UNDERSTANDING COLOUR IMAGING

THE PHYSICAL, THE VISUAL AND THE DIGITAL DOMAINS

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OVERVIEW

- What is a photo and what is an image?
- Colour Science
  - The Physics Perspective
  - Human Vision System
  - Digital Colour
- The Physical Aspects of the Human Vision System
  - XYZ Tristimulus Space
  - x-y Chromaticity Diagram
- Digital Colour
  - Trichromatic Colour Models and Colour Spaces
- Colour Operations and Modern Perspectives
- Conclusions

AN RGB COLOUR IMAGE

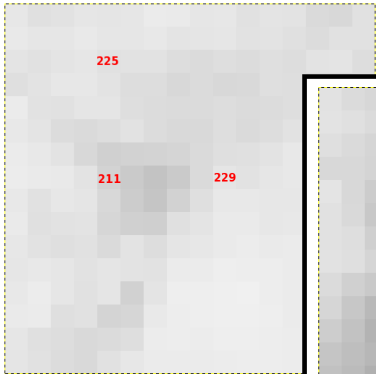
(Original)

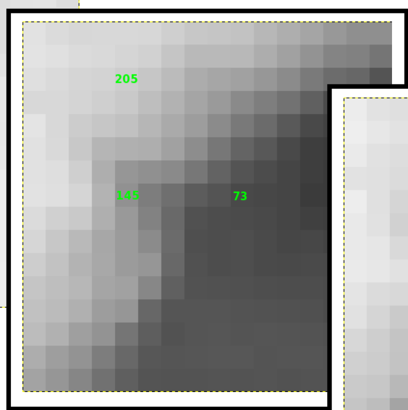
Orange colour in flowers on the head is $(229, 73, 52)$

(Red)

(Green)

(Blue)





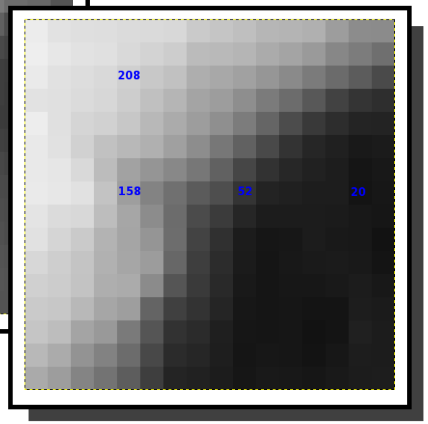
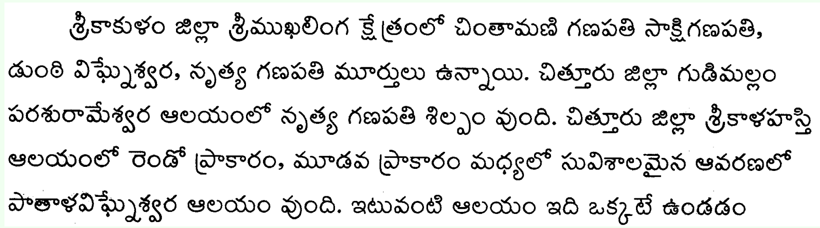


IMAGE BASICS

Types of Images:

- Grayscale images: contain 256 graylevels and these are like our traditional black-and-white pictures
- Binary images: contain **only two brightness levels** and generally used for documents, blue-prints, line-drawings, etc.
- Colour images: the most common form of images today
  - **What is colour and how do we represent it digitally?**

(a) Grayscale (256 levels) image



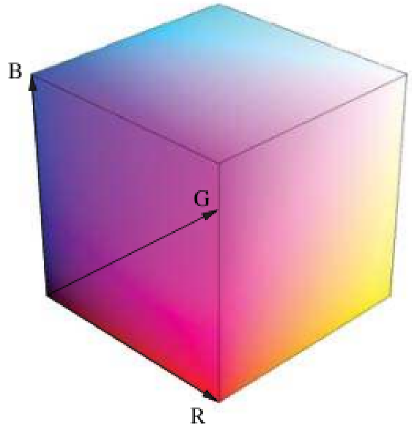
శ్రీకాకుళం జిల్లా శ్రీముఖలింగ క్షేత్రంలో చింతామణి గణపతి సాక్షిగణపతి,
డుంఠి విఘ్నేశ్వర, నృత్య గణపతి మూర్తులు ఉన్నాయి. చిత్తూరు జిల్లా గుడిమల్లం
పరశురామేశ్వర ఆలయంలో నృత్య గణపతి శిల్పం వుంది. చిత్తూరు జిల్లా శ్రీకాళహస్తి
ఆలయంలో రెండో ప్రాకారం, మూడవ ప్రాకారం మధ్యలో సువిశాలమైన ఆవరణలో
పాతాళవిఘ్నేశ్వర ఆలయం వుంది. ఇటువంటి ఆలయం ఇది ఒక్కటే ఉండడం

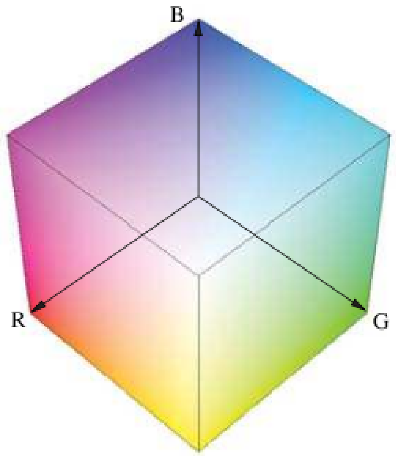
(b) Binary (2 levels) image

(c) Colour (? levels) image

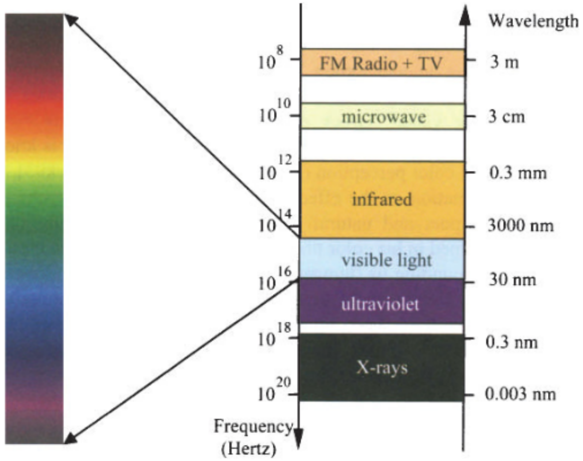
WHAT DO I SEE IN A COLOUR PHOTO?

Colour is not just digital, but . . .

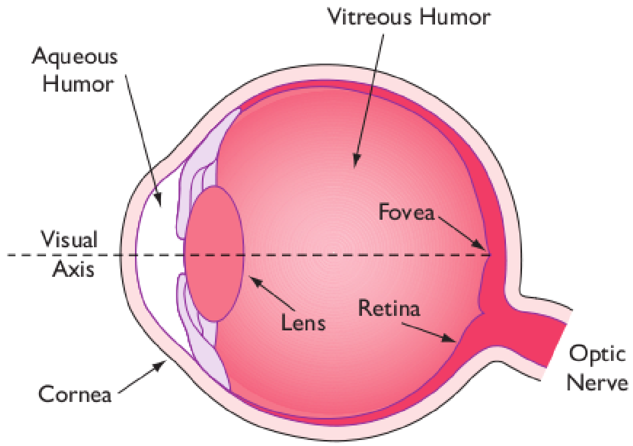




involves Physics, and . . .

