarded as a wave motion of the electromagnetic field, and light particles (photons) are excitations of the quantum field that propagates according to quantum versions of Maxwell's equations for light (Walmsley, 2015). It was not until 2015 that a team of scientists was able to 'trick' light and be able to capture it in both manifestations at once, using a rather sophisticated experiment (Piazza et al., 2015).⁸ It should, of course, be reminded that the world's first-ever permanent colour photograph was taken by no other than James Clerk Maxwell, although it was based on three-colour photography, as will be later explained, thus, some consider it out of scope.

The human eye and its operation was a topic of intense research. In 1604 Kepler, in his *theory of refraction through spherical lenses* tried to unlock the main mechanisms of vision (Kepler, 1604). By extending his theory to the eyes (Fig. 1.2), Kepler showed that the eyes have the clear function to focus an inverted image on the retina, the surface on which light is projected (Barlow, 1982).

In parallel to the work done by physicists on the understanding of the nature of light, researchers in physiology, psychology and anatomy adopted another approach towards the understanding of the way light and colour is perceived by beings and particularly by humans. *Johannes Peter Müller* (1801–1858), a German physiologist, anatomist, ichthyologist, and herpetologist, was among the pioneers of the understanding of the mechanism of the nervous system and senses (Müller, 1835, 1838, 1840). His conclusions regarding the perception of the world were revolutionary in that he suggested how the sensory perception is not the conduction of quality or a state of an external body to consciousness, but the conduction of a quality or a state of the corresponding sensory nerve, caused by an external cause. Müller analysed the physical conditions necessary for the formation of luminous images and provided an excellent description of the structure and operation of the eye by means of a pinhole camera and by means of a focusing system based on a refractive lens. He recognised that light and colour are actions of the retina, and its nervous prolongations to the brain, and that the kind of colour and luminous image perceived depends on the kind of external impression. Colours, in his theory, are just manifestations of excitation with light of different wavelengths. He accepted Newton's colour theory, but dismissed his seven dioptric colours theory and proposed a three-colour basis, based

⁸ The publication of this work is available online at <https://www.nature.com/articles/ncomms7407.pdf> (last accessed March 2022).

Fig. 1.2 Illustration of the structure of the eyes from Kepler's *Astronomiae Pars Optica*



on red, yellow, blue. Karl Ewald Konstantin Hering (1834–1918) was a German physiologist with a main interest in the physiology of the visual system and colour vision. He proposed the *opponent colour theory*, which was a significant paradigm shift of his times. Hering published important work on the spatial sensing and the movement of the eyes (Hering, 1879), on the binocular vision (Hering, 1868), on visual acuity (Hering, 1899; Strasburger et al., 2018) and colour theory (Hering, 1878, 1920, 1964). Interestingly, he also employed linguistics to support his theory, with arguments like *there cannot be a whitish-black, or a reddish-green, or even a yellowish-blue colour, although it is natural to accept, for example, a yellowish-red, or a greenish-blue, or even a greenish-yellow*. This pairing in linguistic terms to define composite colours acts as an indication of a colour vision based on detection of colour opponency, particularly the one of red-green, yellow-blue and white-black. To Hering, the basis of a colour system should consist of red, green, yellow, blue colours. Johannes Adolf von Kries (1853–1928) was a German physiological psychologist, interested in the neural mechanisms of perception. He was the founder of the *duplicity theory* of vision, in which two types of photoreceptors, the cones and rods, are responsible for vision. He supported that rods are highly efficient in low-light conditions but convey only brightness cues, whereas cones are of three types that are efficient in bright-light conditions and can infer colour information (von Kries, 1878, 1905). Von Kries confirmed the two most important theories of

visual sensation of his times, on one hand, the Young-Helmholtz-Maxwell theory, and on the other, Hering's opponent colour theory, in that all theories agreed on the need for three independent variables. *Arthur Peter König* (1856–1901) was a German physicist with important work on physiological optics. He studied under and assisted Helmholtz. His work with Conrad Dieterici (König and Dieterici, 1886, 1892) is a foundation work on the sensitivity of the human rod and cone visual system and made it possible to theorise about defects in vision (dichromacy and colour blindness). In addition, his work suggested a pioneering mathematical definition regarding the *standard observer* (the average normal trichromat), with data that were only replaced by the more accurate data by John Guild and William David Wright some 30 years later. *Santiago Ramón y Cajal* (1852–1934) was a Spanish neuroscientist, pathologist, and histologist, who specialised in neuroanatomy, the central nervous system and the microscopic structure of the brain. This pioneering work made him the father of neuroscience. He used anatomy and a special tissue staining method (Golgi's staining) and was able to visualise and provide detailed drawings of the microstructure of the retina of the eye (Ramón y Cajal, 1894a,b, 1909, 1911). He supported that rods and cones collect light and there are two distinct neural pathways to carry the information of those receptors to the brain. One pathway is for the colourless luminous intensity by the rods and one for the colour information by the cones. Cajal connected the anatomical uniqueness of the fovea with the increased visual acuity in central vision. *Stephen Lucian Polyak* (1889–1955) was a professor of neurology and neuroanatomy in California and Chicago, and is considered to be one of the most prominent neuroanatomists of the 20th century. By studying the retina he was able to reveal the role of the various cells (not only rods and cones) in the retina organisation and their connectivity, thus, he provided a new interpretation of the basic visual processes (Polyak, 1941, 1949, 1970). He showed the retina as a complete complex instrument in which every type of cell plays its particular role in the composition of the signal that is transmitted to the brain. Although he was able to confirm that cones are responsible for the perception of colour, he was not certain of the origin of the differentiation in the spectral response that makes colour perception possible.

When one thinks of vision and visual perception usually comes to a realisation that the visual perception creates only a *shadow* of the *real* world (Plato's 'ideal'); the brain acts creatively and reconstructs a completely personalised and subjectively meaningful approximation of the world. Using this line of reasoning it is easy to understand that it is extremely difficult to objectively model visual perception. Nevertheless, taking into account the prevailing Pythagorean approach to the simplest and smallest solution,⁹ or the more modern Occam's razor,¹⁰ in combination with the Darwinian theory of evolution, which bases evolution on the criterion of natural

⁹ Δεῖν γὰρ ἐπ' ἐκείνων καὶ αὐτόν παρακλεῖσθαι τὸν Πυθαγόραν ζητεῖν ἐξ ἐλαχίστων καὶ ἀπλουστάτων ὑποθέσεων δεικνύειν τὰ ζητούμενα.

¹⁰ Among competing hypotheses, the one with the fewest assumptions should be selected; when two competing theories make exactly the same predictions, the simpler one is the better.

selection,¹¹ along with a statistical view on the experimental data on human perception, it could be naturally deduced that *the human visual perception is as simple as possible and works rather efficiently*. In addition, general rules, as well as ordinal and metric cues that govern visual perception, have been identified and extensively researched, although disagreement on the specific mechanics holds for many years.

All the studies, theories and models on the perception of the world have been strong influences and inspirations for the development of new methods, approaches and technologies to mimic or even supersede the human capacities in vision. A technologically grounded desire to capture objects and shapes by optical means dates back to the early 19th century. It is the same period in which the roots of the art of photography can be traced. Since then, optical capturing technology has evolved at a rapid pace as one highly dynamic domain of active research and development. In the beginning, though, it was the chemistry that provided the first boost. Whatever the means and methods to create temporary or permanent impressions of world images on various surfaces, it all connects to *light, the world and an observer*, the humans and their inventions. Before stepping into the mechanics of the inventions, it is most wise to peek into the basic ingredients and explore the core notions, which are no other than light, vision and colour.

1.2 The Nature of Light

The explanation of the quantum theory of light is apparently beyond the scope of this treatise, but an elaboration on some basic principles that have an impact on the understanding of human vision is necessary for a study of photography or any other technological invention that emulates the human vision. This section summarises the scientific understanding of the nature of light, although, for all practical purposes, those entities cannot be, actually, disconnected with vision, which is discussed in the next section.

A very poetic, yet accurate, view of the nature of light has been given by the esteemed physicist Professor Emeritus George Grammatikakis in his book *Η αυτοβιογραφία του φωτός (The Autobiography of Light)* (Grammatikakis, 2005), which is quoted here from the original Greek; light presents itself as follows¹²:

Γεννήθηκα πριν από αιώνες αιώνων, σε έναν Χώρο όπου δεν υπήρχε χώρος και σε έναν Χρόνο όπου δεν υπήρχε χρόνος. Με έναν περίεργο ωστόσο τρόπο, αισθάνομαι ότι προϋπήρχα της γενέσεώς μου. Κι ενώ από τότε όλα έχουν αλλάξει, εγώ αισθάνομαι ότι τίποτα δεν έχει αλλάξει. Η παρουσία μου μετρά το αιώνιο.

¹¹ Or the catchy phrase ‘survival of the fittest’, coined by Herbert Spencer around 1864, in which is implied the survival of the form that will leave the most copies of itself in successive generations.

¹² In a somewhat free translation, this passage would read:

I was born before the Age of the ages, in a Place without place, in a Time without time. Strangely, however, I feel that I existed before my birth. Although since then everything has changed, I feel that nothing has changed. My presence counts the eternal.

In practice, although in a limiting sense, visible light defines a part of the electromagnetic radiation spectrum that can be sensed by the human vision. A fundamental quantity with which the electromagnetic radiation is usually expressed is the *wavelength*.¹³ Figure 1.3 summarises the total electromagnetic radiation spectrum along with some characteristic objects that match the size of the corresponding wavelengths, in decreasing order from left to right. For example, the range of the microwaves is in the order of the insects, whereas the visible range is in the order of living cells and viruses. The wavelength range of this visible part of the spectrum roughly spans between 380 and 740 nm, although many variations can be found in the relevant bibliography (rounding around 400–700 nm). From classical physics, in which light is simply electromagnetic radiation, the corresponding radiation *frequency*¹⁴ range spans roughly between 400 to 790 THz (in reverse corresponding order), as implied by

$$f = \frac{v}{\lambda} \quad (1.1)$$

where f is the frequency, λ is the wavelength, v is the constant phase speed of a sinusoidal waveform (in this case, light) travelling in linear media. If light travels through vacuum, v equals the well known speed of light c , estimated as

$$\begin{aligned} c &= \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = \\ &= \frac{1}{\sqrt{8.8541878128 \times 10^{-12} \text{ F} \cdot \text{m}^{-1} \times 1.25663706212 \times 10^{-6} \text{ H} \cdot \text{m}^{-1}}} = \\ &= 299792458 \text{ m} \cdot \text{s}^{-1} \end{aligned} \quad (1.2)$$

in which ε_0 is the *electric constant* of the *vacuum permittivity* in farads per metre, and μ_0 is the *magnetic constant* of vacuum, or the *vacuum permeability* in henrys per metre. For simplicity, the speed of light in vacuum is taken to be roughly $3 \times 10^8 \text{ m} \cdot \text{s}^{-1}$ or some $10^9 \text{ km} \cdot \text{h}^{-1}$. The corresponding *spatial frequency* or the *wavenumber*¹⁵ range can be estimated by

$$\tilde{\nu} = \frac{1}{\lambda} \text{ cm}^{-1} \quad (1.3)$$

resulting in the range between 13,513.51 and 26,315.79 cm^{-1} .

Light in physics represents a more general entity called the *electromagnetic radiation*, which is not confined to be visible only. As such, light is ubiquitous and signifies

¹³ Wavelength of a periodic wave is the distance over which the wave repeats in shape; this is also referenced as the spatial period of a wave and is expressed in meters.

¹⁴ Frequency (also temporal frequency) of a periodic wave is a number that denotes the repetitions of the wave shape in unit time and is expressed in Hertz or s^{-1} .

¹⁵ Wavenumber of a periodic wave is the number of repetitions of the signal in unit distance; this is why it is referenced as spatial frequency in contrast to the typical frequency—which is a temporal factor. Wavenumbers are expressed in cm^{-1} .

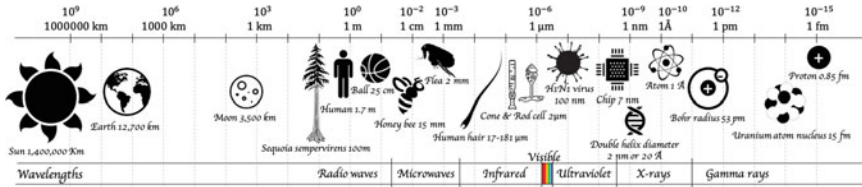


Fig. 1.3 The electromagnetic radiation spectrum

the energy exchange between material objects. Natural sources of light, particularly of visible nature, follow the *black body* model. This is a model of an imaginary ideal object, which can absorb all the incident radiation from its surroundings, and this is the reason it is metaphorically called ‘black’. When a black body is in what is called the thermal equilibrium (at a constant temperature) it emits a characteristic radiation, termed *black body radiation*, which is only determined by the temperature. The *spectral radiance* of the black body is estimated using the *Planck’s law* as

$$L(f, T) = \frac{2hf^3}{c^2} \frac{\alpha(\lambda)}{e^{\frac{hf}{k_B T}} - 1} \xrightarrow{c=\lambda f} L(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{\alpha(\lambda)}{e^{\frac{hc}{\lambda k_B T}} - 1} \quad (1.4)$$

where $L(\lambda, T)$ in $\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-3}$ is the spectral radiance in terms of spectral emissive power per unit area and per unit solid angle for a particular radiation wavelength λ and temperature T , $k_B = 1.380649 \times 10^{-23} \text{ J} \cdot \text{K}^{-1}$ is the Boltzmann constant, $h = 6.62607015 \times 10^{-34} \text{ J} \cdot \text{s}$ is the Planck constant, c is the speed of light and $\alpha(\lambda)$ is the wavelength dependent emissivity, which is taken as unity ($\alpha(\lambda) = 1$) for perfect black bodies.

On the other side, *Wien’s displacement law* approximates how radiations of black bodies at different temperatures peaks at different wavelength, showing that the higher the temperature the lower the wavelength.

$$\lambda_{\text{peak}} = \frac{b}{T} \quad (1.5)$$

where $b = 2.897771955185172 \times 10^{-3} \text{ m}$ (or better $b = 2.897771955185172 \times 10^6$ for results in nm) is the Wien’s displacement constant.

Using Planck’s law, the *spectral emittance* of black bodies at different temperatures is shown in Fig. 1.4. The spectral emittance is simply $M(\lambda, T) = \pi \cdot L(\lambda, T)$. Apparently, as the temperature rises, so does the peak power, but the wavelength gets shorter (the frequency gets higher). Or, in another way, higher frequency light carries more power and corresponds to a higher temperature.

To check the agreement between Planck’s and Wien’s laws, Table 1.1 displays a side by side comparison of the predicted peak wavelength at each temperature of the graph in Fig. 1.4. Although Wien’s law is a simple peak wavelength to temperature

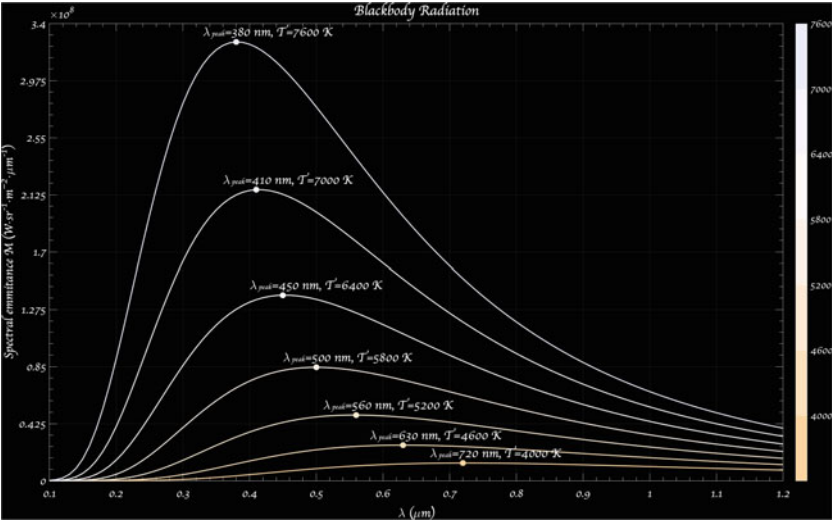


Fig. 1.4 Spectral blackbody emittance in various temperatures

Table 1.1 Comparison of Planck’s and Wien’s predictions

Temperature (°K)	Planck’s λ_{peak} (nm)	Wien’s λ_{peak} (nm)
3000	970	966
4000	720	724
4500	640	644
5000	580	580
5200	560	557
5500	530	527
5800	500	500
6000	480	483
6500	450	446

relation it is quite close to Planck’s law prediction, which covers the whole spectral distribution.

Although colour has not been discussed yet, since black body radiation has been presented as a fundamental model for light sources, the notion of *colour temperature* of a light source should be also mentioned. Colour temperature is nothing more than the temperature of the ideal black body that radiates light of a colour comparable to that of the light source studied. As the colour temperature is connected with black body radiation, only a very limited number of perceived hues can be identified to actually have a temperature. Figure 1.5 shows a typical graph of all the possible colour temperatures from 1000 to 11000 K, the matching peak wavelengths (Wien’s law) from 263 to 2898 nm, and the corresponding perceived colours ranging from red

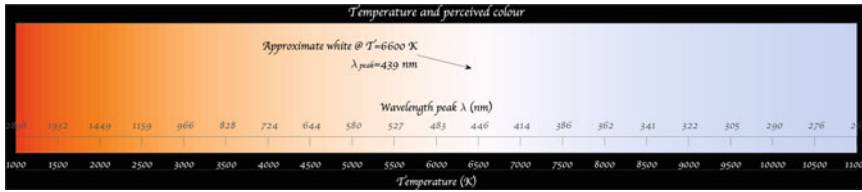


Fig. 1.5 Blackbody emittance and colour temperature

to white to blue.¹⁶ Apparently, many colours that humans perceive, like green, pink, purple, yellow and saturated red and blue are totally missing from this representation. Nevertheless, this is the standard scale of colour temperatures that are being used to create light sources for all lighting purposes.

Spectral radiance and spectral emittance are light quantification entities that belong to the domain of *radiometry*. Radiometry is the science and technology of the detection and measurement of light, with a large number of specific measurement quantities like radiant energy, radiant flux, radiant intensity, radiance, irradiance, radiosity, etc. In addition, formally, *optics* is the scientific domain that is concerned with the study of light and its interactions with matter.

Most of the light radiation that hits the Earth comes from the Sun. The Sun's *apparent magnitude* was measured to -26.74 , whereas a full Moon to a -12.74 and the total integrated magnitude of the night sky was measured to a -6.5 . Apparent magnitudes are expressions that correspond to the apparent stellar objects' luminosity and are in a reverse logarithmic scale, in which smaller values correspond to brighter bodies. In this scale, a difference of 1 in magnitude corresponds to a brightness difference of $\sqrt[3]{100} \approx 2.512$. Using the typical definition of apparent magnitude, $m = -2.5 \log_{10}(F/F_0)$, F_0 being the reference flux density, the overall night sky contribution to the light reaching the Earth can be estimated relative to that of the sun as

$$\begin{aligned} \Delta m &= m_{\text{night sky}} - m_{\text{sun}} = (-6.5) - (-26.74) = 20.24 \\ b &= 10^{0.4\Delta m} = 10^{0.4 \cdot 20.24} = 124738351.4243 \approx 125 \times 10^6 \end{aligned} \quad (1.6)$$

which means the Sun is approximately 125 million times brighter than the overall night sky with no moon. Using the same approach, the Sun turns out to be approximately 400 thousand times brighter than a full Moon. This is clear evidence that the Sun is by far the main source of the total light reaching the Earth. It should be also stressed that the apparent magnitude relates to the light that reaches the surface of the Earth, thus after going through the filters of the Earth's atmosphere. The difference of the Sun's radiation in space with that reaching the Earth's surface (at sea level) is illustrated in Fig. 1.6, where the 2000 ASTM Standard Extraterrestrial Spectrum Reference E-490-00 data are drawn against the Reference Air Mass 1.5 Spectra,

¹⁶ The colour temperatures graph was based on Mitchell Charity's Blackbody colour datafile (bbt_color.txt) found online at <http://www.vendian.org/mncharity/dir3/blackbody/> (last accessed March 2022). The data used correspond to the 10° standard observer and sRGB colour representations, which will be discussed in subsequent sections.

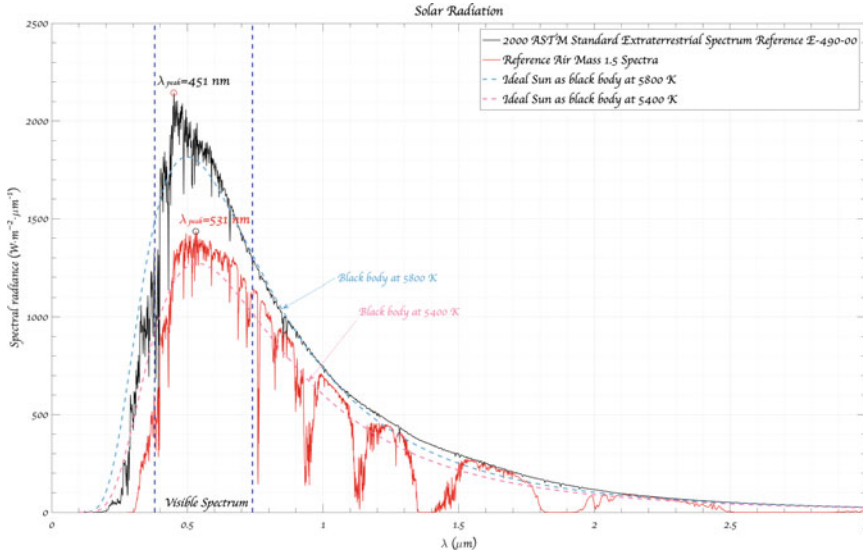


Fig. 1.6 Solar radiation in space and on Earth's surface (at sea level)

along with two black body radiation curves that match the corresponding solar radiation data.¹⁷ This graph that shows the spectral radiance of the solar radiation makes it clear that the Sun emits power in a wide range of wavelengths and, in space, it seems to match the radiation of a black body at a temperature of around 5800 K. The effect of the atmosphere is profound in absorbing a significant amount of the radiation and shifting the overall radiation towards the longer wavelengths, as shown in the Air Mass 1.5 Spectra curve, which matches black body radiation at a temperature around 5400 K. The peak of the solar radiation in space is at approximately 450 nm, whereas on the Earth's surface at approximately 530 nm, a shift of 80 nm with significant implications as will later be explained.

Figure 1.7 shows the same data drawn in the narrow range of wavelengths that are visible. In addition, Fig. 1.8 depicts the spectral composition of the solar radiation at the surface of the Earth under varying atmospheric conditions.¹⁸

¹⁷ The data can be found online at The National Renewable Energy Laboratory of the U.S. Department of Energy. The '2000 ASTM Standard Extraterrestrial Spectrum Reference E-490-00' where found at <https://www.nrel.gov/grid/solar-resource/spectra-astm-e490.html> (last accessed March 2022) and directly downloaded from https://www.nrel.gov/grid/solar-resource/assets/data/e490_00a_amo.xls (last accessed March 2022). The 'Reference Air Mass 1.5 Spectra' data were found at <https://www.nrel.gov/grid/solar-resource/spectra-am1.5.html> (last accessed March 2022) and directly downloaded from <https://www.nrel.gov/grid/solar-resource/assets/data/astmg173.xls> (last accessed March 2022).

¹⁸ Data for this graph were reconstructed from https://upload.wikimedia.org/wikipedia/commons/2/27/Spectrum_of_Sunlight_en.svg (last accessed March 2022), which references that 'Data is from X-Rite i1Pro (118 sensor values between 350 and 740 nm)' but the linked original file at http://www.eecs.qmul.ac.uk/~tb300/pub/Images/Spectrum_of_Sunlight_en.pdf could not be found.

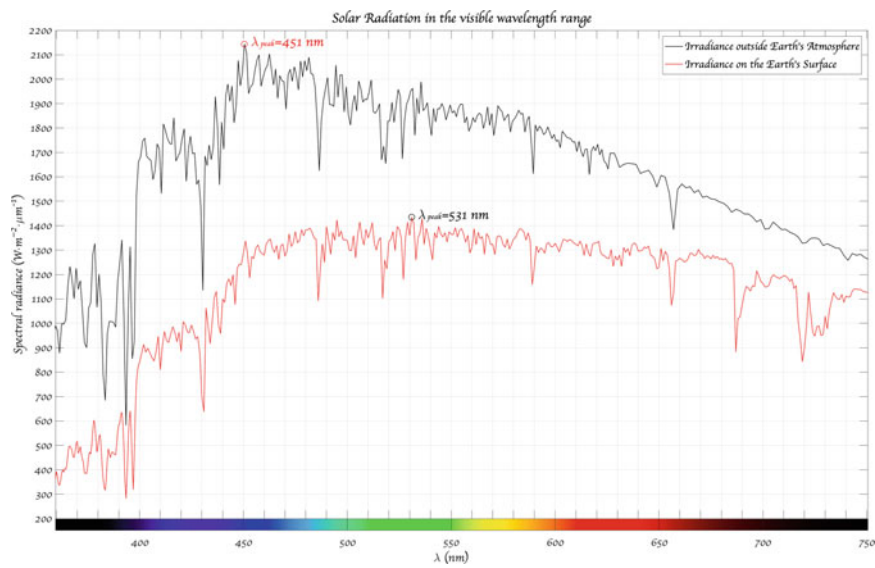


Fig. 1.7 Solar radiation in space and on Earth’s surface in the visible range of the spectrum

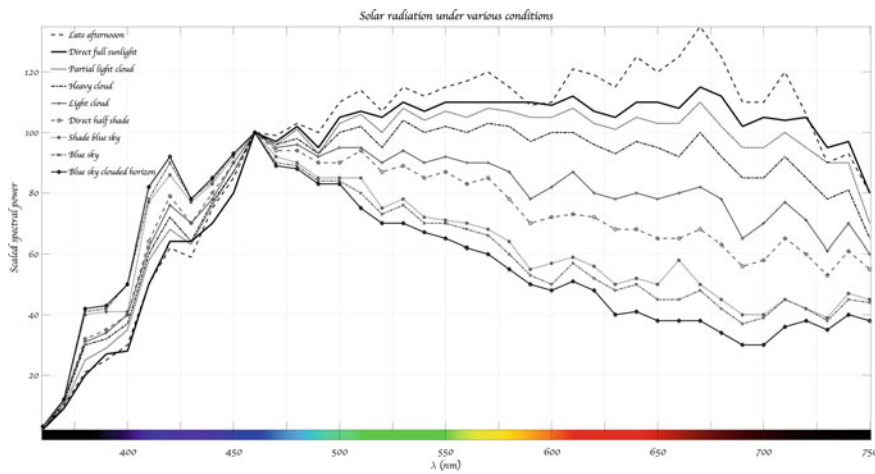


Fig. 1.8 Solar radiation on Earth’s surface under varying atmospheric conditions

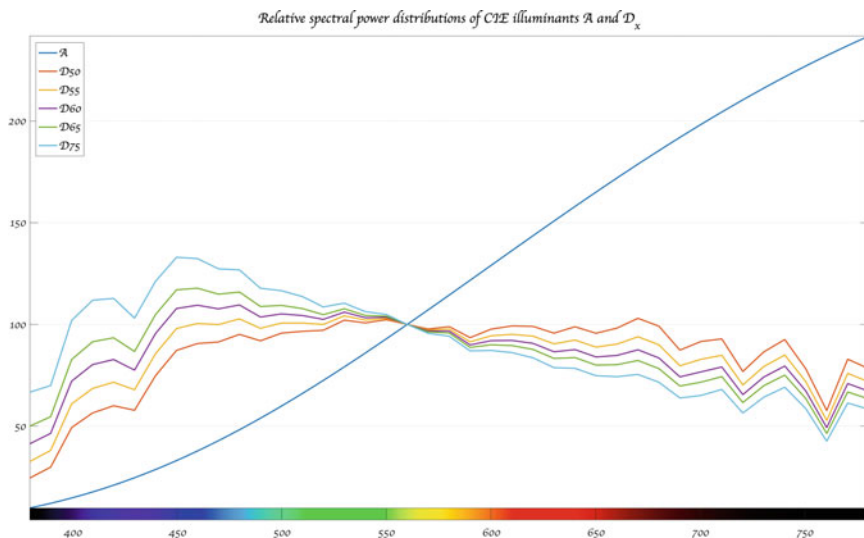


Fig. 1.9 Spectral power distribution of standard illuminants

Apparently, at the dawn of human civilisation, the only additional light source available was that of the fires. As humans progressed, new artificial light sources have been created following a variety of principles. The spectral characteristics of these light sources are usually different from that of the Sun, the Moon and the stars, but those that are based on the black body radiation principle mimic quite well the solar radiation, providing rich spectral power distributions. During the 20th century, experts in the domain tried to establish standards for illumination by artificial means and created several *standard illuminants*. The most common (with code names A, D₅₀, D₅₅, D₆₀, D₆₅, D₇₅) are shown in Fig. 1.9, in which the relative spectral power distribution of these illuminants is drawn against the wavelength of light in the visible range. It is clear that the D-family somehow mimics the spectral distribution of the solar radiation, by including wavelengths throughout the whole range. In addition, the approximate spectral power distribution for various commercially available light sources is shown in Fig. 1.10, including the typical solar mid-day curve for comparison.

After the development of relativity and quantum theory, there have been attempts to ‘dissect’ light and explain its origin and composition. Albert Einstein at the beginning of the 20th century modelled electromagnetic waves using spatially localised discrete wave-packets, which he named *light quanta*. About 20 years later, the term *photons* appeared to substitute the light quanta, from the Greek word for light ($\varphi\omega\varsigma$ —transliterated phos). Photons are produced through various natural processes, including the acceleration of a charge, the energy transitions in atoms and molecules,

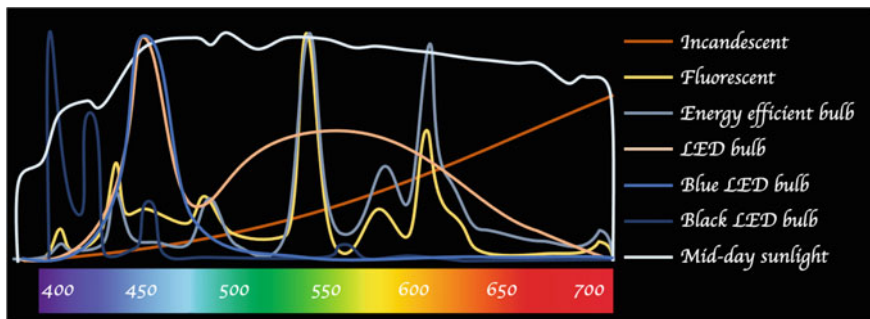


Fig. 1.10 Approximate spectral power distribution of various commercial illuminants

or the mutual annihilation of particles and antiparticles. Photons are the carriers of electromagnetic force. Photons are also destroyed by similar principles. When photons hit the electrons of atoms, these electrons totally absorb (and totally annihilate and destroy) the photons and get to a more excited orbital due to the excess in their energy. Thus, light is created and destroyed all the time during the interactions with the electrons of matter. In addition, light slows down when going through materials (or media, as they are called), in factors relating to the characteristics of the materials. In fact, this factor is extremely crucial for all optical phenomena that relate to light and colour and is expressed as the *index of refraction* or the *refractive index* of a medium. The definition of the refractive index of a medium is expressed as the ratio of the speed of light in vacuum c to the speed of light in the medium v

$$n = \frac{c}{v} \quad (1.7)$$

Apparently, this is a relative quantity, as it compares the behaviour of light in a given medium to light travelling through vacuum. Nevertheless, when the refractive index is used with respect to vacuum it is referenced as an absolute quantity, whereas when it is used with respect to media other than vacuum it is taken as relative. In addition, this index is not constant for a given medium but is also affected by the wavelength of the radiation. It was in 1836 that the renowned mathematician *Augustin-Louis Cauchy* (1789–1857) first defined the *Cauchy's transmission equation* that relates the refractive index to wavelength for various materials, which was later, in 1872, refined by *Wolfgang Sellmeier* to what is known as the *Sellmeier equation* that states

$$n^2(\lambda) = 1 + \sum_i \frac{B_i \lambda^2}{\lambda^2 - C_i} \quad (1.8)$$

where B_i , C_i are the experimentally defined *Sellmeier coefficients*. Figure 1.11 shows two graphs representing the variability of the refractive index of air (left) and of flint

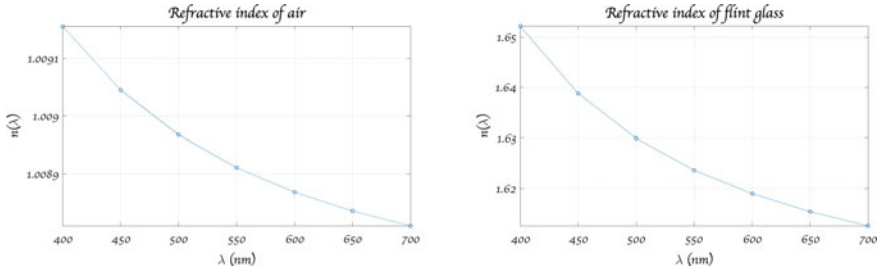


Fig. 1.11 Refractive index of air (left) and flint glass (right) as a function of the wavelength of light

glass (right) as a function of the wavelength of light.¹⁹ It is clear that when the wavelength decreases the refractive index increases and vice versa.

Keeping in mind the ways in which light (as photons) can be created or destroyed with the interactions with electrons, the most profound phenomena of light propagation are *absorption*, *reflection*, *polarisation*, *transmission*, *refraction* and *diffraction*, which are discussed in following paragraphs. It is noted that typically in nature, light has to travel through various media of different substances.

When light is considered to be a spherical wave and it reaches objects or openings, *diffraction* phenomena take place. These phenomena are similar to those of mechanical waves, like sound or the water surface. This phenomenon can be envisioned as the excitation of every particle of the medium and the subsequent transmission of a spherical wave from each particle, which results in a complex representation in which the principle of the superposition of waves holds. The same holds for the case in which the wave passes through openings (or gratings), where each opening acts like a new point source for a spherical wave.

When light is considered to be a beam or ray of photons and it reaches the interface between two media, several possibilities of phenomena exist. Part of the incident light can be *absorbed*, which means that this part of the light is forever lost as it is absorbed by the electrons of the surface of the second medium, which in turn become more energetic. This is usually experienced as an increase in heat. For the rest of the light (the one that was not absorbed) there are two choices, either to undergo *reflection* (and, potentially, *polarisation*), or to undergo *transmission* through the second medium it encounters. Reflection, although it is usually depicted as the bouncing off of part of the incident light, it is actually a light generation process, in which the incident light excites the surface electrons of the second medium, which later return

¹⁹ The data for the refractive index of the air have been downloaded from <https://refractiveindex.info/?shelf=other&book=air&page=Ciddor> (last accessed March 2022), in which the Sellmeier coefficients are $B_1 = 0.05792105$, $B_2 = 0.00167917$, $C_1 = 238.0185$, and $C_2 = 57.362$. The data for the refractive index of flint glass prism have been downloaded from <https://refractiveindex.info/?shelf=glass&book=SCHOTT-F&page=F2> (last accessed March 2022), in which the Sellmeier coefficients are $B_1 = 1.34533359$, $C_1 = 0.00997743871$, $B_2 = 0.209073176$, $C_2 = 0.0470450767$, $B_3 = 0.937357162$, $C_3 = 111.886764$.

to their normal orbitals producing one photon each in the process. Reflection takes two forms in nature, (a) *specular reflection* and (b) *diffuse reflection* (or simply *diffusion*, or *scattering*). Specular reflection is the directional reflection experienced in mirrors, whereas diffusion is the case of reflection at many arbitrary angles produced by rough surfaces. Transmission, on the other hand, although based on the same principle of electron excitation and photon generation, is a cascaded event that takes place within the medium itself by the propagation of the surface excitation to the inner layers of the medium. The vibrations pass from atom to atom following a particular path, which can lead either to a light beam eventually exiting the medium or the process is halted within the medium, as the excitations diminish. When light from a medium continues its propagation into a second medium (of different refractive index) by means of transmission it undergoes *refraction*. Refraction is the bending of the original path along which the light ray was propagating in the first medium due to the change in its velocity. In addition, this bending of light depends on the wavelength of light as will be explained later. This phenomenon is called *dispersion*. Refraction and dispersion are fundamental phenomena of light that play a critical role in colour vision and visual perception of biological systems and also of measurement instrumentation. Last but not least, *polarisation* is the condition in which the electric field of the ray of light is selectively oriented towards a single plane. All these phenomena are summarised in Fig. 1.12. The small 3D representation on the right side shows that all these phenomena, although in 3D space, happen on a single plane, the so-called *plane of incidence*. In the main graph, a ray of light travels through a medium with a refractive index n_1 towards another medium of a higher refractive index $n_2 > n_1$. The ray's angle of incidence at the interface between the two media is θ_i , whereas the angle of specular reflection is denoted as θ_r . The angle of transmission/refraction is denoted as θ_t . In case scattering takes place then the incident ray will result in several other rays depicted with dashed arrowhead lines pointing upwards above the interface. In addition, dispersion due to various wavelengths in the incident ray results in several different transmission angles as denoted by the downward pointing dashed arrowhead lines. The two types of polarisation that are important in this case, *p-polarisation* and *s-polarisation* are also graphically depicted, shown the p-polarisation as an electrical field that propagates on the plane of incidence, whereas the s-polarisation propagates perpendicular to the plane of incidence and this page. Finally, the lower right part of the main graph shows the same effects for the opposite case, in which the light propagates from the medium of the higher refractive index to that of the lower. In this case the reflection is called *internal reflection*. Internal reflection can be escalated to *total internal reflection* when no portion of the ray is able to exit the medium. This is what happens in fibre optics, in which light cannot escape the fibre, or when looking towards the sea surface from below and see the reflected underwater scene.

A simplified representation of light reflection and refraction is shown in Fig. 1.13 for the simple derivation of the corresponding laws of reflection and refraction, based on *Pierre de Fermat's* (1607–1665) *principle of least time*, originally proposed in the 1660s. Fermat's principle states that *the path followed by a ray of light between two given points must be the path that can be traversed in the least time*. Again, in this

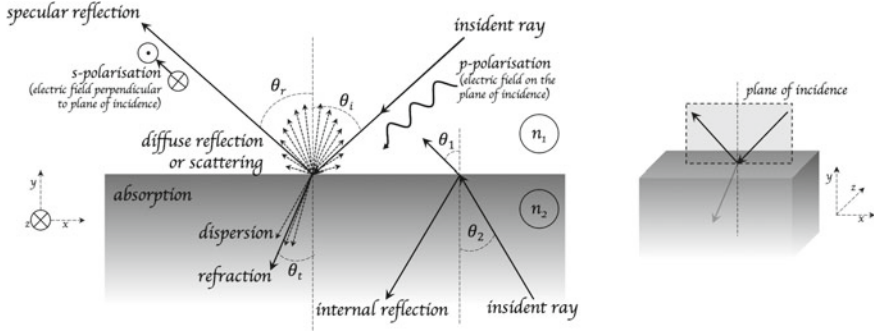
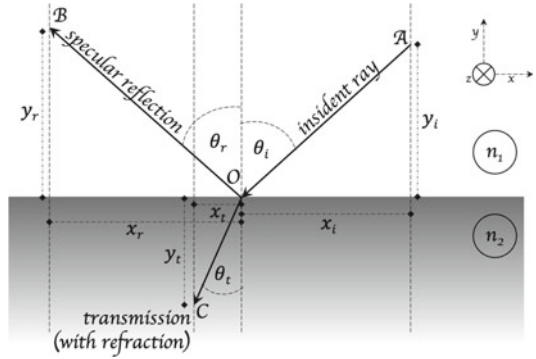


Fig. 1.12 Most important phenomena during light propagation between different media

Fig. 1.13 Simplified representation of light reflection and refraction



case $n_2 > n_1$. The principle can be expressed using functional analysis, supposing a light ray travelling from point $\mathcal{A}$ to point $\mathcal{C}$ on the $X - Y$ plane and passing through media with different refractive indices $n \equiv n(x, y)$, having a speed that varies based on that index, $v(x, y) = c/n(x, y)$, c the speed in vacuum (as shown in Fig. 1.13),

$$T = \int_A^C dt = \text{stationary} \quad (1.9)$$

‘stationary’ in the context of functionals refers to extrema (max, min, saddle points). This equation with a bit of a transformation, taking $x = x(y)$ and of course $dt = ds/v$ becomes an integral over space

$$\begin{aligned} T &= \int_A^C \frac{ds}{v} = \int_A^C \frac{n(x, y)}{c} ds = \int_A^C \frac{n(x, y)}{c} \sqrt{dx^2 + dy^2} = \\ &= \int_A^C \frac{n(x, y)}{c} \sqrt{\dot{x}^2 + 1} dy = \\ &= \int_A^O \frac{n_1}{c} \sqrt{\dot{x}^2 + 1} dy + \int_O^C \frac{n_2}{c} \sqrt{\dot{x}^2 + 1} dy \end{aligned} \quad (1.10)$$

This is a typical functional, in which the Lagrangian is $\mathcal{L}(y, x(y), \dot{x}(y)) = n(x, y) \sqrt{\dot{x}^2 + 1}$, and for which finding the extrema functions includes solving the corresponding *Euler-Lagrange equation*

$$\frac{\partial \mathcal{L}}{\partial x} - \frac{d}{dy} \frac{\partial \mathcal{L}}{\partial \dot{x}} = 0 \quad (1.11)$$

which apparently *results in the equation of a line*, confirming that the ray of light is expected to follow a path on a straight line from point to point in the above integrals. The total time that light will need to reach its destination point is thus a summation of the two time intervals in the two media. Thus in this case, the problem reduces to finding the position for point O for which the time is minimised. Supposing (again as shown in Fig. 1.13) that the total horizontal displacement from $\mathcal{A}$ to $\mathcal{C}$ is $d (=x_i + x_t)$ then

$$T = t_1 + t_2 = \frac{s_1}{v_1} + \frac{s_2}{v_2} = \frac{\sqrt{x_i^2 + y_i^2}}{\frac{c}{n_1}} + \frac{\sqrt{(d - x_i)^2 + y_i^2}}{\frac{c}{n_2}} \quad (1.12)$$

where s_i and v_i are the path length and the speed of light in medium i ; to find where this expression has an extremum, one needs to find where its derivative with respect to x (y is fixed at position $y = 0$ thus only x is variable) becomes zero.

$$\begin{aligned} \frac{dT}{dx} = 0 &\Rightarrow \frac{n_1}{c} \frac{x_i}{\sqrt{x_i^2 + y_i^2}} - \frac{n_1}{c} \frac{(d - x_i)}{\sqrt{(d - x_i)^2 + y_i^2}} = 0 \\ &\xrightarrow[\text{right triangles}]{\text{from the}} \frac{n_1}{c} \sin \theta_i = \frac{n_2}{c} \sin \theta_t \Rightarrow n_1 \sin \theta_i = n_2 \sin \theta_t \end{aligned} \quad (1.13)$$

Thus the position of point of incidence O should be such that (1.13) holds. Actually, Fermat must have figured it out using reverse thinking, starting from Snell's law and understanding that it expressed a differential in x , which in turn leads to a law for time. The same approach can be used for reflection.²⁰

Considering the case of *specular reflection*, light has to traverse from point $\mathcal{A}$ to point O and up to point $\mathcal{B}$. The time needed to traverse this path can be expressed as $t = \mathcal{AO}/v_1 + \mathcal{OB}/v_1$, where v_1 is the speed of light in medium with refractive index n_1 . To find the least time to traverse this path it is sufficient to equate its first derivative with zero as follows

²⁰ An insightful presentation of the principle for reflection and refraction (with concepts from the calculus of variation) can be found in Richard Feynman's *The Feynman Lectures on Physics Vol. I Ch. 26/ Optics—The Principle of Least Time*, found online at https://www.feynmanlectures.caltech.edu/I_26.html (last accessed March 2022).

$$\begin{aligned}
t &= \frac{\mathcal{AO}}{v_1} + \frac{OB}{v_1} \xrightarrow{a=x_i+x_r} \\
t &= \frac{\sqrt{x_i^2 + y_i^2}}{v_1} + \frac{\sqrt{(a-x_i)^2 + y_r^2}}{v_1} \Rightarrow \\
\frac{dt}{dx} &= \frac{x_i}{v_1 \sqrt{x_i^2 + y_i^2}} - \frac{(a-x_i)}{v_1 \sqrt{(a-x_i)^2 + y_r^2}} \xrightarrow{\text{equate with 0}} \\
\frac{x_i}{v_1 \sqrt{x_i^2 + y_i^2}} &= \frac{(a-x_i)}{v_1 \sqrt{(a-x_i)^2 + y_r^2}} \xrightarrow{1/v_1 \text{ eliminated}} \\
\frac{x_i}{\sqrt{x_i^2 + y_i^2}} &= \frac{(a-x_i)}{\sqrt{(a-x_i)^2 + y_r^2}} \Rightarrow \sin \theta_i = \sin \theta_r
\end{aligned} \tag{1.14}$$

This result clearly reveals that the angle of incidence is equal to the angle of reflection in specular reflection. Considering the case of *transmission with refraction*, light has to traverse from point $\mathcal{A}$ to point O and then to point C in the second medium. The time needed to traverse this path can be expressed as $t = \mathcal{AO}/v_1 + OC/v_2$, where v_2 is the speed of light in medium with refractive index n_2 . To find the least time to traverse this path it is sufficient to equate its first derivative with zero as follows

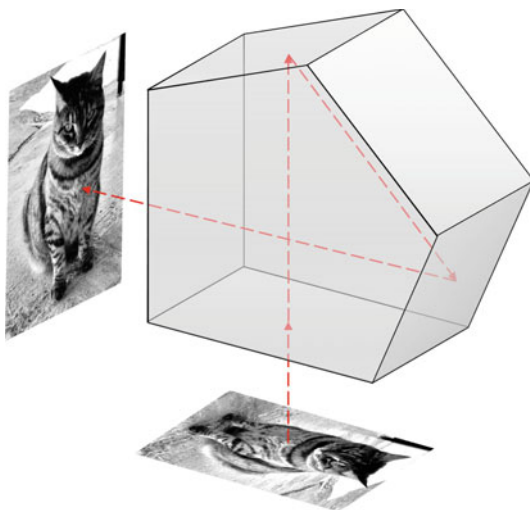
$$\begin{aligned}
t &= \frac{\mathcal{AO}}{v_1} + \frac{OC}{v_2} \xrightarrow{b=x_i+x_t} \\
t &= \frac{\sqrt{x_i^2 + y_i^2}}{v_1} + \frac{\sqrt{(b-x_i)^2 + y_t^2}}{v_2} \Rightarrow \\
\frac{dt}{dx} &= \frac{x_i}{v_1 \sqrt{x_i^2 + y_i^2}} - \frac{(b-x_i)}{v_2 \sqrt{(b-x_i)^2 + y_t^2}} \xrightarrow{\text{equate with 0}} \\
\frac{x_i}{v_1 \sqrt{x_i^2 + y_i^2}} &= \frac{(b-x_i)}{v_2 \sqrt{(b-x_i)^2 + y_t^2}} \Rightarrow \\
\frac{1}{v_1} \frac{x_i}{\sqrt{x_i^2 + y_i^2}} &= \frac{1}{v_2} \frac{(b-x_i)}{\sqrt{(b-x_i)^2 + y_t^2}} \Rightarrow \\
\frac{\sin \theta_i}{v_1} &= \frac{\sin \theta_t}{v_2} \xrightarrow[n_2=c/v_2]{n_1=c/v_1} \\
n_1 \cdot \sin \theta_i &= n_2 \cdot \sin \theta_t \text{ or } \sin \theta_t = \frac{n_1}{n_2} \sin \theta_i
\end{aligned} \tag{1.15}$$

This result clearly demonstrates that the angle of transmission (or the refraction) in a denser medium (higher index) is expected to be smaller than the angle of incidence. The law of refraction is usually referenced as *Snell's law* or even *Snell-Descartes law* since both Snell (Willebrord Snellius, Dutch astronomer, 1580–1626) and Descartes

Fig. 1.14 Reflection on convex and concave mirrors



Fig. 1.15 Application of total internal reflection using a pentaprism



(René Descartes, French mathematician, 1596–1650) defined the same law independently around the same time in the 1600s.

An interesting phenomenon in mirrors is related to the different *image formation in concave and convex mirrors*, as shown in Fig. 1.14, in which two photos of reflections from a spoon side-by-side demonstrate that concave mirrors invert the images whereas convex mirrors do not.

An interesting application of technically exploiting *total internal reflection* in a medium denser than air (for example glass) is shown in Fig. 1.15, in which a glass object is created in such a way that the incoming rays from the bottom undergo total internal reflection at the top and right sides (as shown with the arrowhead dashed lines). The refractive index of the medium and the relative angles of the planes of those sides with respect to the incoming rays guarantee that the light follows a particular direction and exits the medium as shown. This construct is called a *pentaprism* and has been of critical importance in photography for a significant amount of time.

Another interesting phenomenon relating to reflection is that of *polarisation*. Typically, ambient light, natural light from the Sun on the Earth, is unpolarised, which

means that although at any given time a ray of light has a particular electric field orientation (thus it is polarised at that instant), overall, the orientation of the electric field changes so erratically that an outcome net polarisation does not exist. Reflections on media interfaces are quantified by the Fresnel equations (after Augustin-Jean Fresnel, around 1820) that express the reflection coefficients for p-polarised and s-polarised light respectively, as simple expressions of the refractive indices and the involved angles

$$\begin{aligned} r_p &= \frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)} \\ r_s &= -\frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)} \end{aligned} \quad (1.16)$$

which can be further used (in combination with Snell's law) to express the corresponding reflectance as $R = |r|^2$

$$\begin{aligned} R_p &= \left| \frac{n_1 \cos \theta_t - n_2 \cos \theta_i}{n_1 \cos \theta_t + n_2 \cos \theta_i} \right|^2 \\ R_s &= \left| \frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t} \right|^2 \end{aligned} \quad (1.17)$$

Apparently, due to the conservation of energy principle, the transmittance can be simply quantified as

$$\begin{aligned} T_s &= 1 - R_s \\ T_p &= 1 - R_p \end{aligned} \quad (1.18)$$

David Brewster (1781–1868) around 1800 studied the effect of the various angles of incidence and the polarisation of light on reflection (Brewster, 1815). He found out that at certain angles p-polarised light does not result any reflection at all (all light is transmitted in the second medium),²¹ and this happens when

$$\theta_i = \tan^{-1} \frac{n_2}{n_1} \quad (1.19)$$

This particular equation was named *Brewster's law* and the angle *Brewster's angle* (usually denoted θ_B). A significant consequence of this law is that when unpolarised light is being used and the angle of incidence is the Brewster angle, then the reflected light can only be s-polarised. Since the natural light is unpolarised this law explains what happens on water surfaces, lakes, rivers and the sea, where incident rays at particular angles get reflected as s-polarised light and make the surface act like a mirror. For seawater with a refractive index of $n_2 = 1.34$ then Brewster's angle is $\theta_B = 53.267^\circ$. The phenomenon is quite common and appears on many surfaces, like floors, roads, windows, etc. Fig. 1.16 is a classic diagram of the Fresnel reflection

²¹ The original work can be found online at https://play.google.com/books/reader?id=U-U_AAAAYAAJ&hl=en&pg=GBS.PA125 (last accessed March 2022).

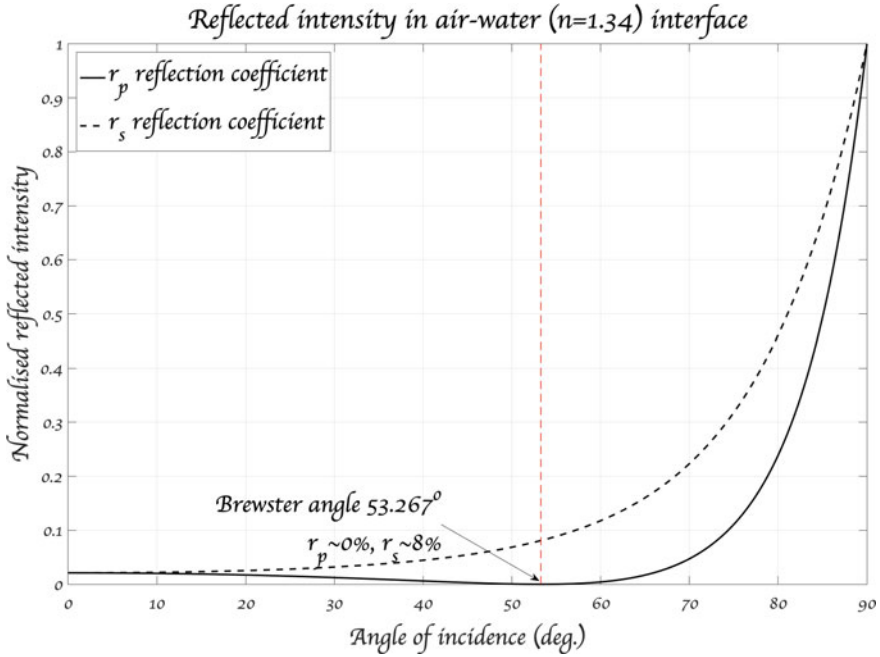


Fig. 1.16 Reflection of light in air-water interfaces with respect to the angle of incidence

coefficients (1.16) for the case of a reflection at the interface between air and seawater (of a refractive index $n_w = 1.34$). The vertical dashed line in the graph denotes the incidence angle, at which all the reflected radiation is s-polarised and all p-polarised radiation undergoes transmission in the water.

The principle of *refraction through a prism* is easily illustrated through a simple graphical representation. This is what is shown in Fig. 1.17, where a ray of light is shown travelling from left to right through air and reaching the prism at a θ_i angle of incidence (the angle of the ray with the surface normal depicted by a dashed line). The ray's transmission in the prism will follow a different angle, θ_{r_1} , due to refraction, which can be estimated using Snell's law as

$$\sin \theta_{r_1} = \sin \theta_i \frac{n_{\text{air}}}{n_{\text{prism}}} \quad (1.20)$$

Since $n_{\text{air}} < n_{\text{prism}} \Rightarrow \theta_{r_1} < \theta_i$ ²² and this is way the ray changes its propagation towards that particular direction shown in the graph. As the light travels through the prism, left to right, it eventually reaches the interface with air again at an angle θ_{r_2} with the normal to the interface at that position. Apparently, as the ray exits the prism

²² The relation of sines is equivalent to the relation of angles in this case, as the angles are in the range of 0 to 90°.

Fig. 1.17 Principle of refraction through a prism

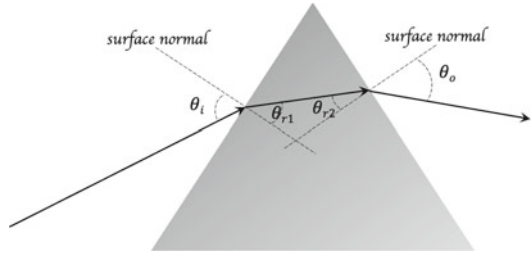
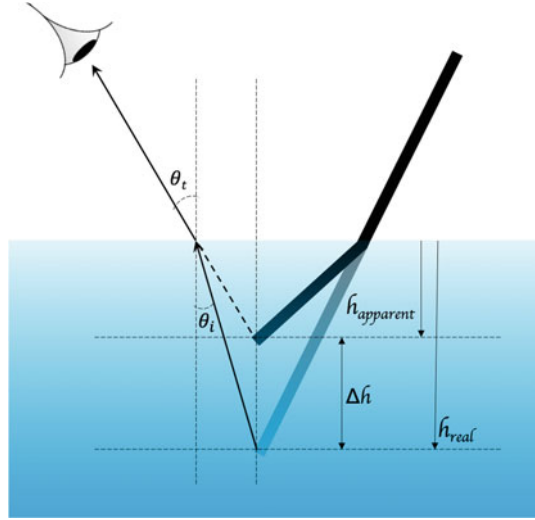


Fig. 1.18 Apparent bending of shapes due to refraction



and enters the air, the change of the medium imposes another change of direction at an angle θ_o (with respect to the normal at the interface) due to refraction, defined by

$$\sin \theta_o = \sin \theta_{r_2} \frac{n_{\text{prism}}}{n_{\text{air}}} \quad (1.21)$$

Again, since $n_{\text{prism}} > n_{\text{air}} \Rightarrow \theta_o > \theta_{r_2}$ and this is why another bending of the ray occurs at the particular direction shown in the graph.

A practical consequence of the phenomenon of refraction is illustrated in Fig. 1.18, in which the bending of light due to the transmission through different media results in the apparent bending of objects that extend through both interfacing media. In this example, a simple straight object that is partially submerged in water appears to bend towards the surface of the water, as a result of the light that is reflected on its surface (underwater) towards the observer above the water level, shown by the ray vectors towards the eye. The graph shows the refractions that occur, which create the appearance of the bending of the object by illustrating the light refraction from a single point on the object's surface.

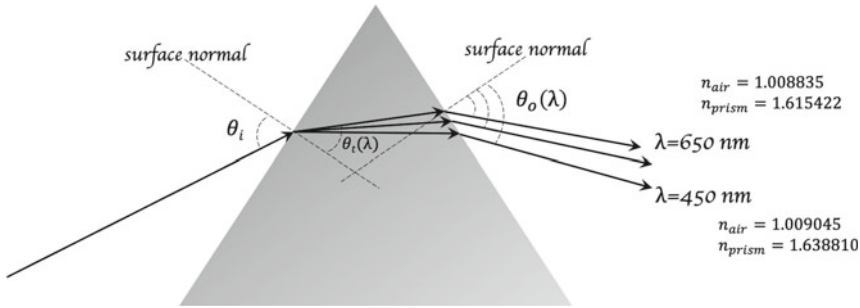


Fig. 1.19 Principle of dispersion through a prism

In addition, as mentioned earlier, the amount of bending of light during refraction through media also depends on the wavelength of light, leading to the phenomenon of *dispersion*, since Cauchy and Sellmeier found out that the index of refraction depends upon the wavelength (1.8). This effect is illustrated in Fig. 1.19 and results in observing light of shorter wavelengths to be bent more than that of longer wavelengths when passing through a prism. As shown in this graph, which depicts the case for a particular glass prism of $n_{\text{prism}} \approx 1.615$, when the original ray of light first meets the prism it starts to ‘decompose’ into rays of different wavelengths. This results in multiple rays reaching the second prism-air interface and to exit the prism resulting in even more pronounced decomposition, with rays of shorter wavelengths deviating significantly in comparison to longer wavelengths.

In order to characterise various media according to the way light undergoes dispersion when travels through them, the *Abbe number* has been defined, also known as *V-number* or *constringence* as

$$V = \frac{n_{\text{intermediate}} - 1}{n_{\text{short}} - n_{\text{long}}} \quad (1.22)$$

where the three refractive indices used, correspond to a predefined short, a long and an intermediate wavelength of light. Practically, in applications relating to visible light, this equation is presented in terms of a particular trio of indices, n_C , n_D and n_F , which correspond to the wavelengths of 656.3 nm, 589.3 nm, and 486.1 nm respectively. The Abbe number takes high values for slightly dispersive media or low values for highly dispersive media. *Flint glass*, that has already been mentioned, is any glass with $V \leq 50$, which means media composed of flint glass are highly dispersive. On the other hand, a glass medium with $V \geq 55$ results in low dispersion and is called *crown glass* (Meyer-Arendt, 1984). It should be noted, though, that the dispersive power of various media is not always proportionate to their refractive power, and this is something that depends on the material. For example, a SCHOTT-K7 crown glass with refractive index $n = 1.5111$ exhibits an Abbe number $V = 60.41$, a chromatic

dispersion²³ of $dn/d\lambda = -0.043741 \mu\text{m}^{-1}$ and a group velocity dispersion-GVD²⁴ of $\text{GVD} = 75.972 \text{ fs}^2\text{mm}^{-1}$, whereas a SCHOTT-F2 flint glass with a refractive index of $n = 1.62$ exhibits an Abbe number $V = 36.37$, a chromatic dispersion of $dn/d\lambda = -0.086475 \mu\text{m}^{-1}$ and a group velocity dispersion of $\text{GVD} = 168.09 \text{ fs}^2\text{mm}^{-1}$.

1.3 Colour Vision

A practical consequence of the dispersion of light due to the different levels of refraction for the various wavelength is the experience, in humans, of what is called the ‘light spectrum’ or the rainbow of colours when white light passes through a prism (Fig. 1.20) or raindrops hover in the air (Fig. 1.21).

Aristotle, in Book II, Chap. 7 of his treatise *On the soul*²⁵ defined light and colour as follows.²⁶

Οὐ μὲν οὖν ἐστὶν ἡ ὄψις, τοῦτ' ἐστὶν ὁρατόν, ὁρατὸν δ' ἐστὶ χροῶμά τε καὶ ὁ λόγῳ μὲν ἔστιν εἰπεῖν, ἀνώνυμον ... τὸ γὰρ ὁρατόν ἐστι χροῶμα, τοῦτο δ' ἐστὶ τὸ ἐπὶ τοῦ καθ' αὐτὸ ὁρατοῦ καθ' αὐτὸ δὲ οὐ τῷ λόγῳ, ἀλλ' ὅτι ἐν ἑαυτῷ ἔχει τὸ αἴτιον τοῦ εἶναι ὁρατόν. πᾶν δὲ χροῶμα κινητικόν ἐστι τοῦ κατ' ἐνέργειαν διαφανοῦς, καὶ τοῦτ' ἐστὶν αὐτοῦ ἡ φύσις διόπερ οὐχ ὁρατὸν ἄνευ φωτός, ἀλλὰ πᾶν τὸ ἐκάστου χροῶμα ἐν φωτὶ ὁρᾶται.

In essence, Aristotle stated that whatever is visible is colour and colour is what lies upon whatever is inherently visible; ‘inherently’ meaning not that it is visible due to its substance but due to containing the cause of being visible. Nothing is visible without light and everything is viewed with its colour.

Humans experience a world full of colour and construct numerous technological devices to capture and display it for art and science. *Yet, what is colour and how can it be defined?* Although light is objectively defined as a physical entity, the same cannot be said about colour. Colour, in essence, is a *human visual perception phenomenon* and is defined and bound by the particular characteristics and limitations of the process that creates it. It has been suggested that colour is a way in which natural evolution formulated the function of the eye-brain system so as to respond efficiently to visual stimuli of various wavelengths that convey important meaning for survival

²³ The derivative of the refractive index of a given medium with respect to the wavelength is an indication of the dispersion power of the medium. Typically, negative values are indicators of a *normal dispersion*, in which the index decreases with increasing wavelength, whereas positive values indicate a medium with *anomalous dispersion*.

²⁴ The group velocity dispersion is an indicator of how fast wavelengths of a composite light travels through a medium and is defined in terms of the GVD parameter $\text{GVD} = -\frac{\lambda}{c} \frac{d^2 n}{d\lambda^2}$. More formally, it is defined as the derivative of the inverse of group velocity of light in the medium with respect to angular frequency $\text{GVD} \equiv \frac{\partial}{\partial \omega} \left(\frac{1}{v_g(\omega)} \right)_{\omega=\omega_0}$.

²⁵ More like *biology* in modern terminology.

²⁶ The passage in Greek was adopted *verbatim ac litteratim* from <https://goo.gl/QGp7QN> (last accessed March 2022).

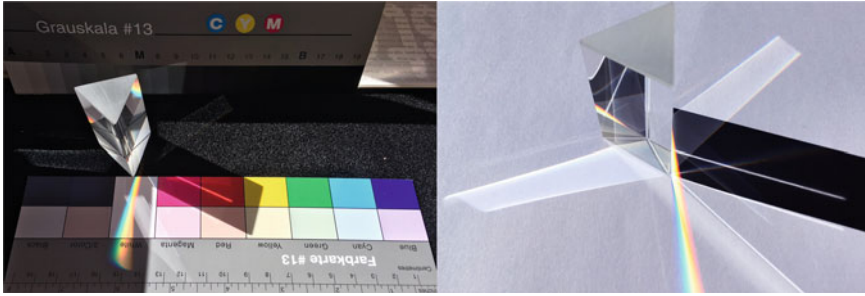


Fig. 1.20 The rainbow of colours produced by a prism under direct sunlight as a result of refraction



Fig. 1.21 Examples of rainbows

(Regan et al., 2001). *Colour does not exist in the objective reality, in nature. Colour is a label given by the brain through a classification process, corresponding to a particular material under particular illuminating conditions in a viewed scene.*

Sensation or perception of colour is actually a complex neuropsychological process that begins with sophisticated mechanisms within the eyes, as will be explained in the subsequent text. A *spectral colour* is what appears to be the perception of a single-wavelength light. An example image consisting purely of 16 distinct spectral coloured patches is shown in Fig. 1.22, in which each depicted patch was created by transforming light of a single wavelength into a digital image representation in what is known as the sRGB colour space. The selected wavelengths for this example were $\lambda = \{400, 420, 450, 460, 480, 500, 520, 556, 560, 580, 600, 620, 650, 670, 690, 700\}$ nm.

Pure spectral colour sensation can be thought of as the analogy of what happens when one tunes a radio; when the frequency changes then the radio station changes. But the analogy fails in all other cases where more than one wavelength is involved; in a radio receiver, one would hear multiple stations at once; not much of a pleasant experience. Since single-wavelength light is extremely rare in nature, the sensation of colour is based on combinations of spectral colours, also with some exceptions or variations to this rule. For example, the sensation of the colour named ‘yellow’ can

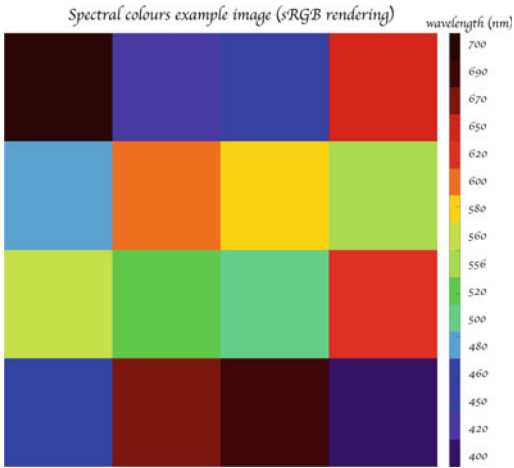


Fig. 1.22 Example of 16 spectral coloured patches rendered in the sRGB colour space

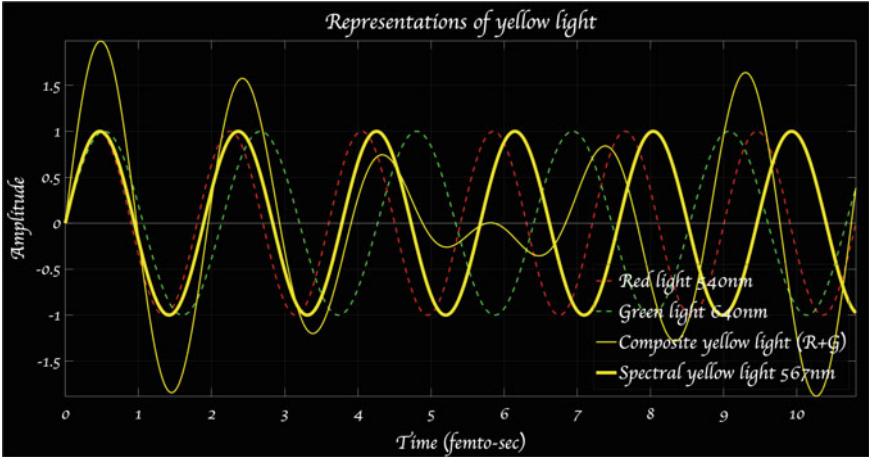


Fig. 1.23 Representations of yellow light as sinusoidal waves

be exactly the same when experiencing a light of around 570nm with a composite light of wavelengths of about 550 nm (called ‘green’) and nm 640 nm (called ‘red’). Figure 1.23 shows a representation of the yellow light issue, in which light is represented as a simple periodic sinusoidal wave (say, the electric field only). Although the perception of yellow is completely indistinguishable for the two cases of a pure and a composite light, the two sinusoidal representations are totally different.

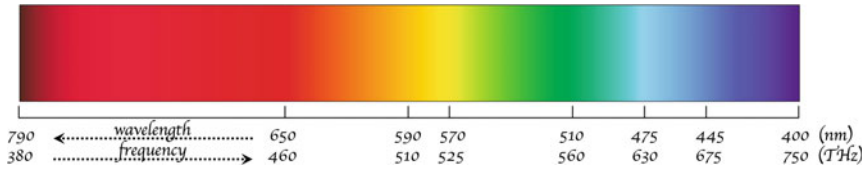


Fig. 1.24 The visible part of the electromagnetic spectrum

Colours are the apparent frequency differentiations or mixtures of light to an observer ranging from 380 nm (or 790 THz, what is called ‘violet’ light) to 740 nm (or 400 THz, what is called ‘red’ light). The conversion between frequency and wavelength is done by using the classic formula

$$\lambda = \frac{v}{c} \quad (1.23)$$

in which λ is the wavelength, v is the frequency and c is the speed of light in vacuum, as defined in (1.2). Each value in the 380–740 nm range corresponds to the sensation of a different colour as shown in Fig. 1.24. As any mixture of light of various frequencies results in the sensation of a distinct colour, an equal amount of light with frequencies in all the visible spectrum results in what is called ‘white’. Easy to say, the absence (or total absorption) of light results in what is called ‘black’.

As vision is linked to the visible electromagnetic radiation on the surface of the Earth, one should consider how this radiation is created, reaches the Earth and illuminates all that is to be seen. The main source of light on the Earth comes from the Sun. To make things more relevant, the part of the electromagnetic spectrum that corresponds to the wavelengths near the maximum of the Sun’s radiation range is what includes the visible spectrum to which human vision adapted. About 99% of the solar radiation reaching Earth’s surface has a wavelength between 300 and 2500 nm (2.5 μm). Of this range, 4% is in the invisible ultraviolet spectrum, 44% in the visible spectrum, and 52% is in the invisible infrared spectrum, as shown in Fig. 1.6. Apparently, the Sun’s light covers the whole visible spectrum (enclosed in the vertical dashed lines) and thus appears white, consisting of roughly equal amounts of energy at all frequencies in that range. This visible part of the electromagnetic radiation spectrum is shown in Fig. 1.7.

In physics, it is known that as the frequency of the electromagnetic radiation increases the more energetic the radiation becomes and the interaction with matter changes completely. Low-frequency radiation (infrared light) primarily sets molecules into vibration and is thus connected with heat. Higher frequency radiation (visible light) primarily elevates electrons to higher energy. Even higher frequency radiation (ultraviolet light) results in ionisation (ejection of electrons from molecules), which has damaging effects on living tissues. Luckily for life on Earth, most of the ultraviolet radiation is absorbed by the Earth’s atmosphere. Also through physics, it has been established that the solar spectral irradiance curve is character-

istic of thermal radiation from a black body at a temperature of about 5800 K (and is roughly a smoothed curve of the black line in Fig. 1.6). That is, the sunlight is thermal radiation from the Sun, which has a surface temperature of around 5800 K. Apparently, as shown in Fig. 1.6 (and also in Fig. 1.7), the actual spectrum that reaches Earth's surface is quite different from what a 5800 K ideal black body could radiate, primarily due to absorption in the atmosphere, which acts as a filter that blocks part of the Sun's energy reaching the surface.

