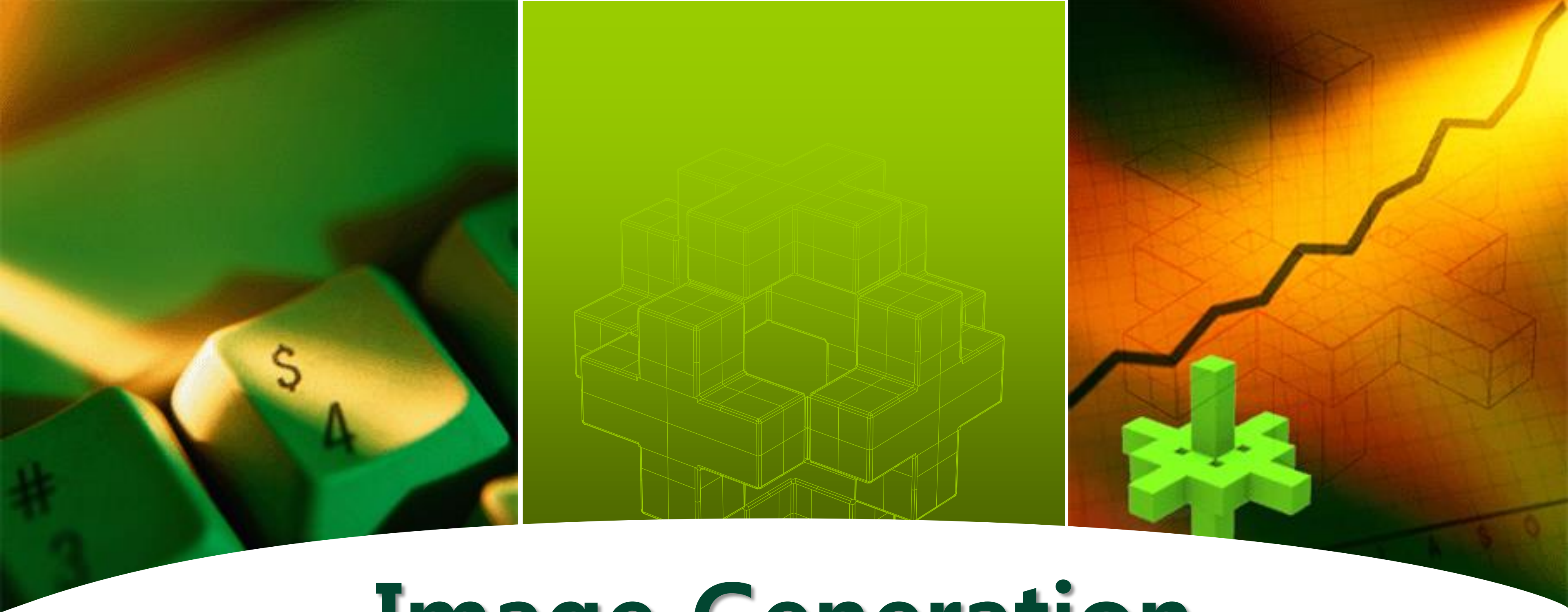
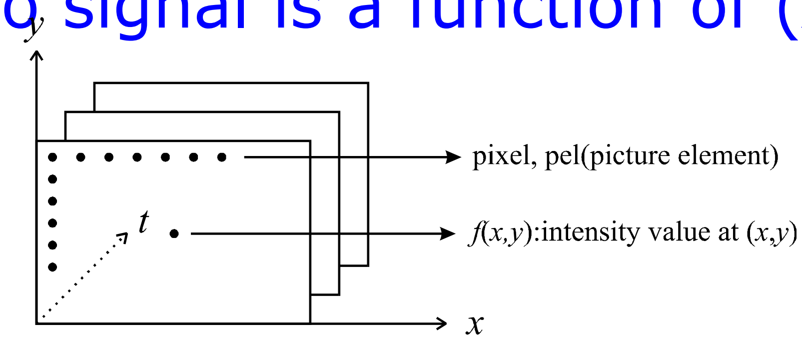


Image Generation and Colors

Lecturer: Sang Hwa Lee

What is Image? (1)

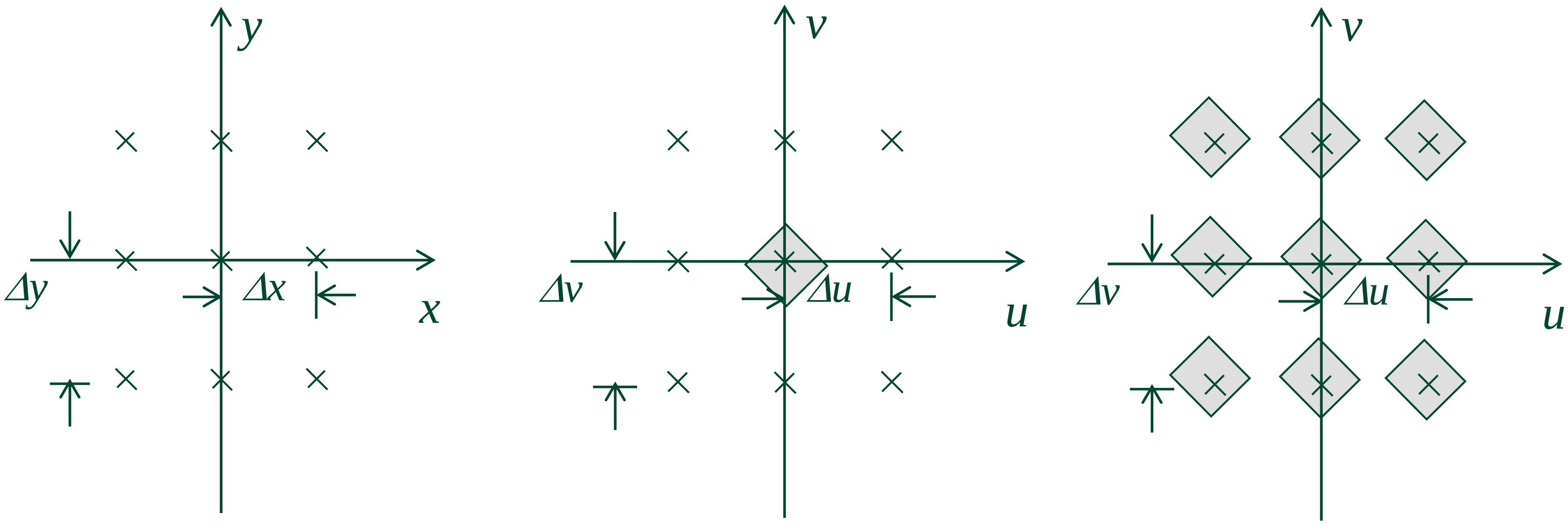
- **Image is a 2-D spatially sampled signal of 3-D world.**
  - Sampling grid: pixel
  - (x,y) : spatial coordinate
  - t : temporal coordinate (video sequence)
- **Image signal is a function of (*x*,*y*).**
  - 3-D surface on the x-y plane
  - $0 \leq f(x,y) \leq L(=255)$: gray - 8bit/pixel, color level- 24bit/pixel
  - Video signal is a function of (x,y,t).



What is Image? (2)

❖ Digital image signal in the frequency domain

- **2-D spatial sampled signal**
- **Base-band spectrum is replicated in the 2-D frequency domain**