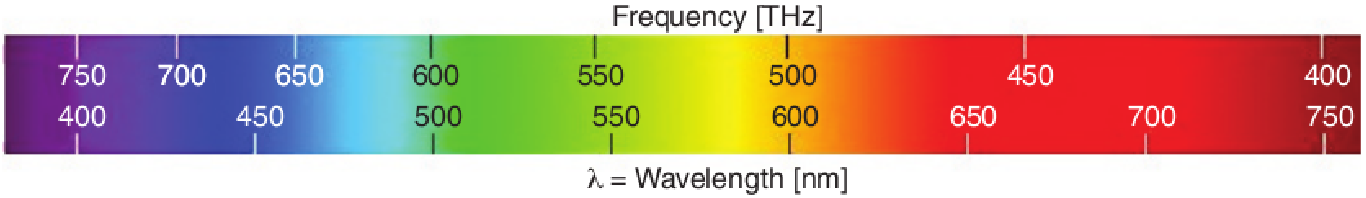


. . . the Human Vision System

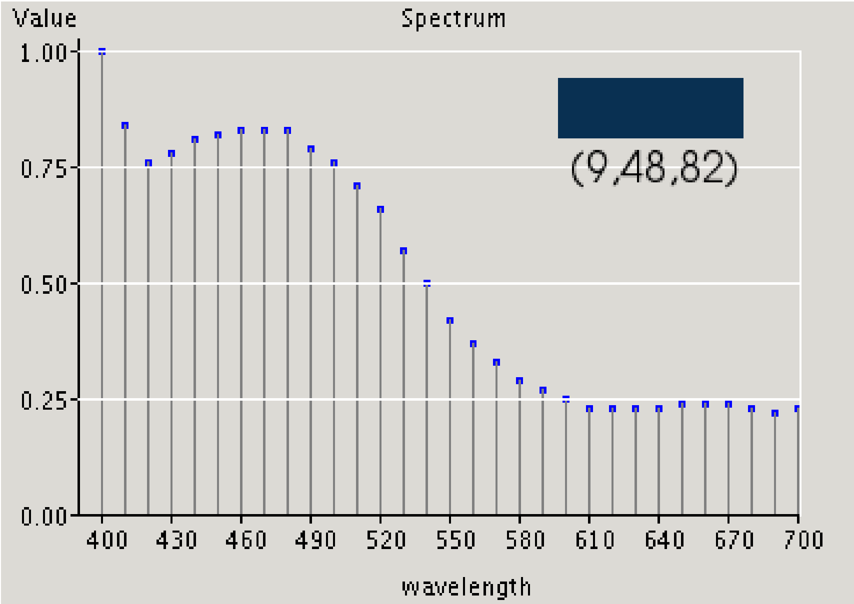


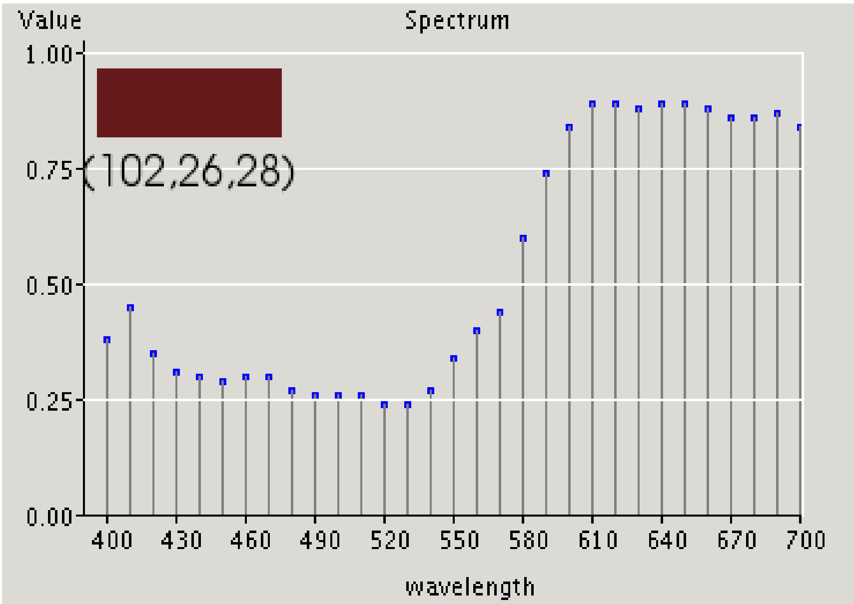
THE PHYSICS OF COLOUR

- Colour is electromagnetic radiation within a specific range of wavelengths ($380\,nm < \lambda < 780\,nm$)

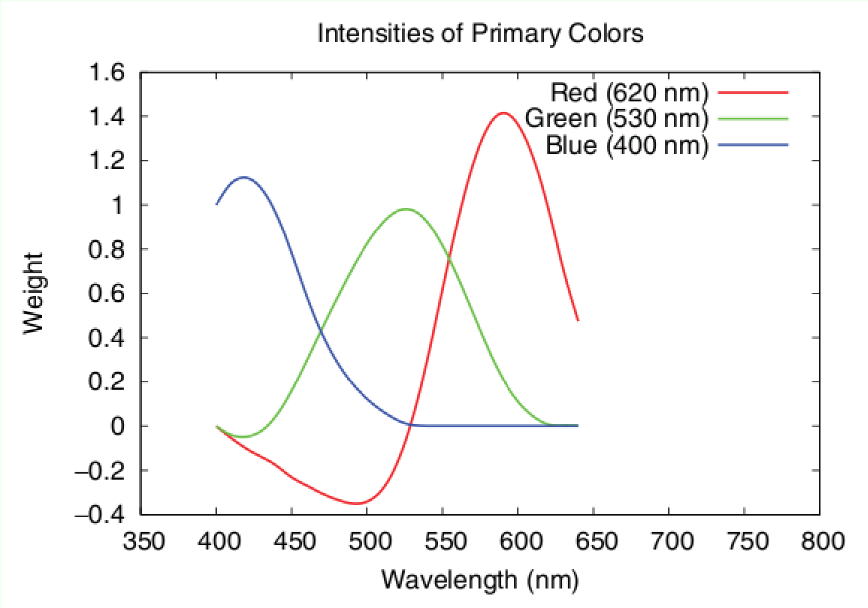


- Colour is a Spectral Power Distribution (SPD)