Although the Sun is white when looked upon from a position outside the Earth's atmosphere, here on the Earth and during sunrise or sunset, when the Sun is low near the horizon, it gets coloured in reds, oranges and yellows. This happens because the sunlight has to pass through a much 'thicker' atmosphere to reach the observer, and appears in red, orange and yellow colours, due to the suppression of the short-wavelength light (violet, blue) by the 'thick' atmosphere, creating those stunning 'warm' scenes that have been magnetising the eyes since the dawn of humanity. As the Sun goes up in the sky, the shorter-wavelength light, primarily the blue, interferes with air molecules in the upper atmosphere and scatters significantly, giving the sky that distinctive blue hue. At that point the Sun looks virtually white. Figure 1.25 shows a typical sunrise photo showing the gradual change of the sun's colour just above the horizon, whereas Fig. 1.26 shows a sunset photo, in which the sun has already set behind a mountainous and cloudy horizon. It is clear how 'warm' the overall colour sensation is in these photos, in contrast to Figs. 1.27 and 1.28, in which typical mid-day photos showcase the blue-ness of the sky; at those moments the colour appearance of the Sun is totally white. A very indicative graph of the change of the Sun's spectral power distribution (resulting in changes in the apparent colour) during different times of day and cloud coverage was shown in Fig. 1.8.

One would expect that a sensation as important as colour vision, with such a profound impact on humans, would have been analysed and explained centuries ago. Indeed, an impressive amount of research has been devoted to the understanding of human vision, probing both the workings of the eyes and the processing within the brain. This is represented by an extensive volume of published work throughout the centuries. The topic of colour vision has been a subject of intense research

Fig. 1.25 A photo of the sun during a sunrise in Northern Greece; it is August 24th, 6:45



Fig. 1.26 A sunset photo in Northern Greece; it is August 24th, 20:15



Fig. 1.27 A mid-day photo in the Anza Borrego desert in San Diego; it is January 29th, 11:50



Fig. 1.28 A mid-day photo at the San Diego marina; it is February 4th, 12:40



in various domains, including science, physiology, psychology, even philosophy. Recently, Pavlidis (2021) published an account of the major contributors towards the foundation of modern colour theory.

As colour vision is a subjective phenomenon in humans, in order for basic colour theory concepts to become apparent, it is important to have at least a brief understanding of the human visual system and its basic structure and functionalities. One very important component of the human visual system is the input sensory system, the eyes. Humans, like many other beings on Earth (possibly elsewhere, too), facilitate a *pair of eyes* to be able to visually perceive the world on the basis of its geometry and its spectral manifestation. This means no other than to understand a scene with efficacy so as to be able to respond to survival challenges. Even though one eye would suffice for *colour vision*, two eyes are certainly needed to support *depth perception*, the full geometry of a scene. The eyes are an excellent example of adaptation in evolution and, as suggested by many research works, like the seminal work of Barlow (1982), compose a system *no-more and yet no-less than what is required*. In the following paragraphs, the basic anatomic structure of the human eye is briefly presented, which provides strong hints on how computer vision technology (also photography) evolved.

According to the Medical Subject Headings (MeSH),²⁷ *vision* is the

the process in which light signals are transformed by the photoreceptor cells into electrical signals which can then be transmitted to the brain.

Colour perception in MeSH²⁸ is defined as

mental processing of chromatic signals (colour vision) from the eye by the visual cortex where they are converted into symbolic representations. Colour perception involves numerous neurones and is influenced not only by the distribution of wavelengths from the viewed object but also by its background colour and brightness contrast at its boundary.

Colour perception has previously been defined as the visual identification of each particular colour hue or its absence (Bergmann, 1858). MeSH defines *visual perception*²⁹ as

the selecting and organising of visual stimuli based on the individual's past experience.

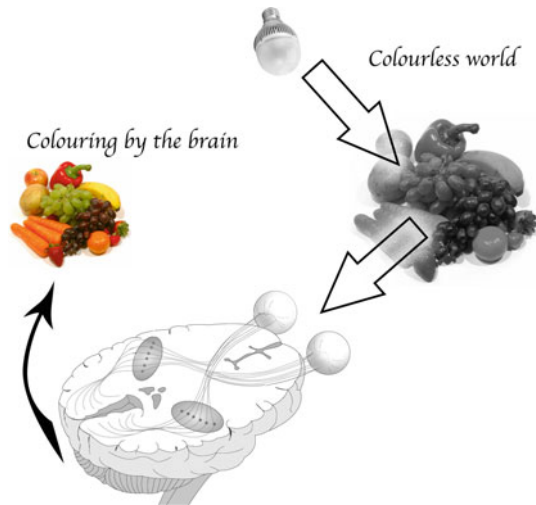
Colour perception is a complex process involving an illuminant (a source of light), a scene, light-responding sensors (the eyes) and a semantics extraction mechanism (a brain), as represented in Fig. 1.29. Typically, the illuminant produces light that shines the scene, the light interacts with all the scene surfaces and some of it bounces off and reaches the eyes of an observer that happens to be in that scene. The visual stimuli in the eyes undergo an electrochemical transformation and the produced signal is

²⁷ MeSH is now hosted as the National Library of Medicine controlled vocabulary thesaurus used for indexing articles for PubMed under the National Centre for Biotechnology Information, U.S. National Library of Medicine, <https://www.ncbi.nlm.nih.gov/mesh/68014785> (last accessed March 2022).

²⁸ See <https://www.ncbi.nlm.nih.gov/mesh/68003118> (last accessed March 2022).

²⁹ See <https://www.ncbi.nlm.nih.gov/mesh/68014796> (last accessed March 2022).

Fig. 1.29 The colour perception in humans



forwarded to a particular specialised part of the brain for the creation of the colour representation and the extraction of meaning. The following paragraphs provide a brief presentation of the mechanisms for colour vision, focusing primarily on the eyes and their characteristics and function.

The eye is nearly a sphere with a 24 mm average diameter. Three membranes enclose the eye, namely, the *cornea* and the *sclera* on the outside, the *choroid* in the middle and the *retina* on the inside (Gonzalez and Woods, 1992). A front-view three-dimensional representation model of a left human eye is shown in Fig. 1.30, displaying also the main parts and geometry of the eye.³⁰ A classic representation of the anatomy of the eye is shown in Fig. 1.31, which shows a section of a left eye with the names of the most basic mechanisms that enable focusing and encoding of light. In this representation, light enters the eye from above towards the bottom, passes through the cornea and the aqueous humour, the iris and the lens, and through the vitreous humour reaches the retina, where it is captured and registered. It is shown also that the optical axis of the eye is different than the visual axis, i.e., the direction perpendicular to the cornea and lens surfaces is different than the direction to the fixation point (Avudainayagam and Avudainayagam, 2011).

The *cornea*, with a diameter of about 11.5 mm (about 12% of the eyeball's total surface) and a thickness of about 0.6 mm, is perfectly transparent, without blood vessels but with many nerve endings (Goldstein, 2006; Cassin et al., 1984). It is a tough tissue to cover and protect the lens but also serves as a significant refractive element with a refractive index of $n_{\text{cornea}} = 1.376$. To the left and right of the endings of the cornea is the *sclera*, from the Greek σκληρός-‘skleros’ (hard), the white part

³⁰ This is based on various sources and particularly based on data from Michel et al. (1990) and Penkhus (1966) and from the *Corneal anatomy* article at the Laboratory of vision and optics, University of Crete, <http://www.ivo.gr/en/patient/cornea-diseases/cornea-diseases.html> (last accessed March 2022).

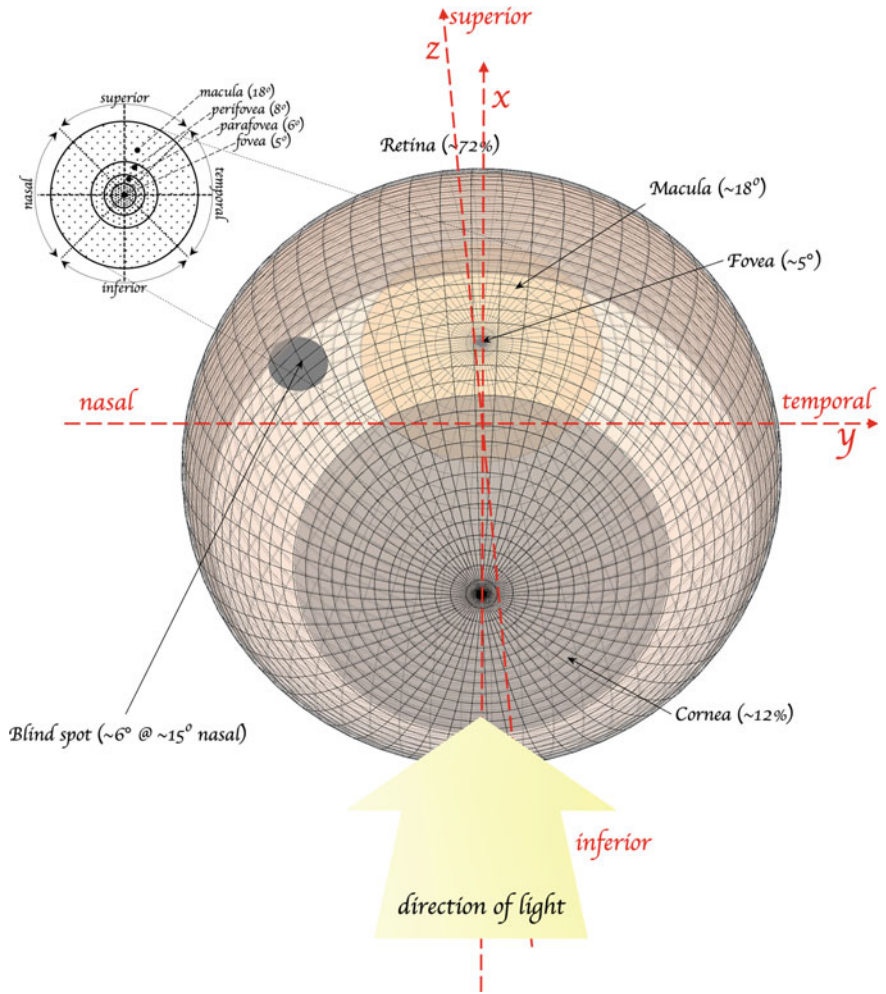
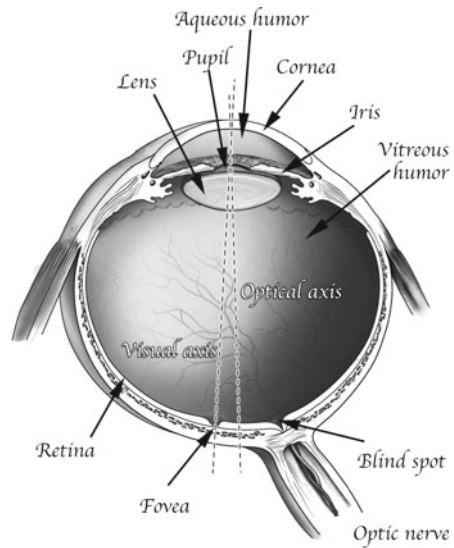


Fig. 1.30 Three-dimensional model of a human eye

of the outer eye, a very tough fibrous layer, which is completely opaque (Cassin et al., 1984). The *choroid* is a pigmented layer inside the sclera and on top of it. It supports the nutrition of the eye and further reduces the backscattering of light within the eye, by absorbing all light that reaches its surface (Gonzalez and Woods, 1992; Cassin et al., 1984).

At front and just below the cornea is the *anterior chamber*, which is a chamber of about 3 mm filled with an *aqueous humour* (water-like fluid) (Cassin et al., 1984). Its purpose is to inflate the globe of the eye and maintain the pressure that keeps the eye nearly spherical in shape, while preventing eye dryness and exposure to particles and pathogens. It also acts as an antioxidant agent and provides nutrition for the

Fig. 1.31 Schematic diagram of a horizontal cross-section of the left human eye



ocular tissues. Aqueous humour is produced continuously and there is a dedicated mechanism for draining the old humour to keep a constant pressure in the eye. The aqueous humour has a limited contribution to the refraction of light with a refractive index of $n_{\text{aqueous}} = 1.336$. As this value is very close to that of the preceding layer, the cornea, aqueous humour has an insignificant impact on the overall refraction in the eye.

Just below the anterior chamber is the *iris*,³¹ a thin, circular structure in the eye, that controls the amount of light entering the eye by adjusting the diameter and size of the pupil.³² Iris is the diaphragm, the protective mechanism,³³ whereas the pupil is the aperture, the opening. The *pupil*, is a circular opening at the centre of the iris to allow light to enter the eye. It appears as a black hole because once light rays enter the eye they cannot be reflected back, as they are totally absorbed inside the eye (Cassin et al., 1984). In the presence of bright light, light-sensitive cells in the retina send signals to the circular iris muscle, which contracts to reduce the size of the pupil (pupillary light reflex). In the sight of objects of interest or in the absence of bright light the pupil dilates. The pupil diameter varies from 2 to 4 mm in bright light to 3–8 mm in the dark, but this might also depend on the age (Winn et al., 1994).

³¹ 'Iris' comes from the Greek mythological secondary goddess Ἴρις related to atmospheric phenomena and particularly the rainbow.

³² The iris is the part that also defines eye colour, due to the existence, concentration and dispersion of types of dark pigment melanin. Melanin exists on the iris to make it opaque and block any light passage. Small concentration of dark pigment typically results in blue colouring due to the presence of the watery aqueous humour, just as water bodies appear blue.

³³ 'Diaphragm' comes from the Greek διάφραγμα (diaphragma), used to describe thin separating or protective membranes.

The *lens*, or *crystalline lens* is a typical refractive transparent variable biconvex structure that makes focusing of light on the retina possible. The lens is able to change its shape in order to adjust its focal length and be able to focus objects at various distances (equivalently to a zoom lens in a photographic camera). The lens is typically circular of around 10 mm diameter, contains no blood vessels or nerves and has a light yellow colour. It absorbs around 8% of the incoming light and absorbs infrared and blocks ultraviolet light in the wavelength range of 300–400 nm, with shorter wavelengths being blocked by the cornea. High-intensity ultraviolet or infrared light may cause damage to the lens (Gonzalez and Woods, 1992; Mainster, 2006). It should be noted that all of the ocular organs have a slight yellowish colour to compensate for the phenomenon of chromatic aberration, to absorb ultraviolet light and transmit wavelengths in the range 300–1600 nm. Regarding the nominal focal length of the lens, this is on average around 22 mm, but obviously varies with accommodation.³⁴ *Accommodation* is the process used in biological lenses to change their focal length, typically by changing their geometry. In human eyes, accommodation leads the lens to become rounder in order to be able to focus at near objects, providing a focusing functionality that covers a range from around 5 cm to infinity. This ability translates to a *lens optical power*³⁵ of 20 dioptres ($= 1/0.05 \text{ m}^{-1}$). In addition, in the characterisation of lenses, the optical power connects to the magnification power of a lens by the formula

$$MP = 0.25 \cdot \Phi + 1 \quad (1.24)$$

where 0.25 (m) is the standard viewing distance (25 cm) and Φ is the optical power. Of course this does not apply to the lens of the eye but to any lens brought very close to the eye while focusing an object at 25 cm distance. The lens of the eye has a refractive index that varies from $n_{\text{lens-outer}} = 1.386$ to $n_{\text{lens-inner}} = 1.406$ from the outer to its inner layers. It is still very close to the value of the cornea, thus does not impact the refraction of light significantly.

Moving towards the inner parts of the eye, there is the *vitreous humour* (glass-like fluid), which is a clear gel that fills the space between the lens and the retina, with the main function to exert pressure and maintain the spherical shape of the eye needed for the ability to correctly focus images. Its viscosity is two to four times that of water, thus giving it the gelatinous texture. It has a composition similar to that of a sparse cornea, with no blood vessels and almost 99% water, but still, denser than the aqueous humour. Its main components are phagocytes that remove cellular debris from the visual field (Cassin et al., 1984). The vitreous humour has a refractive index of $n_{\text{vitreous}} = 1.337$, almost identical to that of the aqueous humour, with no significant impact on the refraction of light.

³⁴ Many researchers suggest a focal length of 16.7–18 mm (Pocock et al., 2013; Serway and Beichner, 2000; Cameron et al., 1999), or in the lecture notes found in the article titled *The Wonder of Accommodation* published at the Physics Classroom, <https://www.physicsclassroom.com/Class/refrn/U14L6c.html> (last accessed March 2022), but this is the front projection focal length, whereas the distance from the lens to the retina is nearly 22 mm.

³⁵ The lens optical power is defined as the reciprocal of the focal length of the lens and is used for many practical applications and the construction and combination of lenses.

Fig. 1.32 Main refractive elements of the human eye

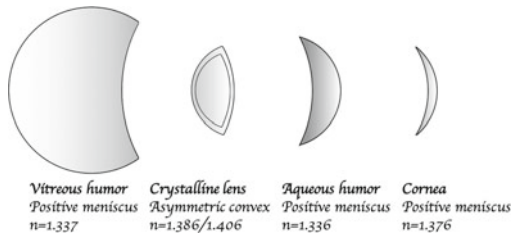
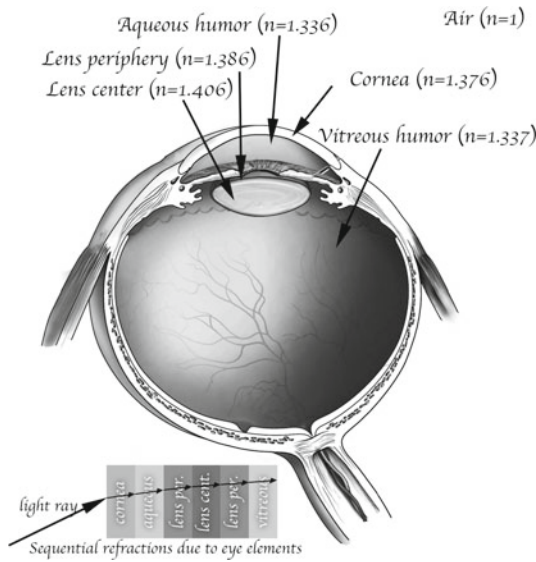


Fig. 1.33 Diagram of the left human eye with refractive indices on the various elements



The cornea, the lens, the aqueous and vitreous humours are the refractive elements of the eye, as schematically depicted in Fig. 1.32, in which the elements are ordered from right to left in the path of light towards the retina. In addition, Fig. 1.33 shows the left eye cross-section with all the elements and the corresponding refractive indices marked. A graphical representation is shown at the bottom of this representation, indicating the amount of relative change in the direction of light imposed by the various elements in the light path towards the retina. Furthermore, Fig. 1.34 shows a graph of the overall light refraction and the refraction based solely on the cornea, as a function on the incidence angle; this figure makes clear that *the cornea is the part of the eye responsible for most of the refraction* for any angle of incidence.

The *retina*, from the Latin *rete* (net), is the third and inner membrane of the eye, covering most of the inner surface (Masland, 2012). It is a thin transparent tissue that covers about 72% of the total surface of the eyeball that consists of five cell layers, the photoreceptors—cones and rods, the bipolar, the horizontal, the amalgam and the ganglion cell layers, as shown in Fig. 1.35 (top is the inner part), with a function to capture light as an electrical signal, to apply initial processing

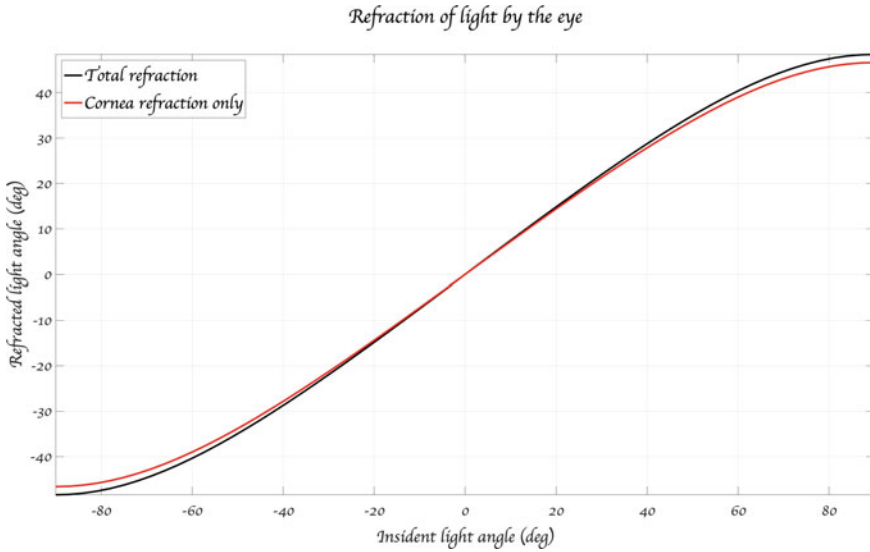


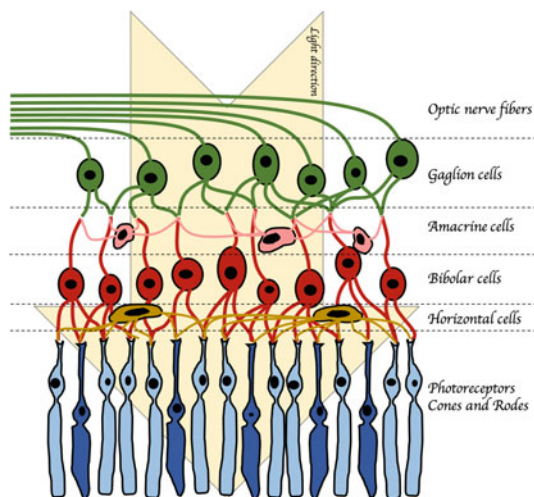
Fig. 1.34 Light refraction curves for various angles of incidence

and to transmit the visual electrical signal to the brain. Light goes through all the nearly transparent layers of the retina until it reaches the photosensitive elements of the photoreceptors (the cones and rods). This initiates a cascade of chemical and electrical events that ultimately trigger nerve impulses that are sent to the brain through the optic nerve. The photoreceptors, the neurones sensitive to light, are positioned in the pigment epithelium, which is rich in blood supply for immediate access to oxygen. The *photosensitive ganglion cells* in the retina are rare cells but with the important function to provide feedback for reflexive responses to bright daylight (iris contraction) (Gonzalez and Woods, 1992; Cassin et al., 1984; Wandell, 1995) and possibly support the opponent colour function of the eyes according to Hering and von Kries (Hering, 1964; von Kries, 1878).

The area of the retina directly perpendicular to the light entrance is the *macula*, a surface that corresponds to an angle of around 18° at the back of the eyeball surface, that is divided structurally into four concentric regions, including the perifovea, the parafovea and the fovea, as shown in the graphical representation of the front-view retina of the left eye in Fig. 1.36.³⁶ A highly important region in the macula is that of the *fovea* (about 5° wide) right at the point opposite to the entrance of light, which is responsible for what is called *the central vision*, the part of the vision with the highest acuity (spatial and spectral resolution). It contains only cones, which are thinner and longer in this area and create a denser concentration. Also, the configuration of the various retina cell layers in this region is different from what was shown in Fig. 1.35

³⁶ The colour image in this graph is a *fundus image*, a photo of the interior of the eye, around 30° wide.

Fig. 1.35 Main functional cell layers of the retina



and mostly looks like the graphical representation in Fig. 1.37. There are no rods in the regions, and the highly packed thinned cones are directly exposed to light, as the other cell layers are displaced.

As illustrated in Fig. 1.36, at a roughly 15° angle there is the *blind spot*, a 6° disc, which is a position where optic nerve fibres converge to leave the eye and connect to the brain. The blind spot, or the optic disc, is a location with no photoreceptive cells, and thus, no light is sensed there.

Cones are three types³⁷ of cone-shaped photoreceptive cells that enable high-resolution daytime colour vision (the *photopic vision*) by responding to different light spectrum regions under bright daylight, whereas, *rods* are rod-shaped cells that are of one type only and are very sensitive even to very low-light conditions, thus enable night vision (or *scotopic vision*, which is also *peripheral vision*, as will be explained later). One may find a large number of studies that focused on counting the numbers of cones and rods but there is no strict agreement. There is, though, an agreement in their relative numbers. For example, Gonzalez and Woods (1992), as well as Montag (2002), reference around 7 million cones and around 100 million rods. The *distribution of cones and rods* in the retina is not uniform; in the fovea, there is a high density of thin cones that decreases and ultimately diminishes towards the periphery with cones becoming thinner and thicker, whereas rod density is near zero in the fovea and increases towards the periphery. A box plot of the cone density in various eccentricities near the fovea is shown in Fig. 1.38, based on the data by Legras et al. (2018).³⁸ The graph clearly highlights how the cone density falls significantly

³⁷ More formally, it is considered that cones are just *one type of cells*, which may contain three types of photopigments, the photo-reactive substances that initiate the chemical cascade that converts light into electrical signals.

³⁸ Data downloaded from <https://doi.org/10.1371/journal.pone.0191141.s001> (last accessed March 2022).

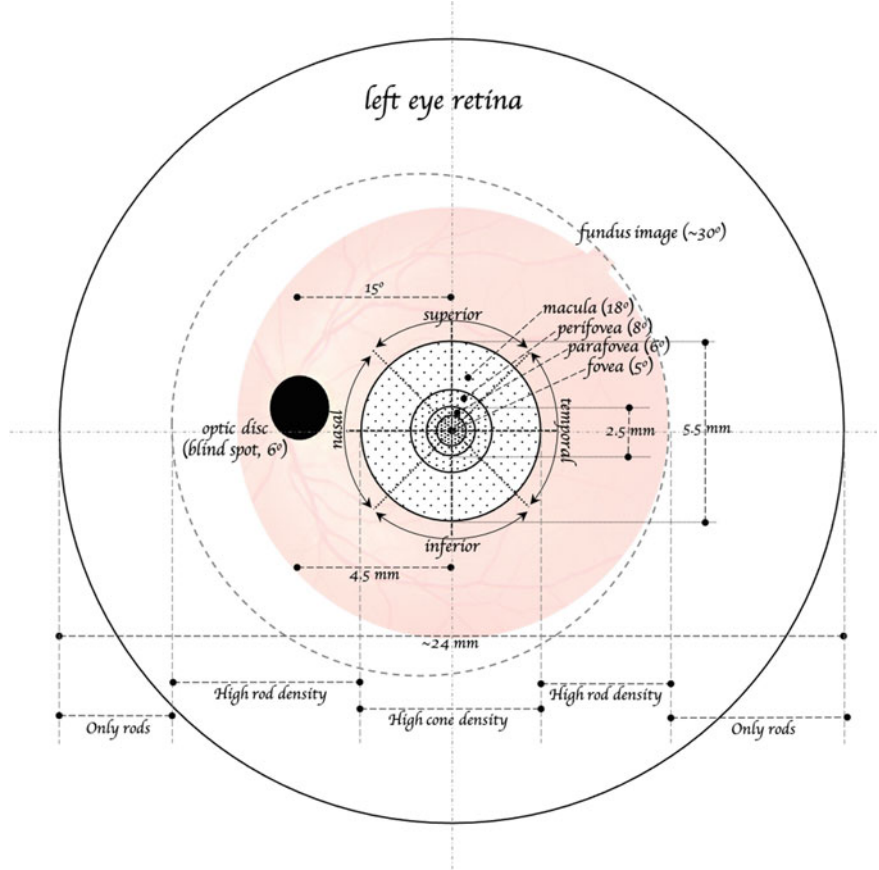


Fig. 1.36 Front view of the retina of the left eye

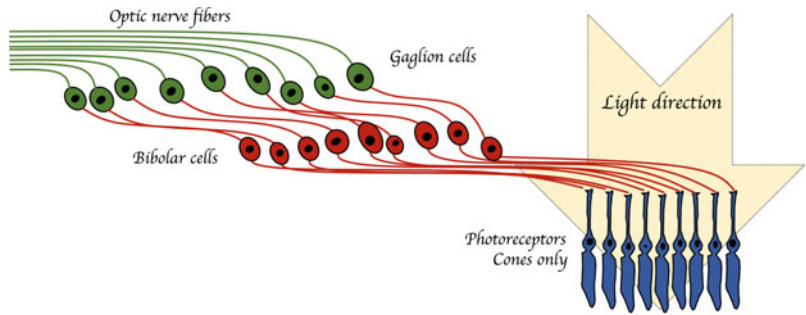


Fig. 1.37 Cell layers of the retina in the fovea

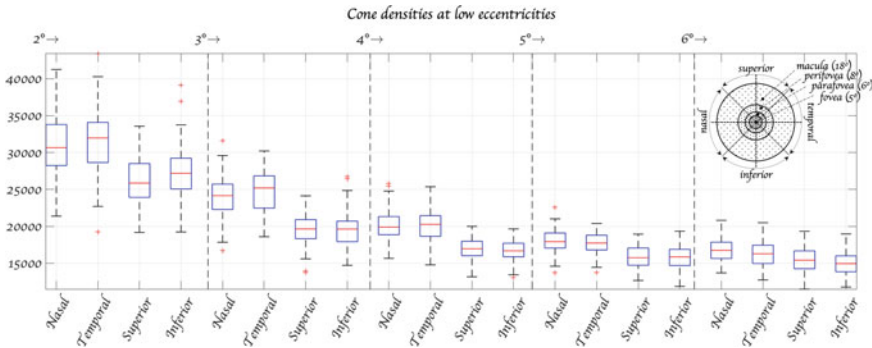
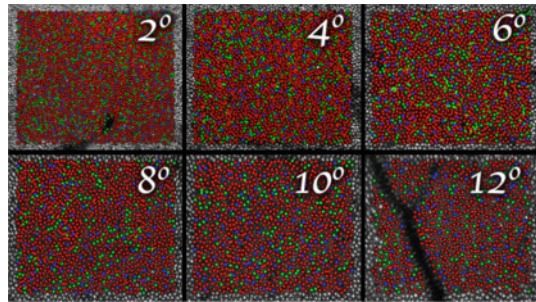


Fig. 1.38 Cone density distribution in the fovea

Fig. 1.39 Cone distribution at low eccentricities. (Figure created based on Zhang et al., 2019, with the kind permission of the authors)



even at low eccentricities. In addition, Fig. 1.39 highlights how the cone mosaic³⁹ changes with eccentricity (Zhang et al., 2019).⁴⁰

What differentiates the cones into three types is the different types of pigment that they contain. Anatomically and through psychophysical experiments it was established that there are three pigments that react differently to light and exhibit maxima in their absorbance to light at 420 nm (violet), 530 nm (green) and 560 nm (yellow), as shown in Fig. 1.40, in which the curves of log-sensitivity are drawn, using the red-green-blue representation convention, from the data by Stockman and Sharpe (2000), which used psychophysical⁴¹ experiments.⁴² Due to this fact, the cones with

³⁹ The cone mosaic is a pseudo-colour representation based on a microphotograph of a small part of the retina. In this representation, the colours denote the wavelength to which each of the cones mostly responds.

⁴⁰ This figure is based on the supplementary material of Zhang et al. (2019), <https://www.pnas.org/content/pnas/suppl/2019/04/02/1816360116.DCSupplemental/pnas.1816360116.sapp.pdf> (last accessed March 2022), used with the kind permission by the authors.

⁴¹ As clearly stated in Nature Research at <https://www.nature.com/subjects/psychophysics> (last accessed March 2022), 'Psychophysics is a field of methodology within psychology concerned with studying the sensation of stimuli. Psychophysics methods typically record the effect of systematic modulation of stimuli on a subject's perception'.

⁴² The data were found at <http://www.cvrl.org/pigments.htm> (last accessed March 2022). Other methods and approaches (e.g. Baylor et al., 1987; Dartnall et al., 1983; Merbs and Nathans, 1992; Westland et al., 2012) gave slightly different values but the overall result is about the same.

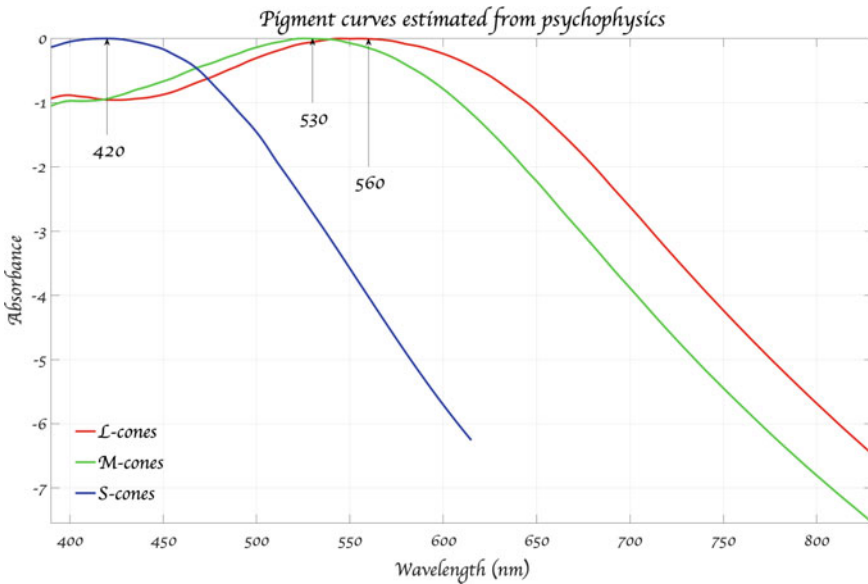


Fig. 1.40 Absorbance spectra of cone pigments

each of the particular pigments respond to a different region of the spectrum and are thus named L, M and S cones (for Long, Medium, Short-wavelength).

Following the cone pigment absorbance pattern, the spectral sensitivities of the cones, typically termed cone fundamentals, are drawn in Fig. 1.41 (Stockman and Sharpe, 2000).⁴³ Typical measurements are taken in a 2° region in the fovea, resulting in the 2° cone fundamentals, whereas in case the measurements consider a 10° region, they are termed the 10° cone fundamentals. The wavelengths that correspond to the maxima of each response are marked on the graphs. Contrary to the standard convention, the curves in these graphs are drawn using the sRGB colour that corresponds to the wavelength of the maximum sensitivity for each cone type. Thus, the ‘blue’ cones’ (S) response is drawn in violet, the ‘green’ cones’ (M) response is green and the ‘red’ cones’ (L) response is yellow.

The *topography of the cone types* in the retina, or the ratio among the three cone types is not constant in all people and large variations have been reported (De Vries, 1949; Brindley, 1954; Vos and Walraven, 1971; Walraven, 1974; Smith and Pokorny, 1975; Williams et al., 1981; De Monasterio et al., 1985; Ahnelt et al., 1987; Vimal et al., 1989; Cicerone and Nerger, 1989; Curcio et al., 1991; Shapley and Brodie, 1993; Cicerone et al., 1994; Roorda and Williams, 1999; Brainard et al., 2000; Hofer et al., 2005; Schmidt et al., 2016). This is due to the fact that all current knowledge

⁴³ The graphs use the data provided at <http://www.cvrl.org/cones.htm> (last accessed March 2022) with information at http://www.cvrl.org/database/text/cones/ss2_10.htm (last accessed March 2022) and <http://www.cvrl.org/database/text/cones/ss10.htm> (last accessed March 2022).

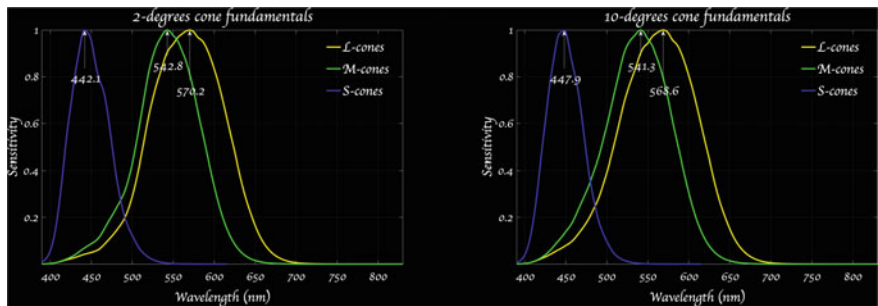


Fig. 1.41 2° and 10° cone fundamentals in the human retina

about colour vision is based on assumptions, models and indirect experimental results with large variances, in some cases inconclusive. Although the current models assume a clear distinction among the three cone types, recent studies, like Schmidt et al. (2016), suggest a more complex contribution of the cones to the overall sensation of colour. Nevertheless, until new evidence suggests a more accurate model, most researches report a ratio for L to M cones equal to 2.0 and an overall 6–7% for S cones in the retina. Interestingly, this topography is not uniform, as in the fovea there are only a few S cones, whose density increases with the eccentricity, and finally decreases as rods replace the cones in higher eccentricities. In particular, in the central region of the fovea, about 1.5 mm in diameter, corresponding to an angle of 0.34°, no S cones are expected to be found.

$$\text{S cones} = 7\%, \quad \frac{\text{L cones}}{\text{M cones}} = 2.0 \tag{1.25}$$

Oversimplified approaches suggest a L : M : S = 60 : 30 : 10 overall ratio.⁴⁴ Using this simplified ratio, Fig. 1.42 shows the corresponding scaled cone fundamentals, where, again, the colour of each response corresponds to the sRGB colour perceived by a light with a wavelength that produces the maximum response (indicated in the graphs). It should be noted here that this is not an accurate representation of the response of the human retina in terms of the energy, as light of short wavelengths (high frequency light) is significantly more energetic than light of longer wavelengths.

A significant research has also been devoted to the understanding of the resolution of vision, the visual acuity and the limitations to human vision. It was as early as the 1850s when Heinrich Müller (1820–1864), a German anatomist involved in the study of the eye, recognised that vision begins with a spatial sampling of the incoming image on the retina, as pointed out by Yellott (1990). Müller combined psychophysics

⁴⁴ See for example the page about *Cones* in the American Academy of Ophthalmology at <https://www.aao.org/eye-health/anatomy/cones> (last accessed March 2022).

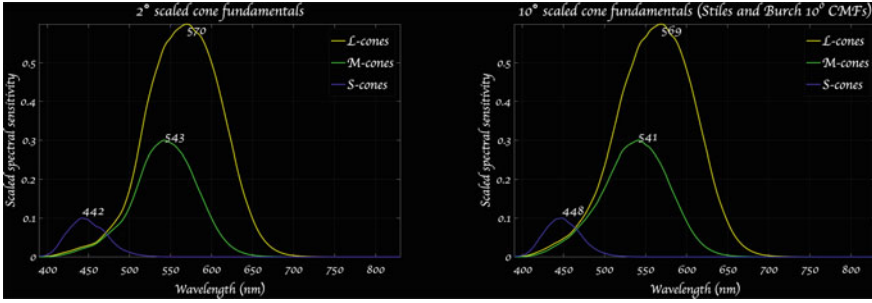


Fig. 1.42 2° and 10° cone fundamentals in the human retina scaled by the L,M,S populations

and anatomy and showed that the rods and cones are discrete photoreceptive elements in the retina (Brindley, 1960). According to Müller, to visually distinguish two points it is sufficient to stimulate just two different cones. In addition, Bergmann (1858), supported that a continuous line would be indistinguishable from a row of dots. Both Bergmann and later Helmholtz (von Helmholtz, 1867), supported the *three-cones theory*, in which two stimulated cones separated by an unstimulated can resolve two points. By using this theory, the estimation of the limits of visual acuity was consistent with the physical dimensions and spacing of the cones in the retina. This results in a frequency limit of 60 cycles/degree. It is now commonly accepted that the optical efficacy of the human eye depends upon the spacing of cones at the central region of the fovea (Snyder and Miller, 1977). As the retina discretises the light hitting the photoreceptor mosaic, it is susceptible to sampling artefacts or *aliasing*, thus, spatial resolution limits do exist (Williams, 1985).

According to average estimates, the density of cones (and cones alone) in this central part of the fovea is about $150,000 \text{ cells} \cdot \text{mm}^{-2}$. This part of the fovea is circular with roughly 1.5 mm diameter, thus an area of $\pi \times (\frac{1.5}{2})^2 \approx 1.767 \text{ mm}^2$, which would correspond to a square area of a side of about 1.33 mm. Some resolution estimates would give

$$\begin{aligned}
 \text{Cells in the are:} & \quad 150,000 \times 1.33^2 \approx 265,000 \text{ total cells} \\
 \text{Cell resolution:} & \quad \sqrt{150,000} \approx 390 \text{ cells per mm \& direction} \\
 \text{Cell resolution in inches:} & \quad \sqrt{150,000} \times 2.54 \approx 980 \text{ cells per inch}
 \end{aligned}
 \tag{1.26}$$

which is some 980 dpi in the terminology used in displays and printers (Gonzalez and Woods, 1992; Montag, 2002).

To derive *an estimate of the eye resolution* in modern-day technical terms (say in MegaPixels or MPixels) is not an easy task. This task is complex firstly because the sensing surface of the eye, the retina, is not uniform in its structure. A simplistic approach would be to say that since only cones are responsible for daytime colour vision, and there are about 7 million of them in the retina, the resolution should be

about 7 MPixels. This is not so true, though. As the retina consists of other photo-sensitive cells which interact and interconnect with the cones this number changes vastly. In addition, only the central part of the fovea is capable of producing sharply focused images, whereas with increasing eccentricity the density and size of the cones change rapidly. This results in having only a very small part of the visual field (the central) sharply focused and the rest just an increasingly blurred interpretation of the visual scene. Furthermore, the eye is constantly moving and reading light, acting like a modern-day video camera. Measurements of the resolution of the eye resulted in estimates of what is known as *visual acuity*. It has been estimated that the visual acuity follows a hyperbolic decline towards the periphery according to the ratio $\frac{E_2}{E_2+E}$, where E is eccentricity and E_2 is a constant of approximately 2° , where acuity is half the foveal value (Strasburger et al., 2011). To get things more complicated, the central part of the vision has been measured to be capable of sub-cone resolution (hyperacuity), meaning that the eye in central vision can detect changes in sub-cone size (or spatial frequency), possibly due to the eye-brain capacity to resolve information also from the motion of the eyes. This *super-resolution vision*, is expressed as an increased ability to distinguish misalignments and enables to distinguish non-aligned objects within 5 arc-seconds, which represents a fraction of the width of a cone. This is equivalent to the detection of a misalignment of light sources at a distance of about 63 km (Montag, 2002). So, overall, an eye is a video capturing device, with a particular viewing angle, focal length and focusing capabilities, particular aberration characteristics, and a circular central high-resolution capacity that lowers with eccentricity.

The distance between two points that is resolvable (and corresponds to the distance between consecutive cones in the fovea), is estimated to be $2\text{--}2.5\ \mu\text{m}$ —(Miller, 1979) estimated it to be $3\ \mu\text{m}$ on a hexagonal arrangement—and corresponds to an angular separation of $0.5'$ or $30''$. The most central part of the fovea, measuring roughly a diameter of $0.29\ \text{mm}$ corresponds to 1° visual angle⁴⁵ (Montag, 2002; Greger and Windhorst, 1996). An example that illustrates the apparent size of objects in relation to the viewing angle is shown in Fig. 1.43, where the celestial objects of the Solar system are drawn in respect to their viewing angle and distance in logarithmic scale for better representation. Based on this, Fig. 1.44 shows a fictional sunset sky, in the Northern hemisphere, with planet Jupiter in place of the Moon, using the actual sizes and the corresponding viewing angles.

Assuming a hexagonal arrangement of the cones, Williams (1985) defined the critical frequency in cycles/deg above which aliasing occurs, namely the Nyquist limit⁴⁶ as $f_N = (\sqrt{3}s)^{-1}$, where s is the centre-to-centre spacing for foveal cones in degrees. According to this estimate and assuming $s = 3\ \mu\text{m}$ cone spacing in the

⁴⁵ It might strike as something too small but this 1° is twice the angular diameter of the sun or the full moon, or a human head at a distance of 12–15 m.

⁴⁶ As known from *digital signal processing*, the *Nyquist frequency* is substantially the frequency at which *aliasing* starts to appear. That is, a standard grating of a signal $\cos(2\pi(N/2 + f))$ above the Nyquist frequency cannot be distinguished from a signal $\cos(2\pi(N/2 - f))$ that is an equal amount below that frequency. The Nyquist frequency is practically applied as a lower limit of sampling in numerous engineering application, as the frequency twice the maximum frequency in the samples.

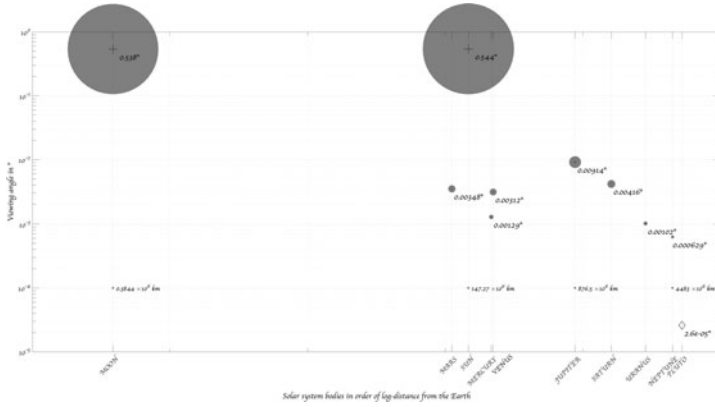


Fig. 1.43 Viewing angles and relative sizes example, using a schematic view of the appearance of celestial objects on the Earth’s sky

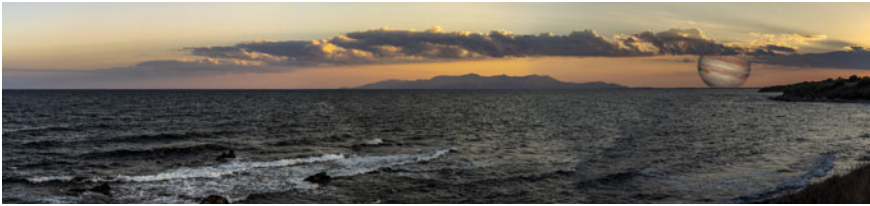


Fig. 1.44 Fictional sunset sky with planet Jupiter in place of the Moon

central fovea, where 0.29 mm correspond to 1° visual angle, yields that the minimum foveal cone spacing is about 0.62 arc-minutes.⁴⁷ Thus the Nyquist frequency can be attained (Williams, 1985)

$$f_N = \left(\sqrt{3} \times \frac{0.62}{60} \right)^{-1} = \frac{60}{1.732 \times 0.62} = 55.874 \approx 56 \text{ cycles per degree} \quad (1.27)$$

In literature can also be found other estimates that more or less converge to the same estimate (Williams, 1985; Cassin et al., 1984; Montag, 2002).

In a seminal work by Curcio et al. (1990), there is a review of previous methods and a new estimate regarding the peak foveal densities, amounting to around 260,000 cones per mm² at a spacing of 2 μm (in line with the other research works), providing an acuity of 77.1 cycles per deg (or about 0.78 arc-minutes per cycle). If one ‘cycle’ means one ‘change’, in modern terminology one would need at least two pixels to

⁴⁷ In an ideal model, cone spacing (centre-to-centre spacing) should be considered as being larger than an individual cone diameter since there is an infinitesimal but still non-zero space between cone cells.

represent it. This would mean that the central visual acuity is about $s = 0.78/2 = 0.39$ arc-minutes per pixel or that the corresponding pixel spacing would be $s = 0.39$ arc-minutes. Suppose for the purposes of the estimate of the eye resolution these values are adopted.

Also suppose, for simplicity, that the retina consists purely of densely packed cones, like in the central fovea. Then, suppose there is one eye only, again for simplicity, which is capable of a field of view (or viewing angle) of about 170° horizontally (60° nasal to 110° temporal) and 150° vertically (60° superior to 70° inferior) (Savino and Danesh-Meyer, 2012; Rönne et al., 1915; Traquair, 1949; Spector, 1990; Howard and Rogers, 2002). Then an estimate of an approximate resolution would proceed as follows.

$$\begin{aligned}
 R &= a_{\text{horiz. degrees}} \times \frac{60 \text{ arc-minutes per degree}}{s \text{ arc-minutes per pixel}} \times \\
 &\quad a_{\text{vert. degrees}} \times \frac{60 \text{ arc-minutes per degree}}{s \text{ arc-minutes per pixel}} \Rightarrow \\
 R &= 170 \times \frac{60}{0.39} \times 150 \times \frac{60}{0.39} \Rightarrow \\
 R &\approx 603.550.296
 \end{aligned} \tag{1.28}$$

where s is the visual acuity, adopted from Curcio et al. (1990). That is roughly *604 MPixels* for the full field of view of a single eye. Furthermore, using the same simplistic line of reasoning, since the human vision is binocular, it would be more accurate to revise these estimates using the part of the field of view that is visible to both eyes (since a single image is created in the brain from the two eye images). Typical estimate of the stereo field of view reports around 120° horizontally with the same 150° vertically. In this case

$$\begin{aligned}
 R &= 120 \times \frac{60}{0.39} \times 150 \times \frac{60}{0.39} \Rightarrow \\
 R &\approx 426.035.500
 \end{aligned} \tag{1.29}$$

That is roughly *427 MPixels* for the full stereo-vision field of view. Apparently, these are entirely wrong estimates for colour image resolution, for various reasons, since they presuppose at least three false statements, that (a) there is a constant high-density cone arrangement, (b) there is a constant high-acuity capacity, (c) the cones are panchromatic (each cone senses the whole spectrum). Not to mention that, as shown by Werner and Steele (1988), cone sensitivity declines at a rate of about 0.1 log-units per decade of age, while contrast sensitivity drops by a factor of 1 log-units by the age of 80 (Schneck and Haegerström-Portnoy, 2003), while it is known by Duane (1908) that the focusing range changes dramatically with age.

It is generally known that the optic nerve contains around 800,000 nerve fibres, which are lagging over the more than 100,000,000 photoreceptors in the retina. This implies interconnections among receptors and fibres in a many-to-one form (Hecht, 1924). Apparently, the cone responses go through a second stage of ‘colour coding’, forming three distinct post-reciprocal channels (colour opponency) (Westland et al., 2012), as follows.

- the $(L+M)$ *luminance channel*, made of additive inputs from the L and M cones
- the $(L-M)$ *chromatic channel*, made of opponent inputs from the L and M cones
- the $S-(L+M)$ *chromatic channel*, made of opponent inputs from the S and $(L+M)$ cones

The human eye is a remarkable instrument that provides constant streams of visual stimuli, which, combined with the eye and head movement, cover roughly a 360° visual field. This vast amount of information requires an equivalent amount of processing power in the brain, which has to connect the stimuli into a meaningful image and extract the semantics. The retina consists of more than 60 types of neurones that play specific roles in the process of visual stimuli. As emphatically stated by Masland (2012), these neurone types are arranged into three main stages, by which the signals from the photoreceptors are decomposed into 12 parallel information streams, then connected to specific types of ganglion cells and then combined with bipolar and amacrine cell activity to finalise the visual signal that is transmitted to the brain, using roughly 20 streams of information. And this is not everything, as many of the encodings that are being transmitted to the brain have not been explained yet (Masland, 2012).

Furthermore, research suggested that in low-light conditions the human eye integrates up to about 15 s of stimuli (Blackwell, 1946), whereas in daylight it becomes much less sensitive, over 600 times less (Knowles Middleton, 1952).

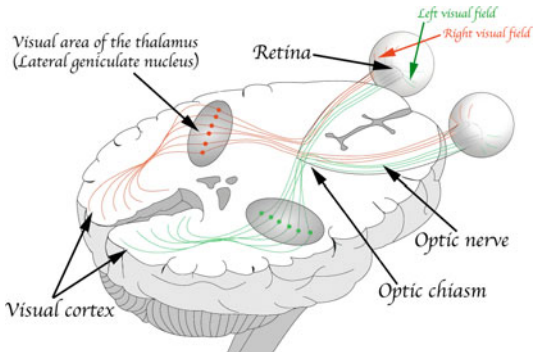
A graphical representation of how an image is ‘imprinted’ on the retina of a left human eye is shown in Fig. 1.45 (Pavlidis, 2017). The image is superimposed over a fundus image. As expected, the image appears inverted and is sharply focused only in the region of the fovea. The dark spot on the right represents the blind spot. Figure 1.46 graphically depicts the overall circuitry of the human visual system, in which the photoreceptor signals are assembled by the *optic nerve*, separated into two main streams that correspond to the left and right visual field, and transferred to the *visual cortex*, the particular part of the cerebral cortex responsible for ‘image processing’ at the back of the brain. This wiring results in having the left half of the visual field of each eye forwarded to the right visual cortex whereas the right half forwarded to the left visual cortex.

As already pointed out, the human visual system is particularly efficient in discriminating different brightness levels (contrast) and alignments. As pointed out by several researchers, the range of light intensity to which the human visual system can adapt is quite extensive, on the order of 10^{10} , with a logarithmic response. Figure 1.47 shows an adaptation of this response based on Gonzalez and Woods (1992), where the long solid curve represents the range of intensities to which the visual system can adapt. In photopic vision, the range is 10^6 (6 log levels). The transition from

Fig. 1.45 Representation of the formation of an image on the retina, from Pavlidis (2017)



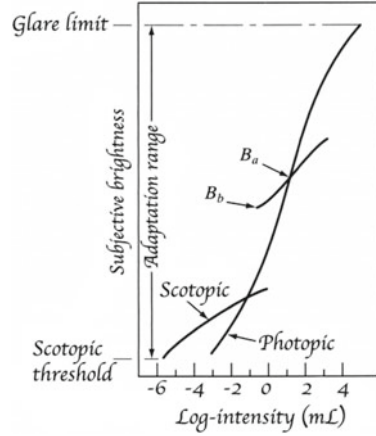
Fig. 1.46 The route of the optical information from the eyes to perception



scotopic to photopic occurs gradually in a range of 0.001–0.1 mL. Nevertheless, the visual system does not operate on its full dynamic range constantly, but rather adjusts its range in accordance to the lighting conditions, in a process called the *brightness adaptation*, as illustrated in Fig. 1.47 for a selected brightness level B_a . In this figure, the short curve intersecting the long one on B_a represents the range of perceived brightness when the eye adapts to this level, whereas B_b indicates that below this limit all stimuli are indistinguishable blacks. The upper limit of the small curve is not strictly defined although if extended too far it will require a new higher adaptation level B_a .

The eye’s ability to discriminate changes in brightness at any adaptation level is rather interesting. Supposing the eye has currently adapted to light intensity I and ΔI the just noticeable difference at that intensity, then the discriminative power of the eye

Fig. 1.47 Intensity of light and perceived brightness



is expressed as the ratio $\Delta I / I$, which evolved into the known Weber-Fechner law (or the *Weber's law*) (Hecht, 1924), stating that this ratio is constant within a wide range of intensities. Weber (1834) discovered that it is possible to discriminate between two weights as long as they differ by 1 or 2 parts in 30. Similarly, it is possible to visually distinguish two lines if they differ by 1 part in 100, regardless of the absolute magnitude of the lines. Weber's law was initially expressed as $\Delta I = K_w \cdot I$, for some constant K_w , the *Weber fraction*, which corresponds to an equation of a line with slope K_w and zero intercept. The contemporary form of the law is expressed by the ratio

$$K_w = \frac{\Delta I}{I} \quad (1.30)$$

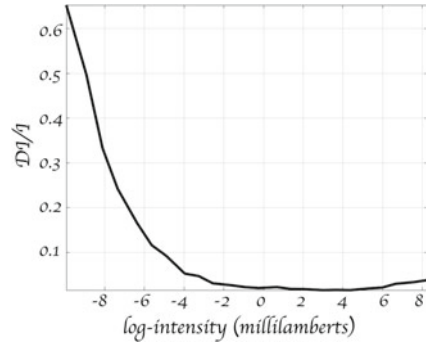
that is transformed into a linear form as $\log(\Delta I) = \log(I) + \log(K_w)$.

Weber's law is particularly useful in assessing the sensitivity of the human visual system. In this approach, small values for K_w represent high sensitivities, whereas larger values represent lower, or even poor sensitivities. Hecht (1924) emphasised that this law only holds roughly within specific limits of the mesopic-photopic vision, and breaks down at the edges of detectable intensities, and particularly at the dark end, where discrimination becomes near impossible. Quantitative evidence for these findings is provided by the significant work of Koenig and Brodhun (1889), leading to the possibility to create a precise visualisation of this law as shown in Fig. 1.48.

According to Hecht (1924), Fechner (1858) used the available astronomical data of that time to describe a relation between the magnitude M of a star and its photometric intensity I as

$$M = k \cdot \log I + C \quad (1.31)$$

Fig. 1.48 Weber's law expressed by quantitative data by König and Brodhun



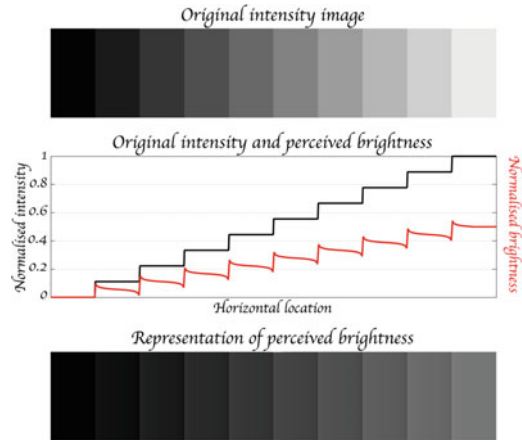
Fechner used his relation and Weber's findings to revisit Weber's law as a *constant fractional relation between two intensities that produce a threshold difference in perceived brightness*. By supposing that the difference threshold represented a unit change in perception, he rewrote the law as

$$S = k \frac{\Delta I}{I} \quad (1.32)$$

integration of which results in $S = k \log I + C$, where S is the sensation (perceived brightness), an expression that is directly analogous to his calculation of the star magnitude-intensity relation. Fechner named this *the psychophysical law*. In effect, this law linearly relates the perceived brightness to the logarithm of the light intensity (like $S \triangleq f[\log(I)]$). So by Fechner's psychophysical law, two lights can be just discriminable, if the responses they generate, differ by a constant amount ΔS . As pointed out in Pavlidis (2017), elaborating on this law an expression of a relation between Weber's and Fechner's laws is revealed, by which *if Fechner's psychophysical law holds, then Weber's law naturally emerges*.

$$\begin{aligned}
 \text{Fechner's law} \leftarrow \Delta S &= \log(I + \Delta I) - \log(I) \Leftrightarrow \\
 \Delta S &= \log\left(\frac{I + \Delta I}{I}\right) \Leftrightarrow \\
 e^{\Delta S} &= \frac{I + \Delta I}{I} \stackrel{\Delta S=c}{=} K \Leftrightarrow \\
 K &= \frac{I + \Delta I}{I} \Leftrightarrow \\
 K \cdot I &= I + \Delta I \Leftrightarrow \\
 (K - 1)I &= \Delta I \stackrel{K_w=K-1}{=} K_w I \Leftrightarrow \\
 \Delta I &= K_w I \rightarrow \text{Weber's law}
 \end{aligned} \quad (1.33)$$

Fig. 1.49 Intensity and perceived brightness are different things



The mapping of the Weber ratio over a wide range of light intensities and background levels ($\Delta I/I = f(I; I_0)$, I_0 being the parameter for the various background levels) is usually referenced as the *contrast sensitivity* of the human visual system. Since the differential of the logarithm of intensity is $d[\log(I)] = \frac{dI}{I}$, it follows that equal changes in the log-intensity of a light source can be related to equal just-noticeable differences over the region of intensities, for which the Weber ratio is constant. This is why some image processing algorithms operate on the log-intensity of images (Pratt, 1991).

Another interesting characteristic of human vision is its tendency to under- and over-shoot at the edges of areas of different intensities, as shown in Figs. 1.49 and 1.50. In Fig. 1.49 although the intensity within each of the patches is constant (upper image), an observer perceives a varying brightness pattern near the boundaries (lower image). The middle graph shows in solid black the profile of the normalised intensity levels to illustrate that each stripe is of a constant brightness; the solid red line represents the perceived brightness, which exhibits a logarithmic behaviour at the location of each step.⁴⁸ The initial image with the intensity stripes is called a *Mach band pattern*, after *Ernst Waldfried Josef Wenzel Mach* (1838–1916),⁴⁹ who first described this phenomenon around 1865. According to this phenomenon, in boundaries of abrupt intensity changes, darker intensities appear into the lighter region and lighter into the darker region.

Another interesting characteristic of the human vision that is called *simultaneous contrast*, forces the perceived brightness to be closely connected with the image content. Due to this effect, an image region's perceived brightness does not depend simply on its intensity but also on the overall relative intensity context, as demonstrated in Fig. 1.51, in which the central squares are of the exact same intensity, however, they

⁴⁸ This graph is based on work by Cornsweet (1970).

⁴⁹ It should be highlighted that Ernst Mach was among those that emphatically distinguished the experienced from the mathematical world (Mach, 1903).

Fig. 1.50 A ramp transition between two intensity levels

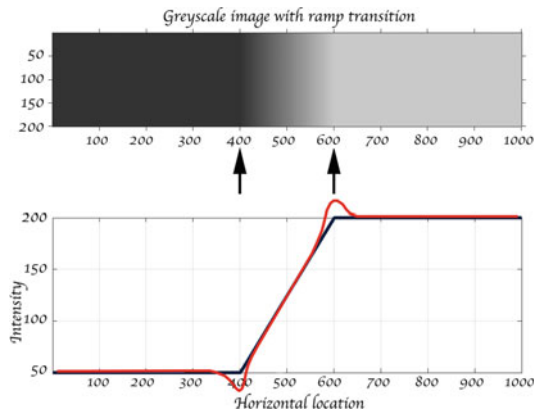
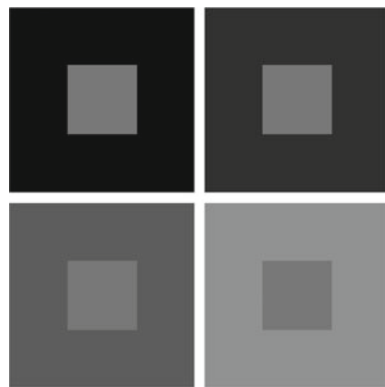


Fig. 1.51 The effect of simultaneous contrast forces patches of the same intensity to appear as of a different brightness

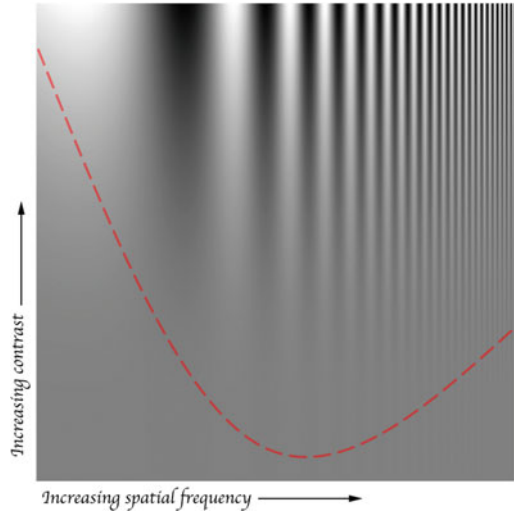


appear to be perceived as darker or lighter depending on the surrounding background (Gonzalez and Woods, 1992).

If an optical system was of linear response, a spatially varying light source would be expected to produce an equivalently varying brightness response. To derive the dynamics of such an optical system one needs to vary the spatial frequency in the input and record the corresponding response, thus taking the so called *optical transfer function* of the system. Given two angular spatial frequencies $\omega_x = 2\pi/T_x$ and $\omega_y = 2\pi/T_y$ with corresponding periods T_x, T_y in the two coordinate directions x and y , the optical transfer function is usually denoted as $\mathcal{H}(\omega_x, \omega_y)$. Typically the frequency spectra of the input $I_i(x, y)$ and of the output $I_o(x, y)$ intensity distributions can be defined as

$$\begin{aligned} I_i(\omega_x, \omega_y) &= \iint_{-\infty}^{\infty} I_i(x, y) e^{-i(\omega_x x + \omega_y y)} dx dy \\ I_o(\omega_x, \omega_y) &= \iint_{-\infty}^{\infty} I_o(x, y) e^{-i(\omega_x x + \omega_y y)} dx dy \end{aligned} \quad (1.34)$$

Fig. 1.52 Modulated sine wave grating for modulated transfer function estimation



Since the optical transfer function has been defined, the input and output spectra are related by

$$\mathcal{I}_o(\omega_x, \omega_y) = \mathcal{H}(\omega_x, \omega_y) \mathcal{I}_i(\omega_x, \omega_y) \quad (1.35)$$

Taking the inverse Fourier transform the output can be derived as

$$\mathcal{I}_o(x, y) = \frac{1}{4\pi^2} \iint_{-\infty}^{\infty} \mathcal{I}_o(\omega_x, \omega_y) e^{-i(\omega_x x + \omega_y y)} d\omega_x d\omega_y \quad (1.36)$$

From (1.35), the ratio of the magnitudes of the input and output frequency spectra are

$$\frac{|\mathcal{I}_o(\omega_x, \omega_y)|}{|\mathcal{I}_i(\omega_x, \omega_y)|} = |\mathcal{H}(\omega_x, \omega_y)| \quad (1.37)$$

which expresses the *modulated transfer function* of the optical system.

A representation of the form of the modulated transfer function of human vision can be obtained by observing the composite sine-wave grating of Fig. 1.52. In this figure, the horizontal axis is the spatial frequency and the vertical axis is the contrast. The region below the red dashed line (low contrast region) appears almost uniformly greyed, but this is just how the perception of changes in this region is lost. This region becomes smaller as the spatial frequency increases but then diminishes completely for extremely high spatial frequencies. The envelope of the visible contrast that the red dashed line denotes, is a representation of what is called the *contrast sensitivity function*, providing an inverted image of the relative sensitivity relating to the spatial frequency (Pratt, 1991). This is also clearly illustrated in Fig. 1.53 that shows the normalised contrast sensitivity of human vision against a log-scale spatial frequency.

Fig. 1.53 Normalised contrast sensitivity of human vision

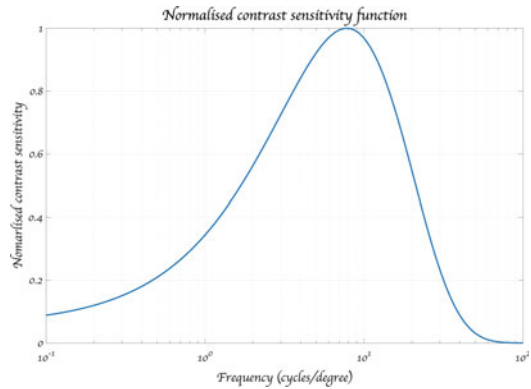


Fig. 1.54 Illustration of light intensities and the corresponding perceived brightness

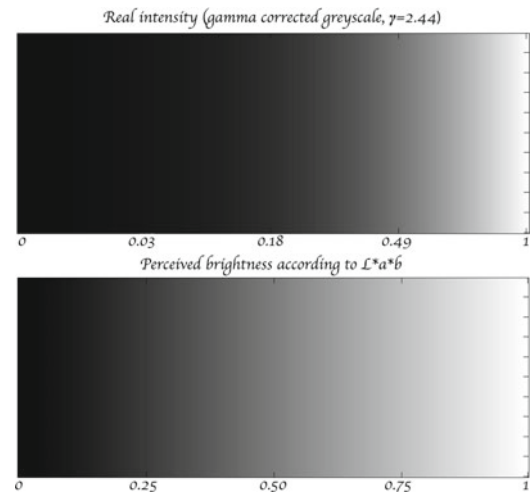
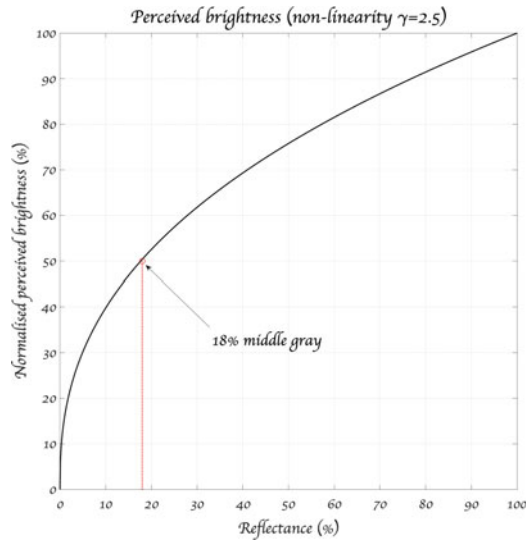


Figure 1.54 illustrates the non-linear response of the eyes to luminance; the upper image shows an intensity scale of the real luminance range, whereas the lower image shows the scale of perceived brightness.⁵⁰ In addition, Fig. 1.55 draws this response as a curve for a better illustration (using $\gamma = 2/5$). The real luminance scale is an approximation of a *gamma corrected*⁵¹ linear luminance scale with $\gamma = 2.44$. In this illustration, the brightness perceived as the middle of the L^*a^*b scale corresponds to a value of 0.18 (or 18%) in the luminance scale. Thus, an 18% intensity would appear to the human eye as being of the exact mean brightness (50% grey), thus 18% intensity corresponds to 50% perceived brightness. Recognising this characteristic, this particular 18% grey level has long been used as a calibration reference in imaging sectors, like photography.

⁵⁰ In this case, in terms of the ‘linearised’ CIEL*a*b colour space, L-channel shown.

⁵¹ Gamma correction is simply the non-linear mapping $L = L^\gamma$.

Fig. 1.55 Simulation of perceived brightness as a function of scene reflectance using $\gamma = 2.5$

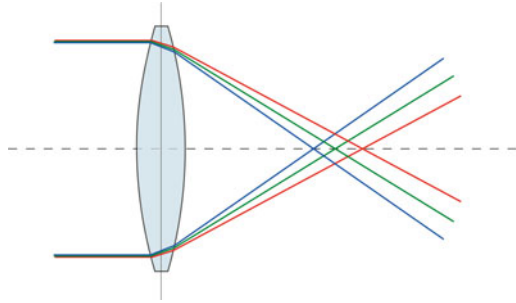


Vision is a very *energy-demanding process*. It is considered to be among the most significant consumers of energy within the brain (Niven and Laughlin, 2008; Medrano and Fox, 1995; Yaspelkis III et al., 1994; Wang et al., 1997; Werkmeister et al., 2015; Bill and Sperber, 1990), which is among the most highly energy-demanding organs of the human body. The brain is estimated to consume about 20% of the total oxygen and about 25% of the total glucose used for energy in the human body (this amount to about 20% of the total energy) (Rolfe and Brown, 1997; Sokoloff, 1989; Weber et al., 2008; Wong-Riley, 2010; Liu and Prokosch, 2021). It has been suggested that vision requires about the same percentage of the total brain energy. As described, the various retinal neural layers are involved in a rather complex process to convert the light energy into electrical signals, even prior to transmission to the brain. Each of these retinal neurones undertakes specific tasks with varying energy demands, and energy metabolism in the retina is complicated. Energy metabolism at both cellular and molecular levels is involved in the activity of these neurones (Liu and Prokosch, 2021). In addition, it has been suggested by experimental findings that the retina requires more energy in the dark than in the light (Forman et al., 1983). Most of the energy is consumed in the retina for the function of repolarisation after depolarisation.⁵²

One may wonder, how efficient such a complex mechanism could be in terms of data communication. In a study on the guinea pig retina by Koch et al. (2006), it has been found that the transfer rate or the bandwidth of the retina is about 875,000

⁵² *Depolarisation* is a cellular process by which a shift in electric charge distribution occurs within the cell that results in less negative charge inside the cell compared to the outside, an essential function of many cells, particularly for cell signalling. *Repolarisation* is the process that inverts the effects of depolarisation and returns the cell to its resting potential, to be ready for the next cycle of depolarisation-repolarisation.

