Digital Image Fundamentals

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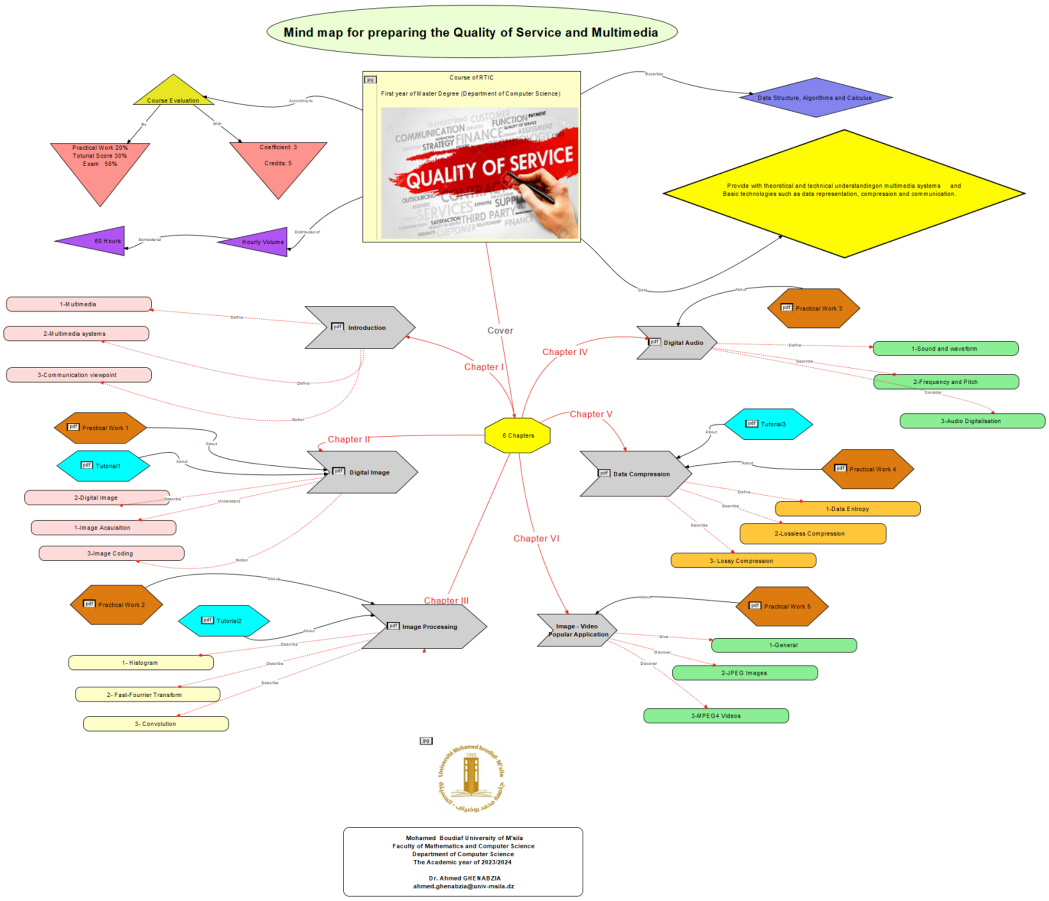
Objectives

the objective of the module is to explore the fundamentals of digital image representation, including acquisition, pixel structure, color models, and image coding techniques. The course aims to provide students with a comprehensive understanding of how digital images are created, stored, and manipulated in computer science applications. By covering topics such as pixel definition, resolution, color spaces (RGB, XYZ, HSV), and various image coding methods (binary, grayscale, color, indexed color), students will gain insights into the complexities and applications of digital image encoding.

Content Map



Mind map for preparing the Quality of Service and Multimedia
Course of RTIC
First year of Master Degree (Department of Computer Science)
QUALITY OF SERVICE
Course Evaluation
According to
By
With
Practical Work 20%
Toturial Score 30%
Exam 50%
Coefficient: 3
Credits: 5
Hourly Volume
Distributed of
Semesterial
60 Hours
Expertise
Data Structure, Algorithms and Calculus
Goal
Provide with theoretical and technical understandingon multimedia systems and Basic technologies such as data representation, compression and communication.
Cover
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2-Multimedia systems
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Give
Discover
Mohamed Boudiaf University of M'sila
Faculty of Mathematics and Computer Science
Department of Computer Science
The Academic year of 2023/2024
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prerequisites

- **Basic Mathematics**: Understanding concepts like algebra (variables, equations), geometry (shapes, dimensions), and arithmetic (operations, fractions) is crucial.
- **Computer Science Fundamentals**: Familiarity with basic computer science concepts like data types, variables, and arrays will be helpful.
- **Programming Skills**: Proficiency in a programming language commonly used in image processing, such as Python with libraries like OpenCV or MATLAB, will be advantageous. This will allow you to implement algorithms, manipulate images, and conduct experiments.

prerequisites assessment

Objectives

Evaluating your proficiency in the foundational knowledge required for understanding digital image processing concepts.

Quiz 1

Which of the following is NOT a valid data type in most programming languages?