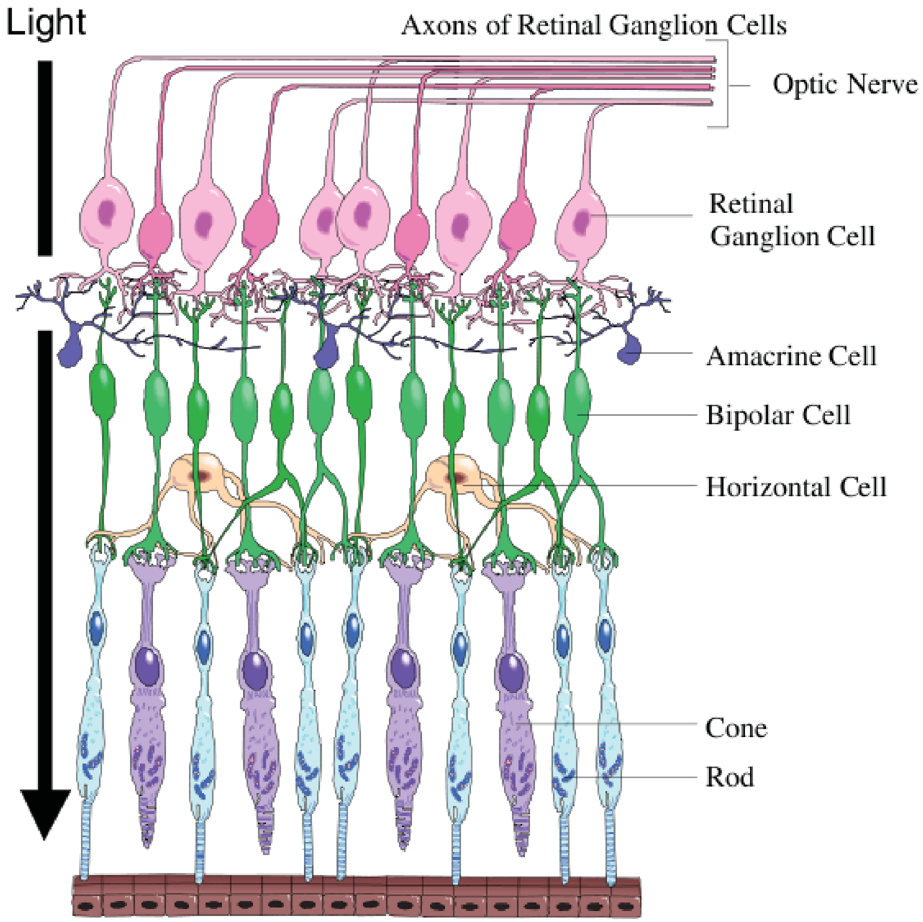




- Rods and Cones
  - rods: low-light achromatic vision
  - cones: well-lighted colour vision
- Three types of cones: S, M, L



SML Cone Responses



Rods and Cones

Trichromatic Theory

- Colour is the response to the three stimuli corresponding to the three types of cones: R for L, G for M and B for S

$$C_i = \int_{-\infty}^{+\infty} R_i(\lambda)P(\lambda)d\lambda$$

$R_i = S, M$ and L

Opponent Colour Theory

- Every colour shade is a linear combination of a colour and its opponent/complementary colour
- Hering (c. 1886) proposed red–green and blue–yellow pairs as primary opponent colours
  - there are no shades like bluish yellow or greenish red

XYZ TRISTIMULUS SPACE

- Committee Internationale De L'Eclairage (CIE) proposed the XYZ Tristimulus Space based on the colour matching experiments as a model of human colour perception
- XYZ values are obtained from the colour matching functions $(\overline{x}, \overline{y}, \overline{z})$ as

$$X = \int_{380\text{nm}}^{780\text{nm}} R(\lambda)\overline{x}(\lambda)\,\mathrm{d}\lambda \qquad Y = \int_{380\text{nm}}^{780\text{nm}} R(\lambda)\overline{y}(\lambda)\,\mathrm{d}\lambda$$

$$Z = \int_{380\text{nm}}^{780\text{nm}} R(\lambda)\overline{z}(\lambda)\,\mathrm{d}\lambda$$

where $R(\lambda)$ is the SPD of the object that is imaged

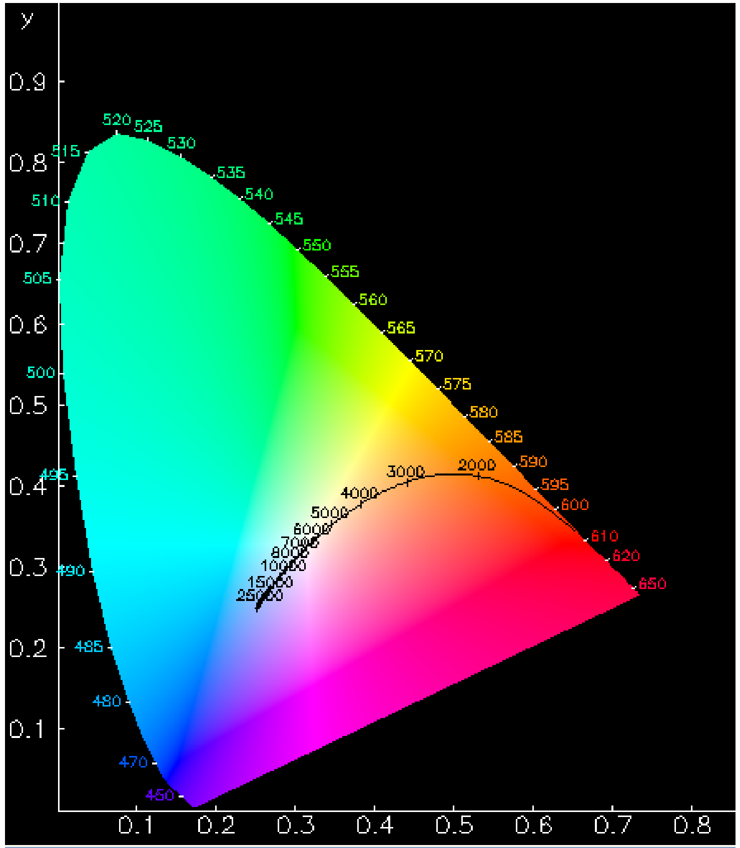
THE (IN)FAMOUS TOUNGUE!

- XYZ Tristimulus values are normalized to give the xyz trichromaticity space

$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z}$$
$$z = \frac{Z}{X+Y+Z}$$

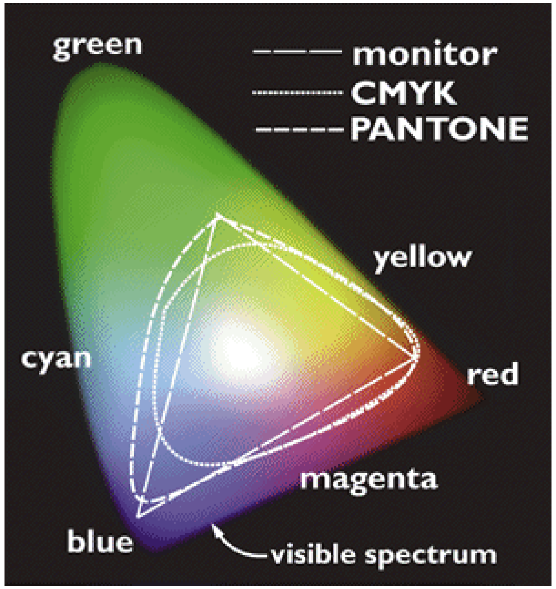
- Only two coordinates are necessary for describing colour

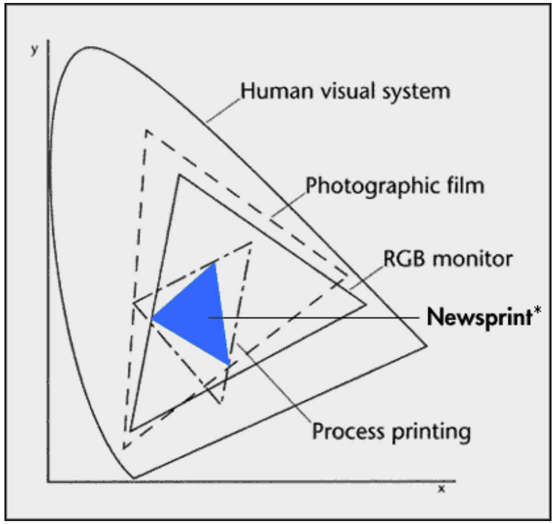
- A plot of x vs. y gives the famous x-y chromaticity diagram (or tongue diagram)



COLOUR GAMUTS

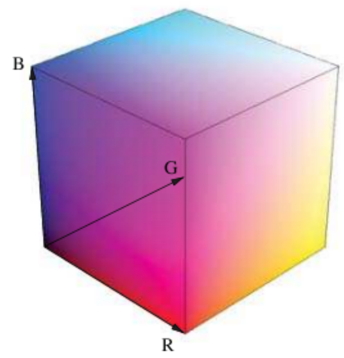
- The entire set of colours that can be perceived or handled by a sensor/device is called its gamut
- The tongue is the gamut of the human vision system
- Although we use a trichromatic system, our human vision system is non-linear and generates a large gamut
- Any linear trichromatic space results in a triangular gamut
- How many colours can we see?