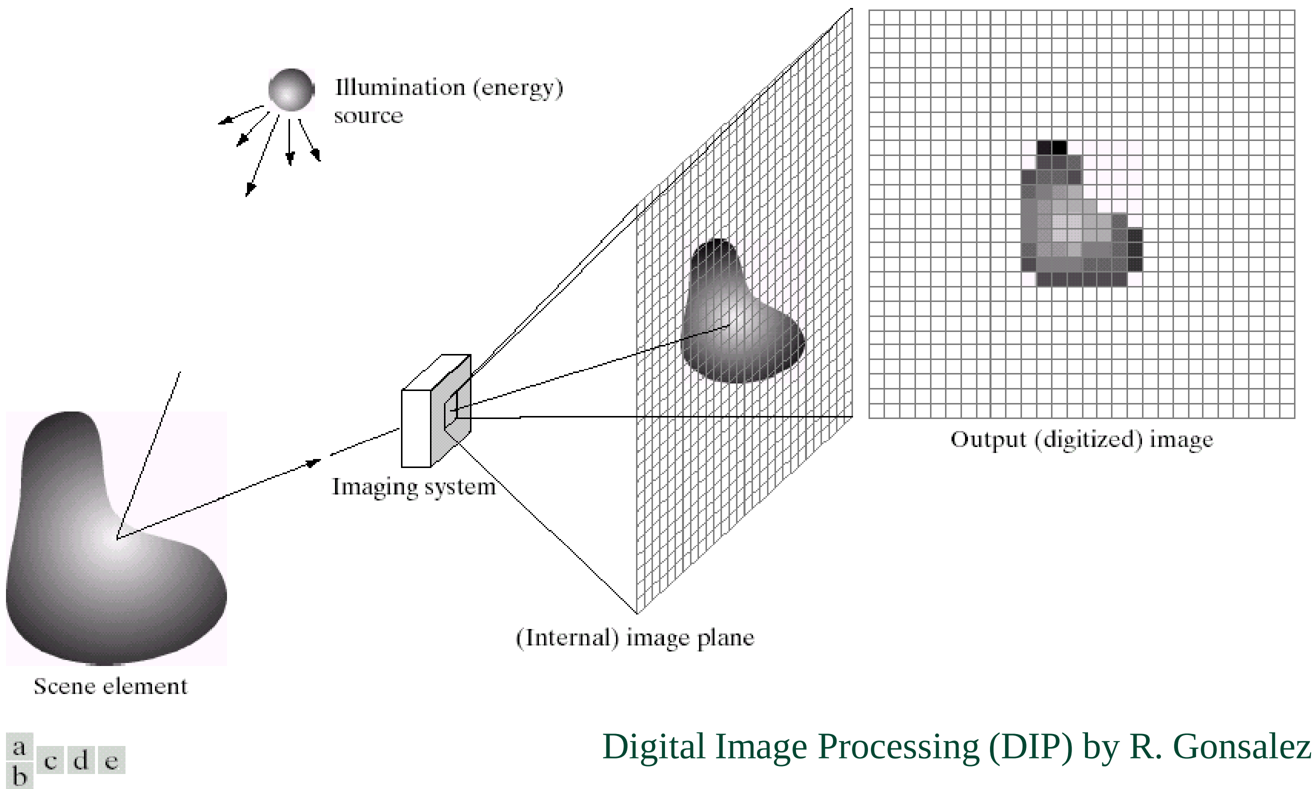
sampling grid

Baseband spectrum of original 3-D wolrd signal

spectrum of sampled signal (2-D discrete image)

Image Generation (1)

- Classical imaging system
  - Reflected light from object surface is accumulated in the electronic sensor.
  - The 3-D points are spatially sampled on the pixels.

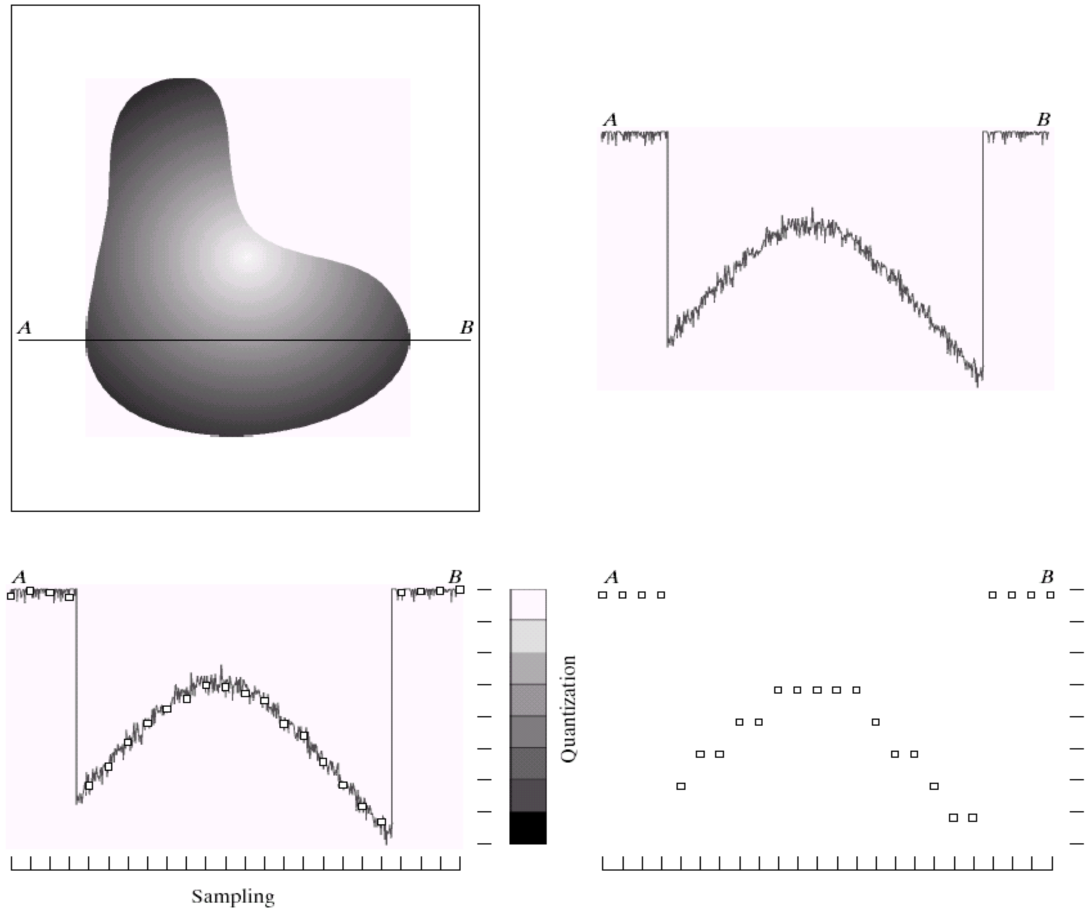


Digital Image Processing (DIP) by R. Gonsalez

FIGURE 2.15 An example of the digital image acquisition process. (a) Energy ("illumination") source. (b) An element of a scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

Image Generation (2)

- Image signal is vey noisy unlike the visual appearance.



Profile of a scan line

Profile on the pixel grid

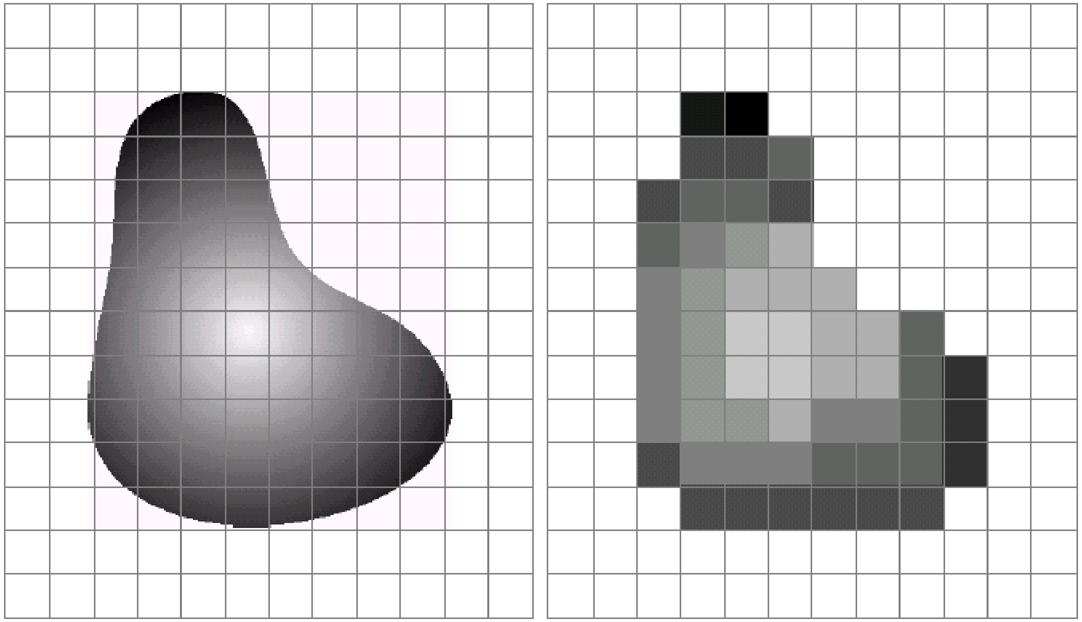
DIP by R. Gonsalez

a b
c d

FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from A to B in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

Image Generation (3)

- Image spatial sampling and quantization
  - By sampling on the sensor grid: loss of detailed visual information
  - By quantization: loss of continuous values of original intensities



DIP by R. Gonsalez

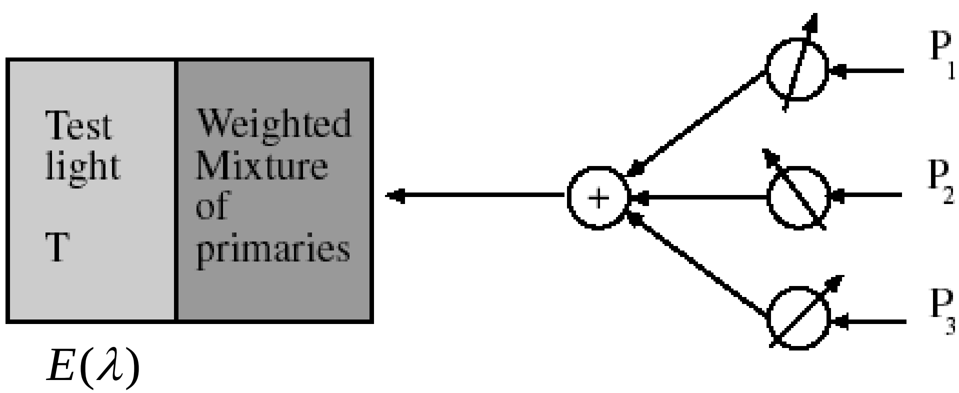
a b

FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.