- Integer
- String
- Vector
- Boolean

Quiz 2

What is the output of the following code snippet?

```
int numbers[] = {1, 2, 3, 4, 5};
cout << numbers[2];
```

- 1
- 2
- 3
- 4

Introduction

IV

In the realm of computer science and digital imaging, the representation of images is a fundamental aspect that involves encoding visual information for computational processing. This process becomes especially critical in the realm of color imagery, where the challenge lies in balancing visual fidelity with memory efficiency.

This exploration delves into the intricacies of digital image representation, covering essential concepts such as the trichromatic model, color spaces like RGB and indexed color, and the bit-depth encoding that defines the richness of colors within an image. The text navigates through the evolution of color representation, from basic binary encoding to sophisticated indexed color tech- niques.

Whether it’s understanding the principles behind RGB spaces, the nuances of grayscale images, or the efficiency of indexed color representations, this discus- sion aims to provide insights into the complex yet fascinating world of digital image encoding and its applications in computer science. Let’s embark on a journey through the pixels and bytes that form the ”genetic code” of digital images.

Acquisition

An image is a planar representation of a scene or object located in a three- dimensional space (plus the temporal dimension). The acquisition, processing, and rendering of an image resemble a processing chain (signal processing) with all its issues, notably the sensors: sensors (digitizer).

A digital image consists of a rectangular sampling grid whose components are pixels carrying information about the light intensity in different locations within the image.

Thus, a digital image is represented by a two-dimensional matrix, with its elements being natural numbers corresponding to quantization levels in the scale of light intensity.

Initially, an input image is captured by a television camera in (2D) and digitized, described by an image function f(x, y) whose value is the light intensity as a function of two parameters x, y, representing the coordinates of the location in the image.

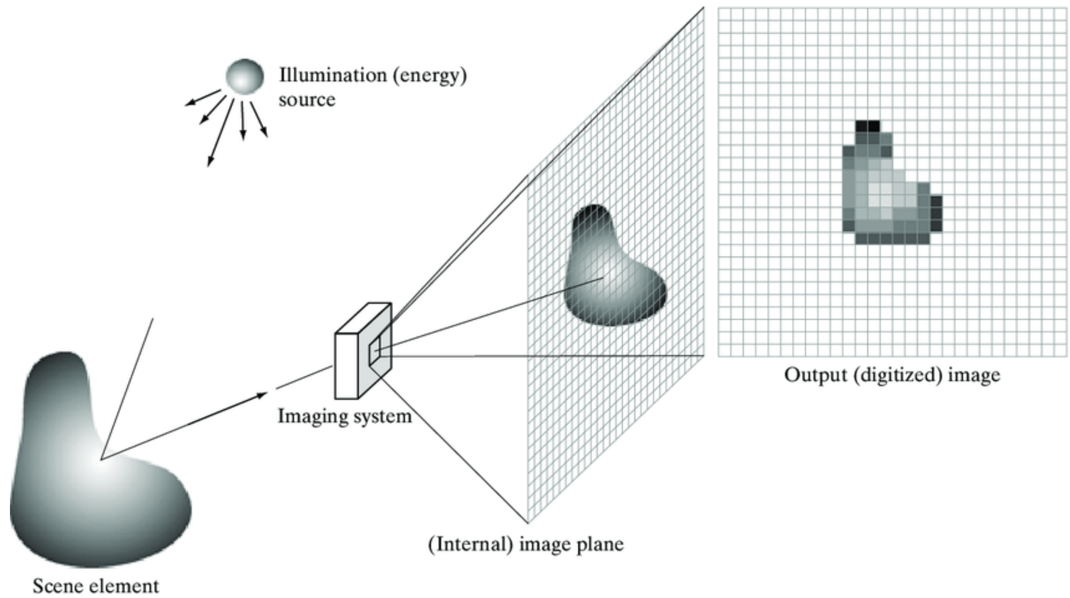


Figure 1: Digital image acquisition process

An image is merely an imperfect representation of a scene, and creating an image involves the intention to present an entity observable by the human eye.

Digital Image

1. The Pixel

A digital image is composed of a set of points called pixels (an abbreviation for Picture Element) to form an image. The pixel thus represents the smallest constitutive element of a *digital image*[*Fundamentals of Digital Image Processing A Practical Approach with Examples in Matlab* p.28]

All these pixels are contained in a two-dimensional array constituting the image, as mentioned in [Figure 2].

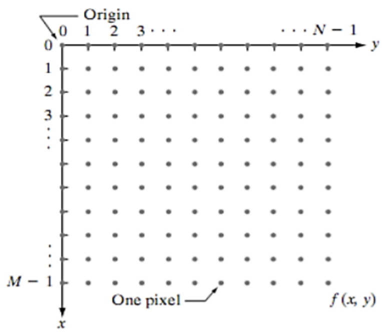


Figure 2: General representation of digital image

We can consider that a pixel has no dimension because, when we look at a photo, a pixel of an object located near the camera corresponds to a smaller size than a pixel of an object located far from the camera, even though these two pixels are part of the same image.

(see Digital Image Explain[mp4])

2. Definition

2.1. Main Display Formats

We refer to definition as the number of points (pixels) constituting an image: it is the product of the number of columns multiplied by the number of rows in the image. An image with 10 columns and 11 rows will have a definition of 10 x 11.

The image is displayed on a screen (also called a monitor), which is an output device that provides a visual representation. This information comes from the computer but in an ”indirect” way.

