Exploring Colour Spaces

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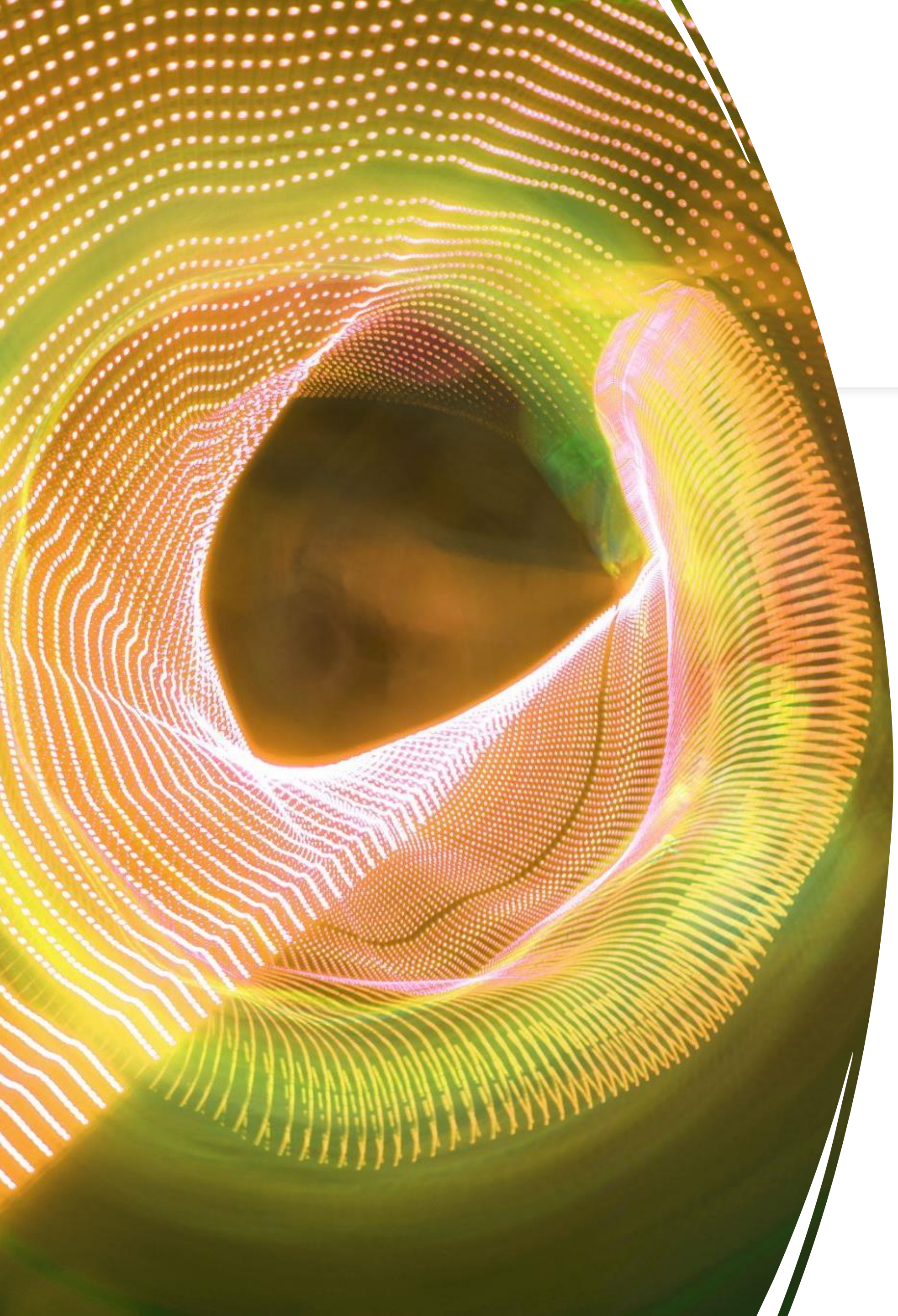
Outline

- Introduction to light and colours
- Retina
- Rods and Cones
- Colour Spaces
- Colour Coding with Python
  - RGB
  - HSI
  - CIE L*a*b*
  - CIE L*u*v*



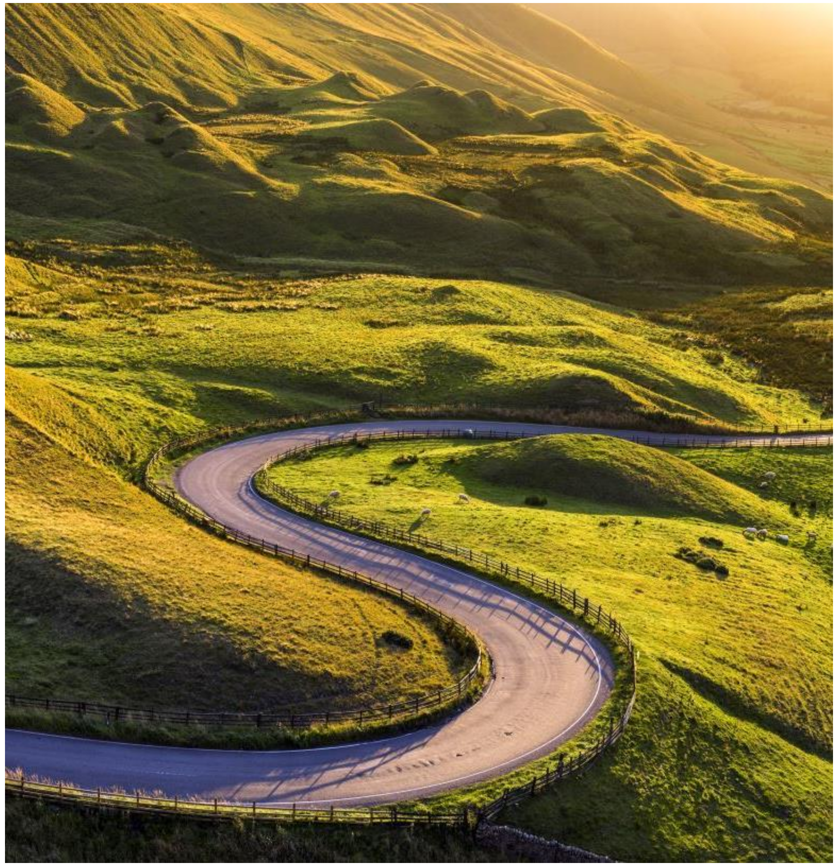
Light and Wavelength

- About half of the **energy emitted** by the Sun that reaches the Earth is **VISIBLE** light.
- Evolution has taken advantage of this quality
- What is **light**?
- It is a particular type of **electromagnetic** radiation the wavelengths of which are visible to us because the cell of our **RETINAS** (**photoreceptors** at the back of our eyes) transform them into **electrochemical** signals the brain uses to construct the **perception** of seeing. *(Falcinelli, 2022)*

A Long Journey

- **Ancient Greece:**

- **Empedocles (5th century BCE):** Light travels as a wave and moves through space at a finite speed. Light consists of particles emitted from luminous bodies.
- **Plato and Aristotle:** Plato believed that vision involves light rays emitted from the eyes that interact with objects. Aristotle suggested that light is a condition of the transparent medium surrounding us.
- **Euclid (circa 300 BCE):** Euclid described the laws of reflection and proposed that light travels in straight lines.
- **Ptolemy (circa 100 BCE):** Expanded on Euclid's work by studying refraction and developing early theories on how light passes through different media.
- **Light, Particles, Reflection, Straight Lines, Refraction**
- (Lloyd,1970)



Some historical hints

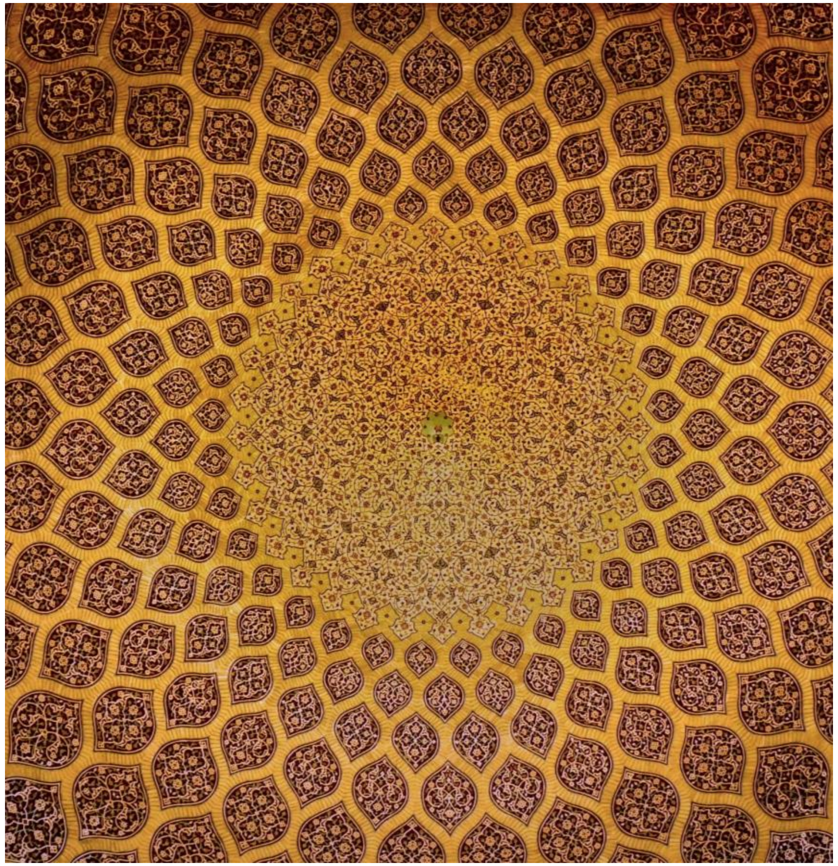
- **Medieval and Islamic Contributions**

- **Al-Kindi** (9th century CE): An Arab philosopher proposed that rays of light travel in straight lines and discussed the properties of reflection and refraction.