Color Spaces

Color Representation

- 3 primaries for 3-D color space
  - **Goal is to reproduct natural colors.**
- Color matching
  - **Linear combination of 3 primaries**
  - **Additive matching:** $\mathbf{M = aP_1+bP_2+cP_3}$
  - **Subtractive matching:** $\mathbf{M+aP_1 = bP_2+cP_3}$



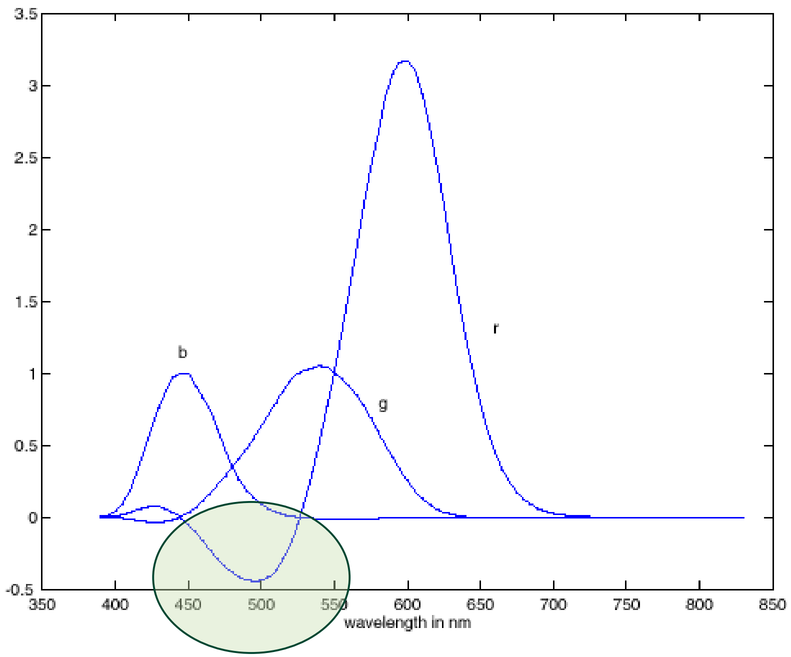
$$a = \int a(\lambda)E(\lambda)d\lambda$$

$$b = \int b(\lambda)E(\lambda)d\lambda$$

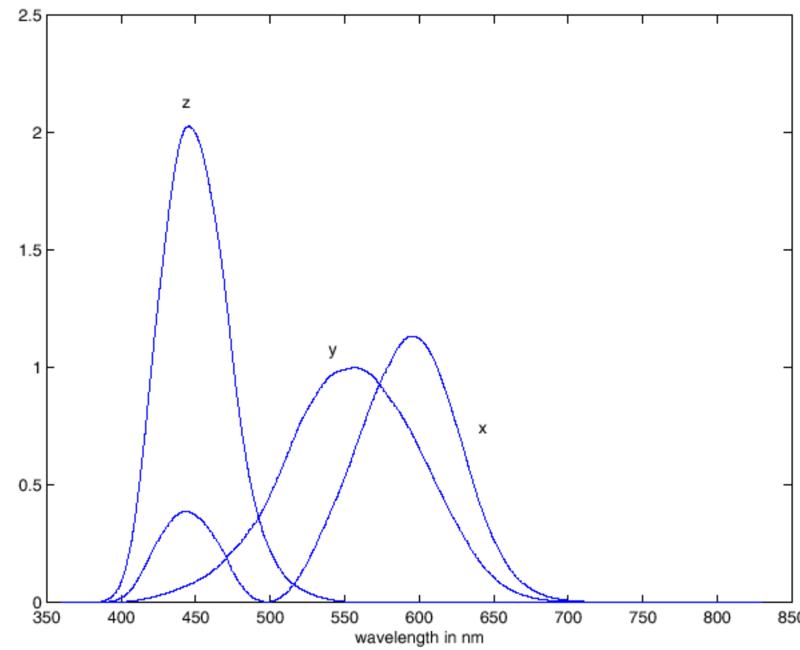
$$c = \int c(\lambda)E(\lambda)d\lambda$$

CIE XYZ Color Space (1)

RGB Color matching function



CIE XYZ matching function



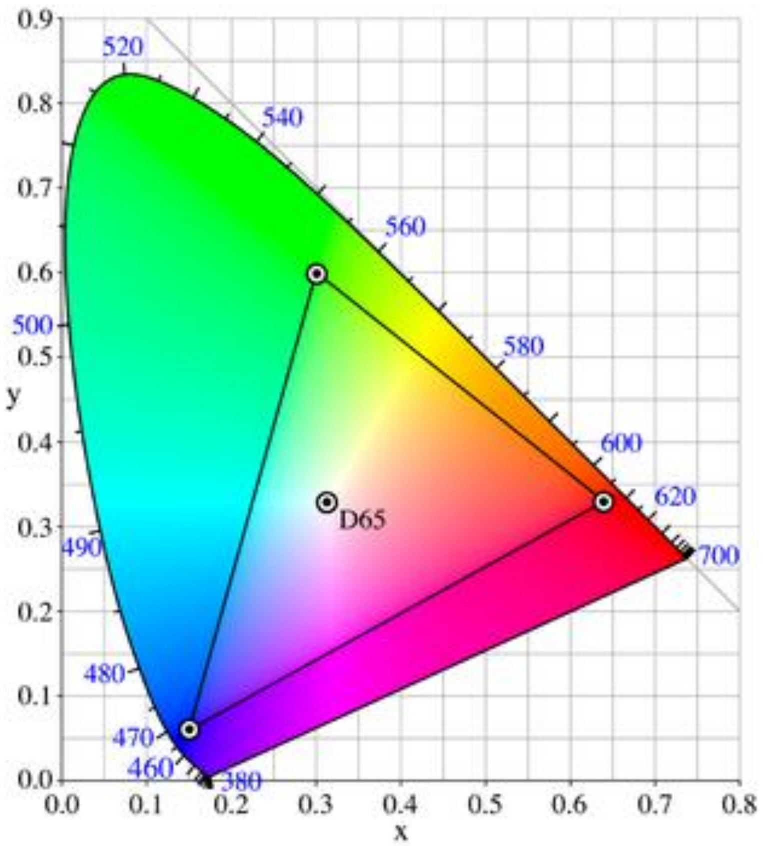
Negative(subtractive)
- not representable in display

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.490 & 0.310 & 0.200 \\ 0.177 & 0.813 & 0.011 \\ 0.000 & 0.010 & 0.990 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

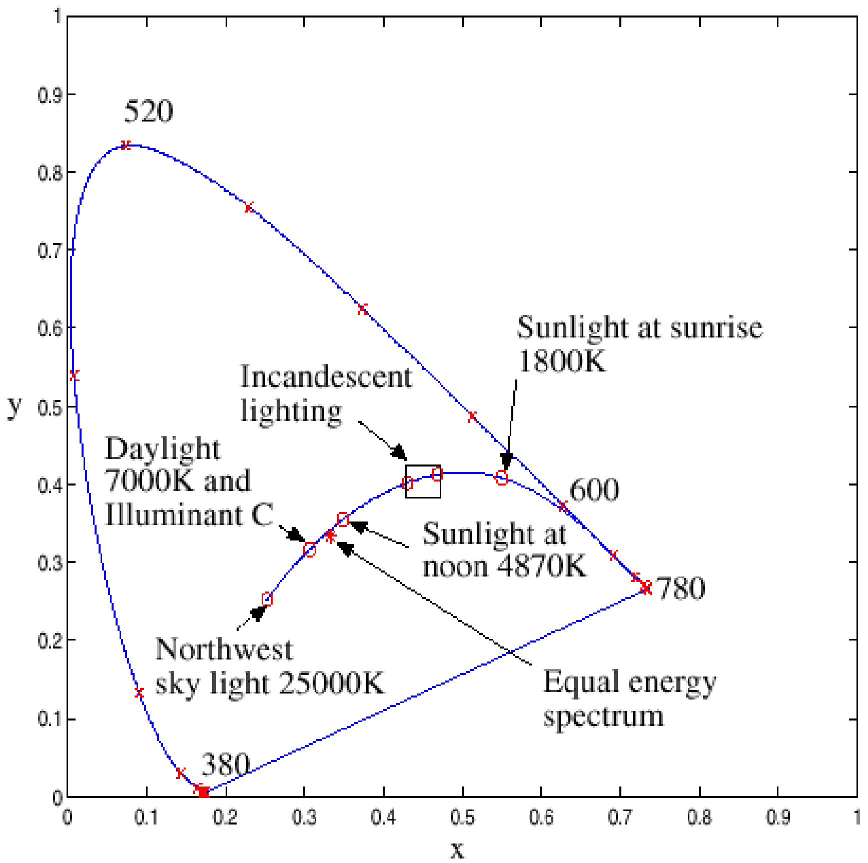
x=X/(X+Y+Z)
y=Y/(X+Y+Z)

$$X = 0.490R + 0.310G + 0.200B$$
$$Y = 0.177R + 0.813G + 0.011B$$
$$Z = 0.000R + 0.010G + 0.990B$$

CIE XYZ Color Space (2)