The processor does not directly send information to the monitor; instead, it processes information from its random access memory (RAM) and then sends it to a graphics card responsible for converting the information into electrical impulses sent to the monitor.

To display these images, standard display formats have been defined based on the evolution of the hardware capabilities of graphics cards and screens. Here are the main ones:

- CGA (320 x 200) 4 colors.
- VGA (640 x 480) 16 colors.

- SVGA (800 x 600) 256 colors.
- XGA (1024 x 768) 256 colors.
- SXGA (1280 x 1024) in 16 million colors.

2.2. Calculation of the total number of pixels in an image

$$TotalNumberOfPixels = columns * rows$$

Example: 10 x 11 = 110 pixels in total for the above image.

3. The Resolution

This is the number of pixels that can be accommodated along a given length (in inches). It is expressed in dots per inch (DPI). Let’s take the example of an image with a resolution of 20 pixels per cm: the size of each pixel is such that on a 1 cm line, we can accommodate 20 pixels (since pixel size is often square, the same number of pixels is accommodated on both axes). A second example involves an image with a resolution of 40 pixels per cm, so there are twice as many pixels for each linear centimeter, and therefore each pixel is half the size.

In this context, it is easy to understand that the smaller the pixel, the better the image quality. An inch measures 2.54 cm, and it is a British unit of measure- ment. Resolution thus establishes the relationship between the pixel definition of an image and its actual representation size on a support, as mentioned in Figure 3.

The higher the pixels per inch, the more information there will be in the image because the resolution of an image defines its sharpness and quality. For comparison, an image at 300 DPI is sixteen times heavier than the same image at 75 DPI.

It is useful to mention that a pixel does not have a predefined size, so if we display an image on the screen, each constitutive pixel of the image will occupy one pixel on the screen.

Resolution is often confused with ”definition”; however, it determines the number of points per unit of surface, with one inch representing 2.54 cm. Res- olution establishes the relationship between the number of pixels in an image and the actual size of its representation on a physical support. A resolution of 300 dpi means 300 columns and 300 rows of pixels per square inch, resulting in 90,000 pixels per *square inch*[*https://www.coursera.org/learn/digital* p.28].

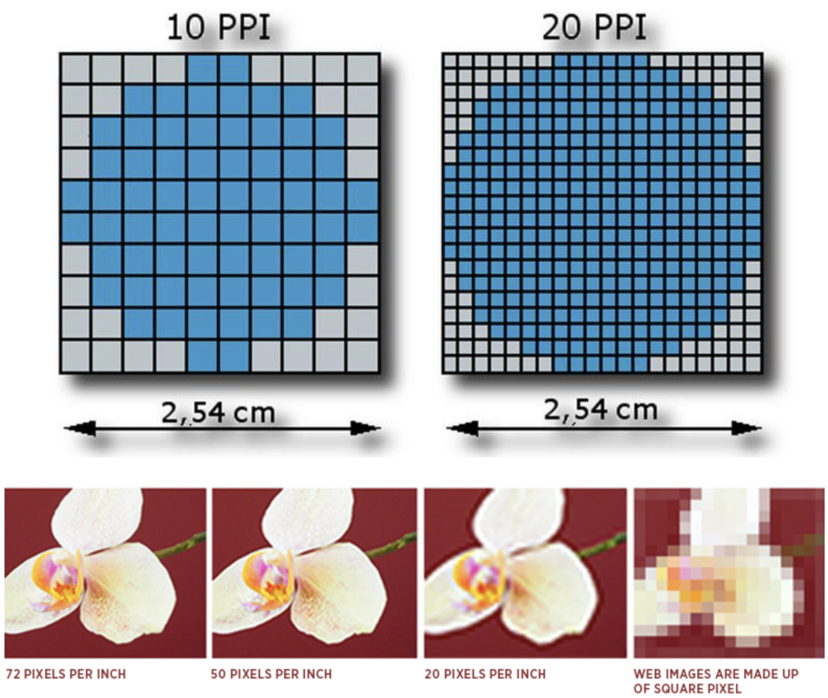


Figure 3: Image Resolution

3.1. Calculating the resolution from the definition and dimension

Example: What would be the pixel definition of a scanned sheet with a width of 8.5 inches and a height of 11 inches at 300 dpi?

Answer:

> « 300 x 8.5 = 2550 pixels
>
> 300 x 11 = 3300 pixels
>
> So, the image definition would be 2550 x 3300 pixels. »

3.2. Some examples of frequently used resolutions

- Computer screens: 72 dpi. This is also the resolution at which images are commonly found on the internet. Not suitable for printing!
- Fax: generally 200 dpi.
- Consumer printers: between 360 dpi and 1400 dpi. This provides quite acceptable quality for everyday tasks (letters, reports, etc.).
- Consumer scanners: 300, 600, or 1200 dpi.
- Professional printing equipment: at least 4800 dpi (for high-quality prints and large sizes, such as posters).

4. Quiz : Exercice

[solution n°1 p. 25]

Question1

What is digital image representation in the context of computer science?

- ○ The way digital images are stored and manipulated by computers.
- ○ The process of capturing light and color in a digital format.
- ○ Both a and b.
- ○ None of the above.

Question2

Why is encoding visual information critical in digital imaging?

Question3

Describe one main challenge in color imagery and provide an example.

Question4

What is a pixel in the context of a digital image?