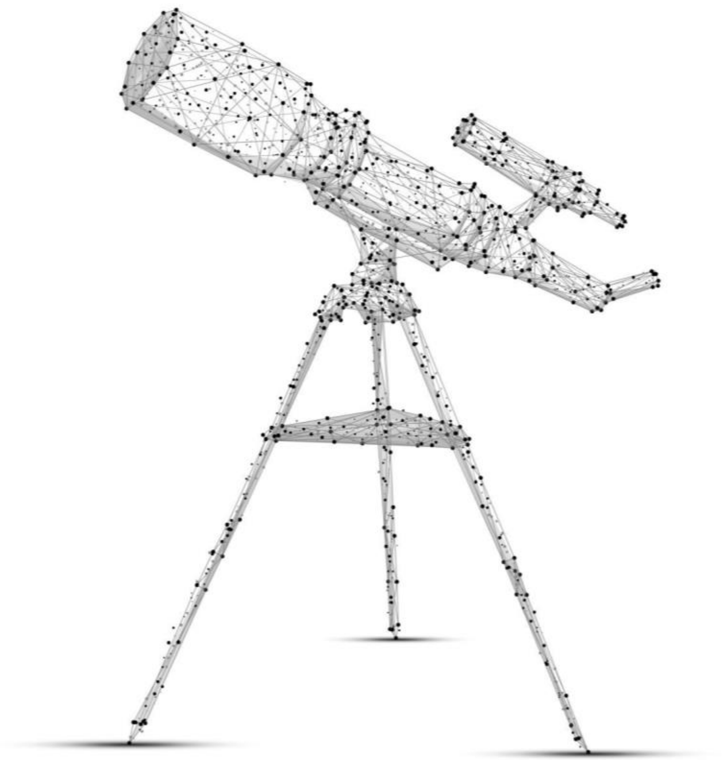
- **Alhazen** (Ibn al-Haytham, 965-1040 CE): challenged previous theories and introduced a comprehensive theory of vision. Light is emitted in all directions from every point on an illuminated surface and that vision occurs when these rays enter the eye.

- **Roger Bacon** (1214-1292 CE): An English philosopher who built upon Alhazen's work, emphasizing experimental methods and contributing to the understanding of reflection and refraction.

- **Reflection, Refraction, Theory of Vision**
- (Lindberg, 1976)



Some historical hints



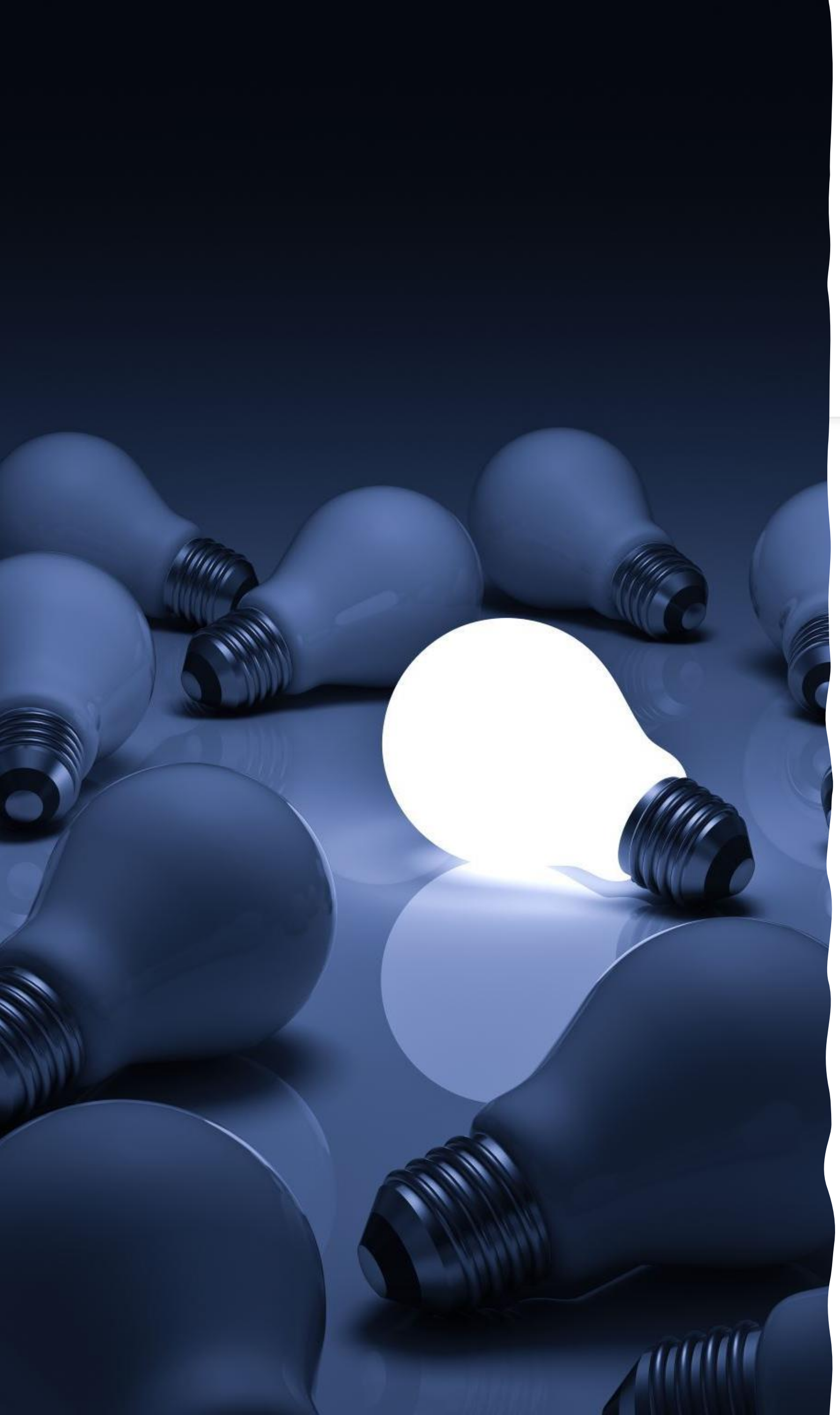
- **Renaissance and Early Modern Period**
- **Johannes Kepler** (1571-1630): Kepler refined the understanding of how light interacts with lenses, leading to the development of improved telescopes. His work "Astronomiae Pars Optica" laid the groundwork for modern optics.
- **René Descartes** (1596-1650): Descartes proposed the **corpuscular** theory of light, suggesting that light consists of particles. He also developed the **law of refraction** (Snell's law) and explained the rainbow's formation.
- **Interaction, Corpuscular, Refraction**.

Some historical hints

- **Scientific Revolution**
- **Isaac Newton** (1643-1727): presented the corpuscular theory of light and conducted experiments on the dispersion of light through prisms. Light is a mixture of colours.
- **Christiaan Huygens** (1629-1695): proposed the wave theory of light in his "Treatise on Light," suggesting that light propagates as waves through the ether. He explained phenomena like diffraction and interference.
- **Corpuscular, dispersion, wave, diffraction and interference**
- (Newton, 1704) (Huygens,1690)

Some historical hints

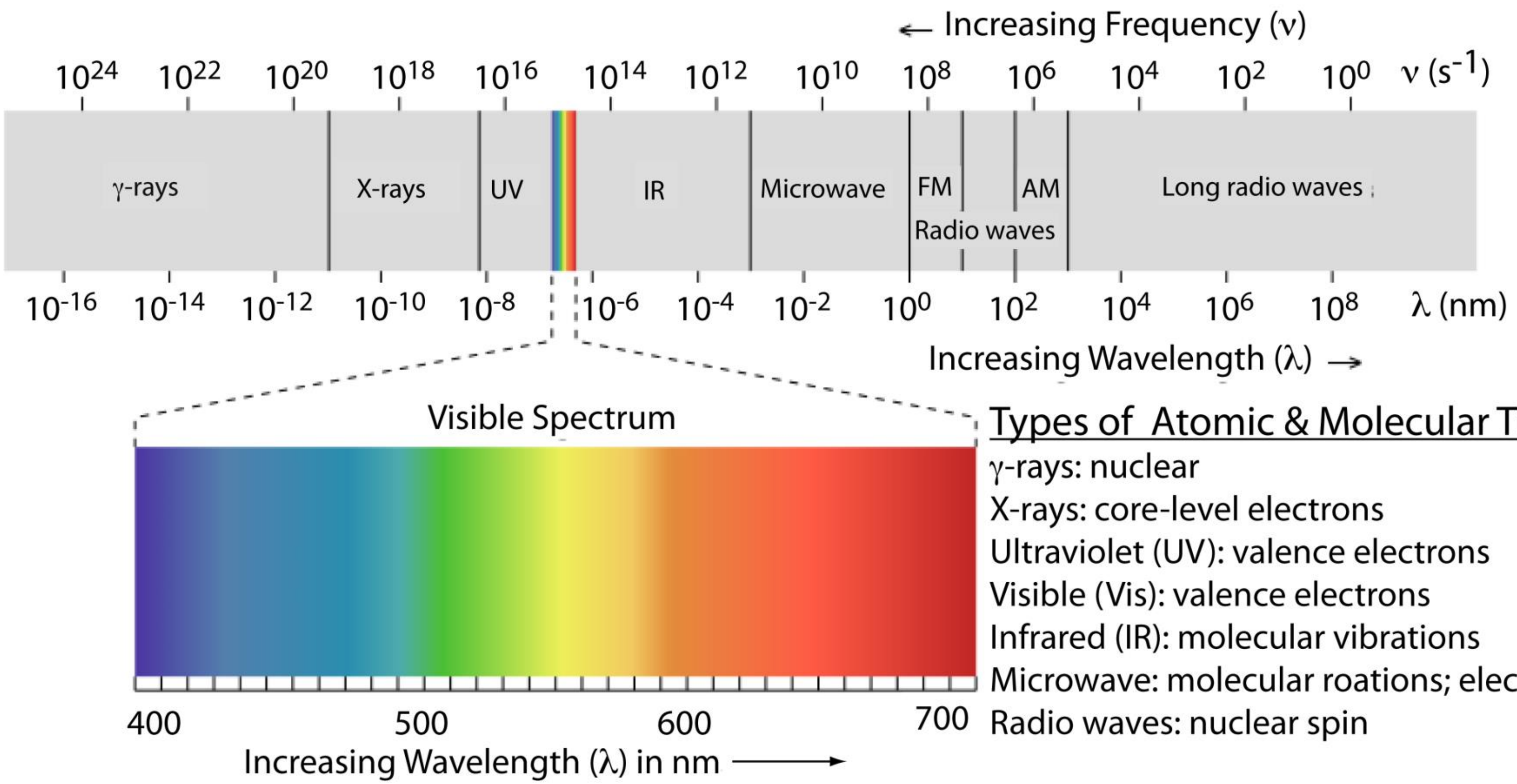
- 19th Century Developments
- **Thomas Young** (1773-1829): Showed interference patterns that could not be explained by particle theory alone paving the way to the double nature of light.
- **Augustin-Jean Fresnel** (1788-1827) worked on wave optics further and validated the wave theory by explaining diffraction and polarization.
- **James Clerk Maxwell** (1831-1879): Maxwell's electromagnetic theory **unified** light with electromagnetism, describing light as electromagnetic waves consisting of oscillating electric and magnetic fields.
- **Double Nature; Wave Optics; Electromagnetic Theory.**



Some historical hints

- **<u>Quantum Era</u>**
- Albert Einstein (1879-1955): Einstein's explanation of the photoelectric effect in 1905 introduced the concept of light quanta or photons, particles of light that carry energy.
- Niels Bohr (1885-1962): Bohr's model of the atom incorporated quantum theory, explaining how electrons absorb and emit light in discrete energy levels.
- Quantum Electrodynamics (QED) describes the interaction between light and matter with high precision, merging wave and particle theories into a comprehensive framework.
- **Photoeletric Effect; Quantum Theory, Quantum Electrodynamics.**
- (Einstein, 1905)