x-y Color coordinate

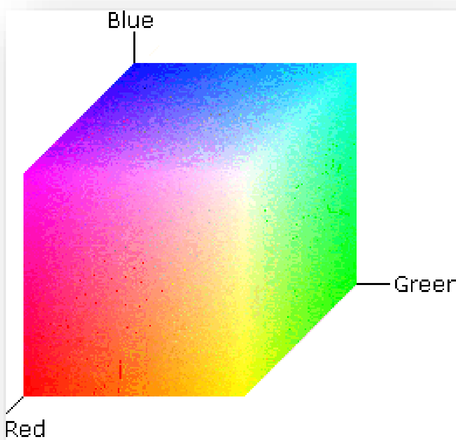


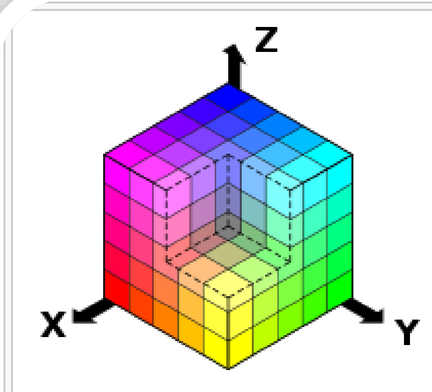
X+Y+Z=1 plane

RGB Color Space

- 3 Primaries of colors
  - Red (645.2nm), Green (526.3nm), Blue (444.4nm)
- 3-D orthogonal rectangular coordinate
  - RGB cube
  - Actually neither independent nor orthogonal to each other
- The more is mixed, the brighter is.
  - Additive mixing
- Variations: sRGB, adobeRGB, …

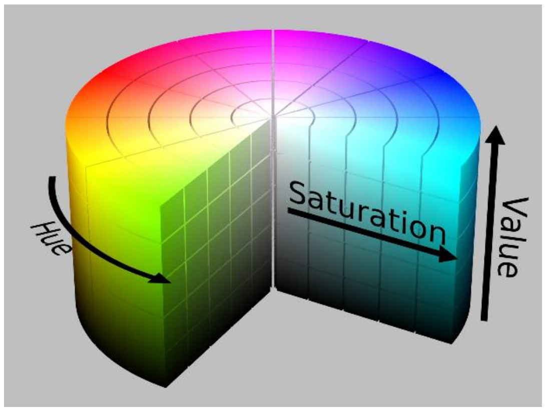
가산혼합의 원리



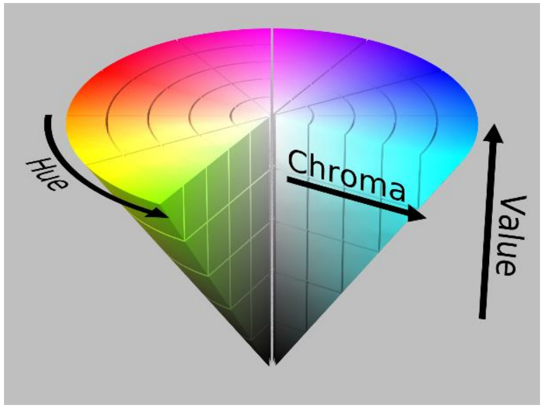


RGB의 큐브 모델

HSV Color Space (1)



Cylinder HSV



Cone HSV

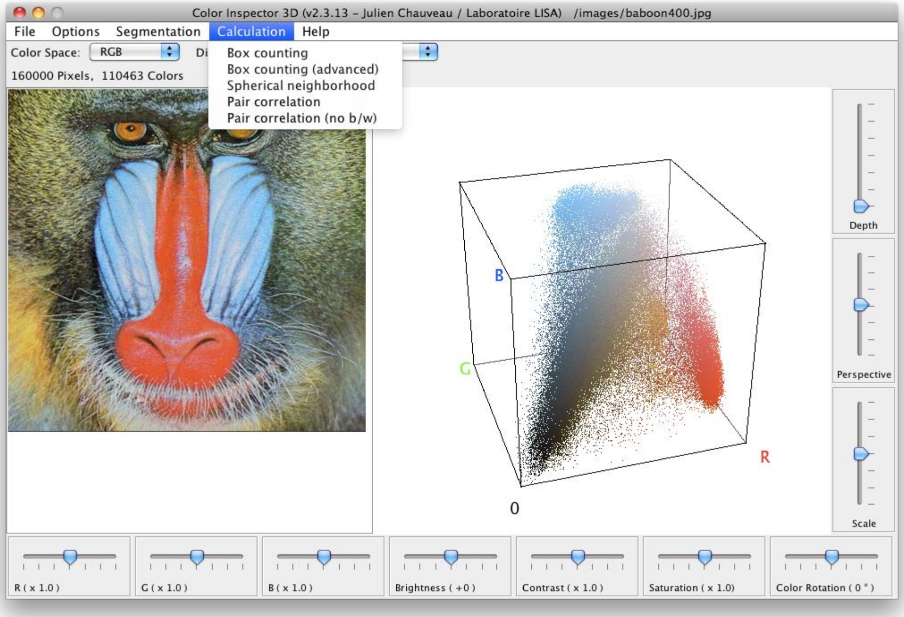
- Cylindrical representation of colors
  - Nonlinear color representation
  - Independent components: (H,S,V)
- Hue
  - Visible light spectrum
  - Red ~ violet mapping to 0°~360°
- Saturation
  - Purity of color
  - the radius of cylinder: 0(achromatic)~1(chromatic)
- Value (Intensity)
  - Luminance or brightness
  - the height of cylinder
- Cone Representation
  - Low values -> Hue components are not distinctive.

HSV Color Space (2)

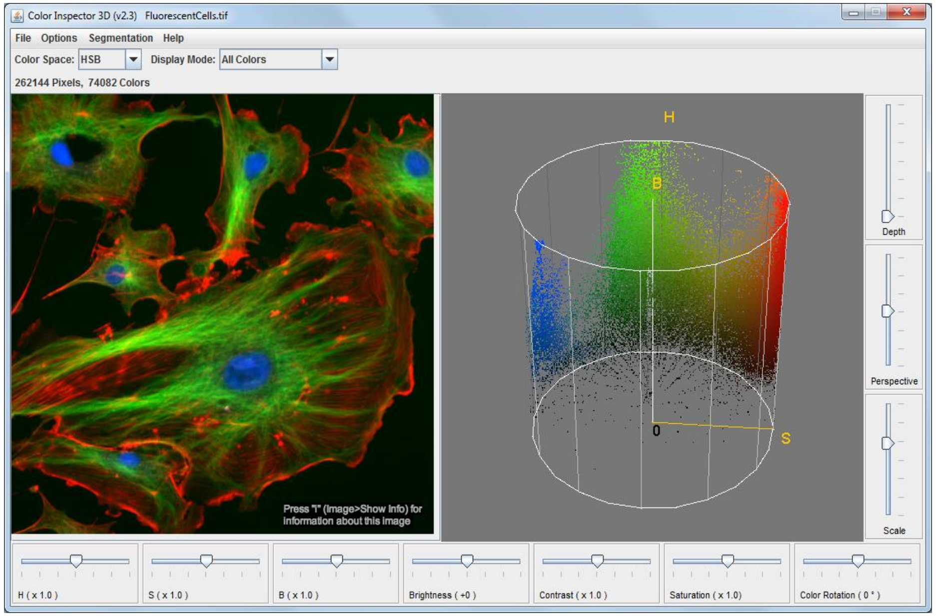
- **Transform of RGB to HSV**

```
RGBtoHSV( float r, float g, float b, float *h, float *s, float *v )
{
        float min, max, delta;
        min = MIN( r, g, b );
        max = MAX( r, g, b );
        *v = max;                               // v
        delta = max - min;
        if( max != 0 )
                *s = delta / max;               // s
        else {
                // r = g = b = 0                // s = 0, v is undefined
                *s = 0;
                *h = -1;
                return;
        }
        if( r == max )
                *h = ( g - b ) / delta;                 // between yellow & magenta
        else if( g == max )
                *h = 2 + ( b - r ) / delta;             // between cyan & yellow
        else
                *h = 4 + ( r - g ) / delta;             // between magenta & cyan
        *h *= 60;                               // degrees
        if( *h < 0 )
                *h += 360;
}
```

RGB and HSV



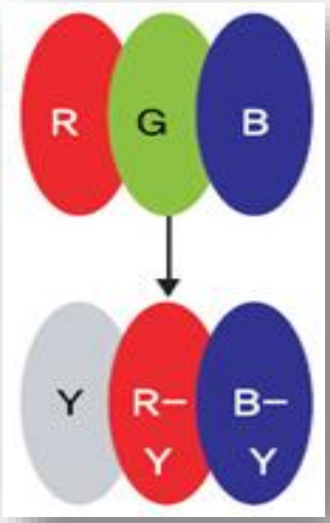
RGB 분포



HSV 분포

YUV Color Space (1)