- ○ A tiny dot that represents a single point in a digital image.
- ○ A large square in a digital image.
- ○ An element used in printing.
- ○ None of the above.

Question5

Given an image with 15 columns and 20 rows, calculate the total number of pixels.

Question6

What is image resolution, and how is it expressed?

- The sharpness of an image, expressed in pixels per inch (PPI) or dots per inch (DPI).
- The size of an image, expressed in inches.
- The color depth of an image.
- None of the above.

Color

1. Introduction

Colors originate from the separation of natural white light into absorbed and reflected components. Every visible light source is composed of a mixture of coherent electromagnetic waves (i.e., pure colors) whose wavelength is between 0.4 micro-meter (violet) and 0.7 micro-meter (red).

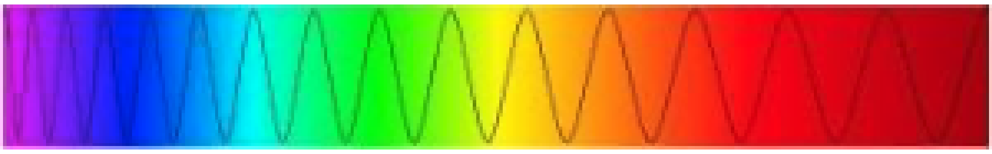
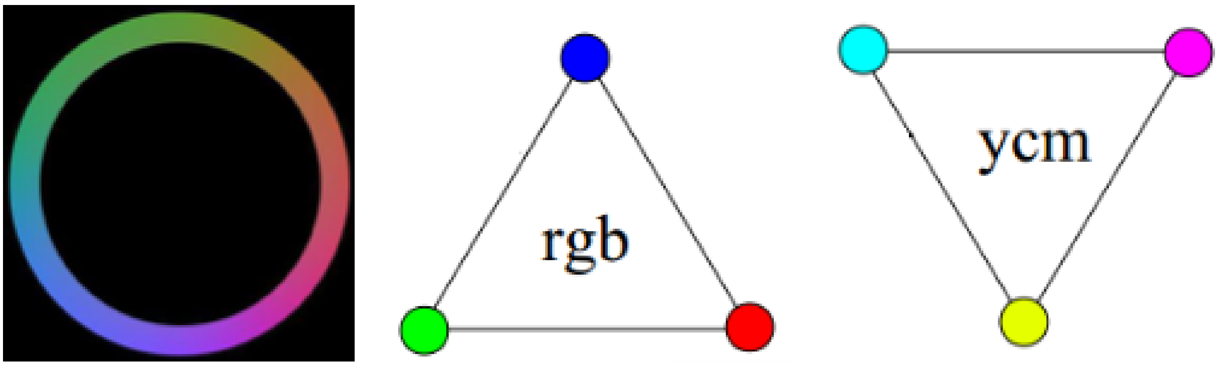


Figure 4: White light spectrum

The main question that we will consider going forward is: ”How to represent these colors in a space that is both easy to manipulate and relevant in terms of color image analysis?”

2. Trichromy

The principle of trichromy lies in the discovery that a triplet of pure colors is sufficient to reproduce, through the mixing of these three components, which we can qualify as primaries, the entirety of colors. The Newton’s color circle can thus be ”summarized” into a triangle of primaries.

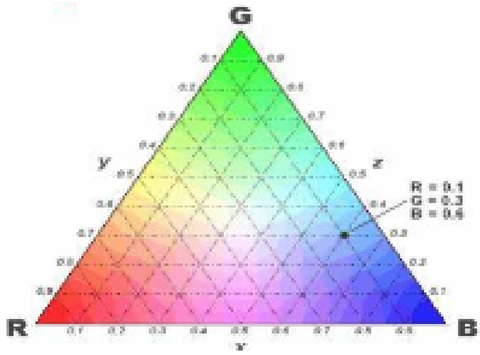


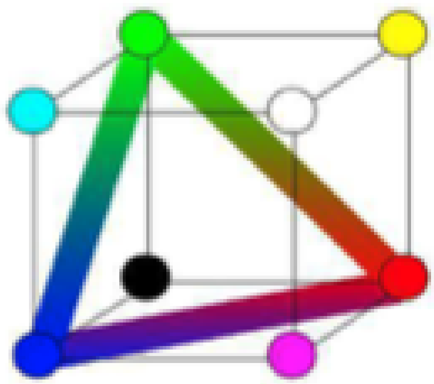
By filling the triangle of primaries according to the law of areas, we obtain the Maxwell triangle

Trichromy allows us to perceive all colors as a three-dimensional vector space, where three primary light sources (r, g, b) vary in intensity between 0 and 100. This principle of additive color synthesis is found in most color reproduction light devices: CRT, LCD, Plasma.

