Chapter 2
Image Data Formats and Color Representation

The soul becomes dyed with the color of its thoughts.
Marcus Aurelius

2.1 Color Representation

The appearance of an object is basically resulted from: the nature of the light reflected from the object, its optical characteristics, and the human perception. The colors are actually electromagnetic waves described by their wavelength. The visible spectrum, i.e., the portion of the electromagnetic spectrum that can be detected by the human eye, ranges from 390 nm (violet) to 750 nm (red).

There are four main attributes that characterize the light: *intensity*, *radiance*, *luminance*, and *brightness*. In the case of achromatic light, the intensity is the only attribute involved. This is the case where the called *gray-scale* is used: intensity varies from black to white (gray levels in between). On the other hand, in the case of chromatic light, the other three attributes are used to measure the quality of the light source. The radiance refers to the amount of emitted energy by the light source, and it is measured in watts (W). The luminance measures the amount of radiation perceived by an observer, and it is measured in lumens (lm). The brightness is associated to the light intensity. Although the brightness has an accurate interpretation in monochromatic images, it is a very subjective property in the case of chromatic images.

Because of the absorption characteristics of the human eye, the colors are considered to be formed from different combinations of the *primary colors* red, green, and blue. These three colors can be added to create the *secondary colors* magenta (red + blue), cyan (green + blue), and yellow (green + red). The white color can be formed if the three primary colors are mixed or if a secondary color is mixed with its opposite primary color (all in the right intensities).

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In color image analysis three attributes are used to differentiate one color from another: *brightness*, *hue* and *saturation*. The hue attribute brings the information concerning the main wavelength in the color, i.e., it is responsible for verifying the color, in the complete spectrum, from red to violet, and magenta. The saturation describes the level of mixture between the hue and the white light, i.e., it defines the “purity” of the color. High values of saturation result in more gray-scale pixels and small values result in pixels with high “purity”. For instance, the red color is highly saturated and the pink color is unsaturated. A fully saturated color does not contain white light. Finally, the *chromaticity* is a description that combines hue and saturation. Hence, it is possible to describe an image according to brightness and chromaticity.

The *color depth* measures the amount of color information available to display or print each pixel of a digital image. A high color depth leads to more available colors, and consequently to a more accurate color representation. For example, a pixel with one bit depth has only two possible colors: black and white. A pixel with 8 bits depth has 256 possible values and a pixel with 24 bits depth has more than 16 million of possible values. Usually, the color depths variy between 1 and 64 bits per pixel in digital images.

The *color models* are used to specify colors as points in a coordinate system, creating a specific standard. In the following, the most common color spaces are briefly presented.

2.1.1 RGB Color Model

The RGB (Red, Green, and Blue) color space is one of the most used color spaces, specially for 8 bit digital images. This model is usually used for representing colors in electronic devices as TV and computer monitors, scanners, and digital cameras. The theory of the trichromatic color vision of Young–Helmholtz and the Maxwell’s triangle is the basis of the RGB model.

The RGB is an additive model where the red, green, and blue colors are combined on different quantities or portions to reproduce other colors. The pixels of an image represented in the RGB model have usually 8 bits depth, resulting in 256 possible intensities, i.e., the range of [0, 255] for each color.

A color in the RGB model can be described indicating the amount of red, green, and blue. Each color can vary between the minimum value (totally dark) and the maximum value (totally intense). When all the colors have the minimum value, the resulting color is black. On the contrary, when all the colors have the maximum value, the resulting color is white.

This model is known as the RGB color cube, because the model is based on the Cartesian coordinate system and its color subspace of interest is a cube. The primary and secondary colors are at the corners of the cube. The black color is at the origin and the white color is at its opposite corner. The diagonal between the black and the white colors is the gray scale.

2.1.2 CMYK Color Model

The CMYK model is composed by the cyan, magenta, yellow, and black colors. The basis of this model is the light absorption, as the visible colors come from the nonabsorbed light. This space is usually used by printers and photocopiers to reproduce the majority of the colors in the visible spectrum. The system used is called quadrichromie, the subtractive color system, in opposition of the additive system RGB. Cyan is the opposite color of red, i.e., it plays as a filter that absorbs the red color. The same occurs with magenta and green, and with yellow and blue.

Actually, the original subtractive model is CMY. Although equal amounts of cyan, magenta, and yellow produce the black color in theory, this combination in practice (printing on a paper) does not produce a true black. In order to overcome this problem, the fourth color (black) is added to the model (CMYK).

It usually occurs that some visible colors on the screen of a computer monitor are not printed properly on a paper. This happens because the CMYK used in the printers is based on a mixture of inks on the paper, and the CMYK used in the computer monitors is a variation of the RGB space. Consequently, the CMYK color spectrum happens to be smaller than the RGB color spectrum.

2.1.3 HSV Color Model

The HSV color system, created by Alvy Ray Smith, is composed by three components: hue, saturation, and value. This model is also known as HSB (hue, saturation and brightness). These three parameters are used to define the color space as explained before. The possible values for the hue attribute range from 0 to 360 and the values for the other two attributes range from 0 to 100.