- Rectangular representation of colors
  - Color TV signal transmission (composite color)
- Reducing the redundancy (correlation) among color components
  - Y: Luminance, brightness
  - U, V : Chrominance (color difference)
- Human visual system (HVS) is less sensitive to chrominance than luminance or RGB
  - Spectral reduction : 4:2:0 format encoding
  - Image and video compression: JPEG, MPEG
- Variations: YCbCr, YIQ (NTSC)



Correlation reduction

YUV Color Space (2)

- **RGB to YUV**

$$\begin{bmatrix} Y' \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.14713 & -0.28886 & 0.436 \\ 0.615 & -0.51499 & -0.10001 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1.13983 \\ 1 & -0.39465 & -0.58060 \\ 1 & 2.03211 & 0 \end{bmatrix} \begin{bmatrix} Y' \\ U \\ V \end{bmatrix}$$

- **RGB to YCbCr**

$$Y = 0.299 \times R + 0.587 \times G + 0.114 \times B + 0$$
$$C_b = -0.169 \times R - 0.331 \times G + 0.499 \times B + 128$$
$$C_r = 0.499 \times R - 0.418 \times G - 0.0813 \times B + 128$$

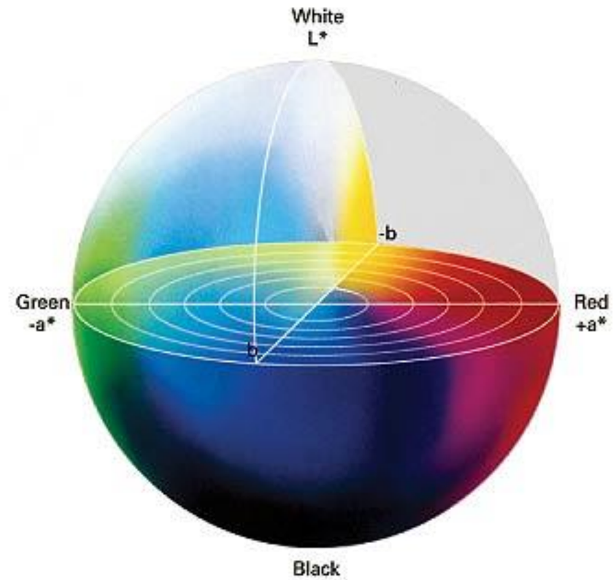
$$R = \mathrm{clamp}(Y + 1.402 \times (Cr - 128))$$
$$G = \mathrm{clamp}(Y - 0.344 \times (Cb - 128) - 0.714 \times (Cr - 128))$$
$$B = \mathrm{clamp}(Y + 1.772 \times (Cb - 128))$$

	R	G	B
Black	0	0	0
White	255	255	255
Yellow	255	255	0
Cyan	0	255	255
Green	0	255	0
Magenta	255	0	255
Red	255	0	0
Blue	0	0	255

Y	U	V
16	128	128
235	128	128
210	16	146
170	166	16
145	54	34
107	202	222
82	90	240
41	240	110

CIE 1976 Lab Color Space

- **Wider representable, more uniform in color space**
  - **L: luminance (0~100)**
  - **a: green ~ red (-1~+1)**
  - **b: blue ~ yellow (-1~+1)**
- **Non-linear transform**



$$L^\star = 116 f(Y/Y_n) - 16$$
$$a^\star = 500\left[f(X/X_n) - f(Y/Y_n)\right]$$
$$b^\star = 200\left[f(Y/Y_n) - f(Z/Z_n)\right]$$

$$f(t) = \begin{cases} t^{1/3} & \text{if } t > \left(\frac{6}{29}\right)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{4}{29} & \text{otherwise} \end{cases}$$

$$Y = Y_n f^{-1}\left(\tfrac{1}{116}\left(L^* + 16\right)\right)$$
$$X = X_n f^{-1}\left(\tfrac{1}{116}\left(L^* + 16\right) + \tfrac{1}{500}a^*\right)$$
$$Z = Z_n f^{-1}\left(\tfrac{1}{116}\left(L^* + 16\right) - \tfrac{1}{200}b^*\right)$$

$$f^{-1}(t) = \begin{cases} t^3 & \text{if } t > \frac{6}{29} \\ 3\left(\frac{6}{29}\right)^2\left(t - \frac{4}{29}\right) & \text{otherwise} \end{cases}$$

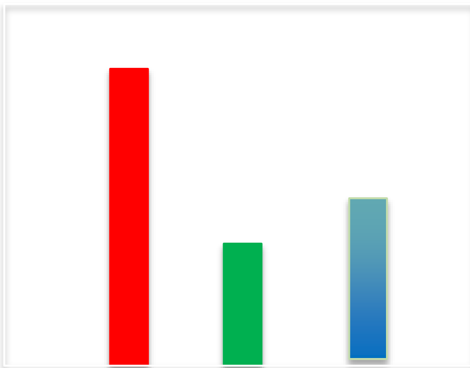
*X_n, Y_n, Z_n: normalized XYZ for standard white color

Beyond 3D Color Models (Multispectral Imaging)

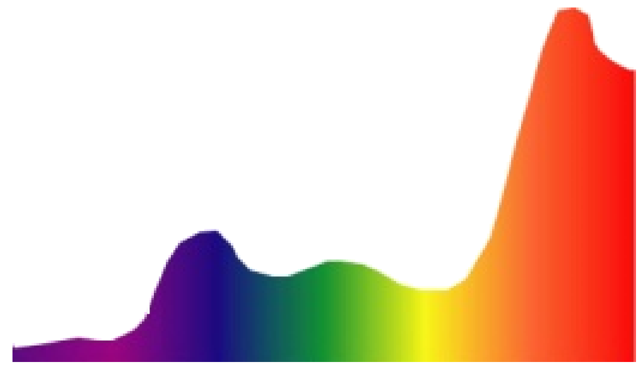
by J. I. Park, Hanyang. Univ.