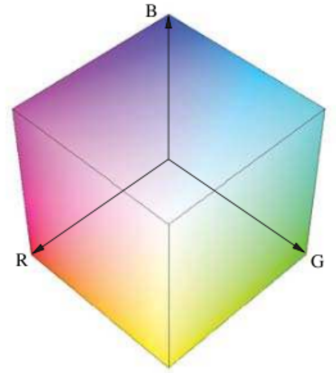


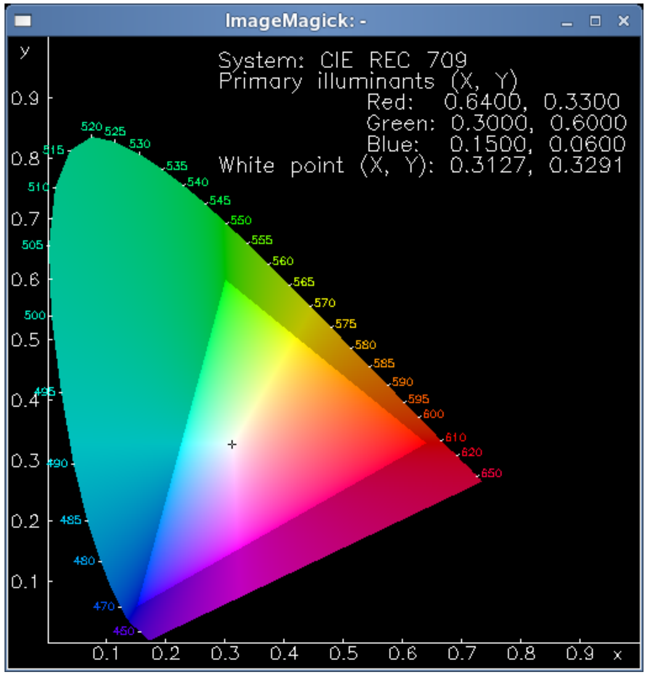


RGB COLOUR SPACE (at last!)

- Define three standard primaries — R, G and B
- Cartesian Coordinate system: Dark Biscuit is (192,128,0)
- Most popular because of hardware support
- Not a very good candidate for colour image processing
  - perceptually non-uniform
  - non-descriptive
  - does not decouple achromatic and chromatic aspects