Electromagnetic Radiation



Types of Atomic & Molecular Transitions

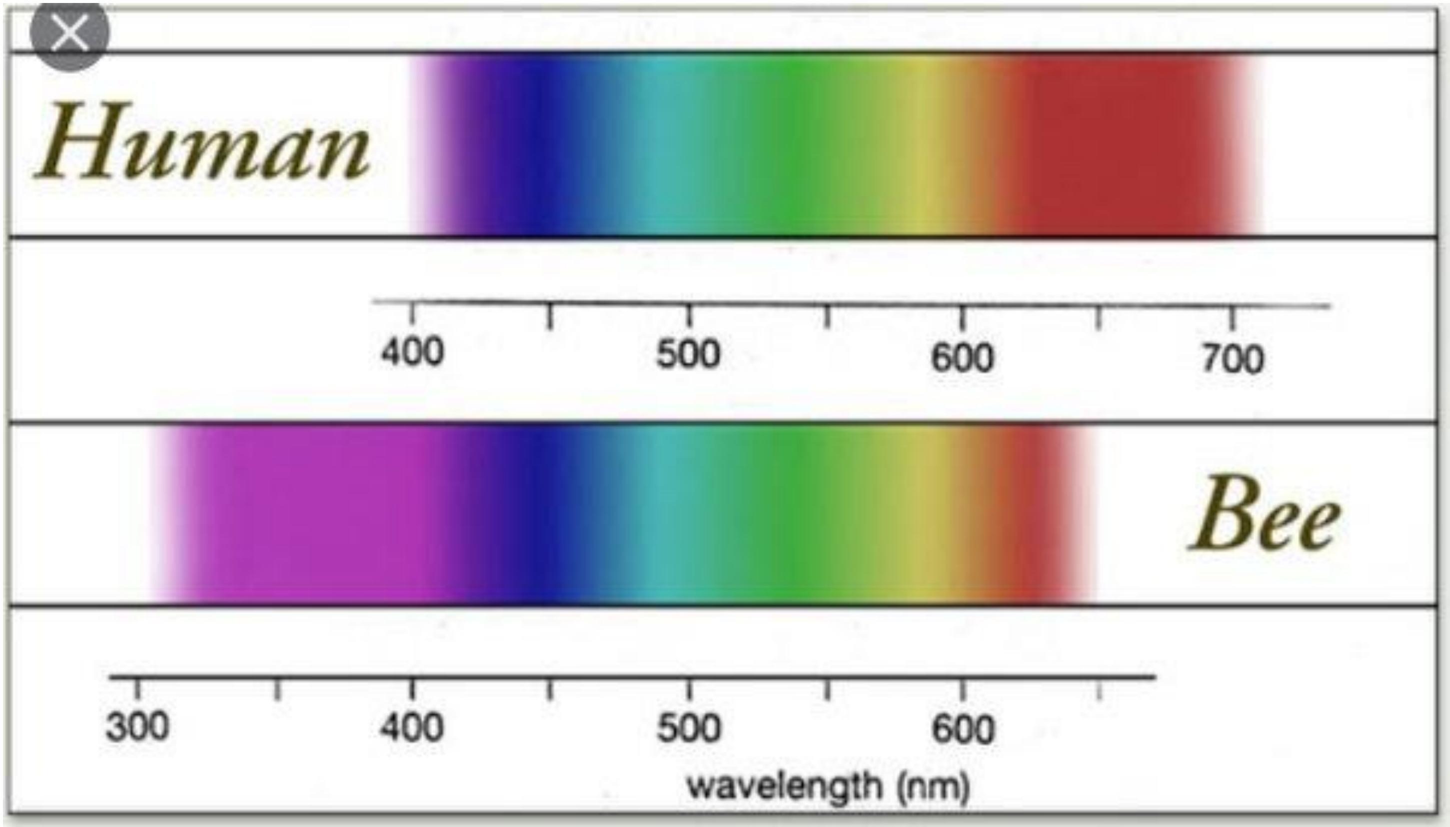
γ-rays: nuclear
X-rays: core-level electrons
Ultraviolet (UV): valence electrons
Visible (Vis): valence electrons
Infrared (IR): molecular vibrations
Microwave: molecular roations; electron spin
Radio waves: nuclear spin

The visible spectrum

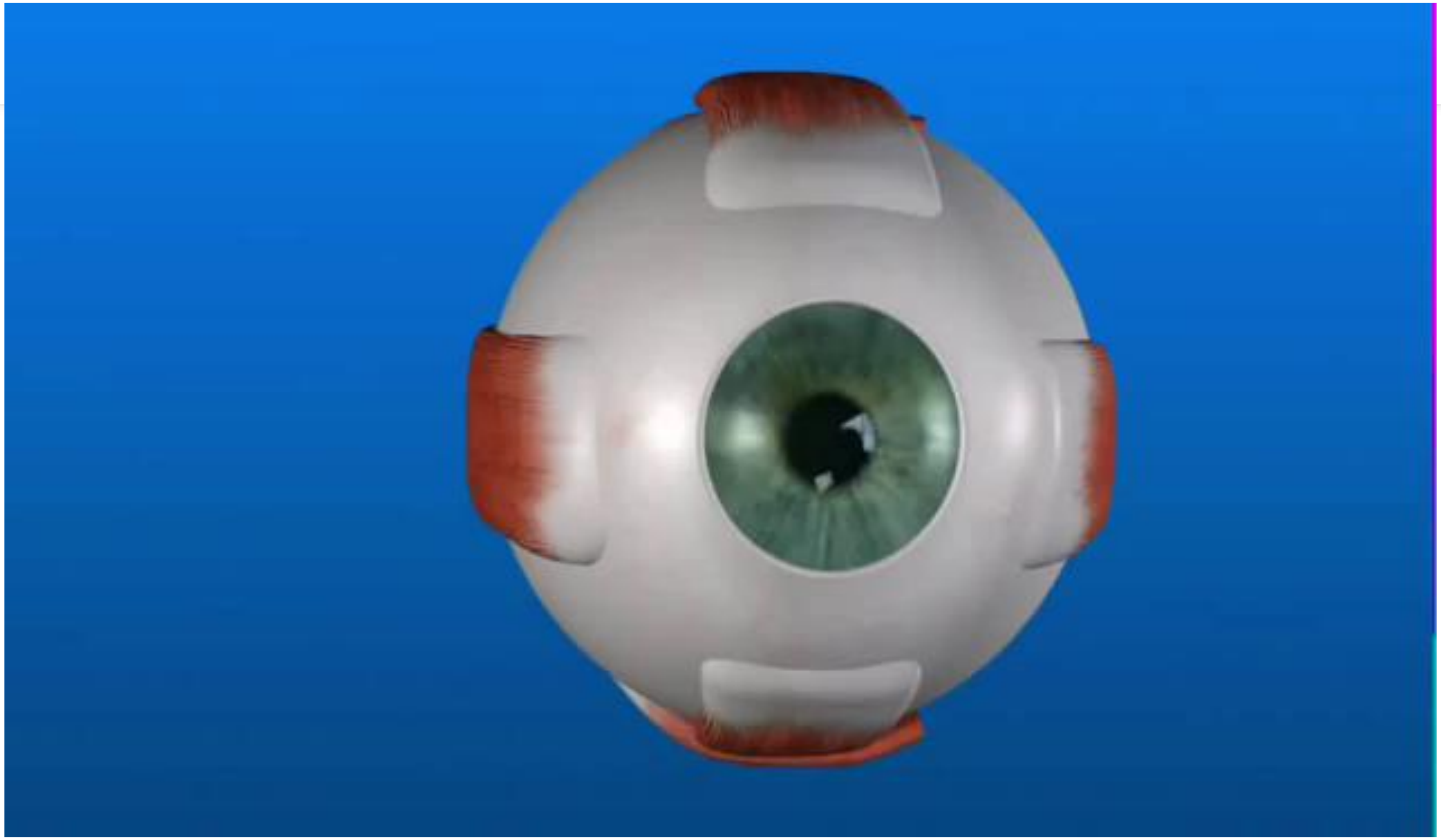
Colour Physics

- From the physics viewpoint, there is no qualitative difference between all electromagnetic radiation and the "tiny" portion of it that we call **LIGHT**.
- The portion between **380 nm** and **760 nm** corresponds to the succession of colours in the rainbow.