The HSV model is based on cylindrical coordinates and it is actually a nonlinear transformation of the RGB system. Hence, it is possible to transform directly a color from the HSV system to the RGB system, and contrariwise (Smith 1978). There are two other color systems related to HSV: the HSL (Luminosity) system and the HSI (intensity) system.

This color system is very interesting, because it allows the separation of the three components of a specific color (hue, saturation, and intensity). It is broadly used in artificial vision systems, as it is a powerful tool for the development of digital image processing algorithms based on the human color perception model. Indeed, the HSV model is well suited to characterize colors in practical terms for human interpretation, differently from the RGB and CMYK models.

In the context of this book, we will make reference to the RGB space only. The details about colors and all the color spaces can be found in Gonzalez and Woods (1991) and Frery and Miranda (2008). The reader is referred to the books by Malacara (2011), Fortner and Meyer (1996) and Fairchild (1997) for further reading.

2.2 Image Formats

There are two main classes of visual information that can be stored in a digital computer: the vector and the raster images. The former are made up by the description of the geometric elements that compose the image using a convenient language. The vector format is ideal to present information that can be described by the junction of simple geometric functions: segments, circumferences, text, and color, for example. In addition, this information can be presented at any scale if necessary. On the other hand, in the case of the raster images, the basic element is a value associated to a position (color recorded to a pixel).

In the following, these two image formats are presented in more detail.

2.2.1 Vector Formats

The core `R` graphics engine was essentially vector based until version 2.11.0, i.e., the plots were (and still are of course) produced very accurately on vector-based devices. Although guaranteeing the very good quality when dealing with vector formats, the lack of support for rendering raster formats leaded to lower quality outputs. However, newer versions of the `R` graphics engine already have support to render raster formats leading to better scaling, faster rendering, and smaller files (Murrell 2011), as it will be presented in the next chapter.

Vector formats have the advantage of being superior when the images need to be visualized at many different scales, however, the files produced are usually of greater size, mainly in the case of very complex images. When using vector formats, the original data resolution and form can be maintained and the graphic output is usually more refined and elegant. In the cases where the encoding of topology is necessary and important, vector formats are also a good choice of output, as one can take advantage of more efficient operations that use topological information. However, operations such as spatial analysis and filtering within polygons are impossible.

When it comes to modifying a plot using different softwares, considerations must be made depending on the modifications required. For instance, removing a single shape from the image is only practicable with vector images. However, changing a white background of an image to transparent is only possible using raster images. A final remark about vector formats is its easy conversion to a raster format, so usually it is more manageable to produce a vector graphic and then convert it to raster if some later modifications are needed. Indeed, it is almost impossible to proceed with the other way around.

Some very known and used vector formats include PDF, PostScript, and SVG, which are presented in more details in the following.

2.2.1.1 PDF

Portable Document Format (PDF) is a file format developed by Adobe Systems in 1993 in order to represent documents independently of the application, the hardware or the operational system used to create them (Adobe Systems Inc. 2004). A PDF file can be used to describe documents with text, graphics, and images in a format which is independent of device and resolution.

PDF is an open pattern, which means that everyone can develop softwares to read and write documents in this format. Consequently, there are several available softwares for viewing documents in this format like Adobe Reader, and that is one of the reasons why PDF is a good choice of format. Additionally, it is a very sophisticated format, so it is able to faithfully produce anything that `R` graphics can do.

2.2.1.2 PostScript

Encapsulated PostScript (EPS) (Adobe Systems Inc. 1999) was developed by Adobe and, besides being a digital image format, it is a language for description of pages. Instead of defining pixels, PostScript is composed by a set of commands which are interpreted by an output device like printers, for instance. This format can be used to store images, raster formats or both of them. As it does not represent pixels directly, it cannot be read using common softwares for image manipulation, they can be only created by them. PostScript is capable to manipulate text and graphics efficiently and with higher quality than raster formats, however it can not store photos.

In order to print documents in this format, the device used must be capable to interpret PostScript. Because of its popularity, EPS is very used as output and by publishing softwares. Vector editing softwares can open files in EPS format; when opened in image editors, EPS documents are rasterized, i.e., they are converted into pixels.

PostScript can be more sophisticated than PDF, however, it does not support some features like semitransparent colors and hyperlinking, for instance. Consequently, differently from PDF, EPS is not able to faithfully produce everything that `R` graphics can do.

2.2.1.3 SVG

Scalable Vectorial Graphics (SVG) (Ferraiolo 2003) is a XML language to describe bidimensional graphics in a vectorial form statically, dynamically, or animatedly. Differently from other vectorial formats, no company has the ownership of SVG, i.e., it is an open format. However, it does not loose in sophistication if compared with PDF and EPS. SVG was created by the World Wide Web Consortium (W3C), which was responsible for creating other pattern as HTML and XHTML. A work group inside W3C started to develop SVG in 1999, having as reference other patterns as PGML (Adobe) and VML (Microsoft). SVG is supported natively by most modern Web browsers and they support most static graphics produced in `R`.