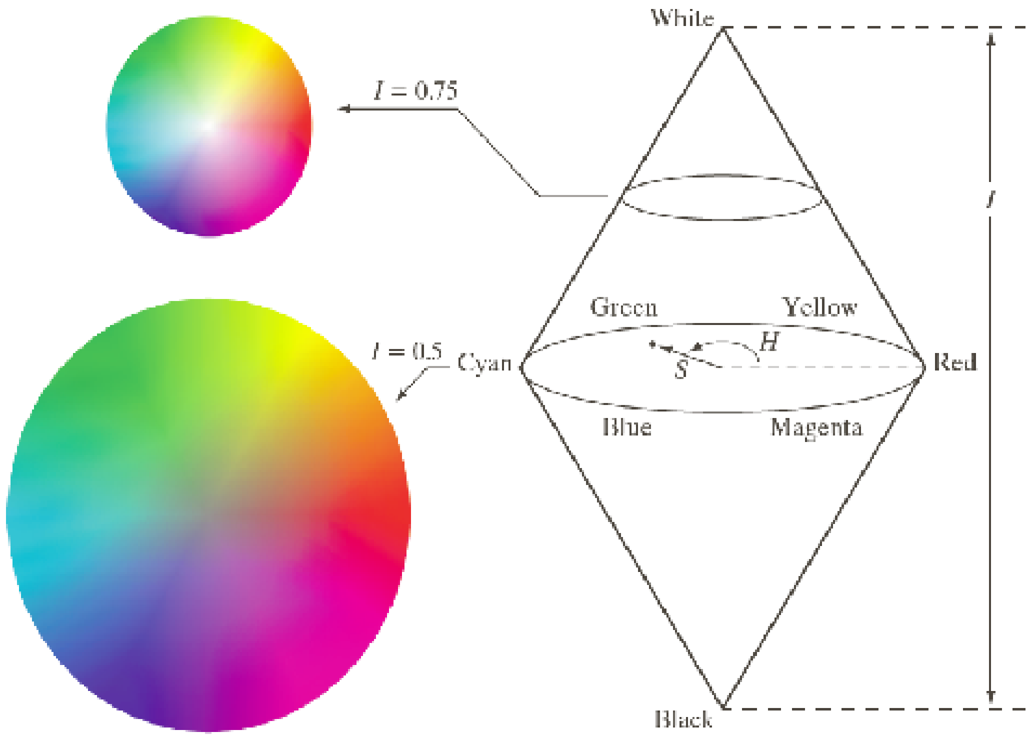






HSV COLOUR SPACE

- Hue and Saturation describe colour
- Value is the achromatic component

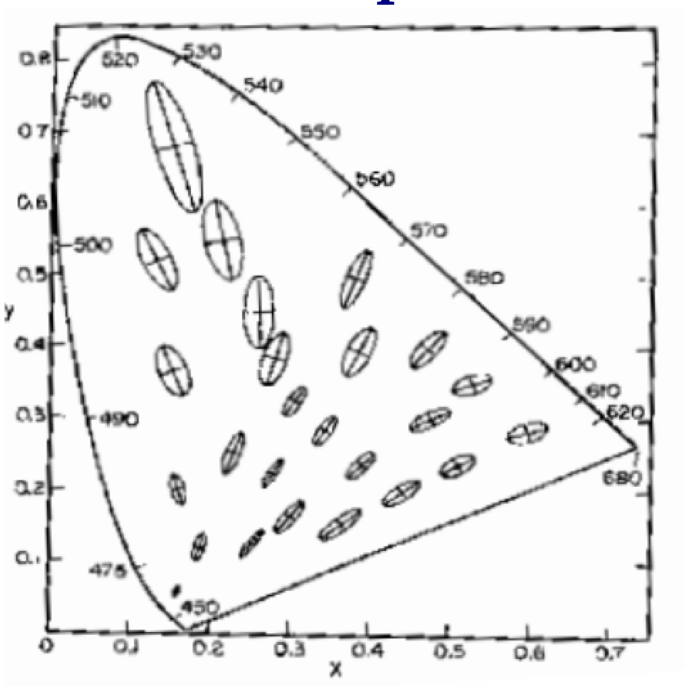


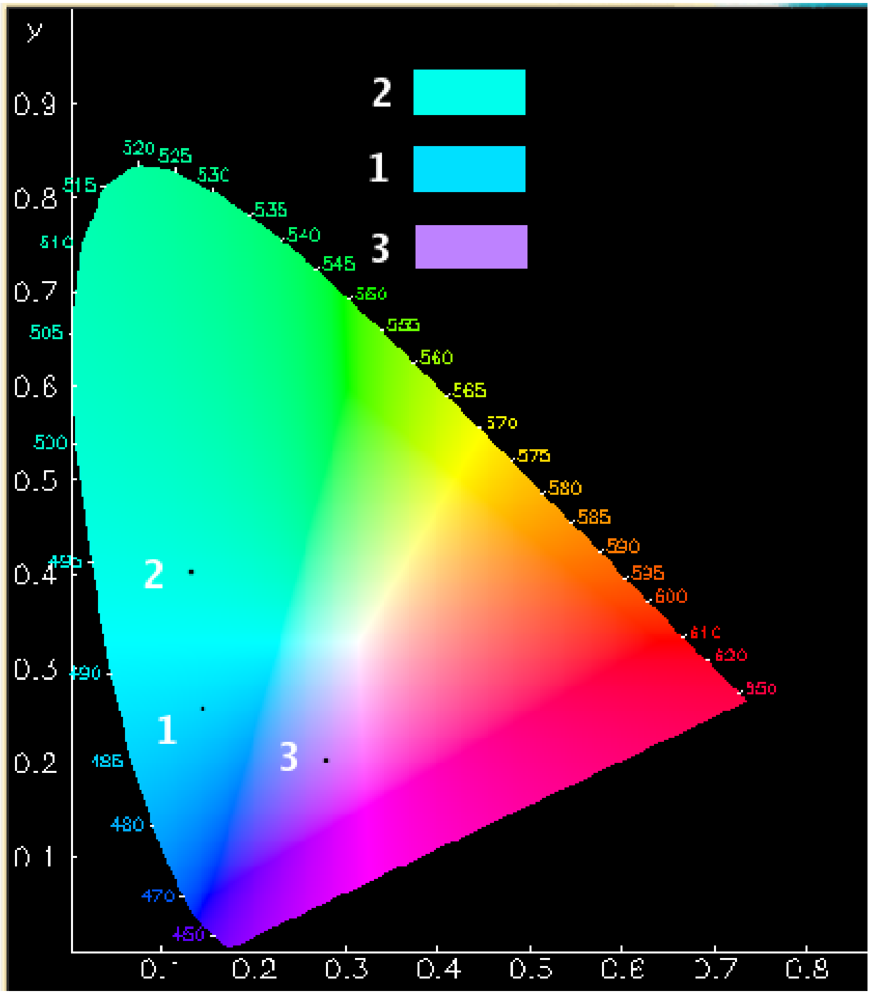
- Hue is the dominant colour (circular axis): red is $0°$, green is $120°$, blue is $240°$
- Saturation is purity of colour (radial axis): red $(0°, 1.0)$ vs. Pink $(0°, 0.60)$
- HSV colour space is either cylindrical or a double cone
- Description-oriented
- Non-Euclidean space
- Perceptually non-uniform (but better than RGB)

NON-UNIFORM PERCEPTION

Equal distance between colours does not mean equally different colours
(e.g. red-green vs. blue-green)

MacAdam Ellipses (1942)





CIELAB SPACE

- Perceptually uniform space created by CIE
- Correct name is L*a*b*
- Lightness (L^*) is achromatic
- a^* and b^* are opponent colour pairs

$$L^* = 116\left(\frac{Y}{Y_0}\right)^{\frac{1}{3}} - 16$$

$$a^* = 500\left[\left(\frac{X}{X_0}\right)^{\frac{1}{3}} - \left(\frac{Y}{Y_0}\right)^{\frac{1}{3}}\right]$$

$$b^* = 200\left[\left(\frac{Y}{Y_0}\right)^{\frac{1}{3}} - \left(\frac{Z}{Z_0}\right)^{\frac{1}{3}}\right]$$

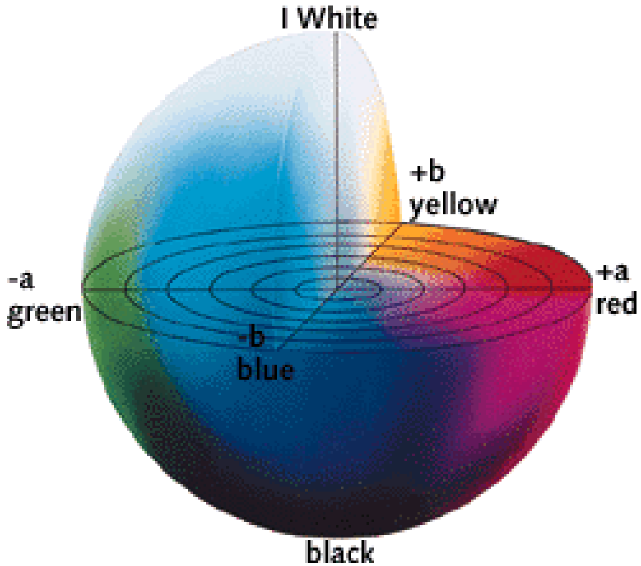


IMAGE PROCESSING

- Basic operations
  - Threshold
  - Ranging
  - Negative
- Enhancement
  - Contrast
  - Gamma
  - Histogram-based
- Spatial and Frequency Domain
  - Noise-removal
  - Edge detection
  - Texture analysis
- Feature Extraction

- Basic operations
  - ??
  - Colour filters
  - Colour negative
- Enhancement
  - Colour space dependent
  - Gamma (3 times?)
  - No histograms
- Spatial and Frequency Domain
  - Scalar or Vector
  - No frequency domain*
- Quantization and half-toning

COLOUR THRESHOLDING

- What do you mean by thresholding?
  - same as for grayscale but 3 times?
- Or, is it to separate coloured and non-coloured?

Original

RGB-Threshold

Colour Threshold

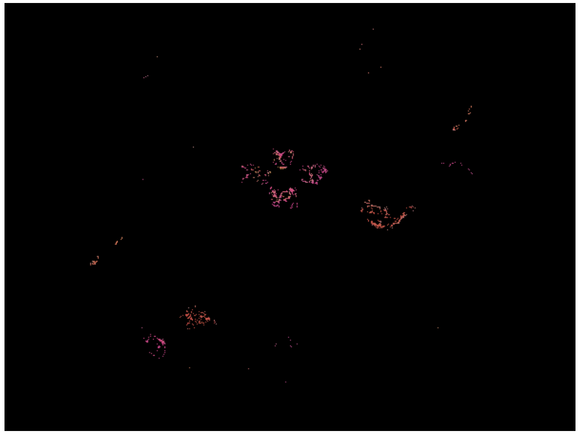
- How did we do the colour threshold?
  - In HSV space - threshold is on saturation (25%)

COLOUR EXTRACTION

- Pick up red coloured regions from the image
- It is surprisingly difficult in RGB space
  - How do you specify red?
- It is almost trivial in HSV space

$$\text{output} = \begin{cases} \text{input} & \text{if } H = 0^\circ \pm \epsilon \\ \text{black} & \text{otherwise} \end{cases}$$