2.1. RGB Space

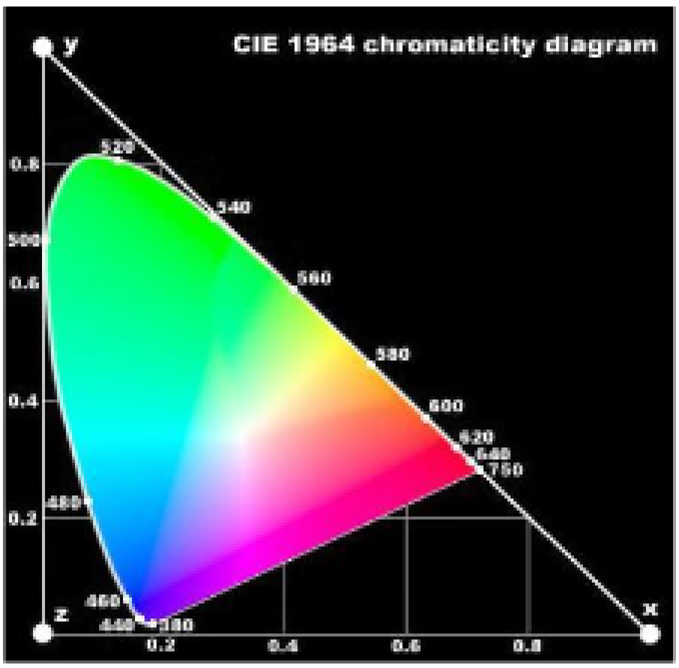
The RGB space is the vector space generated by the three primary components (Red, Green, Blue). The set of produced colors is represented as the interior of a cube, as illustrated in the following color triangle





2.2. XYZ Space

The XYZ space (CIE 1931) is defined through a linear transformation from the RGB space, ensuring that all colors in the visible spectrum are contained within the xyz triangle. The XYZ coordinates of natural colors always have positive values as a result of this transformation.



2.3. HSV Space

Human perception of color is a subjective reaction that can be characterized in terms of brightness, hue, and saturation.

- Brightness corresponds to a sensation expressed with words like light, dark, bright, dim, etc.
- Hue or chromatic tone corresponds to denominations like red, green, blue, etc. It represents the dominant wavelength of a color. White, black, or grays are considered neutral or achromatic.
- Saturation is a measure estimating the colorfulness of a hue independently of brightness. It represents the purity of the perceived color as vivid or pale.

The conversion from RGB to HSV is achieved through a non-linear transforma- tion, and several operators have been proposed for this conversion.

3. Quiz : Exercice

[solution n°2 p. 26]

Question1

What are the primary colors in the RGB color space?

- ○ Red, Green, Blue
- ○ Red, Yellow, Blue
- ○ Red, Green, Yellow
- ○ None of the above.

Question2

Why is the HSV color space important in digital imaging?

Question3

Convert the RGB color (255, 0, 0) to its HSV equivalent

Image Coding

VIII

1. Binary Image

In a black and white image (binary image), a single bit is sufficient to encode the pixel (0 for black, 1 for white), as illustrated in the following figure

1	1	1	1	1	1	1	1	1	1
1	1	1	0	0	0	0	1	1	1
1	1	0	1	1	1	1	0	1	1
1	0	1	1	1	1	1	1	0	1
1	0	1	0	1	1	0	1	0	1
1	0	1	1	1	1	1	1	0	1
1	0	1	0	1	1	0	1	0	1
1	0	1	1	0	0	1	1	0	1
1	1	0	1	1	1	1	0	1	1
1	1	1	0	0	0	0	1	1	1
1	1	1	1	1	1	1	1	1	1

Figure 5: Binary Image

2. GrayScale Image -8 bit-

In an image with 256 shades of gray, each pixel is represented by one byte (8 bits). Here, we only encode the level of brightness, typically using one byte 28 = 256 values. By convention, the value zero represents black (zero brightness), and the value 255 represents white (maximum brightness).

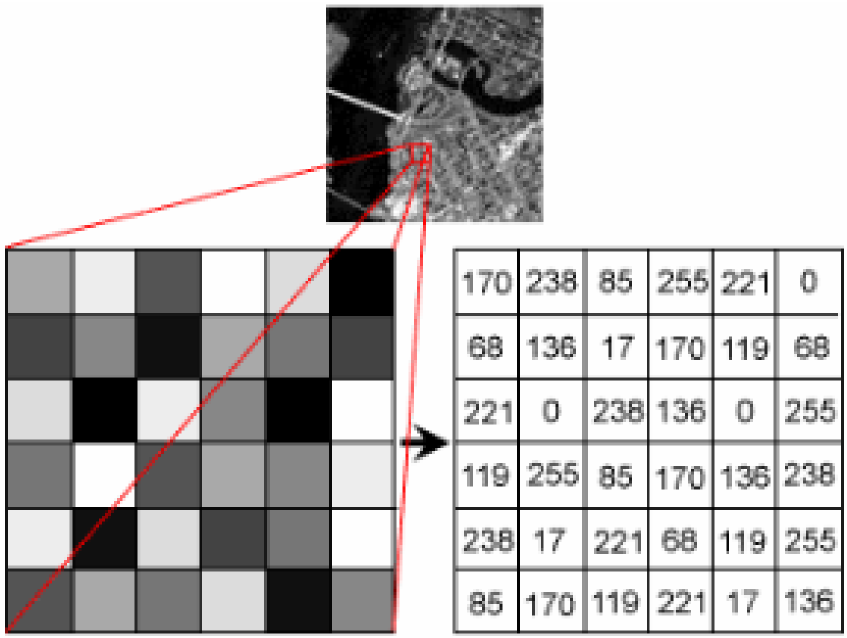


Figure 6: GrayScale pixel representation

Thus, the digital image is represented in the form of a two-dimensional array containing integer values for grayscale images or triplets of integer values for color images. This array of integer values is the ”genetic code” of the image. As for the figure below, we provide an example of an 8 bpp (bits per pixel) photo.