Fig. 1.56 Graphical representation of the chromatic aberration of a biconvex lens



bits per second (or 875 kbps) by a total of around 10^5 ganglion cells. Koch et al. (2006) stated that since the human retina consists of around 10^6 ganglions (10 times those of guinea pigs) then the corresponding bandwidth for the human retina would be around that of an Ethernet connection (probably meaning 8.75 Mbps, near the 10 Mbps usual Ethernet limit of that period⁵³). The study suggested that the firing rate of each neurone is about 1 ms^{-1} (1 kHz), although the final average activity was found to be significantly less, 3 orders of magnitude less, around 4 s^{-1} , and this is due to energy conservation mechanisms.

Unfortunately, the very phenomenon of refraction that makes the formation of colour images through any form of lenses (biological or man-made) possible, in the form of dispersion, is the cause of the occurrence of *chromatic aberration*, which is an inherent inability for any single transparent lens to focus different wavelengths of light at the same focal point, as schematically depicted in Fig. 1.56 for a typical ideal biconvex lens (a very common case). This is only one class of aberrations in visual systems as will be explained in subsequent chapters, but a prominent one in human vision.

Concluding this brief introduction to the human colour vision, a short notice should be included to complete the picture. In addition to the visual perception of elementary signals, like a light of a single intensity or frequency and the physiological processes underlying the transfer of visual signals to the brain, a lot more can be said about the complete process of human visual perception that attaches meaning to the complex visual signals. It has been modelled by various scholars throughout human history, either in terms of the monochrome or the colour version, the monoscopic and stereoscopic aspects, the connection to memory and other brain centres relating to cognition, by employing physiology, philosophy and psychology. Plato, in his famous parable of the *prisoners in the cave*, was among the pioneers who probed the human perception from a philosophical point of view, only to theorise that visual perception is much more than seeing.

⁵³ As also suggested in a 2006 article by Michael Reilly, titled 'Calculating the speed of sight', in the NewScientist site, at <https://www.newscientist.com/article/dn9633-calculating-the-speed-of-sight/> (last accessed March 2022).

1.4 Measuring Light and Colour

To measure and express light's characteristics one needs to resort to notions from *radiometry* and *photometry*. In these domains, the motivation is to measure the power emitted either from a radiation source or off a reflective surface, within specific time and space frames. Radiometry deals with all radiant power and derived quantities. In essence, it is the science of the physical measurement of electromagnetic energy. Photometry deals with the same measurements and quantities but for radiant power perceived by the human visual system. It is the science of the psychophysical measurement of the visual sensation produced by the electromagnetic spectrum (Cohen et al., 1993). It has been suggested that it was *Pierre Bouguer* (1698–1758) that introduced photometry in his 1760 *Traité d'optique sur la gradation de la lumière* (*Optical treatise on the gradation of light*) (Bouguer, 1760), a posthumous edition based on his earlier work in his 1729 *Essai d'optique, sur la gradation de la lumière* (*Essay on optics, on the gradation of light*) (Bouguer, 1729). Although little were known about the human vision at that time, Bouguer understood the mechanics of photometry and founded the domain by performing experiments and deducing the underlying principles.

There are multiple equivalences between radiometry and photometry, as shown in Table 1.2 and briefly explained in the following paragraphs. Basic units for both domains include the *Joule* (*J*) and the *talbot* for the energy, and the *Watt* (*W*) and the *lumen* (*lm*) for the power, in radiometry and photometry respectively. The basic radiometric and photometric quantities are measured in time and space frames defined in seconds (s), squared meters (m²) and steradians (sr), depending on the measurement. The notion of *radiant flux* or *radiant power* can be used to express the energy per unit time radiated by a source, in Watts or Joules/sec. The *spectral flux* or *spectral power* can be used to express the radiant flux per unit frequency or wavelength in Watts/Hz. Radiant flux transforms to *luminous flux* in the case of light, expressed as Φ_v in lumens.

Pointance refers to point sources and expresses the amount of flux originating at the point source and propagating within a cone of a given solid angle ω , which for an omnidirectional (isotropic) point source is simply $\omega = 4\pi$. For the case of photometry, this quantity is *luminous intensity*.

$$I_v = \frac{\Phi_v}{\omega} \xrightarrow[\text{point source}]{\text{omnidirectional}} I_v = \frac{\Phi_v}{4\pi} \quad (1.38)$$

which is generalised for any source (non-omnidirectional) with particular solid angle, using the simplification which expresses a solid angle as a function of the cone apex angle θ

$$\omega = 2\pi \left(1 - \cos \frac{\theta}{2} \right) \quad (1.39)$$

More formally, luminous intensity is directly related with luminous flux in that,

Table 1.2 Radiometry and Photometry quantities

Quantity	Radiometry		Photometry
Energy	Radiant energy (J)	Q_v	Luminous energy (lm·sec=talbot)
Power/Flux (energy per unit time)	Radiant flux/power (W)	Φ_v	Luminous flux/power (lm=cd·sr=talbots·sec ⁻¹)
Sterance/Angular flux density (flux per unit solid angle per unit projected source area)	Radiant sterance Radiance (W·m ⁻² sr ⁻¹)	L_v	Luminous sterance Luminance (nit=lm·m ⁻² sr ⁻¹)
Areance/Flux density (exitance-flux emitted by a surface)	Radiant exitance/Radiosity (W·m ⁻²)	M_v	Luminous exitance/ Luminosity (lux=lm·m ⁻²)
Areance/Flux density (flux incident on a surface)	Irradiance (W·m ⁻²)	E_v	Illuminance (lux=lm·m ⁻²)
Pointance (flux per unit solid angle)	Radiant intensity (W·sr ⁻¹)	I_v	Luminous intensity (cd=lm·sr ⁻¹)

$$\Phi_v = \int_{\Omega} I_v(\vec{\omega}) d\omega \quad (1.40)$$

The luminous intensity I_v in a given direction is equal to the illuminance E_v at a point on the unit sphere centred at the point light source.

Sterance, or *angular flux density* refers to light emitted by an extended light source and expresses the flux per solid angle and emitted, or transmitted, or reflected projected surface area. For the case of photometry, this is *luminance* and defined as

$$L_v = \frac{\Phi_v}{\omega(A \cos \theta)} = \frac{I_v}{A \cos \theta} \quad (1.41)$$

where $A \cos \theta$ is the projected surface area and θ the angle between the direction of light and the direction of the surface normal. More formally, luminance can be defined as the luminous energy per unit volume, which is no other than the photon density multiplied by the energy of a photon. It is also luminous power per unit projected area perpendicular to the light ray per unit solid angle in the direction of that ray

$$L_v(\mathbf{x}, \vec{\omega}) = \int p(\mathbf{x}, \vec{\omega}, \lambda) \frac{hc}{\lambda} d\lambda \quad (1.42)$$

where $p(\mathbf{x}, \vec{\omega}, \lambda)$ is the photon density in a volume defined by a position vector $\mathbf{x}$ and a direction vector $\vec{\omega}$ for a particular wavelength λ ; hc/λ is the speed of a photon at wavelength λ with c the speed of light and h the Planck's constant. Luminance remains constant in the direction of the propagation of the light ray, as long as no scattering or absorption occurs, as a consequence of the conservation of energy.

Areance has two alternatives, either to express the flux emitted by a surface, or the flux incident on a surface. In the first, case, the quantity of *luminosity* is defined in photometry as

$$M_v = \frac{\Phi_v}{A} \quad (1.43)$$

where A is the area of the surface that radiates. Luminosity is formally defined as the luminous energy per unit area emitted by a surface.

$$M_v = \int_{\Omega} L_o \cos \theta \, d\omega \quad (1.44)$$

where L_o denotes the outgoing luminance, $\cos \theta \, d\omega$ the projected solid angle and Ω the hemisphere defined by the radiating surface. Equivalently, for the second case, the quantity of *illuminance* is defined as

$$E_v = \frac{\Phi}{A} \quad (1.45)$$

Illuminance is formally defined as the luminous energy per unit area incident on a surface with a fixed orientation. All incident luminance will be coming over a hemisphere Ω fixed on the surface, thus,

$$E_v = \int_{\Omega} L_v \cos \theta \, d\omega \quad (1.46)$$

where $\cos \theta \, d\omega$ is the projected solid angle ($d\omega$ is the differential solid angle), with $\int_{\Omega} \cos \theta \, d\omega = \pi$.

An interesting derivation of the previous relations is the *inverse square law* for a point source, which states that the illuminance at a distance s is proportional to the luminous intensity of the source and inversely proportional to the square of the distance. Supposing an omnidirectional point source the flux in all space is $\Phi_v = 4\pi I_v$ and a surface area illuminated at distance s would be defined as $A = 2\pi s^2$. Thus

$$E_v = \frac{\Phi_v}{A} \xrightarrow[A=4\pi s^2]{\Phi_v=4\pi I_v} E_v = \frac{I_v}{s^2} \quad (1.47)$$

Conversion between radiometric and photometric quantities involves the notion of *luminous efficiency*, or the dimensionless normalised *luminous efficacy*, the quantity that encodes the efficacy of a source in converting energy into radiation detectable by the human visual system. Formally, luminous efficacy is the ratio of luminous flux to power in lm/W; depending on the context, power can be either the radiant flux (luminous efficacy of radiation) of the light source or even the total power consumed by the source to create and emit light (luminous efficacy of light source). It is emphasised that radiant and luminous flux are totally different quantities, as two sources of the same radiant flux may produce quite a different luminous flux. For

instance, a blue light will be perceived as significantly less bright than a green light of the same radiant flux. Mathematically, luminous efficacy is denoted as K

$$K = \frac{\Phi_v}{\Phi_e} = \frac{\int_0^\infty K(\lambda) \Phi_{e,\lambda} d\lambda}{\int_0^\infty \Phi_{e,\lambda} d\lambda} \quad (1.48)$$

where Φ_e is the radiant flux, $\Phi_{e,\lambda}$ is the spectral radiant flux in $\text{W}\cdot\text{nm}^{-1}$ and $K(\lambda) = K_{\max} V(\lambda)$ is the spectral *luminous efficacy function* of the human vision. The luminous efficacy function is a quantification of the average spectral sensitivity of the human visual perception and has been standardised in the CIE 1931 standard, but has been refined since then multiple times. Plots of the refined 2008 function for daylight and night-time human vision are shown in Fig. 1.57.⁵⁴ The graph shows the efficacy peaking at 555 nm to a value of $683 \text{ lm}\cdot\text{W}^{-1}$ for photopic, and at 506 nm to a value of $1700 \text{ lm}\cdot\text{W}^{-1}$ for scotopic vision, respectively; in both cases the response falls off to negligible values when approaching 340 and 750 nm, marking the edges of the visible part of the electromagnetic spectrum. Apparently, relevant for the vision of colour is the daylight response (cone-based vision), as night-time (rod-based) vision is colourless. In essence, these curves show how sensitive human vision is in the various bands of the spectrum, significantly peaking at the region that is rendered as yellow-green for the case of daylight vision; this also means that any light in this region of the spectrum will be perceived as brighter than any light in all other regions. At night-time, the sensitivity shifts towards the region normally perceived as green-cyan, but since rods are functioning at that time, no colour sensation is synthesised by the brain, only brightness is perceived as an encoding of the incident light intensity. Focusing on photopic vision, using the luminous efficacy function data and the formal definition in (1.48) results in the practical expression of the luminous flux, in terms of the radiant flux and the luminous efficacy function.

$$\Phi_v = 683 \cdot \int_0^\infty V(\lambda) \Phi_{e,\lambda} d\lambda \quad (1.49)$$

Apparently, the luminous efficacy function V_λ acts as a weighting factor and allows for the conversion of radiant flux to luminous flux at any wavelength. As the eye does not resolve all wavelengths equally well, the efficacy function is a very important way to determine the luminous flux from a source. When the luminous efficacy is normalised by the maximum possible efficacy, the *luminous efficiency function* V is created, or the *luminous coefficient*, which is another preferable representation due

⁵⁴ Luminous efficacy curves in this diagram are based on CIE 2008 data found at <http://www.cvrl.org/lumindex.htm> (last accessed March 2022). Those data correspond to the 10° viewer, as indicated at <http://www.cvrl.org/database/text/lum/CIE2008v10.htm> (last accessed March 2022). Particularly for the photopic function, it has been suggested that an approximation may be used that yields as a non-linear regression fit to the experimental data, in the form $V(\lambda) = 1.019e^{-285.4(\lambda-0.559)^2}$.

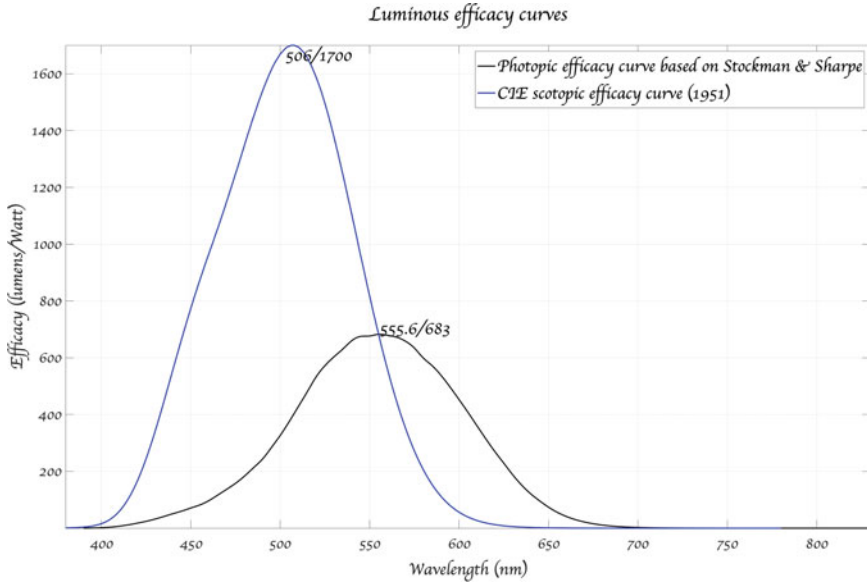


Fig. 1.57 Luminous efficacy curves for photopic and scotopic human vision

to its $[0, 1]$ limits. The luminous flux from a monochromatic source producing light at a single wavelength is easiest to determine as

$$\Phi_v = 683 \cdot V \cdot \Phi_e \quad (1.50)$$

Assuming the 10° efficacy functions above, a 10 mW laser pointer at a wavelength of 680 nm produces a luminous flux of $0.010 \times 0.0163 \times 683 = 0.111$ lm, whereas another 10 mW laser pointer at 630 nm produces a luminous flux of $0.010 \times 0.275 \times 683 = 1.88$ lm, which is more than an order of magnitude greater. In another simple example of a light source rated at 100 W with an output of 5000 lm, the luminous efficiency of the source is estimated to

$$\frac{\Phi_v}{683 \cdot \Phi_e} = \frac{5000 \text{ lm}}{683 \text{ lm} \cdot \text{W}^{-1} \cdot 100 \text{ W}} = 0.0732 \quad (1.51)$$

or 7.32%, whereas the efficacy of the source is simply

$$\frac{5000}{100} = 50 \text{ lm} \cdot \text{W}^{-1} \quad (1.52)$$

Generally, an observer's response R to a light with a spectral power distribution $S(\lambda)$ is the integral of the response at each wavelength.

Table 1.3 Examples of luminous flux produced by various light sources using the same amount of electric power

Type of light source using 100 W electric power	Typical luminous efficacy of light source (lm·W ⁻¹)	Luminous flux (lm)	Illuminance on 10 m ² (lux)
Tungsten incandescent	15	1500	150
Halogen	20	2000	200
Mercury vapour	50	5000	500
Fluorescent	60	6000	600
Metal halide	87	8700	870
LED	90	9000	900
High pressure sodium vapour	117	11700	1170
Low pressure sodium vapour	150	15000	1500

$$R = \int_{\lambda_{min}}^{\lambda_{max}} V(\lambda) S(\lambda) d\lambda \quad (1.53)$$

with λ_{min} , λ_{max} the limiting wavelengths of the visible spectrum.

Table 1.3 lists various types of light sources and the luminous flux and illuminance they produce when they use the same amount of electric power (say 100 W) and shine upon the same surface area (say 10 m²), based on typical luminous efficacy values for each of the source type.⁵⁵ It is clear how different the results are, with efficacies ranging from 15 to 150 lm·W⁻¹.

It should be emphasised here that these examples are realistic, and manufacturers provide those data for the light sources they manufacture. Nevertheless, these should be considered as the *initial* characteristics, because as the sources age, their power distribution shifts slightly and they no longer radiate at precisely the wavelengths they did when they were new.

Luminous flux connects with the perception of light by humans, as it is expressed as a weighted sum of radiant flux in the visible spectrum, due to the human eye's non-uniform response to all wavelengths. This is done by weighting the power at each wavelength with the luminous efficacy function of human vision. Vice versa, the ratio of the total luminous flux to the radiant flux, i.e., the perceived luminosity to the radiated energy, is the luminous efficacy, expressing how efficient the human vision is in perceiving radiated energy in the visible spectrum. The unit for the luminous intensity, coming from the Latin word for *candle*, is the *candela*, which roughly corresponds to the intensity of light emitted by a common wax candle. Using this

⁵⁵ These estimates are taken using the online conversion tools at <https://www.rapidtables.com/calc/light/watt-to-lumen-calculator.html> (last accessed March 2022) and <https://www.rapidtables.com/calc/light/lumen-to-lux-calculator.html> (last accessed March 2022).

intuition and (1.38), for an omnidirectional source of 1 candela (a wax candle) is equivalent to about 12.57 lumens of luminous power.

It is clear from the definitions of the basic radiometric and photometric quantities that it is not trivial to determine the luminous flux from a source that radiates over a spectrum, as this involves knowing the spectral power distribution of that particular source, knowing the amount of power radiated at each wavelength, in a given wavelength resolution. To know the precise power distribution for a source in a given resolution depends on the characteristics of the source, thus is easier for some and more difficult for other sources. Standard incandescent lamps produce a continuous spectrum in the visible spectrum (like the Standard Illuminant A, or the D_x family, in Fig. 1.9), thus requiring the integration over the whole spectrum, whereas other light sources, like a mercury vapour lamp, emit in compact discrete wavelengths only, thus requiring a simple summation over a limited amount of wavelengths. The easiest case is that of laser light sources, which ideally emit a light of a single wavelength.

As implied in various paragraphs throughout this chapter, a light source may be characterised or modelled by the radiant power at each wavelength, expressed in the visible spectrum. This expression provides the spectral power distribution that conveys all the basic physical data about the light and may serve as the foundation upon which to begin a quantitative analysis of colour. To measure the spectral power distribution of a light one needs a *spectrophotometer*. Using such devices, both the luminance and the chrominance of a colour may be derived in a standardised representation expressed by widely accepted colour systems, such as the CIE system.⁵⁶ These colour systems have been successful in predicting colour perception from the spectral power distribution, even though the process is not reversible (one cannot get the distribution from the colour perception).

A precise quantitative representation of any colour for computations and practical applications has been a challenge for numerous researchers since Newton. It was soon realised that colour is a subjective phenomenon and only through experiments it could be approached, indirectly. Historically, as soon as this realisation matured, researchers begun probing for the response of the human visual system to light and its mechanism in interpreting the colour content in visual signals.

CIE made a decisive step towards standardisation in colour measurement in 1931 by adopting the system proposed by John Guild (1889–1979), a British scientist who worked at the National Physical Laboratory (NPL) in Teddington, England. Guild's work was motivated by the need for standardisation in colour science, which pervaded the domain since the beginning of the 20th century and included the definition of a *standard observer*, the *standard human vision fundamentals* and *colour matching*

⁵⁶ CIE stands for the *Commission Internationale de l'éclairage*, the International Commission on Illumination, the international authority on light, illumination, colour, and colour spaces, founded in 1913 after the restructuring of the International Commission on Photometry (CIP), originally founded in 1900. Visit CIE at <http://cie.co.at> (last accessed March 2022). The CIE is recognised by the International Commission for Weights and Measures (CIPM), the International Standardisation Organisation (ISO) and the International Electrotechnical Commission (IEC) as an international standardisation body. The reference to a 'CIE system' denotes any CIE approved colour space for representing the gamut of the perceived colours.

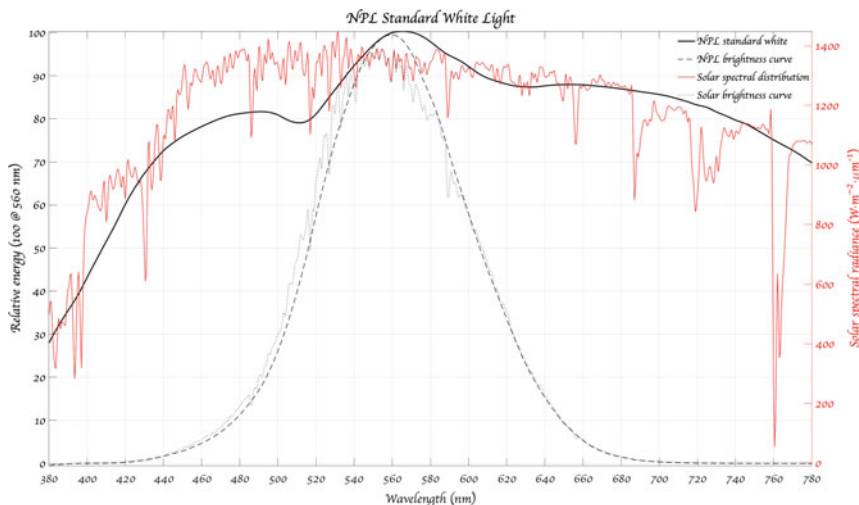


Fig. 1.58 Energy distribution of the NPL Standard White Light

functions, along with a *standard colour space* for a variety of practical purposes. Guild was involved in colour matching experiments, in order to derive a concrete colour space model, for an ‘objective’ description of colours, using, as reference light source, the *NPL standard white light*, the spectral distribution of which is shown in Fig. 1.58, as derived by Guild’s Table I, in Guild (1931); the human vision luminous efficacy data and the perceived brightness of the white light are also shown from the original data Guild provided, along with the solar radiation energy distribution on the Earth’s surface and the perceived brightness of the Sun, based on modern high-resolution data. As described earlier, one simply needs to multiply the spectral distribution of a light source by the luminous efficacy of the eye to get the perceived brightness.

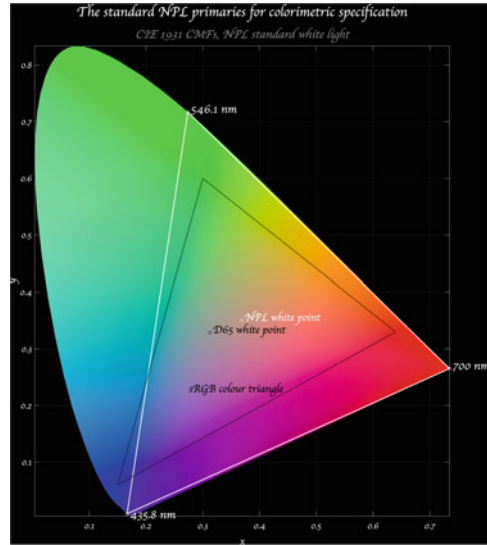
The goal of the original colour matching experiments was to create mixtures of three primary spectral (monochromatic) colours in order to match a given colour and derive the human vision colour matching functions. Based on the well-known Grassmann’s laws for a linear colour system, in which any spectral colour Q_λ (or, as Guild named it, *colourimetric quality of a monochromatic stimulus*) is a linear combination of primaries R, G, B ,⁵⁷

$$Q_\lambda = aR + bG + cB \quad (1.54)$$

where R, G, B are the primaries and a, b, c are the *trichromatic coefficients*, which may be estimated by getting the contribution of each primary by using instrument adjustment factors and the convention that $a + b + c = 1$. As Guild used the NPL

⁵⁷ Even though any triplet of independent colours may serve as a basis, R, G, B was the standard representation of the set of the three primary colours for colour matching experiments.

Fig. 1.59 A representation of the NPL primary colours for colourimetry on the CIE colour space that Guild helped develop

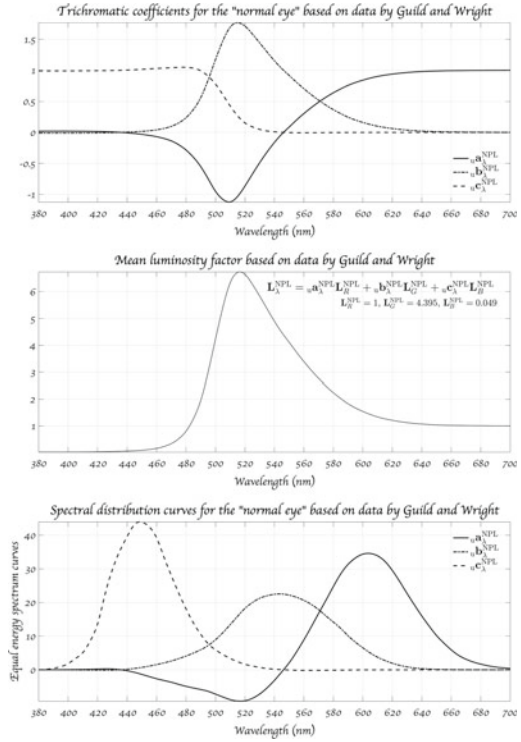


standard, these primaries corresponded to 700 nm, 546.1 nm and 435.8 nm respectively,⁵⁸ perceived as red (at the limit of vision), green and violet-blue respectively. These primaries can be drawn approximately as shown in Fig. 1.59 on a typical CIE colour diagram. Suffice to say that any triangle that connects primaries encloses the complete gamut of colours that can be produced by those primaries, assuming the additive system is in effect. The white triangle denotes the gamut for the NPL primaries. The modern-day sRGB triangle is also drawn in the diagram for comparison. Guild made a quite intricate setup and incorporated data from other experiments, particularly those of Wright (1929), in order to reach to a proposal for the standard.

This intricate setup involved the compensation for the perception of white by each participant (which is expected to be different), the extraction of luminosity factors, the colour matching based on the working primaries and the white balancing of the results, the extraction of the trichromatic coefficients and their redefinition for the standard primaries, the incorporation and transformation of the data by Wright, and the final derivation of the colour matching functions. The results of the experiments are shown in Fig. 1.60, in terms of three graphs, created by interpolating the values from Guild's original data. The first graph is the representation of the 'standard observer', which shows the standard trichromatic coefficients of the *normal eye* (${}_u a_{\lambda}^{\text{NPL}}$, ${}_u b_{\lambda}^{\text{NPL}}$, ${}_u c_{\lambda}^{\text{NPL}}$). The second graph shows the mean luminosity factor (L_{λ}^{NPL}) for the complete visible spectrum. The third graph shows the spectral distribution

⁵⁸ Guild, in his subsequent experiments, transformed the standard primaries into *working primaries* by using (1.54) and the results of the initial experiments, and by considering R, G, B to be the working primaries and Q_{λ} the standard primaries, through inversion of this system of linear equations.

Fig. 1.60 Specification of the standard observer by the Guild-Wright experiments



curves of the primaries for the standard observer that are produced by assuming an equal energy spectrum of an arbitrary value of 100 at all wavelengths.

Figure 1.61 shows the resulting chromaticity graph from the Guild-Wright experiments regarding the standard observer, for primaries at 700, 546.1 and 435.8 nm (NPL white light). The graph shows the spectral colours, marked by their corresponding wavelength and the location of the reference white. All perceived colours are within the concave space that the spectral curve denotes and a line connecting the 380 nm end with the 700 nm end (the so-called *line of purples*).

Multiplication of the trichromatic coefficients with the ratio of the luminous efficacy (shown in Fig. 1.58) to the luminosity factor results in the most useful colour matching functions, which are shown in Fig. 1.62.

$$\begin{aligned}
 \bar{r}_{\lambda} &= {}_u\bar{a}_{\lambda}^{NPL} = {}_u a_{\lambda}^{NPL} \frac{V_{\lambda}}{{}_u L_{\lambda}^{NPL}} \\
 \bar{g}_{\lambda} &= {}_u\bar{b}_{\lambda}^{NPL} = {}_u b_{\lambda}^{NPL} \frac{V_{\lambda}}{{}_u L_{\lambda}^{NPL}} \\
 \bar{b}_{\lambda} &= {}_u\bar{c}_{\lambda}^{NPL} = {}_u c_{\lambda}^{NPL} \frac{V_{\lambda}}{{}_u L_{\lambda}^{NPL}}
 \end{aligned} \tag{1.55}$$

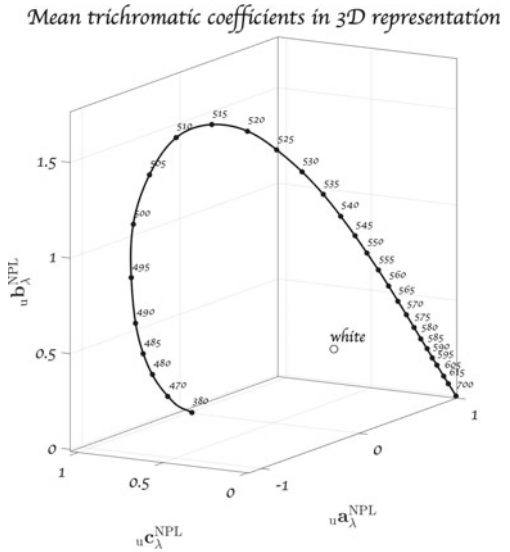


Fig. 1.61 Chromaticity diagrams by the Guild-Wright data

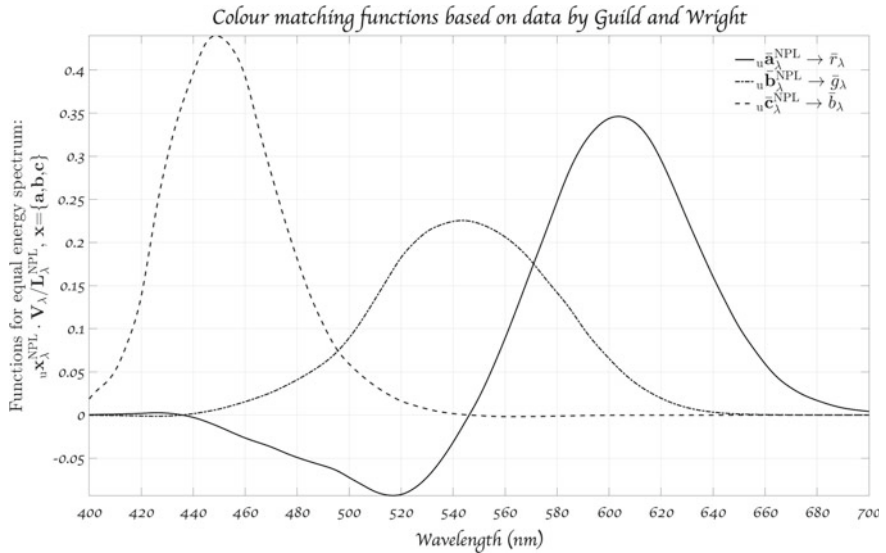


Fig. 1.62 Colour matching functions for the NPL primaries by the Guild-Wright data

Smith and Guild (1931) laid out a corrected version of the original data and results of Guild’s experiments, and also presented the CIE standard’s adopted ‘resolutions’. They presented a definitive view of the basic colour theory of that time, which can be summarised to that *colours are expressed in a linear trichromatic system*

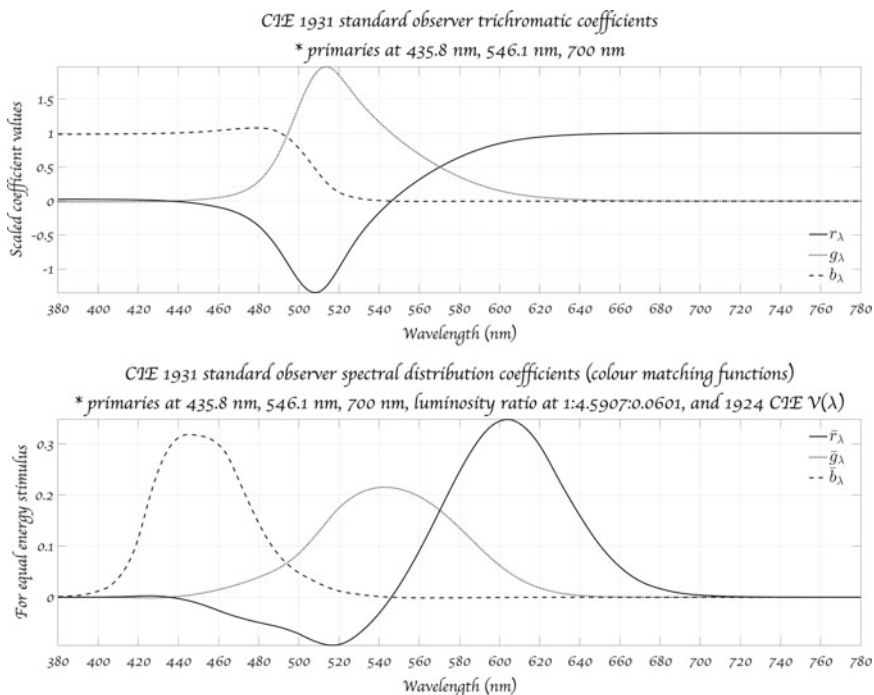


Fig. 1.63 The definition of the standard observer in the CIE 1931 standard

using three primaries that correspond to linearly independent colour sensations. The presentation of the CIE 1931 standard in this publication was based on the five resolutions that constituted it.

Resolution 1 defined the notion of the standard observer as defined by Guild's corrected data. Those data defined the CIE rgb colour space (as trichromatic coefficients and colour matching functions) and the corresponding data were included in Table I of Smith and Guild (1931). The NPL standard white light was used as a reference with primaries at 435.8, 546.1 and 700 nm and the relative luminositities were fixed at the ratio of 1:4.5907:0.0601. A plot of those data for the CIE 1931 standard observer are shown in Fig. 1.63; the first graph shows the r_λ , g_λ , b_λ trichromatic coefficients, whereas the second graphs shows the colour matching functions $\bar{r}_\lambda$, $\bar{g}_\lambda$, $\bar{b}_\lambda$.

Resolution 2 defined the standard illuminants for coloured illumination applications, simply referenced as A, B and C, corresponding to a gas lamp at 2848 K, the same lamp with liquid filters composed of particular copper and cobalt sulphate solutions, and the same lamp with different liquid filters again based on copper and cobalt sulphate solutions, respectively. Tables II and V of Smith and Guild (1931) included the relative energy spectral distribution of the illuminants for practical applications. It was specified that the illuminant B would correspond to a blackbody at a temperature of 4800 K (currently estimated at 4874 K) and that the illuminant C

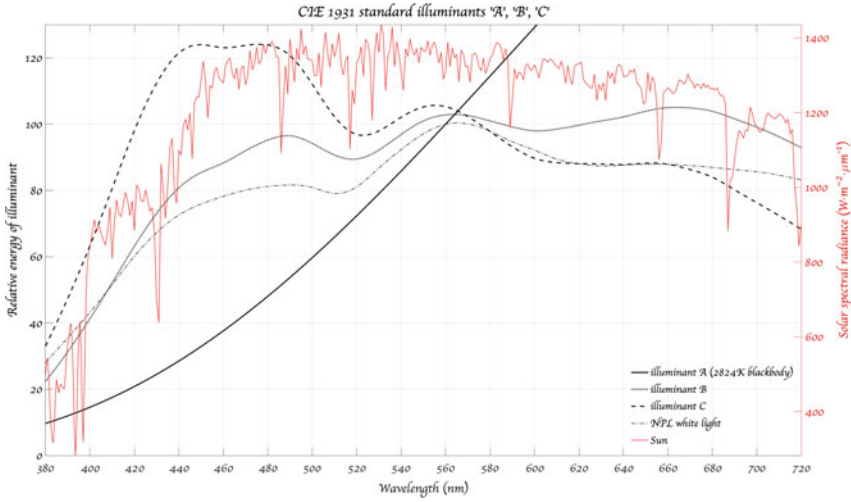


Fig. 1.64 The spectral power distribution of the CIE 1931 standard illuminants

to a blackbody at 6500 K (currently estimated at 6774 K). The previously used NPL standard white light was similar to illuminant C. Based on CIE 1931 data, Fig. 1.64 plots the relative spectral power distribution of the three standard illuminants in the visible spectrum, including the distribution of the NPL standard white light and the solar radiation at sea level (right-side y-axis).

Resolution 3 specified the conditions and particular setup for the colourimetric measurements of reflective and opaque media.

Resolution 4 specified that colourimetry is based on trichromacy and any colour should be expressed as a linear combination of three independent scales.

Resolution 5 defined the *CIE 1931 XYZ colour space*, as a projection of the original RGB space to a space where no negative values are allowed and one of the three variables corresponds to the perceived luminance. Thus, X , Y and Z correspond to *fictional primaries*, totally outside the perceivable colour gamut. This transformation is described and supported by detailed data in Tables III and IV of Smith and Guild (1931). Originally, Smith and Guild (1931) presented this projection using a two-dimensional representation of the colour space, particularly the blue-green representation, and emphasised that the estimates for the definition of the new x , y , z axes were not strict, as only the *alychne* was a mathematically and conceptually established notion. *Alychne*, from the Ancient Greek ἀλυχνος, meaning no illumination - no light, was defined by Schrödinger (1994), as the line of zero perceived luminance, which can be expressed, using the luminosity factor, as

$$r + gL_G + bL_B = 0 \quad (1.56)$$

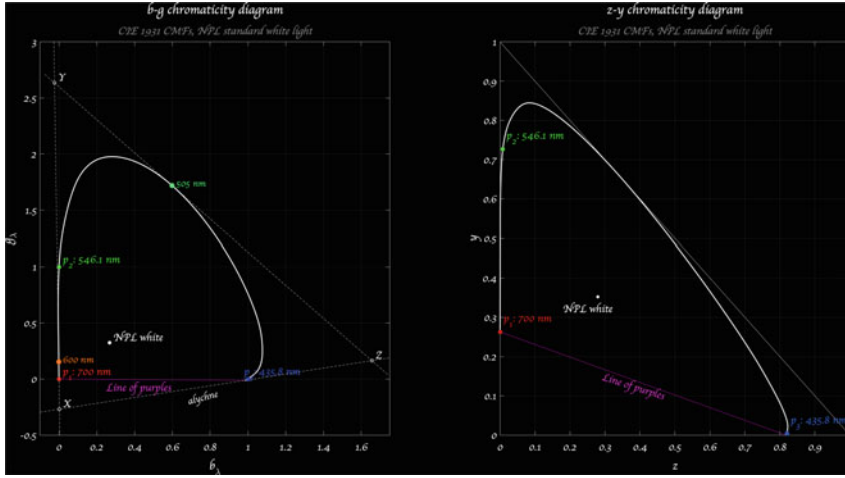


Fig. 1.65 Derivation of the $z - y$ colour space from the $b - g$ colour space

where the luminosity factors of the primaries are normalised by the factor of the first primary, corresponding to 1:4.5907:0.0601 (as stated in CIE 1931 standard Resolution 1). As the colour matching function for the second primary is extremely close to the general luminosity sensation (luminous efficacy), the variable to be used for the side closer to that primary was Y . Thus the alychne includes the X and Z coordinates, and the $b - g$ and the transformation to the $z - y$ colour space are depicted in Fig. 1.65. For the case of the $b - g$ space, the equation of the XZ line can be estimated by

$$\begin{aligned}
 s_{XZ} &= \frac{L_R - L_B}{L_G - L_R} \\
 k &= \frac{(r_0 - 1)L_R + g_0L_G + b_0L_B}{L_G - L_R} \\
 g &= s \cdot b + k
 \end{aligned} \tag{1.57}$$

where s_{XZ} is the slope of line XZ , k is the displacement factor and (r_0, g_0, b_0) are the chromaticity coordinates of the B primary equal to (0.0272, -0.0115, 0.9843) according to the Guild data. There is no strict method, according to Smith and Guild, to define the XY and ZY line equations, so suitable selections that fit the needs of applications and fulfil the basic prerequisites would suffice. They stated that the XY line should be tangent to the spectral locus at the location of the R primary, making it difficult to replicate their results. The Tables they presented are relatively sparse and there is noise in the measurements, thus, one may resort to interpolation and suggestions by other researchers (Fairman et al., 1997; Wold and Valberg, 1999; Service, 2016). Fairman et al. (1997) suggested to find the tangent to the spectral locus at the position of 670 nm, but since the interpolated original data were noisy at

that location the 600 nm location was selected. The corresponding XY line equation can be expressed using the derivative of the locus at the selected location,

$$s_{XY} = \frac{dg_{[600 \text{ nm}]}}{db_{[600 \text{ nm}]}} \quad (1.58)$$

$$g = s_{XY} \cdot b$$

where s_{XY} is the slope of the XY line. The same method is used for the ZY line, which, according to Smith and Guild *should pass near the spectral locus in a direction that secures satisfactory metrical properties*. Following Fairman et al. (1997), the selected locus point is at 505 nm and the corresponding ZY line equation can be expressed using the derivative of the locus at the selected location,

$$s_{ZY} = \frac{dg_{[505 \text{ nm}]}}{db_{[505 \text{ nm}]}} \quad (1.59)$$

$$g = s_{ZY} \cdot (b - b_{[505 \text{ nm}]}) + g_{[505 \text{ nm}]}$$

where s_{ZY} is the slope of the ZY line. The intersection of the three lines result the locations of the X , Y and Z primaries in the RGB space as

$$XYZ = \begin{bmatrix} 1.2661 & -1.6116 & -0.81979 \\ -0.26852 & 2.6351 & 0.16421 \\ 0.0023934 & -0.023487 & 1.6556 \end{bmatrix} \quad (1.60)$$

where the columns of the XYZ matrix are the coordinates of the X , Y and Z primaries in the RGB space. Inverting and normalising the XYZ matrix transforms to the fictional XYZ space. This results a transformation matrix T that can be used to project the RGB colour space to the new XYZ space.

$$T = \begin{bmatrix} 0.4879 & 0.30029 & 0.21181 \\ 0.17413 & 0.82109 & 0.0047813 \\ 0.0000 & 0.0088345 & 0.99117 \end{bmatrix} \quad (1.61)$$

Smith and Guild (1931) presented a slightly different transformation matrix, due to their different approximations,

$$T = \begin{bmatrix} 0.49000 & 0.31000 & 0.20000 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00000 & 0.01000 & 0.99000 \end{bmatrix} \quad (1.62)$$

Transformation from RGB to XYZ space can be based on the formula suggested by Fairman et al. (1997),

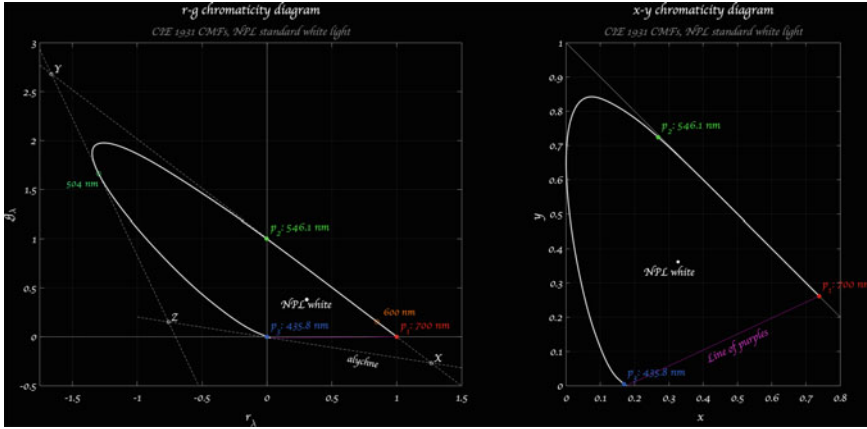


Fig. 1.66 Derivation of the $x - y$ colour space from the $r - g$ colour space

$$\begin{aligned}
 \begin{bmatrix} r_\lambda \\ g_\lambda \\ b_\lambda \end{bmatrix} &= \begin{bmatrix} r_\lambda \\ g_\lambda \\ b_\lambda \end{bmatrix} \\
 s &= \sum_{i=1,2,3} T_{i,1} \cdot r_\lambda + \sum_{i=1,2,3} T_{i,2} \cdot g_\lambda + \sum_{i=1,2,3} T_{i,3} \cdot b_\lambda \\
 x &= T_1 \cdot \text{rgb} \oslash s \\
 y &= T_2 \cdot \text{rgb} \oslash s \\
 z &= T_3 \cdot \text{rgb} \oslash s
 \end{aligned} \tag{1.63}$$

in which $T_{i,j}$ is any i, j element of the transformation matrix and T_i is any i row vector of the matrix, and the $\oslash$ operator denotes the element-wise division. Applying this transformation to the RGB data Smith and Guild (1931) provided, result in the XYZ data shown in the $x - y$ diagram in Fig. 1.65. A more common representation is that of the $r - g$ space transformation to $x - y$ space, as shown in Fig. 1.66, which can be accomplished by following the same principle as in the case of the $b - g$ space. Smith and Guild (1931) provided extensive data in Tables III and IV in 1 nm intervals.

Overall, the resulting $\bar{x}$, $\bar{y}$, $\bar{z}$ colour matching functions based on the estimate of that xyz space are shown in Fig. 1.67.

Apparently, since colour is ultimately a subjective sensation defined on an average basis by the CIE standards, the calculation of the CIE chromaticity coordinates, thus, the ‘objective colour’ for a given light source or a surface requires the inner product of its spectral power distribution with the three colour matching functions, which results the tristimulus values, from which the chromaticity coordinates are derived and any colour may be quantified in the sense that the CIE 1931 standard defined.

In that sense, colour capturing and reproducing devices, such as imaging sensors and displays, can record and depict the gamut of human colour vision only if certain

CIE 1931 standard observer spectral distribution coefficients XYZ (colour matching functions)

** primaries at 700 nm, 546.1 nm, 435.8 nm, luminosity ratio at 1:4.5907:0.0601, and 1924 CIE $V(\lambda)$*

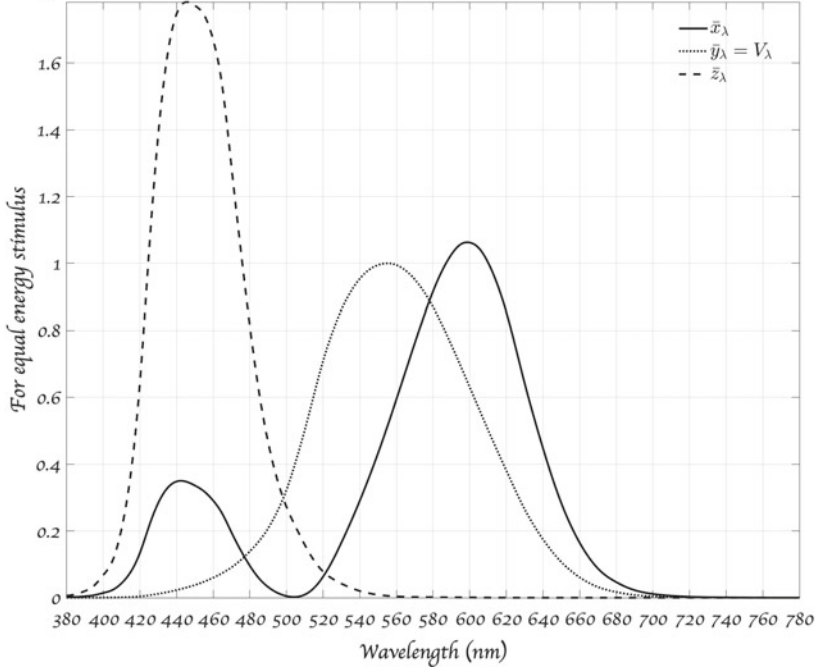


Fig. 1.67 Estimated colour matching functions from Smith and Guild data

qualifications and limitations are imposed. In most cases, no sensor or display can cover the whole gamut of human-perceived colours, although there can be devices that record ‘colours’ outside of the visible spectrum, if it is meaningful to discuss such ‘colours’ at all.

For the history, the CIE 1931 colour matching functions, set fourth by John Guild, were based on colour matching experiments that used a bipartite field that subtended 2° of visual angle at the retina. In 1964, a second set of experiments extended those results for a visual angle of 10° , thus, forming the CIE 1964 colour matching functions. It should be reminded that S cones (blue colour sensation) are expected to be very sparse at the central part of the retina, even totally missing at the very centre. Widening the angle results in including those cones in the functions with higher probability, resulting in more accurate models. For practical applications, the CIE 1931 and 1964 XYZ tristimulus values are transformed into xy coordinates using the simple formulas

$$\begin{aligned} x &= \frac{X}{X + Y + Z} \\ y &= \frac{Y}{X + Y + Z} \end{aligned} \quad (1.64)$$

producing the more familiar $x - y$ chromaticity diagrams. Using these diagrams and Grassmann's additivity law it is easy to see that mixtures of two primaries fall on the same line that connects the corresponding points, and that any three primaries define a colour space with a gamut easily identified on the diagrams. On the other hand, stimuli of identical chromaticity but different luminance are depicted on the same point. What was soon realised was that the CIE standards are colour specification systems and not colour appearance systems, in addition to being perceptually non-uniform, meaning that any Euclidean distance between two points on the chromaticity diagrams may correspond to a significantly different distance in the stimuli represented by the two points (Westland et al., 2012). The latter has significant consequences in the design of colour recording and reproduction devices, thus, led to the development of another standard, the CIE 1976, formally known as the CIELAB (or CIE Lab, or even CIE $L^*a^*b^*$) colour specification system, which (in a general form) is a non-linear transformation of the original system,

$$\begin{aligned} L^* &= 116 \left(\frac{Y}{Y_n} \right)^{\frac{1}{3}} - 16 \\ a^* &= 500 \left[\left(\frac{X}{X_n} \right)^{\frac{1}{3}} - \left(\frac{Y}{Y_n} \right)^{\frac{1}{3}} \right] \\ b^* &= 200 \left[\left(\frac{Y}{Y_n} \right)^{\frac{1}{3}} - \left(\frac{Z}{Z_n} \right)^{\frac{1}{3}} \right] \end{aligned} \quad (1.65)$$

in which X_n, Y_n, Z_n are the tristimulus values of a predefined achromatic (neutral or white) reference stimulus. Hunt and Pointer (2011) reworked the general formula into a more precise representation,

$$\begin{aligned} L^* &= 116f \left(\frac{Y}{Y_n} \right) - 16 \\ a^* &= 500 \left[f \left(\frac{X}{X_n} \right) - f \left(\frac{Y}{Y_n} \right) \right] \\ b^* &= 200 \left[f \left(\frac{Y}{Y_n} \right) - f \left(\frac{Z}{Z_n} \right) \right] \end{aligned} \quad (1.66)$$

where

$$\begin{aligned} f(\mathfrak{R}) &= \mathfrak{R}^{\frac{1}{3}}, \quad \text{if } \mathfrak{R} > \left(\frac{6}{29} \right)^3 \\ f(\mathfrak{R}) &= \frac{841}{108} \mathfrak{R} + \frac{4}{29}, \quad \text{if } \mathfrak{R} \leq \left(\frac{6}{29} \right)^3 \end{aligned} \quad (1.67)$$

This representation is particularly effective in colour specification for reflective surfaces, in which L^* represents the brightness, a^* represents the red-green opponency, and b^* represents the blue-yellow opponency in a colour, somehow, matching the

Table 1.4 CIE standard illuminant D65 specification

Standard observer	XYZ tristimulus values			xyz chromaticity coordinates		
	X	Y	Z	x	y	z
CIE 1931 2°	95.047	100	108.883	0.31271	0.32902	0.35827
CIE 1964 10°	94.811	100	107.304	0.31382	0.331	0.35518

opponent colour system in human vision, which leads to more accurate colour differences specification. Typically, for the reference white, the CIE standard illuminant D65 (also D₆₅) specification is used, which defines the values shown in Table 1.4.⁵⁹

In addition, CIE defined in 1976 the CIELUV (or CIE Luv, or even CIE L*u*v*) standard colour specification system to be used for the characterisation of light sources, or self-luminous objects, in general. The transformation equations from the CIE 1931 standard are as follows.

$$L^* = \begin{cases} 116 \left(\frac{Y}{Y_n} \right)^{\frac{1}{3}} - 16, & \text{if } \frac{Y}{Y_n} > \left(\frac{6}{29} \right)^3 \\ \left(\frac{29}{3} \right)^3 \left(\frac{X}{X_n} \right), & \text{if } \frac{Y}{Y_n} \leq \left(\frac{6}{29} \right)^3 \end{cases} \quad (1.68)$$

$$u^* = 13L^*(u' - u'_n)$$

$$v^* = 13L^*(v' - v'_n)$$

where u' and v' are the coordinates of the CIE 1976 UCS (uniform chromaticity space) defined as

$$u' = \frac{4X}{X + 15Y + 3Z}$$

$$v' = \frac{9Y}{X + 15Y + 3Z} \quad (1.69)$$

1.5 The Scientific Photograph

Photography can be defined as the art and science of permanently capturing light radiated by light sources and scenes that interact with it. As such, it is primarily a measurement process. Originally, the technology to implement it was based on electrochemical interactions, using light-sensitive substances. It was developed into a digital technology, based on photon counting with light sensitive semiconductors that transform photons into electric current. Either way, since photography is a

⁵⁹ The values for the spectral power distribution of the CIE standard illuminant D65 can be found at <http://www.cvl.org/cie.htm> (last accessed March 2022).

measurement process, it is subject to the *measurement theory*, a domain that deals with the quantification of physical entities. Thus, it is also subject to limitations, systematic and measurement errors.

This realisation leads to further questions. Is there an ideal photograph that is the result of accurate light measurement? Can a photograph be of absolute spatial and spectral fidelity? As such, is there a *scientific photograph*? Could a scientific photograph actually be defined at all? What is the relation between such a scientific photograph and the photograph that is an accurate record of reality or an emotional expression to the human perception? Is there a relation between the ideal and the aesthetic photograph?

Amidst the frantically productive period of photographic development of the late 19th century, Vogel (1875a) stated regarding *photography and truth*:

Admirers of photography assert so often that this young art represents the pure truth, the true counterpart of nature. Photography can, indeed, when rightly applied, produce truer pictures than any other art, but they are not absolutely true, and because they are not absolutely true it becomes important to learn the sources of error, and they are manifold.

Vogel went on describing the limitations and inherent problems, which he considered to be both of an objective nature (e.g., the optics) and of a subjective one (e.g., aesthetics and perception).

Clerc (1954) discussed the issue of the *ideal scientific reproduction* for the case of the conventional analogue photography that involved negative film and printing on paper. Clerc distinguished the ideal scientific reproduction to the *aesthetic picture*, focusing primarily on the differentiation of the illumination and the apparent brightness, mixed with notions of vision adaptation and scene atmosphere sensation, due to the different lighting conditions in the original photographed scene and the viewed printed photograph under varying illuminations. Clerc emphatically stated that

A finished photograph should give an impression of the original scene, but to say that the camera cannot lie is possibly the most misleading statement ever made.

Clerc divided the photographic tone reproduction process into two parts, one objective and one subjective. The objective part relates to the recognition of the limitations of the equipment and materials used that eventually lead to a model that predicts what is expected of a method and process of photography. The subjective part relates to the methods and techniques connected with the reproduction of the sensation of being inside the photographed scene, which may guide for rather radical changes in the rendering process.

Many changes have occurred since that time. Photography went digital and colour recording and reproduction standards have evolved and matured to even more accurate human vision approximation. Nowadays, imaging devices apply those standards and can readily provide transformations from one colour space to another. Yet, the ideal scientific reproduction still remains a challenge.

Chapter 2

A Brief History of Photography



—Παντάπασι δὴ, ἦν δ' ἐγώ, οἱ τοιοῦτοι οὐκ ἂν ἄλλο τι νομίζοιεν τὸ ἀληθὲς ἢ τὰς τῶν σκευαστῶν σκιάς.^b

Plato, *The Republic*

^bAnd above all, such people would not believe anything real, except only those shadows.

Abstract The origins of photography in its current form can be traced back to the early 19th century, with the first permanent photographic recordings. Sir John Frederick William Herschel is credited for naming this n , combining the Greek words *φως*+*φλογιστόν*, demoting *to inscribe, to write or to draw with light*; he is also credited for the words *negative* and *positive* in photography. Evidence suggests that the history of photography is not at all a brief one, but this chapter focuses on presenting a concise account of the major developments that led to modern photography. Apparently, this history is still being written, and the presentation in this chapter is just an account of milestones. As more and more advanced light capturing devices become available in various forms and technologies for a wide range of purposes, nowadays, imaging devices acquire and process digital images, which are collections of discrete-time, discrete-space and intensity-quantised samples of the amount of light detected.

2.1 Introduction

The history of photography in the form known today is considered to have begun in the early 19th century, when the first permanent photographs were made possible. It was around 1839 when the polymath Sir John Frederick William Herschel coined the term photography from the Greek *φως* + *γράφω*, meaning *to inscribe, to write or to draw with light* (Herschel, 1843a; Schaaf, 1979). Herschel is an important figure in

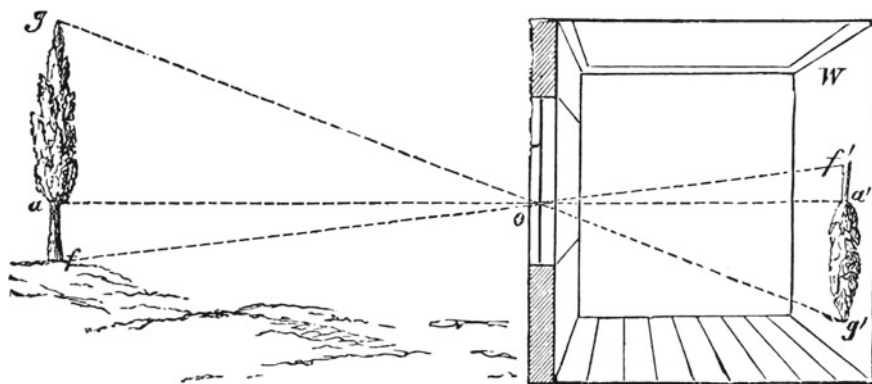


Fig. 2.1 The pinhole effect for an inverted image projection in a confined dark space

photography, as he made significant contributions by inventing various photographic processes, including the *chrysotype* and *cyanotype*, the latter of which was the origin of the term *blueprint* that is so known in engineering (but also in everyday life). It is also considered that he coined the terms *negative* and *positive* in photography.

Interestingly, the basic equipment of photography, the *photographic camera* (or, simply, the camera), has a history that begins long before the introduction of photography. The word camera originates in the ancient Greek *καμάρα*, meaning a structure with an arched cover or a vaulted construction, which became *camara* or *camera* in Latin, initially indicating a vault or arched chamber particularly for a council or legislative chamber. Through a particular phenomenon in optics, the *pinhole* phenomenon, in a dark space with a small opening to light (a pinhole), inverted images of a scene are projected on the opposite surface to the opening. The whole dark space structure with the small hole is called a *camera obscura*, from the Latin *camara obscura* for the dark room. The principle of the pinhole phenomenon, in a camera obscura, is illustrated in Fig. 2.1.¹

Published just at the time of the great photographic innovations, Robert Hunt's 1854 *A Manual of Photography* (Hunt, 1854) is a valuable source of information for the history of photography and the developments of the chemical processes relating to photographic phenomena. Among other valuable sources, Josef Maria Eder's 1905 *History of Photography*, and particularly the renewed 1945 English edition (Eder, 1945) was heavily used as an extremely valuable source for information on the 19th century photography. Evidence and theories suggest that the history of photography is not brief, but in the context of this treatise, a nevertheless brief history of photography is presented in an attempt to highlight the efforts of humans through the ages to understand and capture images permanently.

¹ This figure is based on Fig. 3 of Hermann Wilhelm Vogel's 1875 *The Chemistry of Light and Photography*.

2.2 Milestones in Photography

Matt Gatton (Gatton et al., 2006; Gatton, 2009) theorised that *art* might actually originate in early photography. Photography not in the way considered today, as a permanent imprint of light reflected from objects, but as a controlled (or not) focusing of images onto surfaces. In Gatton's theory, during the Palaeolithic period (c.3.3 million to c.11.5 thousand years ago), humans got accustomed to *camera obscura* or *pinhole* effects, by which inverted images of the world were projected on surfaces inside their tents or caves through small holes or openings.² It has also been suggested that this is why cave paintings are distorted in a particular way, which might correspond to typical optical phenomena.

Relevant research on Neolithic structures also suggests that pinhole effects were known in the Neolithic period (c. 12 thousand to 6.5 thousand years ago) and might have played a role in Neolithic structures, particularly burial sites, as suggested by Simcox and Brown (2016) and Aaron Watson.³ Watson and Scott (2017) theorised that the distinctive architecture of Neolithic passage tombs served as a format of a camera obscura. In their fieldwork in Wales and Scotland they found evidence that optical projections inside such tombs are straightforward. The researchers concluded that the pinhole effect on the tomb walls would have been a quite spectacular and spiritual experience.

The *Mozi*, or *Mojing*, or the *Mohist Canon*, a Chinese text dating to the 4th century BCE that describes the philosophy of Mohism, has a particularly interesting early record of the camera obscura. In fact, this seems to be the earliest written record of camera obscura. Needham (1962) translated and described the optics in Mohism based on Mozi⁴ and previous translations and commentaries. More recently, Mozi (2013) provided an English translation of Mozi, also with explaining comments. The texts of interest are concentrated in Book 10, Chaps. 40–43 (Canons and their expositions), which encode knowledge about physics and including the specifics of the Mohist optics. In Needham (1962), the texts relating to the pinhole camera are quoted as follows.

Canon. The collecting-place is the place where the change starts.

Exposition. It is an empty hole, like the sun and moon depicted on the imperial flags.

Author's comment. We do not know which is the right word in the first part of this proposition. Khu might refer to the whole enclosed space of the camera obscura.

In addition, the texts relating to the focal point and the image inversion are quoted as follows.

Canon. The image is inverted because of the intersection. The intersecting place is a point. This affects the size of the image. The reason is given under point.

² Matt Gatton maintains a website dedicated to what is called *archaeo-optics* at <http://paleo-camera.com> (last accessed March 2022).

³ See Aaron Watsons' *archaeo-optics* website at <https://www.aaronwatson.co.uk/archaeooptics-overview> (last accessed March 2022), and also Matt Gatton's site.

⁴ The original text with an English translation can be found online in the Chinese Text Project page at <https://ctext.org/mozi> (last accessed March 2022).

Exposition. An illuminated person shines as if he was shooting forth (rays). The bottom part of the man becomes the top part (of the image) and the top part of the man becomes the bottom part (of the image). The front of the man (sends out, as it were) light (rays, some of which are) hidden below (i.e. strike below the pinhole) (but others of which) form its image at the top. The head of the man (sends out, as it were) light (rays, some of which are) hidden above (i.e. strike above the pinhole) (but others of which) form its image at the bottom. At a position farther or nearer (from the source of light, reflecting body, or image) there is a point (the pinhole) which collects the (rays of) light, so that the image is formed (only from what is permitted to come through the collecting-place).

Furthermore, the text includes descriptions for the formation of shadows, the reflection on mirrors and their combinations, and refraction. The ideas of the formation of light and image formation was also considered by ancient Greeks, but their original conceptions were different from those of the Chinese, particularly in that light is emitted by the eyes (with a few exceptions). Gatton (2017) theorised that the Eleusinian Mysteries in ancient Greece (popular around 600 BCE, lasted until around the 4th century CE) exploited pinhole technology to immerse participants into a deep spiritual experience, by using the *Telesterion* (Initiation Hall) as a camera obscura to project large images of the goddess Demeter to the participants in a very dark room.

Abū ‘Alī al-Hasan ibn al-Hasan ibn al-Haytham⁵ (965–1040), or simply Alhazen, one of the most influential figures in the science of the optics, published, around the 1020s, his important seven-volume treatise, *Kitāb al-Manāẓir* (كِتَاب الْمَنَازِير), the *Book of Optics* (Alhazen, 1021; Risner, 1572). Based on experiments and logic he proposed a totally different theory of vision, a better founded theory for the nature of light and colour, and described the phenomena of reflection and refraction. Alhazen provided the first clear explanation of a camera obscura⁶ and the inverted projection through an aperture. Almost two centuries later, *Erasmus Ciolek Vitello* (or *Witelo*, c.1270–1285) publishing his *Vitellonis Thuringopoloni opticae libri decem* (*Ten Books of Optics*), in which he brought Alhazen’s theories to Europe, translated them to Latin, and further extended his theories.

Around 1200 *Albertus Magnus* (1193–1280), a German Dominican friar, philosopher, and scientist, is credited the discovery of the element *arsenic* (As) (Emsley 2003) and is considered to have experimented with photosensitive chemicals, including the salt *silver nitrate* (AgNO_3), a precursor to other silver compounds useful in photography. In the *History of Photography*, Eder (1945), refers to Albertus Magnus as *Count Albert von Bollstädt*, and highlights that he was the first to suggest of the property of silver nitrate to turn black when in contact with organic substances. Eder (1945) refers to him with great respect.

He was one of the most learned men of the Middle Ages and was looked upon as one of the oldest and most renowned alchemists

...

Owing to his many-sided education and culture, he was honored with the surname Albert the Great, also as ‘Doctor universalis.’

أَبُو إِلَى الْحَسَنِ بْنِ الْحَسَنِ بْنِ إِلَهِيَّتِهِمْ⁵

⁶ Alhazen used the term أَلْبَيْتُ الْمُثْلِمِ (*Al-Bayt al-Muthlim*), which translates to *dark room*.

Fig. 2.2 Nicaise le Fèvre's drawing of the calcination of antimony by focused sunlight



In 1566 *Georg Fabricius* (1516–1571), discovered the *silver chloride* (AgCl), by combining an aqueous solution of silver nitrate with a chloride salt, like *sodium chloride* (NaCl) or *cobalt(II) chloride* (CoCl_2) (Fabricius, 1566; Potonniée, 1936).

In 1568 *Daniele Matteo Alvisè Barbaro* (1514–1570), an Italian cleric, diplomat, architect and translator, is attributed the description of the integration of a lens with a diaphragm (aperture) in the camera obscura (Barbaro, 1568).⁷

Wilhelm Homberg, or *Guillaume Homberg* (1652–1715), was a German natural philosopher with a significant contribution to chemistry. In fact, it was suggested that he was a founding figure of the modern chemistry as a science on its own, by systematically reviewing the relevant knowledge and paving the way for the transition from alchemy into science (de Fontenelle, 1785; Franckowiak and Peterschmitt, 2005; Principe, 2020). Homberg developed a close relationship with Philippe II, Duc d'Orléans, nephew of Louis XIV, who eventually built the finest chemical laboratory of that period, by transforming part of his residence at the Palais Royal. This laboratory also included a massive convex lens, which immediately attracted Homberg's attention and started experimenting by focusing sunlight on various chemicals, leading to a completely revised theory. He is also significant in photography since he experimented with silver salts (like silver nitrate) and their sensitivity to light, and was able to demonstrate the photochemical interaction (Principe, 2020). Figure 2.2 shows the *La calcination Solaire de L'antimoine*, the calcination of antimony by focused sunlight, by Le Fèvre (1660).⁸

⁷ See for example in <https://bit.ly/3qN9nY5> (last accessed March 2022) and <https://bit.ly/3wOuRVa> (last accessed March 2022).

⁸ This figure is based on the Public Domain figure attributed to the Welcome Collection, which was downloaded from <https://bit.ly/30Pq2PO> (last accessed March 2022). Nicaise le Fèvre (1610–1669), a.k.a. Nicasius or Nicolas le Febure or le Fevre, was a French chemist and alchemist.

Robert Boyle (1627–1691), an Anglo-Irish chemist, physicist, and inventor, is considered a key person in modern chemistry, one of the founders of modern chemistry and experimental scientific method. He is best known for his law for the gases, which connects volume and pressure in an inverse relationship. His 1661 *The Sceptical Chymist* (Boyle, 1661) is regarded as a cornerstone in chemistry, whereas his 1664 *Experiments and Considerations Touching Colours* (Boyle, 1964) is a treatise most relevant to light, colour and photography. In this treatise, Boyle seems to have adopted a corpuscular nature of light and hypothesised that colours are some sort of *modifications* of light. He documented various experiments with light and materials, along with chemical experiments with colour, which may be regarded as foundation work for photography. Boyle, in *Experiment XXXVI* of the *Experiments and Considerations Touching Colours*, clearly demonstrated his interest in silver salts and their sensitivity to light, although he initially hypothesised that it was a result of air and moisture.

That having dissolv'd good Silver in Aqua-fortis, and Precipitated it with Spirit of Salt, upon the first Decanting of the Liquor, the remaining Matter would be purely White; but after it had lain a while uncover'd, that part of it, that was Contiguous to the Air, would not only lose its Whiteness, but appear of a very Dark and almost Blackish Colour, I say that part that was Contiguous to the Air, because if that were gently taken off, the Subjacent part of the same Mass would appear very White, till that also, having continu'd a while expos'd to the Air, would likewise Degenerate.

Josef Maria Eder, in his voluminous *History of Photography* (Eder, 1945), references Boyle and his experiments concerning silver chloride. Eder (1945) highlights how Boyle departed from the mysticism of those ages, and how in the lengthy series of his experiments he presented a detailed account of various kinds of chemical changes of colour. Eder (1945) also places special emphasis on *Experiment XXXVI* and marks it as *a very important passage relating to the history of photography*.