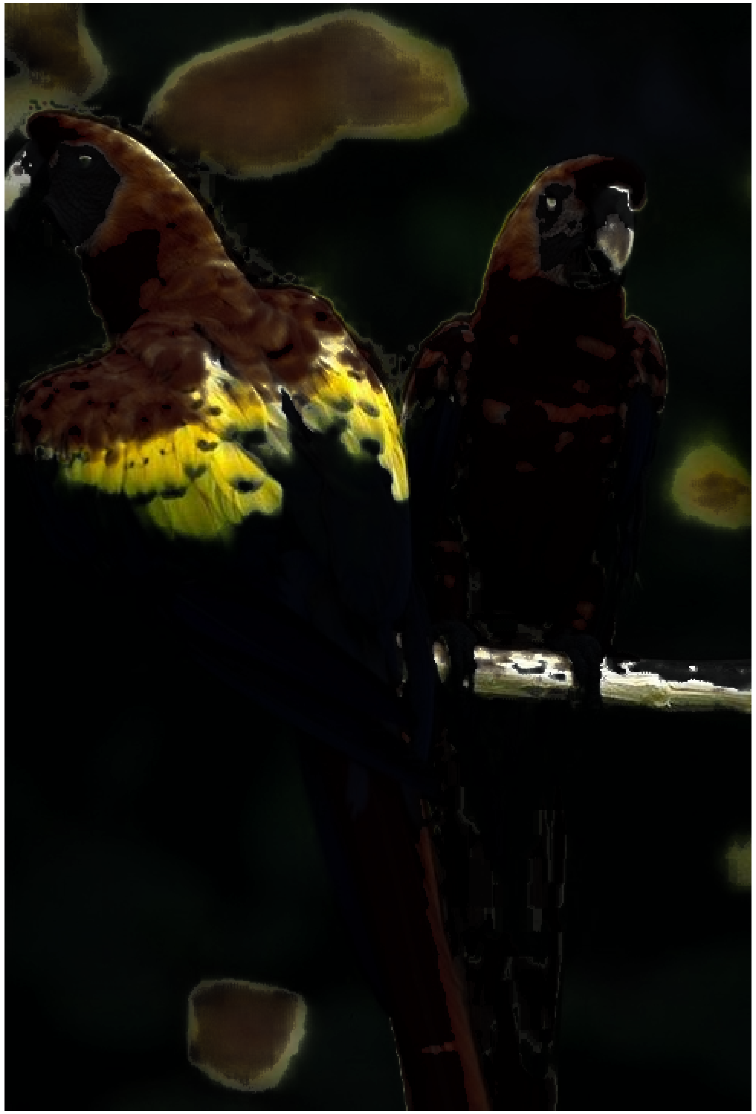
Original



RGB-Ranging

HSV Ranging

YET ANOTHER EXAMPLE!



COLOUR NEGATIVES

- Standard approach: invert each component in RGB space
- Two alternatives
  - In HSV, replace hue with its complementary hue
  - In HSV, replace hue and saturation with their inverses

Original

RGB Neg

Hue Neg

Hue-Sat Neg

In this case, the RGB approach appears better

CONTRAST ENHANCEMENT

- Histogram equalization is often used to enhance contrast
- Modify the histogram of the image such that it becomes as uniform as possible
- For a colour image, apply it three times
- A better alternative: apply only to V component in HSV space

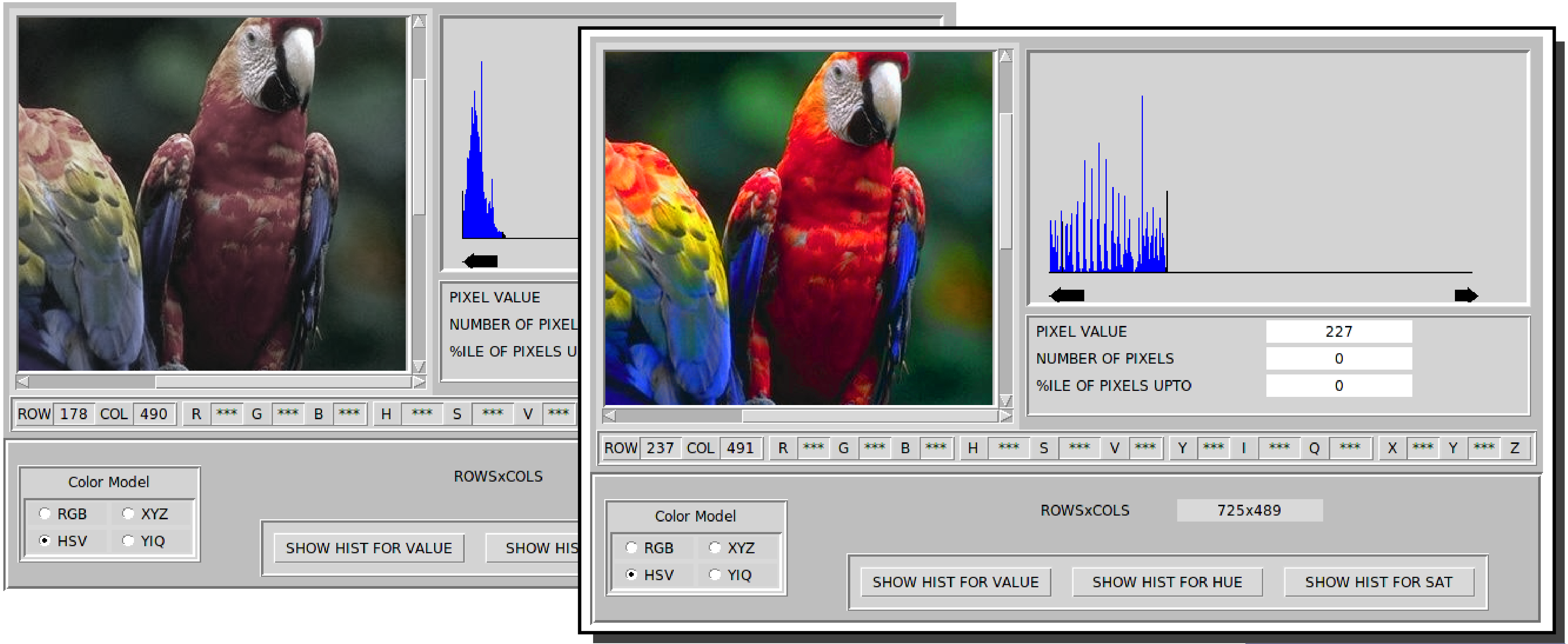
Original

RGB Equalization

V Equalization

RESTORING FADED COLOURS

- Manipulating saturation enhances faded colours
  - Faded colours have low saturation
  - Increasing saturation value brightens colours



SUMMARY

- For image enhancement, it is better to use a colour space that separates chromatic and achromatic (intensity) components
- We saw examples from HSV space but similar results are obtained from CIELAB space
- There are many unanswered questions as yet
  - enhancing faded colours (saturation in HSV?)
  - creating cartoon type images from photos
  - eliminating effects of illuminants
  - colour filters

MODERN TIMES(!)

- Treat colour as a vector
  - working separately on individual components leads to loss of correlation between colour planes
  - colours get mixed up
- Treat colour as a quaternion
  - allows convolution and fourier transforms to be defined
- Treat colour from a physics perspective
  - operations as spectral transformations

- Using masks and convolution — normally done on individual components
- Loss of correlation between colour planes

Vector Based Approaches

Newer algorithms use Vector-based approaches

- colour is a three-dimensional vector
- image is a vector valued function of two variables

$$I(x, y) = \mathbf{C}$$

- image processing $\rightarrow$ meaningful mathematical operations on the vector-valued function $I(x, y)$

Vector Median Filter

Take a 3×3 nbrhood, N, of p.