Animal Species and Humans

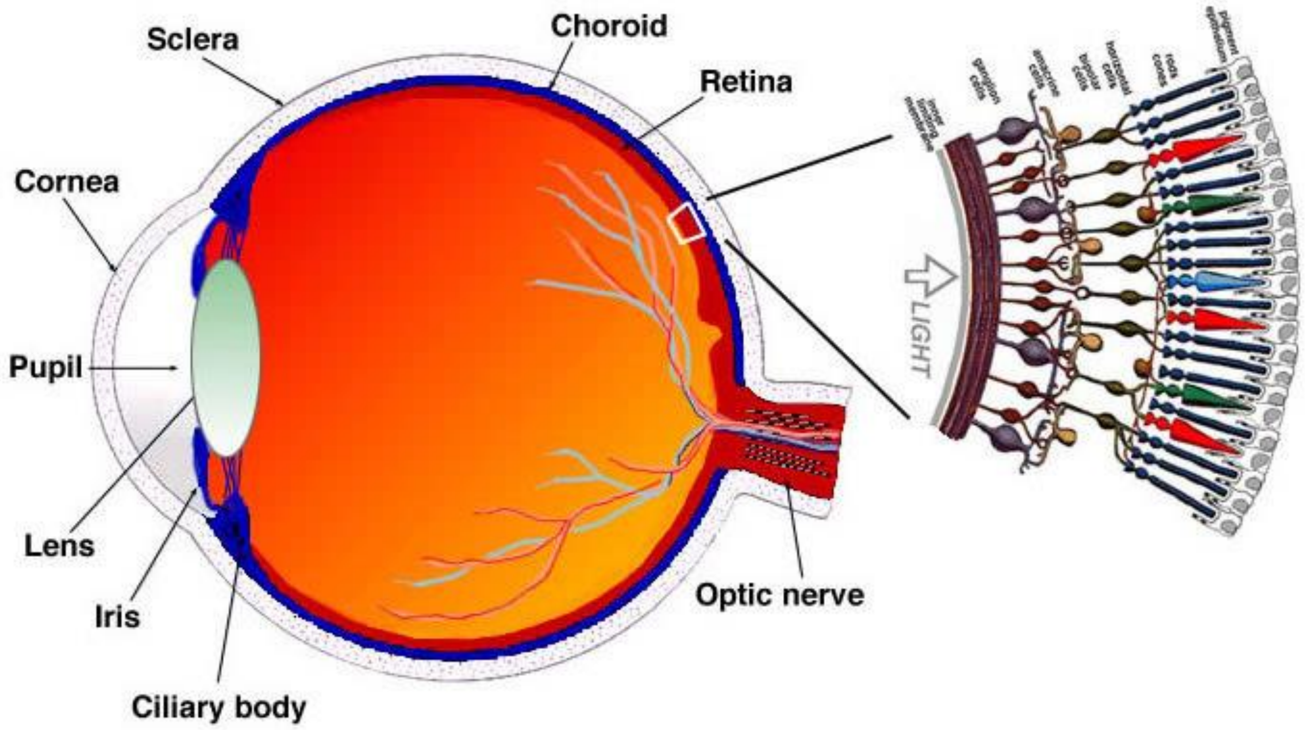


Light – Eye - Retina



Credits: American Academy of Opthalmology https://www.aao.org/

Retina

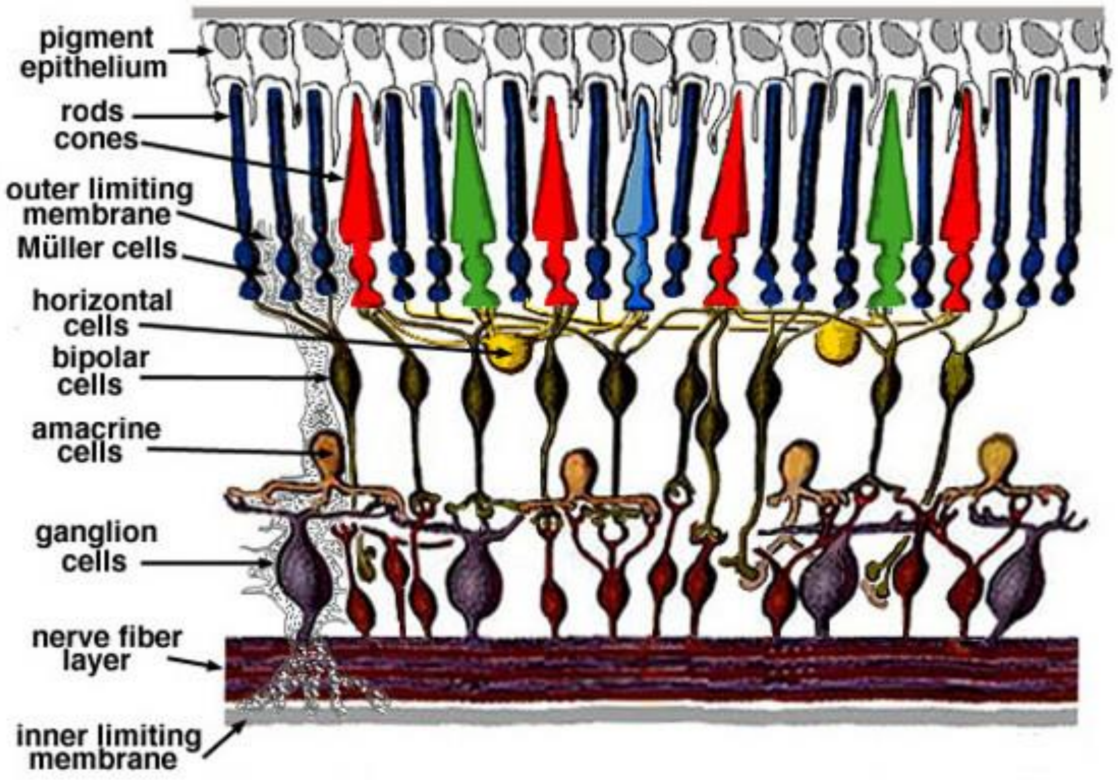


Kolb, H. (2012). Simple anatomy of the retina.

Cones and Rodes

- "Almost all of our vision is mediated by **CONES** and the PHOTOPIC system, yet cones make up barely **5% of our retinal photoreceptors**."
- "We possess **RODS** and a **SCOTOPIC** system, with rods comprising **95% of our retinal photoreceptors**"

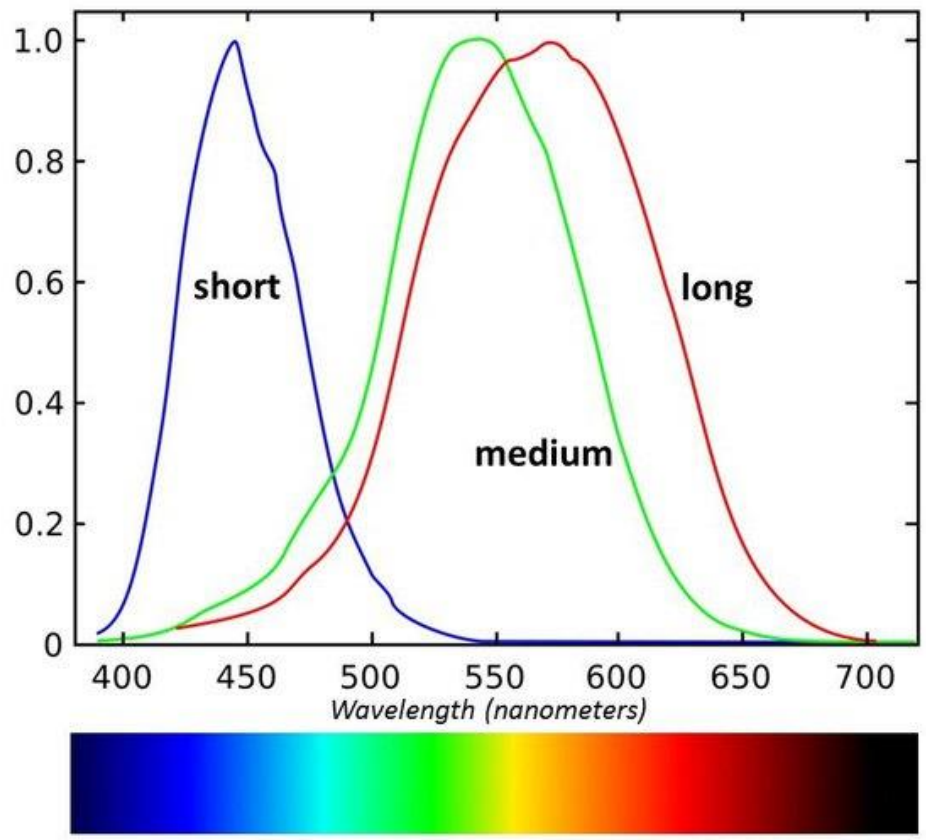
(Lamb, 2016)



Kolb, H. (2012). Simple anatomy of the retina.

Normalised Fraction of light absorbed by cones

- We have three types of cones according the wavelength they reflect (L, M, S): Long, Medium, Short Wavelength
- Sometimes you can find the three approximately named as RGB
- Green cones account for 65% of the total, Red cones account for 33 %, and Blue only for 2%.



Colour Spaces and Colour Models

- "The purpose of a colour model (also called a colour space or colour system) is to facilitate the specification of colours in some standard way.
- In essence, a colour model is a specification of (1) a coordinate system, and (2) a subspace within that system, such that each colour in the model is represented by a single point contained in that subspace." (Azad and Hasan, 2017)

Colour Spaces and Models: RGB

- **RGB** color space is a color model used in various devices such as digital cameras, computer monitors, and televisions. It stands for Red, Green, and Blue, which are the **three primary** colors of light.
- **RGB** color space is based on the additive color theory, where colors are created by combining these three primary colors in varying intensities.

Colour Spaces and models: RGB

- **Primary Colors**:

Red (R): One of the three primary colors in the RGB model.

Green (G): Another primary color in the RGB model.

Blue (B): The third primary color in the RGB model.

- **Additive Color Mixing:**

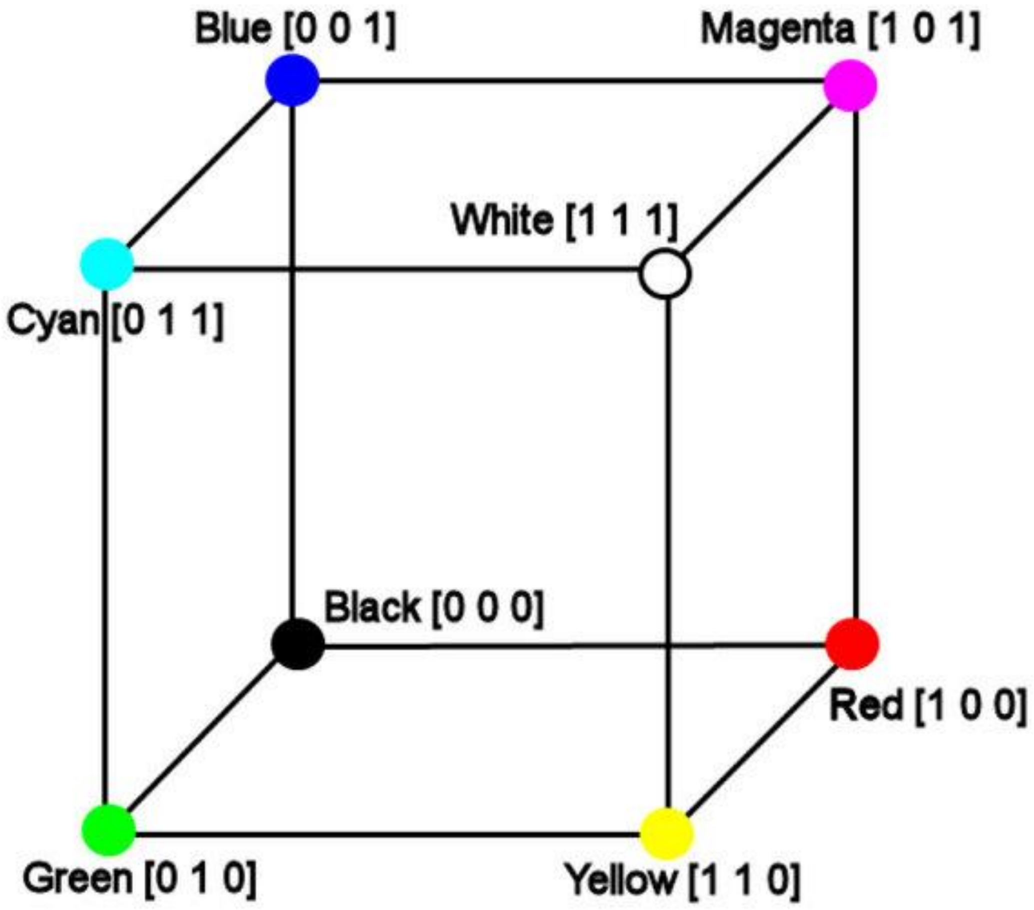
In the RGB color space, colors are created by **adding different intensities of red, green, and blue light**. When combined at full intensity (255, 255, 255), they produce white light.

When all three colors are absent (0, 0, 0), they produce black. Intensity values can also be normalised in the continuous range [0,1].