Multispectral Imaging

Full spectral information
Vector space



R G B

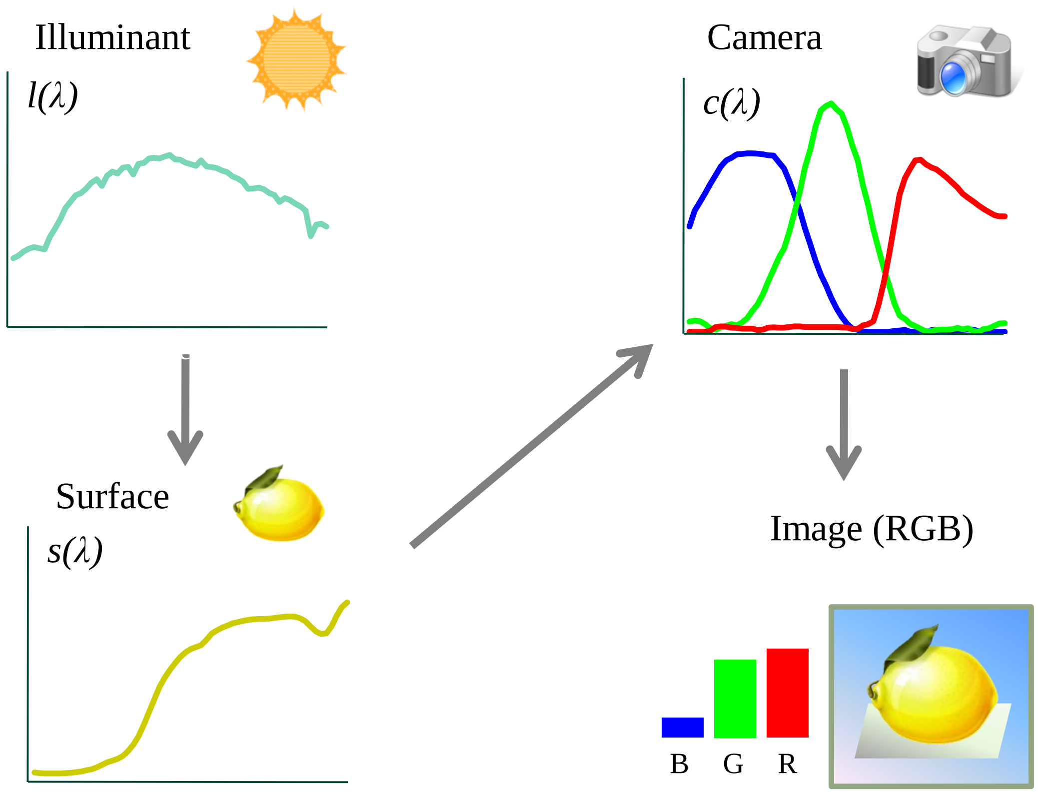


Ordinary 3D color space
➔ loss of spectral information
➔ Vector space

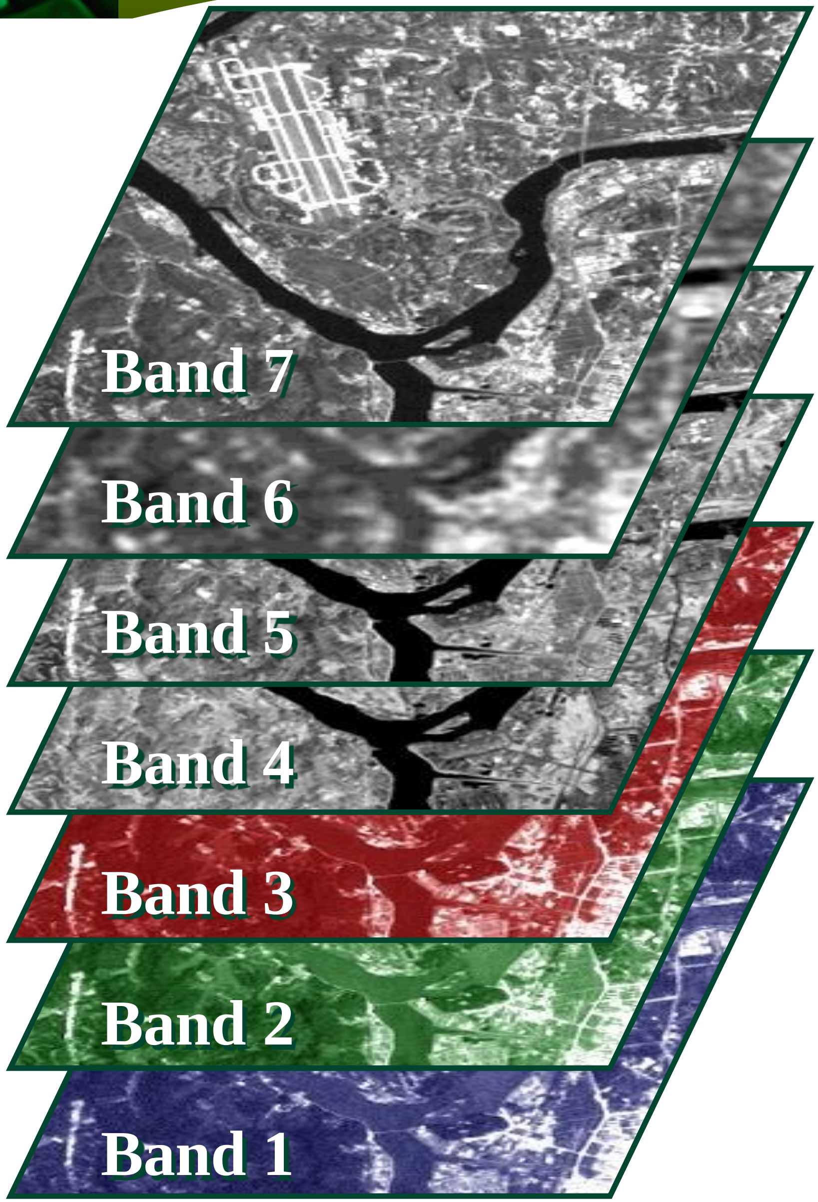
Full spectrum representation
➔ Function space

RGB Imaging Model

$$I_{mn} = \int s(\lambda) c_m(\lambda) p_n(\lambda) d\lambda$$



Multispectral Bands



Band No.	Name	Wavelength (μm)	Characteristics and Uses
1	Visible blue	0.45–0.52	Maximum water penetration
2	Visible green	0.52–0.60	Good for measuring plant vigor
3	Visible red	0.63–0.69	Vegetation discrimination
4	Near infrared	0.76–0.90	Biomass and shoreline mapping
5	Middle infrared	1.55–1.75	Moisture content of soil and vegetation
6	Thermal infrared	10.4–12.5	Soil moisture; thermal mapping
7	Middle infrared	2.08–2.35	Mineral mapping

3,2,1
fusion

Natural Color Fusion

Multispectral Functions (1)

Painting reconstruction

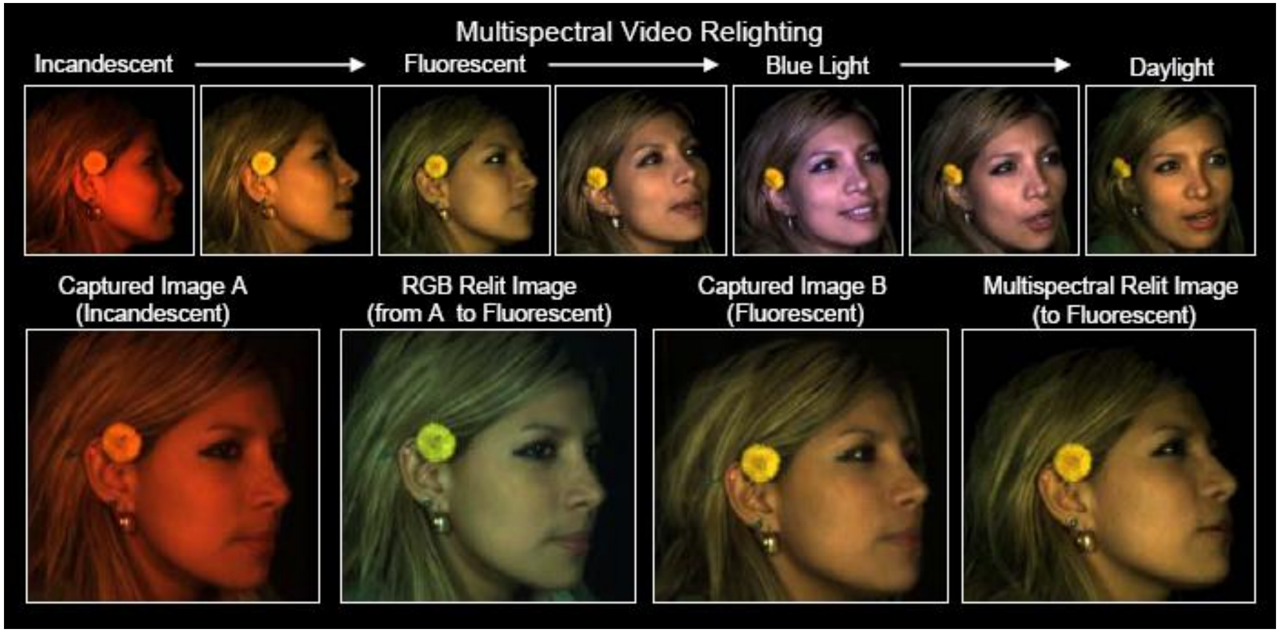
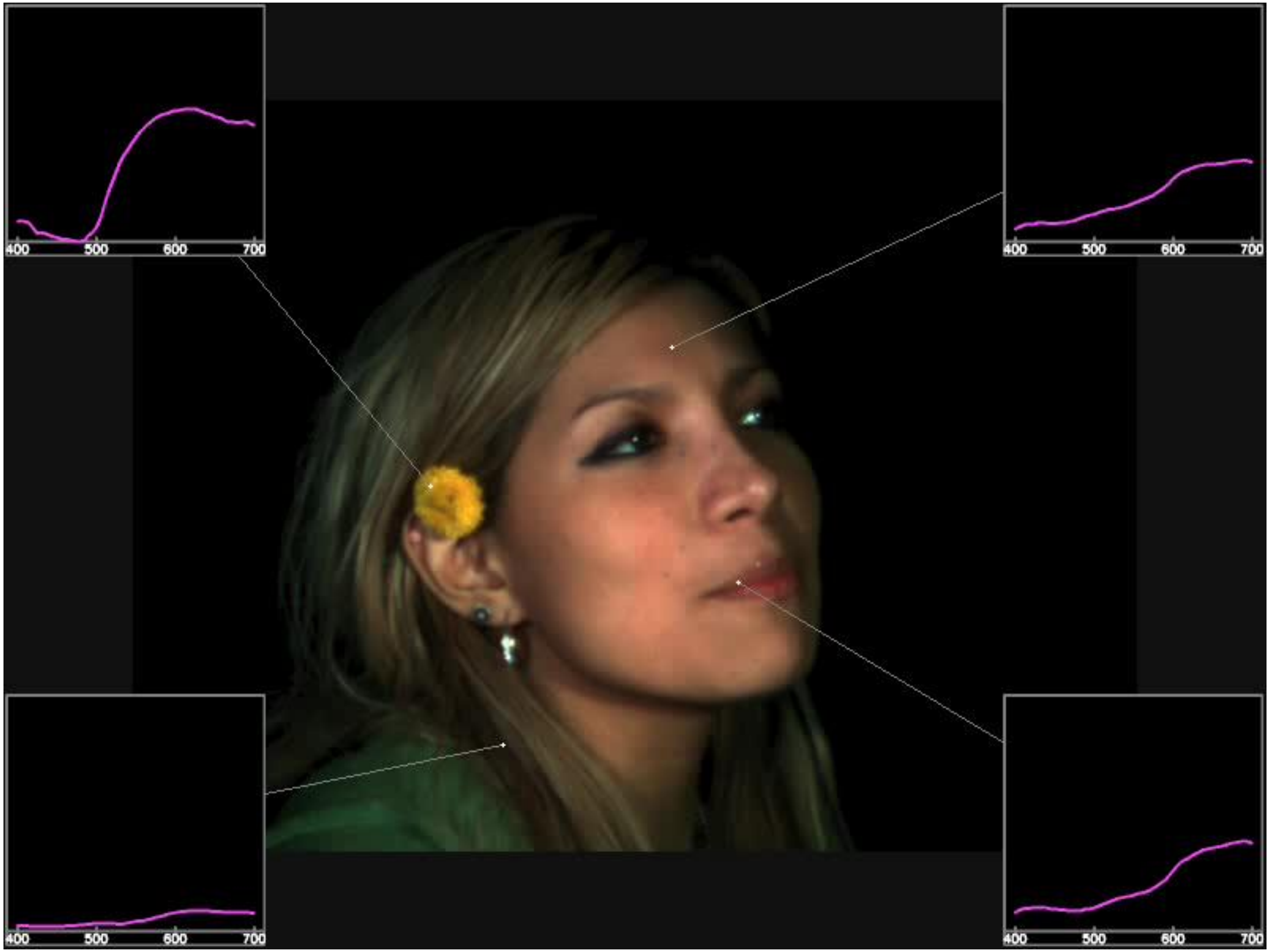