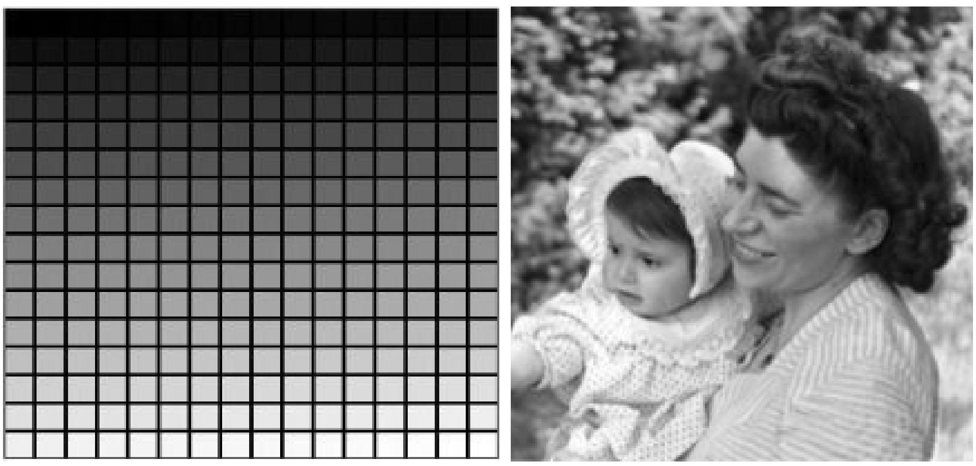


Figure 7: GrayScale images

It is helpful to have an understanding of the 256 shades of gray, as illustrated

in Figure 8.

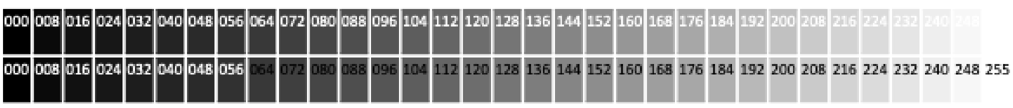


Figure 8: 265 gray degrees

This process is commonly used to reproduce black and white photos or text.

3. Color image

In a color image, we demonstrate that color can be expressed as a linear combination of three primary colors, for example, Red (R), Green (G), and Blue (B). Thus, any color x is expressed as x = aR + bG + cB, where a, b, c are doses of the primary colors. Each of these elements has shades ranging from 0 to 255: 256 colors. To represent 256 colors, it takes 8 bits, which is 1 byte. Since there are three different RGB elements, we thus need 3 bytes to account for all the *nuances* *Fundamentals of Digital Image Processing A Practical Approach with Examples in Matlab* p.28.

The RGB (or RGB in English) coding is used in many digital devices (scanners, cameras, screens, etc.). The principle is simple: one byte is used to code a number between 0 and 255 (hence 256 values), which corresponds to the value of the red, green, or blue component of the pixel (0 being the absence of this component, and 255 the saturation). The combination of these three components produces the final color.

The 24 bits of a color are broken down into 3 sets of 8 bits, meaning 3 bytes:

- 8 bits are dedicated to the red primary hue.
- 8 bits are dedicated to the green primary hue.
- 8 bits are dedicated to the blue primary hue.

Usually, a good image corresponds to doses ranging from 0 to 255. Consequently, an image of this type can be represented by 3 matrices (one for each primary color), each with elements of 8 bits, totaling 24 bits per pixel. We quickly realize the data volume for large and high-definition images. A 640x480 color image (24 bits) occupies a volume of 921,600 bytes. This leads us to use compression techniques to reduce the size of image files.

One of the early display standards, the CGA standard, allowed the display of pixels in a palette of 4 different colors. For this, each pixel had to be coded with 2 bits.

For example:

Decimal	Binary	Color
0	00	Black
1	01	Green
2	10	Red
3	11	Yellow

Lookup Table

Then,increase. Now, we can have images with 16 colors. Since 16 = 24, it is sufficient to code each pixel with a sequence of 4 bits. Here is an example of a common palette:

Decimal	Binary	Color	Decimal	Binary	Color
0	0000	Black	8	1000	Dark Gray
1	0001	Blue	9	1001	Light Blue
2	0010	Green	10	1010	LightGreen
3	0011	Cyan	11	1011	LightCyan
4	0100	Red	12	1100	Light Red
5	0101	Magenta	13	1101	LiMagentaYellow

6	0110	Brown	14	1110	White
7	0111	Gray	15	1111	

Lookup Table

We can continue this way to discover images with increasingly sharp details thanks to their large number of colors: with 8 bits per pixel, we get 256 colors (since 28 = 256); with 16 bits, 65,536 colors; with 24 bits, over 16 million colors; with 32 bits, over 4 billion. From 24 bits onward, we refer to it as true-color display, given how perfect the realism is. In this context:

- 1 bit: 21 possibilities: black and white image
- 2 bits: 22 possibilities: 4 colors
- 4 bits: 24 possibilities: 16 colors
- 8 bits: 28 possibilities: 256 colors
- 24 bits: 224: 16,777,216 million colors

4. Indexed Color Image

Enables obtaining up to 256 fixed colors defined in advance in a palette. It uses only a single layer.