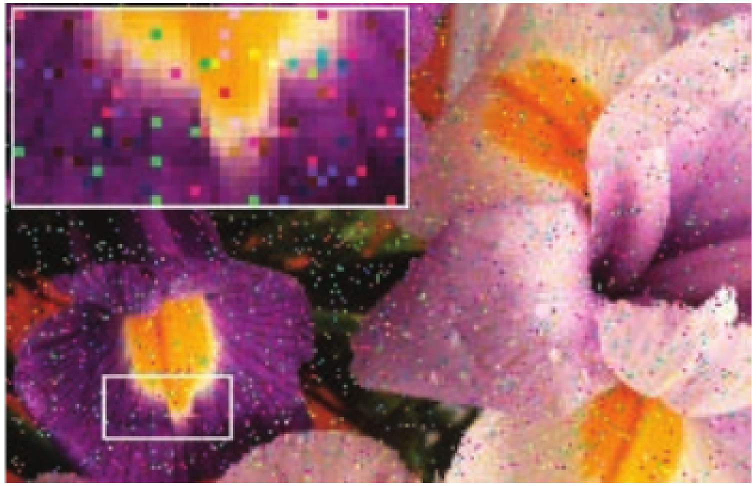
Let $\mathbf{c_i} = (r_i, g_i, b_i), i \in N$.

Define $\overline{\mathbf{c}} = \sum_{i \in N} \mathbf{c_i} / |N|$

Compute $d_i = ||(\mathbf{c_i} - \overline{\mathbf{c}})||^2, i \in N$

Sort $\mathbf{c_i}$ according to d_i in ascending order

Replace c_{center} with the first $\mathbf{c_i}$ in the sorted list

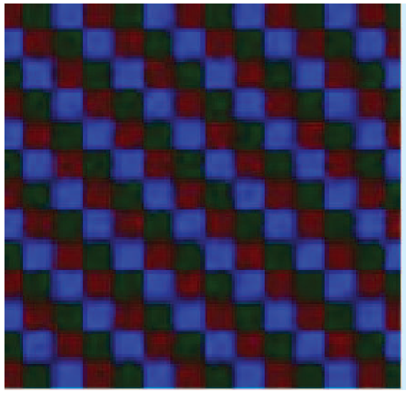


Original

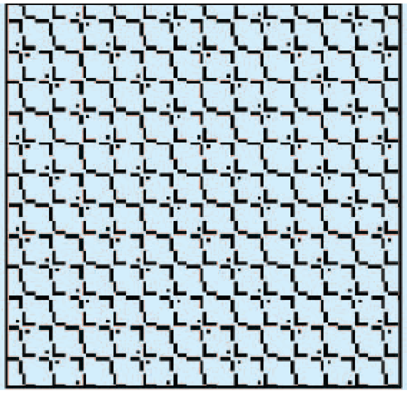
VMF Output

EDGE DETECTION

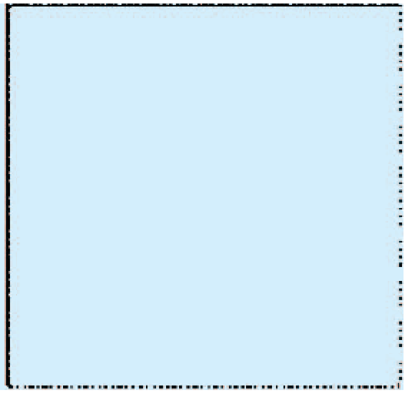
- New developments are vector-based methods
- Edge detection is a derivative operation
- Compute colour derivatives using partial and total derivatives concepts
- Vector versions of Canny have been developed
- Cumani edge detector is a new vector based method that improves upon Canny



Original



Vector Edges



Grayscale Edges

VECTOR DERIVATIVES

- Horizontal and Vertical directional gradient operators are

$$u = \frac{\partial R}{\partial x}\vec{r} + \frac{\partial G}{\partial x}\vec{g} + \frac{\partial B}{\partial x}\vec{b}$$
$$v = \frac{\partial R}{\partial y}\vec{r} + \frac{\partial G}{\partial y}\vec{g} + \frac{\partial B}{\partial y}\vec{b}$$

- Let us define the following

$$g_{xx} = u \cdot u = \left|\frac{\partial R}{\partial x}\right|^2 + \left|\frac{\partial G}{\partial x}\right|^2 + \left|\frac{\partial B}{\partial x}\right|^2$$
$$g_{yy} = v \cdot v = \left|\frac{\partial R}{\partial y}\right|^2 + \left|\frac{\partial G}{\partial y}\right|^2 + \left|\frac{\partial B}{\partial y}\right|^2$$
$$g_{xy} = \frac{\partial R}{\partial x}\frac{\partial R}{\partial y} + \frac{\partial G}{\partial x}\frac{\partial G}{\partial y} + \frac{\partial B}{\partial x}\frac{\partial B}{\partial y}$$

VECTOR EDGE DETECTION

From the derivatives defined in the previous slide, the maximum rate of change of f and the direction of the maximum contrast are

$$\theta = \frac{1}{2}\arctan\left(\frac{2g_{xy}}{g_{xx} - g_{yy}}\right)$$

$$F(\theta) = \frac{1}{2}\{(g_{xx} + g_{xy}) + \cos 2\theta(g_{xx} - g_{yy}) + 2g_{xy}\sin\theta\}$$

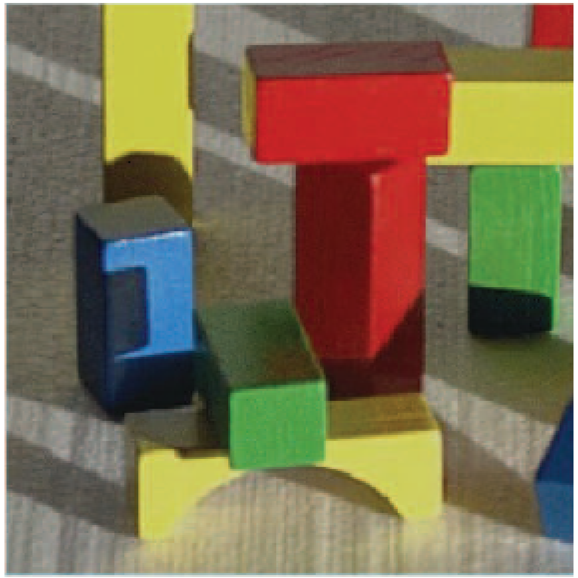
The edges are obtained by thresholding $F(\theta)$

CANNY EDGE DETECTOR
(Vector Version)
&
CUMANI EDGE DETECTOR

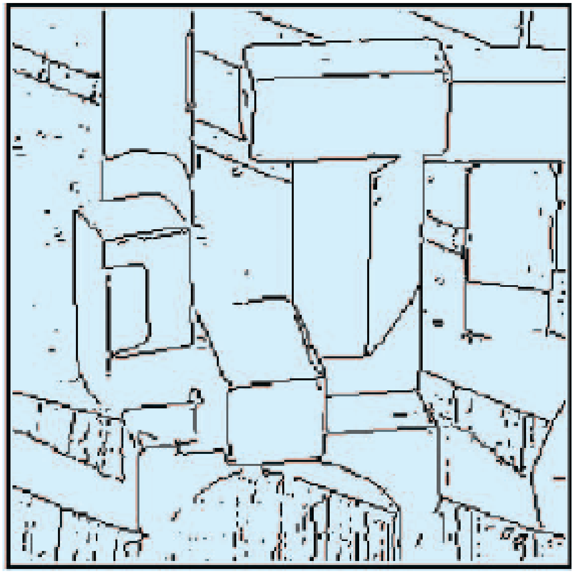
- have two thresholds on $F(\theta)$
- do non-max suppression and edge linking