Image relighting

Multispectral Functions (2)



스펙트럼 곡선의 변화

by J. I. Park

Models of Multispectral Imaging

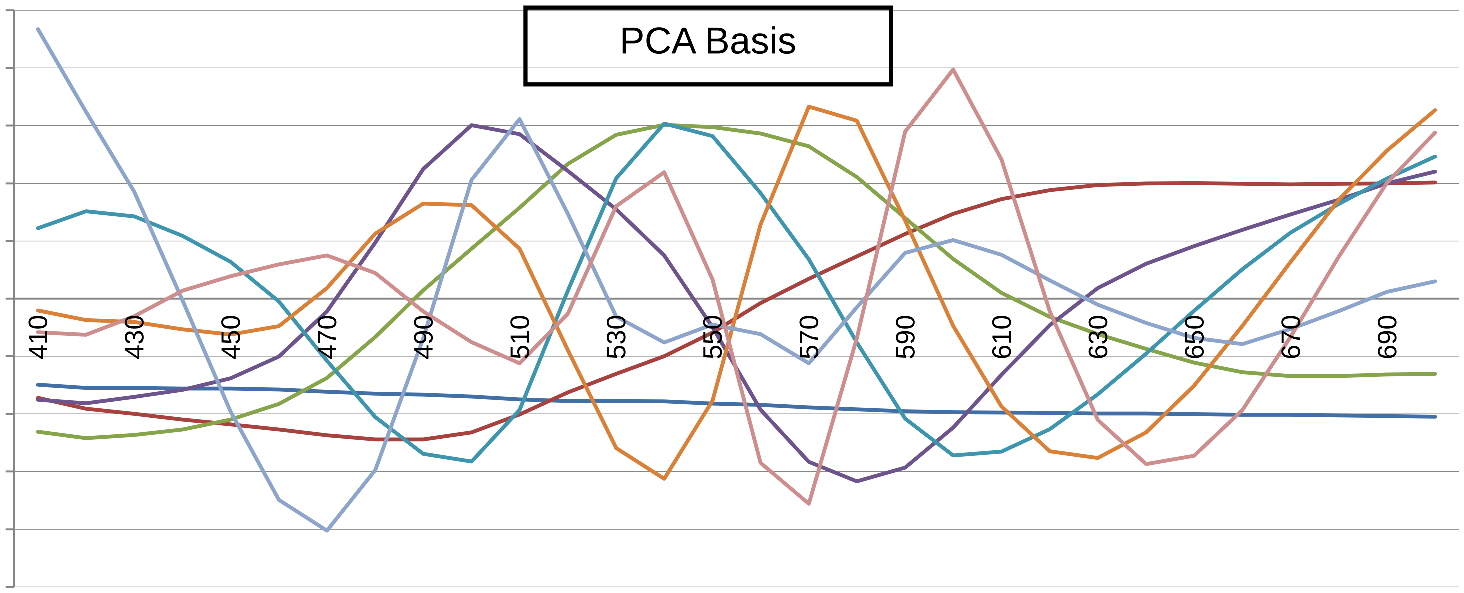
- $I_{mn} = \int s(\lambda) c_m(\lambda) p_n(\lambda) d\lambda$
- **Using reflectance basis function**

$$\boxed{s(\lambda) = \sum_{k=1}^{K_s} \sigma_k b_k(\lambda)}$$

- $I_{mn} = \sum_{k=1}^{K_s} \sigma_k \int b_k(\lambda) c_m(\lambda) p_n(\lambda) d\lambda$

Parkkinen Basis (1)

- Parkkinen et al, "Characteristic spectra of munsell colors," Opt. Soc. Am. A,6, 318-322 (1989).
  - **8 basis spectral functions**

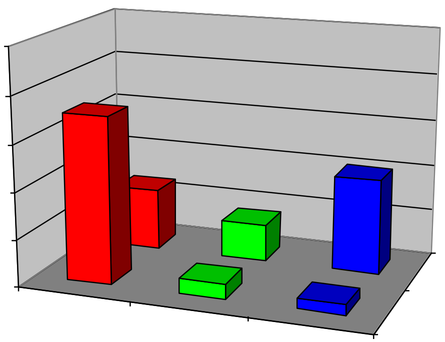


Graph by J. I. Park

Parkkinen Basis (2)

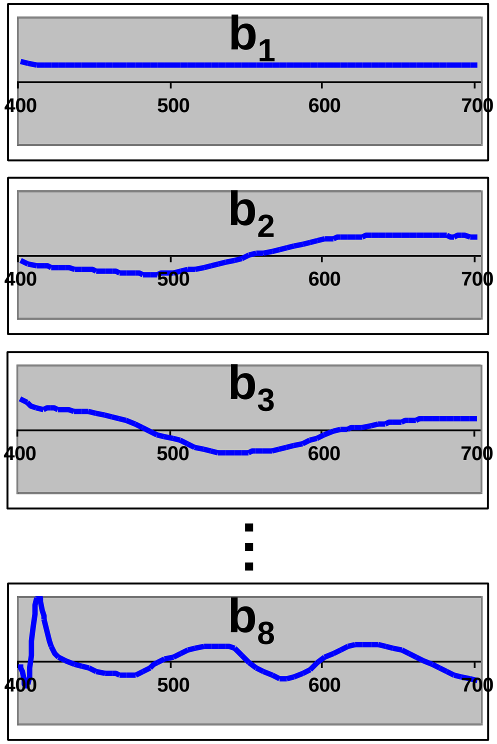
Frame1

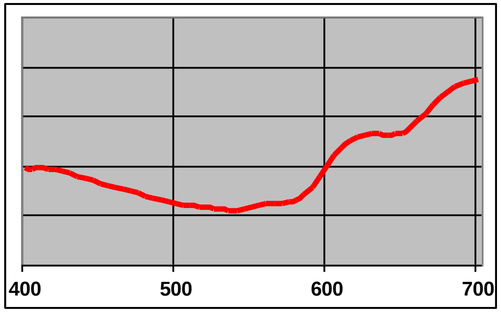
Frame2



Measured Data from various illumination

Parkkinen Basis



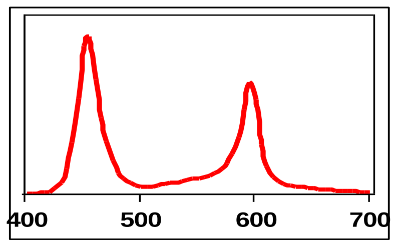


Estimated Spectral Reflectance

Multispectral Relighting (1)

Multispectral
Image(D65)

Illumination Spectrum L_A



Captured Image
(Fluorescent)

Multispectral Relit
Image to L_A

Captured Image under L_A
(Ground-Truth)

RGB Relit Image from
Fluorescent to L_A

Multispectral Relighting (2)

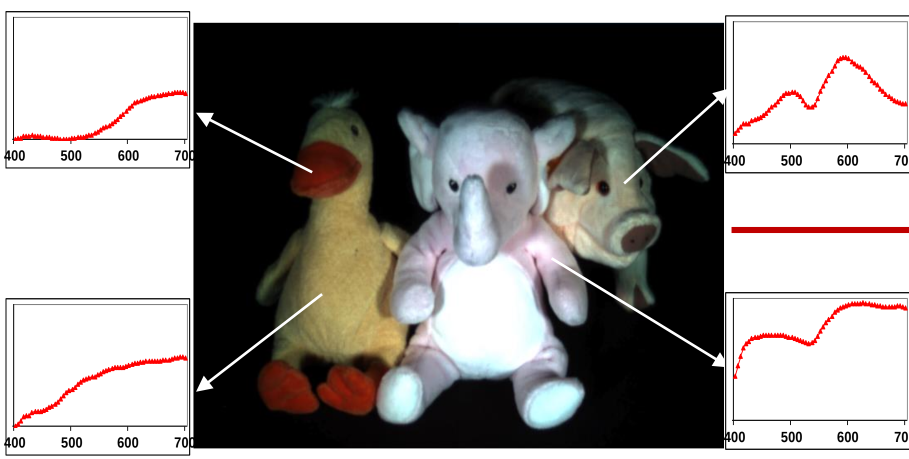
Captured Image A
(Incandescent)

RGB Relit Image from A
(to Fluorescent)

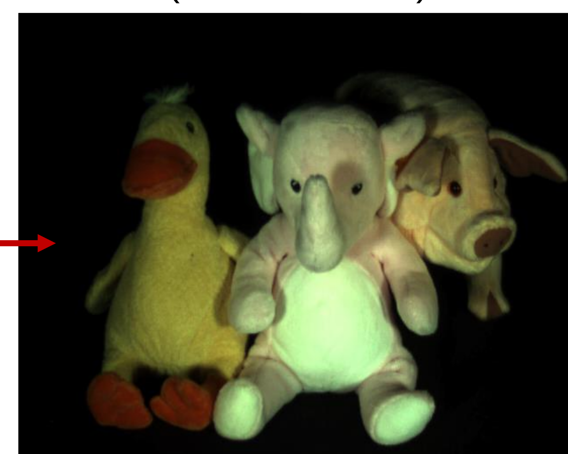
Captured Image B
(Fluorescent)

Captured Images
(Multiplexed Illum.)