Angelo Sala (1576–1637) was an Italian physician and chemist from Vicenza, whose primary interest was in the role of atoms in chemical changes. According to Eder (1945), he spent a lot of his time in compounding drugs and medicines. Eder (1945) described that Sala in his *Septem planetarum terrestrium spagirica recensio* (*The seven terrestrial planets*) (Sala, 1614) reported that powdered silver nitrate turns black in sunlight, and named it *lapis lunaris*. Specifically, Sala (1614) stated

Si lapidem lunarem pulveratum ad solem exponas instar atramenti nigerimus evadit.

to denote that when powdered silver nitrate is exposed to sunlight, it turns black as ink. Eder (1945) pointed out that Sala established the effect on paper, as he noticed that paper that wrapped silver nitrate for a year was eventually coloured in black. Nevertheless, as Eder (1945) suggested, it seems that little attention was paid on this discovery at that time. Sala, in his *Opera medica chimicæ* (Sala, 1647), a large volume on chemistry and medicine, he described how to manufacture the so-called *Hollenstein*, caustic stone, by smelting silver nitrate. Regarding silver nitrate, Eder (1945) stated that exact and authentic information about it is to be owed to Angelo Sala. His experiments with that substance and silver salts were an important step towards the invention of the photographic process. His work contributed significantly

towards a better understanding of chemical reactions, and the important realisation that some substances are composed of chemical combinations of other substances.

Around 1722, *Petit* noticed that solutions of *nitrate of potash* (KNO_3) and *muriate of ammonia* (NH_4Cl) crystallised more readily in the light than they did in darkness and would produce prettier vegetation⁹ in sunlight than in the shade (Hunt, 1854; Eder, 1945).

Johann Heinrich Schulze (1687–1744) was a German polymath, that studied medicine, chemistry, philosophy and theology. Eder (1945) insisted since 1881 that Schulze should be attributed the discovery of photography, as he was the first to differentiate between light and heat in photo-chemical processes like the darkening of various substances mixed with silver nitrate when exposed to sunlight, and he was able to harness this phenomenon for practical photographic applications. This is also pointed out by Stroebel and Zakia (1993). Various sources point out that Schulze conducted experiments with silver nitrate around 1717, while Eder (1945) dated the final discovery to 1727. Schulze seems to have come to his most important conclusions by chance, as he was experimenting with *nitric acid* (HNO_3) containing nitrate of silver for dissolving chalk. He accidentally exposed this silver nitrous mixture of chalk and nitrous lime to light, and noticed that silver salts were sensitive to light. Further investigation of this finding led Schulze to a series of experiments that conclusively resulted in that the darkening was caused by light and not by heat. Those experiments were the first of their kind, and draw a sharp distinction between the chemical action of light and that of heat. Schulze provided a rather interesting demonstration of his discovery by covering silver salts mixtures with stencils of words and exposing to sunlight; the result was to produce copies of the text in dark characters, impressions which persisted as long as the mixture was not completely exposed. This is the main reason Eder (1945) and other sources (Watt, 2003; Litchfield, 1903) attribute the discovery of photography (in the broad sense) to Schulze. Even if one does not admit that this was a permanent photographic image imprint, it was certainly a foundation work for later developments. Another interesting fact pointed out by Eder (1945) is that Schulze was initially interested in phenomena of phosphorescence, but ended up coining a new term, *scotophor* and *scotophorus*¹⁰ (in contrast to phosphorus) for his experiments of substances darkening through light.

Charles-François Tiphaigne de La Roche (1722–1774) was a French author, who wrote, in 1760, a work named *Giphantie* (Tiphaigne de La Roche, 1760, 1761), which is a view of what has passed, what is now passing, and during the present century, what will pass in the world, as Eder (1945) quoted. The title *Giphantie* was a perfect anagram of the authors name *Tiphaigne*. Notwithstanding the many fanciful predictions in the book, Tiphaigne still deserves admiration. The book, among others, contains hints to the possibility of producing persisting photographic images and provoked a great deal of discussion. Eder (1945) hypothesised that Tiphaigne probably used the discoveries of Schulze, enlarged them, and covered them with the

⁹ Here, *vegetation* relates to the crystalline structure of plants growing out of salt solutions.

¹⁰ Like the etymology of *phosphorus* (φως, phōs, light + -φόρος, -phoros, -bringer), *scotophorus* comes from the Greek σκότος, skotos, darkness + -φόρος, -phoros -bringer.

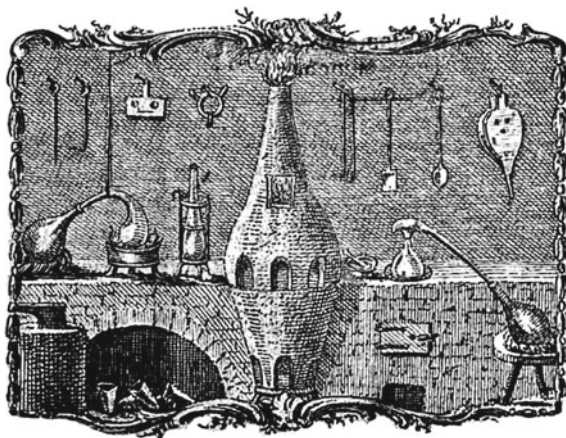
alchemic jargon of that time. Since the original ideas, of Schulze for example, were not so known at that period, it was assumed that this book presented the first original idea for the production of images by light. In *Giphantie*, Part I, Chap. XVIII, *La Tempeste* of the 1761 edition, one may read:

Tu sçais que les rayons de lumière, réfléchis des différents corps, sont tableau, & peignent ces corps sur toutes les surfaces polies, sur la rétine de l'œil ; par exemple, sur l'eau, sur les glaces. Les esprits élémentaires ont cherché à fixer ces images passagères; ils ont composé une matière très-subtile, très-visqueuse & très-prompte à se dessécher & à se durcir, au moyen de laquelle un tableau est fait en un clin d'œil. Ils enduisent de cette matière une pièce de toile, & la présentent aux objets qu'ils veulent peindre. Le premier effet de la toile, est celui du miroir; on y voit tous les corps voisins & éloignés, dont la lumière peut apporter l'image. Mais, ce qu'une glace ne sauroit faire, la toile, au moyen de son enduit visqueux, retient les simulacres. Le miroir vous rend fidèlement les objets, mais n'en garde aucun; nos toiles ne les rendent pas moins fidèlement, & les gardent tous. Cette impression des images est l'affaire du premier instant où la toile les reçoit: on l'ôte sur le champ, on la place dans un endroit obscur; une heure après, l'enduit est dessché, & vous avez un tableau d'autant plus précieux, qu'aucun art ne peut en imiter la vérité, & que le temps ne peut en aucune manière l'endommager. Nous prenons dans leur source la plus pure, dans le corps de la lumière, les couleurs que les peintres tirent de différent matériaux, que le laps des temps ne manque jamais d'altérer. La précision du dessein, la vérité de l'expression, les touches plus ou moins fortes, la gradation des nuances, les règles de la perspective; nous abandonnons tout cela à la nature, qui, avec cette marche fûre qui jamais ne se démentit, trace sur nos toiles des images qui en imposent aux yeux, & sont douter à la raison si ce qu'on appelle réalités ne sont pas d'autres espèces de fantômes qui en imposent aux yeux', à l'ouïe, au toucher, à tous les sens à la fois. L'esprit élémentaire entra ensuite dans quelques détails physiques; premièrement, sur la nature du corps gluant, qui intercepté & garde les rayons; secondement, sur les difficultés de le préparer & de l'employer; troisièmement, sur le jeu de la lumière & de ce corps desséché: trois problèmes que je propose aux physiciens de nos jours, & que j'abandonne à leur sagacité.

Eder (1945) provided the translated text to that passage, which he attributed to the 1761 English translation of the original text that is interesting to include in this section.

You know that the rays of light, reflected from different bodies, produce an image and that the objects appear delineated on all polished surfaces, as on the retina of the eye, in water and on mirrors. The elementary spirits have studied how to fix these fugitive images. They have composed a most subtle substance which is very viscous and prepared so as to dry quickly and harden; by the help of which a picture is produced in a few moments. They coat a piece of canvas with this stuff and hold it before the objects which they wish to depict. The first result apparent on the canvas is exactly that of a mirror, all objects, near or far, from which the light can throw a picture, are seen on it. But what the mirror cannot do, the canvas does by fixing the images by means of its sticky coating. While the mirror reproduces for us the objects faithfully, it retains none; our canvases reproduce them no less faithfully, but also hold them permanently. This impression of the images is the work of the first moment they are received on the canvas, which is immediately carried away into a dark place. An hour later the viscous coating has dried, and you have a painting which is the more precious, because no art can attain its reality and time cannot damage it in any way. We take from their purest source, in the luminous bodies, the colors which painters must extract from different materials, which time never leaves unchanged. The faithful rendering of the design, the truth of expression, the strokes of the brush more or less strong, the gradations of shading, the rules of perspective—all these we leave to nature, who, with a sure and never-erring hand,

Fig. 2.3 Drawing of a chemistry lab from the German edition of Scheele's dissertation



paints pictures on our canvas which deceive the eye and make one's reason to doubt, whether the so-called real objects are not phantoms of the imagination which deceive not only eyes, ears, and feelings, but all the senses together ... The elementary spirit then entered upon some physical discussions: first, on the nature of the glutinous matter which intercepts the rays and retains them; second, on the difficulties of its preparation and use; third, on the struggle between the rays of light and this dried substance; three problems which I submit to the physicists of my time and leave to their discernment.

Carl Wilhelm Scheele (1742–1786), a Swedish-German pharmaceutical chemist, published in 1777 his famous dissertation on the experiments on air and fire in Latin, *Aeris atque ignis examen chemicum* (Scheele, 1777), which was also published in German as *Chemische Abhandlung von der Luft und dem Feuer* and translated to French as *Traité chimique de l'air et du feu*, and to English as *Chemical Observations and Experiments on Air and Fire* (Eder, 1945; Fors, 2008), practically laying the foundation of photochemistry.¹¹ Figure 2.3 shows a drawing of a chemistry lab from Scheele's German edition.¹² Hunt (1854) stated that with this treatise, Scheele

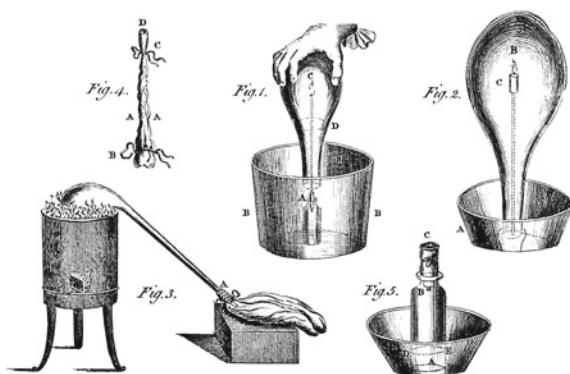
...gave the world the first philosophical examination of this peculiar change in a salt of silver, and proved the dissimilar powers of the different rays of light in effecting this change.

In line with this statement is Eder (1945), stating that Scheele's dissertation, which was based on Schulze's investigations, is of the greatest importance to the history of photochemistry. As a headline and summarisation of Scheele's work, Eder (1945) recognised the verification of the reaction of silver chloride in light, the introduction of the prismatic solar spectrum for the investigation of colour sensitiveness, and the discovery that ammonia is an agent for separating silver chloride and metallic silver from photochloride. Scheele recognised the difference in behaviour of silver chloride

¹¹ See Scheele (1780) for an English edition, Scheele (1781) for a French edition, and Scheele (1894) for a German edition of Scheele's dissertation.

¹² This figure was based on the public domain Wikimedia file at <https://commons.wikimedia.org/wiki/File:ScheeleRoyalSwdAcadChemObservatnsAir%26Fire.jpg> (last accessed March 2022).

Fig. 2.4 Scheele's drawings of his experimental setups from the English edition of his dissertation



blackened by light, and the unchanged silver chloride with respect to ammonia, which reveals knowledge of a *fixative* for silver chloride images, unfortunately unnoticed for many decades. Scheele did a considerable work towards broadening the knowledge of chemistry and he is attributed the discovery of *oxygen* and many inorganic and organic substances. He was the first to prepare *hydrofluoric acid* and to isolate *chlorine* (Eder, 1945; Myers, 2003). Figure 2.4 shows Scheele's experimental setups from the English edition of his dissertation.

Joseph Priestley (1733–1804), an English chemist and natural philosopher (among many other interests and occupations), also a prolific writer who published over 150 works, is credited with the independent discovery of oxygen (he called it *dephlogisticated air*), in 1774, by the thermal decomposition of mercuric oxide, having isolated it (Schlesinger, 1935; Eder, 1945). Priestley occupied himself in investigating the causes of the spontaneous reddening of nitric acid, and described his experiments in great detail (Priestley, 1775). His experiments demonstrated that nitric acid turned red quickly in sunlight, and kept its colour unchanged after several days in the dark, even though subjected to a considerable degree of heat (Eder, 1945). Priestley was a proponent of the *phlogiston theory*,¹³ thus, he postulated that light acted similarly to phlogiston. Priestley is also credited the discovery of *hydrogen chloride*, *ammonia*, *sulphurous acid*, *nitrogen oxide*, and other chemical elements and substances (Eder, 1945).

Jean Senebier (1742–1809), a Genevan Calvinist pastor and naturalist, made important contributions in the application of the laws of chemistry and physics to animal and plant life. He paid particular attention to the action of sunlight, and was able to provide extensive evidence that plants consume carbon dioxide and produce oxygen, explaining the process of photosynthesis. In 1783, he published *Recherches sur l'influence de la lumière solaire pour métamorphoser l'air fixe en air pur par la végétation* (*Research on the influence of solar light on the metamorphosis of fixed*

¹³ The phlogiston theory hypothesised the existence of a fire-like element called phlogiston (from the Greek φλογιστόν, flammable), contained within combustible bodies and released during combustion. This theory led to experiments that concluded with the discovery of oxygen.

air into pure air by plants) (Senebier, 1783), where he provided important data about the colour change of the different woods and many resins under sunlight. Senebier repeated Scheele's experiments, and provided data on the time needed for chloride of silver to darken under various spectrum ranges, concluding, for example, that under violet light it only required 15 s, whereas under red light it requires 20 min, also demonstrating that silver chloride assumes various colours (Hunt, 1854; Eder, 1945). Senebier's experiments, published in 1782, as *Mémoires physico-chymiques sur l'influence de la lumière solaire pour modifier les êtres des trois règnes de la nature, & sur-tout ceux du règne vegetal*, (*Physicochemical memoirs on the influence of sunlight on the modification of the beings of the three kingdoms of nature, and above all those of the vegetable kingdom*) (Senebier, 1782a, b, c), were received with appreciation, as they were thorough and of great importance in photochemistry, as well as plant physiology. Eder (1945) concludes that with Senebier, the study on the chemical action of light in the eighteenth century reached its climax, and that Senebier's works contain significant observations and must be considered as a rich source of knowledge.

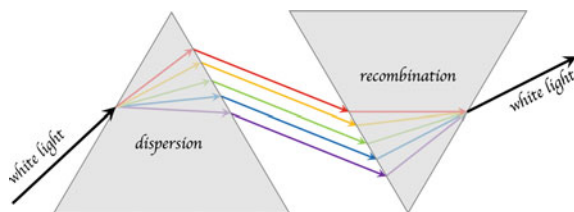
Thomas Wedgwood (1771–1805), an English photographer and inventor, is widely known as an early experimenter in the field of photography, who worked on creating permanent pictures by capturing camera images on materials coated with a light-sensitive chemical. In his experiments he was able to create non-permanent imprints of *shadow image photograms*. Nevertheless, his basic idea and partial success led historians to call him the first photographer (Fox Talbot, 1844; Hunt, 1854; Eder, 1945). In 1802, Wedgwood together with Humphry Davy published *An Account of a Method of Copying Paintings upon Glass, and of making Profiles by the Agency of Light upon Nitrate of Silver* (Wedgwood and Davy, 1802), where they described the process for copying paintings, and highlighted the issues and challenges. In their own words,

White paper, or white leather, moistened with solution of nitrate of silver, undergoes no change when kept in a dark place; but, on being exposed to the day light, it speedily changes colour, and, after passing through different shades of grey and brown, becomes at length nearly black. The alterations of colour take place more speedily in proportion as the light is more intense. In the direct beams of the sun, two or three minutes are sufficient to produce the full effect . . . The copy of a painting, or the profile, immediately after being taken, must be kept in an obscure place . . . No attempts that have been made to prevent the uncoloured parts of the copy or profile, from being acted upon by light have as yet been successful.

Apparently, Wedgwood was unable to fix his pictures to make them immune to the further effects of light, but still, one may argue that these pictures could potentially be preserved indefinitely by storing them in total darkness and protecting them from prolonged exposure to light. Last but not least, Eder (1945) argues that Wedgwood and Davy could have learned from Scheele about a fixative for the silver chloride images, but it seems that Davy declared it had not been discovered, resulting in serious negative consequences for the development of photography.

Johann Wilhelm Ritter (1776–1810) was a German chemist, physicist and philosopher, who primarily focused his research on the polarities in nature. Ritter learned about Herschel's discovery of heat rays, or the infrared radiation in 1800, and decided

Fig. 2.5 Achromatic prism configuration using two prisms



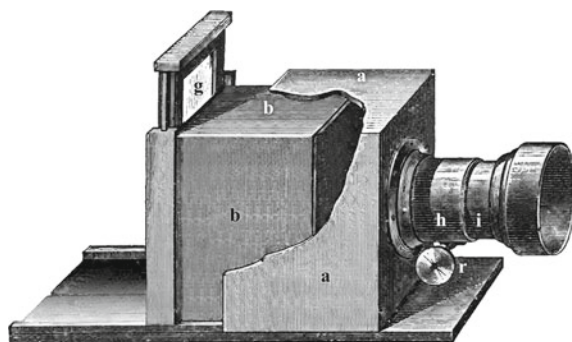
to look for an opposite (cooling) radiation at the other end of the visible spectrum. Apparently, he was not able to find that type of radiation, but instead he established a theory about the invisible violet part of the spectrum. Ritter first published his discovery of the invisible violet rays in his 1801 paper *Versuche über das Sonnenlicht* (*Experiments on sunlight*) (Ritter, 1801) (see also the Ritter 1803 edition). He named the light rays at that part of the spectrum the *chemical rays*, which, eventually, became known as ultraviolet radiation. Ritter exploited the knowledge that photographic paper covered with silver chloride would turn black when exposed to sunlight and, thus, he exposed the paper to light beyond violet, proving the existence of ultraviolet light by the rapid darkening of the paper (Hunt, 1854; Eder, 1945). Furthermore, as Eder (1945) stated, in 1805 Ritter experimented using *achromatic prisms* (see Fig. 2.5), and established (a) that the *chemical rays* follow the same laws of diffraction and dispersion as the visible rays and (b) that formations of achromatic prisms may cancel the dispersion, a property which proved to be immensely important for the construction of photographic lenses which tackle the inherent issue of chromatic aberration that will be discussed in following sections.

Thomas Johann Seebeck (1770–1831), a Baltic-German physicist was particularly interested in the relationship between heat and magnetism, which he described in 1822. Later, in 1823, Hans Christian Ørsted called this phenomenon *thermoelectric effect*.¹⁴ In 1810, Seebeck experimented with the interaction of light with silver chloride, and observed how the chemical would be coloured by the colour of light. He also experimented with the ultraviolet light interactions. In particular, Seebeck, reported that the violet rays rendered silver chloride brown, the blue rays resulted a shade of blue, the yellow rays a white, and the red rays a red colour (Hunt, 1854; Eder, 1945). Seebeck was a friend to Goethe and contributed to Goethe's *Theory of Colours* published in 1810 (von Goethe, 1810, 1840). Eder (1945) mentioned another dissertation by Seebeck, titled *Von der chemischen Aktion des Lichtes und der farbigen Beleuchtung* (*On the chemical action of light and coloured illumination*), in which Seebeck clearly detailed that chloride of silver was capable of absorbing all natural colours of the solar spectrum and of coloured glass, apart from Senebier, who made far less detailed statements on the *photochromy* of silver chloride.

Hermann Ludwig Ferdinand von Helmholtz (1821–1894), born in Potsdam, Kingdom of Prussia (Germany), was a physicist, physician and philosopher with a signif-

¹⁴ The thermoelectric effect is the direct conversion of temperature differences to electric voltage and vice versa.

Fig. 2.6 Helmholtz's depiction of the camera obscura of his time



icant scientific contribution in many fields of research, including theories of energy conservation, electrodynamics, thermodynamics, philosophy of science, aesthetics and more (Fig. 2.6). Helmholtz was particularly intrigued by the physics of perception and focused on optics and acoustics. He is particularly known for his theories of vision and visual perception. Helmholtz quickly became famous for his 1851 invention of the *ophthalmoscope*, a device with which it is possible to see the retina of the eye (*fundus* image of the eye¹⁵). In the 1860s, with the appearance of Helmholtz's *Handbuch der physiologischen Optik* (*Handbook of Physiological Optics*) (vonHelmholtz, 1867, 1909a, b, c),¹⁶ old and new experimental observations have been unified and explained under a single theory. This theory has long been known as *the Young-Helmholtz theory of colour vision*, though some researchers argue that it should be known as *the Young-Helmholtz-Maxwell theory of colour vision* (Sherman, 1981; Kremer, 1993; Heesen, 2015). The famous 'Fig. 95' from the *Handbook*, a drawing of Helmholtz's ophthalmoscope, is reconstructed in Fig. 2.7 from the 1867 edition (this figure became 'Fig. 104' in the 1909 edition of Volume I of the *Handbook*). Figure 2.8 shows Helmholtz's diagrams for the ophthalmoscope apparatus (from the 1909 edition of Volume I of the *Handbook*).

Joseph Nicéphore Niépce (1765–1833) was a French inventor, who among many contributions¹⁷ is widely recognised as one of the most significant figures in photography. He begun work on fixing photographs during 1814 but could not succeed for around 10 years (Hunt, 1854; Eder, 1945). Around 1822 he succeeded the *first permanent imprint of a photograph* using a material that hardened when exposed to light. The first photograph needed an exposure to light for several hours. Niépce

¹⁵ A *fundus* is a part of a hollow object (particularly an organ) that is furthest from the opening. In the context of vision, a fundus image of the eye shows the retina, the part of the eye that is opposite to the opening, the pupil.

¹⁶ Also in subsequent smaller treatises like *Ueber die Theorie der zusammengesetzten Farben* (*On the Theory of Compound Colours*) and *The recent progress of the theory of vision* (von Helmholtz, 1852a, b, 1885).

¹⁷ The Niépce brothers in 1807 invented and patented the *Pyréolophore*, the world's first internal combustion engine that was actually built and applied to a river boat; ten years later, they were the first to develop a fuel injection system and made an engine work with it.

Fig. 2.7 Reconstruction of Helmholtz's drawing of the ophthalmoscope

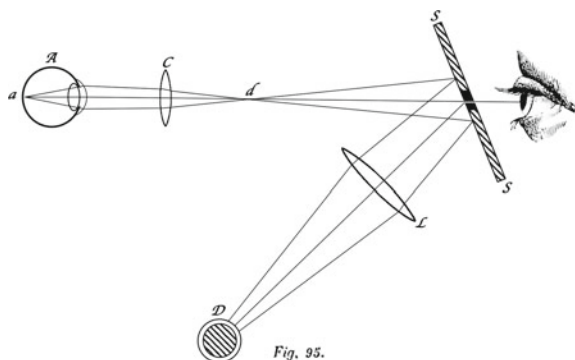
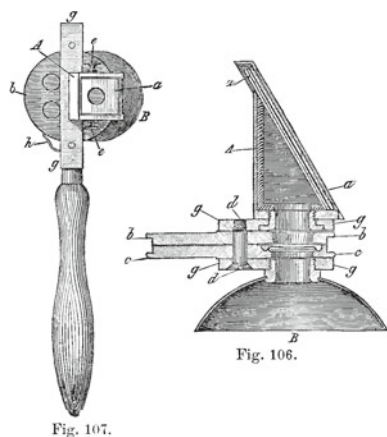


Fig. 2.8 Helmholtz's drawings of the ophthalmoscope apparatus

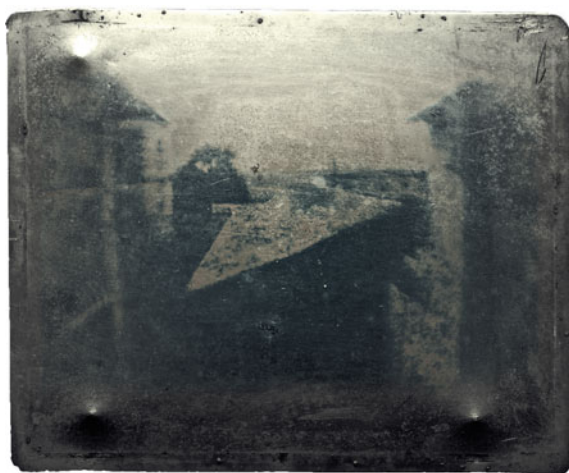


named his discovery *heliography*.¹⁸ In 1827, he wanted to submit a paper, a *Mémoire* on his methods accompanied by proofs, to the Royal Society of London, but the Society declined to listen to the lecture on the invention and the *Mémoire* was never published, as he kept his process a secret (Hunt, 1854; Eder, 1945). This memoir was accompanied with several heliographs on metal (plated copper and pewter) and on glass plates (Hunt, 1854). Figure 2.9 is considered to be *the earliest surviving photograph captured with a camera obscura*.¹⁹ It is Niépce's heliographic image taken in 1827, in his *Le Gras* estate, in Saint-Loup-de-Varennnes, France. As Eder (1945) summarised in a headline, Niépce is to be credited for the discovery of photography

¹⁸ As Hunt (1854) pointed out, *heliography* (sun-drawing) would be a more appropriate name than photography, since it was still a problem in that era, whether light, or some agent associated with light (like the sun-helios), is active in producing the chemical changes we are considering.

¹⁹ This is a composite image based on two Public Domain Wikipedia photos (a) <https://bit.ly/3wGTtzh> (last accessed March 2022) and (b) <https://bit.ly/3oqNx9E> (last accessed March 2022). The two images were superimposed and slightly coloured to match the appearance of the original exhibited at the Harry Ransom Center, the University of Texas, <https://www.hrc.utexas.edu/niepce-heliograph/> (last accessed March 2022).

Fig. 2.9 View from the window at Le Gras, in Saint-Loup-de-Varennes, France: the earliest surviving permanent photograph by Niépce



in the camera, with which he produced, in 1822, the first permanent photograph on glass, by using the *asphalt process*. The 1822 photograph was a contact-exposed copy of an engraving of Pope Pius VII, which, unfortunately is said to have been destroyed by accident (Eder, 1945). Niépce experimented fervently with a number of substances and settings and, finally, concentrating on *bitumen of Judea*, or *Syrian asphalt*, which is a naturally occurring asphalt used for various purposes since ancient times. This was not a random choice, as Niépce was very interested in etchings, and that substance was used by artists as an acid-resistant coating on copper plates for making etchings.²⁰ The contact method which Niépce used to make copies of engraving, was based on using simple sheets of paper printed with ink in a printing press, in which the plates were created photographically by the asphalt process. In essence, Niepce presented an early version of *photocopying*. Figure 2.10 shows the earliest surviving photocopy of an engraving, made by Nicéphore Niépce. As Hunt (1854) reported, heliography is in many respects peculiar, as it requires an exposure of many hours (six to eight hours) to full sunshine, depending on the intensity of light, and cannot be used during the winter season, as the cold and moisture render the varnish brittle, and detach it from the glass or metal. Niépce got in touch with Daguerre and they signed a partnership in 1829, but in four years Niépce died and Daguerre took over the development on their technology, where he made significant improvements discussed in subsequent paragraphs.

Louis Jacques Mandé Daguerre (1787–1851) was a French painter and the developer of the *diorama* theatre, but he is mostly known as one of the fathers of photography, with the invention of his own permanent photographic process. Around

²⁰ The principle and do-it-yourself information can be found at the website of the *Maison Nicéphore Niépce* museum of photography, at <https://photo-museum.org/niepce-invention-photography/> (last accessed March 2022).

Fig. 2.10 The earliest surviving photocopy artefact by Niépce



Fig. 2.11 A drawing of Daguerre's diorama

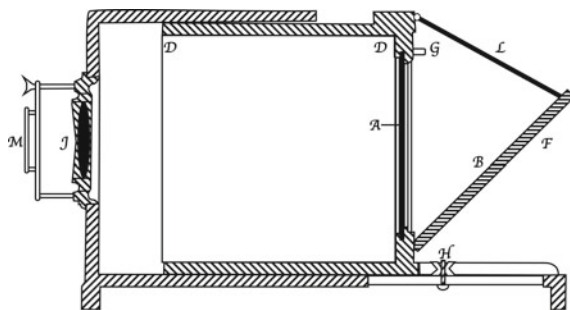


1820 he conceived the idea of improving the *panorama*,²¹ applying it as a variation in his invention of the diorama, which may be considered as the precursor of modern cinema. Daguerre's diorama, which consisted of paintings, succeeded in presenting realistic changes from morning to evening. In addition, Daguerre was able to make figures appear and disappear, using pictures painted on both sides of the thin linen that he lighted from both sides (Eder, 1945). The diorama became one of the main attractions of Paris with significant popularity. A drawing depicting the diorama found in Tissandier (1874) is shown in Fig. 2.11. Daguerre was concerned about light and its action, but he had experimented only with phosphorescent substances and the camera obscura. His endeavour and contribution to photography was sealed by a contract with Nicéphore Niépce in December 1829. As Eder (1945) informs, the signed agreement begun as follows.

Between Niépce and Daguerre, formed to co-operate for the further improvement of the invention of Niépce which was perfected by Daguerre.

²¹ It is considered that the term *panorama* was coined around 1792 by painter Robert Barker (1739–1806), from the Greek παν (all) and όραμα (view). Barker used this term to describe his paintings of Edinburgh, displayed on a cylindrical surface.

Fig. 2.12 Daguerre's camera obscura diagram



Niépce and Daguerre started working on finding a light-sensitive material that would shorten the exposure and would produce clearer and crisper images. It has been suggested that, by chance, Daguerre was led to notice the light sensitivity of *iodide of silver* (AgI), when he realised how a silver spoon lying on an iodised silver plate exposed to light left its perfect image on the plate. Daguerre informed Niépce and suggested the use of iodised silver plates in the camera. It was the year 1831. Nevertheless, Niépce did not succeed in obtaining satisfactory results, although he did manage to produce a negative on an iodised silver plate in the camera obscura. Daguerre pursued this idea and finally managed to obtain pictures.

In January 1839, *Dominique François Jean Arago* (1786–1853), a French mathematician, physicist, astronomer, and politician, an advocate for many scientists and inventors, was the first to report on Daguerre's discoveries to the Royal French Academy of Sciences. Nevertheless, the detailed public announcement was made on August 1839, under the title *La Daguerreotype, origine et histoire de cette découverte* (*The Daguerreotype, origin and history of this discovery*), and was published in the Proceedings of the Academy of Sciences. The first publicly accessible description of the process was made in the handbook *Historique et description des procedes du daguerreotypie et du diorama* (*An historical and descriptive account of the various Processes of the Daguerreotype and the Diorama*) (Daguerre, 1839a, b; Eder, 1945). Daguerre's camera was a plain wooden box with a simple Chevalier lens of flint and crown glass.²² A mirror was fixed at 45° behind the focusing glass of the camera, so that the camera user could view the picture from above in its original upright position. In the early applications of this method, the required exposure was still long, so only immovable objects and scenes could be captured, and the daguerreotypes were reversed (Eder, 1945). A reproduction of Daguerre's diagram (vertical section) of his camera is shown in Fig. 2.12, based on a figure in Hunt (1854). In this diagram, A is a ground glass to adjust the focus, B is a mirror at 45° for observing the objects and L is its support, D is the box for the adjustment of focus, which is fixed at position by the screw H , J is the lens (achromatic and periscopic object glass) with about 2.5 cm diameter and a focal length of about 35 cm, and M is the lens cover. When the required focus was attained, the glass at posi-

²² *Charles Chevalier* (1804–1859), was a French optician who built the first daguerreotype lenses.

tion $\mathcal{A}$ was replaced by the prepared photosensitive plate. Taking the picture with the camera is the third of the five steps in daguerreotype process, including the pre- and post-processing of the photosensitive plate. As stated previously, the early process still required a long exposure. Daguerre, in his ongoing experiments, noticed that a nearly invisible *latent image* could be created by a much shorter exposure, which could subsequently become visible by chemical treatment. This was a crucial discovery. In the improved process, the photosensitive plate was a silvered copper plate, around 16×22 cm, carefully polished and previously subjected to the vapours of iodine at normal temperature, resulting in the formation of a very thin coat of silver iodide. The *development*²³ of the initially invisible image included the exposure of the iodised silvered plates to the slightly heated vapour of mercury, in a wooden mercury box with a saucer-like hollow iron bottom holding the mercury, where the temperature was monitored by a thermometer. The resulting visible image was then *fixed*²⁴ by removing the unaffected silver iodide with concentrated and heated salt water. As, in the original camera the images were reversed, Chevalier attached a reversing prism in front of the lens tube to correct for this reversal, and the camera was put on sale. The resultant plate produced an exact (positive) reproduction of the scene, but the daguerreotype plate was sensitive to the atmosphere and friction, thus it was almost always sealed under glass (Eder, 1945; Hunt, 1854). The 1837 *L'Atelier de l'artiste* shown in Fig. 2.13 is considered to be the earliest reliably dated daguerreotype.²⁵ The 1838 *Boulevard du Temple*, shown in Fig. 2.14,²⁶ is among the earliest surviving daguerreotypes, considered the earliest photograph of a living person. In this picture, taken with an exposure of more than ten (10) minutes, the traffic of the otherwise crowded boulevard totally disappeared, with the exception of only the objects and persons that stood still for most of the exposure duration, like the man who stood still for the polishing of his boots, a man reading a newspaper to his left, a woman waiting under the lantern to his right and some faint traces of a couple more persons throughout the scene. Various examples of beautiful daguerreotypes can be found in cultural institutes and organisations like Europeana, the Getty Institute and the Library of Congress. Figure 2.15 shows the earliest known photograph of Abraham Lincoln captured in 1846 or 1847 by Nicholas H. Shepherd,²⁷ and a 1851 photo by Hermann Krone named *Damenbildnis*.²⁸ In addition, Fig. 2.16 shows a daguerreotype of the US Capitol captured around 1846 by John Plumbe.²⁹

²³ In the photography terminology, *development* is the chemical process by which the initially invisible effect of light on a photosensitive material becomes visible.

²⁴ Here, *fixing* is used to denote that the material was made insensitive to further exposure to light, thus no alteration of the formed image could occur.

²⁵ This figure is based on the Public Domain Wikipedia file at https://en.wikipedia.org/wiki/File:Daguerreotype_Daguerre_Atelier_1837.jpg (last accessed March 2022).

²⁶ This figure is based on the Public Domain Wikipedia file at [https://en.wikipedia.org/wiki/File:Boulevard_du_Temple_by_Daguerre_\(unmirrored\).jpg](https://en.wikipedia.org/wiki/File:Boulevard_du_Temple_by_Daguerre_(unmirrored).jpg) (last accessed March 2022).

²⁷ Library of Congress, online at <https://www.loc.gov/pictures/item/2004664400/> (last accessed March 2022).

²⁸ Europeana, online at https://www.europeana.eu/en/item/2058401/_providedCHO_f8077e99_2b64_8dd9_720d_a4f104be55a4 (last accessed March 2022).



Fig. 2.13 Daguerre's 1837 *L'Atelier de l'artiste*



Fig. 2.14 Daguerre's *Boulevard du Temple*



Fig. 2.15 Left: Nicholas H Shepherd, 1846/47, *Abraham Lincoln, Congressman-elect from Illinois, Three-quarter length portrait, seated, facing front*, 12 × 9.5 cm, Library of Congress Prints and Photographs Division Washington, D.C. 20540 USA. Right: Hermann Krone, 1951, *Damenbildnis*, Hermann Krone Sammlung, Germany

Fig. 2.16 John Plumbe, ca 1846, *United States Capitol, Washington, D.C., east front elevation*. Library of Congress Prints and Photographs Division Washington, D.C. 20540 USA



Fig. 2.17 Mary Montgomery, Charles, Montgomery, and John Rodgers, 1850/51. *Children of Lt. Montgomery C. Meigs, in donkey cart with dog*, Library of Congress Prints and Photographs Division Washington, D.C. 20540 USA



Figure 2.17 shows a daguerreotype of children in a donkey cart with a dog, captured between 1850–51, probably by Mary Montgomery, Charles Montgomery, and John Rodgers.³⁰ Figure 2.18 shows a daguerreotype of the landscape view of Niagara Falls.³¹ A rare landscape daguerreotype showing Folkestone railway viaduct is depicted in Fig. 2.19.³² Daguerreotypy soon became a commercial success and a strong cultural trend. The degree of enthusiasm awakened was graphically depicted in a 1839 caricature by Maurisset. Théodore Maurisset's 1839 *La Daguerreotypomanie* (*Daguerreotypomania*) is shown in Fig. 2.20³³ (Eder, 1945). Hunt (1854) clarified that the required exposure for the best effect, varied with the quantity of light, and its regulation was a matter of exercise and judgement, although a perfect precision should be considered impossible. In Hunt's words,

At Paris this varies from three to thirty minutes. The most favourable time is from seven to three o'clock. A drawing which, in the months of June and July, may be taken in three or four minutes, will require five or six in May or August, seven or eight in April and September, and so on, according to the season. Objects in shadow, even during the brightest weather, will require twenty minutes to be correctly delineated.

²⁹ Library of Congress, online at <https://www.loc.gov/pictures/item/2004664419/> (last accessed March 2022).

³⁰ Library of Congress, online at <https://www.loc.gov/pictures/item/2004664346/> (last accessed March 2022).

³¹ Europeana, online at https://www.europeana.eu/en/item/2058401/_providedCHO_efc107f1_a8c6_4439_16a4_2b1f1ef3aa40 (last accessed March 2022).

³² Europeana, online at https://www.europeana.eu/en/item/2058401/_providedCHO_0029253f_3b38_0559_0f56_24f14e7343df (last accessed March 2022).

³³ This figure is based on the Public Domain lithograph 84.XP.983.28 at the J. Paul Getty Museum, Gift of Samuel J. Wagstaff, Jr., online at <https://www.getty.edu/art/collection/objects/46529/theodore-maurisset-la-daguerreotypomanie-daguerreotypomania-french-december-1839/> (last accessed March 2022).

Fig. 2.18 *Landscape view of Niagara Falls, Horseshoe Falls. Trees beyond and in the foreground, National Media Museum, United Kingdom*



Fig. 2.19 *A rare landscape daguerreotype showing Folkestone railway viaduct, Royal Photographic Society Collection at the National Media Museum, United Kingdom*



Daguerreotype was never patented as it was practically purchased by the French Government for a pension for life to Daguerre and Nicéphore Niépce's son, Isidore, after Nicéphore passed away in 1833 (Hunt, 1854).

William Henry Fox Talbot (1800–1877) was an English scientist and photography pioneer who invented the precursors to contemporary photographic processes, and also the precursor to *photogravure*. He is credited the invention of a complete photographic process that is able to work fast and result permanent imprints of negatives of natural images and contact copies. Apart from a scientist he was also an artist and contributed significantly to the development of photography as an art form. Talbot's initial approach was called *photogenic drawing*. Eder (1945) argued that to Talbot belongs the honour of being the first to introduce a practical and workable method of photography using a camera obscura; a method that resulted a negative image on light-sensitive paper, from which positive images or prints could be obtained by contact printing. Since 1823, Talbot has been extensively using the techniques of *camera*



Fig. 2.20 La Daguerreotypomania (Daguerreotypomania)

obscura and *camera lucida*³⁴ as drawing aids (see Fig. 2.21³⁵ and Fig. 2.22³⁶ for the principles of the two methods). As Eder (1945) emphasised, Talbot was not satisfied with results thus obtained, and this motivated him to search for methods to chemically fix images in the camera obscura, without knowledge of the works by Niépce and Daguerre, but already exposed to the works of Schulze, Scheele, and Wedgwood with light-sensitive silver salts. He started experimenting with silver chloride and finally reached to a process of rapid image imprint and fixation. Quoting from *The Pencil of Nature* (Fox Talbot, 1844),

This process, of the formation of a subchloride by the use of a very weak solution of salt, having been discovered in the spring of 1834, no difficulty was found in obtaining distinct and very pleasing images of such things as leaves, lace, and other flat objects of complicated forms and outlines, by exposing them to the light of the sun. The paper being well dried, the leaves, &c. were spread upon it, and covered with a glass pressed down tightly, and then placed in the sunshine; and when the paper grew dark, the whole was carried into the shade, and the objects being removed from off the paper, were found to have left their images very perfectly and beautifully impressed or delineated upon it. But when the sensitive paper was placed in the focus of a camera obscura and directed to any object, as a building for instance,

³⁴ Although the principles of camera lucida were known since Kepler, it was William Hyde Wollaston (1766–1828) who patented it, as his invention, in 1807.

³⁵ This figure is an enhanced and processed version made by the Public Domain figure available in various sources.

³⁶ This figure is an enhanced and processed version of the figure in Dollond et al. (1830).

Fig. 2.21 Camera obscura as a drawing aid

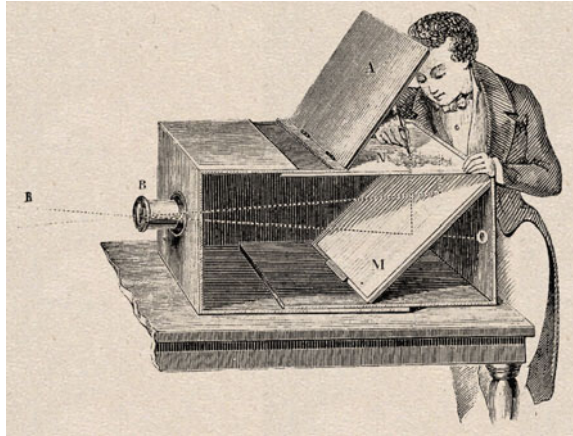
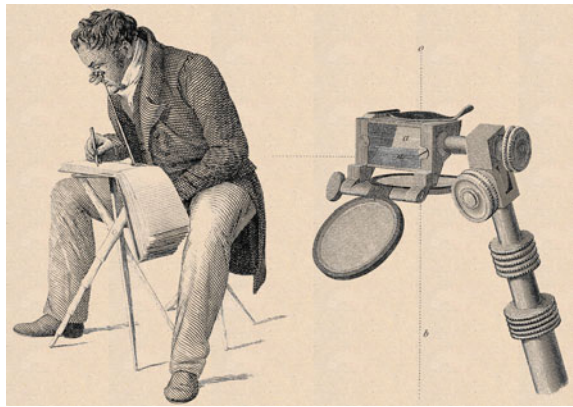


Fig. 2.22 Camera lucida as a drawing aid. From the Beinecke Rare Book and Manuscript Library, Yale Digital Collections



during a moderate space of time, as an hour or two, the effect produced upon the paper was not strong enough to exhibit such a satisfactory picture of the building as had been hoped for.

This passage reveals that Talbot initially succeeded in experiments, in which the object of interest was in contact with the photosensitive paper and exposed to light, whereas the same process could not be directly applied with much success in the camera obscura. With these results, he turned to other substances and experimented with iodide of silver, as suggested by Davy. To his surprise, in his experiments silver iodide proved to be totally insensitive to light, contrary to the knowledge of that time. This did not discourage Talbot, who saw in silver iodide a potential fixative, in particular, a solution of *potassium iodide* (KI). During 1835 he devised a process of repeated alternate washes of salt and silver and managed to reduce the exposure time (on a bright day) to ten (10) minutes. Talbot rushed to publish his invention in January 1839 just about the time Daguerre published his own method. As Daguerre did not disclose the science behind his method, Talbot sent a letter to the Royal

Society London, the some month, to publicise and describe his method, titled *Some account of the art of photogenic drawing, or the process by which natural objects may be made to delineate themselves without the aid of the artist's pencil* (Talbot, 1843). Further improvements of his work led to a method of making the paper so sensitive, that with a camera using a lens of 2.5 cm in diameter and a focal length of 38 cm, a square picture of 20–23 cm could be produced, in general, in 10 s. Even in a dark winter day, this paper would rapidly become dark, while in 5–6 s it would darken even by the light of a wax candle. Talbot was even able to take impressions of leaves on this paper under moonlight (Brewster, 1843). In 1841 Talbot announced and patented his latest method, which he named the *calotype*, from *καλός* + *τύπος*, meaning beautiful picture/impression, or *talbotype* (Hunt, 1854; Eder, 1945). Talbot, in a second patent brought further improvements that involved changes of chemical, exposure and post-processing nature, also including magnification considerations and suggestions on the printing and the publication process of multiple copies from negatives. In a third patent, Talbot presented a method to make the paper impervious to water, a method of obtaining more complete fixation of photographic pictures on paper, a method to substitute glass with porcelain, and a method to form images on polished steel surfaces. These were not his only inventions and patents, as he continued to improve his methods and discover new innovative applications (Hunt, 1854). Figure 2.23 is a processed version of Talbot's 1835 negative image of *The Oriel Window*, side by side with the corresponding positive.³⁷ Talbot published *The Pencil of Nature* (Fox Talbot, 1844) and *Sun Pictures in Scotland* (Fox Talbot, 1845), which were illustrated with original salted paper prints from his calotype negatives (including one negative), and made some important early photographs of Oxford, Paris, Reading, and York. These were the earliest published photographic albums. Figures 2.24, 2.25, 2.26, 2.27 and 2.28 show some of Talbot's works in his *Sun Pictures in Scotland* collection.³⁸ In particular, Talbot published the Lace (Fig. 2.26) to showcase a *negative* image, and commented on how the conversion to a positive would affect the clarity that the negative image provides.

Sir John Frederick William Herschel (1792–1871) was an English polymath, inventor, and an important figure in photography. He was primarily concerned with the investigation of the physical laws that govern the chemical phenomena in photography, and apparently not photography as a form of artistic expression. He was able to invent new and interesting photographic processes, including *cyanotype*, *chrysotype* and *amphitype*, and studied the photographic properties of chemicals like *mercury*, *ferro-tartrate of silver*, and the colouring substances of flowers. Herschel experimented heavily with chemicals in search of understanding of the underlying processes and the discovery of new methods. Herschel's father, *Sir Frederick William Herschel* (German *Friedrich Wilhelm Herschel*, 1738–1822), was involved in experiments about light beyond the visible, and he is credited by many researchers and

³⁷ This figure is a processed version of the Public Domain image, exhibited online at the Metropolitan Museum of Art, <https://www.metmuseum.org/art/collection/search/282004> (last accessed March 2022).

³⁸ All works presented here are Public Domain.

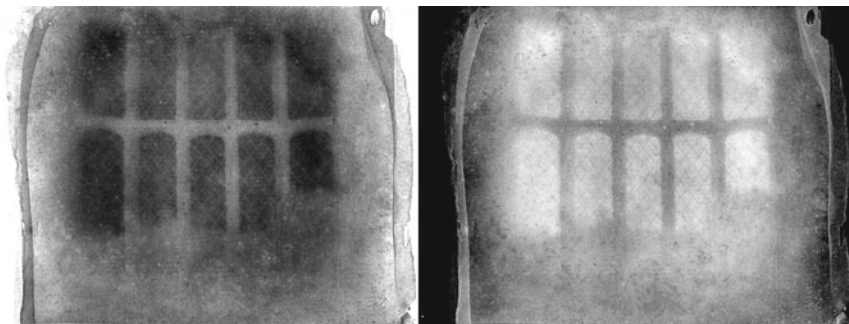


Fig. 2.23 Processed and inverted version of *The Oriel Window, South Gallery, Lacock Abbey*. From The Metropolitan Museum of Art, The Rubel Collection, Purchase, Ann Tenenbaum and Thomas H. Lee and Anonymous Gifts, 1997.382.1

Fig. 2.24 The Pencil of Nature: Plate III - Articles of China. From The Metropolitan Museum of Art. Gift of Jean Horblit, in memory of Harrison D. Horblit, 1994.197.1–.6



Fig. 2.25 The Pencil of Nature: Plate XIII - Queen's College, Oxford, Entrance Gateway. From The Metropolitan Museum of Art. Gift of Jean Horblit, in memory of Harrison D. Horblit, 1994.197.1–.6



Fig. 2.26 The Pencil of Nature: Plate XX - Lace. From The Metropolitan Museum of Art. Gift of Jean Horblit, in memory of Harrison D. Horblit, 1994.197.1–.6



Fig. 2.27 Sun Pictures in Scotland: Loch Katrine Pier, Scene of the Lady of the Lake. The Met Museum. Gilman Collection, Purchase, Alfred Stieglitz Society Gifts, 2005.100.261



historians of science the discovery of the infrared radiation, the *radiant heat* in his own words, and the significant connection between light and heat, in his 1800 publication *Investigation of the Powers of the prismatic Colours to heat and illuminate Objects* (Herschel, 1800; Hunt, 1854; Ware, 2020). As Eder (1945) emphatically stated, Sir William Herschel discovered in 1800 the infrared spectrum and then, one year later, Ritter discovered the ultraviolet rays and their action on chloride of silver. On the other hand, Sir John Herschel, among other contributions in the science of photography, investigated the chemical power of ultraviolet rays. Herschel discovered *sodium thiosulfate*, or *hyposulphite of soda*, or simply *hypo* ($\text{Na}_2\text{S}_2\text{O}_3 \cdot x\text{H}_2\text{O}$) to be a solvent of *silver halides* (AgX) and fixative for silver chloride-based photographic processes in 1819, and published his discovery in his paper *On the hyposulphurous acid and its compounds* (Herschel, 1819; Eder, 1945). Herschel stated,

Fig. 2.28 Sun Pictures in Scotland: Scott Monument Under Construction. The Cleveland Museum of Art, Andrew R. and Martha Holden Jennings Fund 1987.23



...muriate of silver, newly precipitated, dissolves in this salt (hyposulphite), when in a somewhat concentrated solution, in large quantity and almost as readily as sugar in water.

Although Herschel informed about the discovery that hypo could be practically used as a photographic fixer, it seems that this knowledge escaped his contemporaries, and significantly delayed the photographic innovations. Herschel communicated this knowledge to the photography pioneers of his times, especially Talbot, but it was not until 1839 that Daguerre finally adopted its use and made a significant improvement of the daguerreotype, thus triggering further publicity of this approach (Eder, 1945). The same year, in 1839, Herschel made a photograph on glass, which is, today, the earliest surviving such photograph. Figure 2.29 shows Herschel's first glass-plate photograph, capture in 1839, depicting his father's telescope.³⁹ Herschel's research on the subject was further refined and was presented at the Royal Society London, published under the title *On the chemical action of the rays of the solar spectrum on preparations silver and other substances, both metallic and and on some photographic processes* in 1840 (Herschel, 1840). Around 1841–1842, Herschel experimented with colours derived from plants, adopting a die-and-bleach process, resulting directly in positive images. The images were coloured but not in the colours of the captured scene. He published the details of this method in the 1842 *On the action of*

³⁹ This is a composite of the negative photo found as a Public Domain Wikipedia picture at <https://bit.ly/3kx8Fdf> (last accessed March 2022), on the left, and the corresponding positive, on the right.

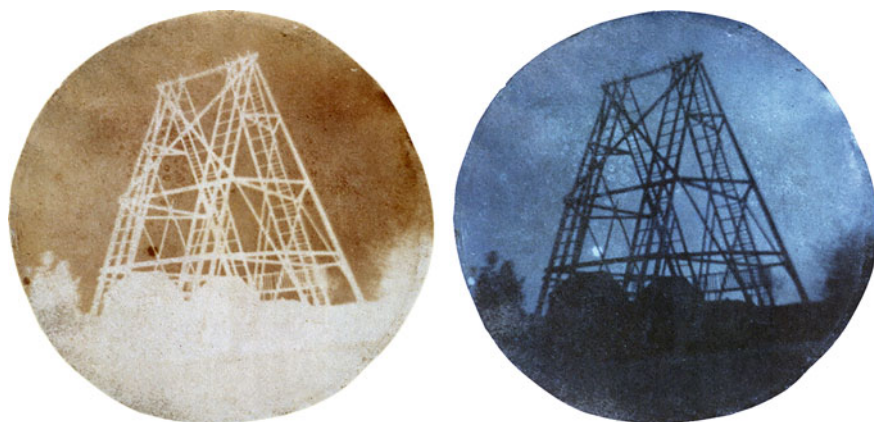


Fig. 2.29 Sir John Herschel's first glass-plate photograph, showing Sir William Herschel's telescope

the rays of the solar spectrum on vegetable, and on some new photographic processes (Herschel, 1842). In this publication, Herschel predicted this was not a viable process, due to being extremely slow and susceptible to further changes with time. Nevertheless, he made experiments with photosensitive emulsions of vegetable juices and invented *phytotypes*⁴⁰ and *anthotypes*.⁴¹ An example of an experimental phytotype, captured c.1841, is shown in Fig. 2.30.⁴² Interestingly, in the same paper, Herschel added in August 29 1842 a Postscript, in which he announced two other new process, the *cyanotype* and the *chrysotype*, which he further refined and described in a following paper titled *On Certain Improvements on Photographic Processes Described in a Former Communication, and on the Parathermic Rays of the Solar Spectrum* (Herschel, 1843b). Cyanotype was the result of the application of chemistry earlier described by chemist Alfred Smee (1818–1877), thus Herschel was based on stable evidence. He described that by depositing *Prussian blue* on paper and exposing to sunshine for half to one hour, negative images are produced, easily fixed by soaking the surface in a solution of sulphate of soda (hypo), resulting in a bright blueprint. Prussian blue ($\text{Fe}_4^{\text{III}}[\text{Fe}^{\text{II}}(\text{CN})_6]_3$) is a common name for iron salts produced by oxidation of *ferrous ferrocyanide salts*, a soluble form of which may be produced from *potassium ferrocyanide* ($\text{C}_6\text{FeK}_4\text{N}_6$) and *iron*. Anna Atkins (1799–1871), a botanist and photographer, apart from being the first woman photographer, she user cyanotype to create the earliest book illustrated with photographic images, the *Photographs of British Algae: Cyanotype Impressions* (Atkins, 1843). Figure 2.31 shows an example

⁴⁰ From the Greek φυτο- (phyto-) the plant and -τυπία (-typia, -type).

⁴¹ From the Greek ανθο- (antho-) the flower and -τυπία (-typia, -type).

⁴² This is a processed picture based on the photo exhibited by the History of Science Museum, Inventory number 31765, online at <https://www.mhs.ox.ac.uk/collections/imu-search-page/record-details/?TitInventoryNo=31765> (last accessed March 2022).

Fig. 2.30 Direct positive contact-copy phytotype of the engraving *Grecian lady looking at the moon* by Herschel, c.1841



page from that book, along with the inverted image to create the positive.⁴³ According to Hunt (1854), *chrysotype*⁴⁴ appeared at the same time as the cyanotype, as a process of an analogous character, in which the *chloride of gold* (AuCl) is the agent, as also detailed in the Postscript of the 1842 paper (Herschel, 1842). Chrysotype (gold print) uses colloidal gold to record images on paper. Herschel's process involved coating paper with *ferric citrate* ($\text{C}_6\text{H}_5\text{FeO}_7$), which when in contact with an etching and exposed to the sun resulted in darkening of the unmasked regions, subsequently submerged to a *chloroaurate solution* ($\text{HAuCl}_4 \cdot (\text{H}_2\text{O})_x$) to develop the photograph. Using Herschel's own words (Herschel, 1842),

Paper is to be washed with a moderately concentrated solution of ammonio-citrate of iron, and dried. The strength of the solution should be such as to dry into a good yellow colour, not at all brown. In this state it is ready to receive a photographic image, which maybe impressed on it either from nature in the camera-obscura, or from an engraving on a frame in sunshine. The image so impressed, however, is very faint, and sometimes hardly perceptible. The moment it is removed from the frame or camera, it must be washed over with a neutral solution of gold of such strength as to have about the colour of sherry wine. Instantly the picture appears, not indeed at once of its full intensity, but darkening with great rapidity up to a certain point, depending on the strength of the solutions used, &c. At this point nothing

⁴³ This picture is based on the Public Domain Wikipedia picture <https://bit.ly/3HdQh2W> originating in the New York Public Library Digital Collections at <https://on.nypl.org/3CaRFj2> (last accessed March 2022).

⁴⁴ The terms is a combination of the Greek χρυσό- (chryso-) gold, and τύπος/τυπία (typia) type.



Fig. 2.31 Anna Atkins' cyanotype of *Dictyota dichotoma*, captured in 1849

can surpass the sharpness and perfection of detail of the resulting photograph. To arrest this process and to fix the picture (so far at least as the further agency of light is concerned), it is to be thrown into water very slightly acidulated with sulphuric acid and well soaked, dried, washed with hydrobromate of potash, rinsed, and dried again.

Such is the outline of a process to which I propose applying the name of Chrysotype, in order to recal by similarity of structure and termination the calotype process of Mr. Talbot, to which in its general effect it affords so close a parallel.

Chrysotype negatives have a particular dark violet colour, high contrast, and are of high detail, as shown in Fig. 2.32⁴⁵ and Fig. 2.33.⁴⁶ It is evident from Herschel's 1837 *Note on the art of photography, or the application of the chemical rays of light to the purposes of pictorial representation*, published in the Proceedings of the Royal Society London, that he is the first to have used the term *photography*⁴⁷ and *photographic* to generalise the various approaches relating to the photochemical process of permanent image imprint (Herschel, 1843a; Eder, 1945). Herschel was also the first to produce photographs on glass and to apply the terms *negative* and

⁴⁵ This is a processed part of the exhibit found at the Google Arts and Culture Institute, of Herschel's experimental prints featuring a contact copies of engravings, dated 1840, owned by he Royal Society London.

⁴⁶ This is a processed part of the *Experimental photogenic drawing (chrysotype)* by Sir John Herschel, c.1842, a contact copy of an engraving, Inventory number 21518, History of Science Museum.

⁴⁷ It has been suggested that Herschel was outrun in coining the term by *H'ercules Florence* (1804–1879) who has supposedly independently invented photography in Brazil and coined the term *photographie* (French) in 1834, although he never published formally for this invention and terminology (Kossoy 2004).

Fig. 2.32 Herschel's 1840 experimental chrysotype



Fig. 2.33 Herschel's experimental chrysotype, c.1842



positive (Stephen et al., 1908). Herschel's cyanotype that became the first process for photocopying, the *blueprinting*, although it was Talbot that pursued commercial success (Ware, 2020). Eder (1945) concludes that

Talbot therefore laid the foundation for our photographic printing methods with bromide and chloride of silver, and Herschel completely solved the question of perfect fixation with sodium thio-sulphate (hypo).

Frederick Scott Archer (1813–1857) was an English sculptor and photographer. Archer was familiar with the calotype, which he considered useful for capturing images of his sculptures, although he was not so satisfied by the low resolution and contrast attained, during rather long exposures. He was motivated by those imperfections of the previous processes and pursued a different approach. Around 1848 he started experimenting with *collodion*,⁴⁸ which was recently discovered by *Louis-Nicolas Ménard* (1822–1901) and *Florès Domonte* and was named by *Augustus Addison Gould* (1805–1866), from the Greek *κολλώδης* (*kollodis*), gluey. In 1851 he published his paper *On the use of collodion in photography*⁴⁹ presenting the newly discovered wet collodion process (Archer, 1851), for which he published a more detailed account in the next year in a treatise titled *A Manual of the Collodion Photographic Process* (Archer, 1852), further refined in his 1854 *The Collodion Process on Glass* (Archer, 1854). In his first publication, Archer described in detail the process of creating the new solution,

Pour a quantity (say 1 oz.) of collodion into a bottle containing dry iodide of silver. Shake them well together, rid then allow the excess of iodide of silver to settle. The collodion will in this way take up a certain quantity of the silver salt, and become opaque; it should then be transferred o another bottle containing iodide of potassium, to be again well shaken up until the iodide of silver is entirely dissolved, rid the solution becomes transparent.

and applying it evenly on a plate of glass. Then the surface is ready to be exposed to light. The development of the picture required either *gallic acid* ($C_7H_6O_5$) or *pyrogallic acid* ($C_6H_6O_3$). Archer (1852) in the detailed publication of the method, noted that the ability to remove the thin collodion film from the glass is the strongest point of his method, along with the ease by which the film can be produced on glass.

The strength of the film allows the removal of the drawing from the glass on which it has been produced, and this a most distinctive feature in the process.

Figure 2.34⁵⁰ and Fig. 2.35⁵¹ show selected photographs by Archer, exhibited at the J. Paul Getty Museum, Los Angeles. Archer devised a coating method for the

⁴⁸ Collodion is a flammable, syrupy solution of *nitrocellulose* ($C_6H_7O_2(ONO_2)_3$ (Tri_nitrat)) in *ether* ($(C_2H_5)_2O$) and *alcohol* (C_2H_5OH). There is flexible collodion, typically used in surgery, and non-flexible collodion, often used in theatrical make-up.

⁴⁹ The text of this publication can be found online at <http://www.samackenna.co.uk/fsa/thechemist.html> (last accessed March 2022).

⁵⁰ Frederick Scott Archer, [Castle], about 1851, Albumen silver print, 16.3 × 21.8 cm (6 7/16 × 8 9/16 in.), 84.XP.1006.2, The J. Paul Getty Museum, Los Angeles, online at <http://www.getty.edu/art/collection/objects/46989/frederick-scott-archer-castle-british-about-1851/> (last accessed March 2022).

⁵¹ Left: Frederick Scott Archer, [Castle, Kenilworth], 1851, Albumen silver print, 23 × 18 cm (9 1/16 × 7 1/16 in.), 84.XP.1006.5, The J. Paul Getty Museum, Los Angeles, online at <http://www.getty.edu/art/collection/objects/46988/frederick-scott-archer-the-grand-entrance-kenilworth-british-1851/?dz=0.5000,0.5000,0.63> (last accessed March 2022). Right: Frederick Scott Archer, [The Grand Entrance, Kenilworth], 1851, Albumen silver print, 23 × 18 cm (9 1/16 × 7 1/16 in.), 84.XP.1006.1, The J. Paul Getty Museum, Los Angeles, online at <http://www.getty.edu/art/collection/objects/46992/frederick-scott-archer-castle-kenilworth-british-1851/> (last accessed March 2022).



Fig. 2.34 *Castle*, c.1851, by Frederick Scott Archer



Fig. 2.35 *The Grand Entrance, Kenilworth*, c.1851, by Frederick Scott Archer, left; *Castle, Kenilworth*, 1851, by Frederick Scott Archer, right

collodion film, on being removed from the glass plate, so that it can be preserved and used for prints virtually indefinitely, for which he acquired a patent (Eder, 1945). The wet collodion process could result either a positive or a negative image, and Archer proposed a longer exposure for the production of negatives in order to capture stronger contrast, to be able to print higher quality images. In a way, the wet collodion process brought the fine detail pictures of the daguerreotype with the ability to print copies of the calotype, reducing, at the same time, the relative exposure



Fig. 2.36 The 1852 *View of the Colosseum in Rome* by Frederic Flacheron, left, and the 1853 *Amsterdam, View of Reguliersbreestraat* by Eduard Isaac Asser, right

time required. Figure 2.36 presents two early wet collodion photographs, the 1852 *View of the Colosseum in Rome* by Frederic Flacheron and the 1853 *Amsterdam, View of Reguliersbreestraat* by Eduard Isaac Asser.⁵² Figure 2.37 presents two early portraits created with the wet collodion process that results in a direct positive, also known as *ambrotype*; on the left, the c.1860 *Portrait of man, sitting with left hand stuck inside coat* by Mats Landin,⁵³ and, on the right, the c.1860 *Veteran and his wife* by an Anonymous creator.⁵⁴ Figure 2.38 is based on the 1870–1875 negative titled *Glass plate negatives of Sydney Harbour from the Holtermann residence, St. Leonards*⁵⁵; the positive is the direct inverse image. Eder (1945) informs that Archer and Gustave Le Gray⁵⁶ entered into a dispute regarding the priority in the invention of

⁵² Both photographs are provided as Public Domain by the Rijksmuseum at <https://www.rijksmuseum.nl/en/collection/RP-F-F80368> (last accessed March 2022) and <https://www.rijksmuseum.nl/en/collection/RP-F-AB12280-M> (last accessed March 2022) respectively.

⁵³ This figure is based on the Public Domain photograph at the Nordiska museet, online at <https://digitaltmuseum.se/011013850387/portratt-av-man-sittande-med-vanstra-handen-stucken-inannfor-rocken-ambrotyp> (last accessed March 2022).

⁵⁴ This figure is based on the Public Domain photograph available online at https://commons.wikimedia.org/wiki/File:1860_Anonyme_Un_vétérán_et_sa_femme_Ambrotype.jpg (last accessed March 2022).

⁵⁵ This figure is based on the Public Domain negative wet collodion negative owned by the Mitchell Library, State Library of New South Wales and found online at https://digital.sl.nsw.gov.au/delivery/DeliveryManagerServlet?embedded=true&toolbar=false&dps_pid=FL9207437 (last accessed March 2022).

⁵⁶ More on Le Gray in the following sections.



Fig. 2.37 The c.1860 *Portrait of man, sitting with left hand stuck inside coat* by Mats Landin, left, and the c.1860 *Veteran and his wife* by an Anonymous creator, right



Fig. 2.38 The 1870–1875 negative titled *Glass plate negatives of Sydney Harbour from the Holtermann residence, St. Leonards* by Charles Bayliss and Bernard Holtermann, and its inverse positive

the collodion process for several years. About the time Archer published his method, Le Gray published his 1851 *Nouveau Traité théorique et pratique de photographie sur papier et sur verre: contenant les publications antérieures et une nouvelle méthode pour opérer sur in papier sec restant sensible huit à dix jours* (*New theoretical and practical treatise on photography on paper and glass*) (Le Gray, 1851), where he claimed to have used collodion before Archer, but due to a typesetter mistake he was able to support it only after the text was corrected in 1854. Eder (1945) also informs that Archer's followers gave the collodion process the name *archerotypie* (or *archertype*).

Jean-Baptiste Gustave Le Gray (1820–1884) is considered to be the most influential French photographer of the 19th century due to his technical and artistic contributions. He is credited to have theoretically proposed the wet collodion process but he was outrun by Archer in practically applying it. According to Eder (1945), Le Gray was the first to employ, in June, 1850, a solution of collodion cotton in ether, which when poured on glass furnished a transparent film that served as a carrier for the photographic image, and described this method, although in a very obscure manner in his 1850 *Traité pratique de photographie sur papier et sur verre* (Le Gray, 1850), also published a year later as *Nouveau Traité théorique et pratique de photographie sur papier et sur verre: contenant les publications antérieures et une nouvelle méthode pour opérer sur in papier sec restant sensible huit a dix jours* (Le Gray, 1851). Following the translation by Eder (1945), Le Gray is quoted stating that

I invented a method with collodion on glass with hydrofluoric acid methyl ether, potassium fluoride, and sodium fluoride dissolved in a 40° alcohol, mixed with ether and saturated with collodion; I then sensitised with acid silver nitrate and obtained in this manner images in the camera obscura with twenty seconds exposure in the shade. I developed the image with a very weak solution of iron sulphate, and fixed with hyposulphite. I hoped to achieve with this process a very great sensitivity. By the use of ammonia (NH₃) and potassium bromide (KBr) obtained great variations in the results.

Both Hunt (1854) and Eder (1945), as other sources, agree that Le Gray's formula was practically impossible to execute, since *potassium fluoride* (KF) is not a photographic agent and *hydrofluoric acid ether* (HF) was not known at all at that time, thus, it does not seem possible that Le Gray could have obtained successful photographic results in accordance with his above statements. Hunt (1854), in p. 215, commented on Le Gray's description of his collodion method, as follows.

...but I believe the quantity of the bromide of potassium to be by far too large, and that the pictures would sustain less injury by using a solution of one half the strength indicated.

Le Gray's technical contributions included, apart from his proposal of the collodion process, improvements on paper negatives, specifically the waxing method he applied before exposure that preserved the paper and made it more receptive to fine detail, as well as a method to achieve *combination printing*.⁵⁷ In particular, Hunt (1854) credited significant merit to Le Gray for being the most successful operator with waxed paper (calotype process on waxed paper). Le Gray left a large collection of beautiful photographs, including monuments, portraits, and seascapes. In 1999, Le Gray's print *Beech Tree, Fontainebleau* (c.1856) was sold for £419,500, setting a world record for the most expensive single photograph ever sold at auction, which stood until 2003 when a daguerreotype by Joseph-Philibert Girault de Prangey was sold for £565,250. Figures 2.39, 2.40, 2.41, 2.42 and 2.43 present a selection of Le

⁵⁷ Combination printing is the photographic technique of using two or more negatives for the creation of a single image, using a blending approach. This was a rather useful method to tackle high dynamic range scenes, in which parts of the scene might be under- and other parts over-exposed. By careful planning of the exposure, the photographer could capture the photographs needed to make the envisioned composite image.

Fig. 2.39 Le Gray's 1856
*La Reine Hortense - Yacht de
l'empereur, Havre*, Albumen
silver print from glass
negative



Fig. 2.40 Le Gray's 1856
*Tree Study, Forest of
Fontainebleau*, Albumen
silver print from glass
negative



Gray's excellent technical and artistic work.⁵⁸ Eder (1945) quotes Le Gray expressing that,

La photographie est appelée à un grand rôle clans le progrès de l'art. Son resultat immédiat sera de détruire les infériorités et d'élever les artistes de talent.

Photography is called to a great role in the progress of art. Its immediate result will be to destroy inferiorities and elevate talented artists.

⁵⁸ These figures are based on the corresponding Public Domain photographs exhibited at The Metropolitan Museum of Art, online at <https://www.metmuseum.org/art/collection/search/285467> (last accessed March 2022), <https://www.metmuseum.org/art/collection/search/265065> (last accessed March 2022), <https://www.metmuseum.org/art/collection/search/261941> (last accessed March 2022), <https://www.metmuseum.org/art/collection/search/306320> (last accessed March 2022), <https://www.metmuseum.org/art/collection/search/284986> (last accessed March 2022).