- Encoded in 8 bits per pixel (bpp): 28 = 256 possibilities
- Each pixel can have up to 256 possible fixed colors

As we can observe in Figure 9., with 256 colors, some gradients in this image may appear dithered, and the quality is close to a photo, but there is room for improvement.

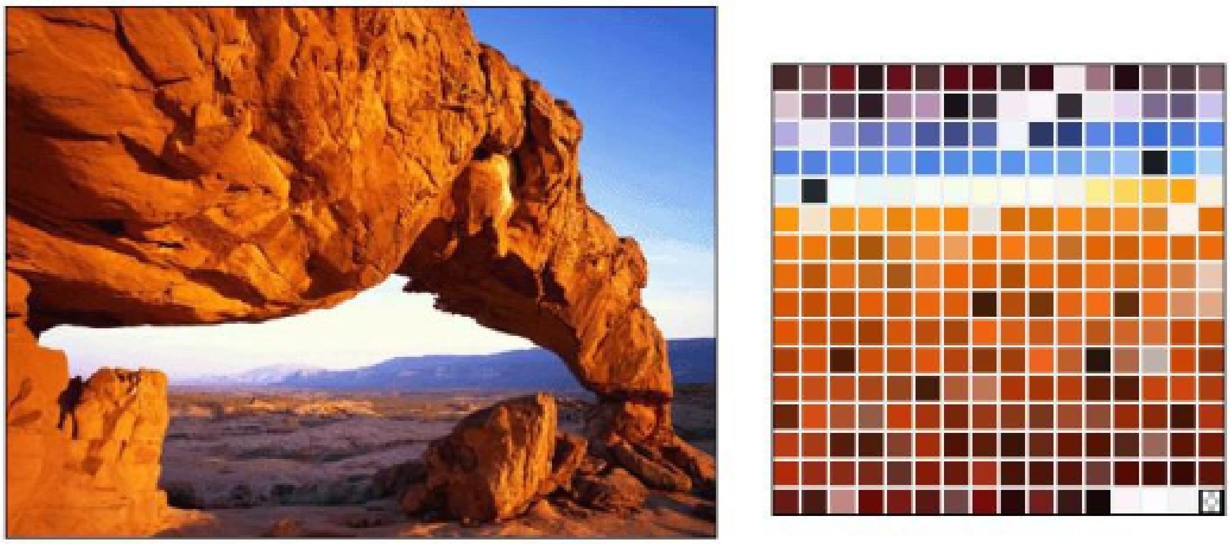


Figure 9: Indexed Color image Example

We can observe that the most natural way to represent a color image is to use three matrices. However, for large images, this leads to significant memory usage

We will demonstrate more precisely the principle of this representation as indicated in Figure 9 .

Indeed, these colors are stored in a color table (colormap), which is an nx3 matrix (where n is the number of colors). The image is then a matrix containing integers ranging from 1 to n, with each integer serving as an index relative to the color table.

Example: The element shown in Figure 10 contains the integer 18, which refers or points to the 18th row of the color table to determine the color of the corresponding pixel.

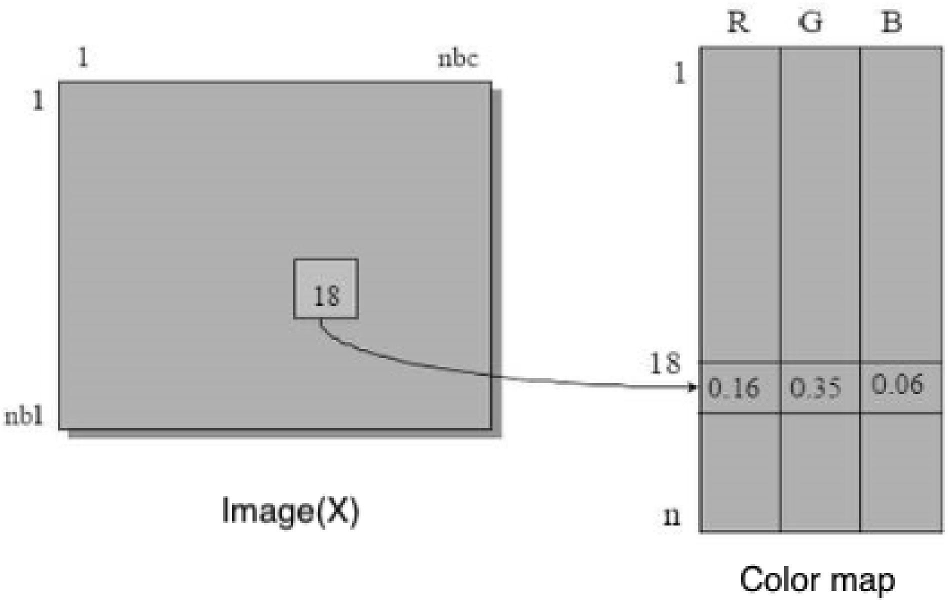


Figure 10: ColorMap

5. Quiz : Exercice

[solution n°3 p. 26]

Question1

How is a binary image encoded?

- Using only black and white pixels.
- Using a full range of colors.
- Using grayscale values.
- None of the above.

Question2

What is the main difference between grayscale and color images in terms of pixel encoding?

Question3

Encode the color image pixel with RGB values (125, 200, 50).