  OR
- calculate eigenvectors of $F(\theta)$ for extreme values
- find zeros of derivative

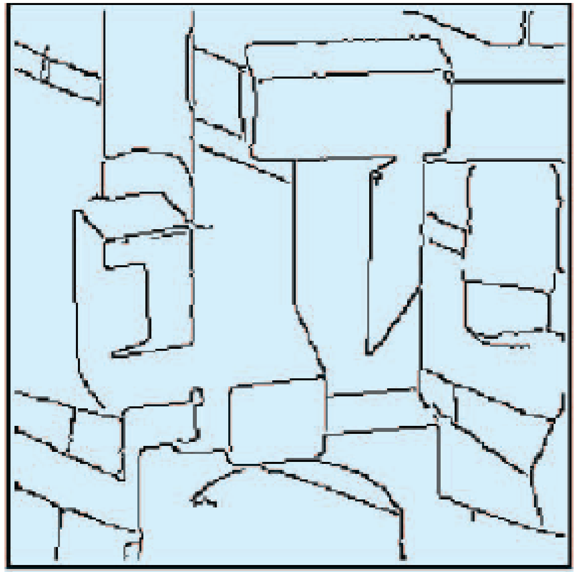
EXAMPLE



Original



Cumani Edges



Canny Edges

- Canny misses some edges but the overall image is clean
- Cumani is more sensitive but also picks up some noise

CAN'T DO WITHOUT LENA!

QUATERNIONS

- Recently, Sangwine and Ell proposed a novel approach based on representing colour as a quaternion

Quaternions provide a new vector based approach to colour image processing

$$q = k + r\vec{i} + g\vec{j} + b\vec{k}$$

- Colour is a pure quaternion — no real component
- Quaternions are hypercomplex numbers and addition, multiplication operations are defined on them

$$\begin{aligned} q_1 + q_2 &= (r_1 + r_2)\vec{i} + (g_1 + g_2)\vec{j} + (b_1 + b_2)\vec{k} \\ q_1 \times q_2 &= (-r_1 r_2 - g_1 g_2 - b_1 b_2) + (g_1 b_2 - b_1 g_2)\vec{i} + \\ &\qquad (b_1 r_2 - r_1 b_2)\vec{j} + (r_1 g_2 - g_1 r_2)\vec{k} \end{aligned}$$

- Quaternion multiplication is non-commutative

- With addition and multiplication defined, convolution may be defined
- As multiplication is non-commutative, convolution requires a left and a right mask

$$Q(x,y) \star h(s,t) = \sum_{s=-r}^{r} \sum_{t=-r}^{r} h_L(s,t) \times Q(x+s, y+t) \times h_R(s,t)$$

- Analogous Quaternion Filters exist for most operations
  - Smoothing
  - Edge detection
  - Sharpening, etc.
- Quaternion filters can be colour sensitive

Spatial Filtering (Quaternion-Based)

QUATERNIION EXAMPLES

Example of Sobel Operator

Smoothing Operation

FREQUENCY DOMAIN OPERATIONS

- Frequency domain operations did not really exist until recently for colour images
  - FFT may be computed on each component but how to combine
- Quaternions allow a more holistic definition for frequency domain operations on colour images
- Hypercomplex FT is defined as

$$F(u,v) = S\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} e^{-j2\pi\frac{mu}{M}} f(m,n) e^{-k2\pi\frac{nv}{N}}$$

- The vectors on the two sides must be orthogonal

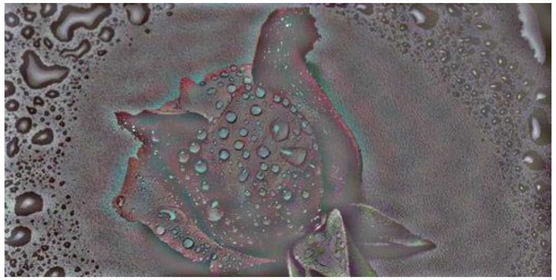
QFT OPERATIONS

Original

Low-Pass $w_0 = 35\%$

Low-Pass $w_0 = 10\%$

Original

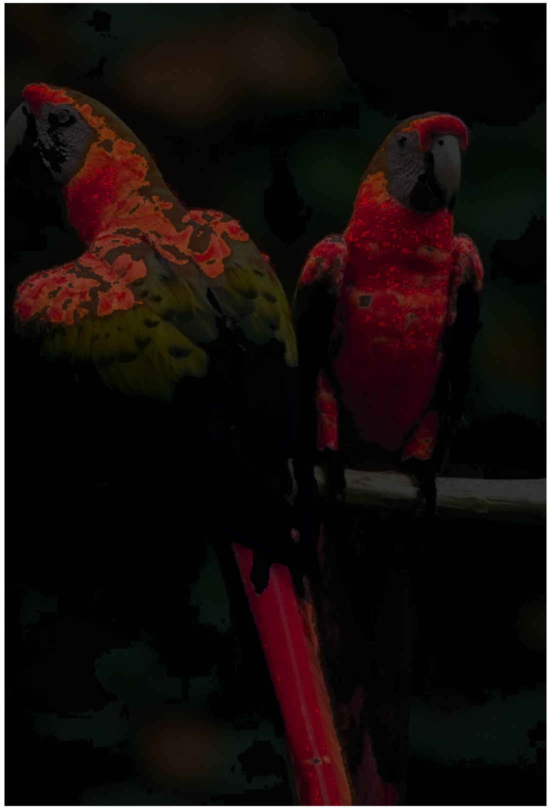


High-Pass $w_0 = 10\%$

- Images are analogous to those obtained for grayscale FT

SPECTRAL OPERATION

- We compute a wavelength corresponding to an (R,G,B) colour triplet through (X,Y,Z) tristimulus space and use it for filtering
- Example shows an image with pixels having colours within the band of 620 ± 40 nm



PHYSICS-BASED OPERATIONS

A recent discovery from Ravindranath, a PhD student at University of Hyderabad . . .

- In Physics, colour changes $\Rightarrow$ $\text{SPDF}_{new} = f(\text{SPDF}_{old})$
- He found that many such transforms can be expressed as 3×3 matrices in RGB colour space
- Example 1: **Removing effect of street lights in photos of the sky** (by filtering out spectral components around 600 nm)

$$\begin{pmatrix} 0.3044 & -0.0991 & -0.0025 \\ -0.0077 & 0.9887 & -0.0003 \\ 0.0150 & 0.0034 & 1.0001 \end{pmatrix}$$

LIGHT POLLUTION EFFECT

a

b

ANOTHER SPECTRAL OPERATION

Example 2: Simulating effect of illuminating a scene with brighter light

Original

Lamp $3\times$ Brighter

Brightened in GIMP

COLOUR BLINDNESS

- The most common form of colour blindness is Red-Green colour blindness
  - cannot distinguish between red and green colours
  - can we simulate what a colour blind person sees using colour image processing?
- Roshanak Zakizadeh, one of the M. Tech students, did some work on this: it is now being continued by another student, Anku



CONCLUSION

- Colour image processing is very popular today, but with many open questions and issues
  - analysis of colour spaces and models
  - scalar vs. vector processing, quaternions and other representations
  - image processing operations and applications
- Not yet addressed — a physical basis
  - colour is a very physical phenomenon but processing is done entirely on the digital domain
  - links between digital operations and physical processes tenuous at best
  - a great need to link digital operations to physical processes that manipulate colour in nature
  - applications will be revolutionary
- At University of Hyderabad, we have now a good team working on colour image processing and producing results

THANK YOU!