Fig. 2.41 Le Gray's 1857
The Great Wave, Sète,
Albumen silver print from
glass negative



Fig. 2.42 Le Gray's 1858
*The French and English
Fleets, Cherbourg*, Albumen
silver print from glass
negative



Fig. 2.43 Le Gray's 1866
Soldier and Military Camel,
Albumen silver print from
glass negative



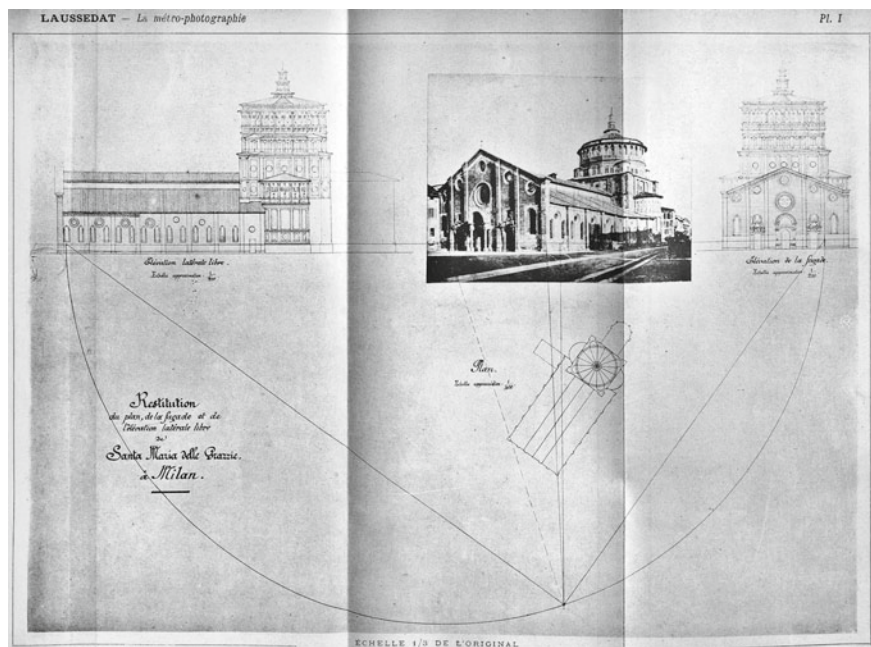
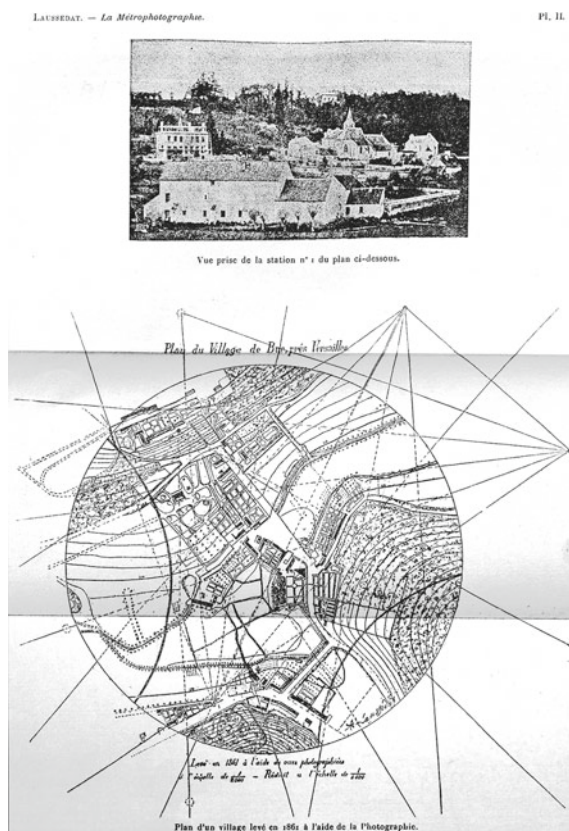


Fig. 2.44 Laussedat's photogrammetric rectification of Santa Maria delle Grazie in Milan

Aimé Laussedat (1819–1907) was a French engineer, observational astronomer, geodesist, surveyor, photogrammetrist, and cartographer. He is considered the father of *photogrammetry*, the metrology of three-dimensional spaces based on photographs. Originally, he worked with the camera lucida in topographic studies. With the advent of early photography, he was among the first to apply it directly into survey and cartography, and he even constructed his own photographic equipment, bridging the camera obscura with topographic technology. He named his process *iconometry* and *metrophotography* and applied it in the reconstruction of architecture and mapping (Gruner, 1977). Laussedat has been using photography since 1851 (Atkinson, 1995; Granshaw, 2019). Figure 2.44 shows Laussedat's photogrammetric rectification of Santa Maria delle Grazie in Milan, from Laussedat's 1899 *La Métrophotographie* (Laussedat, 1899). He continued validating his work and he was able to produce a map of Paris by 1861. The same year he demonstrated the technique to a commission of the French War Ministry at the village of Buc, near Versailles, using a camera with a 50 cm focal length, properly levelled, plates of 24 × 30 cm and the wet collodion process. Within four hours, he was able to select the proper camera locations and expose eight photographic plates; within four days he completed and presented the plan of Buc with success, which was highly appreciated by the commissioners (Granshaw, 2019). Figure 2.45 shows his plan of a Village created using multiple-view photogrammetry (roof-top photography), from Laussedat's 1899 *La Métrophotographie* (Laussedat, 1899).

Fig. 2.45 Laussedat's photogrammetric plan of the Village of Buc, near Versailles



Richard Leach Maddox (1816–1902) was an English physician by training and an amateur photographer that made a considerable contribution to photography, and paved the way towards a new era in that field, by inventing the *gelatine negative plates* in 1871. Maddox due to his training as a physician was particularly interested in microorganisms and had been using photography to capture images of the micro-world. He was an established *photomicrographer* (or *microphotographer*), by photographing microorganisms using the microscope, capturing, what was then called, *microscopical photographs*. Beale (1868) asked Maddox to revise Part IV *On taking photographs of microscopic objects. Apparatus. Illumination. Chemical solutions. Practical manipulation. Printing. Photographs for the magic lantern*, in the fourth, 1868, edition of his book; Maddox was mostly responsible for the part regarding photomicrography (or microphotography) in the following editions. Eder (1945) informs that Maddox devoted himself to photography as early as the 1850s and received medals for his microphotographs in 1853 from the Photographic Society of London and in 1865 at the Dublin International Exhibition. Regarding photography in general, Maddox had been using Archer's collodion process, already in practice

since 1851. The process required that the photographic plates be exposed while the emulsion was still wet, and be processed immediately after exposure in the camera. Maddox noticed that his health deteriorated due to the ether vapour in the process, and quickly began searching for an alternative. In 1871 he published his findings in a paper titled *An Experiment with Gelatino-Bromide* (Maddox, 1871). Maddox seems to have experimented using various bases to combine silver bromide with little success, until he used gelatine. He prepared several plates and exposed them by contact-printing using other negatives, and a variety of exposure times. He reported in his paper that

The resulting prints were very delicate in detail, of a colour varying between a bistre and olive tint, and after washing dried to a brilliant surface. The colour of the print varied greatly, according to the exposure. From the colour and delicacy it struck me that with care to strain the gelatine or use only the clearest portion, such a process might be utilised for transparencies for the lantern and the sensitive plates be readily prepared.

The successful experiment with gelatine silver bromide emulsion was according to Eder (1945) his major contribution, resulting in a totally new process. This process, the gelatine silver dry plate process, revolutionised photography by bringing great benefits, including the potential to commercialise ready-made plates, the ability to develop the negatives in a convenient time (and not immediately), and the potential to use significantly smaller cameras, thus, paving the way to film photography.⁵⁹ Beautiful photographs taken using the gelatin silver dry plate process are shown in Figs. 2.46, 2.47, 2.48 and 2.49.⁶⁰ The years following the proposal of the gelatine dry plate method by Maddox, significant innovations reinforced it and unlocked its potential, including the washing of the emulsion to remove the potassium-ammonium nitrate in 1873 by J. Johnson, the heating of the emulsion to increase its sensitivity in 1874 by C.E. Bennett, and the addition of iodides and chlorides to the emulsion in 1874 by King and R. Kennett. In a few more years, in 1878, the English company Wratten and Wainwright, founded in 1877 as a photographic supply firm, begun selling gelatin dry plates. By the 1880s, the company had successfully marketed other dry plates including *London Instantaneous*, *Slow*, and *Ordinary* plates that soon became the industry's benchmark. Maddox earned the appreciation of his colleagues and was awarded the Progress Medal of the Royal Photographic Society in 1901, to be honoured as *the inventor of the gelatine silver bromide dry plates, causing a revolution in photography and its application* (Eder, 1945).

Alexander Parkes (1813–1890) was an English chemist, metallurgist and inventor. He is credited for creating the first man-made plastic, the *parkesine*. Parkes filed 80 patents related to metallurgy, electroplating and plastics, among which was parkesine. Parkesine is the world's first fully synthetic plastic, in particular, *thermoplastic*, a

⁵⁹ As described in the Encyclopædia Britannica's corresponding lemma (<https://www.britannica.com/technology/gelatin-process> (last accessed March 2022)), gelatine is still the standard binding medium for the silver halide crystals used in ordinary photographic film.

⁶⁰ These figures are based on the Public Domain photographs exhibited at the Museum of New Zealand, Te Papa Tongarewa Website, online at <https://collections.tepapa.govt.nz/category/314538> (last accessed March 2022).

Fig. 2.46 *Lake Ada, Milford Sound, NZ, 1883, by William Hart, Museum of New Zealand, Te Papa Tongarewa (C.016824)*



Fig. 2.47 *Pango Pango (sic) Harbour; 'Sauimatani' & Bloomfield, 1884, by Burton Brothers, Museum of New Zealand, Te Papa Tongarewa (C.017669)*



Fig. 2.48 *Humphreys' Boarding House, Te Wairoa, after eruption, 1886, by Burton Brothers, Museum of New Zealand, Te Papa Tongarewa (C.010721)*



Fig. 2.49 *Bruce Bay, NZ, Mount Cook in the distance*, 1876–1886, by William Hart, Museum of New Zealand, Te Papa Tongarewa (C.015604)



celluloid based on nitrocellulose.⁶¹ Parkes first created celluloid as a bulk material for forming objects in 1855 and a year later, in 1856, parkesine was discovered as a solid residue remained after evaporation of the solvent from collodion. Parkesine was showcased in a variety of shapes and colours by Parkes at the 1862 Great International Exhibition,⁶² held at South Kensington, London, for which he was awarded the bronze medal, and also at the Paris Universal Exhibition in 1867, for which he received the silver medal (Mossman, 1994). Due to failures in the production of parkesine, in 1869, Daniel Spill (1832–1887) took over Parkes' firm and renamed parkesine as *xylonite*, while in the same year, John Wesley Hyatt (1837–1920) patented it at the US Patent Office as *celluloid*, the main material for photography and movie films for many decades. Mossman (1994) insists that celluloid was actually invented by Parkes, and Hyatt should be credited for refining and simplifying its production and transform it to a marketable product.

John Carbutt (1832–1905) was an English photography innovator and entrepreneur, who, among other innovations, is known as the first to use celluloid for photographic film and to market dry-plate glass negatives. In 1866, after moving to the United States, he served as the official photographer for the Union Pacific Railroad. He was particularly interested in stereo-photography and produced a number of

⁶¹ *Thermoplastic*, or *thermosoft plastic*, is a plastic polymer material, which when heated softens and becomes pliable or even mouldable, while being solid in normal temperature conditions. *Celluloid* represents a family of materials, which are produced by mixing nitrocellulose and camphor (C₁₀H₁₆O), a source of various common materials and crucial for the development of the photographic film.

⁶² A collection of the 1862 Parkes' parkesine objects can be found at the Website of the Science Museum Group Collection, at [https://collection.sciencemuseumgroup.org.uk/search/objects/makers/alexander%20parkes/date\[from\]/1862/date\[to\]/1862?q=parkesine](https://collection.sciencemuseumgroup.org.uk/search/objects/makers/alexander%20parkes/date[from]/1862/date[to]/1862?q=parkesine) (last accessed March 2022).

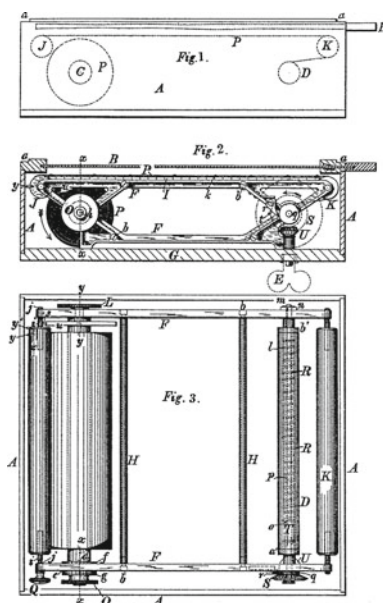


Fig. 2.50 Carbutt's 1866 *Westward, the Monarch Capital Makes Its Way* (top) and *Camp of Pawnee Indians on the Platte Valley* (bottom), in the Library of Congress

stereographs and stereographic cards. Figure 2.50 shows two Carbutt's stereographs from the Library of Congress.⁶³ In 1879, Carbutt founded the *Keystone Dry Plate Works* in Philadelphia with the initial intention to market gelatin dry plates, and became the first to develop sheets of celluloid coated with photographic emulsion, resulting, after years of perfection, into celluloid film, in 1888. The Keystone Dry Plate Works company became the location for significant innovations in photography, including improved glass plate photography, x-ray imaging, the first 35 mm celluloid film, and very early colour photography procedures. Around 1890 Carbutt created

⁶³ This composite figure is based on Public Domain photos retrieved from the Library of Congress, at <https://www.loc.gov/item/2002722872/> (last accessed March 2022) and <https://www.loc.gov/item/2005675917/> (last accessed March 2022) respectively, belonging to the collection *Stereographs made under the auspices of the Union Pacific rail road company on the Excursion to the 100th meridian, October, 1866.*

Fig. 2.51 Schematics of the Eastman roll film holder presented in the U.S. Patent 317,049



a film of 35 mm width for *William Kennedy Dickson's*⁶⁴ *Kinetoscope*,⁶⁵ setting the standard for the 35 mm film. Realising that a major drawback of early celluloid films was its lack of elasticity, around 1889, more flexible celluloid appeared by various companies, such as the Eastman Kodak Company, taking a crucial step forward in the photography and motion pictures technology.

George Eastman (1854–1932) was an American entrepreneur, co-founder of the *Eastman Kodak Company* (simply known as *Kodak*⁶⁶). Eastman was a significant figure in photography with multiple contributions and patents that led the evolution towards mainstreaming handheld camera photography. He helped in the development and marketing of the roll film, also particularly useful for capturing motion pictures. The first practicable roll film patent was issued in 1884 (Eastman, 1884; Eastman and Walker, 1884), followed by a subsequent 1885 patent for a roll film holder (Eastman, 1885), and a 1888 patent, in which Eastman presented the *Kodak camera*, the first camera to utilise the roll film (Eastman, 1888). By the next year, 1889, Eastman marketed film stock, eventually transforming *Kodak* to the leading supplier of film stock internationally by 1896. Schematics of the Eastman roll film holder presented in the U.S. Patent 317,049 are shown in Fig. 2.51, and the schematics of the Eastman

⁶⁴ William Kennedy Dickson (1860–1935) was a Scottish inventor, the creator of the *Kinetoscope*, during his employment by Thomas Edison.

⁶⁵ The *Kinetoscope* was an early motion-picture device with the capability to present motion pictures to a single individual spectator; although not a projection device, it set the basic principles for all cinematic projection.

⁶⁶ It has been suggested that the work *Kodak* has no particular meaning, and Eastman coined it to represent a strong, uncommon, memorable name.

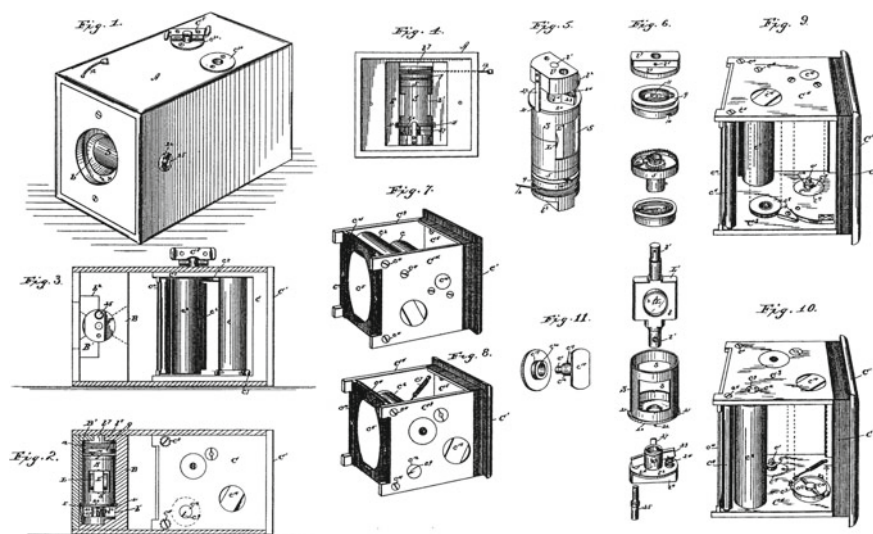


Fig. 2.52 Schematics of the Eastman camera presented in the U.S. Patent 388,850

Kodak camera under the U.S. Patent 388,850 are shown in Fig. 2.52. The Kodak camera eventually became the first of the *box cameras*, a simple and portable type of cameras widely adopted by the public, influencing many manufacturers. The box camera, apart from the benefit of using the roll film, did not necessitate the use of a tripod. Kodak marketed the whole package of a roll film pre-loaded camera along with the processing and printing service, using the slogan *You press the button – we do the rest*, as they offered their customers to return their cameras for processing of the film. Figure 2.53⁶⁷ shows a representative Kodak box camera photograph taken during 1889 in Washington, D.C., which is exhibited online at the Library of Congress. As shown, Kodak camera photographs were round pictures of 2.5 inches in diameter, and were mounted on cards, usually with colourful borders. Likewise, Fig. 2.54⁶⁸ shows another representative Kodak camera photograph, also taken during 1889 in Washington, D.C., and exhibited online at the Library of Congress. Two more such examples of 1889 Kodak camera photographs, part of the collections of the Library of Congress, are shown in Fig. 2.55.⁶⁹

⁶⁷ Painter, U. H., photographer. (1889) *Waffle vendor near U.S. Treasury, Washington, D.C.* [Photograph] Retrieved from the Library of Congress, <https://www.loc.gov/item/2002723170/> (last accessed March 2022).

⁶⁸ Painter, U. H., photographer. (1889) *Franklin Square, Washington, D.C., snow view.* [Photograph] Retrieved from the Library of Congress, <https://www.loc.gov/item/90712663/> (last accessed March 2022).

⁶⁹ Left: Painter, U. H., photographer. (1889) *Two boys on horses at corner of 14th St. and I St. N.W., Washington, D.C. View looking east on I St.* [Photograph] Retrieved from the Library of Congress, <https://www.loc.gov/item/90712665/> (last accessed March 2022). Right: Painter, U. H.,



Fig. 2.53 Waffle vendor near U.S. Treasury, Washington, D.C., 1889 by Uriah Hunt Painter, the Library of Congress

Hermann Wilhelm Vogel (1834–1898) was a German photochemist and photographer who discovered dye sensitisation, which is of great importance in photography. Eder (1945) informs that Vogel was ‘destined’ to be a merchant, and only due to his strong desire to devote himself to science, and a bit of (bad) luck, he was able to change the course of his life, a quite fortunate overturn for photography. His scientific activities were many-sided and prolific, with his most important success being the colour-sensitising of photographic films. The results of his investigations are reported in numerous separate publications, particularly in the *Photographische Mitteilungen*.⁷⁰ His *Handbuch der Photographie* (*Handbook of Photography*) appeared in four Parts and various editions since 1870, *Theil I. Photochemie und Beschreibung der Photographischen Chemicalien* (Part I. Photochemistry and Description of Photographic Chemicals) (Vogel, 1890), *Theil II. Das Licht im Dienste der Photographie und die Neuesten Fortschritte der Photographischen Optik* (Part II.

photographer. (1889) *Market scene, Washington, D.C., snow view*. [Photograph] Retrieved from the Library of Congress, <https://www.loc.gov/item/90712666/> (last accessed March 2022).

⁷⁰ *Photographische Mitteilungen* or *Photographic Communications* was a leading technical journal founded by Vogel in 1864, which he edited until his death. For those interested, the 1868 whole fourth year edition, covering issues 37–48, can be accessed online at https://archive.org/details/bub_gb_SnRKAAYAAJ (last accessed March 2022).



Fig. 2.54 Franklin Square, Washington, D.C., snow view, 1889 by Uriah Hunt Painter, the Library of Congress

Light in the service of photography and the latest advances in photographic optics) (Vogel, 1894), *Theil III. Die Photographische Praxis* (Part III. *The photographic practice*), (Vogel, 1897), and *Theil IV. Photographische Kunstlehre* (Part IV. *Photographic art theory*) (Vogel, 1891). Many of his articles were translated into foreign languages, like the 1871 English edition (translation and adaptation) of the *Handbuch* titled *Handbook of the Practice and Art of Photography* (Vogel, 1871), and the 1875 English translation of *Die Chemischen Wirkungen des Lichts und die Photographie* titled *The Chemistry of Light and Photography* (Vogel, 1875a). Vogel (1871) in the *Introduction* of the *Handbook* begins by expressing his excitement about the scientific and technological developments of that era, and particularly about the invention and fast development of photography.

A careful study of the history of invention will show but few periods as rich in new ideas and facts as the past hundred years. With the rise of the explaining natural sciences—chemistry and natural philosophy—commenced a new era by applying the discoveries to actual life and industrial pursuits. Thus originated the steam engine gas sulphuric acid the manufacture of soda, beet—root sugar the manufacture of ultramarine not to mention numerous other things in which the physical or chemical action of heat was used in a new form. In an analogous manner we see another of the natural forces, formerly unused, enter as an active agent into our industry,—electricity. Weber created the electro-magnetic telegraph; Jacoby the galvanoplastic process.



Fig. 2.55 *Two boys on horses at corner of 14th St. and I St. N.W., Washington, D.C. View looking east on I St. (left) and Market scene, Washington, D.C., snow view (right), 1889 by Uriah Hunt Painter, the Library of Congress*

Finally, the present age brought forth an art in which the chemical action of light is the principal agent. This art is Photography. It has existed only twenty-five years, and still we may say that no invention of this century has since its first appearance experienced such a gigantic development and exercised so powerful an influence on our social, artistic, and scientific relations as this one.

The *Introduction* of the *Handbook* is certainly a valuable source for the photographic developments of that period. The *Handbook* covered all the topics relating to photography, ranging from the science and technology to the practical aspects, the best practices, the art and aesthetics. Vogel recognised that silver iodide formed with an excess of potassium, which is almost completely insensitive, becomes light-sensitive with *tannin* ($C_{76}H_{52}O_{46}$), *gallic acid* ($C_7H_6O_5$), or *ferrous sulphate* ($FeSO_4$), and that the action of these *chemical sensitisers* for halide combinations of silver salts (silver iodide, bromide, chloride) is due to their ability to combine iodine, bromine, or chlorine. During the period before Vogel's contribution, most of the photographic processes resulted in light-sensitive chemical highly reactive in short wavelengths (blue light); as a matter of fact, green, yellow and red light acted little or not at all in the process. Due to this fact, the most successful techniques, like the daguerreotype, the dry collodion process, and the gelatine silver bromide process, were, somewhat, colour blind, requiring post-processing, for example to attain a colour-correct reproduction of paintings. Vogel successfully remedied this defect in 1873 by discovering colour sensitisation with the so-called *optical sensitisers* (later, *colour sensitisers*). At that time, research focused on finding a solution for the problem of halation

in collodion plates, and gallic acid, *uranium nitrate* ($\text{UO}_2(\text{NO}_3)_2$), and *corallin* (yellowish-red dye) were being added to the plates, resulting in significantly reduced halation. Vogel observed in 1873 that those plates were significantly more sensitive to the green part of the spectrum, which was unknown until then. His insight led him to experiment with other dyes, for which he observed similar effects to other parts of the spectrum, like corallin sensitising silver bromide collodion into the yellow and green, or green aniline sensitising silver bromide collodion into the red. This discovery was largely influential both for the correct toning of black and white photographs, but also for the meaningful developments in *three-colour photography* that emerged during that period (Eder, 1945). In *Ueber die chemische Wirkung des Sonnenlichtes auf Silberhaloidsalze* (*On the chemical action of sunlight on silver halide salts*) (Vogel, 1875b), Vogel summarised some of his important findings.

- (1) Chlorsilber, Bromsilber und Jodsilber sind nicht blos für die stark brechbaren, sondern auch für die schwach brechbaren Strahlen des Sonnenspectrums empfindlich, für die letzteren jedoch in erheblich geringerem Grade.
- (2) Die Empfindlichkeit der Silberhaloidsalze für verschiedene Spectralfarben hängt nicht allein ab von ihrer optischen Absorptionsfähigkeit für die betreffenden Strahlen, sondern auch von der optischen Absorptionsfähigkeit beigemischter Körper.
- (3) Farbige Körper, die den photographischen Reductionsprozess befördern und gewisse Spectralfarben absorbiren, steigern, in geeigneter Weise angewendet, die Empfindlichkeit des Silbersalzes für die absorbirten Strahlen in erheblichem Grade. Dadurch ist man im Stande, die Empfindlichkeit der Silbersalze für rothe, gelbe und grüne Strahlen sehr bedeutend zu erhöhen.
- (4) Mischungen verschiedener Farbstoffe wirken wie ihre Einzelbestandtheile zusammen.

In summary, silver halide salts are sensitive to all rays, although considerably less to the weakly refracted (green, yellow, red) and this sensitivity depends also on the optical absorptivity of admixed bodies. Thus, it is possible to significantly increase the sensitivity of the silver salts to red, yellow, and green rays by mixing selected dyes, which act additively, each individual dye enhancing a particular spectrum sensitivity. Vogel, along with the publication of his discovery in 1873, he exhibited his first spectrum photographs on colour-sensitised plates, and further confirmed his results in 1874 by making comparative exposures with his small spectrograph. Vogel's experimental verification of dye sensitisation was demonstrated in his spectrum photographs, as shown in Fig. 2.56, found in Eder (1932). In 1864 he invented his test for silver, a titration (volumetric analysis) with *iodide of potassium* solution (KI) and *starch paste* ($(\text{C}_6\text{H}_{10}\text{O}_5)_n$) as indicator. In 1863 he founded the Photographic Society, in Berlin, from which started the Society for the Promotion of Photography in 1869, the German Society of Friends of Photography in 1887, and the Free Photographic Union in 1889, exhibiting active but also 'vivid' participation. He received many honours, among them, in 1894, the gold medal of the Vienna Photographic Society (Eder, 1945).

James Clerk Maxwell (1831–1879) the renowned Scottish mathematician and scientist that has already been referenced in the previous chapter for his contribution to the theory of light and colour, is also related to the history of photography, although in an indirect way. As presented earlier, Maxwell's work was crucial for the formation

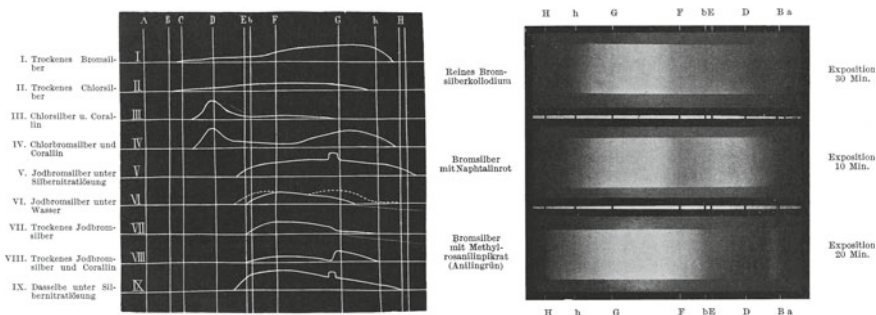


Fig. 2.56 Vogel's experimental verification of dye sensitisation

of what is accepted today as the Young-Helmholtz-Maxwell three-primary colour theory (or trichromacy). This theory suggests that any three independent colours may serve as the basis for the representation of any other perceivable colour. Following this line of reasoning, as early as 1855, Maxwell (1857) proposed that three photographs with filters may be combined or superimposed to project a full colour image.

This theory of colour may be illustrated by a supposed case taken from the art of photography. Let it be required to ascertain the colours of a landscape, by means of impressions taken on a preparation equally sensitive to rays of every colour.

Let a plate of red glass be placed before the camera, and an impression taken. The positive of this will be transparent wherever the red light has been abundant in the landscape, and opaque where it has been wanting. Let it now be put in a magic lantern, along with the red glass, and a red picture will be thrown on the screen.

Let this operation be repeated with a green and a violet glass, and, by means of three magic lanterns, let the three images be superimposed on the screen. The colour of any point on the screen will then depend on that of the corresponding point of the landscape; and, by properly adjusting the intensities of the lights, &c., a complete copy of the landscape, as far as visible colour is concerned, will be thrown on the screen. The only apparent difference will be, that the copy will be more subdued, or less pure in tint, than the original. Here, however, we have the process performed twice first on the screen, and then on the retina.

Maxwell (1856) presented an experiment using three-colour photography to support his theory of three primary colours in a Lecture at the Royal Institution of Great Britain, May 17, 1861, titled *On the Theory of Three Primary Colours*, in which he is quoted saying:

Three photographs of a coloured ribbon taken through the three coloured solutions respectively, were introduced into the camera, giving images representing the red, the green, and the blue parts separately, as they would be seen by each of Young's three sets of nerves separately. When these were superposed, a coloured image was seen, which, if the red and green images had been as fully photographed as the blue, would have been a truly-coloured image of the ribbon. By finding photographic materials more sensitive to the less refrangible rays, the representation of the colours of objects might be greatly improved.

Maxwell collaborated with the established photographer Thomas Sutton to acquire these photos. Sutton photographed a tartan ribbon three times, through red, green,



Fig. 2.57 Reconstruction of the famous tartan ribbon colour photograph

and blue filters, also making a fourth photograph through a yellow filter, which, according to Maxwell's account, was not used in the demonstration. The photos were printed on glass so that projection would be relevant using the same filters used in capturing the photographs. Apparently, although the relevant bibliography credits Maxwell and Sutton for the very first permanent colour photograph, this is not totally correct; Maxwell presented the concept and with the help of Sutton they presented the proof of the concept, which resulted in three monochrome glass photographs. As pointed out by artist and photographer Paul Elter in an article title *Maxwell's first colour photograph...?*,⁷¹ Maxwell should be credited for *the first attempt at tri-colour separation* and not *the first colour photograph*. A digital reconstruction of the famous tartan ribbon colour photograph is shown in Fig. 2.57.⁷²

Thomas Sutton (1819–1875) was an accomplished English photographer, distinguished also by his numerous publications in technical journals. He owned a photographic studio and a photographic print company for calotype negatives, in Jersey, around 1855. With his business partner *Louis Désiré Blanquart-Evrard* (1802–1872), he founded the journal *Photographic Notes*, and authored a number of books on photography, including the 1858 *Dictionary of Photography* (Sutton, 1858). As an author, he wrote, probably, the first photographic novel, in 1865 (Eder, 1945). In 1859, Sut-

⁷¹ Paul Elter's article can be accessed online at <http://www.elter.ca/alizarin/2021/12/7/maxwells-first-colour-photograph-part-one> (last accessed March 2022).

⁷² Creation of this composite image was based on the following process: (a) the three channel images were downloaded from Paul Elter's article at <http://www.elter.ca/alizarin/2021/12/7/ebkt9istvpqp3bnh3k3sn5q1178wvvg> (last accessed March 2022); (b) the channel images, which are actually colour images, were converted to the HSV colour space representation, and the third channel-V was only selected, as this channel represents the brightness in the images; (c) the three channels were combined to create a new colour image.



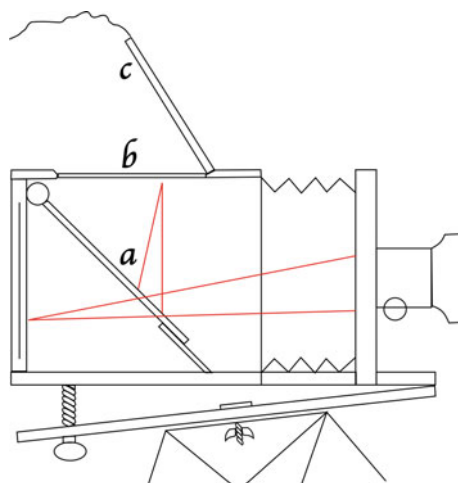
Fig. 2.58 Sutton's Panoramic Camera, London, c. 1861, photo by Rodney Start, Museums Victoria Collections

ton developed the earliest *panoramic camera*, using his patented wide-angle lens (initially of 120°), which was a spherical lens filled with distilled clear water; the lens projected images onto a curved plate at the back of the camera. The photographic plate was dipped in emulsion in the special compartment, and the photograph was taken while the plate was still wet. Figure 2.58 shows Thomas Sutton's invention manufactured by the Ross Optical Company, c. 1861.⁷³ In 1861, Sutton created and patented the first *Single Lens Reflex* (SLR) camera,⁷⁴ in which he used glass plates. Initially designed for portraiture, the SLR camera was based on a box body, used a bellows focusing system, and a mirror placed at an angle of 45° to control the direction of the image produced by the lens. The mirror could swing up to uncover the plate for the exposure, covering the viewing screen on top. Figure 2.59 a diagram of the first SLR camera, designed in 1861 by Sutton, based on the figure provided in Coe (1978). A mirror (a) reflects the image onto a ground-glass screen (b), set in the top of the camera and screened by a hood (c). The mirror swings up to cover the screen during exposure of the plate, which is placed in the back of the camera. Last but not least, James Clerk Maxwell collaborated with Sutton in producing Maxwell's 1861 demonstration of trichromacy through photography, as explained in a previous paragraph.

⁷³ Museums Victoria Collections, <https://collections.museums victoria.com.au/items/407437> (last accessed March 2022).

⁷⁴ *Single lens* for using just one and the same lens for focusing, composition and exposure, and *reflex* (from reflection) for using a mirror to reflect the incoming light to the viewfinder during composition.

Fig. 2.59 Sutton's design of the single lens reflex camera



Louis Arthur Ducos du Hauron (1837–1920) was a French pioneer, to whom great credit is given for the invention of the progress of three-colour printing and the successfully application of Vogel's colour sensitisation into photographic practice. By the age of 22, du Hauron was involved with photography, and particularly an early type of cinematography, which he patented in 1864. He soon realised the importance of the three-colour process and proposed a patent (French Patent No. 83,061) for a new process in 1868, which was based on three photographs produced based on collodion plates and coloured filters, but was only partly successful, as the method required colour sensitised plates, yet to be invented. He applied the three-colour principles using both additive and subtractive methods for photography and printing respectively. Du Hauron adopted Vogel's invention of colour sensitisation and dyed his plates accordingly around 1875 and significantly improved the results (Eder, 1945). Plainly, du Hauron's concept for colour photography, *heliography*,⁷⁵ was based on the superimposition of three photographs, taken using blue, yellow, and red filters; these three diapositives in the primary colours, if combined in a peep box, gave rise to the polychrome effect. He published his method under the title *Les Couleurs en photographie: solution du problème* (*Colours in photography: solution of the problem*) (du Hauron, 1869). Using du Hauron's words from that treatise,

Le problème, formulé de la sorte, semble tout d'abord formidable de complication. Malgré sa complexité très-réelle, il peut cependant se ramener à des termes moins décourageants, et voici comment je m'en suis rendu maître:

J'ai appelé à mon aide un principe de physique fort connu. Ce principe est celui en vertu duquel les couleurs simples se réduisent à trois, le rouge, le jaune et le bleu, dont les combinaisons en diverses proportions produisent l'infinie variété des nuances de la nature.

Partant de cette donnée, je me suis dit:

«Si je décompose en trois tableaux distincts, l'un rouge, l'autre jaune, l'autre bleu, le tableau en apparence unique, mais triple en réalité quant à la couleur, qui nous est offert par la

⁷⁵ Based on the Greek *ἥλιος* for helios, the sun and *χρώμα* for chroma, the colour.

nature, et si de chacun de ces trois tableaux j'obtiens une image photographique séparée qui en reproduise la couleur spéciale, il me suffira de confondre ensuite en une seule image les trois images ainsi obtenues pour jouir de la représentation exacte de la nature, couleur et modelé tout ensemble».

Eder (1945) translated du Hauron's words on his 1869 patent (No. 83,061) specification as follows.

We imagine the whole surface of a piece of paper covered alternately with extremely fine lines of red, yellow, and blue of equal size, with no space between them; when viewed at close range the three-colour system of the lines can be distinguished, but seen from a distance they merge into a single colour tone, which, when viewed by looking through a transparent medium, will appear white, but when viewed on an opaque background will show grey if none of the three colours predominates.

This is no other than the principle for all successful technologies for display and printing. Du Hauron also invented a three-colour camera, in which the three-colour separations could be made simultaneously by a single exposure behind complementary light filters. He was granted a French patent in 1874 (No. 105,881) for a *camera heliochromatique* or a *photographic apparatus for the purpose of taking at one time three pictures from one and the same object* (Eder, 1945). One of the most recognisable du Hauron's colour photographs is the 1877 *View of Agen*, a landscape photograph in southern France, which was printed using the subtractive method, and is shown in Fig. 2.60.⁷⁶ Du Hauron authored a series of publications on this subject, some co-authored with his brother Alcide, including *L'héliochromie (Heliochromy)* (du Hauron, 1874), *Traité pratique de photographie des couleurs: système d'héliochromie Louis Ducos du Hauron (Practical treatise on colour photography: heliochromy system Louis Ducos du Hauron)* (du Hauron and du Hauron, 1878), *Les couleurs en photographie et en particulier l'héliochromie au charbon (Colours in photography and in particular carbon heliochromy)* (du Hauron, 1870), *La triplique photographique des couleurs et l'imprimerie (The photographic triplique of colours and printing)* (du Hauron, 1897).

Émile-Hortensius-Charles Cros (1842–1888) was a French well-known poet, writer, and inventor. Eder (1945) recognised him as an 'ingenious man', as he was interested in and proposed various technological innovations, like the transmission technology for the telegraph, the reproduction of recorded sound, colour photography, even extraterrestrial communications. Cros studied medicine and philology. He was a member of the *College Libre de Medicine* in Paris and worked on the invention of an autographic telegraph instrument in 1867, a phonograph named the *paléophone*⁷⁷ in 1879, a means of communication among planets by optical telegraphy in 1869, and also a medical work on the mechanics of the brain in 1880 (Eder,

⁷⁶ This figure is an adaptation of the Public Domain Wikipedia photograph published online at <https://en.wikipedia.org/wiki/File:Duhauron1877.jpg> (last accessed March 2022).

⁷⁷ Several sources refer to this invention, which appears to have been filed for a patent concurrently with Edison's *phonograph*. Cros, unlike Edison, did not complement his idea with drawings or a prototype, and never really implemented it. Initially he did not even have a name for the invention, which he eventually named the *paléophone*, from the Greek παλαιός- paleo- (old, ancient) and -φωνη -phon (voice).



Fig. 2.60 Du Hauron's 1877 *View of Agen* three-colour photograph

1945). In 1869 he published his concept of three-colour negative photography. His proposal was to use the typical negative photography through green, violet, and orange glass filters, which would subsequently be transformed into red, yellow, and blue positives. The three positive impressions, superimposed on gelatin using sufficiently transparent pigments, and transferred onto a single support sheet, would recompose the original colours of the photographed scene. Apparently, Cros used the subtractive colour approach. It is interesting that Cros and du Hauron presented their three-colour photography approaches at the exact same day, May 7, 1869, to the French Society of Photography, although each of them totally unaware of the other's research (Eder, 1945). Also interesting is the fact that Cros conceded the invention to du Hauron, despite having sent a sealed paper at the French Academy of Sciences on December 2, 1867, whereas du Hauron patented his method on November 28, 1868, although claiming to have written an unpublished paper on the subject in 1862 (Eder, 1945).⁷⁸ Cros published his method under the title *Solution générale du problème de la photographie des couleurs* (*General solution to the problem of colour photography*) as an article in the French journal *Les Mondes* on February, 25, 1869, which also appeared as a pamphlet (Cros, 1869). Cros clearly accepted

⁷⁸ Eder (1945) also informs about the story behind those developments. Cros' 1867 letter to the Academy of sciences contained a report of his experiments, but provided no details of the process, which Cros kept as a secret. He was, eventually, 'forced' to disclose the details after du Hauron patented his process in 1868 and published his first articles on the subject in the beginning of 1869.

a red-yellow-blue colour basis and expressed the classic mixing approach by using three greyscale photographs that correspond to the brightness of the three primary colours.

Les trois espèces élémentaires de la couleur sont: le rouge, le jaune, le bleu. Il s'agit donc de prendre trois épreuves différentes, l'une de tous les points plus ou moins rouges ou qui contiennent du rouge, la seconde de tous les points jaunes ou contenant une proportion de jaune, la dernière de tous les points bleus ou contenant du bleu. Ces trois épreuves, en les supposant obtenues en teintes uniformes comme celles de la photographie ordinaire, exprimeront en noirs et en gris, plus ou moins foncés, les quantités respectives de rouge, de jaune, de bleu qu'il y a dans tous les points du tableau.

In his description, Cros presented his method as an analysis and synthesis approach, *analysis* being the decomposition of the colour scene into three monochrome representations, and *synthesis* being the recombination and mixing of the three representations into a single full colour result. For the analysis, he proposed three methods for acquiring the three photographs needed, (a) by employing coloured liquids as typical light filters, (b) by using rotating prisms as colour selecting mechanisms in the camera, and (c) by using special monochromatic lighting on the scene. For the synthesis he proposed (a) the successive and (b) the simultaneous synthesis, which is subdivided into three types, (i) synthesis by reflection, (ii) synthesis by refraction, and (iii) synthesis by transparency, by means of antichromatic positives. The later approach, is the typical superposition of the three positives on white or transparent surfaces. According to Eder (1945), Cros constructed a camera for three-colour photography, and he is also credited for the invention of *hydrotypes*.⁷⁹

Jonas Ferdinand Gabriel Lippmann (1845–1921) was a Franco-Luxembourgish physicist and inventor, who developed an entirely different method of permanent colour photography, for which he was awarded the 1908 Nobel in physics. The Nobel price was awarded *for his method of reproducing colours photographically based on the phenomenon of interference*.⁸⁰ Although Lippmann's *interference photography* soon disappeared from photographic practice, it still remains a culminating point of scientific solutions to the problem of permanent colour photography by direct exposure in the camera (Eder, 1945). Lippmann's work focused particularly on the field of electricity, thermodynamics and optical phenomena. He presented his interference photography method to the Paris Academy of Sciences in 1891, showing his first experiments that were carried on with silver bromide albumen plates sensitised for colour with *cyanine* ($C_{29}H_{35}IN_2$). Description of the method by Lippmann himself, at his Nobel Lecture is as follows.⁸¹

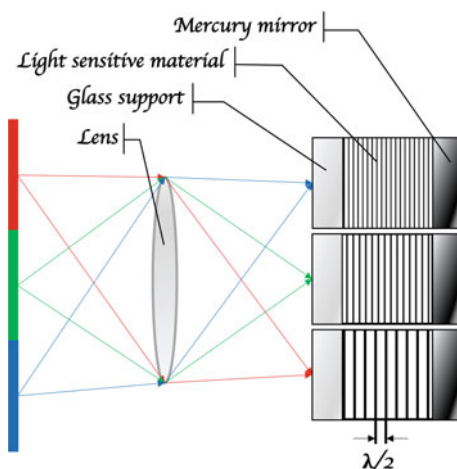
A plate is covered with a sensitive transparent layer that is even and grainless. This is placed in a holder containing mercury. During the take, the mercury touches the sensitive layer and

⁷⁹ Cros coated a glass plate with bichromated gelatine, exposed under a glass diapositive, washed with water, and soaked the coating with suitable dye solutions, which were absorbed only in the non-exposed parts, thus he obtained diapositives in colour, which he called *hydrotypes* (Eder, 1945).

⁸⁰ The Nobel Prize in Physics 1908, <https://www.nobelprize.org/prizes/physics/1908/summary/> (last accessed March 2022).

⁸¹ Gabriel Lippmann, December 14, 1908, Nobel Lecture, available online at <https://www.nobelprize.org/prizes/physics/1908/lippmann/lecture/> (last accessed March 2022).

Fig. 2.61 Principle of Lippmann's interference colour photography



forms a mirror....During exposure, interference takes place between the incident rays and those reflected by the mirror, with the formation of interference fringes half a wavelength distant from each other. The fringes imprint photographically through the whole thickness of the film and form a casting for the light rays. When the shot is afterwards subjected to white light, colour appears because of selective reflection. The plate at each point only sends back to the eye the simple colour imprinted. The other colours are destroyed by interference. The eye thus perceives at each point the constituent colour of the image.

The principle of operation of Lippmann's interference colour photography is shown in Fig. 2.61. As each different colour corresponds to a different wavelength, the interference patterns that form in the sensitive layer is also different, following the $\lambda/2$ rule. Berget (1891) as well as Eder (1945) and Ranson et al. (2008) provide specifics of the principle and the method, including the details for the chemical form of the sensitive layer based on albumen film containing potassium bromide, sensitised in a silver bath, then washed, then flowed with cyanine solution, and dried, before coming to contact with the reflecting layer. After exposure, a latent image is developed, and after fixation with potassium cyanide solution and drying, a colourful picture appears when viewed in reflected light (Eder, 1945). Apparently, although quite impressive and ingenious, interference colour photography has limited practical value due to the difficulty in creating the emulsion, the need for long exposures, the good reproduction only of spectral colours, the inability to create prints and the particular conditions for viewing the photographs. In a way, Lippmann's method is more connected with *holography* than any other type of photography. Using modern terminology, the Lippmann process amounts to a *double Fourier transformation*. During exposure, what is imprinted is the Fourier transform of the spectrum of the light, in the intensity profile of the interference. During viewing, another Fourier transform restores the initial light composition (Ranson, 2008). Pushing the limits even further, Lippmann, in 1908, presented an idea for the production of composite photographs using an array of micro-lenses, imitating insects' eyes. To view these

images, one needs a similar array of lenses. The image appears three-dimensional with a shift in the perspective when changing the viewing position. Lippmann called this method *photographie integrale* (*integral photography*) (Eder, 1945). At that time, it was impossible for Lippmann to provide results, and many years passed before anyone could put it to actual use. The principle of using numerous lenses was later termed *light field photography*⁸² and Lippmann's method was the foundation of three-dimensional, colour, and animated *lenticular* processes.⁸³

Auguste Marie Louis Nicolas Lumière (1862–1954) and *Louis Jean Lumière* (1864–1948), also known as the *Lumière brothers*, were French manufacturers of photography equipment, best known for their two major contributions in photography and cinematography, with their invention of the *autochrome* and the *cinématographe* motion picture system respectively. As Antoine Lumière's sons, they were well acquainted with photography, since Antoine Lumière owned a firm that manufactured dry plates, for which (Eder, 1945) reported a production of sixty dozen plates per day. The brothers grew the company considerably, and made a significant breakthrough in photochemical practice, in 1907, through the invention of *autochrome* plates. At first, the Lumière brothers were interested in developing a motion picture system that would not suffer from the drawbacks of Edison's kinetograph (and kinoscope), including the need for electrical supply, the capacity for a single viewer at a time, the blurry and dark images, and the heavy equipment. They patented their *cinématographe* in 1895 and started producing and displaying films the same year. Around 1905 they decided to give up cinematography and film business, and focused on colour photography, which they started researching in the early 1890s. They worked on processes like Lippmann's interference heliochromy, and their own bichromated glue process. In 1903 they patented their colour photographic process, the *Autochrome Lumière*, but unveiled the process at the French Académie des Sciences a year later. This was their first real and lasting commercial success, which came after a long period of developments to overcome the challenges of large scale autochrome plates production, eventually launching on the market in 1907 (Lavédrine & Gandolfo, 2013). The autochrome plates carry mixed red, green, and blue potato starch grains on a glass plate, on which a thin film of panchromatic gelatine emulsion is applied. The exposure takes place through the glass and the colour grain base. After seeing autochromes, the eminent photographer Alfred Stieglitz (1864–1946) is quoted saying⁸⁴:

The possibilities of the process seem to be unlimited and soon the world will be colour-mad, and Lumière will be responsible.

An autochrome is the very first single colour photograph, the result of an additive colour process, a positive transparency on a glass support. The glass plate is var-

⁸² Light field cameras (or plenoptic cameras), are devices that capture not only the intensity of light, like ordinary cameras, but also the direction that the light rays are travelling in space.

⁸³ Lenticular printing is a process that uses lenticular lenses, arrays of lenses, meant to be viewed from slightly different angles, to produce the effect of parallax or motion.

⁸⁴ The source of the text is the National Science and Media Museum 2009 article *History of the Autochrome: the Dawn of Colour Photography*, online at <https://blog.scienceandmediamuseum.org.uk/autochromes-the-dawn-of-colour-photography/> (last accessed March 2022).

nished and covered with equal portions of the three coloured starches as evenly as possible, and then further covered with black carbon particles to fill in any gaps among the grains of starch. The plate is subjected to pressure from a rolling machine before getting a second coat of varnish, dried, and made light sensitive with a coating of silver gelatin bromide emulsion. The plate is placed in a camera in such a way that the starch layer acts like a composite colour filter. The plate is then developed to result in a positive photograph (Collection, 2022). A micro-photograph of an autochrome plate is shown in Fig. 2.62, revealing the three-coloured potato starch grains, forming a random mosaic of microscopic grains that act as micro-filters of light in microscopic regions. Autochrome plates were manufactured and marketed until 1935. Figures 2.63, 2.64, 2.65, 2.66, 2.67, 2.68, 2.69 and 2.70 present some representative early photographs made with the autochrome plates process; Fig. 2.63 is a composition of Alfred Stieglitz's 1907 *Kitty Stieglitz*⁸⁵ with Constantin Mitrofanovitch Flórin'sky's 1907 *Officer of His Majesty Tzar Nicholas II*⁸⁶; Fig. 2.64 shows Flórin'sky's 1907 *Olga Victorovna Dmitrieff*⁸⁷; Fig. 2.65 shows Flórin'sky's 1907 *Temple of Amour*⁸⁸; Fig. 2.66 shows John Jäderström's 1909 *Inez och Iwan Jäderström vid Gammeludden (södra Stäket)*,⁸⁹ whereas Fig. 2.67 shows Jäderström's 1911 *Solnedgång vid Riddarfjärden Stockholm*,⁹⁰ and Fig. 2.68 shows Jäderström's 1912 *Familjen J.W Andreen*.⁹¹ Figure 2.69 shows the famous dreamy photograph by Mervyn O'Gorman in 1913, *Christina in red cloak*,⁹² and Fig. 2.70 shows another famous O'Gorman's photograph, *Christina on the beach*,⁹³ both of which attracted a lot of media attention and publicity, particularly due to the riddle of the real identity of Christina.⁹⁴

⁸⁵ Based on the Public Domain photograph exhibited online at <http://www.getty.edu/art/collection/objects/62792/alfred-stieglitz-kitty-stieglitz-american-1907/> (last accessed March 2022).

⁸⁶ Based on the Public Domain photograph exhibited online at <https://www.metmuseum.org/art/collection/search/270349> (last accessed March 2022).

⁸⁷ Based on the Public Domain photograph exhibited online at <https://www.metmuseum.org/art/collection/search/270350> (last accessed March 2022).

⁸⁸ Based on the Public Domain photograph exhibited online at <https://www.metmuseum.org/art/collection/search/270348> (last accessed March 2022).

⁸⁹ Based on the Public Domain photograph exhibited online at <https://digitaltmuseum.se/021016633463/> (last accessed March 2022).

⁹⁰ Based on the Public Domain photograph exhibited online at <https://digitaltmuseum.se/021016633324> (last accessed March 2022).

⁹¹ Based on the Public Domain photograph exhibited online at <https://digitaltmuseum.se/021016633584> (last accessed March 2022).

⁹² Based on the Public Domain photograph, online at <https://picryl.com/media/mervyn-ogorman-color-photography-454211> (last accessed March 2022).

⁹³ Based on the Public Domain photograph, online at <https://picryl.com/media/mervyn-ogorman-color-photography-c0bfed> (last accessed March 2022).

⁹⁴ See for example the article about Christina at <https://blog.scienceandmediamuseum.org.uk/christina-mervyn-o-gorman-1913-photograph-girl-in-red/> (last accessed March 2022) and at <https://www.dailymail.co.uk/femail/article-3066019/Who-lady-red-Mystery-young-woman-cascading-blonde-hair-earliest-colour-photos.html> (last accessed March 2022).

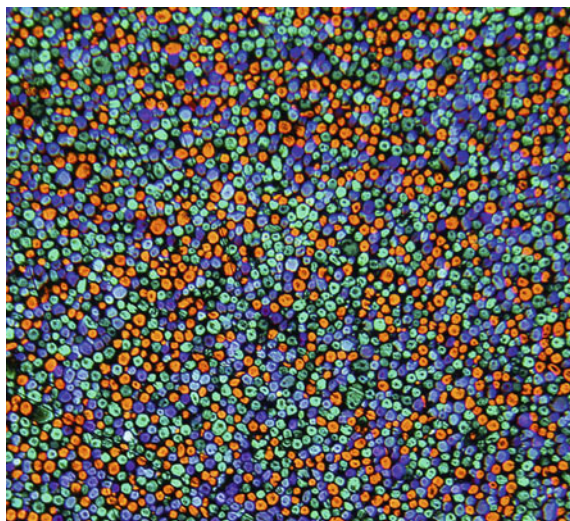


Fig. 2.62 Micro-photograph of an autochrome plate revealing the three-coloured potato starch grains



Fig. 2.63 Alfred Stieglitz, 1907, *Kitty Stieglitz*, The J. Paul Getty Museum, left; Constantin Mitrofanovitch Flórinisky, 1907, *Officer of His Majesty Tzar Nicholas II (Jaeger Regiment)*, The Metropolitan Museum of Art, right

Fig. 2.64 Constantin Mitrofanovitch Flórinsky, 1907, *Olga Victorovna Dmitrieff*, The Metropolitan Museum of Art



Fig. 2.65 Constantin Mitrofanovitch Flórinsky, 1907, *Temple of Amour*, The Metropolitan Museum of Art



Fig. 2.66 John Jäderström, 1909, *Inez och Iwan Jäderström vid Gammeludden (södra Stäket)*, DigitaltMuseum



Fig. 2.67 John Jäderström, 1911, *Solnedgång vid Riddarfjärden Stockholm*, DigitaltMuseum



Fig. 2.68 John Jäderström, 1912, *Familjen J.W Andreen*, DigitaltMuseum



Fig. 2.69 Mervyn O'Gorman, 1913, *Christina in red cloak*, PICRYL



Fig. 2.70 Mervyn O’Gorman, 1913, *Christina on the beach*, PICRYL



Sergei Mikhailovich Prokudin-Gorskii, or *Sergey Mikhaylovich Prokudin-Gorsky* or *Gorskii* (Сергей Михайлович Прокудин-Горский, 1863–1944) was a chemist, photographer and artist in the Russian Empire, who has left an important legacy through his pioneering work in colour photography, with which he was able to document the Imperial Russia prior to World War I (Allshouse, 1980; Library of Congress, 2001). Gorskii studied arts and science in Russia and then Germany and France, where he was largely exposed to the chemistry of colour photography. He seems to have been influenced and inspired in scientific pursuits by his teacher, the world-known chemist *Dmitri Ivanovich Mendeleev* (1834–1907), the creator of the periodic table of elements. Upon his return to Russia, he became member of the Russian Imperial Technological Society and developed courses to teach colour photography, as he was convinced of the educational value of this form of presentation. At the beginning of the 20th century, Gorskii begun working on the development of new colour sensitive photographic plates, and presented his first results in 1905 (Allshouse, 1980). His approach was the three-colour photography, using three exposures taken sequentially about one second apart. The result was to imprint three monochromatic greyscale negatives using filters to block selected parts of the spectrum. As the three photographs were not exposed concurrently, only fixed (or at least non-moving) subjects could be captured successfully. Viewing the actual colour photograph involved the projection of the three monochromatic plates, registered so that they form a single image. Figure 2.71 shows the most famous of Gorskii’s photographs, the 1908 *Leo N. Tolstoi in Iasnaia Poliana*.⁹⁵ Gorskii showcased his photographs and his vision to use them in education (to the glory of Russia) to Tsar Nicholas II, in 1909, and was able to get the permission and means for a large-scale trip around Russia, using a specially modified coach, fully equipped for photography (including a dark room).

⁹⁵ Based on the Public Domain colour photograph found in the Library of Congress, at <https://www.loc.gov/pictures/resource/ds.02147/> (last accessed March 2022), as part of record 2012647142 <https://www.loc.gov/pictures/item/2012647142/> (last accessed March 2022).

The majority of the photographs taken in that expedition, which took place between 1909 and 1915, are now exhibited, in monochrome positives and colour composites, in the U.S. Library of Congress.⁹⁶ Figures 2.72, 2.73, 2.74, 2.75, 2.76 and 2.77 show selected Sergei Gorskii's works from the period 1909–1911; these figures present the original three negative glass plates in positive form, along with the corresponding colour-uncorrected reconstruction, after the application of deformable image registration to align the three colour channels, which were of the exact same scene due to Gorskii's sequential photography. Figure 2.72 shows Gorskii's 1909 *Krest i a nsk i a di e vushki* (Peasant girls).⁹⁷ Figure 2.73 shows Gorskii's c.1910 *Trans-Siberian Railway metal truss bridge on stone piers, over the Kama River near Perm, Ural Mountains Region*.⁹⁸ Figure 2.74 shows Gorskii's 1910 *Formovka khudozhestvennago lit i a* (Moulding of an artistic casting).⁹⁹ Figure 2.75 shows Gorskii's 1910 *Spaso-Preobrazhenskii sobor i Vkhodoierusalimskaia tserkov'v Torzhke* (Cathedral of the Transfigured Saviour and the Church of the Entry into Jerusalem in Torzhok).¹⁰⁰ Figure 2.76 shows Gorskii's 1911 *V Borodinskom muzei e, Borodino* (In the Borodino Museum, Borodino).¹⁰¹ Figure 2.77 shows Gorskii's 1911 *mir Bukharsk, Bukhara* (Emir of Bukhara, Bukhara).¹⁰²

The years following the era of the frantic photographic developments of the 19th century, came the era of the optimisations and improvements, many of which are due to major players, like Kodak. Around 1909, Kodak replaced the highly flammable nitrate base of films with a safer acetate base. Between 1912 and 1926, Kodak

⁹⁶ Gorskii's photographs in the U.S. Library of Congress can be accessed online at <https://bit.ly/34x2VeL> (last accessed March 2022).

⁹⁷ Digital colour composite from the three registered Public Domain monochrome originals found in the Library of Congress, at <https://www.loc.gov/pictures/resource/prok.01043/> (last accessed March 2022), as part of record 2018678943 <https://www.loc.gov/pictures/item/2018678943/> (last accessed March 2022).

⁹⁸ Digital colour composite from the three registered Public Domain monochrome originals found in the Library of Congress, at <https://www.loc.gov/pictures/resource/prok.00023/> (last accessed March 2022), as part of record 2018681190 <https://www.loc.gov/pictures/item/2018681190/> (last accessed March 2022).

⁹⁹ Digital colour composite from the three registered Public Domain monochrome originals found in the Library of Congress, at <https://www.loc.gov/pictures/resource/prok.00507/> (last accessed March 2022), as part of record 2018679475 <https://www.loc.gov/pictures/item/2018679475/> (last accessed March 2022).

¹⁰⁰ Digital colour composite from the three registered Public Domain monochrome originals found in the Library of Congress, at <https://www.loc.gov/pictures/resource/prok.01167/> (last accessed March 2022), as part of record 2018680428 <https://www.loc.gov/pictures/item/2018680428/> (last accessed March 2022).

¹⁰¹ Digital colour composite from the three registered Public Domain monochrome originals found in the Library of Congress, at <https://www.loc.gov/pictures/resource/prok.00402/> (last accessed March 2022), as part of record 2018680009 <https://www.loc.gov/pictures/item/2018680009/> (last accessed March 2022).

¹⁰² Digital colour composite from the three registered Public Domain monochrome originals found in the Library of Congress, at <https://www.loc.gov/pictures/resource/prok.01886/> (last accessed March 2022), as part of record 2018681340 <https://www.loc.gov/pictures/item/2018681340/> (last accessed March 2022).

Fig. 2.71 Sergei Gorskii,
*Leo N. Tolstoi in Iasnaia
Poliana, 1908*

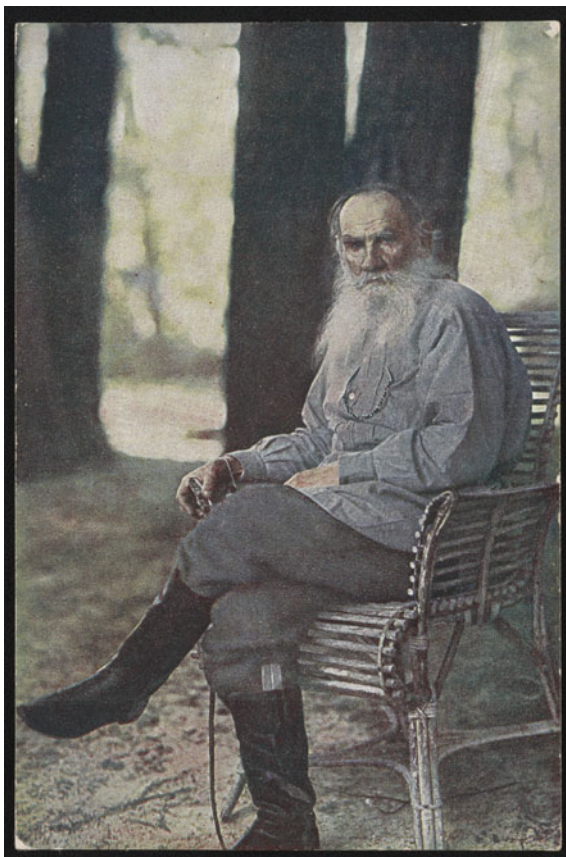


Fig. 2.72 Sergei Gorskii,
*Krest i a nsk i a di e vushki
(Peasant girls), 1909*



Fig. 2.73 Sergei Gorskii,
Trans-Siberian Railway
metal truss bridge on stone
piers, over the Kama River
near Perm, Ural Mountains
Region, c.1910



Fig. 2.74 Sergei
Gorskii, *Formovka*
khudozhestvennogo lit i a
(Moulding of an artistic
casting)



Fig. 2.75 Sergei Gorskii,
Spaso-Preobrazhenskii sobor
i Vkhodoierusalimskaia
tserkov'v Torzhke (Cathedral
of the Transfigured Saviour
and the Church of the Entry
into Jerusalem in Torzhok),
1910

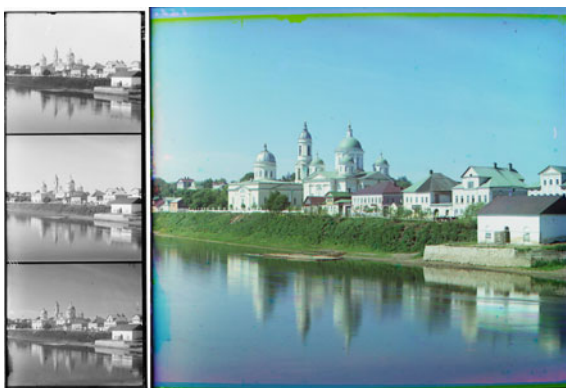


Fig. 2.76 Sergei Gorskii,
V Borodinskom muzei e,
Borodino (In the Borodino
Museum, Borodino), 1911



Fig. 2.77 Sergei Gorskii,
mir Bukharsk, Bukhara
(Emir of Bukhara, Bukhara),
1911



marketed the foldable *Vest Pocket camera* with great success (see Fig. 2.78). The camera used the 127 film (a format between the typical 35 mm and the 120 medium format), and was equipped with a 72 mm lens with apertures between f/6.8 and f/11. The camera was known as the *Soldiers Camera*, as it was small enough to carry around easily. In 1914, Kodak marketed the *Autographic film* system, a system which allowed photographers to add written information on the film at the time of exposure. *Harold Eugene Edgerton* (1903–1990), known also as *Papa Flash*, an American professor of engineering, is credited with the transformation of the stroboscope into a commonly usable device, the development of sonar and deep-sea photography (his equipment was used by Jacques Cousteau), and the invention of the xenon flash lamp for strobe photography in 1923.¹⁰³

Although the *reflex* cameras have appeared in the previous decades, their modern history as practical, portable, and easy to use cameras, begun with the family of the

¹⁰³ Some of Edgerton's iconic high strobe light photographs can be accessed online at the J. Paul Getty Museum (<https://www.getty.edu/art/collection/artists/1669/harold-edgerton-american-1903-1990/>, last accessed March 2022), and in the Library of Congress (<https://www.loc.gov/photos/?q=Harold+Edgerton>, last accessed March 2022).

Fig. 2.78 A Kodak Vest
Pocket camera of 1915



Twin Lens Reflex (or TLR) cameras. The German optical instruments manufacturer Rollei was the first to create and market a practical TLR camera, in 1928, the medium format *Rolleiflex*. Figure 2.79 shows a 1928 K1 Rolleiflex.¹⁰⁴ The Rolleiflex achieved a widespread popularity, which sparked an interest both in reflex cameras and in medium format photography. Rolleiflex soon became a name of a family of high-end cameras that run for many years. TLR cameras use two objective lenses of the same focal length, one for the composition and focusing of the subject and the other for the actual exposure. The camera is typically held at the waist, with the viewfinder mounted on top and viewed from above. In 1934 the *135 film cartridge* was introduced, which made the 35 mm film very easy to use for photography. A year later, in 1935, Kodak introduced the *Kodachrome* multi-layered colour reversal film, the first successfully marketed colour film that used a subtractive colour approach, whereas previous systems, such as Autochrome, used additive approaches. Kodachrome was so successful that it outlasted all other brands. In 1936, Ihagee Kamerawerk Steenberg GmbH, in Germany, created and marketed the *Kine Exakta*, the first 35 mm single-lens reflex (SLR) photographic camera, shown in Fig. 2.80. In 1939, Agfa, in Germany, introduced the 35 mm *Agfacolor negative film* for motion picture production, and the negative was intended for making positive projection prints on 35 mm film. Three years later, Kodak's 1942 *Kodacolor* was the world's first true colour negative film intended for making paper prints. Some five years later, in 1947 Harold Edgerton created the *rapatronic camera*, a high-speed camera capable of capturing

¹⁰⁴ The figure is a composite of a TLR diagram and a photo of a Rolleiflex K1 of 1928 found at the RolleiClub library, <http://www.rolleiclub.com/thedarkroom/?p=2927> (last accessed March 2022).

Fig. 2.79 A 1928 Rolleiflex twin lens reflex camera and the principle of operation of TLRs

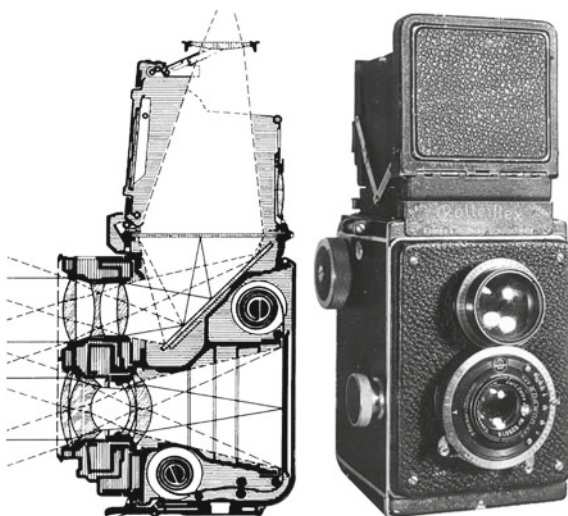


Fig. 2.80 The 1936 Ihagee Kine Exakta, the first 35 mm SLR camera



images with a really short exposure time, in the scale of nanoseconds, originally to capture the rapid changes of matter during nuclear explosions. 1948 is the year in which the *Hasselblad camera* was introduced, later named the Hasselblad 1600F, to denote the highest shutter speed of $1/1600$ s and 'F' for 'focal plane' (Fig. 2.81). It was a 6×6 cm format focal-plane shutter SLR camera.¹⁰⁵ The 1600F was a breakthrough in photographic cameras, as its modular design supported exchanging lenses, viewfinders and film magazines. Hasselblad's reputation grew considerably and in 1962, NASA started using their cameras in space flights, which pushed this trend even further, while, at the same time, NASA's requests brought new innovations in

¹⁰⁵ A focal-plane shutter camera is equipped with a shutter immediately in front of the focal plane, or the photographic film.

Fig. 2.81 The 1948 Hasselblad camera (1600F)



camera technology, like the motor drive, which appeared in the Hasselblad 500 EL, 1965. Such cameras were used on Apollo 8 and on Apollo 11. In addition, on the Apollo 11 mission, an extensively modified EL camera was used on the Moon surface, covering thus, photography in the spacecraft and in space. Hasselblad cameras were used for all following NASA Apollo missions and the Space Shuttle period. Two of the most iconic photographs to have been captured, are shown in Figs. 2.82 and 2.83.¹⁰⁶ A silver Hasselblad Data Camera (HDC) with Réseau plate, fitted with a Zeiss Biogon 60 mm $f/5.6$ lens, was chosen to document the lunar surface attached to astronaut Armstrong's chest. Since then, and following the limited weight protocols of the missions, a total of twelve camera bodies were left behind on the lunar surface, as only the film magazines were brought back to Earth (Hasselblad, 2022). In 1937, *Edwin H. Land* (1909–1991), an American scientist and inventor, co-founded the *Polaroid Corporation*. Land invented inexpensive polarising filters, a practical instant photography method, and developed the *retinex theory of colour vision* (Land, 1959). While working on Maxwell's early experiments in coloured images, Land realised that the human vision was capable of full colour perception, even when viewing images in total absence of green or blue wavelengths. About two decades later, in 1977, he formulated his retina-and-cortex (retinex) theory, denoting the collaborative work of the retina with the brain (Land, 1977). Land opened his paper with the headline,

A retina-and-cortex system (retinex) may treat a color as a code for a three-part report from the retina, independent of the flux of radiant energy but correlated with the reflectance of objects.

¹⁰⁶ *Earth Rising over the Moon's Horizon*, NASA photograph, accessed online at https://www.nasa.gov/mission_pages/apollo/40th/images/apollo_image_11a.html (last accessed March 2022). *A close-up view of astronaut Buzz Aldrin's footprint in the lunar soil*, NASA photograph, accessed online at https://www.nasa.gov/mission_pages/apollo/40th/images/apollo_image_11a.html (last accessed March 2022). Regarding, the Apollo 11 image library, 'no copyright is asserted for NASA photographs', <https://www.hq.nasa.gov/alsj/a11/images11.html> (last accessed March 2022).