RGB Cube

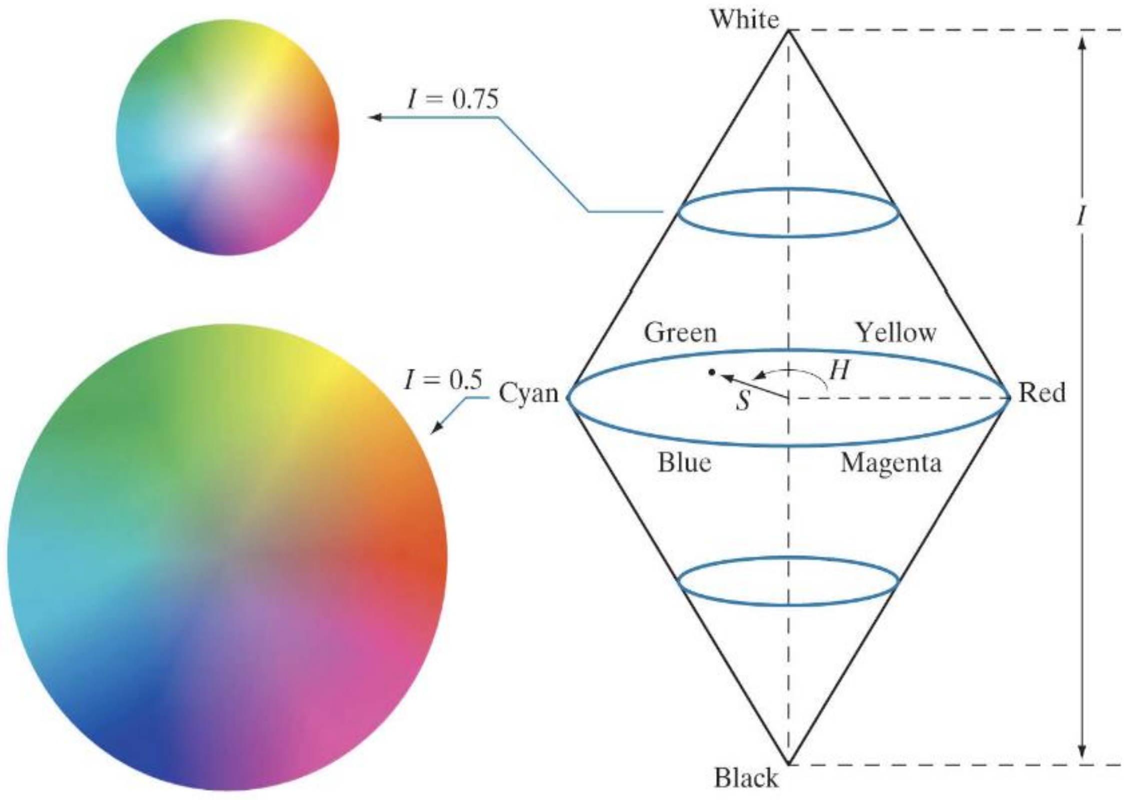
In the RGB model, each color appears in its primary spectral components of red, green, and blue. This model is based on a Cartesian coordinate system. The color subspace of interest is the cube shown

In the RGB colour cube, the three axes represent the intensity of the red, green, and blue colors. The origin (0, 0, 0) is black, and the opposite corner (255, 255, 255) is white. That is (1,1,1) if normalised. Different colours are found at various points within the cube, based on their RGB values.



Colour Spaces and models: HSI

- **Hue** (H): Hue represents the pure colour of the image. Described as the attribute that distinguishes one colour from another. Typically measured in degrees, ranging from 0° to 360°, where 0° and 360° both correspond to red, 120° to green, and 240° to blue. The other colours are distributed between these primary hues.
- **Saturation** (S): Saturation refers to the intensity or purity of the colour. A fully saturated color has no white light added, resulting in a vivid, pure colour. Saturation is often represented as a percentage, ranging from 0% (completely desaturated) to 100% (fully saturated).
- **Intensity** (I): Intensity, also known as brightness or value, represents the perceived brightness of the colour. It's a measure of how much light the colour reflects or emits. In the HSI colour space, intensity is typically represented as a value ranging from 0 to 1, where 0 represents black (no light) and 1 represents the brightest possible colour.



HIS(Hue, Saturation, Intensity)

$$H = \begin{cases} \theta & \text{if } B \leq G \\ 360 - \theta & \text{if } B > G \end{cases}$$

$$\theta = \cos^{-1}\left\{ \frac{\frac{1}{2}[(R - G) + (R - B)]}{\left[(R - G)^2 + (R - B)(G - B)\right]^{1/2}} \right\}$$

$$S = 1 - \frac{3}{(R + G + B)}[\min(R, G, B)]$$

$$I = \frac{1}{3}(R + G + B)$$

CIE L*a*b* and CIE L*u*v* colour spaces

- Humans see a broad spectrum of colours and colour shades. However, colour perception differs between individuals.
- Colour across devices such as monitors and printers can vary significantly unless these devices are properly calibrated.
- **CIE L*a*b*** and **CIE L*u*v*** provide a structured way to **define** and **manipulate colours** in a consistent manner across different devices and mediums.
- They are two of the most widely used models in various applications, particularly in image processing, printing, and colour management systems.

CIE L*u*v* vs. CIE L*a*b*

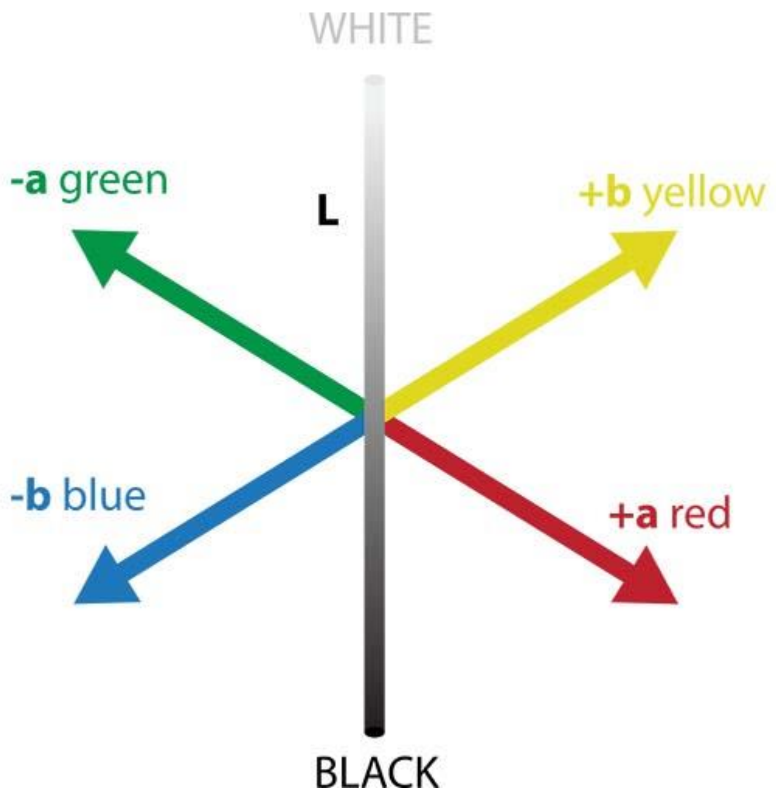
- **Perceptual Uniformity**
- **CIE L*a*b***: Designed to be perceptually uniform, aiming to ensure that perceptual differences between colors are consistent across the color space. However, it is more commonly used for surface colors (reflective colors).
- **CIE L*u*v***: Also designed to be perceptually uniform but tends to perform better in terms of representing additive color mixing, making it more suitable for applications involving light sources and displays.

CIE L*a*b* channels

L* (Lightness)*
Range: 0 to 100

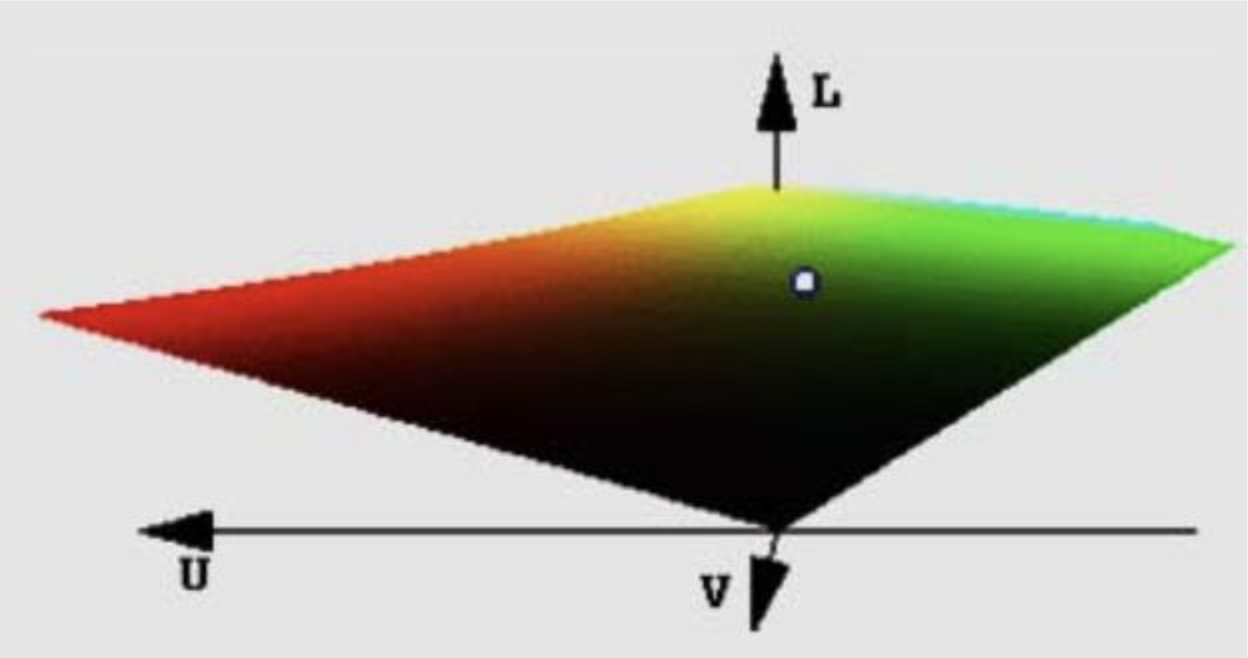
a* (Green-Red Axis)*
Range: Typically -128 to 127

b* (Blue-Yellow Axis)*
Range: Typically -128 to 127



CIE L*u*v* channels

- **L* (Lightness):**
  - Value range: 0 to 100
  - A value of **0** corresponds to **black**, and a value of **100** corresponds to diffuse **white**.
- **u* (Chromaticity coordinate):**
  - the color's position on the **red-green** axis.
  - Theoretically, the range is from -134 to +220, but practical values usually fall within a narrower range, approximately -100 to +100.
- **v* (Chromaticity coordinate):**
  - the color's position on the **yellow-blue** axis.
  - Value range: Theoretically, the range is from -140 to +122, but practical values usually fall within a narrower range, approximately -100 to +100.