Final Exam

1. Final Exam 1

Exercise 1

Considering that we have a 4 bit image with 10x10 resolution that generated using this expresion

$I(x, y) = (x * y) mod 16$

and $x, y \in [0, 10]$

1. Generate the image I
2. give the right interval that values can be on pixels
3. Calculate the storage size of I
4. Propose the good way to implement this transformation on the image - using Algorithms-
    - horizontal mirroring on the image matrix I
    - Increase the brightness of the image matrix I by adding 5 to each pixel value
    - Flip the image matrix I to the right (rotate by 90 degrees clockwise)
    - Change the image matrix I to a binary image. Set a threshold of 8, where all pixel values greater than or equal to 8 become 1, and the rest become 0.

2. Final Exam 2

Quiz 1

What is a pixel?

- ○ A three-dimensional object in a digital image
- ○ The smallest constitutive element of a digital image
- ○ A color model used in digital imaging
- ○ A type of file format for images

Quiz 2

Which of the following is a correct example of a standard display format and its resolution?

- ○ CGA: 320 x 200, 4 colors
- ○ VGA: 800 x 600, 16 colors
- ○ SVGA: 1024 x 768, 256 colors
- ○ XGA: 1280 x 1024, 4 colors

Quiz 3

How is resolution commonly expressed in digital images?

- Pixels per meter (PPM
- Dots per inch (DPI)
- Colors per inch (CPI)
- Bits per inch (BPI)

Quiz 4

Which color space is known as "true color"?

- RGB
- XYZ
- HSV
- 24-bit color

Quiz 5

Define a digital image and describe its primary components.

Quiz 6

Explain the difference between resolution and definition in the context of digital images.

Quiz 7

Describe the process of image acquisition in digital imaging.

Quiz 8

An image has a resolution of 640 x 480. Calculate the total number of pixels in this image.

Quiz 9

If a scanned image has a width of 8.5 inches and a height of 11 inches, scanned at 300 DPI, what is the pixel definition of this image?

Conclusion

This chapter provided a comprehensive overview of digital image representation, delving into fundamental concepts like:

- **Pixels:** The building blocks of digital images, forming a two-dimensional grid.
- **Resolution:** The density of pixels, determining image sharpness and quality.
- **Color representation:** Explored various models like RGB, HSV, and indexed color.
- **Image coding:** Techniques used to encode pixel information based on color depth (bits per pixel).

The chapter highlighted the trade-off between image quality and data storage requirements. While higher resolutions and color depths offer finer details and more realistic colors, they also come at the cost of larger file sizes. Understanding these concepts equips you with the knowledge to make informed decisions regarding image representation for various applications.

Exercise solutions

Solution n°1

[exercice p. 12]

Question1

What is digital image representation in the context of computer science?

○ The way digital images are stored and manipulated by computers.

○ The process of capturing light and color in a digital format.

◉ Both a and b.

○ None of the above.

Question2

Why is encoding visual information critical in digital imaging?

Encoding visual information is critical in digital imaging because it allows for efficient storage, manipulation, and transmission of visual data, ensuring that images can be accurately represented and reproduced across different devices.

Question3

Describe one main challenge in color imagery and provide an example.

One main challenge in color imagery is color consistency across different devices. For example, the same image might appear differently on a smartphone screen compared to a computer monitor due to variations in display technology and color calibration.

Question4

What is a pixel in the context of a digital image?

◉ A tiny dot that represents a single point in a digital image.

○ A large square in a digital image.

○ An element used in printing.

○ None of the above.

Question5

Given an image with 15 columns and 20 rows, calculate the total number of pixels.

300

Question6

What is image resolution, and how is it expressed?

- ◉ The sharpness of an image, expressed in pixels per inch (PPI) or dots per inch (DPI).
- ○ The size of an image, expressed in inches.
- ○ The color depth of an image.
- ○ None of the above.

Solution n°2

[exercice p. 16]

Question1

What are the primary colors in the RGB color space?

- ◉ Red, Green, Blue
- ○ Red, Yellow, Blue
- ○ Red, Green, Yellow
- ○ None of the above.

Question2

Why is the HSV color space important in digital imaging?

The HSV color space is important because it aligns more closely with human perception of colors, making it easier to manipulate and understand color properties such as hue, saturation, and value.

Question3

Convert the RGB color (255, 0, 0) to its HSV equivalent

The RGB color (255, 0, 0) converts to HSV (0, 100%, 100%).

Solution n°3

[exercice p. 21]

Question1

How is a binary image encoded?

- ◉ Using only black and white pixels.
- ○ Using a full range of colors.
- ○ Using grayscale values.
- ○ None of the above.

Question2

What is the main difference between grayscale and color images in terms of pixel encoding?

Grayscale images encode each pixel with a single value representing light intensity, whereas color images encode each pixel with multiple values representing different color channels (e.g., RGB).

Question3

Encode the color image pixel with RGB values (125, 200, 50).

The RGB values (125, 200, 50) represent the pixel's red, green, and blue intensities, which combine to display the specific color at that pixel location.

References

Fundamentals of Digital Image Processing A Practical Approach with Examples in Matlab	https://pce-fet.com/common/library/books/17/5186_FundamentalsofDigitalImageProcessing-APracticalApproachwithExamplesinMatlab.pdf
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