Fig. 2.82 Earth Rising over the Moon's Horizon. Image Credit: NASA



Fig. 2.83 A close-up view of astronaut Buzz Aldrin's footprint in the lunar soil. Image Credit: NASA



Fig. 2.84 The 1949 Contax S camera



In 1948, Land marketed the first *Polaroid instant camera*, which made it possible to photograph and develop a picture in about one minute. In 1949, VEB Zeiss Ikon introduced and marketed the *Contax S* (Spiegelreflex, mirror reflex) camera, as the first 35 mm SLR camera with a *pentaprism* based viewfinder and the M42 lens mount, both of which became industry standards. Since Contax S, 35 mm SLR cameras were equipped with a waist-level viewfinder that provided a laterally reversed image. The usage of the pentaprism made it possible to device an eye-level viewfinder, and provide an upright (non-reversed) view of the scene, a critical breakthrough in the 35 mm SLR technology that played a key role in their popularity and successful marketing. The principal of total internal reflection that takes place in the pentaprism has already been discussed in a previous section (Fig. 1.15). Figure 2.84 shows a Contax S camera.¹⁰⁷ In 1957, the Asahi Optical Company created the *Pentax* 35 mm SLR camera, a highly successful market model that had a significant impact in the 35 mm SLR design throughout the world. Asahi Optical Company changed its name to Pentax due to the world-acceptance of the Pentax camera family; the product redefined the company. Pentax introduced a number of unique innovations, like the *rapid wind lever* for advancing the film instead of the knob winders, the *film rewind crank*, the *instant mirror return*,¹⁰⁸ and the *microprism* as a focusing aid.¹⁰⁹

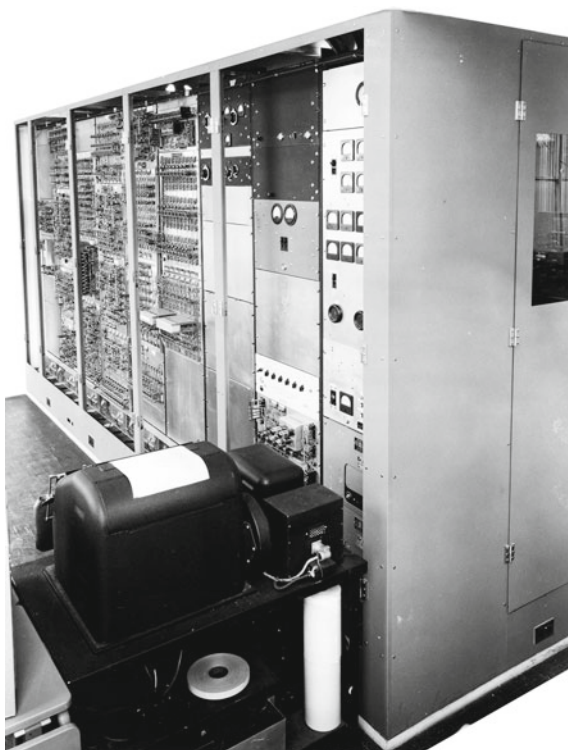
During the late 1940s and early 1950s, the U.S. National Bureau of Standards undertook the development of a first generation electronic computer, which was named *Standards Eastern Automatic Computer* (SEAC) and was eventually put to uninterrupted operation in the mid 1950s. SEAC is claimed to be the first fully operational stored-program electronic computer in the US, which was occasionally

¹⁰⁷ Figure based on the Contax S camera, made by VEB Zeiss Ikon in Germany, 1949, part of the Kodak Collection at the National Media Museum, Bradford, online at <https://collection.sciencemuseumgroup.org.uk/objects/co8210865/contax-s-camera-35mm-camera-single-lens-reflex-camera> (last accessed March 2022).

¹⁰⁸ SLR cameras are equipped with a mirror to reflect the incoming light from the lens to the viewfinder for the composition and focusing.

¹⁰⁹ A microprism is an aid to focusing, built in to a focusing screen, with the role of exaggerating the blur in unfocused images.

Fig. 2.85 Photograph of part of the input and output devices of SEAC in 1950

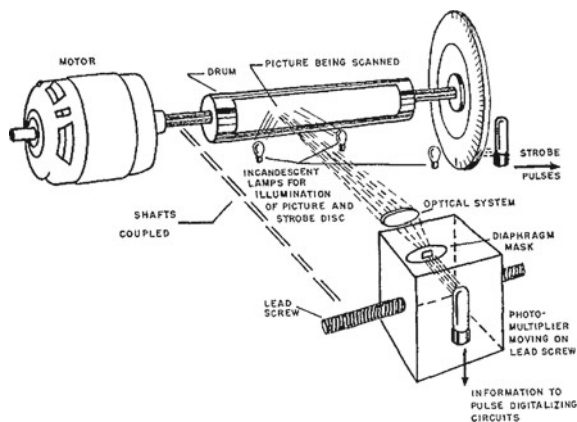


operated by a remote teletype, making it one of the first computers to be controlled remotely. A photograph of part of the input and output devices of SEAC in 1950 is shown in Fig. 2.85.¹¹⁰ SEAC was in operation until 1964 and one of its major contributions was in the development of *digital imaging*, a research led by Russell A. Kirsch (Shupe & Kirsch, 1953; Kirsch, 1998). *Russell A. Kirsch* (1929–2020) was an American engineer, who worked in the creation of the SEAC and is recognised as the developer of the *first digital image scanner*. This was an invention of enormous importance for digital photography and a kick-start of digital imaging in general. In 1957, Kirsch's team developed a digital image scanner and made the first digital scans. The diagram of the scanner is shown in Fig. 2.86, taken from Kirsch et al. (1957), the paper describing the technology and various insightful experiments.¹¹¹ This was the first technology for *digitisation*. Kirsch's rotating drum scanner and programming allowed images to be fed into it and be digitised to be stored

¹¹⁰ Figure based on the Public Domain Wikipedia photograph provided by the National Institute of Standards and Technology, online at https://en.wikipedia.org/wiki/File:SEACComputer_020.jpg (last accessed March 2022).

¹¹¹ The paper is provided in Public Domain by NIST, online at https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=821692 (last accessed March 2022).

Fig. 2.86 Diagram of the first image scanner technology in 1957



in SEAC's memory. Kirsch and his colleagues also devised an oscilloscope-based method to view the stored images. Figure 2.87 shows one of the very first images to have been scanned, a photo of Kirsch's three-month-old son Walden.¹¹² The image was captured as a 176×176 array, a total of 30,976 picture elements, in an area 5×5 cm, with a resolution of a single bit per picture element, which denotes a purely black and white representation. A combining of several scans with different scanning thresholds resulted a greyscale representation (Hernandez, 2007). In recognition of its importance in the development of *digital photography* and digital imaging, in general, this image was included in Life magazine's *100 photographs that changed the world* (Life Magazine, 2003). Kirsch's scanning technology and digital image representation, occurred in a world hungry for a digital technological development, one that could not have left photography unaffected. First off, it was in 1965 when *Frederic Crockett Billingsley* (1921–2002), an American engineer deeply involved in digital image processing for space missions, coined the term *pixel*, although there are suggestions that the term was around at that time (Lyon, 2006). Etymologically, the term is a combination of *pix-* (from *pictures*, shortened to *pics*) and *-el* (for *element*).

Noble (1968) presented, for the first time, the basic principle of operation of a matrix of image detectors and the required digital electronics. He presented a proof of concept with the implementation of a 10×10 array, based on *Metal-Oxide Semi-*

¹¹² Figure based on the NIST Digital Archives record titled *Image of infant son of Russell A. Kirsch, first picture fed into SEAC in early 1957*, online at <https://nistdigitalarchives.contentdm.oclc.org/digital/collection/p16009coll19/id/1541/rec/3> (last accessed March 2022), National Institute of Standards and Technology Digital Archives, Gaithersburg, MD 20899.

Fig. 2.87 The first digital image made on a computer in 1957, showing Russell Kirsch's baby son



conductor (MOS)¹¹³ technology and *photodiodes*.¹¹⁴ Noble's array was implemented on a 70×70 mm chip, and was capable of capturing at a frame-rate up to 500 frames per second. Noble also discussed the potential and feasibility of scaling up this technology, which he found to be straightforward. The technology proposed by Noble included one or more MOSFET amplifiers per pixel, so that the generated charge could be transformed into an amplified voltage with reduced noise, thus giving rise to the technology of *Active Pixel Sensors (APS)*—although the term was coined many years later, in Matsumoto et al. (1985)—as a replacement to previous *Passive Pixel Sensors (PPS)*, in which no amplification was implemented. A major breakthrough

¹¹³ The *Metal–Oxide Semiconductor Field-Effect Transistor (MOSFET)*, also known as the *Metal–Oxide Silicon* transistor (MOS transistor, or MOS), represent an insulated gate field effect transistor, with the ability to change conductivity that can be used for amplifying or switching electronic signals. It was introduced in 1960, by its inventors *Mohamed M. Atalla* (1924–2009) and *Dawon Kahng* (1931–1992) that constructed it in 1959 at Bell Labs. MOSFET technology was highly influential and has since been the basic building block of modern electronics, the most frequently manufactured device in history.

¹¹⁴ Photodiodes are *p–n junctions*, interfaces of two types of semiconductor materials, a p-type (for 'positive', with excess of holes) and an n-type (for negative, with excess of electrons), that converts light into electrical current, due to the photoelectric effect. When photodiodes absorb photons of a certain energy, electric current is produced. The response time of photodiodes is inversely proportional to their surface area.

in the digital imaging technology was the invention of the *Charge Coupled Device (CCD)*, in 1969, by *Willard Sterling Boyle* (1924–2011) and *George Elwood Smith* (1930–), for which they were awarded the Nobel Prize in Physics 2009, *for the invention of an imaging semiconductor circuit—the CCD sensor*. As described in the Nobel Prize awards page, Boyle and Smith sketched an electronic memory design, but their concept instead became the basis for a light sensitive device. The CCD is an array of light sensitive cells that become electrically charged when exposed to light, due to the involved emission of electrons. Application of voltage to the cells results in the generation of electrical signals that correspond to the digital image that is recorded. Boyle and Smith worked at the AT&T Bell Labs and the invention of the CCD was not their primary concern. Smith (2010), in his Nobel Lecture tried to frame the process that led to the invention by mentioning the three challenging tasks at their labs at that time, magnetic bubbles, the picturephone and the MOS transistor technology. Quoting from his Lecture,

In a discussion lasting not much more than an hour, the basic structure of the CCD was sketched out on the blackboard, the principles of operation defined, and some preliminary ideas concerning applications were developed.

On the same page, Boyle (2010), in his Nobel Lecture framed the same picture.

The invention of the CCD took place one afternoon over one of our frequent brainstorming sessions at the blackboard. We began drawing a diagram, and before it was finished, we knew we had something special. After a few weeks of work, George asked the ‘shop’ to make a model of our device. Somewhat to our surprise, the very first model worked as we had hoped. The first 3-bit device was born.

The original CCD technology was published with details in Boyle and Smith (1970), and was patented by Boyle and Smith under the US patent 3,858,232 (Boyle & Smith, 1974b). Their work resulted in another significant invention that considerably improved the technology, the Buried Channel CCD, which was also patented under the US patent 3,792,322 (Boyle & Smith, 1974a). The first patent specifically targeting the application of CCDs to imaging was granted to *Michael Francis Tompsett* (1939–) in 1978 (U.S. Patent 4,085,456), who filed the application in 1971 (Tompsett, 1978). Tompsett was a British physicist, engineer, and inventor, who, apart from being the person that applied the principle of CCDs to create real-world digital cameras, is known for his work on compact, low power, high performance, and low cost infrared and CCD imaging. Several companies begun developing serious programs on CCD and it was Fairchild Semiconductor, a semiconductor company in California, that in 1973 begun commercial production of CCDs and by 1974 had a linear 500-element device and a two dimensional 100×100 pixel device.

Steven J. Sasson (1950–) has been an electrical engineer at Kodak, under the supervision of Gareth A. Lloyd, assigned in 1975 to attempt and build an electronic camera using a CCD. He used the Fairchild 100×100 CCD and managed to create a self-contained electronic camera, the first portable digital camera, which he patented with Lloyd as *Electronic still camera* under US patent 4,131,919, filed in 1977 and granted in 1978. The schematic block diagram of the camera is shown in Fig. 2.88 (Lloyd & Sasson, 1978). The camera was far from being a commercial grade

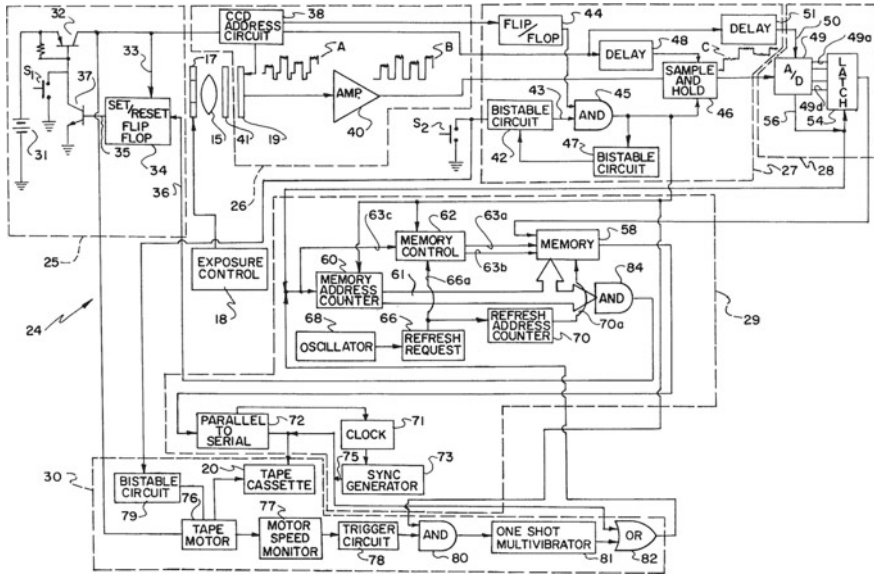


Fig. 2.88 Schematic block diagram of a solid-state image sensor, and signal processing circuitry in the camera

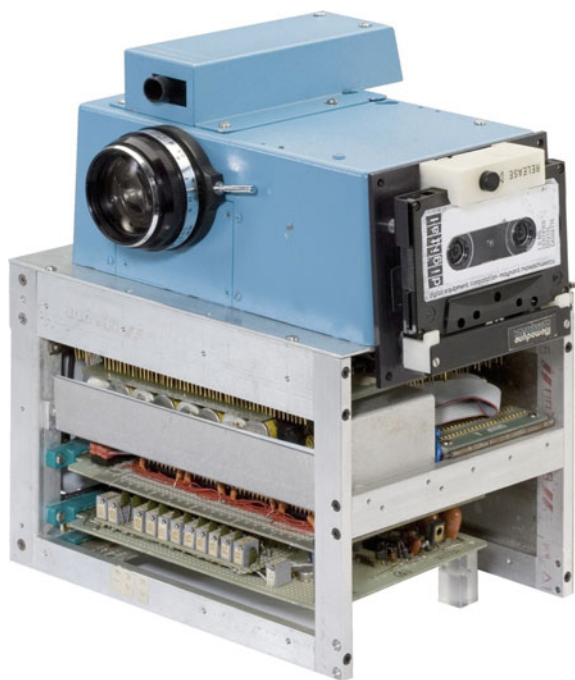
product. It was a laboratory prototype that used the Fairchild CCD, weighted around 4 kg, and was equipped with a cassette tape recorder to store the photographs, in a process that required 23 s. The camera was capable of recording black-and-white photographs. Although Sasson was not the first to produce a digital camera, he is certainly credited for creating the *first handheld digital camera*. Figure 2.89 shows Sasson's digital camera at the George Eastman Museum.

Just about the same period, in 1975, *Bryce E. Bayer* (1929–2012), while working at Kodak, invented the *Bayer filter*, a filter for digital imaging sensors that made colour photography possible for digital cameras. Bayer filed for a patent for his invention under the title *Colour imaging array* in 1975 and he was granted the US patent 3,971,065 a year later (Bayer, 1976a). In his own words, the filter can be summarised to

A sensing array for color imaging includes individual luminance- and chrominance- sensitive elements that are so intermixed that each type of element (i.e., according to sensitivity characteristics) occurs in a repeated pattern with luminance elements dominating the array. Preferably, luminance elements occur at every other element position to provide a relatively high frequency sampling pattern which is uniform in two perpendicular directions (e.g., horizontal and vertical). The chrominance patterns are interlaid therewith and fill the remaining element positions to provide relatively lower frequencies of sampling.

In practice, what Bayer named luminance sensitive elements was implemented by green filters, and chrominance was implemented by red and blue filters, in a one-to-one arrangement on top of the image sensing elements of the sensor. This colour

Fig. 2.89 The first handheld digital camera



selection was based on the three-colour vision theory, in which (a) mid-range wavelengths, in the region of what is perceived as green (more precisely yellow, as explained in Chap. 1), are considered to be closely linked to the perceived brightness, (b) brightness conveys most of the information in a viewed image and (c) the human vision is most responsive in the region of the greens; thus the double amount of green elements in the filter. Figure 2.90 shows the basic diagram for the filter, and Fig. 2.91 shows a diagram of the colour encoding provided in the framework of a camera, from Bayer's patent (Bayer, 1976a). Apparently, the final output of the colour pixels is the result of the switching network shown in Fig. 2.91, in which the resulting ratio of green:red:blue pixels for a 6×6 array is 18:13:5. It should be emphasised that the encoding required by the filter, changes completely the originally one-to-one relation of the photo sensitive elements of image sensors to the resulting image pixels. Obtaining a final full-colour image requires the application of *demosaicing* methods, to interpolate the set of red, green, and blue values for each pixel location, using sets of surrounding raw values.

More or less, the board was set for digital photography. Then, it was just a matter of development, improvements, further innovation and, most importantly, public adoption. In 1986, Kodak invented the world's first *megapixel*¹¹⁵ sensor, capable of recording 1.4 million pixels that could produce 5×7 -inch digital photo-quality

¹¹⁵ It is reminded that one megapixel (MP) is one million pixels. *Mega-* is a unit prefix in metric systems denoting a factor of one million (10^6), and comes from Greek: μέγας for great.

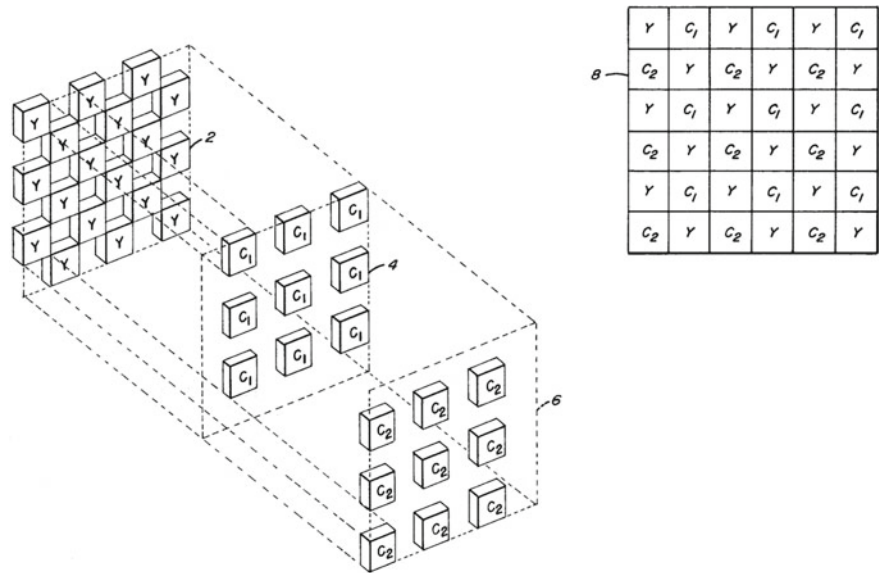


Fig. 2.90 Basic sketch of the Bayer filter arrangement

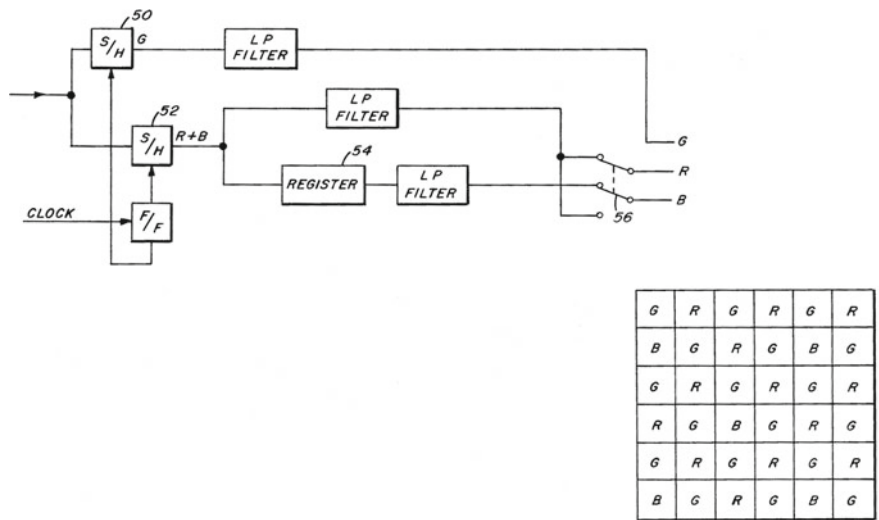


Fig. 2.91 Diagram of the switching network to interpolate the colour values for the image pixels

prints. In 1988, Fuji created the first fully digital camera, the *Fuji DS-1P*, with 16 MB storage space. In 1990, *Dycam Model 1* was the first commercially available digital camera. In 1991, Kodak released *DCS-100* the first *Digital SLR*, or simply *DSLR* camera with 1.3 megapixel resolution enclosed in a Nikon F3 body, requiring a large companion storage unit.

Eric R. Fossum (1957–) while working for NASA, developed, in 1993, a new CMOS active pixel sensor to tackle the problems of CCDs for space missions, including the significant power consumption, the noise, and the low readout speed. The new technology remained known as the *CMOS Image Sensor* or CIS. Fossum published the research in 1993 (Fossum, 1993) and filed for patents in 1994 (Fossum et al., 1995; Fossum and Nixon, 1998). The CMOS sensors after significant improvements over the following years up to around 2003 achieved imaging performance comparable with CCD sensors, and later exceeded CCD sensors, due to their significant advantages of low production cost, low power consumption and miniaturisation capability.

In 1994, SanDisk defined and manufactured the *CompactFlash* flash memory mass storage device to be used mainly in portable electronic devices, one of the most successful storage media in digital photography. In 1995, Casio created the first consumer digital camera with an liquid crystal display (LCD) for previewing and viewing photographs, the *Casio QV-10*. A year later, in 1996, Kodak created the *Kodak DC-25*, the first camera to have used CompactFlash memory for storage. In 1988, *JPEG* and *MPEG* became the international standards for digital image and video interchange. In 1995, Ricoh marketed the *Ricoh RDC-1* the first camera with video capture capability. In 1999, Nikon released *Nikon D1*, a 2.74 megapixels camera, a camera completely created by Nikon with a price under \$6,000 and compatibility with Nikon F lenses. In 2006, DALSA Semiconductor announced a CCD of 111 megapixels targeting astronomy applications, the first sensor to pass the 100 megapixels mark. In 2009, Kodak announced that Kodachrome film that has been manufactured since 1935, was discontinued and all processing ended in 2010.

2.3 Closure?

Apparently, the history of photography is still being written, and the above list is just an account of milestones in this history. Nowadays, advanced light capturing devices are available in various forms and technologies for a wide range of purposes. Digital technology is driving all those devices as nearly any (electronic) device in the 21st century. Apparently, the digital revolution turned digital data ubiquitous, thus digital data are also used for light capturing, processing and interpretation. In particular, imaging devices acquire and process digital images, which are collections of discrete-time, discrete-space and intensity-quantised samples of the amount of light entering the device, in a typical digitisation process. Digitisation results in a digital representation (replica) of an actual object or event, which may become available to the world of digital devices, where archival, documentation, sharing, processing, interpretation and interaction are readily available.

Chapter 3

A Photography Primer



—Περὶ μὲν οὖν τοῦ ἄνευ φωτὸς μὴ ὁρᾶν εἴρηται ἐν ἄλλοις· ἀλλ’ εἴτε φῶς εἴτ’ ἀήρ ἐστι τὸ μεταξὺ τοῦ ὁρωμένου καὶ τοῦ ὁμματός, ἢ διὰ τούτου κίνησις ἐστὶν ἡ ποιοῦσα τὸ ὁρᾶν.^c

Aristotle, Sense and the sensible

^c So that the view can not be done without light, was said elsewhere. But whether light or air is the mediator between the thing that is seen, and the visible, the motion that passes through this mediator is the one that produces the view.

Abstract Any introductory text on photography typically includes a specific set of information, beginning with the description of the basic apparatus, the camera, its components, the technology involved, and the photographic results expected by particular exposure scenarios. Various settings and different results, handouts and cheat sheets for the building of photography insight is of increased interest, particularly in the context of a modern world in need of quick answers and concise helpful information. Going the other way around, this insight may result in successfully selecting exposure scenarios to attain particular results. This chapter focuses on building this insight.

3.1 Introduction

In almost all introductory texts on photography one may find a common set of information, including a description of the photographic camera and the basics of its usage, the principles of lighting and exposure, and the basics of photographic composition. This chapter serves this very purpose, focusing on the technology involved, along with the photographic results expected by particular exposure scenarios. Various settings and different results, handouts and cheat sheets for the building of insight is of increased interest. This insight may result in successfully selecting exposure

scenarios to attain particular results. This chapter focuses on building this insight, although without in-depth details, which are considered in the following chapters of this treatise.

Focus of this chapter is the SLR type of camera, which, in essence, represents a functional and structural super-set of all 35 mm commercial photographic cameras. Nevertheless, it should be noted that there are a number of different types of photographic cameras; commonly, nine (9) different types of digital still image capturing devices are recognised:

1. *DSLR cameras*, belong to the widely accepted standard for advanced amateur and professional photography;
2. *Mirrorless cameras*, are the most dynamic type of camera currently in the market due to certain benefits;
3. *Compact cameras*, or, sometimes, *point-and-shoot cameras*, are the easy to use, small and lightweight apparatuses to enable automated photography for virtually every purpose and condition;
4. *Bridge cameras*, represent a type of cameras specifically marketed to fill the gap between compact cameras and DSLR/mirrorless cameras, particularly targeting entry-level photography enthusiasts;
5. *Instant cameras*, are compact, highly automated cameras, implementing the point-and-shoot scenario using particular popular instant filtering capabilities and the ability to instantly print the captured images;
6. *Action cameras*, are special-purpose devices, targeting the capturing of outdoors activities that usually involve fast movement and action, thus, focusing on being efficient, durable, lightweight and weatherproof;
7. *Panoramic (360°) cameras*, represent a relatively new family of still and motion capture cameras that target the recording of spherical panoramic views, capturing virtually everything that is visible from a viewpoint; they are also, typically, used for outdoors activities, although not restrictively, and they are built to be efficient, lightweight and weatherproof;
8. *Smartphone cameras*, define a whole new family of capturing devices, built with specific limitations in mind, still, offering significant photography functionalities, basically, through sophisticated software and miniaturisation manufacturing techniques;
9. *Medium and large format cameras*, represent the elite group of photographic cameras, equipped with high quality large sensors and expensive lenses, into, typically, larger and significantly heavier bodies, targeting professional photography users and applications.

Table 3.1 is a comparative table for those digital camera types. Practically, and in short, larger format cameras are expected to produce higher quality outputs at the expense of larger, heavier bodies and significantly higher costs. Compact designs with small sensor sizes bring low cost point-and-shoot automation at the expense of lower quality output, fewer manual controls and less customisation. Current trends in professional level cameras tip the scales in favour of mirrorless full-frame cameras,

Table 3.1 Pros and cons of various digital camera types

Camera type	Pros	Cons
DSLR	Complete manual control; optical viewfinder; various interchangeable lens options; high quality output; customisation and gear; dedicated auto-focusing system	Large size; heavy; expensive; knowledge demanding
Mirrorless	Practically, DSLRs without the pentaprism-mirror-viewfinder system; less mechanical noise; less vibration; complete manual control; compact design; various interchangeable lens options; high quality output; customisation and gear	Slow and energy consuming electronic viewfinder; shorter battery life; higher cost in entry level cameras
Compact	Easy to use; increased automation; low cost; compact design	Limited control; small sensor size; low quality output; no or limited lens options
Bridge	Easy to use; compact design; low cost; lens options	Small sensor size; decreased lens quality; increased energy consumption; medium quality output
Instant	Easy to use; compact design; instant print; low cost	No lens options, very limited manual control; specific applications
Action	Easy to use; ultra compact and lightweight; weatherproof; mountable on various surfaces	Small sensor size; virtually no manual control; typically no viewfinder; very limited customisation; decreased battery duration
360°	Easy to use; ultra compact and lightweight; weatherproof; mountable on various surfaces; special immersive captures	Small sensor size; virtually no manual control; typically no viewfinder; very limited customisation; decreased battery duration; difficult to control the orientation
Smartphones	Ultra compact; lightweight; easy to use; always available; readily cloud and media integrated	Typically, limited manual control; very small sensors; lower quality output; limited or no lens options
Medium/large format	Large sensor size; high quality output; lower noise; interchangeable lens options; large dynamic range	Very high cost, large size; heavyweight; challenging depth of field setting

so the the benefits of smaller sizes and lighter bodies can be harnessed. The following paragraphs summarise the basics of photography focusing on the specifics of DSLR cameras.

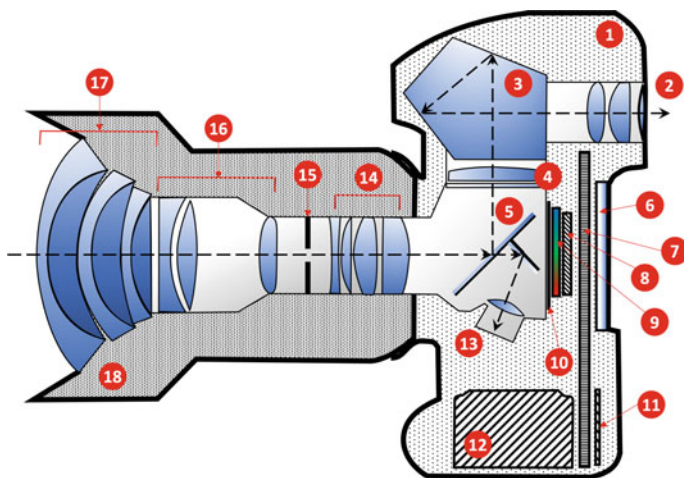


Fig. 3.1 A graphical representation of the anatomy of a typical DSLR camera. (1) camera body; (2) viewfinder; (3) pentaprism; (4) focusing screen; (5) reflex and relay mirror; (6) display; (7) electronics; (8) sensor; (9) filters; (10) shutter; (11) storage media; (12) battery; (13) autofocus system; (14) focusing lens elements; (15) aperture; (16) zoom lens elements; (17) light gathering lens elements; (18) lens

3.2 Anatomy of the Digital Camera

Although there is today a wide range of photographic camera types, the description in this section focuses on those known as *Digital Single Lens Reflex* (or simply *DSLR*) cameras that have long been the preference of many professional photographers and enthusiasts for a wide range of applications. Figure 3.1 shows a classic representation of the anatomy of a DSLR camera, whereas a cross section of an actual camera is shown in Fig. 3.2.¹ The basic parts of any camera in the DSLR range, practically include (a) the camera body (the ‘dark room’ or the embodiment of the camera obscura) and (b) the lens system. As shown, the lens, is actually a complex system and not a single element, including multiple optical elements, the aperture mechanism, as well as mechanical parts and electronics for various functionalities. The camera body is equipped with some crucial equipment, including the shutter, the viewfinder aided by the pentaprism, the imaging sensor, and the image viewing, processing and storage electronics. Typically, most, if not all, of the control equipment and software are in and on the camera body. The main parts of the camera are treated in a technical manner in the following chapters, thus, in the following paragraphs only a brief description is provided with indicative examples and few technical information, particularly for the photography enthusiasts.

¹ This figure is based on the Public Domain image at <https://libreshot.com/inside-slr-camera/> (last accessed March 2022).

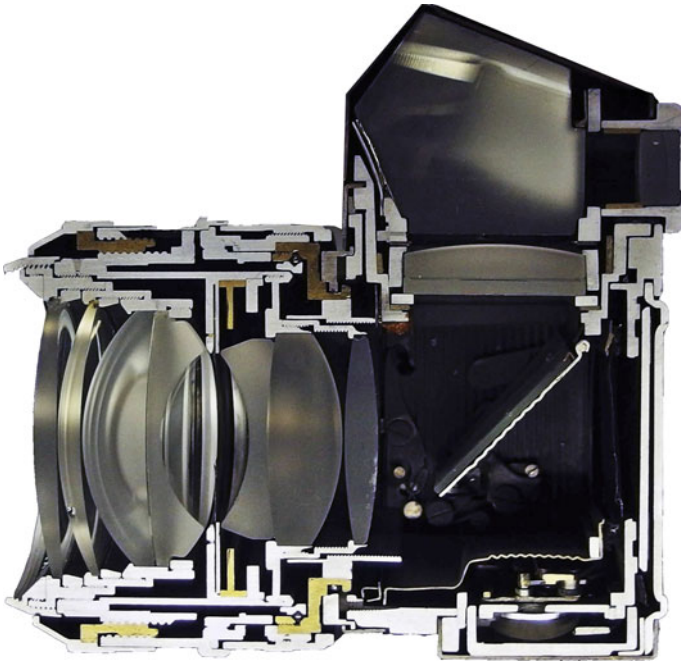


Fig. 3.2 A cross section of an SLR camera

3.2.1 The Lens

The lens is an inseparable part of the camera. It is responsible for collecting light and directing it (focusing it) to the sensor in order to capture an image. Apparently, understanding lenses and their function is a key element in each photographer's theoretical training. Choosing the right lens for a particular project is a process of balancing between capabilities, application, quality, cost, size, weight and speed.

Central concepts related to the lens are the field of view or *viewing angle*, the perspective, the image quality, the *focal length*, the *zoom* and the *aperture*. Each lens usually consists of multiple optical 'elements', the elementary lenses aimed at directing and focusing light on the surface of the imaging sensor, for an accurate recording of a scene. A representation of the anatomy of a typical camera lens is shown in Figs. 3.1 and 3.2.

The distance at which each lens focuses an image is characteristic to the lens and is called the *focal length*. Lenses are categorised exactly according to this quantity, thus, depending on the focal length, three main types of lenses are available: the normal, the wide-angle, and the telephoto lens.

- A *normal lens* is one that typically has a focal length of 50 mm when focusing the image on a classic 35 mm film (the most widespread commercially available film type). It is called *normal* because it renders images that simulate the image

that humans see in terms of the perspective and size of objects (distance from the eyes, relative size, space perspective, relative scene coverage, etc.).

- The *wide-angle lens* is a lens with a small focal length (typically up to 50 mm), which has the ability to cover a larger scene from the same distance. It is called *wide-angle* because of the wide viewing angle that it can achieve, as it can ‘fit’ more objects on the same surface by changing the perspective of the scene. The wide-angle lens is usually a smaller lens than the normal lens, although this may not always be the case.
- The *telephoto lens* is the opposite of the wide-angle lens. It provides a longer focal length and therefore is expected to be (typically) larger in size. Its focal length is greater than 50 mm and has the ability to bring distant objects closer, while limiting the viewing angle. As ‘tele-’ comes from the Greek ‘τηλέ’, which literary means ‘from a distance’, the name obviously relates to the very property of bringing distant objects closer.

The focal length is closely related to the viewing angle that each lens achieves and determines how the focused image is ‘magnified’ relative to the image a person perceives in the same position. At the same time, the different focal lengths of the lenses result in determining the perspective of the scene, sometimes leading to a misjudgement of the space itself. When the same scene is photographed with a wide-angle lens and a telephoto lens, there is an obvious change of perspective, with the wide-angle lens greatly enhancing the perspective and producing distorted geometries. Figures 3.3, 3.4, 3.5, 3.6, 3.7 and 3.8 present some indicative examples throughout the range of focal lengths available in various cameras. Figure 3.3 shows a typical smartphone ultra-wide angle photography example of architecture, with a bit of a dramatic effect filtering. Figure 3.4 shows a DSLR-based fisheye (ultra-wide angle) photography portrait example at a celebration event; the photograph was cropped left and right, without any magnification or geometry distortion. Figure 3.5 shows another wide angle portrait example taken by a compact camera (also considered an early bridge camera) in black and white. Figure 3.6 shows an example of the normal lens on a full-frame DSLR camera. Figure 3.7 shows an example of a portrait photograph using a telephoto lens on a DSLR; the photograph was cropped left and right, nevertheless without any magnification. Figure 3.8 shows an example of a super-telephoto lens on a full-frame DSLR camera.

In addition to the influence in the captured scene perspective, there are other factors to be considered that are related to the focal length of the lens. For example, telephoto lenses are particularly prone to ‘shake’ (any type of vibration of the camera) as any motion is exacerbated due to the narrow viewing angle. Longer focal lengths therefore require less exposure time (higher shutter speeds) or mechanical stabilisation to minimise that issue.²

² Some believe there is a rule of thumb applied in these cases, which is to use inverse exposure time at least as long as the focal length, for example for a 200 mm lens use no less than 1/200 shutter speed.



Fig. 3.3 Ultra-wide angle lens photography example; iPhone 11 Pro Max, 13 mm lens, ISO 20, $f/2.4$, $1/300$

Fig. 3.4 Ultra-wide angle lens photography example; Nikon D40, 15 mm lens, ISO 1600, $f/2.8$, $1/30$, cropped left-right without magnification



Fig. 3.5 Wide angle lens photography example; Olympus SP320, 38 mm lens, ISO 64, f/2.8, 1/30



Furthermore, wide-angle lenses offer a better response to lens flare than telephoto lenses. Some lens flare example images for the three types of lenses are shown in Fig. 3.9,³ Fig. 3.10,⁴ Fig. 3.11.⁵

Apparently, as photographers have to deal with various scenes and capturing situations and applications, they need to be able to use all varieties of viewing angles and thus, should have many lenses with them all the time. This is a major challenge in various ways, as it involves extremely high costs of acquiring and maintaining the lenses and the camera, and a lot of weight to carry with, all the time. By the way, all these lenses are called *prime lenses*, with the term corresponding to any type of fixed focal length lens. An attempt to meet this challenge is made by the so called *zoom lenses*. Zoom lenses are special types of lenses that provide a range of focal lengths, by being able to vary their focal length, in terms of a simple rotation of a ring on their body. Zoom lenses, unlike prime lenses, can cover a wide range of focal lengths and can provide multiple operation and application options. Actually, these

³ Photograph credit Benjamin Huggett; downloaded from <https://unsplash.com/photos/Fz35xk6wE9k> (last accessed March 2022).

⁴ Photograph credit Jack Sloop; downloaded from <https://unsplash.com/photos/qelGaL2OLyE> (last accessed March 2022).

⁵ Photograph credit Luemen Carlson; downloaded from https://unsplash.com/photos/e_14VK5oJJM (last accessed March 2022).

Fig. 3.6 Normal angle lens photography example; Sony a7R III, 50 mm lens, ISO 100, $f/1.4$, $1/2000$



Fig. 3.7 Telephoto lens photography example; Nikon D40, 120 mm lens, ISO 200, $f/2.8$, $1/800$, cropped left-right without magnification





Fig. 3.8 Telephoto lens photography example; Sony a7R III, 400 mm lens, ISO 100, f/6.3, 1/500



Fig. 3.9 Lens flare in a photo taken with a wide angle 20 mm lens

lenses have become extremely popular and a wide range of zoom lenses to meet all the needs of photographers is available nowadays. Various prime lenses are shown in Fig. 3.12,⁶ whereas various zoom lenses are shown in Fig. 3.13.⁷

Table 3.2 presents some examples of lenses' characterisation and their intended or suggested use with a full frame digital camera (or a 35 mm equivalent).

In contrast to the DSLR cameras, in typical compact cameras, where the lens is integrated into the camera, in almost all cases there are zoom lenses. The properties

⁶ Photograph credit Lucas Favre; downloaded from <https://unsplash.com/photos/zae9zxwLbrA> (last accessed March 2022).

⁷ Photograph credit Voice and Video Sales, Ruffner Street, San Diego, CA, USA; downloaded from https://unsplash.com/photos/ffnKhW_48-Y (last accessed March 2022).



Fig. 3.10 Lens flare in a photo taken with a normal (55 mm) lens



Fig. 3.11 Lens flare in a photo taken with a telephoto 105 mm lens

of these lenses are usually referred to in multiplicative terms, e.g. $3\times$, $4\times$, etc. This multiplier refers to the ratio between the longer and the shorter focal lengths that the lens can provide, without any reference to the actual focal length provided. So this size is relative and, by itself, conveys no information regarding the focal length range provided by the lens. For example, a $5\times$ lens can correspond to a range of focal lengths like the following

- 30 mm–150 mm (wide angle to telephoto)
- 17 mm–85 mm (ultra-wide angle to telephoto)
- 10 mm–50 mm (ultra-wide angle to normal)



Fig. 3.12 Various prime lenses with focal lengths of 16 mm, 30 mm, and 35 mm



Fig. 3.13 Various zoom lenses with focal lengths of 18–35 mm, 24–70 mm, and 24–105 mm

Table 3.2 Lens types and general application range for a full frame digital camera

Focal length (mm)	Characterisation	Typical usage
<21	Ultra wide angle	Architecture, landscape, small interiors, astrophotography, special photography
21–35	Wide angle	Landscape, interiors
35–70	Normal	Street level, interiors
70–200	Short-medium telephoto	Portrait, wild life, astro/planet photography
>200	Medium-super telephoto	Portrait, sports, wild life, astro/planet photography

Another benefit usually provided by compact digital cameras is the *digital zoom*. This functionality should be differentiated from the usage of the term ‘zoom’ in ‘zoom lenses’, as the digital zoom actually corresponds to the image magnification by employing approaches of digital image processing. This is a post process in the camera and has nothing to do with the optics and the lens of the camera. As such, it is highly inadvisable, since any processing of the image and particularly a magnification is definitely expected to result in degraded image quality even relying on highly sophisticated algorithms.

Lenses, no matter the quality and cost, are expected to produce visual distortions, which may often lead to significant obvious degradation of the photos, due to inherent characteristics. One such typical problem is the decrease in contrast that may occur. Another problem is a blurring introduced by the lens. One other typical problem in almost all lenses is what is called the *chromatic aberration*, due to the slightly different focal lengths for different light frequencies, the higher the frequency the smaller the focal length—blue light is focused in front of green, which is focused in front of red). Another issue is a radially decreasing brightness (vignetting), which leads to photos with darker corners. Yet another important problem is any geometric distortion that may be caused by the lens as light passes through its optical elements and leads to a distortion of the perspective or the shape of objects (typically a loss of parallelism in parallel lines). It should be noted that these problems are present in varying degrees in all lens. These issues are explained in the following chapters.

The Aperture

The *diaphragm* is a key mechanism of the camera, which is typically located in the lens and aims to limit or control the amount of light entering the camera through the lens. The *aperture*, which expresses how much the diaphragm opens, is limited to a value range that expresses the diameter of the diaphragm opening in relation to the lens focal length. It is usually referred to as *f-number* and is defined as the ratio of the focal length to the diameter of the diaphragm, for example $f/2.8$ or $1:2.8$ (meaning $1/2.8$ of the focal length).

As the value of the aperture is essentially in the denominator of the fraction, a larger opening in the diaphragm means a smaller f-number. Lenses capable of providing a wider aperture (smaller f-number values) are often called ‘fast lenses’, as for the same camera sensitivity and the same lighting conditions those lenses make it possible for less exposure time. In general, fast lenses are less common and usually significantly more expensive. Any lens provides a range of f-number values that comes predetermined by the manufacturer. Zoom lenses, as lenses of variable focal length, provide a variable range of f-number values according to their focal length selection. Thus, a standard 18-55 mm lens can offer an aperture of at most $f/4.5$ wide at 18 mm and at most $f/5.6$ wide at 55 mm. Usually, changes in zoom lenses’ focal length affects the value corresponding to the wider aperture setting, which increases with the focal length of the lens.



Fig. 3.14 Example of the effect of aperture in the same scene

Table 3.3 General influence of the f-number selection

f-number	Aperture size	Required shutter	Resulting DoF	Contrast and colour
Large	Smaller	Slower	Wider	Crisper
Small	Bigger	Faster	Narrower	Less crisp

One of the most important effects of the setting of the aperture is the indirect adjustment of the so-called *depth of field* (DOF), or the range of distances from the lens in which it achieves pure focus (focused zone). Typically, a wide aperture (small f-number) defines a small depth of field, while a narrow aperture (large f-number) defines a large depth of field. A typical illustration of the difference in the depth of field due to different aperture values is shown in Fig. 3.14. The image on the left is captured with $f/1.4$ whereas the image of the right with $f/16$.

As it will be explained in the following chapters, the depth of field is not equally distributed closer and further from the point of focus, and it also varies with the focusing distance, with greater distances enlarging the depth of field. The general influence of the aperture settings is shown in Table 3.3, whereas the influence of the aperture in the depth of field is shown in Table 3.4, in which the values correspond to a digital SLR with a $1.6\times$ crop factor and a constant aperture at $f/4.0$.

Arthur (Usher) Fellig (1899–1968), also known as *Weegee*, was a photojournalist in the US (of European origins), famous for his crisp and high-contrast black and white street photographs. He is credited for coining the phrase ‘*f/8 and be there*’, as a hint regarding his basic photographic approach, although a look at his work and settings would not sufficiently support it. A collection of his works can be found and

Table 3.4 Influence of the aperture on the depth of field

Focal length (mm)	Focus distance (m)	DoF (m)	Near DoF (%)	Far DoF (%)
10	0.5	0.482	29.8	70.2
20	1	0.421	39.9	60.1
50	2.5	0.406	46.0	54.0
100	5	0.404	48.0	52.0
200	10	0.404	49.0	51.0
400	20	0.404	49.5	50.5

appreciated at the International Centre of Photography.⁸ Regardless the origin of the phrase, *f/8 and be there* has remained an extremely popular expression in photography jargon, and it is still being used to denote how important it is to take the initiative and shoot a picture, rather than analysing the optimal shooting technique. As it will be explained in subsequent paragraphs, *f/8* is considered to be a general-purpose aperture setting that leads to successful photo captures in various settings and conditions. As a matter of fact, it is connected, in many cases, with the *hyperfocal distance*, an important concept relating to sharply-focused wide-depth-of-field photographs, for every distance from the camera.

3.2.2 The Shutter

The camera shutter is a moving protective barrier surface, like a curtain, just in front of the photosensitive surface of the imaging sensor. It is usually deployed to block any light hitting the sensor and it is retracted to open the way for light to reach the sensor for a period of time set by the photographer (or the camera in automated operation) in order to expose a photo. Important in photography is the duration at which the shutter remains retracted and allows light to hit the sensor.

There are various types of shutters, basically into two main categories, the focal plane and the leaf shutters. Leaf shutters are located inside the lenses, being an integral part of them, and are rarely found in typical cameras nowadays. They consist of interlocking blades and have some important advantages, such as silent operation, good flash synchronisation at any speed, but also some disadvantages, such as the fact that no lens change can occur with a film in the camera (analogue cameras) and the fact that the lenses that carry this particular shutter have an increased cost.

Focal plane/curtain shutters are located inside the body of the camera, specifically in front of the photosensitive surface. Typically, these consist of two ‘curtains’ that move in the same direction. The main advantages of this type of shutter are the fast

⁸ The Arthur Fellig collection at the ICP, online at <https://www.icp.org/browse/archive/constituents/weegee?all/all/all/all/0> (last accessed March 2022).

speeds that can be achieved, the ability to change lenses without exposing to light, the ability to use lenses of lower cost and weight. The main disadvantages are the more difficult flash synchronisation and the distortions of images with objects in high speed motion.

The speed that a shutter can achieve typically varies from 1/8000 sec to 30 sec with a special B (Bulb) setting, at which photographers can retract the camera shutter for as long as required (low-light photography, night sky photography, etc.). A typical shutter speed scale includes values like 1/2000, 1/1000, 1/500, 1/250, 1/125, 1/60, 1/30, 1/15, 1/8, 1/4, 1/2, 1", 2", 4", 8". In many cameras this setting is expressed in inverse numbers, for example for a desired shutter speed 1/125 the camera setting is expressed as 125.

The shutter not only controls the exposure duration, the amount of time the light is permitted to reach the photosensitive surface, but also controls how motion in a scene is captured. When high speed is used, or equivalently short exposure times, any moving object in the scene is frozen and clearly depicted. On the other side, when low speed is used, or long exposure times, moving objects reflect light towards the camera for a longer period of time and thus are imaged from more than one location, resulting in appearing in *motion blur*.

3.2.3 The Sensor

The digital camera's sensor is essentially a matrix of miniature photosensitive components, which act as 'cavities' (also called *photosites*) for the collection of light. Thus, the photographic exposure in the digital camera is, practically, equivalent to the collection of photons. At the end of the collection process, an estimate of the relative amount of photons in each cavity is made, by means of an electric current that is produced due to the photoelectric effects, to which a distinct value is finally assigned (e.g. from 0 to 4096 for creating a RAW image).

The cavities do not have the ability to recognise the colour of the light falling upon them except for its intensity. In order to be able to capture colour a special trick is applied, with each cavity being covered by a special filter that allows the passage of a particular light frequency range (a single colour), implementing the *Bayer filter* technique. By convention, each cavity captures only one of the three primary colours (red, green or blue), discarding 2/3 of the incoming spectrum in this process. To create the pixels of the final image, the camera combines the colours of adjacent photosites. The Bayer filter is the device used to ensure that monochromatic light enters each photosensitive cavity of the sensor. This filter essentially consists of alternating series of red-green and green-blue filters in a ratio that includes twice the number of greens in relation to the other two colours. This technique is not used in all digital cameras. For example, the *Foveon* (Sigma) sensor captures all three primary colours at each point on its surface, taking advantage of a three-dimensional layout on its photosensitive surface (i.e. it measures each colour response at a different depth on its surface). In addition, some Sony cameras are differentiated and capture

not only three, but four colours with a similar pattern (red, green, blue and emerald - RGBE filter). The decoding of the typical Bayer mosaic approach is simple,

- each 2×2 area of cavities is an entity and is examined separately;
- a pixel is created with the contribution of two greens, one red and one blue cavity in each 2×2 area;
- areas with overlay may be combined to complete the colour information with various methods.

As the imaging sensor in the digital camera is essentially a matrix with discrete value locations, various peculiarities arise that need to be taken into account. The most common is the appearance of the *moiré pattern*, a repetitive pattern that occurs due to the fact that there is a finite resolution in the sensor (issue known as *aliasing*).

As the light measurement is based on the sensor cavities located at some (even very small) distance from each other, a quantity of light is lost as it falls into the ‘gaps’ between the cavities. To minimise this issue, micro-lens devices (micro-mirrors) are used angled on top of the gaps to direct the photons into the cavities and minimise the light loss.

A lot has been said about the physical size of the imaging sensor and its connection to the captured image size, resolution and quality. This subject is treated in the following chapters, but suffice to say that *size does matter*. Bigger sensors are able to have bigger photosites, thus significantly improved capacity to capture light. One should have always in mind that the selection of a sensor size also affects the selection of the appropriate lens as will be explained in the following section about the crop factor and will be elaborated in the following chapters.

The Crop Factor

The crop factor is defined as the ratio of the diagonal of the imaging sensor to the diagonal of the standard full frame sensor, which is defined as the sensor with size equal to that of a typical 35 mm film. As reference is the 35 mm film, this makes sense in cameras that compare to this standard and not larger format media.

Since most commercially available digital cameras have a sensor smaller than that of the full frame, for various reasons, the crop factor is either referred to as a fraction of the full frame, but for even smaller sensors the size is references in fractions of inches. A typical and very popular crop factor value is $1.6\times$, used in a large number of camera brands and models. Examples of full frame sensors include cameras such as the Nikon D5 series, the Canon EOS 6D series, the Sony Alpha a7 series, the Pentax K-1 series, the Panasonic S1R series, the Leica Q2. Typical examples with a $1.3\times$ cropped frame are the Canon 1D series cameras. The $1.5\times$ crop factor appears on the many manufacturers as APS-C originating in Nikon’s DX series, while the $1.6\times$ crop factor is mainly on Canon camera models.

Smaller frame sizes, like 1/4”-2/3” are commonly used in mobile phones and compact cameras. It is worth noting that in many cases the cost of a camera is directly

proportional to the size of the sensor. In such cases, usually, there is reference to the absolute sensor size and not the crop factor offered.

As the crop factor essentially limits the size of the sensor, the smaller the sensor, the smaller the coverage area of a scene and therefore the wider the lens angle that will be required to achieve an equivalent coverage with a full frame sensor. That is, the size of the sensor directly affects the type of lens (focal length) to be used. So, for example, a sensor with a $1.6\times$ crop factor and a 50 mm lens on the camera corresponds roughly to an 80 mm lens for a full frame sensor. In general, smaller sensors for a corresponding viewing angle, magnification range and aperture range require wider lenses, (which are also lighter, smaller and cheaper) to achieve a typical range of viewing angles and aperture settings.

Another effect of the size of the sensor is on changing the depth of field for the same setting on the camera lens aperture. Specifically, the depth of field decreases as the sensor gets bigger (for the same subject and the same distance). For the same depth of field and perspective, a full frame camera with 80 mm and $f/1.4$ aperture, produces equivalent results with a $1.6\times$ sensor camera with a 50 mm lens and $f/0.9$ aperture, which, unfortunately, is an aperture setting that is not available in standard amateur-grade lenses, but only in very expensive lenses.

Last but not least, another important effect of sensor size is related to the refraction of light due to the diaphragm. Larger sensors are more ‘resistant’ to unwanted refraction and can use smaller aperture values before the refractive disk becomes larger than the circle of confusion leading to blurry images (which is analysed in the following chapters). That is, larger sensors are, practically, expected to produce clearer photos for closed diaphragms (large f -numbers). An illustration of the notion of the *circle of confusion* which connects to the notion of *bokeh* (another word from the photography jargon) is presented in Fig. 3.15⁹; the photo was created using a Canon EOS Rebel T6i with a 50 mm lens, $f/1.8$ aperture ISO 800 and $1/30$ shutter.

ISO Sensitivity

ISO sensitivity or ISO speed or simply ISO, is a standard way of describing light sensitivity of the imaging sensor. It is usually referred to or described as a doubling scale, consisting of ISO 50, ISO 100, ISO 200, . . . , where a higher value means a greater sensitivity to light, somehow, corresponding to the standard definition of film speed in ASA.

Nevertheless, in stark contrast to the ASA sensitivity of the film, the ISO in digital cameras connects to an electronically controlled process that is associated with artificial digital signal amplification of the captured light intensity. In essence, it does not refer to the formal concept of ‘sensitivity’, but to an amplification factor that produces a result equivalent to the sensitivity in films. As the process involves electronically amplifying the signal that corresponds to the light captured by the

⁹ Photo credits Diego Passadori. The photo was downloaded from <https://unsplash.com/photos/95e125Cqhq8> (last accessed March 2022).

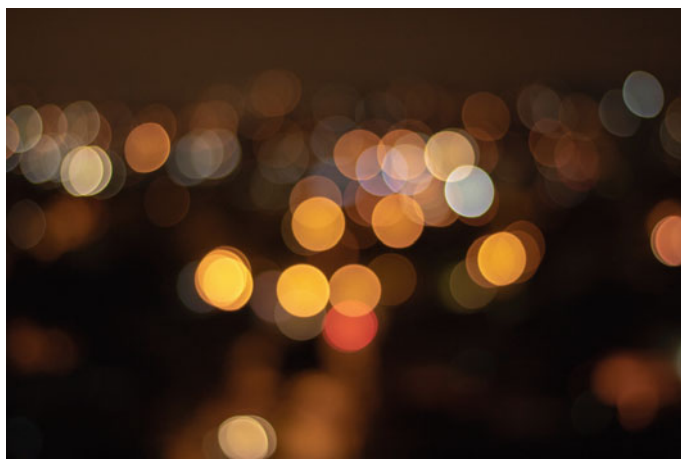


Fig. 3.15 Illustration of bokeh

sensor, the final image contains also enhanced levels of imaging noise, which is expressed as randomly coloured pixels particularly in dark areas of a scene. This is a very typical problem with digital camera sensors and a very obvious and worrying issue in digital photography. In almost every camera, no matter how expensive it is, the problem exists and connects to high ISO values (high signal amplification), and thus, photography educators usually advice against using those settings, except in cases in which no other approach is available for an adequate capture. Particular attention should be paid to the ‘Auto ISO’ setting provided by many cameras, as this can lead to an automatic change of sensitivity and ultimately to an undesirable result.

3.2.4 Exposure Control

Another special feature that should not be missing from an introductory presentation of the camera and its operation is that of the light metering function that aids in properly adjusting the exposure settings. It should be noted that all photometric systems in a camera deal with a fundamental challenge, that is to measure reflected light from the scene and not the actual light that falls on the surface of the object being photographed. This is why in studio settings, professional photographers use specialised photometric equipment.

Light metering has been long standardised based on the brightness of reflected light that appears as a medium grey colour (the well known 18% grey). Light metering generally achieves the desired result when there is a broad range of brightnesses in the scene (i.e., there is a large scatter in the scene brightness histogram), whereas it does not when there is a ‘concentrated’ histogram.

The basic light metering methods are *centre-weighted*, *partial*, *spot* and complex like *evaluative*, *zonal* and *matrix*. The differences in these measurement modes are on the size of the measurement areas or their relative position on the surface of the image. The centre-weighted metering used to be the most common method of photometry due to the good performance in landscapes with bright skies. Today, it is being replaced by the most modern complex methods (evaluative, matrix). The results of the original method are more clearly predictable in relation to the newer methods. Partial metering provides much greater control in the exposure, especially when the photographer wants to emphasise or focus on a specific point or detail of a scene. Classical example where partial photometry is preferred is that of portrait photography with the presence of back-lighting. Spot metering uses a very small estimation area and is suitable for creative use in special lighting conditions and when there is a reference target. Both spot and partial metering are suitable for artistic photography in unusual lighting conditions.

One last functionality that should be mentioned in this brief description of light metering methods is that of manual exposure correction, or exposure compensation (EC). This functionality allows the photographer to preset the camera behaviour during the light metering to achieve a particular effect or result, typically in difficult lighting conditions. Practically, the photographer chooses if the desired photo should be brighter or darker to what the camera perceives as perfect. Exposure compensation is usually provided in up to ± 2 to ± 3 settings, or ‘stops’ as they are commonly called in the photography jargon, where each stop doubles/halves the amount of light entering the camera. However creative, this functionality must be used carefully and mainly to reduce lighting (negative correction) as otherwise there is a risk of overexposure that results in unrecoverable loss of areas in the final image.

3.2.5 Photography Cheat Sheets

The two final Tables in this introduction represent an attempt to summarise the key elements of the digital camera, their effect and the suggested uses. In particular, Table 3.5 presents the typically suggested camera settings for various application cases. In this table, the ‘...’ notation denotes a wide range of values, virtually all values provided by the photographic equipment in use. In addition, Table 3.6 presents the overall camera settings cheat sheet, in which the effect of all the settings are presented, using typical example values.

Table 3.5 Camera settings for application cases

	Portrait	Landscape	Interior	Low light
ISO	... -200	... -200	200–800	800-...
Aperture	... -f/4.5	f/11-f/32	... -f/5.6	f/2.8-...
Shutter	1/200-...	1/200-...	... -1/90	B
Lens	80mm-...	Fisheye-...	28 mm–80 mm	Fisheye-...
Impact	Detailed image; pale colours; shallow depth of field	Detailed image; crisp hues; wide depth of field	Image noise; narrow depth of field; motion blur	High image noise; narrow depth of field; heavy motion blur

Table 3.6 Camera settings cheat sheet

	Low/Small	Medium	High/Large
ISO	ISO100: Low/nominal sensitivity; photography under strong light	ISO400: Slightly boosted sensitivity; photography under ‘normal conditions’	ISO6400: Highly boosted sensitivity; photography under low light
Aperture	f/32: Significant light attenuation and wide depth of field	f/7: Typical light attenuation and depth of field	f/2.4: Low attenuation of light and narrow depth of field
Shutter	2”: long exposure time; motion blur	1/200: typical exposure time; limited motion blur	1/1600: short exposure time; no motion blur and freezing of moving objects
Lens	10 mm: wide-angle photography; increased contrast; wider depth of field; strong geometry distortion	50 mm: normal photography as close to human vision as possible	200 mm: telephotography; slight decrease in contrast; narrower depth of field; distortion of distances
Sensor	1/2”: captures small scene portion; needs wider lenses and longer exposures; worst quality	Full frame: captures a scene exactly like a typical 135 film	Medium/Large format: wider photosites result in higher quality but narrower depth of field

3.3 A Camera Model as a Basis for This Treatise

Although photography has been considered as a form of art, there is a considerable amount of technology and theoretic knowledge into it. Particularly when photography is used in measurement applications with metric accuracy, there is a number of topics to be studied carefully for a clear understanding of the technical aspects and the associated expected results. Even in typically artistic expression forms,

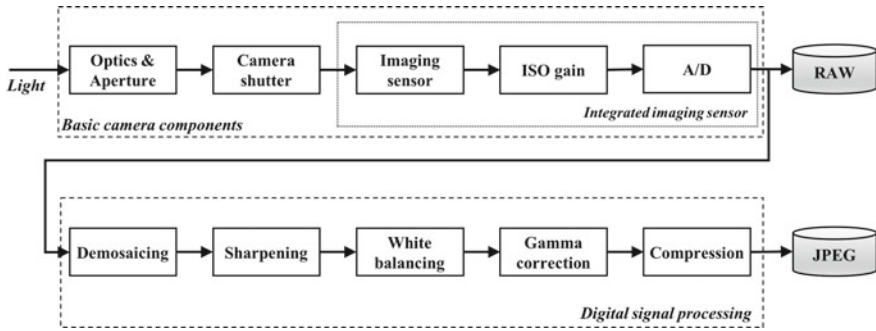


Fig. 3.16 A widely adopted model of a typical image capturing process in a digital camera

photography relies today in highly sophisticated devices that turn the light reflected by the objects of the world into voltages and then to bits of image intensity data. A typical representation of the image sensing process in modern digital camera systems is shown in Fig. 3.16, as described by Szeliski (2011). This model is based on previous models (Healey and Kondepudy, 1994; Tsin et al., 2001; Liu et al., 2008), whereas a complex and more accurate 24-parameter model has been proposed in Chakrabarti et al. (2009).

Apparently, there is a complex process that takes place in photographic cameras that begins with light entering a ‘black box’ that is made up of electronic and mechanical components with a special aim to capture an image of the world. The final outcome, the digital image on a memory chip, is a product of a combination of physical properties, science and engineering. Properties of light propagating through various media, optics and characteristics of lenses, photoelectric and quantum phenomena, amplification electronics and sophisticated digital technologies are all combined into a workflow to result a single photograph.

Chapter 4

Technical Aspects of Photography



—Σωκράτης: Κινδυνεύεις μέντοι λόγον οὐ φαῦλον
εἰρηκέναι περὶ ἐπιστήμης, ἀλλ' ὃν ἔλεγε καὶ Πρωταγόρας.
τρόπον δέ τινα ἄλλον εἶρηκε τὰ αὐτὰ ταῦτα. φησὶ γάρ πού
«πάντων χρημάτων μέτρον» ἄνθρωπον εἶναι, «τῶν μὲν
ὄντων ὥς ἔστι, τῶν δὲ μὴ ὄντων ὥς οὐκ ἔστιν».^f

Plato, Theaetetus

^f You risk not having said an insignificant word about knowledge, but what Protagoras also said. In another way, he said the same. Because he says somewhere: “man is the measure of all things, of those that exist that they do, of those that do not exist that they do not”.

Abstract To capture an image of the world relates to being able to focus light exactly onto a photo-sensitive surface, while keeping a high spatial resolution, for the correct amount of time. Lenses are the nature’s answer to the main challenge. The camera shutter is a device that controls the incidence of light on the photosensitive surface by covering and uncovering the surface for an accurately timed period. The imaging sensor is the main component for digital imaging and is situated at the back of any modern digital camera, at the same location the film used to be in analogue cameras. At its heart, the sensor is an analogue device that counts the number of photons that hit its surface. Last but not least, today’s digital cameras not only focus light onto a photosensitive surface but also deal with a number of digital signal processing techniques to deliver the final photograph. This chapter explores the technical aspects of photography, providing a baseline mathematical understanding.

4.1 Optics, Lenses and the Aperture

Exposing a light sensitive surface (like a film or an imaging sensor) to direct light results in capturing, in each photosensitive unit, the average intensity of the light coming from all possible directions; the overall result is a blurry image with some

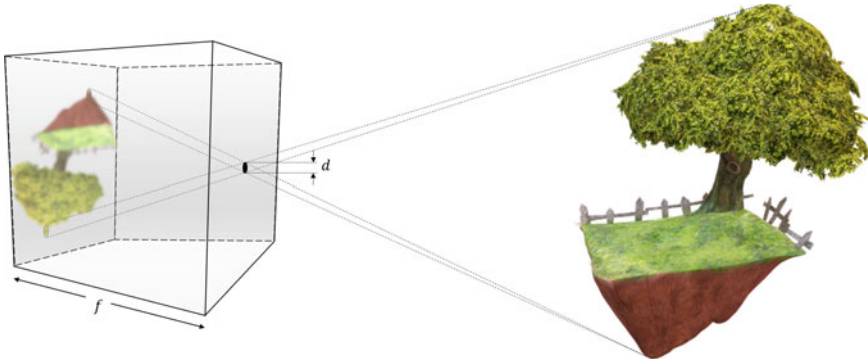


Fig. 4.1 General representation of the focusing effect through a pinhole in a camera obscura

minor regional variations affected by spatial intensity and spectral variations in the scene. Apparently, this result is not a useful medium. To capture an image of the world relates to being able to focus the incoming light exactly onto the photo-sensitive surface, while keeping a high spatial resolution. Lenses are the nature's answer to this problem in all physical systems that need to detect light in high resolution, and has traditionally been the choice for imaging systems in technology.

As discussed in previous chapters, before the usage of lenses to focus images, humans have witnessed and potentially harnessed pinhole effects for light focusing; when a confined dark space has a small opening (pin hole) to light, then images of the outside world are projected on a surface at the opposite side of the opening. If this is the case, one might question the need for any additional components to focus images on surfaces. The issue is that the focusing provided by a pinhole arrangement in the typical camera obscura comes with particular limitations. Figure 4.1 shows a schematic representation of image focusing through a pinhole in a camera obscura; each point in the scene (right side) spherically radiates light in all directions, some of which is directed through the pinhole to the opposite wall of the camera obscura. The diameter of the opening plays a crucial role, as it defines how big each (infinitesimal) point of the scene becomes in the projected image, guided by purely geometry, as shown in the representation. *Joseph Petzval* (1807–1891), a mathematician, physicist, and inventor from the Kingdom of Hungary, is one of the founders of geometrical optics, which were directly applied and advanced photography. Among a number of important studies, he analysed pinhole cameras and created a formula for the pinhole diameter that is optimal to attain sharply focused images, by relating the opening (here, the aperture) with the geometrical characteristics of the camera and the wavelength of light.

$$d = 2\sqrt{f \cdot \lambda} \quad (4.1)$$

This simple and elegant formula expresses that there is dependence on the aperture, the focusing distance (focal length), and the wavelength, but no dependence on the distance in the scene. For example, for a camera with a focusing distance of $f = 20$ cm, a monochromatic yellow-green light source radiating at $\lambda = 555$ nm (the position

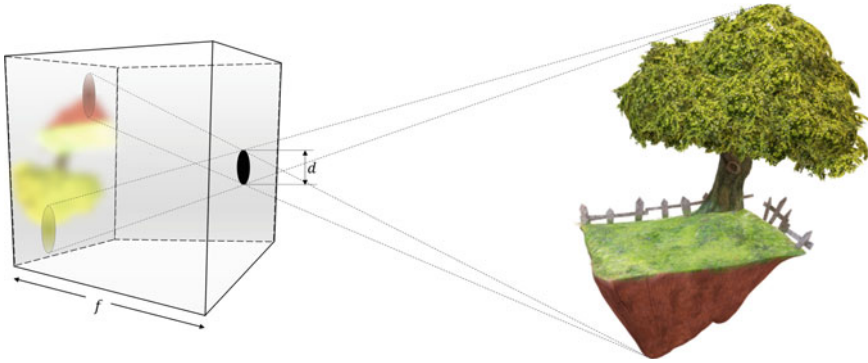


Fig. 4.2 A wide pinhole results in a blurry image in the camera obscura

of maximum photopic response of the human visual system) would require an optimal aperture of $d \approx 0.67$ mm, whereas for a monochromatic blue source at $\lambda = 470$ nm, the optimal aperture would be $d \approx 0.61$ mm, and for a monochromatic red source at $\lambda = 660$ nm, the optimal aperture would be $d \approx 0.72$ mm. As a result, for a given camera obscura and pinhole size, not all wavelengths will be at perfect focus, resulting in chromatic aberration (discussed in subsequent sections). Looking at it in another way, for a particular pinhole opening, say $d = 1$ mm, and wavelength, say $\lambda = 555$ nm, the perfect focusing distance would be $f = 45.05$ cm; changing the wavelength to $\lambda = 470$ nm would result in $f = 53.19$ cm, whereas using light of $\lambda = 660$ nm would result in $f = 37.88$ cm. In another example, if the camera obscura is a room of, say, 2 m wall-to-wall distance, then monochromatic light at $\lambda = 555$ nm would be perfectly focused if the pinhole would be of $d \approx 2$ mm. When the pinhole is wider than optimal, then much more light enters the camera, creating brighter but less focused images, as shown in Fig. 4.2. The optimal case is graphically shown in Fig. 4.3. Although, in general, narrow apertures are expected to be preferable for focused images (always in relation to the size of the camera), they also significantly limit the amount of light entering the camera, thus, resulting in darker images. Another aspect relating to the pinhole camera is the *magnification* of the scene achieved with the same aperture, which is illustrated in Fig. 4.4. For a given pinhole opening, when the focusing surface is moved closer to the pinhole (f becomes smaller), then the image gets smaller and smaller. Young (1971) estimated the pinhole resolution limit in terms of the pinhole radius s ($d = 2s$) to be

$$r = 0.7 \cdot s \quad (4.2)$$

Due to the inherent issues of pinholes, the preferable choice for light focusing is to use lenses. Typically, camera lenses (complex systems consisting of a tube, a number of simple focusing elements and an aperture) are being used to collect light and focus it on the light sensitive surface at the back of the camera. A lens

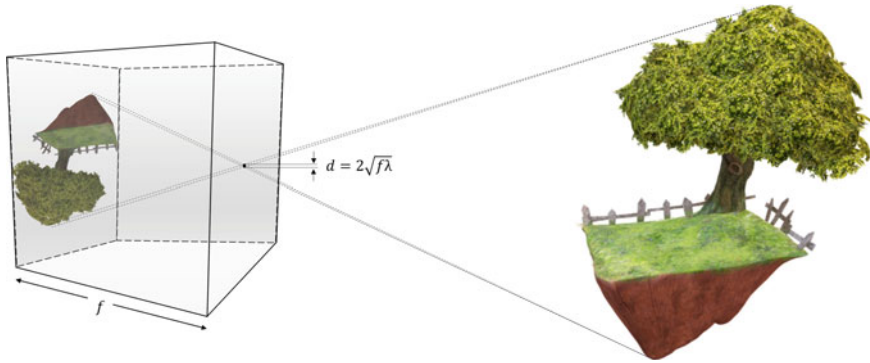


Fig. 4.3 The ideal pinhole for a camera obscura results in the perfectly focused image

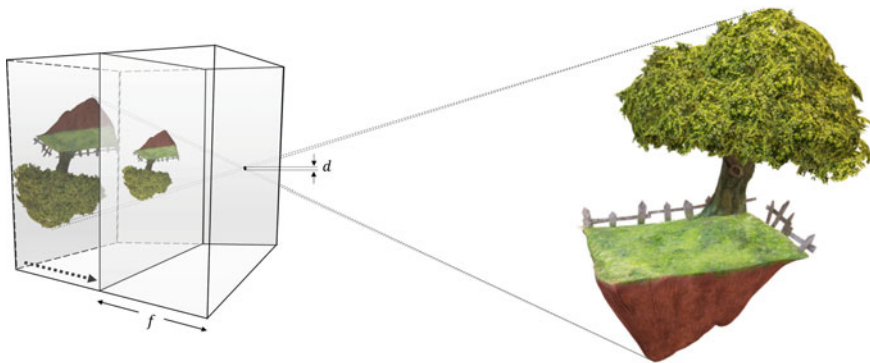


Fig. 4.4 Illustration of the magnification effect in the camera obscura

system can be thought of as a kind of a funnel that gathers light and channels it to the photosensitive components of a camera. The simplest form of a lens system is a totally dark cylindrical tube with one base open to the sensor and the other base sealed and with a tiny hole at its centre. This forms what is called a *pinhole camera*. A pinhole camera is nothing more than a camera with a lens of fixed focal length and aperture diameter, typically capable of low resolution images with a large depth of field (scene objects at any distance seem to be in focus although everything is a bit blurry). Although this simplified lens system is practically inadequate for metric applications, usually it suffices to treat a lens as an ideal pinhole that simply projects all rays through a common centre of projection, and thus derive models based on it to describe the process of capturing light. Apparently, if one needs to model focus, exposure, vignetting, and aberration, more sophisticated models need to be considered (Möller, 1988; Hecht, 1998; Ray, 2002).