(Plataniotis, Venestanopoulos, 2000), (Fairchild, 2013)

Python Libraries to be installed on your laptop

Link GitHub Repo:

https://github.com/alessandrobruno10/etxcp

Working Environment:

Google Colab

Python dependencies to be installed:

pip install scikit-image
pip install opencv-python
pip install matplotlib

Import

ipywidgets
IPython.display
cv2
Numpy
PIL
matplotlib

Link to GitHub repo:

You may want to visit the GitHub repo by scanning the QR code or by copying and pasting the following URL in your browser:

https://github.com/alessandrobruno10/etxcp

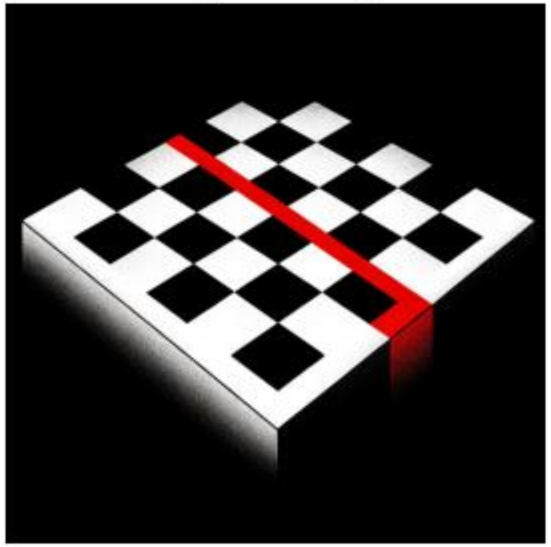
Some functions to play around with colour spaces

- **Input Image (RGB)**
- **Showing R, G, and B separately**
- **Converting RGB image in HSI**
- **Converting RGB image in CIE L*a*b***
- **Converting RGB image in CIE L*u*v***
  Showing each channel out of them