2.2.2 Raster Formats

In the context of digital images, an image format is a common manner to organize and store image data. The format defines how the data are arranged and the used compression type or level. Generally speaking, raster graphics or bitmap files (map of bits), contain a representation of a graphic stored as pixels at a fixed resolution. A common example is a digital photo or a scanned image. Some of the most usual raster formats are GIF, JPEG, PNG, TIFF, and BMP. The book of (Murray and Ryper 1994) is an excellent reference for the main graphic formats.

Image formats can be divided into two classes: binary and continuous tone. A binary image has only two tones, while a continuous tone image contains all the gray levels between white and black. Table 2.1 presents some known raster formats divided into the two classes mentioned before.

The formats presented in the following are directly related to the storage and distribution of photos.

2.2.2.1 TIFF

TIFF (*Tagged Image File Format*) is a flexible format that usually stores 8 bits or 16 bits per color (red, green, blue) for a total of 24 or 48 bits, respectively. The extensions used are TIFF or TIF. This format supports several image compression patterns, including JPEG, JPEG-LS and JPEG-2000. There are different common image readers, but not all of them are capable of reading all kinds of TIFF files. Consequently, this format is mostly regarded as a family of formats than as a unique one. The data inside TIFF files can be *lossless compressed* or *lossy compressed*. Some digital cameras can save in TIFF format using the compression algorithm called LZW [Lempel-Ziv-Welch, see Nelson (1989)] for storing data without loss (lossless compression). This format is not broadly supported by Web browsers, but it is broadly accepted as a photo file pattern for printing business. TIFF supports specific color spaces for certain printing devices defining the CMYK by a set of

Table 2.1 Image formats

Binary	Continuous tone
CCITT Group 3	JPEG
CCITT Group 4	JPEG-LS
JBIG (also JBIG1)	JPEG-2000
JBIG2	BMP
TIFF	GIF
	PDF
	PNG
	TIFF

particular printing inks: cyan (C), magenta (M), yellow (Y) and black (K) colors that compose a subtractive color space.

2.2.2.2 JPEG

JPEG (*Joint Photographic Experts Group*) files store data in a format with loss (in major cases). Almost all digital cameras can save images in JPEG format, which supports 8 bits per color for a total of 24 bits, usually producing small files. When the used compression is not so high, the quality of the image is not so much affected, however, JPEG files can suffer from noticeable degradations when edited and saved recurrently. For digital photos that need repetitive edition or when small artifacts are unacceptable, formats without loss besides JPEG should be used for a better storage. This format is also used as the compression algorithm for many PDF files.

2.2.2.3 PNG

The PNG (*Portable Network Graphics*) format was created as a free and open source version of GIF. This format supports true color (16 million of colors) while GIF only supports 256 colors. PNG stands out when an image is formed by large uniformly colored areas. The lossless PNG format is more appropriate for the edition of figures and the lossy formats, as JPEG, are better for final distribution of photos, because JPEG files are smaller than PNG files. Many old Web browsers do not support PNG format, however, all new browsers support most common variations of this format, including transparency in 8 bits.

2.2.2.4 BMP

BMP (*Windows Bitmap*) supports graphic files inside the Microsoft Windows Operational System. Typically, BMP files data are not compressed which results in big size files. The main advantage of this format is it simplicity and broad acceptation.

2.2.2.5 PBM Formats

The PBM (*Portable Bitmap*) (Henderson 1993) format concerns actually in three different image formats for binary images, gray-scale images and color images. These formats are uncompressed and have a common structure. The three formats are:

- PBM (Portable BitMap)—binary images
- PGM (Portable GrayMap)—gray-scale images
- PPM (Portable PixMap)—color images

The original definition of these formats (invented by Jef Poskanzer in the 1980s) had the aim to enable the transmission of images through electronic mail (e-mail), which did not allow file attachment at that time. Hence, the formats PBM, PGM, and PPM represented the content of the images using ASCII characters. This characteristic allowed the insertion of an image inside an e-mail as if it was normal text. However, this usually resulted in large size messages. The format definition was later modified in order to allow also the binary representation.

The PBM format has the following fields (in this order):

- An identifier (magic number): P1 (PBM ASCII), P2 (PGM ASCII), P3 (PPM ASCII), P4 (PBM binary), P5 (PGM binary) or P6 (PPM binary);
- White space
- Image width in pixels
- White space
- Image height in pixels
- For PGM or PPM:
  - Maximum gray-scale value
  - White space
- Values of the pixels corresponding to the total size of the width multiplied by the height for the PBM and PGM formats and three times this number for the PPM format (three bands). The pixels of the image are ordered from top to bottom and from left to right.

When the content is represented in ASCII, the values of the pixels are given in decimal notation and are separated by a white space, a tabulator space or carriage returns. In the binary versions of the formats, the values of the pixels are stored as plain bytes without any separation.

The tools provided by `R` for reading and writing images in the formats presented are described in the next chapter.

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