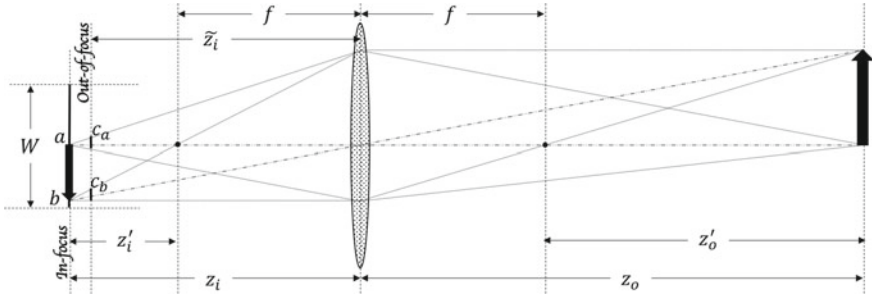


Fig. 4.5 The simplified thin convex lens projection model

A widely used simple convex lens model is the *thin lens model* shown in Fig. 4.5. This model describes the way light rays bend and focus through a single piece of glass with a very low curvature that is equal on both sides. Using the physics of refraction the distance from the lens to an object z_o and the distance behind the lens to the focused image z_i are related with the most basic equation in thin lens optics, the *thin lens equation*.

$$\frac{1}{z_o} + \frac{1}{z_i} = \frac{1}{f} \quad (4.3)$$

in which f is called the *focal length* of the lens. In this model, the *lens power* is usually expressed as $P = 1/f$, (f : in meters) in dioptries. For instance a 100 mm lens has a power of 10 dioptries, and a 17 mm lens has a power of 58.82 dioptries. In addition, the *linear or transverse magnification* of the convex thin lens is defined as the ratio of the object size in the created image, and it is usually a signed number to denote the inversion of the created image,

$$M = -\frac{z_i}{z_o} \quad (4.4)$$

The *Newtonian form* of the convex thin lens equation is expressed in terms of the *extrafocal distances*, which are the distances to the focal length points, $z'_o = z_o - f$ in front and $z'_i = z_i - f$ at the back of the lens, as shown in Fig. 4.5,

$$z'_o z'_i = f^2 \quad (4.5)$$

When the distance to the object is quite large ($z_o \rightarrow \infty$), the focal length becomes equal to the distance behind the lens where the image is focused ($z_i = f$). This is exactly the case in a pinhole camera of f distance between the pinhole and the sensitive surface, under central projection (Fig. 4.6), with a *field of view* given by simple geometry,

$$\tan \frac{\theta}{2} = \frac{W}{2f} \Rightarrow \theta = 2 \tan^{-1} \left(\frac{W}{2f} \right) \quad (4.6)$$

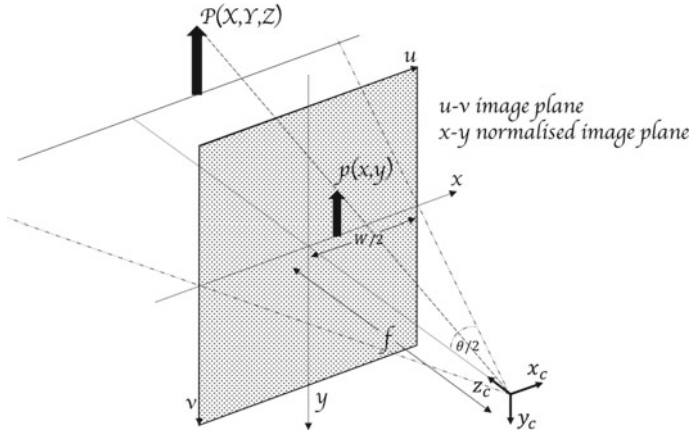


Fig. 4.6 The general central projection model showing the image plane at front

where θ is the field of view, W is the sensor width and f the focal length, from which one may also deduce that

$$f = \frac{W}{2 \tan \frac{\theta}{2}} \quad (4.7)$$

Given a fixed lens with known focal length f and an object at known distance from the lens z_o , using (4.3) one may compute the distance z_i behind the lens where the object will be at perfect focus, a distance slightly different than the nominal focal length of the lens. This difference decreases exponentially with the distance z_o .

If for any reason the (rear) focal plane is set to a position different than the proper z_i (the ‘in-focus’ plane in Fig. 4.5), say to a position $\tilde{z}_i$ (the ‘out-of-focus’ plane in Fig. 4.5) then single points at z_i , like a and b , become discs (shown as thick segments in the figure), c_a and c_b , and, as a result, the created image on the plane appears blurry. Any such disc is called the *circle of confusion*,¹ which relates to the best attainable image resolution at that particular focus plane. Since lenses depart from being perfect focusing devices, even at best focus a point is sensed as a circle or a spot. The term *circle of least confusion* is usually used to denote the smallest possible circle or spot for a given lens at best focus and ideal imaging conditions (Ray, 2002). Mathematically, the circle of confusion relates to the concept of the *point spread function* of a focused optical system, which describes the response of the system to a point source. The point spread function is a specification of the more general *impulse response* in systems, thus, it is the impulse response of a focused optical system.

It should be clarified here that, as shown in Fig. 4.5, there are *two* focal planes or *planes of focus*, the *front focal plane* and the *rear focal plane*; the former corresponds to the plane in front of the camera and the latter to the plane inside the camera

¹ Often referenced also as *disk of confusion*, *circle of indistinctness*, *blur circle*, *blur spot*.

(‘behind’ the lens). They are both parallel to the sensing surface and perpendicular to the optical axis of the camera system. Both planes are imaginary and are located at the points of perfect focus for a given lens.

Departing from image sensing and capturing, in image display, visual acuity and the concept of the circle of confusion relate to a standard viewer, the standard viewing distance and the required image magnification as

$$c = \frac{d}{25} \cdot \frac{1}{r \cdot m} \quad (4.8)$$

where c is the circle of confusion in mm, d the viewing distance in cm, r the desired image resolution in lp/mm (line pairs per millimetre) and m the required magnification. The 25 cm standard distance in the equation stems from the fact that typically, at the distance of 25 cm, a standard good viewer is able to distinguish an image resolution of 5 lp/mm, which is equivalent to a circle of confusion of 0.2 mm in the viewed image. As an example, viewing a displayed image at 1 m distance at a $16\times$ magnification corresponds to a circle of confusion of

$$c = (100/25)/(5 \cdot 16) = 0.05 \text{ mm}$$

Kodak (1972) related the circle of confusion with the lens focal length, using the convention of a critical viewing limit of 2 min of arc that resulted in the estimate of

$$c \approx \frac{f}{1720} \quad (4.9)$$

which assumes that the image would be viewed at a distance

$$d_v = f \cdot m \quad (4.10)$$

where d_v is the viewing distance with an angle of view equal to that of the sensed image. Apparently, this is an ideal estimate, as images are viewed at ‘incorrect’ distances, since the lens focal length is not typically known at viewing time, thus, nowadays, viewing distance criteria are relating to the camera format. Such a criterion is the $d/1500$ circle of confusion diameter limit (d meaning the imaging sensor diameter),

$$c = \frac{\sqrt{W^2 + H^2}}{1500} \quad (4.11)$$

where W is the sensor width and H is the sensor height. Thus, for a full frame camera with a sensor size of 36 mm $\times$ 24 mm the circle of confusion diameter limit is 0.029 mm, whereas for an APS-C camera with a sensor size of 23.6 mm $\times$ 15.7 mm it is 0.019 mm.²

² A large collection of circles of confusion for various camera models can be found on lists published online, like in http://www.dofmaster.com/digital_coc.html (last accessed March 2022). There are

4.1.1 Lens Types

Modern camera lenses are complex systems of simple optical elements of various geometric structures. Regardless the lens complex structure, its purpose remains the same, to be able to focus light at a predicted distance onto the photo-sensitive surface inside a camera. According to the functionalities lenses provide, they are categorised into two main classes of categories, the first class relating to their ability (or not) to change focal length and the second relating to their application. Regarding their capability to change focal length on demand, lenses are categorised into

- *Prime lenses*, which are lenses of a fixed focal length (sometimes called FFL due to this fact), like a 35 mm, or a 50 mm, or a 100 mm lens. Prime lenses are usually capable of enhanced optical quality and wide maximum aperture, while being lighter and smaller in size, due to fact that their structure is simpler, which, in turn, results in fewer optical degradation (aberrations). In low-light conditions prime lenses are typically a better option due to their wider aperture.
- *Zoom lenses*, which are lenses of variable focal length, like a 17–55 mm, or a 35–80 mm lens. Zoom lenses are complex systems of optical elements that can be mechanically rearranged in order to change the provided focal length. The fact that there is a need for multiple optical elements makes these lenses costly, heavy and large. In addition, the complex optical system may degrade the captured image quality and narrow down the maximum aperture. Zoom lenses are further divided into *panfocal* lenses that are capable of maintaining focus, and *varifocal* lenses that lose focus when they change their focal length respectively. Typical consumer lenses follow the varifocal paradigm. Major advantage of zoom lenses is that a single lens can cover a wide range of applications, reducing the need for the frequent replacement of the camera lens, which speeds up machine maintenance, while at the same time replacing the need for purchasing high cost and carrying multiple heavy lenses. In compact systems, where the lens is integrated into the camera, almost always zoom lenses are encountered. The properties of these lenses are typically indicated in multiplicative terms, like $3\times$, $4\times$. *These terms refer to the ratio between the largest to the smallest focal length the lens can provide, with no reference to the focal length itself.* So this is a relative lens indication, and often consumers do not know the real focal length range of the lens. For example, a $5\times$ lens may correspond to a number of focal length choices, like 30 mm–150 mm (wide-to-telephoto), or 17 mm–85 mm (wide-to-telephoto), or even 10 mm–50 mm (wide-to-normal), in full-frame sensor terms.

Regarding their application, lenses are categorised into three main types, depending on their focal length.

- *Normal lenses*, sometimes called *standard lenses* are lenses with a focal length approximately equal to the diagonal of the camera sensor (usually rounded up),

also online circle of confusion calculators, like the one in http://www.dofmaster.com/digital_coc.html#coccalculator (last accessed March 2022).

which results in a field of view similar to that of the human eye, appearing ‘natural’ to an observer (this means that a normal lens is expected to preserve the perceived distances and relative sizes). Normal lenses are often considered to cover an angle of view between 40° and 62° . In the case of a full-frame camera sensor, a 50 mm lens is considered to be the normal lens, whereas for other sensor sizes the lens focal length has to be adjusted to compensate for the size difference (for example, a 35 mm lens provides the equivalent result on an APS-C camera sensor that is of about 2.3 times smaller area).³ Normal lenses are used in applications in which capturing a scene using a mechanism equivalent to a human eye is important. In these applications spatial sensing agrees with human perception of relative sizes and distances.

- *Wide-angle lenses* are lenses with focal lengths smaller than the one of a normal lens for the same camera sensor, providing a significantly wider coverage of the sensed scene from the same position. Typically, they have a focal length shorter than the diagonal of the camera sensor. It is often considered that wide-angle lenses cover an angle of view between 64° and 84° , while there are special cases of ultra wide-angle lenses, like the *fisheye lenses* that cover 180° (with some variations depending on the approach). Again, the sensor size has to be taken into account in estimating the correct lens focal length that guarantees the appropriate angle of view (smaller sensors require smaller focal lengths for the same angle of view). Apparently, there are two types of applications for these lenses, one relating to capturing a wide scene with multiple interest points in various locations, like in landscape photography, and another relating to capturing a wide scene from a very small distance, like in interior spaces. One major feature of these lenses is that they exaggerate the relative size differences, leading to relatively bigger near objects and relatively smaller distant objects. Wide-angle lenses are usually smaller than normal lenses, as the lens size is related to the focal length.
- *Telephoto lenses* are the opposite of the wide-angle lenses. They are lenses with a long focal length and are therefore usually larger in size. In comparison to the diagonal of the camera sensor their focal length is longer. Telephoto lenses are a special case of *long-focus lenses* that differentiate from their general group in that their physical length is shorter than their focal length. This is possible by the use of the so called *telephoto group*, a special arrangement of optical elements that extends the light path to create a long-focus lens in a much shorter physical design. It is often considered that telephoto lenses cover a narrow angle of view of less than 35° (which can be as narrow as 1°). As in the other types of lenses, smaller sensor sizes require smaller focal lengths for the same angle of view. A direct effect of telephoto lenses (and long-focus lenses in general) is to ‘bring’ distant objects near the camera, thus typical applications include portraits, sports, events and wildlife, photography from a distance, in general. On the negative side, these lenses are useless in confined spaces with not enough distance to get the subject in frame. In addition, telephoto lenses require shorter exposure times to guarantee

³ This relates to the so called *crop factor* that will be explained in following paragraphs.

sharp captures, as even the slightest vibration results in significant motion blurring in the captured image.

The *field of view* or *angle of view* is a typical measure of the angular extent of an imaged scene and depends on both the lens and the sensor, as indicated in the above description of the lens types. A classical mathematical description of the field of view for a lens focused at infinity is

$$\text{FOV} = 2 \tan^{-1} \left(\frac{d}{2 \cdot f} \right) \quad (4.12)$$

where d is a selected sensor dimension (can be the diagonal for example) and f is the effective focal length, which for the simplified model of a thin lens is equal to the nominal focal length. Thus, on a full frame camera (sensor size 36 mm $\times$ 24 mm),

- a 17 mm wide-angle lens has an
 $\text{FOV} = 2 \tan^{-1} \left(\frac{\sqrt{36^2+24^2}}{2 \cdot 17} \right) \cdot \frac{180^\circ}{\pi} \approx 104^\circ$ diagonally
- a 50 mm normal lens has an
 $\text{FOV} = 2 \tan^{-1} \left(\frac{\sqrt{36^2+24^2}}{2 \cdot 50} \right) \cdot \frac{180^\circ}{\pi} \approx 47^\circ$ diagonally
- a 500 mm telephoto lens has an
 $\text{FOV} = 2 \tan^{-1} \left(\frac{\sqrt{36^2+24^2}}{2 \cdot 500} \right) \cdot \frac{180^\circ}{\pi} \approx 5^\circ$ diagonally

The angle of view is demonstrated in Fig. 4.7, where the set of photos shown were taken with the same camera, fixed at the same location, using six different lenses (focal lengths). These photos were taken using a camera with an APS-C sensor of a physical size of 23.6 $\times$ 15.7 mm. Using (4.12), it is easy to estimate the angles of view for each of the photos, and those estimates are listed in Table 4.1.

A set of sample photos taken using the same camera but different lenses is shown in Fig. 4.8, which also showcases the different applications.

Since the field of view is influenced by the sensor size, sensors that are smaller than the classical full frame sensor (like those in compact cameras and smart mobile devices) result in smaller fields of view for the same lens, thus, to be able to attain the same field of view in those cameras, wider angle lenses are required.

4.1.2 The Diaphragm and the Aperture

One of the most important mechanisms, usually built-in in camera lenses, which controls the amount of light entering the camera is the ideally opaque mechanism called the *diaphragm*. The word diaphragm comes from the Greek διάφραγμα that is a composite of δια+φράγμα (through+fence). The diaphragm is capable of controlling the opening of the ‘pupil’ of the lens by providing control over an adjustable hole. This adjustable hole is formally referenced as the *aperture*. The centre of the aperture is a point on the optical axis of the lens. There is a range of valid values for an aperture that relate to how wide or narrow the opening is for light to enter the camera. This

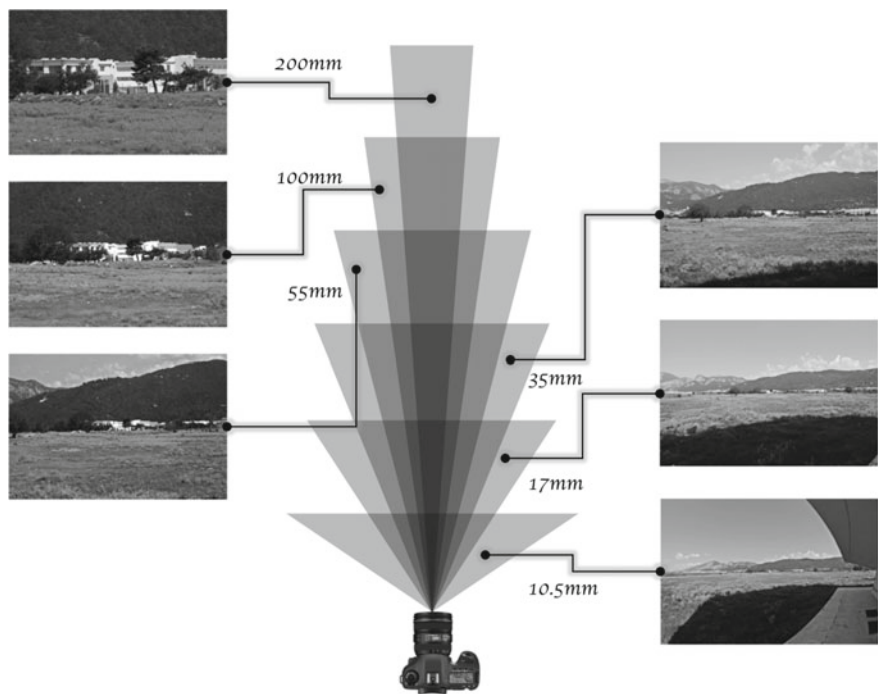


Fig. 4.7 Demonstration of the change in the field of view by different focal length lenses

Table 4.1 Estimates of diagonal FOV for various focal lengths on the same APS-C camera

Focal length (mm)	Approximate FOV (°)
10.5	107
17	80
35	44
55	29
100	16
200	8

range of values follows a predetermined logic for the step size from one value to the another. The most commonly used quantity for an aperture is the *aperture value*, which is defined as *the ratio of the focal length to the aperture diameter*,

$$\text{Aperture value} = \frac{\text{Focal length}}{\text{Aperture diameter}} \tag{4.13}$$

For example, $f/2.8$ or $1 : 2.8$ corresponds to an aperture with a diameter of $1/2.8$ focal lengths. In this notation, the *aperture value* is a fraction, thus a maximum



Fig. 4.8 A set of examples of photos taken with the same camera using different camera lenses

aperture value corresponds to the minimum possible denominator. The *f-number* of a lens is the value in the denominator of the aperture value fraction. Since the aperture diameter is substantially in the denominator of the fraction, a wider aperture (bigger aperture value) means a smaller *f-number*. Lenses capable of providing a large aperture diameter are often called *fast lenses*, since for the same camera sensitivity and lighting conditions, less exposure time is required (fast capturing), due to more light entering the camera from the wide aperture. In general, fast lenses are less widespread due to their higher cost.

The way the *f-numbers* progress in a camera aperture is directly related with dividing (or multiplying) the amount of light entering by 2, a step that is usually referenced as one *stop* or one *exposure value (EV)*. These stops or EVs are multiples of 2, which corresponds to halving (or doubling) the area of the opening of the aperture at each step. Following this reasoning in modern camera systems, the aperture setting is adjusted in discrete steps, the *f-stops*, with each *f-stop* corresponding to an *f-number* and an increase or decrease of the aperture diameter by a factor of $1/\sqrt{2}$ (doubling or halving the area of the opening, since the unit diameter is $\sqrt{2}$). Thus, a valid *f-number* scale can be defined using powers of the square root of two,

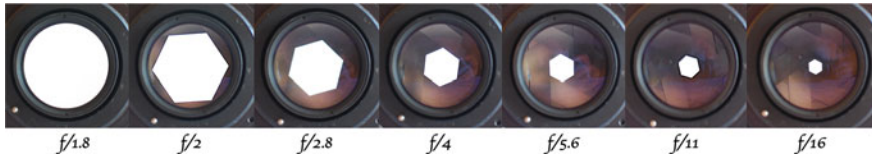


Fig. 4.9 Aperture values for a prime normal lens



Fig. 4.10 Prime and zoom lenses and their specifications

$$f/1 = \frac{f}{(\sqrt{2})^0}, f/1.4 = \frac{f}{(\sqrt{2})^1}, f/2 = \frac{f}{(\sqrt{2})^2}, f/2.8 = \frac{f}{(\sqrt{2})^3} \dots \quad (4.14)$$

with a proper rounding. In this sequence each f -number is *1-stop* higher than the one to its right, permitting double the amount of light to enter. Figure 4.9 shows how the diaphragm of a prime normal lens regulates the aperture for some standard aperture values.

Based on the definition of the aperture value, it should be emphasised that when two totally different lenses are used with the same f -number then the same amount of light is expected to enter the camera, even though the aperture diameter may be different in the lenses. That is, an aperture of $f/9$ on a 80 mm lens corresponds to a diameter of $80/9 = 8.89$ mm, whereas the same aperture value on a 35 mm lens corresponds to a diameter of $35/9 = 3.89$ mm (a 5 mm difference); although the two lenses are completely different, they let the same amount of light to enter the camera.

Lenses are typically marked with their maximum possible aperture value (smallest f -number), for example 50 mm/1:1.8, or 60 mm/1:8, as shown in Fig. 4.10, where (on the left side) two prime and one zoom lenses are shown with their main specifications printed on their front side; in the case of the zoom lens, a range of aperture values is marked that corresponds to the focal lengths that the lens provides. Figure 4.10, on the right side also presents two more prime (a 35 mm nearly-normal for APS-C and a 10.5 mm fisheye) and two more zoom lenses (a 17–35 mm wide-angle and a 70–200 mm telephoto). Short focal length and prime lenses are typically capable of very wide

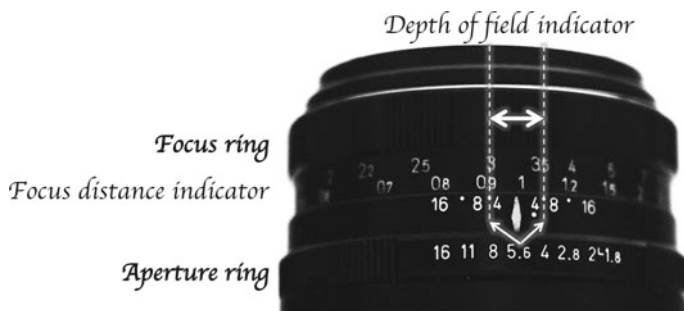


Fig. 4.11 Top view of a normal prime lens set at 5.6 f -number and a focusing distance of around 3.25 m

apertures (say, a maximum aperture of $f/1.4$), whereas longer focal length lenses are more likely to have narrower apertures (say, a maximum aperture of $f/5.6$). Only high-end and very expensive variable focal length lenses are capable of wide apertures throughout the supported focal lengths range, whereas typical consumer grade lenses have a varying maximum aperture with the selected focal length (which either way cannot be lower than $f/3.5 - f/5.6$).

Figure 4.11 shows a top view of a prime normal lens with all the indicators and settings rings. Typically, lenses include a focus ring, to manually set the focus plane, and the aperture ring, to manually select the proper f -number. In addition, the lens provides some insight on the *depth of field*⁴ that is supported by the lens at the current f -number selection; in this figure, the focus ring was set to about 1 m distance, and the aperture was set to 5.6, thus, the indicating arrows and dashed lines show the predicted depth of field, in this case, between 0.9 m and 1.1 m.

4.1.3 Depth of Field

Depth of field is a range of distances that appear acceptably sharp for a given camera system. This range is about the front plane of focus, that single plane at which there is perfect focus. Sharpness gradually fades on both sides (front and back) of the plane of focus. This sharpness fading occurs rather smoothly, which gives a clear distinction of the subject of interest with the rest of the scene. In general, the depth of field depends on the camera sensor, the aperture and the focusing distance. In addition, the viewing distance and the print size also influence the perceived depth of field.

A simplified drawing of the geometry of the depth of field for an ideal symmetrical thin lens is shown in Fig. 4.12. Supposing a point object at perfect focus (on the front

⁴ The depth of field, as discussed in the next section, is the range of distances from the camera at which all objects appear in acceptable focus.

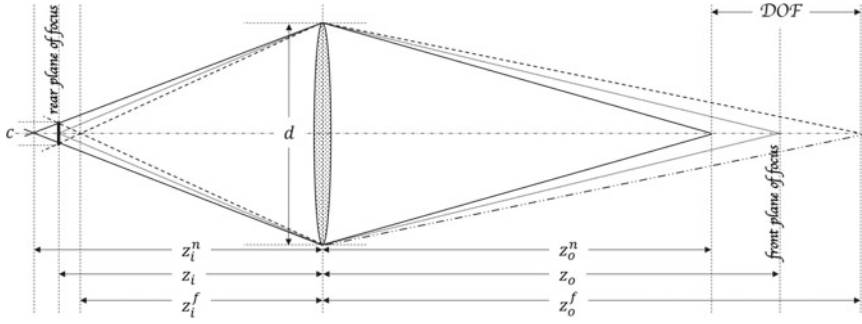


Fig. 4.12 Geometry of the depth of field for an ideal thin lens

focal plane, at location z_o), this point object is focused on the rear focal plane at location z_i . Point objects at distances from $z_o^{(n)}$ to $z_o^{(f)}$ will be focused between $z_i^{(f)}$ to $z_i^{(n)}$ at the rear of the lens respectively, and apparently, will be confined within a disc of diameter c at the rear focal plane. This geometry is controlled by the diaphragm's aperture d . Since the depth of field defines the range of in-focus objects, c is the acceptable circle of confusion. From the similar triangles that are being formed,

$$\frac{z_i^{(n)} - z_i}{z_i^{(n)}} = \frac{z_i - z_i^{(f)}}{z_i^{(f)}} = \frac{c}{d} \quad (4.15)$$

In addition, according to the fundamental formula of a thin lens,

$$\frac{1}{z_o} + \frac{1}{z_i} = \frac{1}{z_o^{(n)}} + \frac{1}{z_i^{(n)}} = \frac{1}{z_o^{(f)}} + \frac{1}{z_i^{(f)}} = \frac{1}{f} \quad (4.16)$$

Thus, it is easy to solve for $z_o^{(n)}$ and $z_o^{(f)}$ given known $\{f, d, c, z_o\}$,

$$\left. \begin{aligned} \frac{1}{z_i} &= \frac{1}{f} - \frac{1}{z_o} \Rightarrow z_i = \frac{f z_o}{z_o - f} \\ \frac{z_i^{(n)} - z_i}{z_i^{(n)}} &= \frac{c}{d} \Rightarrow 1 - \frac{z_i}{z_i^{(n)}} = \frac{c}{d} \Rightarrow \frac{z_i}{z_i^{(n)}} = 1 - \frac{c}{d} = \frac{d - c}{d} \end{aligned} \right\} \Rightarrow$$

$$\Rightarrow \frac{\frac{f z_o}{z_o - f}}{z_i^{(n)}} = \frac{d - c}{d} \Rightarrow$$

$$\Rightarrow \frac{1}{z_i^{(n)}} = \frac{\frac{d - c}{d}}{\frac{f z_o}{z_o - f}} = \frac{(d - c)(z_o - f)}{f z_o d} \quad (4.17)$$

and since $\frac{1}{z_o^{(n)}} = \frac{1}{f} - \frac{1}{z_i^{(n)}}$

$$\begin{aligned}
\frac{1}{z_o^{(n)}} &= \frac{1}{f} - \frac{(d-c)(z_o-f)}{f z_o d} \Rightarrow \\
&\Rightarrow \frac{1}{z_o^{(n)}} = \frac{z_o d - (d-c)(z_o-f)}{f z_o d} \Rightarrow \\
&\Rightarrow z_o^{(n)} = \frac{f z_o d}{z_o d - (d-c)(z_o-f)} \Rightarrow \\
&\Rightarrow z_o^{(n)} = \frac{f^2 z_o d}{d f + c(z_o-f)}
\end{aligned} \tag{4.18}$$

which is further simplified by exploiting the formula of the f -number $N = \frac{f}{d}$,

$$z_o^{(n)} = \frac{z_o f^2}{f^2 + N c(z_o - f)} \tag{4.19}$$

Using the same line of reasoning for the furthest plane of focus in the depth of field,

$$z_o^{(f)} = \frac{z_o f^2}{f^2 - N c(z_o - f)} \tag{4.20}$$

By knowing the near and far limit of focus, it is able to compute the depth of field simply as

$$\text{DOF} = z_o^{(f)} - z_o^{(n)} \tag{4.21}$$

Setting the far limit of depth of field $z_o^{(f)}$ to infinity in (4.20) and solving for the focus distance z_o gives

$$\begin{aligned}
z_o^{(f)} [f^2 - N c(z_o - f)] &= z_o f^2 \Rightarrow \\
&\Rightarrow z_o^{(f)} f^2 - z_o^{(f)} N c(z_o - f) = z_o f^2 \Rightarrow \\
&\Rightarrow z_o^{(f)} f^2 - z_o^{(f)} N c z_o + z_o^{(f)} N c f = z_o f^2 \Rightarrow \\
&\Rightarrow z_o (f^2 + z_o^{(f)} N c) = z_o^{(f)} (f^2 + N c f) \Rightarrow \\
&\Rightarrow z_o = \frac{z_o^{(f)} (f^2 + N c f)}{f^2 + z_o^{(f)} N c} \Rightarrow \\
&\Rightarrow z_o = \frac{f^2 + N c f}{\frac{f^2}{z_o^{(f)}} + N c} \left. \vphantom{\frac{f^2 + N c f}{\frac{f^2}{z_o^{(f)}} + N c}} \right\} \Rightarrow \\
&\text{which for } z_o^{(f)} \rightarrow \infty \left. \vphantom{\frac{f^2 + N c f}{\frac{f^2}{z_o^{(f)}} + N c}} \right\} \Rightarrow z_o = \frac{f^2}{N c} + f = H
\end{aligned} \tag{4.22}$$

This particular value of z_o is called the *hyperfocal distance* H . By using this distance as the object's distance, then solving (4.19) for the near limit of the depth of field gives

$$z_o^{(n)} = \frac{f^2 \left(\frac{f^2}{Nc} + f \right) d}{d f + N c \left[\left(\frac{f^2}{Nc} + f \right) - f \right]} \Rightarrow \Rightarrow \dots \Rightarrow z_o^{(n)} = \frac{\frac{f^2}{Nc} + f}{2} = \frac{H}{2} \quad (4.23)$$

Thus, by knowing the hyperfocal distance one may readily know that with the specific camera, lens and aperture, everything between $H/2$ and infinity (∞) will be in focus.

Substituting the hyperfocal distance into (4.19) and (4.20) results into

$$\begin{aligned} z_o^{(n)} &= \frac{z_o(H - f)}{H + z_o - 2f} \\ z_o^{(f)} &= \frac{z_o(H - f)}{H - z_o} \end{aligned} \quad (4.24)$$

In addition, since $H = \frac{f^2}{Nc} + f \approx \frac{f^2}{Nc}$, (4.24) simplifies to

$$\begin{aligned} z_o^{(n)} &= \frac{H z_o}{H + (z_o - f)} \\ z_o^{(f)} &= \frac{H z_o}{H - (z_o - f)} \end{aligned} \quad (4.25)$$

Overall, the depth of field can be estimated by

$$\text{DOF} = z_o^{(f)} - z_o^{(n)} = \frac{2 H z_o (z_o - f)}{H^2 - (z_o - f)^2} \quad (4.26)$$

Table 4.2 lists a number of depth of field and hyperfocal distance estimates for a full-frame camera when perfect focus is at 10 m. These estimates are made for six lenses (35, 50, 75, 100, 200 and 500 mm) and three aperture settings ($f/1.2$, $f/5.6$, $f/11$). Similarly, Table 4.3 lists a number of depth of field and hyperfocal distance estimates for an APS-C 1.6× camera for the same experimental conditional as in the case of the full-frame camera.⁵ The depth of field limits were computed using

⁵ The circle of confusion for the full-frame camera was set to 0.03255 mm (although it is usually considered to be 0.03 mm) while for the APS-C 1.6× camera was set to 0.20333 mm (although it is usually considered to be 0.019 mm) to match the results given by the online depth of field calculator at <https://www.cambridgeincolour.com/tutorials/dof-calculator.htm> (last accessed March 2022).

Table 4.2 Examples of depth of field estimates for various configurations of a full frame camera; focal plane set at 10 m

Lens (mm)	f -number	Near limit (m)	Far limit (m)	DOF (m)	Hyperfocal plane (m)
35	1.2	7.59	14.66	7.07	31.40
50	1.2	8.65	11.84	3.19	64.05
75	1.2	9.36	10.74	1.38	144.08
100	1.2	9.63	10.40	0.77	256.12
200	1.2	9.91	10.10	0.19	1024.27
500	1.2	9.99	10.01	0.03	6400.91
35	5.6	4.03	∞	∞	6.76
50	5.6	5.80	36.43	30.63	13.77
75	5.6	7.57	14.74	7.17	30.93
100	5.6	8.47	12.20	3.73	54.96
200	5.6	9.57	10.47	0.89	219.64
500	5.6	9.93	10.07	0.14	1372.02
35	11	2.56	∞	∞	3.46
50	11	4.12	∞	∞	7.03
75	11	6.13	27.16	21.03	15.79
100	11	7.38	15.49	8.11	28.03
200	11	9.19	10.96	1.77	111.92
500	11	9.87	10.14	0.27	698.73

Eqs. (4.19), (4.20) and (4.21), whereas the hyperfocal distance was computing using Eq. (4.22).

From the above analysis, it is clear that for a given camera and lens, the diaphragm’s aperture (the f -number) strongly influences the depth of field. By closing the aperture (bigger f -number) the depth of field is expected to get lengthier. For example in Table 4.2, for a 50 mm lens, the depth of field varies from 3.19 m to 30.63 m to ∞ for an f -number of 1.2, 5.6 and 11 correspondingly. In addition, by increasing the f -number, the near limit ($z_o^{(n)}$) gets closer and closer to the camera, while the far limits ($z_o^{(f)}$) goes farther and farther to infinity. Overall, big f -numbers (small apertures) correspond to large depth of fields. On typical lenses like the one in Fig. 4.11 there is a clear indication of the depth of field for any focus distance and aperture setting.

For metric applications, like in photogrammetry, where depth of field may influence the measurements (an infinite depth of field would be ideal in such applications) it is advised to plan a number of indicative experiments in order to have a clear understanding of the depth of field provided by any combination of the available cameras, lenses and aperture settings. Typical tests use specific standard patterns photographed at the same location using various settings, like the ones shown in Fig. 4.13. In cases in which the attainable depth of field is not adequate for a

Table 4.3 Examples of depth of field estimates for various configurations of an APS-C 1.6× camera; focal plane set at 10 m

Lens (mm)	<i>f</i> -number	Near limit (m)	Far limit (m)	DOF (m)	Hyperfocal plane (m)
35	1.2	8.34	12.48	4.13	50.24
50	1.2	9.11	11.08	1.96	102.51
75	1.2	9.59	10.45	0.86	230.61
100	1.2	9.76	10.25	0.48	409.94
200	1.2	9.94	10.06	0.12	1639.57
500	1.2	9.99	10.01	0.02	10246.57
35	5.6	5.19	135.60	130.41	10.79
50	5.6	6.88	18.29	11.41	22.01
75	5.6	8.33	12.51	4.19	49.48
100	5.6	8.99	11.27	2.28	87.92
200	5.6	9.73	10.29	0.56	351.49
500	5.6	9.96	10.04	0.09	2196.09
35	11	3.55	∞	∞	5.51
50	11	5.29	91.06	85.77	11.23
75	11	7.17	16.52	9.35	25.22
100	11	8.19	12.84	4.66	44.81
200	11	9.48	10.58	1.10	179.04
500	11	9.92	10.09	0.17	1118.25

photogrammetric reconstruction, *focus stacking*⁶ has been proposed as a technique to enhance the three-dimensional reconstruction results (Kontogianni et al., 2017b, a), although with limitations in the application.

4.1.4 Focal Length Multiplier

Adopting the simplified thin lens model shown in Fig. 4.5 it becomes evident that any convex lens on a camera accepts light from its visual field to focus it on the opposite side, on the photosensitive surface of the camera sensor. Apparently, as the lens is circular thus is the inverted image that is created at the back of the lens. Nevertheless, the usual format of photographs is rectangular, and so are the sensors (and the photographic films in the past), thus being able to keep only a rectangular part of the focused image, as shown in Fig. 4.14. The figure depicts an ‘optimum’ or

⁶ *Focus stacking*, or *focal plane merging* and *z-stacking*, or *focus blending*, is a digital image processing technique aiming to reconstruct a photo of a wide depth of field by combining a number of narrow depth of field photos focused at different distances. Focus stacking is particularly useful in macro photography or microscopy, where the depth of field is particularly narrow.

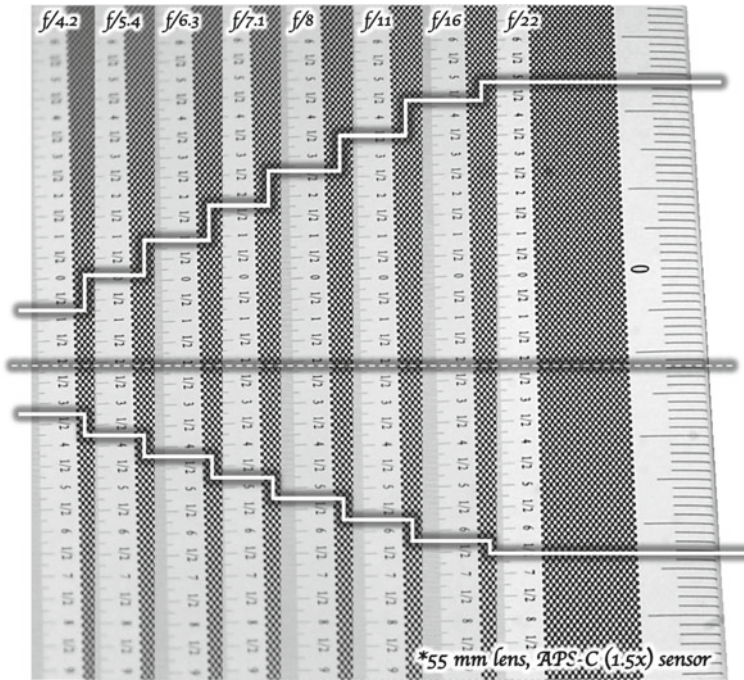


Fig. 4.13 Typical depth of field demonstration for a particular camera sensor and lens combination; the horizontal line corresponds to the focal point, whereas the ‘stairs’ correspond to the varying DOF limits

‘economical’ case, in which the focused circular image matches the photosensitive rectangular sensor, since the sensor corresponds to a rectangle inscribed in the image circle. However, this ‘matching’ needs both a particular lens and a particular sensor size. If the same lens is used in a camera with a smaller sensor, it is clear that a smaller portion of the focused image is captured (as the sensor is a smaller rectangular surface centred on the centre of the circle). There is also the alternative that a lens that has been created for a small sensor is used on a camera with a larger sensor. In this case, the circular focused image is of smaller diameter, which is not enough to cover all the sensor surface, and leaves the four corners of the sensor in total darkness. This case is depicted in Fig. 4.15, where the sensor size does not match the lens (or the other way around) and the focused image cannot cover the entire sensor surface, thus leading to an effect similar to *vignetting*.⁷

In the case of the smaller sensor, the sensor fills with a smaller part of the image that the lens is capable of providing and effectively results in a ‘cropped’ version of the possible full image, making the lens appear to be of a longer focal length (like zooming in to the central part of the scene). The exact opposite effect appears for a

⁷ Generally, vignetting is a radial reduction, a fade off, of an image’s brightness or saturation towards the periphery, which will be discussed in following paragraphs.

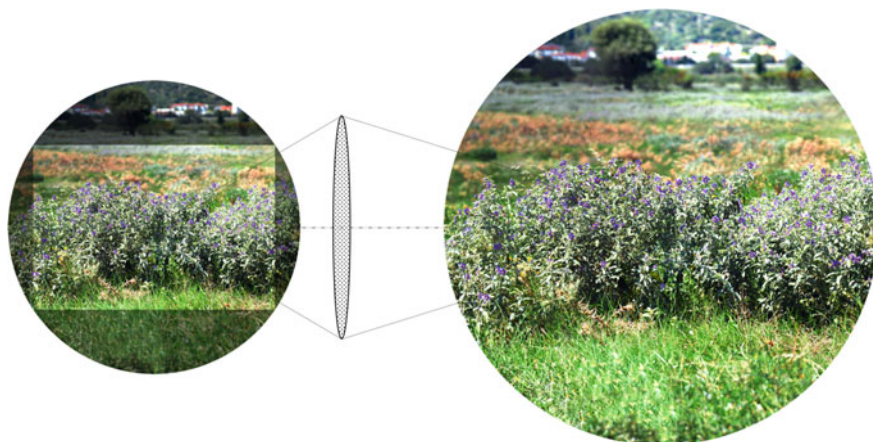


Fig. 4.14 The focused image by a thin lens and the rectangular part that is captured by a camera sensor

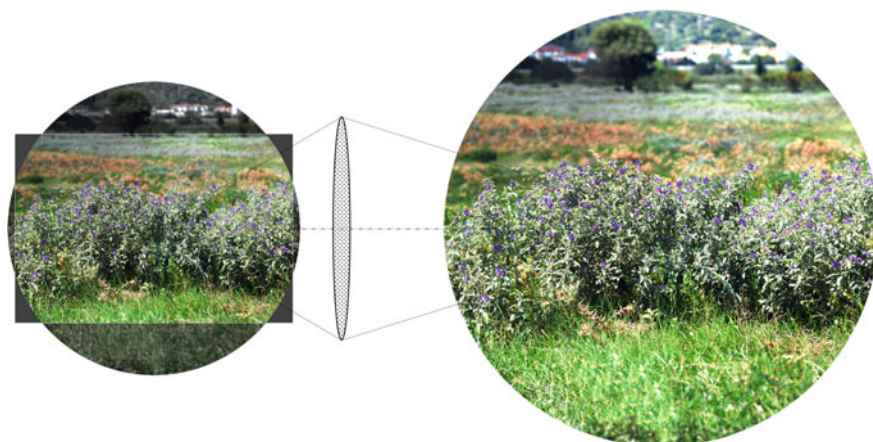


Fig. 4.15 The focused image by a thin lens manufactured for a small sensor and the rectangular part that is captured by a large camera sensor

larger sensor and a lens intended for a small sensor. This effect is usually described as *focal length magnification*, or focal length multiplication, typically considered as an important factor of the sensor (and not the lens), the already mentioned crop factor. Thus, this is a *dual effect*; when it is examined for a particular lens and different sensor sizes it is referenced as the crop factor, whereas when it is examined for a particular sensor size and different lenses it is referenced as the focal length magnification. Table 4.4 presents examples of five variations of a 50 mm lens, manufactured for a full-frame, a 1.3 $\times$, a 1.5 $\times$, a 1.6 $\times$ and a 2.0 $\times$ sensor, and the effect of focal length magnification on those five sensor sizes respectively. Apparently, the matching of

Table 4.4 Examples of focal length multiplication for various sensor sizes and 50 mm lenses manufactured for specific sensors

Sensor crop factor	50 mm 1.0× (mm)	50 mm 1.3× (mm)	50 mm 1.5× (mm)	50 mm 1.6× (mm)	50 mm 2× (mm)
1.0	50	38	33	31	25
1.3	65	50	43	41	33
1.5	72	58	50	47	38
1.6	80	62	53	50	40
2.0	100	77	67	63	50

lenses and sensors happens in the diagonal, thus all sensors ‘see’ a prime (50 mm) lens only for that case. In all other cases the captured image is magnified (zoomed in or out). For example, a full frame sensor ‘sees’ the 50 mm lens that was manufactured for a 2.0× crop factor as a wider angle 25 mm lens, which leaves a large part at the sensor corners in total darkness, whereas a 1.6× sensor ‘sees’ the 50 mm lens for a 1.3× crop factor as a narrower angle 62 mm lens.

4.1.5 Lens Aberrations

Although the thin lens model is a good approximation for the representation and prediction of optical processes, real lenses are far from being perfectly crafted infinitely thin optical instruments. Thus several issues arise, resulting in both spatial and spectral distortions in the images captured by a camera. Typically these distortions are referenced as *aberrations*, either *geometric* or *chromatic*. To alleviate these issues, lenses are usually compound systems of optical elements.

A critical concept in handling and quantifying *geometric aberrations* is that of the *paraxial rays*. Paraxial rays are rays which are virtually parallel to the optic axis, or more formally, paraxial rays are of a small angle (θ) with respect to the optic axis, and are close to the axis. As known, for small angles, $\sin \theta \approx \tan \theta \approx \theta$ and also $\cos \theta \approx 1$. Considering the Maclaurin expansion of $\sin \theta$,

$$\sin \theta = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \frac{\theta^7}{7!} \dots \tag{4.27}$$

it becomes clear that the paraxial rays result in an approximation that uses only first-order terms; this is called the *paraxial approximation* (or *first-order theory*). Using this approximation, geometric aberrations can be quantified by estimating the amount by which light rays miss the paraxial image point, the point at which paraxial rays meet. Thus, aberrations may be determined by calculating the location of the paraxial image of an object point and then tracing a large number of rays to determine the amounts by which the rays depart from the paraxial image point.

If the second term ($\frac{\theta^3}{3!}$) is also retained then the corresponding theory is the *third-order theory*. Ideally, for a point monochromatic source the light wave emerging from the lens would be spherical, or inversely, only a spherical wavefront can converge to a point through a lens. In practice this does not happen and the corresponding distortion is a wave aberration. This distortion from the ideal sphere is called the *optical path difference* D , mathematically related to the coordinates of the point x_0, y_0 , five constants $S_1, \dots, S_5$, and the height of the (image) point above the optic axis h'_0 ,

$$D = S_1(x_0^2 + y_0^2)^2 + S_2 y_0(x_0^2 + y_0^2)h'_0 + S_3(x_0^2 + 3y_0^2)h_0'^2 + S_5 y_0 h_0'^3 \quad (4.28)$$

These five constants $S_1, \dots, S_5$ correspond to five distinctive aberrations. *Philipp Ludwig von Seidel* (1821–1896), back in 1857, was concerned with the *spatial (geometric) aberrations* of lenses and identified those five basic types of aberration relating to monochromatic light, although usually taken as the general case (Seidel, 1857). These aberrations can often be found in the relevant literature as *Seidel aberrations*:

- *Spherical aberration*, due to the spherical surface of the lens;
- *Coma*, due to the spherical surface of the lens, evident for off-axis object points;
- *Astigmatism*, due to asymmetries in lenses' surfaces, and *oblique astigmatism*, due to off-axis ray asymmetry;
- *Curvature of Field*, due to the bending of rays at large angles;
- *Distortion*, due to the geometry of the lens and lens imperfections.

In addition to the spatial (geometric) aberrations, lenses are prone to *spectral or chromatic aberrations*, which relate to the inability of a single thin lens to focus all wavelengths of the incoming light on the same focal plane, due to the phenomenon of dispersion.

Another issue in lenses, which could be included in the set of chromatic aberrations, is the *vignetting*, the effect of having a radially varying image brightness with a fall-off at the four image corners.

Of course, although multiple optical elements are being combined to alleviate those aberrations, it turns out that they too introduce some aberrations, mostly of geometric nature, which results in a distortion of the scene perspective or the objects' shapes.

Last but not least, all these issues vary in each lens.

Spherical Aberration

In lenses made with spherical surfaces (like the typical doubly convex lenses) light rays that are parallel to the optic axis at different distances from the axis, travel through different parts of the lens, which means longer or shorter distances within the lens. Thus, parallel rays at different distances from the optic axis fail to converge

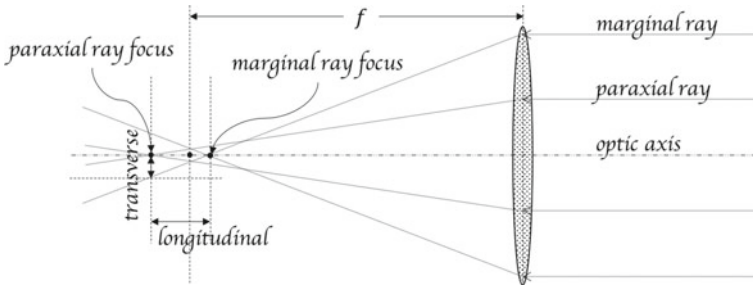


Fig. 4.16 Graphical representation of spherical aberration

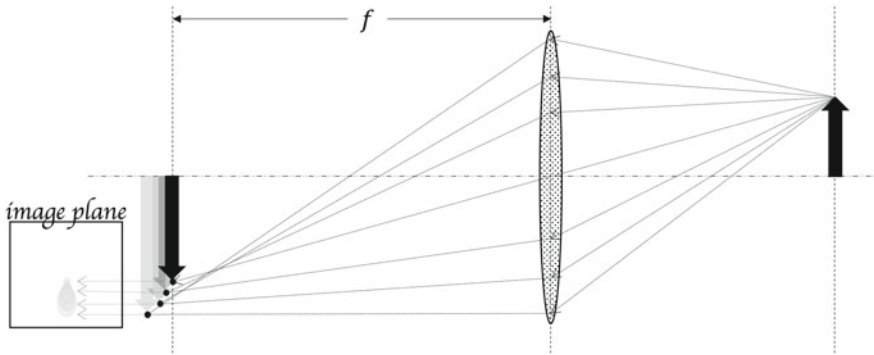


Fig. 4.17 Graphical representation of coma

at the same point, with rays near the axis converging at further points than rays far from the axis, as graphically depicted in Fig. 4.16.

The same phenomenon appears also for rays originating from a point on the optic axis, as those rays pass through different parts of the lens and thus, cannot be focused at the same point.

Coma

Coma is an aberration affecting rays originating from off-axis points. It causes points to appear as comet-like blurs or asymmetrical patches with tails on the image plane, directed away from the optic axis (positive coma), as graphically depicted in Fig. 4.17.

The magnitude of coma is usually deduced from the optical sine theorem. Lenses that produce coma may still be capable of sharp images in the central image regions but with increased blurriness toward the edges. Even in cases in which spherical aberration has been reduced or eliminated, there is still coma as any off-axis point is formed by rays that travel through different parts of the lens.

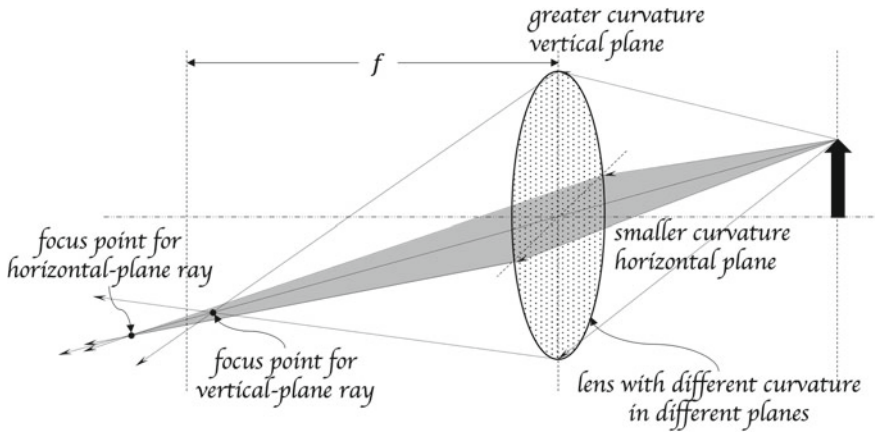


Fig. 4.18 Graphical representation of astigmatism

Astigmatism

Astigmatism is the kind of defect commonly encountered as a result of different lens curvatures in different planes. If the behaviour of light from a point source object is examined, then for a perfect lens it should form a focused bright spot on the opposite side of the lens. But if the focal length of the lens is different for different planes of incident light, there will be no point where all the rays from the object reach a sharp focus. The result is graphically depicted in Fig. 4.18. Seen from the point of view of the off-axis rays, as these rays head through the lens to the point of their focus on the image plane, they pass through a tilted (for them) lens. Thus these rays have to pass through a different lens profile, leading to not being focused at the same distance.

A more general type of astigmatism, which occurs for off-axis rays through any spherically ground lens, is called *oblique astigmatism*. Oblique astigmatism is the kind of astigmatism commonly encountered as a result of different lens curvatures in different planes. Even spherical lenses that are perfectly symmetrical exhibit a type of astigmatism for light which approaches the lens from a point off the optic axis. Oblique astigmatism is an aberration of off-axis rays that causes radial and tangential lines in the object plane to focus sharply at different distances in the image space, as graphically depicted in Fig. 4.19. The image of a point forms focal lines at the sagittal and tangential foci and in between (in the absence of coma) an elliptical shape.

Curvature of Field or Petzval Curvature

The Petzval or field curvature is the aberration in which lenses project planar objects as curved (non-planar) images. Put differently, light from all points of an object are brought to a sharp focus on a curved instead of a planar surface. The effect is more

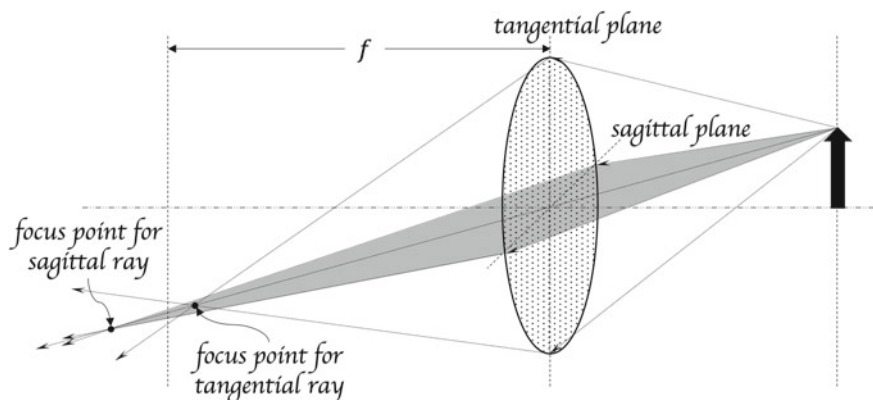


Fig. 4.19 Graphical representation of oblique astigmatism

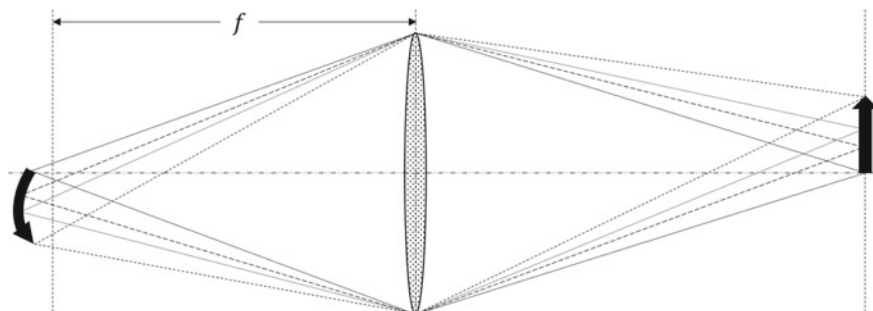


Fig. 4.20 Graphical representation of curvature of field

pronounced for off-axis rays, since those rays pass through an effectively smaller lens diameter and an effectively higher lens power, as graphically depicted in Fig. 4.20. According to the Seidel parameters (S_4) the longitudinal focus displacement is proportional to the square of the image height (h'_0), but the field curvature does not introduce any loss of definition (sharpness is preserved).

Distortion

The previously presented aberrations, mainly due to lens imperfections may be minimised by using complex combinations of optical elements. Regardless the correction though, there are still more aberrations that occur due to the geometry of the lenses, that result in having image points radially displaced toward or away from the optic axis, proportionally to the third power of the transverse distance from the axis. As a result, the image formed is geometrically distorted so that a square appears to be either barrel-shaped (*barrel distortion*) or cushion-shaped (*pincushion distortion*).

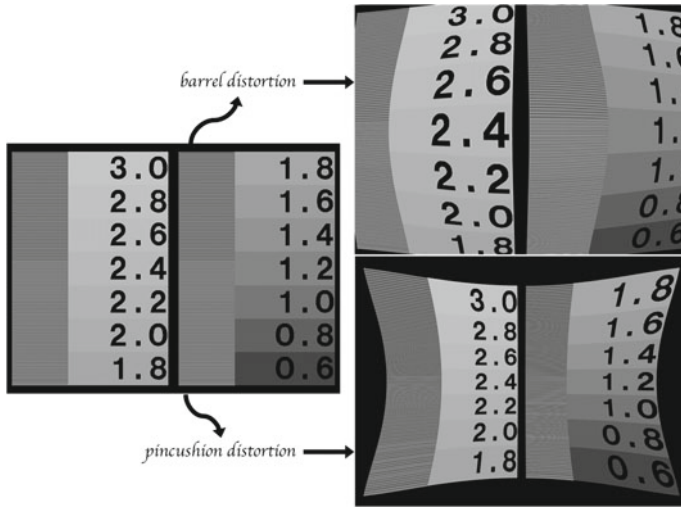


Fig. 4.21 The two types of axial geometric distortions

Using a different definition, in radial distortion, the coordinates of imaged points are displaced towards (pincushion) or away (barrel) from the image center proportionally to the radial distance.⁸

In fact, what happens is that light from off-axis points diverge from the ideal location in the formed image in a manner proportional to the distance from the axis. As light rays enter through different areas of the lens, it is equivalent to passing through different focal lengths, thus resulting in different magnification factors radially around the center in the image plane. This way, although the formed image is sharply focused, points from a regular grid converge to image points for which the distance from the image center either increases or decreases faster than expected, resulting in a distorted imaged scene, as graphically depicted in Fig. 4.21. A decrease in the magnification with distance from the optical axis results in the *negative distortion* called barrel distortion, whereas an increase in the magnification with distance from the axis results in the *positive distortion* called pincushion distortion. The problem is easily observed in simple magnifiers with thick double convex lenses, for which the maximum achievable magnification is practically limited by this issue.

Radial distortion has been a major issue in photogrammetry applications where metric accuracy is of utmost importance and has been extensively studied, and modelled using the general polynomial equation (Slama, 1980; Zhang, 1999; Heikkila and Silven, 1997, 1996), based on early work by Conrady (1919), later revised by Brown (1971) and the model proposed by Brown (1966),

$$r_d = r + \delta_r = r (1 + \kappa_1 r^2 + \kappa_2 r^4 + \kappa_3 r^6 + \dots) \quad (4.29)$$

⁸ Let's suppose here, without loss of generality, that the image center coincides with the optical axis.

κ being the distortion parameters or coefficients. Although this general form expresses the most commonly used radial distortion models, a selection of possible polynomials along with rational functions, have been proposed in the relevant literature (Slama, 1980; Zhang, 1999; Heikkila and Silven, 1997, 1996; Hartley and Zisserman, 2003), including

$$\begin{aligned}
 & 1 + \kappa_1 r \\
 & 1 + \kappa_1 r^2 \\
 & 1 + \kappa_1 r + \kappa_2 r^2 \\
 & 1 + \kappa_1 r^2 + \kappa_2 r^4 \\
 & \frac{1}{(1 + \kappa_1 r)} \\
 & \frac{1}{(1 + \kappa_1 r^2)} \\
 & \frac{(1 + \kappa_1 r)}{(1 + \kappa_2 r^2)} \\
 & \frac{1}{(1 + \kappa_1 r + \kappa_2 r^2)} \\
 & \frac{(1 + \kappa_1 r)}{(1 + \kappa_2 r + \kappa_3 r^2)} \\
 & \frac{(1 + \kappa_1 r^2)}{(1 + \kappa_2 r + \kappa_3 r^2)}
 \end{aligned} \tag{4.30}$$

The simplest radial distortion models make use of low-order polynomials,

$$\begin{aligned}
 \hat{x}_c &= x_c(1 + \kappa_1 r_c^2 + \kappa_2 r_c^4) \\
 \hat{y}_c &= y_c(1 + \kappa_1 r_c^2 + \kappa_2 r_c^4)
 \end{aligned} \tag{4.31}$$

where κ_1, κ_2 and $r_c^2 = x_c^2 + y_c^2$ are the radial distortion parameters, and (x_c, y_c) are the image point coordinates after perspective division and before scaling (by the focal length) and shifting (by the image centre at (c_x, c_y)), which correspond to the translated and rotated three-dimensional scene point coordinates. The final radially distorted coordinates are defined as

$$\begin{aligned}
 x_s &= f x_c + c_x \\
 y_s &= f y_c + c_y
 \end{aligned} \tag{4.32}$$

f being the lens focal length.

Last but not least, it should be emphasised that a special case of lenses, the *fish-eye* lenses, cannot be efficiently modelled with the radial distortion polynomials; these lenses can be more effectively represented by polar projection models with the polar north coinciding with the optical axis (Szeliski, 2011),

$$(\cos \theta \sin \theta, \sin \theta \sin \phi, \cos \phi) = s(x, y, z) \quad (4.33)$$

with the mapping equations expressed as,

$$\begin{aligned} x' &= s\phi \cos \theta = s \frac{x}{r} \tan^{-1} \frac{r}{z} \\ y' &= s\phi \sin \theta = s \frac{y}{r} \tan^{-1} \frac{r}{z} \end{aligned} \quad (4.34)$$

in which s is an arbitrary scaling factor representing the radius of the sphere and (ϕ, θ) are the angles that parametrise the spherical surface onto which the projection takes place with $(\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta) \propto (x, y, f)$; $r = \sqrt{x^2 + y^2}$ is the radial distance in the (x, y) plane and $s\phi$ the equivalent notion in the (x', y') plane; s plays a role similar to the focal length f when for small values of (x, y) the mapping equation simplify to $x' \approx s \frac{x}{z}$.

Chromatic Aberration

Regardless of any geometric aberration present or corrected in a lens, there is still another issue to consider, one that relates to the dispersion of light. Since the index of refraction for a lens varies slightly with the wavelength of light passing through, the lens is susceptible to focusing light of different wavelength at different distances. Apparently this corresponds to having different magnification factors for lights of different wavelengths. Put in another way, since the actual focal length of lenses depends on refraction and the index of refraction is influenced by wavelength (practically, the colour of light), different colours tend to focus at different distances, with shorter wavelength light (i.e. blue) focusing at shorter distances, as shown in Fig. 4.22. As a result of this aberration, there is a geometric displacement and loss of focus for light at wavelengths not coinciding with those that focus at the nominal focal length and sensor location. The appearance of this aberration takes the form of monochromatic phantom object borders, especially at sharp contrast edges in the captured images. Chromatic aberration is typically tackled with combinations of lenses that attempt to cancel the effect element upon element.

Vignetting

Vignetting is another issue inherent in real-world lenses, which is rather a property of lenses. Vignetting is the effect of image brightness falling off towards the edge of the image frame and particularly the frame corners. Vignetting is caused by a number of factors and can be distinguished, according to Ray (2002), to (a) mechanical, (b) optical, (c) natural, (d) pixel vignetting (in digital imaging), and (e) photographic film (in analogue imaging) vignetting. Among these types, natural and mechanical

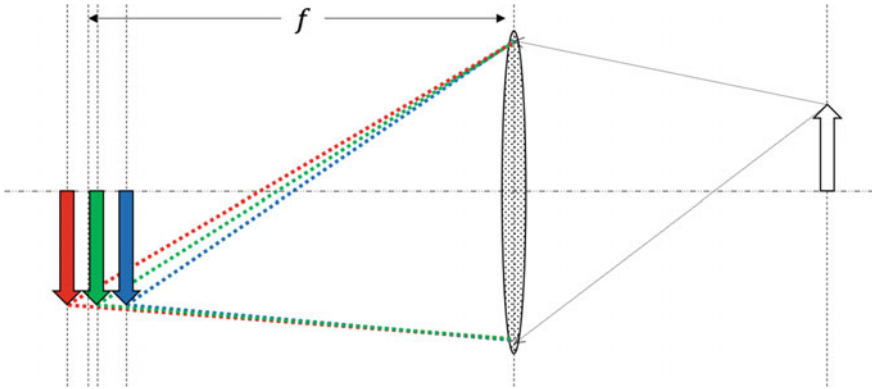


Fig. 4.22 Graphical representation of chromatic aberration, in which light of different wavelengths focuses with a different focal length and at a different distance, resulting in both a geometric (in-plane) displacement and a loss of focus

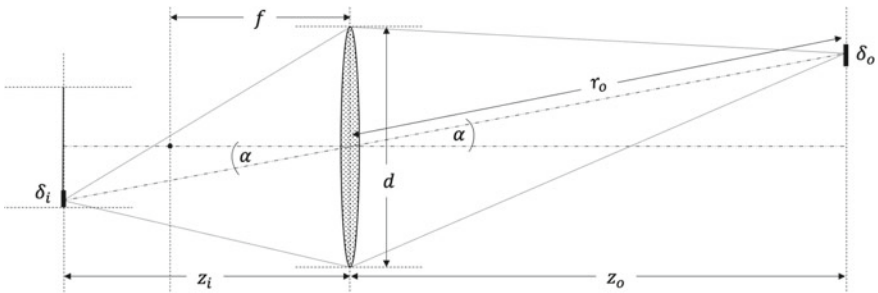


Fig. 4.23 Graphical representation for the illustration of the effect of natural vignetting in lenses

vignetting stand out as the types of phenomena usually to contribute to most to the overall effect (Ray, 2002).

Natural vignetting (also *natural illumination falloff*) is caused by the blocking of light rays, or put in another way, by the foreshortening in the object surface, projected pixel, and lens aperture. The falloff in natural vignetting is approximated by the $\cos^4$ law of illumination falloff, as it is proportional to the fourth power of the cosine of the angle, at which the light hits the photosensitive surface. Suppose light is leaving from an object's surface patch of size δ_o at an off-axis angle α , as shown in Fig. 4.23. For the general case of off-axis sources, the amount of light reaching the lens is reduced by a factor $\cos \alpha$ relative to the off-axis angle. In addition, the amount of light is also reduced by the typical $1/r^2$ radial distance factor, in this case $r : r_o = z_o / \cos \alpha$. An additional foreshortening occurs for the actual area of the aperture through which light passes, which is also proportional to $\cos \alpha$, thus the lens as seen from the object point is no longer a circular but ellipsoid with an area $A = \pi \cdot d/2 \cdot \cos \alpha (d/2)$. By

considering all those factors together, the amount of light starting off the object patch δ_o , passing through the aperture to the image plane is proportional to⁹

$$\delta_o \cos \alpha \frac{1}{r_o^2} A = \delta_o \cos \alpha \frac{\cos^2 \alpha}{z_o^2} \pi \frac{d}{2} \cos \alpha \frac{d}{2} = \delta_o \frac{\pi}{4} \frac{d^2}{z_o^2} \cos^4 \alpha \quad (4.35)$$

From the geometry in the described case and considering that the surface elements δ_* are parallel disk-shaped patches (without loss of generality) one may use the solid angle Ω that the center of the lens ‘sees’ these surface elements to derive a relation among them as follows

$$\Omega = \left\{ \begin{array}{l} \frac{\delta'_o}{r_o^2} = \frac{\delta_o \cos^3 \alpha}{z_o^2} \quad \text{at the object side} \\ \frac{\delta'_i}{r_i^2} = \frac{\delta_i \cos^3 \alpha}{z_i^2} \quad \text{at the image side} \end{array} \right\} \Rightarrow \quad (4.36)$$

$$\frac{\delta_o \cos^2 \alpha}{z_o^2} = \frac{\delta_i \cos^2 \alpha}{z_i^2}$$

$$\Rightarrow \frac{\delta_o}{\delta_i} = \frac{z_o^2}{z_i^2}$$

where $\delta'_* (= \delta_* \cos \alpha)$ are the foreshortened areas of the patches and r_i is the distance of the imaging surface element from the lens centre; apparently, the ratio of the areas of the object surface δ_o and the corresponding image surface δ_i are analogous to the ratio between z_o and z_i squared. From (4.35) and (4.36), it is easy to derive the relation among the amount of light reaching the imaging surface, the aperture diameter d , the focusing distance $z_i (\approx f)$, and the off-axis angle α ,

$$\delta_o \frac{\pi}{4} \frac{d^2}{z_o^2} \cos^4 \alpha = \delta_i \frac{\pi}{4} \frac{d^2}{z_i^2} \cos^4 \alpha \approx \delta_i \frac{\pi}{4} \left(\frac{d}{f} \right)^2 \cos^4 \alpha \quad (4.37)$$

which is termed the *fundamental radiometric relation* that connects the scene radiance L with the captured image irradiance E , more formally expressed from the equation of the flux received by the lens from the object patch δ_o with the flux density projected onto the imaging patch δ_i ,

$$E \delta_i = L (\delta_o \cos \alpha) \omega \Rightarrow$$

$$E = L \frac{\delta_o}{\delta_i} \cos \alpha \frac{\pi \left(\frac{d}{2} \right)^2 \cos \alpha}{\left(\frac{z_o}{\cos \alpha} \right)^2} \approx L \left(\frac{z_o}{f} \right)^2 \frac{\pi}{4} \cos^2 \alpha \left(\frac{d \cos \alpha}{z_o} \right)^2 \Rightarrow \quad (4.38)$$

$$E = L \frac{\pi}{4} \left(\frac{d}{f} \right)^2 \cos^4 \alpha$$

⁹ For more information see Szeliski (2011), Horn et al. (1986), Nalwa (1994), Hecht (1998), Ray (2002).

where $\omega = \pi \left(\frac{d}{2}\right)^2 \cos \alpha / \left(\frac{z_o}{\cos \alpha}\right)^2$ is the solid angle subtended by the lens.