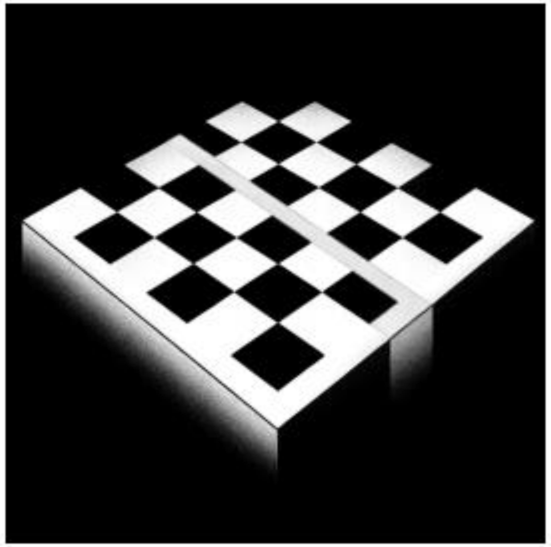
Colour Channels

- RGB Image

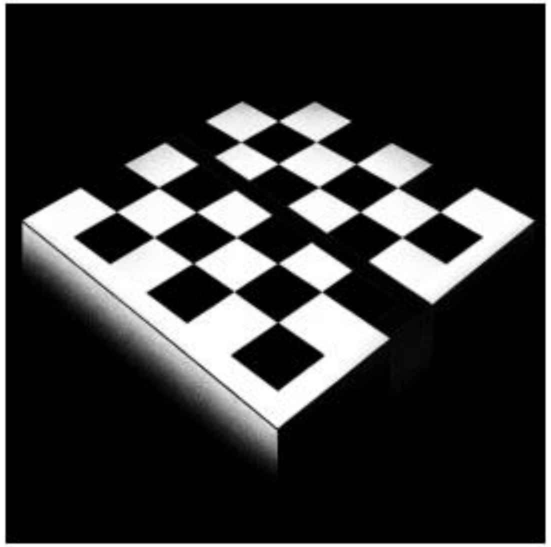
Original Image



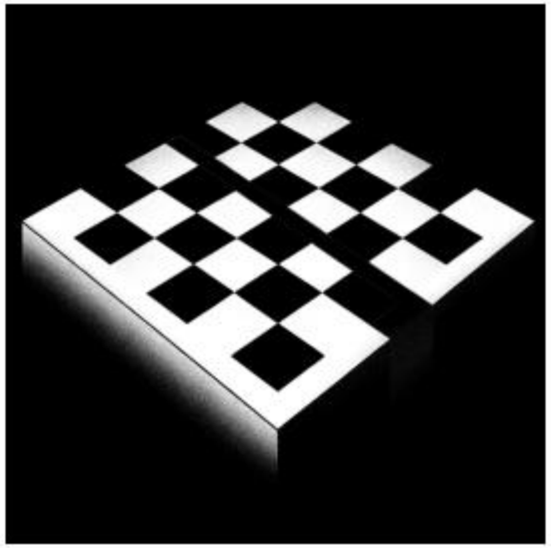
Red



Green

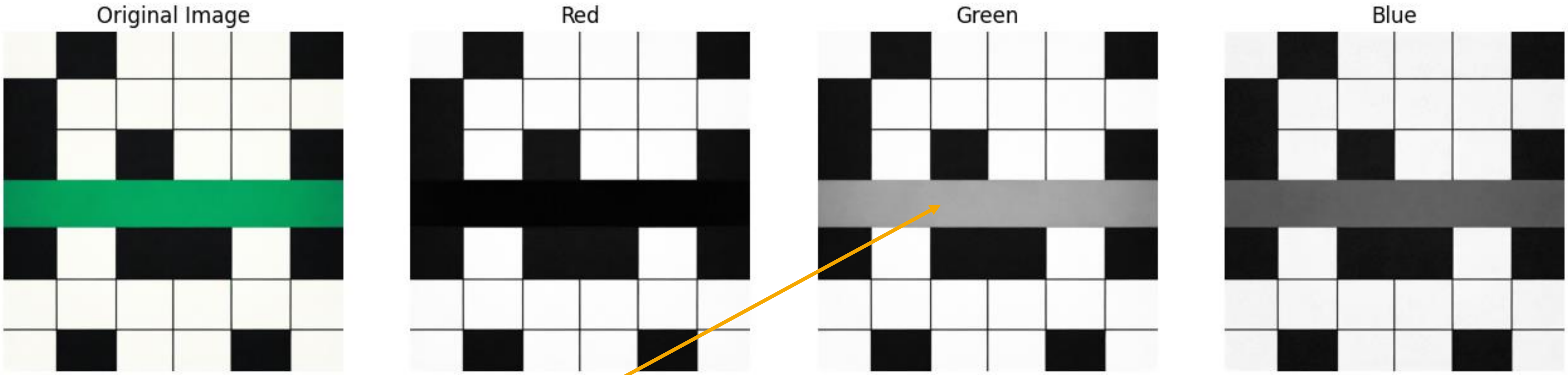


Blue



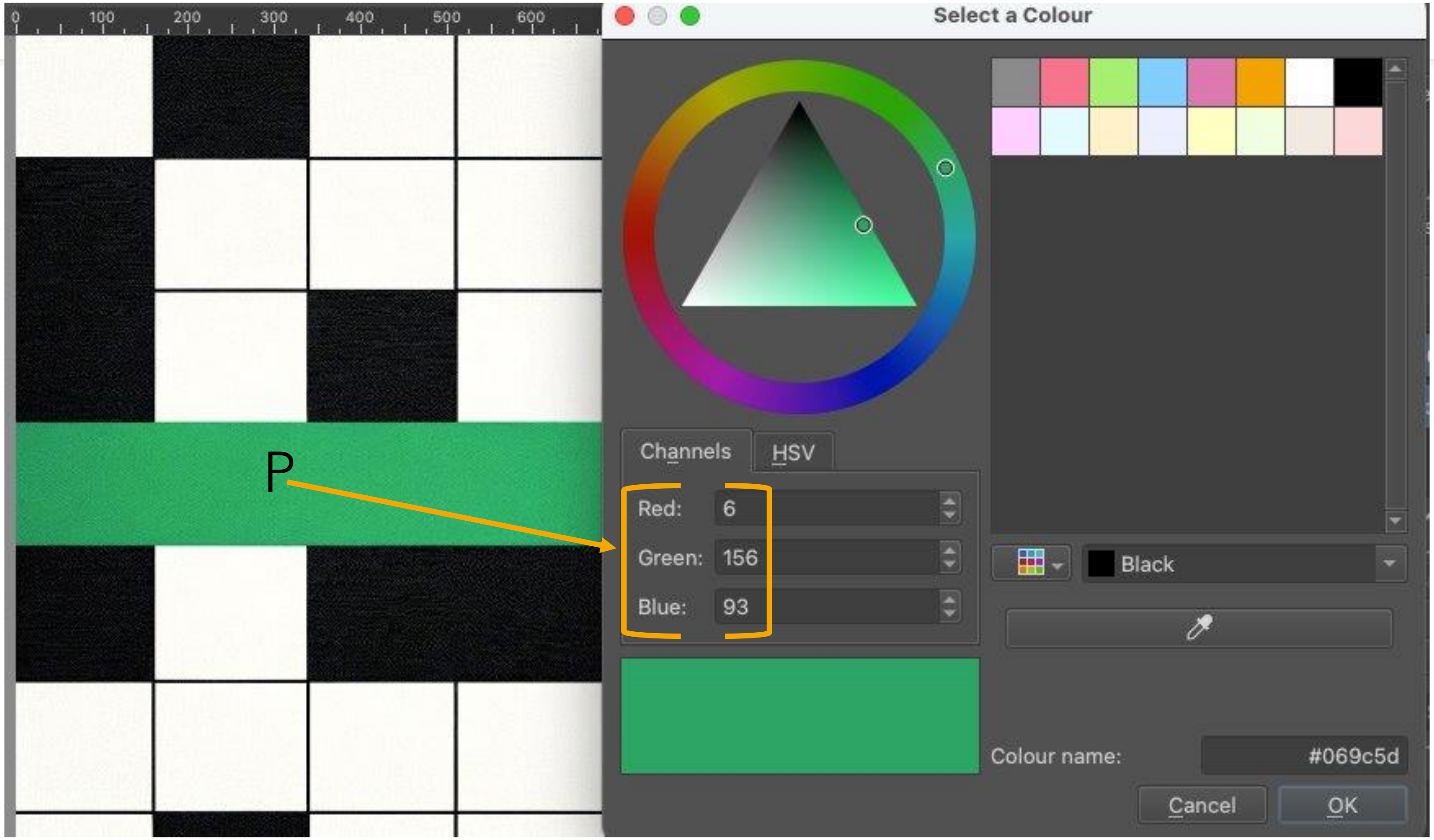
Colour Channels

- RGB Image



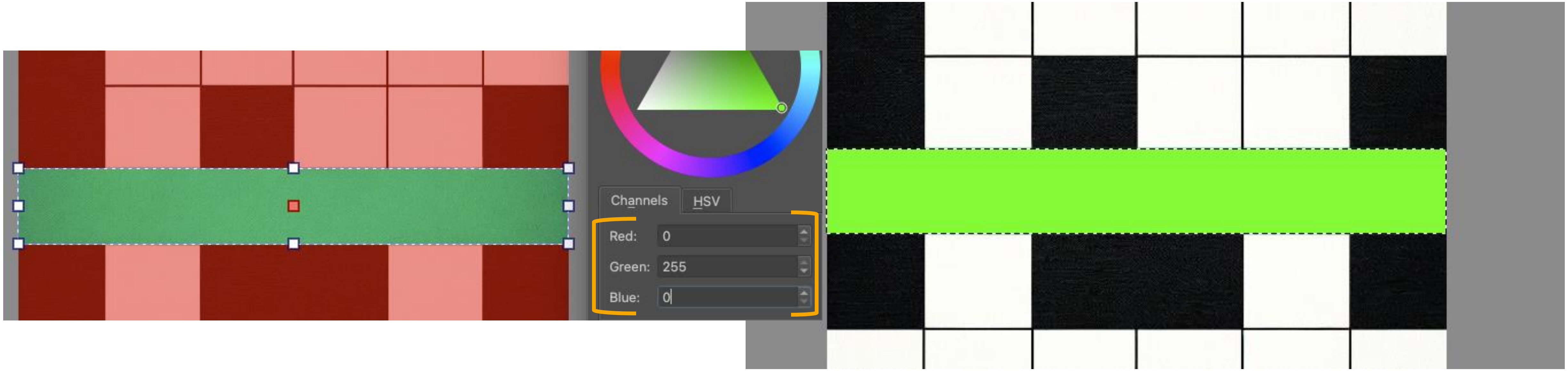
We expected a white rectangle here!

Zooming in on green

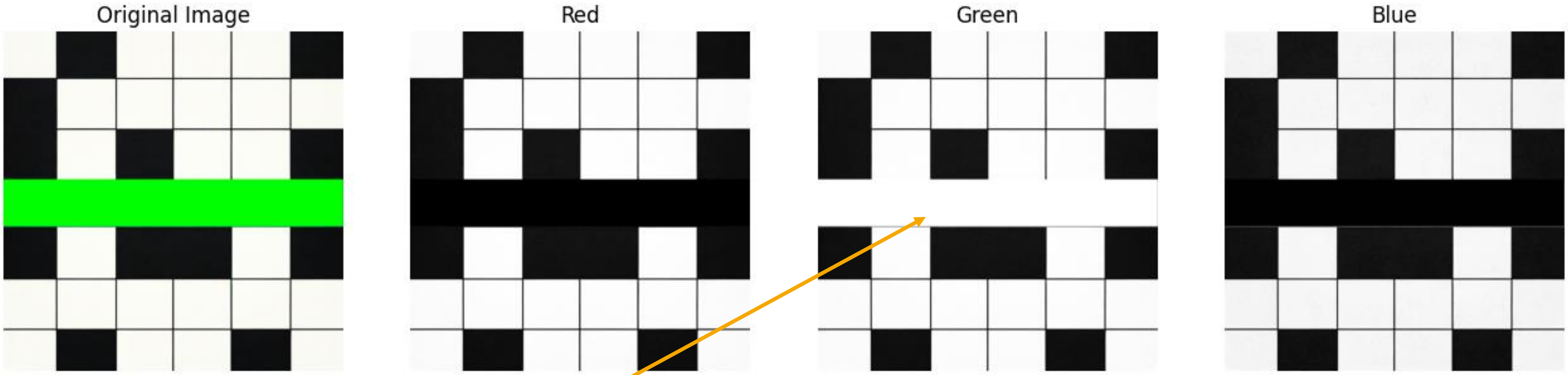


P (6,**156**,93)

Let's convert it in solid green



Colour Channels

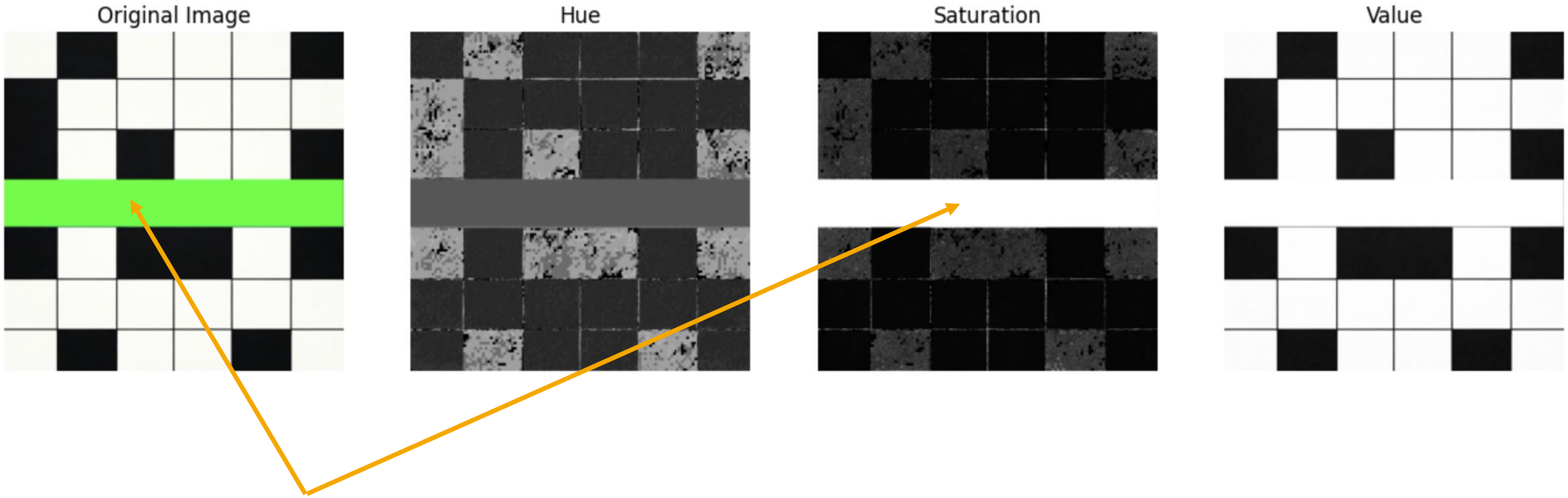


We have got it here as the green in the input image is saturated there is no white mixing

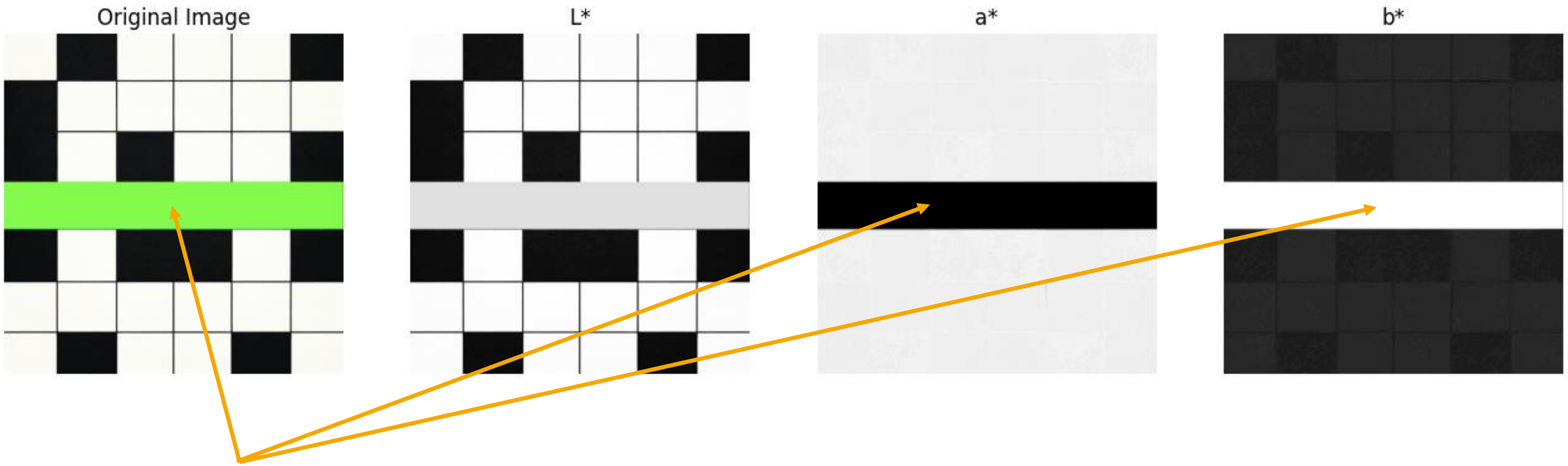
RGB to HSI(Hue Saturation Intensity)

- Let's try interpreting how colour changes in hue, saturation, and intensity can be tackled with HSI colour space and channels.
- We will use the same prototypical images to grasp colour channel differences better.

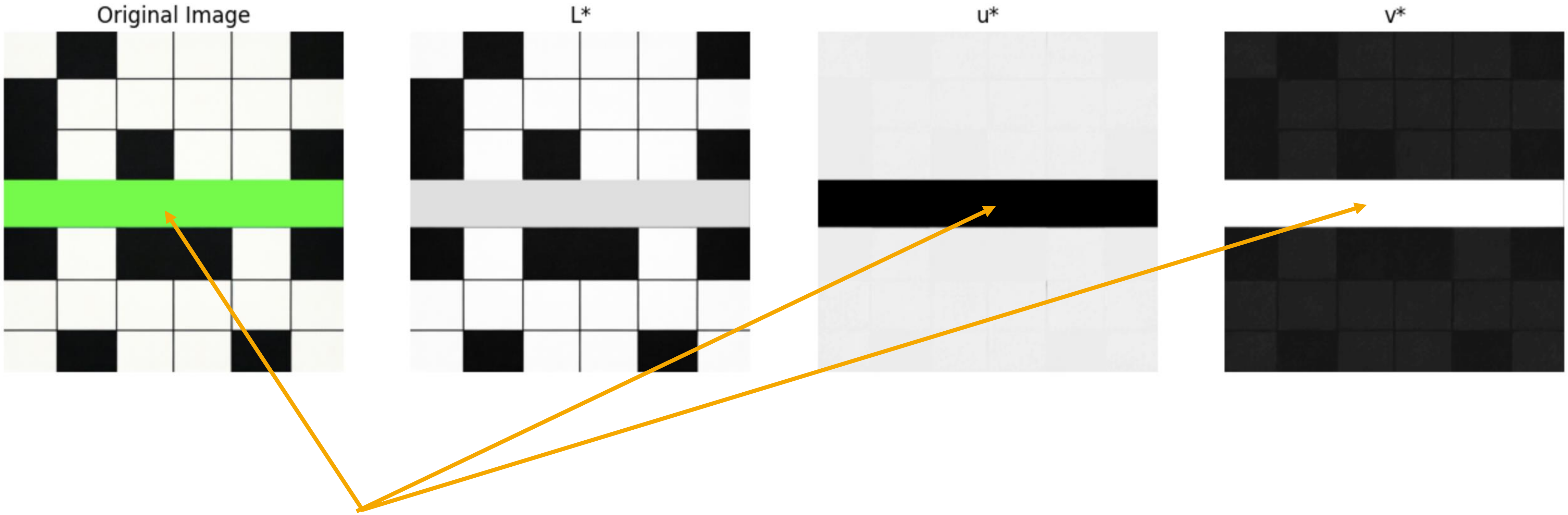
RGB-to-HSI (Hue, Saturation, Intensity)