It should be noted here that, as shown in the above analysis, the amount of light captured in the imaging surface depends on its area, which is a fact to be taken seriously into account when choosing camera systems for metrology and photogrammetry. It is due to this fact that compact and mobile phone cameras with small sensors are unable to capture enough light and rely on electronic amplifiers to create images, resulting in much noisier outcomes, and significantly sophisticated algorithms are used to alleviate the problem. Last but not least, wide angle lenses are expected to be particularly prone to natural vignetting, whereas telephoto lenses are in general less affected.

Another prominent type of vignetting is the *mechanical vignetting*, which occurs when light from off-axis sources is partially occluded or blocked by external objects, particularly near the periphery of the lens. These blocking objects can be any type of lens hoods or even filters stacked onto the lens. The resulting illumination falloff also depends on the aperture, with wider apertures corresponding to more pronounced vignetting. It is emphasised that mechanical vignetting cannot be easily expressed mathematically and a full ray-tracing of the actual lens design is required.¹⁰

The *optical vignetting* is caused by the shading of rear optical elements in a complex multi-element lens system. As rear elements are shaded by elements in front of them, the effective lens opening for off-axis light is reduced, resulting in a light falloff at the periphery. Again, in this case the aperture plays also an important role, with wider apertures resulting in more pronounced optical vignetting.

The special cases of *pixel vignetting* and *film vignetting* correspond to the falloff due to the different angles the light hits the photosensitive surface in either case. Apparently, light at the normal direction produces stronger signals than one at an oblique angle. In digital cameras there are image processing algorithms embedded to compensate for this type of vignetting.

4.1.6 A Curiosity of Convex Lenses

Closing this section on the lenses, it is interesting to note a ‘curiosity’ of the typical doubly convex lenses in their capacity to create real or ‘virtual’ images depending on the distance of the imaged object in relation to their focal length. The situation is depicted in Fig. 4.24. When an object is very close to such a lens, closer than the focal length ($z_o' < f$), then the object is not inverted like in the typical case, in which the object is further than the focal length ($z_o > f$), as shown in the thin lens model (Fig. 4.5). The lens acts as a magnifying glass creating a ‘virtual’ image that is projected at the front and not at the back of the lens (pay attention to the location of z_i'). In Fig. 4.24 the far grey object is focused inverted whereas the black object close to the lens is magnified and projected to an upright virtual image. Apparently, when

¹⁰ In practice, there are empirical models to approximate the situation (Kang and Weiss, 2000; Zheng et al., 2009).

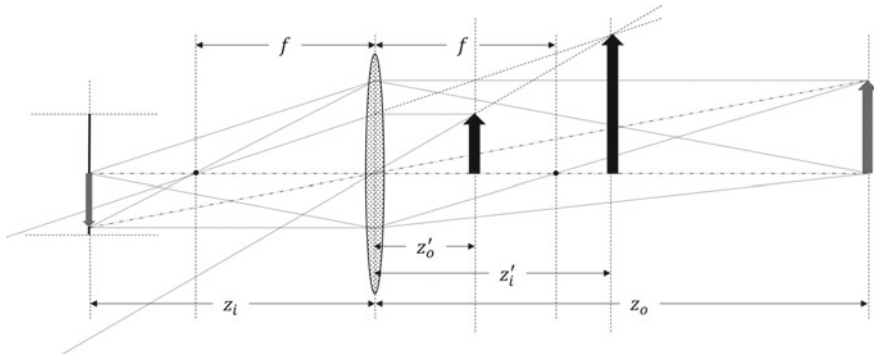


Fig. 4.24 The real and the virtual image created by a doubly convex thin lens depending on the object distance

the object moves further from that close distance it begins to blur until it reaches the distance equal to the focal length ($z'_o = f$) where it is totally blurred (no focus is possible, remember the fundamental lens equation (4.3)), and even a small movement away from the lens results in the classical inversion of the imaged object.

4.2 The Shutter

The camera shutter is a mechanical, electrical or electromechanical device that controls the incidence of light on the photosensitive surface of the camera by covering and uncovering the sensitive surface for an accurately timed period. This controlled *exposure* of the sensitive surface to the incoming light is usually marked by the *shutter speed*, a quantity that corresponds to the exposure time. Usually, for exposure times longer than 1 s the shutter speed equals the exposure time followed by a seconds symbol (like 3" for 3 s), whereas, for exposure times shorter than 1 s the shutter speed equals the reciprocal to the exposure time (for example a speed of 500 correspond to an exposure time of 1/500 sec). The timing mechanism in camera shutter systems was originally pneumatic or clockwork, but recently has been changed to be mostly electronic. Camera shutters support *instantaneous exposure* typically ranging from 30 to 1/4000s, or *Bulb exposure* that keeps the shutter open as long as the shutter button is pressed.

There are a number of different types of shutter mechanisms, including the *focal-plane shutters*, *simple leaf shutters*, *rotating shutters*, *hemispheric shutters*, *diaphragm shutters*, *central shutters*, and *electronic shutters*. The most common are the leaf and focal-plane shutters. Leaf shutters are usually within the lens, rarely immediately behind or in front of the lens. Focal-plane shutters are curtain-like flat surfaces mounted just in front of the photosensitive surface. Modern digital cameras use a combination of mechanical and electronic shutter. It should be stressed that

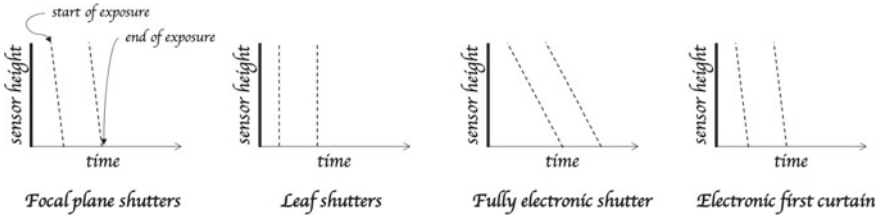


Fig. 4.25 Representation of the temporal response of basic types of camera shutter mechanisms

electronic shutters can accommodate extremely faster speeds. Electronic shutters are of two types, the *rolling shutters*, and the *transfer shutters*. No mechanical or other moving components are used and the shutter is ‘simulated’ by the way pixel cell charges are being transferred. In essence, digital sensors can be switched on and off on demand, thus they can be controlled as both the sensitive device and the shutter. However there is a restriction in that the exposure cannot end for the whole sensor at the same time, as in most digital sensors, reading-out the captured light (as charge) has to be done one row at a time, resulting in a required time to get the full frame exposure. This characteristic gives rise to what is called the *rolling shutter effect*, which is the deformation of moving objects (skew or wobble) due to the capturing of the motion at different exposure times. The temporal profile of the exposure for various types of shutter mechanisms are shown in Fig. 4.25.

A particular type of photographic shutter is the *Kerr cell shutter* that is used for very short exposure times to the nanosecond scale (10^{-9} sec), based on the effect of *birefringence*.¹¹ The Kerr cell can be controlled to open and close like a shutter for a really short duration and it has been used in the early 20th century to measure the speed of light.

Last but not least, when cameras are using flashes, special attention should be paid to the synchronisation of the shutter and the flash triggering, which might turn out to be quite complicated (at least used to be with traditional equipment). Modern electronic flashes with virtually instantaneous response have effectively addressed most relevant issues.

In practice, controlling the shutter speed provides two main functionalities, (a) control over the amount of light entering the camera, which means to be able to set the right amount of light to be captured for a correctly exposed image, (b) control over the captured motion, which means to be able to freeze motion or accept motion blur. For the purposes of photogrammetry and metrology applications high speeds are preferable to ensure images free of motion blur, which, unfortunately, comes with the cost of needing much more light in the scene.

¹¹ A material is birefringent when its refractive index depends on the polarisation and propagation direction of light passing through it.

4.3 The Imaging Sensor

Within digital cameras, the imaging sensor (simply called *the sensor*) is the main component for digital imaging and is situated at the back of the camera.¹² The sensor is a special flat rectangular semiconductor that is sensitive to light, capable of absorbing photons and releasing electrons. At their heart, *imaging sensors in digital cameras are analogue devices that count the number of photons that hit their surface*. They replaced the film in traditional analogue cameras and are crucial parts of the modern cameras. Among the most important factors that affect the captured image quality relate to the sensor size and specifications (like the analogue gain, the sensor noise, or the resolution of the analogue to digital conversion).¹³ Some cameras provide insight into these factors by storing parameter values in the EXIF tags¹⁴ embedded in the image files. In general, those parameter values can be found in the camera manufacturers' specifications and a number of Web sites are devoted to providing in-depth comparative studies.¹⁵

4.3.1 The Imaging Sensor in Digital Cameras

Ideally, the imaging sensors release an electron for every photon they capture and count the number of electrons to form an image. Since in reality this cannot be achieved, systems resort to estimates that include noise (the *photon noise* or *read noise*) and a *limited dynamic range*. Photon noise relates to the process of measuring photons. Dynamic range relates to the peak signal to noise floor ratio at specific settings, noise floor being a combination of photon noise, amplifier noise (ISO gain in Fig. 3.16) and analogue to digital conversion resolution (A/D in Fig. 3.16), which in terms of the electrons released in the process can be expressed as

$$D = \frac{n_e^{(\text{peak})}}{n_e^{(\text{noise})}} \quad (4.39)$$

¹² In special digital cameras, it is in a separate component called the *digital back* that is detachable from the main camera body.

¹³ It should be stretched that the sensor size is not the direct reason for a low quality image but the overall required camera setup, particularly the lens, for a given result.

¹⁴ EXIF comes from Exchangeable image file format, as defined by the Japan Electronic Industries Development Association and the Camera and Imaging Products Association specifications, initially released in 1995. EXIF uses existing file formats, like JPEG or TIFF, and defines additional metadata tags. The current (2016) EXIF standard specification can be found in <http://www.cipa.jp/std/documents/e/DC-008-Translation-2016-E.pdf> (last accessed March 2022).

¹⁵ Like in the Roger Clark's website, *Digital Camera Reviews and Sensor Performance Summary*, online at <http://www.clarkvision.com/imagedetail/digital.sensor.performance.summary/> (last accessed March 2022).

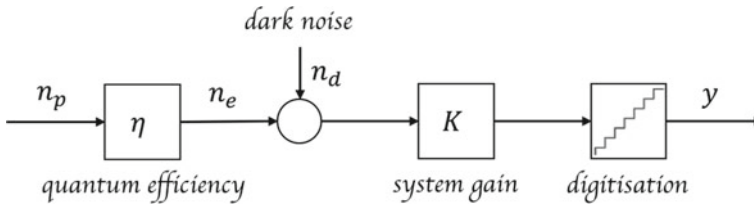


Fig. 4.26 A simplified single pixel model in imaging sensors

where D is the dynamic range per pixel, $n_e^{(\text{peak})}$ is the electrons count that correspond to the peak signal per pixel and $n_e^{(\text{noise})}$ is the electrons count that corresponds to the noise per pixel. Modern technologies are capable of as low photon noise as 1 electron which modifies the equation as,

$$D = \frac{n_e^{(\text{peak})}}{\sqrt{(n_e^{(\text{noise})})^2 + i_d(T) \cdot t + 1}} \quad (4.40)$$

where t is the exposure time, $i_d(T)$ is a function of temperature T that corresponds to the electrical current in total dark, and the 1 corresponds to the single photo-electron. It should be noted that the photon noise is modelled as a Poisson distribution and is approximated by the square root of the photons count (for example as few as 36 photons are expected to be associated with 6 electrons of noise, thus resulting in $D = 6$, whereas 360,000 photons are associated with 600 electrons of noise and a dynamic range of $D = 600$ for the imaging sensor). This fact emphasises the need for high photon counts when a high dynamic range and thus a better image quality is required.

A simplified representation of a single pixel model is shown in Fig. 4.26, in which n_p is the number of photons, n_e is the number of electrons released given a sensor quantum efficiency η , and n_d is the number of electrons in total light absence (dark noise); the model includes also the system amplifier with a gain K and the analogue to digital subsystem; the final output y is an intensity value for the single pixel.

Figure 4.27 shows a more concrete mathematical model of a single pixel in imaging sensors taking into account the exposure time, thus representing mean values and standard deviations during the exposure time. In this model, the *total quantum efficiency* is defined as

$$\eta(\lambda) = \frac{\mu_e}{\mu_p} \quad (4.41)$$

and expresses the fraction of the average number of photons absorbed by the sensor during the exposure time as a function of the photon wavelength λ . The average number of photons that hit a pixel of area A during the exposure time t_{exp} can be computed from the irradiance E on the sensor surface

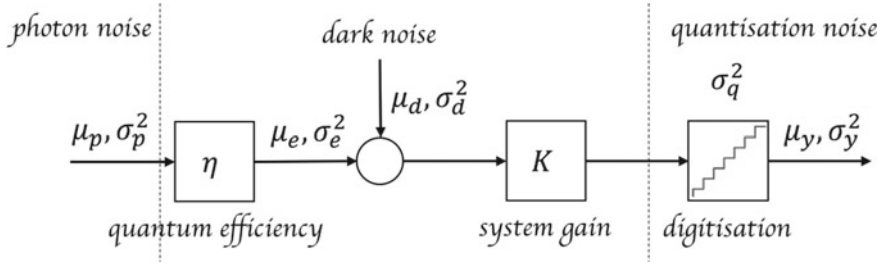


Fig. 4.27 A mathematical single pixel model in imaging sensors over an exposure time

$$\mu_p = \frac{A \cdot E \cdot t_{\text{exp}}}{h \cdot \frac{c}{\lambda}} \quad \text{W/m}^2 \quad (4.42)$$

where c the speed of light and h the Planck's constant.

Overall, the process modelled as shown in Fig. 4.27 is assumed to be linear and the mean output digital signal μ_y is defined as

$$\mu_y = K(\mu_e + \mu_d) \quad \text{or} \quad \mu_y = \mu_y^{(\text{dark})} + K\mu_e \quad (4.43)$$

in which the dark signal $\mu_y^{(\text{dark})}$ generally depends on parameters like the exposure time and the ambient temperature and corresponds to the output in the absence of input. The end-to-end relation between a pixel intensity exiting the sensor and the number of photons entering the sensor is thus given by

$$\mu_y = \mu_y^{(\text{dark})} + K \cdot \eta \cdot \mu_p = \mu_y^{(\text{dark})} + K \cdot \eta \cdot \frac{A \cdot E \cdot t_{\text{exp}} \cdot \lambda}{h \cdot c} \quad (4.44)$$

In addition, the number of electrons that are released n_e follows a Poisson distribution as imposed by the quantum mechanics, thus the mean number equals the variance $\sigma_e^2 = \mu_e$. The statistics of this quantity imposes a type of *shot noise* that is given for all types of cameras regardless the technology and manufacturer. As a linear model is assumed, all sources of noise can be added to produce the overall noise as

$$\begin{aligned} \sigma_y^2 &= K^2(\sigma_e^2 + \sigma_d^2) + \sigma_q^2 \\ &= \underbrace{K^2\sigma_d^2}_{\text{offset}} + \underbrace{\sigma_q^2}_{\text{slope}} + K(\mu_y - \mu_y^{(\text{dark})}) \end{aligned} \quad (4.45)$$

The resulting quality of the output can be evaluated by the signal to noise ratio,

$$\text{SNR} = \frac{\mu_y - \mu_y^{(\text{dark})}}{\sigma_y} \quad (4.46)$$

which by using the previous definitions can be expressed as

$$\text{SNR}(\mu_p) = \frac{\eta \cdot \mu_p}{\sqrt{\sigma_d^2 + \frac{\sigma_q^2}{K^2} + \eta \cdot \mu_p}} \quad (4.47)$$

For an ideal sensor ($\eta = 1$, $\sigma_d = 0$, $\sigma_q/K = 0$) would apparently result into $\text{SNR}_{\text{ideal}} = \sqrt{\mu_p}$.

A typical imaging sensor architecture consists of numerous miniature *wells*, really small cells, or ‘boxes’, or cavities, or photosites, in which light particles are expected to enter and excite the sensitive semiconductor. There are two dominant technologies in imaging sensors, (a) the *charge-coupled device (CCD)* and (b) the *complementary metal oxide on silicon (CMOS)*. In CCDs, photons are accumulated in the wells and then charges are transferred from well to well to the sense amplifiers and then the analogue to digital converter. There is a difference in the shutter technology between digital still cameras and digital video cameras, in that video cameras make use of a rolling shutter that exposes and transfers each pixel line separately. In CMOSs, photons accumulated in the wells directly affect the conductivity of the semiconductor, enabling the control of the exposure duration, and the local amplification before the electrical signal is being transferred to the next subsystems using multiplexing. Since CMOS technology outperforms the CCD technology in terms of low power consumption, although initially of lower image quality, it is the current preference by most digital camera manufacturers in a wide range of applications. More in-depth technical descriptions regarding the characterisation of imaging sensors can be found in the most recent EMVA Standard 1288 (EMVA, 2016).

4.3.2 The Sensor Image Array

Imaging sensors are compact complex systems, consisting mainly of a photosensitive region and all the required electronics to convey the optical information to the image processing and storage systems of cameras. Usually, imaging sensors are compared according to their pixel count in the Megapixel scale (millions of pixels), which is a type of a function of the region on the sensor chip that is photosensitive. By design, the photosensitive part of a sensor includes a number of micro-devices for each of the pixels. As the sensitive region is a field of microscopic devices, the physical dimensions, although quite small, are not infinitesimal. The physical spacing between adjacent sensor cells is typically called the *sampling pitch*, usually expressed in micrometers-squared or microns-by-microns (millionths of a meter $1 \mu\text{m} = 10^{-6} \text{m}$). As any single pixel is formed using regular arrangements of cells, the sampling pitch defines the area each pixel occupies. Sensors with small sampling pitch have a high sampling density, thus being able to provide a high resolution image for a given active sensor area. However, a small pitch also relates to a small actual area on chip, which limits the amount of photons that can be captured. Apparently, this makes such sensors inefficient for fast frame rates (capturing of motion) and for low light conditions (York and Jain, 2011).

As the grid on the imaging sensor is regular, the sampling pitch also corresponds to the pixel size. Converting between the sampling pitch (pixel size) and the image size is fairly straightforward, assuming a square pixel area,

$$p = \frac{s_w}{W} \quad (4.48)$$

where p is the sampling pitch, usually in μm , s_w is the sensor size in the horizontal direction (width), usually in mm and W is the horizontal image size (width) in pixels. Thus, an imaging sensor with a width of 30 mm that outputs images with a width of 6000 pixels has a sampling pitch of $p = s_w/S = 30/6000 = 0.005 \text{ mm} = 5 \mu\text{m}$; equivalently, a sensor with a square sampling pitch (pixel size) of $4 \mu\text{m}$ that outputs images of 6000 pixels wide has a sensor width of $s_w = p \cdot W = 4 \cdot 10^{-6} \cdot 6000 = 0.024 \text{ m} = 24 \text{ mm}$.

In terms of the light being captured, the cell surface area is of importance as derived by basic quantum mechanics. To estimate the number of photons entering each cell per second, we need to know the light energy hitting the sensor per second and the energy per photon. The average per photon energy can be computed using $E = h_c/\lambda$, given the wavelength λ of the light is known. Supposing the light is produced by a point source and distributed spherically in space, every second, a certain amount of light reaches the photosensitive cells at a given distance r from the source, thus the intensity of light (energy per unit area per unit time) at any point at this distance is $I = P_e/(4\pi r^2)$, P_e being the power of light emitted. Supposing that a photosensitive cell has a surface area A , the energy per unit time on this area is $P_r = I \cdot A$, P_r being the power received by the cell. Finally, a rough estimate of the number of photons that fall onto a cell per unit time results from the division $n = P_r/E$, overall,

$$n = \frac{\frac{P_e}{4\pi r^2} A}{\frac{h_c}{\lambda}} = \frac{\lambda P_e}{4\pi h_c r^2} A \quad (4.49)$$

This relation creates a direct correspondence between the number of photons n and the receiving surface area A , in which $n \propto A$. This is another expression equivalent to the one derived in (4.42). Thus, supposing two imaging sensors with different sampling pitches, say one with $25 \mu\text{m}$ and one with $40 \mu\text{m}$, the corresponding cell areas are $625 \mu\text{m}^2$ and $1600 \mu\text{m}^2$, which means that the second sensor has $1600/625 = 2.56$ times the surface of the first and by (4.49) the second sensor will be able to receive 2.56 times more photons for the same lighting and camera configurations and the same exposure time.

Assuming that a scene can only be captured optimally by a single combination of parameters relating to the lighting, (the exposure time and the aperture setting, for a particular lens) a digital camera with a smaller sensor will need more time to attain the optimal result. If this exposure time is not achievable (for various reasons) then the camera system should increase its sensitivity, meaning the ISO gain, which results in multiplying the overall sensor output, including the existing dark noise, with the effects previously described.

A frequently used imaging sensor parameter is the so called *fill factor* that deals with how a pixel is physically laid out. The fill factor represents the active sensing cell area as a fraction of the theoretical sensing cell area, which is the product of the horizontal and vertical sampling pitches. It is the percentage of the cell area that is consumed by the actual photo sensitive surface. High values are preferable, with a fill factor of 100% being the ideal, as all the amount of incident light can be captured for the particular sensor. However, the imaging sensor needs additional electronics between the actual active areas of cells. Practically, most sensors do not have a 100% fill factor, as sensor designers need space for the readout and charge transfer circuitry. A typical solution to enlarge the active area is to use microlenses, which are lenses placed directly above a cell to direct the incident light in the actual active region. The fill factor of a camera can be determined empirically using a photometric camera calibration process (York and Jain, 2011; Szeliski, 2011).

4.3.3 The Crop Factor and Other Considerations

Analogous to the definition of the crop factor in lenses, there is also a crop factor defined for imaging sensors. The crop factor in sensors relates with the ratio of the sensor area to a reference sensor area. The reference area has been defined as the area of the classic consumer *135 film* with an area of about 36×24 mm. Just for historical purposes, the 135 film is the official name of the most common photographic film that was specified by the ISO 1007:1995 Standard,¹⁶ first introduced by Kodak in 1934. Another popular name for the standard film was also 35 mm *film* due to its 35 mm overall width. An actual negative photographic film along with its dimensions is depicted in Fig. 4.28.

A digital imaging sensor with a size equal to the active area of a 135 film is termed a *full frame sensor*. Although debatable in the context of imaging sensors, the term *crop factor* refers to the amount the angle of view of lenses for film cameras would decrease when mounted on digital cameras with sensors smaller than the full frame. Figure 4.29 presents the actual effect of cropping using a single lens mounted on cameras with different sensors. In this figure, the central disk represents the amount of the scene focused by a full frame compatible lens. The biggest rectangle inscribed in this disc corresponds to the full frame sensor given 3:2 dimensions, thus showing the amount of the focused image that will be captured by the camera. All other dash-line rectangles correspond to various sensors with smaller sizes that are typical in the digital camera manufacturing world. The captured images correspond to the same camera location (all images are centred around the same viewing point).

¹⁶ ISO 1007:1995 – Photography – 135-size film and magazine – Specifications of the ISO/TC 42 Photography Technical Committee, available online @ <https://www.iso.org/standard/5472.html> (last accessed March 2022), now revised by ISO 1007:2000, available online @ <https://www.iso.org/standard/28855.html> (last accessed March 2022).

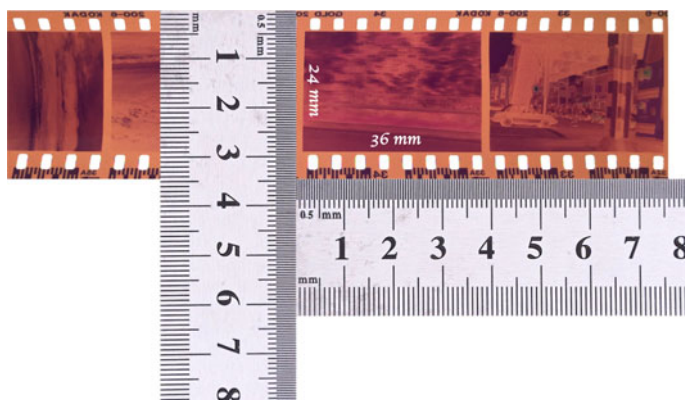


Fig. 4.28 Standard 135 photographic film dimensions

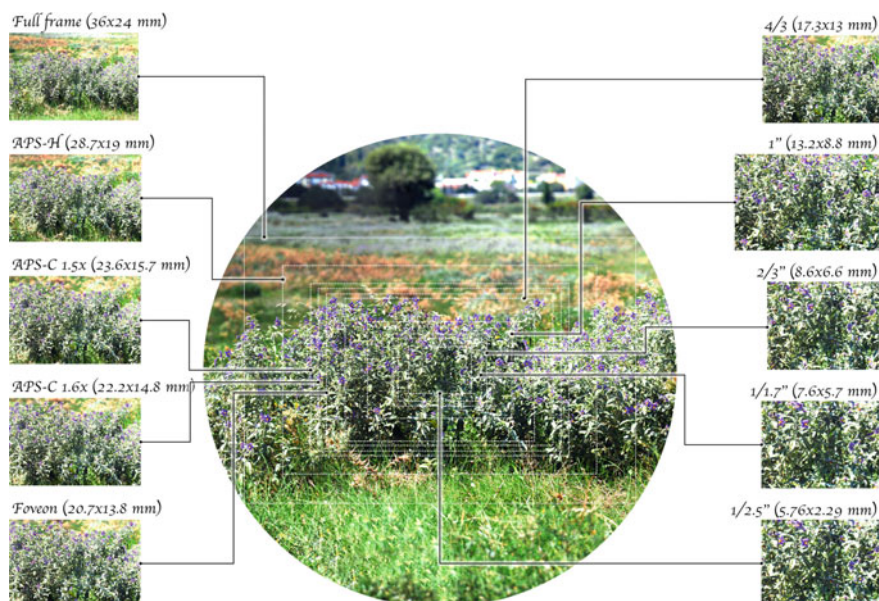


Fig. 4.29 Sensor sizes, crop factors and field of view for the same lens

An implication of having different sensor sizes is that if one requires the subject to occupy the same fraction of the image plane, different lenses should be used accordingly, or the camera with a smaller sensor should move further away from the subject. Having, for example, a full-frame camera sensor coupled with a 200 mm lens would be equivalent to having a $1.5\times$ crop factor camera sensor coupled with a 133 mm lens. For the same case, a 1" sensor (13.2×8.8 mm), which corresponds to roughly a $2.7\times$ crop factor, would require a 74 mm lens to capture roughly the

Table 4.5 Camera set-ups for equivalent depth of field results

Sensor size	Focal length (mm)	Aperture size
35 mm	50	f/5.6
1.3×	40	f/4.5
1.5×	33	f/3.7
1.6×	31	f/3.5
1-inch	18	f/2.1
2/3-inch	13	f/1.4
1/2.3-inch	9	f/1.0

same image. For a smartphone 1/2.5” sensor size (5.76×2.29 mm) that corresponds to roughly a $7\times$ crop factor, the required lens for the same image would be 28 mm. Another important parameter that needs to be considered for different sensor sizes is the *lens speed*, with smaller sensors requiring lenses with a wider aperture (faster lenses) to be able to capture the adequate amount of light for the smaller sensor surface and the equivalent exposure time. Of course, in choosing the correct combination of sensors and lenses one has to account also for the size, weight and cost of the appropriate lens, with bigger sensors requiring bigger, heavier and a lot more expensive lenses, in general, but these factors are not of interest in this section.

Apart from these implications, there is another set of variables that need to be examined. First, the *influence of the sensor size on the depth of field*; the bigger the photosensitive surface the shallower the depth of field for a given aperture and focus distance, as a bigger sensor requires longer focal lengths for a given subject to fill the frame. Since longer focal length lenses are linked with shallower depths of field, thus bigger sensors become also linked with shallower depths of field. Table 4.5 presents set-ups for different sensors to attain equivalent depth of field results with maintained perspective.¹⁷ Apparently, there are cases for which such an equivalent result would require lenses not available in consumer-grade equipment.

Another influence of the sensor size to be considered relates with the aperture size and the *diffraction airy disk*, the best-focused spot of light. Large sensors enable smaller apertures before the diffraction becomes an issue by resulting in an airy disk bigger than the circle of confusion. There is a limit, termed the *diffraction limit*, characteristic to each sensor size, above or below which gradual diffraction occurs resulting in losing sharpness in the captured images.¹⁸ Table 4.6 presents the diffraction limited aperture for different sensors that produce 24 MPixels images.¹⁹

Ultimately, as discussed in the previous paragraphs, the physical size of the imaging sensor is a decisive factor for various reasons, including the targeted, predeter-

¹⁷ The Table has been compiled by using the calculator provided @ <https://www.cambridgeincolour.com/tutorials/digital-camera-sensor-size.htm> (last accessed March 2022).

¹⁸ Lens characteristics should also be considered for a practical assessment of the final image quality.

¹⁹ The Table has been compiled by using the calculator provided @ <https://www.cambridgeincolour.com/tutorials/digital-camera-sensor-size.htm> (last accessed March 2022).

Table 4.6 Aperture estimates for the diffraction limit of various sensors that output the same 24 MPixels images

Sensor size	Aperture size
35 mm	f/11.3
1.3×	f/9
1.5×	f/7.4
1.6×	f/7
1-inch	f/4.4
2/3-inch	f/3
1/2.3-inch	f/2.1

mined or required outcomes and equipment combinations. What has already been established is that the sensors with large photosites are capable of turning out photos with better dynamic range, less noise and improved low light performance, mainly due to the fact that they provide enough surface for light to be efficiently captured, for a given amount of exposure time. At the same time small sensors, with their discussed limitations, lead to compact designs and significantly smaller, simpler and cheaper but also faster lenses, enabling the modern mobile imaging technologies.

4.3.4 Sensor Noise

In general, large camera sensors consist of large photosites that enable capturing of large counts of photons, resulting in high dynamic range images (spectral resolution) with low noise. Since the number of captured photons is high for a given exposure time and aperture, the signal to noise ratio is also high, as the usable visual information is significantly stronger than the background noise in the device. Of course, a complete study of the signal to noise ratio should take into account noise that depends on the sensor chip quality and the visual information extraction process that the sensor employs (how it creates pixels from the photosites), but this does not have a significant impact on the general idea. Nevertheless, since the noise is of higher frequency, sensors with higher pixel counts for the same amount of noise would produce cleaner images.

As implied by the simplified model of a single pixel in Fig. 4.27, noise is added from various sources throughout the process, which may include photon, fixed pattern, dark current, shot, amplifier and quantization noise (Healey and Kondepudy, 1994; Tsin et al., 2001). Particularly, for the case of low light conditions where the noise is due to low photon counts, a Poisson model can be more appropriate than a Gaussian model for the noise, as suggested by Szeliski (2011). For example, Liu et al. (2008) use the Gaussian model, along with empirical data for the camera response functions obtained by Grossberg and Nayar (2004), to estimate the noise

level function for a given image. As suggested by Szeliski (2011), an alternative approach would be to pre-calibrate the noise level functions by using multiple photos of a scene that includes various colours and luminance values, like standard colour charts (McCamy et al., 1976). Apparently this process must be followed for various exposure times and ISO settings (gain).

The sensor noise level in digital images has to be carefully taken into account in a number of computer vision and image processing applications, such as image denoising, edge detection, and stereo matching. If the pre-calibration process can be followed, or at least repeated shots of the same scene can be obtained, the simplest approach to estimate the noise level would be to look at regions of near-constant value and make variance estimates of noise in those regions (Liu et al., 2008).

4.3.5 Amplification, Conversion and Post-processing

The analogue electrical signal that is produced due to the photoelectric effect at the camera sensor is subsequently boosted by an electronic amplifier just before it is converted to digital by an analogue-to-digital converter. The amplification gain of the analogue signal is controlled by the *ISO setting*, which is typically expressed in ISO standard units like 64, 100, 200, 400, 800 or 1600. In theory, a high ISO setting (amplification gain) enables the operation under low light conditions, but in practice, it usually results in amplified sensor noise (Szeliski, 2011).

In film photography the ISO, or ASA, value indicated the film sensitivity to light. Films with low ISO are less sensitive and require high illumination in the scene to be able to capture correctly exposed images for a given exposure time. At the same time, low ISO films result in fine grained images, and this is due to the fact that the smaller the size of the silver halide grains in the emulsion of the films the less light-sensitive the film. Low ISO films are also termed *slow films*, since they require longer exposure times, whereas high ISO films are also termed *fast films* as they are able to capture images with short exposure times.

The ISO standard for colour negative films was originally the combination of the ASA Z38.2.1-1943 (later ASA PH2.5-1960) and DIN 4512:1934 film speed standards in 1974. The current version in effect is ISO 5800:1987 Corrigenda 1:2001,²⁰ a revision of ISO 5800:1987 that was the revision of the original ISO 5800:1979. For black and white films, the current standard is ISO 6:1993,²¹ first published as ISO 6:1974. For colour reversal films, the current standard is ISO 2240:2003,²² originally published as ISO 2240:1994. In colour negative films, the values of the ISO

²⁰ ISO 5800:1987/Cor 1:2001, <https://www.iso.org/standard/35540.html> (last accessed March 2022).

²¹ ISO 6:1993 – Photography – Black-and-white pictorial still camera negative film/process systems – Determination of ISO speed, <https://www.iso.org/standard/3580.html> (last accessed March 2022).

²² ISO 2240:2003 – Photography – Colour reversal camera films – Determination of ISO speed, <https://www.iso.org/standard/34533.html> (last accessed March 2022).

sensitivity corresponds to the the values of the ASA system, in which doubling the film speed represents a doubling of a film's sensitivity.

The current standard for ISO speeds in digital photographic cameras is ISO 12232:2006,²³ originally published in 1998 and revised in 2006. It should be emphasised that *the ISO setting in digital cameras does not relate to the sensitivity of the sensor as in the case of films, but to the electronic amplifier gain*. The ISO values in digital cameras are defined in such a way to correspond to the ISO values of films in terms of the brightness of the captured image. Since the digital camera 'sensitivity' controlled by the ISO setting relates only to the electronic amplification and not to any type of material science (like in films), there is an extremely broad range of ISO values available (values of ISO 4,560,000 have been reported²⁴). The downside is that extremely high ISO values require also extremely fast and effective noise reduction processes.

Figure 4.30 presents a set of images captured with a Nikon D5200 digital camera (APS-C sensor) with an AF-S Nikkor 35 mm f/1.8 prime lens, using various ISO settings; the first photo was taken using ISO 100 (the nominal –lowest– setting for the camera) and the subsequent photos were taken by doubling the ISO up to the limit that is available for the particular camera (ISO 12,800 is not shown for image size reasons). In addition, Fig. 4.31 shows a magnified portion of those images centred at roughly the same grey position on all the images in Fig. 4.30, to highlight how noise in the images increases with the increasing ISO value. All photos were captured with an aperture value fixed at f/5.6 and a shutter speed (exposure time) that varied according to the ISO value, in order to create a set of images of equivalent luminance (each time the ISO doubled the shutter speed was halved). The lighting was constant at all times. Clearly, the final output of the particular camera and lens, includes not only monochromatic but also colour noise, that is the 'grains' that appear even in the grey background are not neutral but rather have various hues, which is an issue of both the electronic signal noise and of the chromatic aberrations from the lens.

The sensor component that gives the digital cameras their digital character is the Analogue to Digital Converter, alternatively referenced as ADC, or AD Converter, or A/D Converter. This component is responsible for the conversion of the analogue signal reported by the sensor and corresponds to the counts of photons that were captured in the photosites, to a set of digital values that make sense in modern digital equipment, and particular in digital storage. Practically, the ADC is a chip that classifies the voltages of the photosites into levels of brightness represented by binary numbers in prefixed time steps. The analogue to digital conversion is a core technology that takes analogue signals and transforms them into digital. Digital signals are signals with two characteristics: they are *discrete in time and quantised in value*. This means that, typically, there is a clock running in constant steps that

²³ ISO 12232:2006 – Photography – Digital still cameras – Determination of exposure index, ISO speed ratings, standard output sensitivity, and recommended exposure index, <https://www.iso.org/standard/37777.html> (last accessed March 2022).

²⁴ See for example the online article at <https://petapixel.com/2015/09/13/this-is-iso-4560000-with-canon-crazy-new-camera/> (last accessed March 2022).

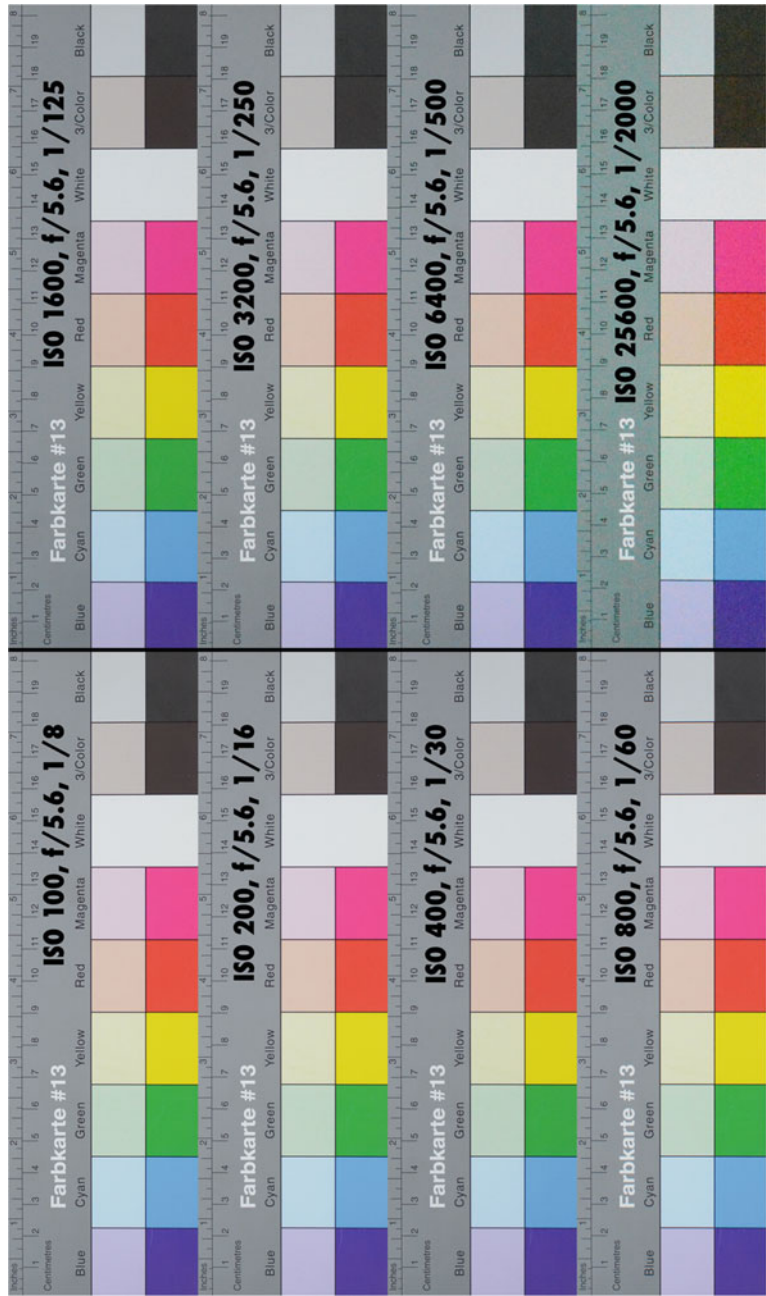


Fig. 4.30 Photos of a colour calibration pattern with different ISO settings

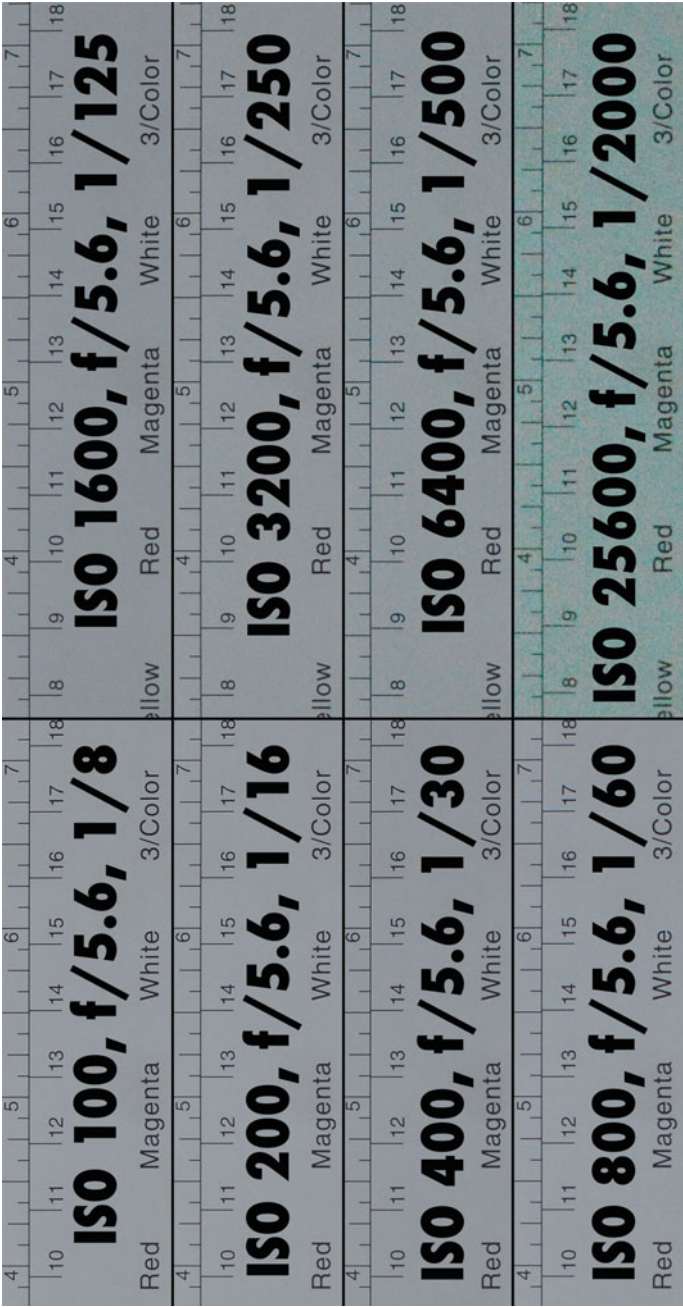


Fig. 4.31 Magnified portion of the colour calibration pattern in Fig. 4.30

marks the time in which the original signal is sampled and its value is ‘rounded’ according to a ‘rounding’ principle. This ‘rounding’ principle could be, for example, to convert to the closest integer taking the middle of the range between two integer values as the decisive threshold. In this case, the values 0.43, 2.56, 7.02, 1.85 would be converted to 0, 3, 7, 2. In case the rounding principle uses exactly one decimal digit then those values would be converted to 0.5, 2.5, 7.0, 2.0. There are infinite number of such rules that one may devise according to the needs of a particular analogue to digital conversion. Any adopted rounding principle that maps the values of the original analogue signal to a finite set of other (proper) values is called *quantisation*.

In a widely adopted convention in digital imaging, every colour channel is represented by 256 intensity levels (from 0 for black to 255 for white), which means that 8 bits are needed to represent those values in the binary arithmetic system (since $2^8 = 256$ and the maximum number 255 is represented as 1111 1111 in the binary system). Of course, this particular representation, although widely used and adequate for most storage, display and print systems, is rather limiting, and wider ranges of values have been proposed and are used for finer intensity steps. For example, 12-bit images can represent $2^{12} = 4096$ intensity values for the same black to white scale, which gives a 16 times smaller step between two consecutive values than in the case of 8-bit images. The number of available steps between the minimum and the maximum digital value that result from this quantisation defines the resolution of the conversion, which becomes higher as the steps become smaller. Thus, an 8-bit conversion is of lower resolution than a 12-bit conversion.

An example of the impact of the ADC or the spectral quantisation resolution in the final image is shown in Fig. 4.32, in which a greyscale image is depicted with four different quantisation resolutions; 8 bits per sample (or bps) have been used for the top-left image (256 distinct grey levels in the photo), 6 bps for the top-right image (64 distinct grey levels), 4 bps for the bottom-left image (16 distinct grey levels) and 3 bps for the bottom-right image (8 distinct grey levels). The effect of quantisation is illustrated particularly in regions of smooth gradients, like in the sky and the sea, where the grey values in large areas have been rounded to a single grey value and the smooth gradients have been replaced with abrupt changes. The 8 bps representation is visually pleasing as the dynamic range in the image roughly matches the human visual perception. In all other cases, the lower resolution has a direct impact in the perceived image quality, which is greatly reduced with the lowering of the quantisation resolution.

In high quality digital cameras, there is an option to store and retrieve for usage the image just after the ADC. This particular image is the so called *RAW image*. It is a digital file with values that represent the sampled and rounded counts of the photons captured in the photosites of the sensor. Usually, RAW images are data of higher quantisation resolution, and it has been suggested that 10 bits are adequate to avoid most rounding errors and loss of information, but, typically, manufacturers prefer to provide an ADC with 12, 14 or even 16 bits per sample to compensate for rounding errors (quantisation noise) and increase the resolution in the darker regions of a scene, thus imitate the human visual system that adjusts its sensitivity and dynamic range according to the illumination of the scene. A higher resolution

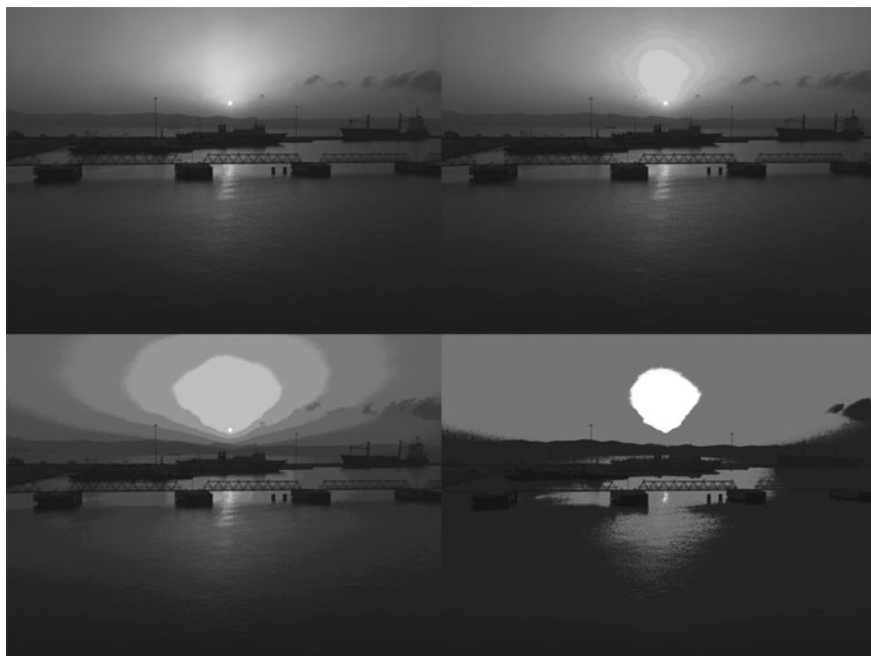


Fig. 4.32 Demonstration of the visual effect of the quantisation resolution

results in an increasing ability of the camera to report deeper shadows and smoother gradients. Apparently, the RAW representation is not an actual viewable image, and special software is needed to convert it to a form that can be visualised in a computer.

In any technique used to accomplish the ADC, the two quantities that are considered are the resolution (bits per sample) and the noise level, which corresponds to how many of those bits per sample are useful. The best way to assess those quantities for a given camera is to follow a calibration process, typically by taking repeated shots of the same subject (Szeliski, 2011).

4.3.6 Exposure

Putting all things together, as shown and demonstrated in the previous paragraphs the crucial factor in photography is the correct exposure that will create an image fairly similar to the one the human observer experiences. To attain a correctly exposed image, a digital camera uses three parameters, the lens aperture that controls the amount of light entering the device, the shutter speed that controls the amount of time the photosensitive surface will be exposed to the incoming light and the ISO sensitivity that controls the amount of amplification applied to the electronic signal

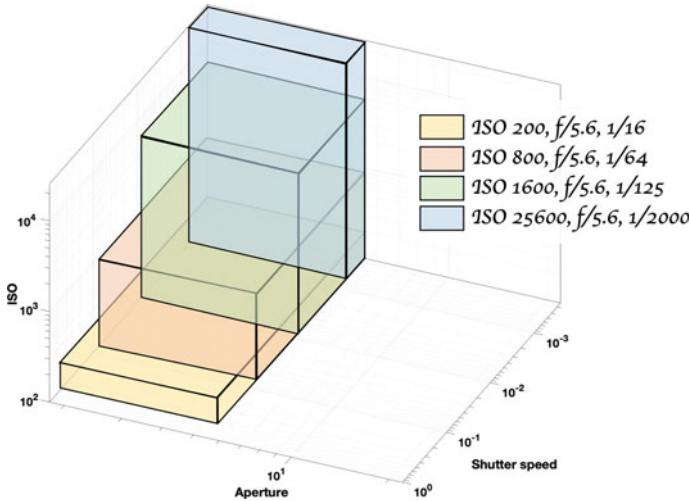


Fig. 4.33 The exposure volume of equivalent settings

that is created on the camera sensor due to the photoelectric effect. Since the exposure is basically controlled by those three parameters, in the bibliography there is much talk about the so called *the exposure triangle*, an intuitive visualisation of those factors as vertices of a triangle. Nevertheless, there is a simpler and more intuitive way to visualise the three parameters together focusing on their cooperative influence on the exposure and this is in terms of a parallelepiped solid object or a three-dimensional volume having as sides the three factors. An example is shown in Fig. 4.33, where four parallelepipeds are shown that correspond to the same volume for the exposure values in Fig. 4.30. This visualisation uses logarithmic axes for better illustration purposes. All volumes have the same value in the Aperture axis (that is $f/5.6$), which was fixed for the examples presented in Fig. 4.30. The other two parameters change accordingly to always create a solid object with the same volume.

In image-based metrology applications, like in photogrammetry, feature matching approaches are employed to extract spatial and spectral information. Since noise is typically high frequency content in images, and features are also high frequency characteristics, the noise in an image can disguise as a feature and mislead a photogrammetry method. Thus, it is strongly advised that in metrology applications the ISO setting of the digital camera is kept to its minimum (which is the nominal value of the sensor). Since a low ISO value renders a camera less sensitive to light, there might be cases in which it is impossible to capture a scene with the lowest ISO value, even in presence of a tripod that enables the use of extended exposure times.

4.4 Digital Post-processing

The lower part of the camera model adopted in this treatise and shown in Fig. 3.16 corresponds to the digital image processing that is applied to the sensor signal before the final image is stored as a typical digital image file, typically a JPEG image, in the internal storage of the camera. In this model, the post-processing steps include demosaicing, sharpening, white or colour balance, gamma correction and compression.

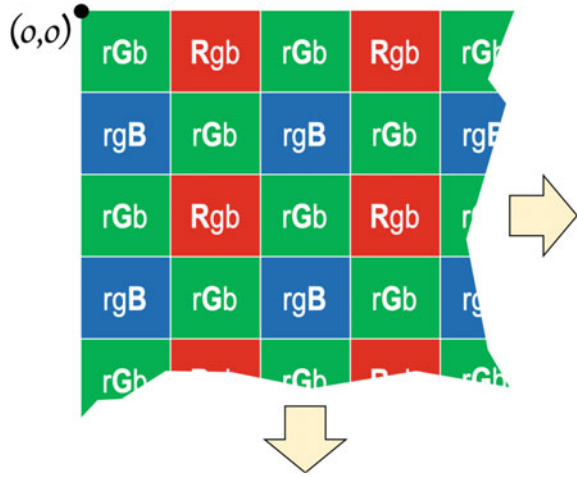
4.4.1 Demosaicing

First things, first. Apparently, the spectral sensing in camera systems refers to their ability to capture the colours in a scene. As discussed, colour is a quality of light that relates to frequency (or the wavelength). Most of the common camera systems use the *additive RGB colour system* to represent colours in images.²⁵ In this approach, the intensities of three primary colours, namely red, green and blue, are being mixed to represent any colour. Imaging sensors in digital cameras *respond to light intensity*, thus, sensing of colour is not inherent and as straightforward as expected. As described in the previous paragraph, the miniature *wells*, of photosites in sensors respond to the intensity of incident light and no colour (frequency) information is captured. Since the sensors are ‘colour blind’ scientists and engineers had to come up with tricks to enable colour detection. A very successful trick uses a group of tiny colour filters just above the sensor photosites, usually being called *colour filter arrays*. Among the most successful and still the most common approach uses the so called *Bayer filter*, which is graphically depicted in Fig. 4.34. This filter was developed and patented by Bayer as early as 1976 (Bayer, 1976b). Other approaches have already appeared in some devices, like the Foveon sensor that is based on layering colour sensing surfaces instead of using filters. The design of the Bayer filter matches the human visual perception by being biased towards the green light (green filters cover half of the overall surface). The actual colour pixels are the product of an interpolation, usually called the *demosaicing* that is using values of neighbouring photosites on the sensor surface to estimate the actual colour pixels of the final image. Usually, regions of 2×2 photosites are being used to create a single colour pixel, taking also into account those neighbouring photosites’ values.

Assuming that each photosite is to create a pixel, then a photosite contributes a single colour component and the two other components have to be estimated. The apparent way to do the estimate is to use the direct neighbours, where,

²⁵ There are special cases in which different imaging systems are using more than three colour channels, or they are able to record light in many wavelength bands (more than the typical three), such as in the case of remote sensing, where a large number of wavelength bands are being captured to provide terrain classification.

Fig. 4.34 The widely adopted Bayer filter for digital cameras; the Bayer pattern, left, and the corresponding estimated pixel values, right



$$I_{(i,j)} = \begin{cases} (R_{(i,j)}, g_{(i,j)}, b_{(i,j)}) & \text{for odd } i, \text{ even } j \\ (r_{(i,j)}, g_{(i,j)}, B_{(i,j)}) & \text{for even } i, \text{ odd } j \\ (r_{(i,j)}, G_{(i,j)}, b_{(i,j)}) & \text{otherwise} \end{cases} \quad (4.50)$$

where I is the reconstructed image, $I_{(i,j)}$ is the image pixel at the location (i, j) , capital letters (R, G, B) correspond to values from the photosite and lowercase letters (r, g, b) correspond to estimates from neighbouring photosites. The easiest way to generate those estimates is to use interpolation and particularly bilinear interpolation, which computes weighted averages of the neighbouring photosites' values. At a red photosite,

$$\begin{aligned} g_{(i,j)} &= \frac{1}{4} (g_{(i,j-1)} + g_{(i,j+1)} + g_{(i-1,j)} + g_{(i+1,j)}) \\ b_{(i,j)} &= \frac{1}{4} (b_{(i-1,j-1)} + b_{(i-1,j+1)} + b_{(i+1,j-1)} + b_{(i+1,j+1)}) \end{aligned} \quad (4.51)$$

At a blue photosite,

$$\begin{aligned} g_{(i,j)} &= \frac{1}{4} (g_{(i,j-1)} + g_{(i,j+1)} + g_{(i-1,j)} + g_{(i+1,j)}) \\ r_{(i,j)} &= \frac{1}{4} (r_{(i-1,j-1)} + r_{(i-1,j+1)} + r_{(i+1,j-1)} + r_{(i+1,j+1)}) \end{aligned} \quad (4.52)$$

Finally, at a green photosite,

$$\begin{aligned}
 r_{(i,j)} &= \frac{1}{2} (r_{(i-1,j)} + r_{(i+1,j)}) \\
 b_{(i,j)} &= \frac{1}{2} (b_{(i,j-1)} + b_{(i,j+1)})
 \end{aligned}
 \tag{4.53}$$

It should be noted that the bilinear interpolation approach to image demosaicing is the simplest straightforward and computationally efficient approach but it introduces artefacts to the image and a number of algorithms have been proposed to tackle this issue (see Li et al. 2008 for more information).

4.4.2 Colour Balance

Colours of real-world objects are affected by the lighting conditions and special mechanisms are needed to compensate for the differences in these conditions in order to be able to consistently capture and image the ‘correct’ colours. In humans, this mechanism is provided by the brain, but digital cameras apply special algorithms to emulate the process of compensating for different types of light. Thus, the colours that result from the demosaicing process have to go through *colour balancing* (and/or *white balancing*) in order to reverse any biases in the overall image appearance (such as the yellowish appearance of photos under incandescent lighting, or the blueish appearance of photos under fluorescent lighting). A white balancing approach relates to the *colour temperature* of the light source in the scene during the image capturing. Colour temperature, measured in degrees K (Kelvin), refers to the relative warmth or coolness of white light and it theoretically describes the spectrum of light radiated from a black body with that surface temperature. For example, a temperature of 3,000 K corresponds to an orange light, a temperature of 5,000 K corresponds to a neutral light and a temperature of 8,000 K corresponds to a blue light. What is counter-intuitive is that the colour becomes cooler (moves from red to blue) as the temperature rises, but this is the result of higher frequencies of light (towards blue) carrying higher electromagnetic energy. Table 4.7 presents some common light sources and the corresponding colour temperatures.²⁶ By matching the captured scene illumination with the correct source, the colours of the scene appear realistic to a human observer. The process that changes the colours of the image is a linear transformation, implemented using matrix multiplication, given that the values of the red R'_w , the green G'_w , and the blue B'_w components of a pixel that is supposed to correspond to white (colour balancing) are known,

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 255/R'_w & 0 & 0 \\ 0 & 255/G'_w & 0 \\ 0 & 0 & 255/B'_w \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix}
 \tag{4.54}$$

²⁶ Adapted from <https://www.cambridgeincolor.com/tutorials/white-balance.htm> (last accessed March 2022) and https://en.wikipedia.org/wiki/Color_temperature (last accessed March 2022).

Table 4.7 Common light sources and the corresponding colour temperatures

Light source	Colour temperature (K)
Candle light	1,000–2,000
Tungsten lamp light	2,500–3,500
Sunrise or sunset in clear sky	3,000–4,000
Fluorescent lamp light	4,000–5,000
Flash light	5,000–5,500
Vertical daylight in clear sky	5,000–6,500
Overcast sky	6,500–8,000
Heavily overcast sky	9,000–10,000
Clear blue poleward sky	15,000–27,000

where R' , G' , and B' are the red, green, and blue components of the each image pixel before colour balancing.

4.4.3 Bit-Mapping and Gamma Correction

Supposing a camera is able to capture and record RAW images (say in 12 bites per sample), the final image in most cases is a JPEG image file, typically of 8 bps per colour channel (usually red, green and blue). As mentioned earlier, the RAW image contains the digitised photon counts (actually the corresponding voltage) in a 12 bps resolution, which creates an intensity representation that ranges in $[0, 4095]$. The creation of the final JPEG imposes a mapping of those values to the corresponding $[0, 255]$ range that the 8 bps can represent. A linear mapping from the 12-bit values to the 8-bit values assigns too many bits to the bright regions of the images and less (not actually enough) bits to the darker regions. To alleviate this issue, a γ (gamma) factor is imposed, with a typical value of 2.2, and instead of using the direct linear mapping with a slope of $8/12 = 1/1.5 \approx 0.66$ a slope of $1/\gamma \approx 0.45$ is being used. Figure 4.35 depicts the two different approaches.

The mapping using the gamma factor is termed *gamma correction*, originally used to compensate for the effect of the image brightness being non-linearly related with the voltage. The classical luminance-voltage-gamma formula is

$$L = V^{\frac{1}{\gamma}} \tag{4.55}$$

L being the luminance, V the voltage and $\gamma \approx 2.2$. This being the case in images from voltages, the inverse should be taken to transform the images back to voltages for display systems using $\hat{V} = L^\gamma$. The profile of the mapping imposed by the various gamma values in gamma correction is shown in Fig. 4.36, in which the linear mapping ($\gamma = 1$) is also shown as a reference in the middle graph. Figure 4.37 presents a

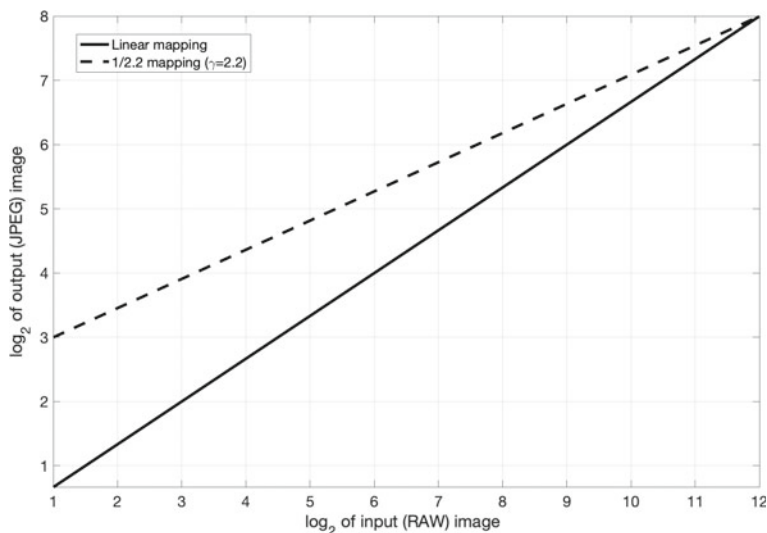


Fig. 4.35 RAW to JPEG image mapping without and with a γ factor

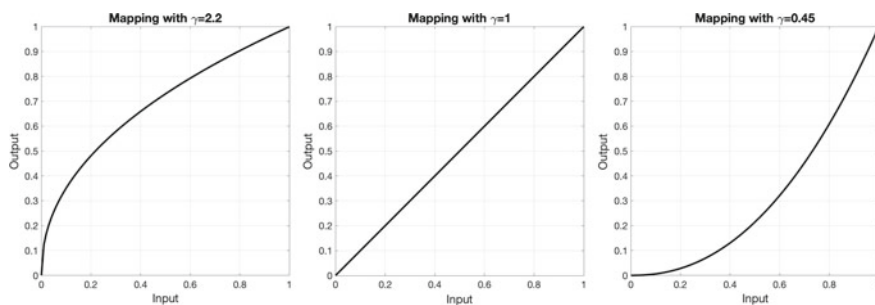


Fig. 4.36 Three gamma mapping functions for $\gamma = 2.2, 1, 0.45$

practical example of the application of gamma correction on a greyscale image shown to the left; the middle image is the result of gamma correction with $\gamma = 2.2$ and the image to the right is the result of gamma correction with $\gamma = 0.45$. It is apparently clear how a gamma factor greater than 1 results in enhancing the dark regions of the image, whereas a gamma factor less than 1 makes those regions even darker.

4.4.4 Compression

The most common final step in the processing of images in a digital camera is the image compression. Image compression typically results in JPEG images, which



Fig. 4.37 Example of gamma correction of a greyscale image; left is the original image, middle is the image after gamma correction with $\gamma = 2.2$ and right is the image after gamma correction with $\gamma = 0.45$

is still the file format of choice for all-purpose image interchange applications and the Web. A JPEG image is a compressed image after the application of a lossy compression algorithm.²⁷ In addition to the level of compression (which is usually referenced in cameras as JPEG quality), the camera user is able to select a set of image processing options, even before the image is compressed and saved, including the adjustment of contrast, sharpness, saturation, noise reduction and white balance (or colour balance, or gamma correction, as discussed above). Even if the user does not interfere with these options, these processes do apply on the data (with default settings) before the image is converted to a JPEG and saved. Apparently, all these processes are irreversible (they cannot be undone after the image is saved). A typical natural world image compressed with JPEG would result in a 10 times smaller file with minimal or non-noticeable distortion (quality degradation). Although non-noticeable, the distortion might be significant for computational methods that rely on accurate pixel values for computations, thus any metrology applications relying on the accurate pixel values are directly affected by the level of compressed selected during the compression step in digital cameras and should be carefully selected.

²⁷ A lossy compression algorithm, in contrast to a lossless algorithm, allows the distortion of the colour information for the sake of compression. Typically, depending on the amount of compression required, this distortion may vary from non-noticeable to significant. Image compression is not within the scope of this treatise. For those interested in the domain the bibliography is really vast. A simplified description of colour spaces and image compression can be found in Pavlidis (2017).

Glossary

Aperture priority Aperture priority commonly abbreviated to A or Av (for aperture value) is a setting on your camera that allows you to adjust the aperture value (otherwise known as the f-number or f-stop) while the camera automatically selects a shutter speed to produce an image with the correct exposure. As you adjust the aperture for different photographic effects, the camera's internal light meter measures the lighting conditions of the scene and adjusts the shutter speed accordingly.

AF AF is an abbreviation for autofocus. The AF feature automatically adjusts the camera lens to focus on a subject, creating a sharp image. There are several types of AF focus modes. Single focus, known as AF-S (Nikon) or One Shot AF (Canon) will cause the camera to lock focus on a subject and the camera won't re-focus while you keep the shutter actuator depressed half way. Continuous or tracking focus—AF-C (Nikon) or AI Servo (Canon) on the other hand, continuously readjusts the focus if you keep the shutter button half-depressed. This maintains focus on moving subjects. Some cameras also have a mode called AF-A (Nikon) or AI Focus AF (Canon) that switches between the two modes automatically.

Auto Auto is short for automatic and is sometimes signified by a small green rectangle on the camera's shooting mode selector wheel. In this mode, the camera calculates and adjusts all camera settings for correct exposure, taking into account shutter speed, aperture, focus, white balance, ISO and light metering automatically. Some cameras have automatic modes programmed to specialize in taking photographs of a particular subject. For example, action or sports mode prioritizes a higher ISO value and faster shutter speeds. It is represented by a running figure on your dial if your camera offers such modes.

AWB Light is different under different conditions. AWB or Automatic White Balance works in-camera to measure the white balance (WB) of a scene and remove any color casts that may impede on a photograph. In short, it tries to automatically analyze and color correct your scene. It works fairly well in most cases but can be tricked. Note: if you shoot in RAW format you can easily tweak the White Balance later in post-production.

Bulb Bulb or B is a mode designed for longer exposures like those often seen in time-lapse photography. In Bulb mode, when you depress the shutter button, the shutter will remain open until the button is pressed again (or until it is released, depending on your camera). This mode is usually used in conjunction with a tripod and a remote shutter release and is necessary to achieve exposures longer than 30 s (the maximum exposure time on most cameras).

CMYK CMYK stands for cyan, magenta, yellow and black. Black is referred to as K which is shorthand for the key plate—a printing tool which makes the artistic detail of a picture in black ink. CMYK is the color space used for most color reproduction printers (magazines, posters, business cards, etc.). This four-color mode utilizes each color in set amounts to create a color print. It is a subtractive process, so each additional color means more light is absorbed to create colors. Because RGB (the color space in which your camera records an image) provides a larger range of colors available on the digital screen, a printed image will be inconsistent with the image you see when you press “print”. Converting an image to CMYK in Photoshop or Illustrator before printing will produce an image on the screen that is much closer to the printed product, allowing you to print an image accurately.

DOF Depth of Field or DOF is the zone of focus in a photograph. Depth of field is affected by the aperture. A large aperture creates a shallow depth of field with a small amount of the image will be in focus. A small aperture creates a large depth of field with more in focus. Depth of field is also defined by lens focal length and the distance from the subject to the camera.

DPI DPI or dots per inch is often used interchangeably with PPI or pixels per inch. Technically, DPI measures the number of dots that can be printed in a line within the span of one inch. PPI also measures the number of dots in a line within the span of an inch but on a computer screen instead. Printers and screens with higher DPI or PPI values are clearer and more detailed. You need to know the DPI of your printer or lab to correctly size your images for printing.

DSLR DSLR stands for Digital Single-Lens Reflex camera. A DSLR camera has a mirror that reflects the light coming in from the lens and directs it through a prism or set of mirrors to the viewfinder. This arrangement allows you to see what you are shooting by looking through the viewfinder. When the shutter button is depressed, the mirror flips up and allows the light coming through the lens to reach the camera sensor.

f-number The f-number is a term that indicates the size of the aperture opening on your lens. Every aperture is expressed as an f-stop or f-number, like f/8 or f/2.8.

F-stop The f-stop is a term that indicates the size of the aperture opening on your lens. Every aperture is expressed as an f-stop or f-number, like f/8 or f/2.8.

ISO ISO stands for International Standards Organization. In film photography, ISO (or formerly ASA) was an indication of how sensitive a roll of film was to light. In digital photography, ISO measures the relative sensitivity of the camera sensor. This value can be adjusted in-camera. The higher the number, the more light the sensor can capture. However, the greater the sensitivity of the film or sensor, the grainier the image will be (in digital photography it’s called noise).

JPEG JPEG (sometimes shortened to JPG) is an image file format. It stands for “Joint Photographic Experts Group”—the name of the group that created the format. It’s one of the most common image formats saved by digital cameras, the other being RAW. JPEG files are lossy which means that images in this file format are compressed. Lossy formats are smaller and easier to handle, but they suffer from a loss of quality.

Manual Manual Mode is a shooting mode on your camera that when activated, means that you have complete control over every setting on your camera. This includes the aperture, shutter speed, ISO, white balance, metering mode, and more. Note: Manual Mode and Manual Focus are NOT the same thing and are not exclusive of one another. Meaning you can shoot in Manual Mode using Autofocus, or in an Automatic mode using Manual Focus.

Program Program shooting mode has the camera adjust aperture and shutter speed automatically, while allowing you to adjust other settings like ISO, flash, white balance and focusing functions.

RGB Based on the human perception of colors, RGB stands for Red, Green, and Blue. RGB is an additive color space designed for viewing imagery on digital displays (see CMYK above).

Shutter Priority Shutter Priority Mode (also known as SP or TV for Time Value) is a setting that allows you to select the shutter speed while the camera automatically adjusts the aperture for proper exposure. As you adjust the shutter speed the camera’s internal light meter measures the lighting conditions of the scene you’re shooting and adjusts the aperture accordingly. This mode is best used for shooting fast moving objects or when you want to blur or freeze a moving subject.

SLR SLR or “single lens reflex” refers to a non-digital camera with single-lens reflex capabilities (see DSLR).

TIFF Short for Tagged Image File Format, TIFF is a file format for digital images that does not lose color and detail in the way that lossy compression formats such as JPEG files do. This type of file format is described as lossless.

TTL TTL stands for Through the Lens and refers to an automatic flash metering system. The flash fires a short burst prior to the actual exposure, the camera reads the amount of light coming through the lens, and sets the power of the flash according to the selected aperture. This mode is most often used with the flash on the camera.

USM USM stands for Ultra Sonic Motor, a type of autofocus motor in lenses trademarked by Canon. Equivalent systems include Nikon’s SWM (Silent Wave Motor), Sigma’s HSM (Hyper-Sonic Motor) and Olympus’ SWD (Supersonic Wave Drive Motor). They are designed to have the lens’s autofocus work as silently as possible.

WB WB stands for White Balance, the act of balancing the color cast found in different lighting conditions for an accurate image (see AWB). White Balance can be set in-camera and adjusted in post-processing if you have shot in RAW format.

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