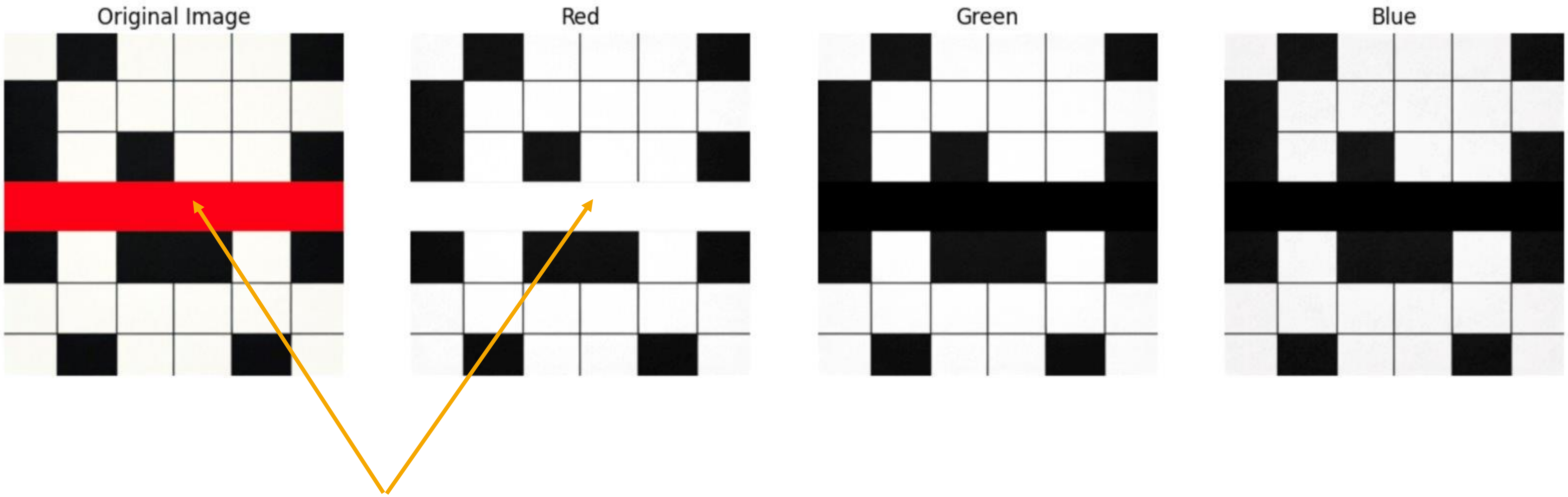
RGB-to-CIE L*a*b*



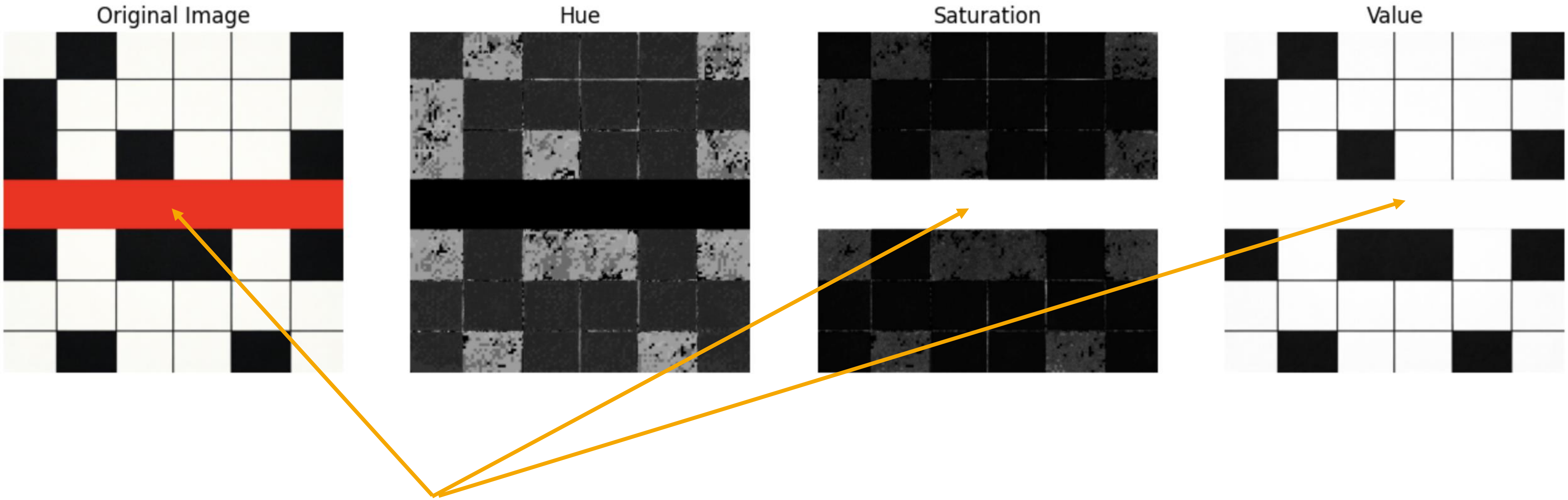
RGB-to-CIE L*u*v*



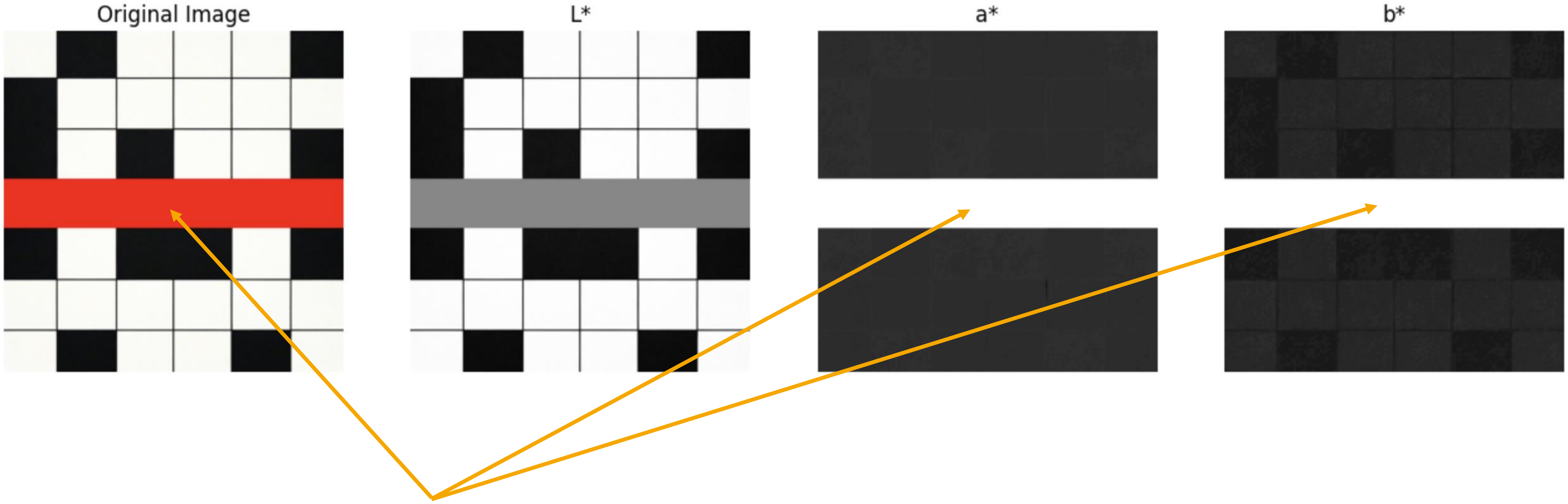
RGB



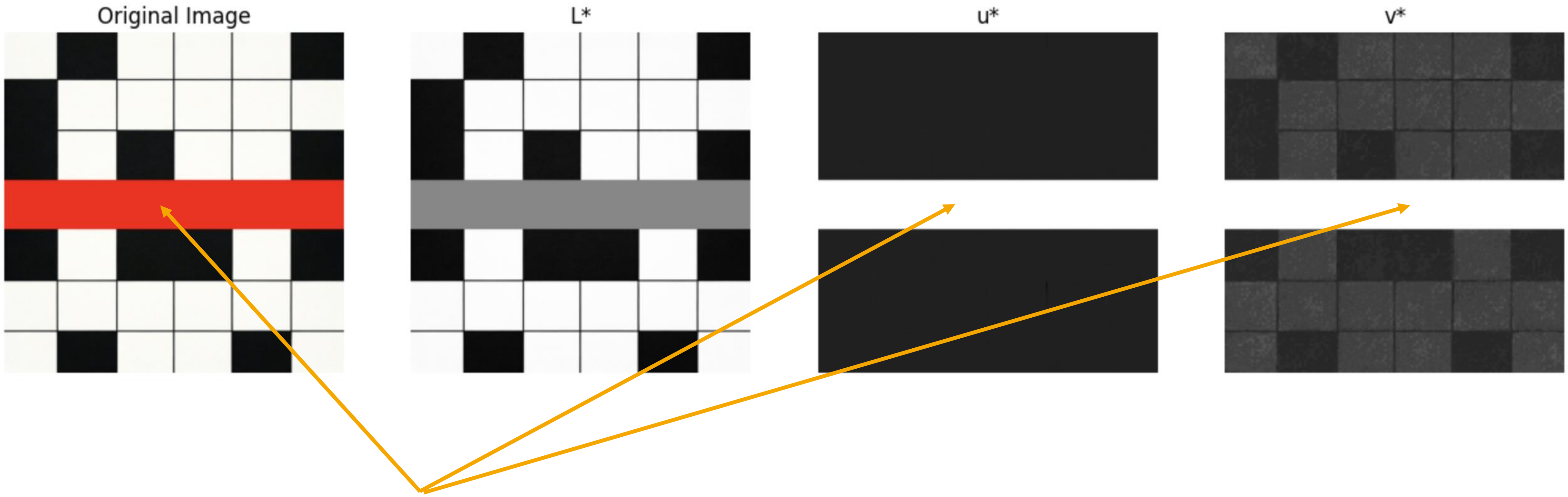
RGB-to-HSI



RGB-to-CIE L*a*b*



RGB-to-CIE L*u*v*



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