Multispectral Image (D65)



Multispectral Relit Image
(to Fluorescent)



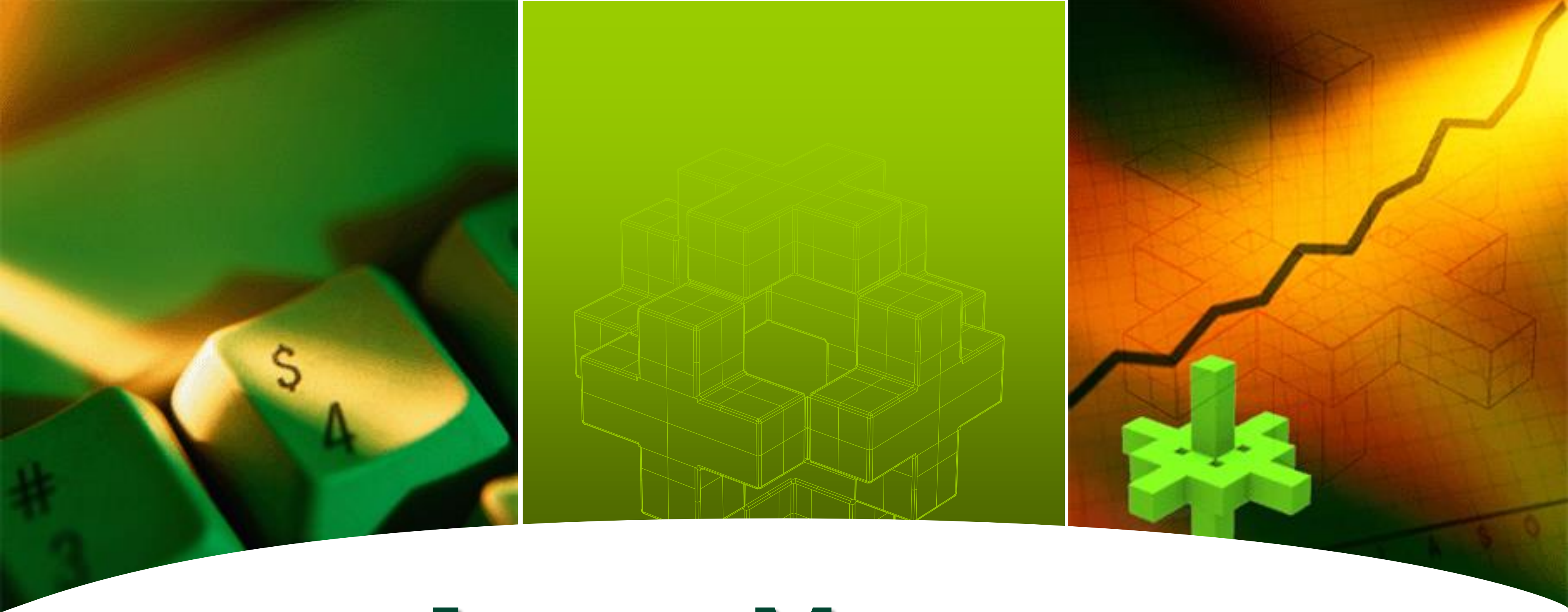


Image Measure (Similarity/Quality)

PSNR

- Evaluation of image similarity
  - **Original image vs processed image**
  - **restoration, noise reduction, interpolation**
- Peak SNR
  - **Mean-squared error**
  - **Most general measurement of similarity**
- It is not exact!
  - **PSNR does not consider image structures to evaluate the similarity.**

$$PSNR = 10\log\frac{255^2}{E\left[(I_o(x,y)-I_p(x,y))^2\right]}\ \mathrm{dB}$$

SSIM

- Structural Similarity Index
  - New measure for image similarity
  - Combining with luminance change, contrast change and structural change
- MSSIM (mean SSIM) for SSIM(x,y) of all pixels

$$l(\mathbf{x},\mathbf{y}) = \frac{2\mu_x\mu_y + C_1}{\mu_x^2 + \mu_y^2 + C_1} \qquad s(\mathbf{x},\mathbf{y}) = \frac{\sigma_{xy} + C_3}{\sigma_x\sigma_y + C_3} \qquad c(\mathbf{x},\mathbf{y}) = \frac{2\sigma_x\sigma_y + C_2}{\sigma_x^2 + \sigma_y^2 + C_2}$$

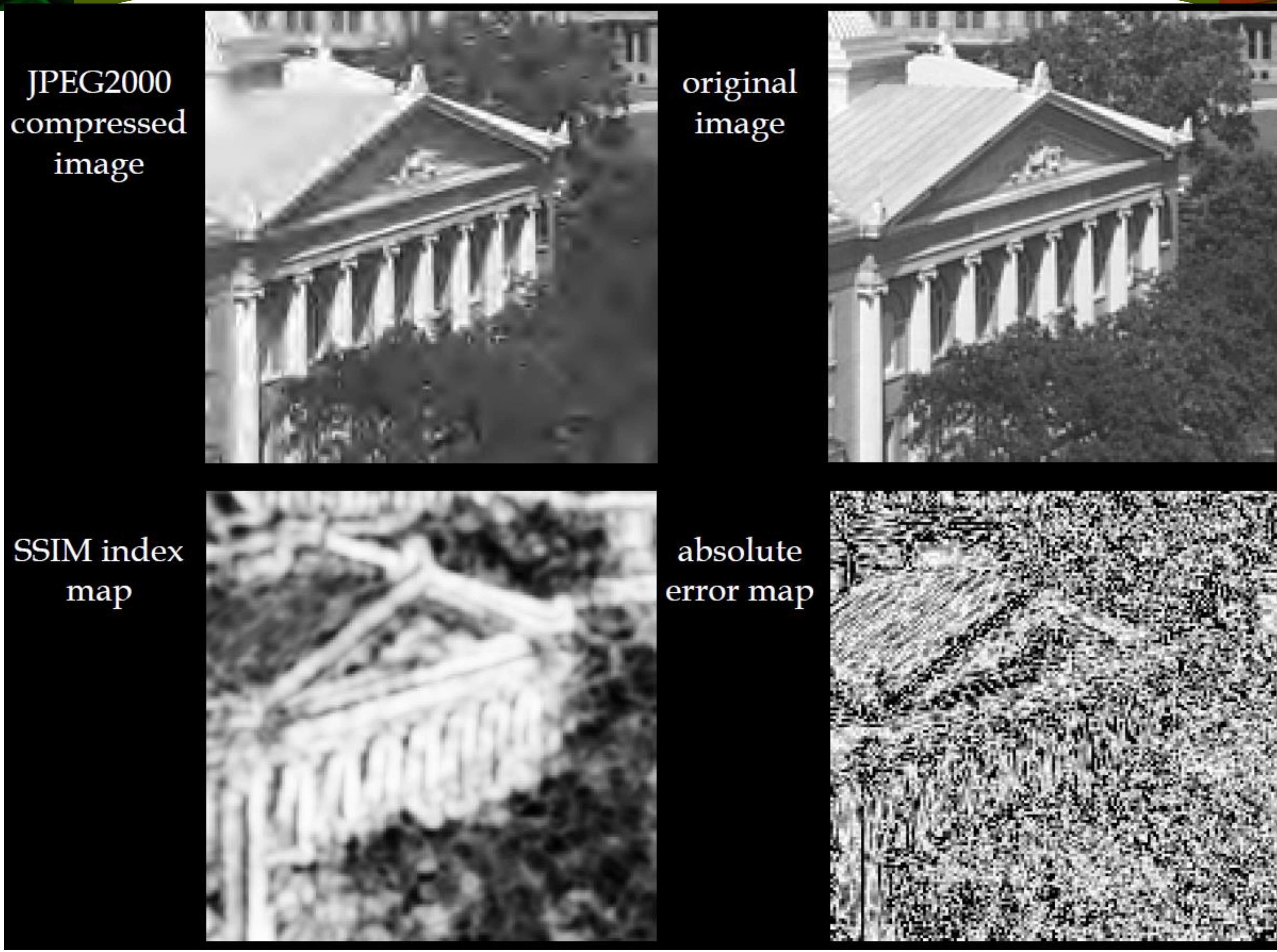
$$SSIM(x,y) = l(x,y)\cdot c(x,y)\cdot s(x,y)$$

Comparison

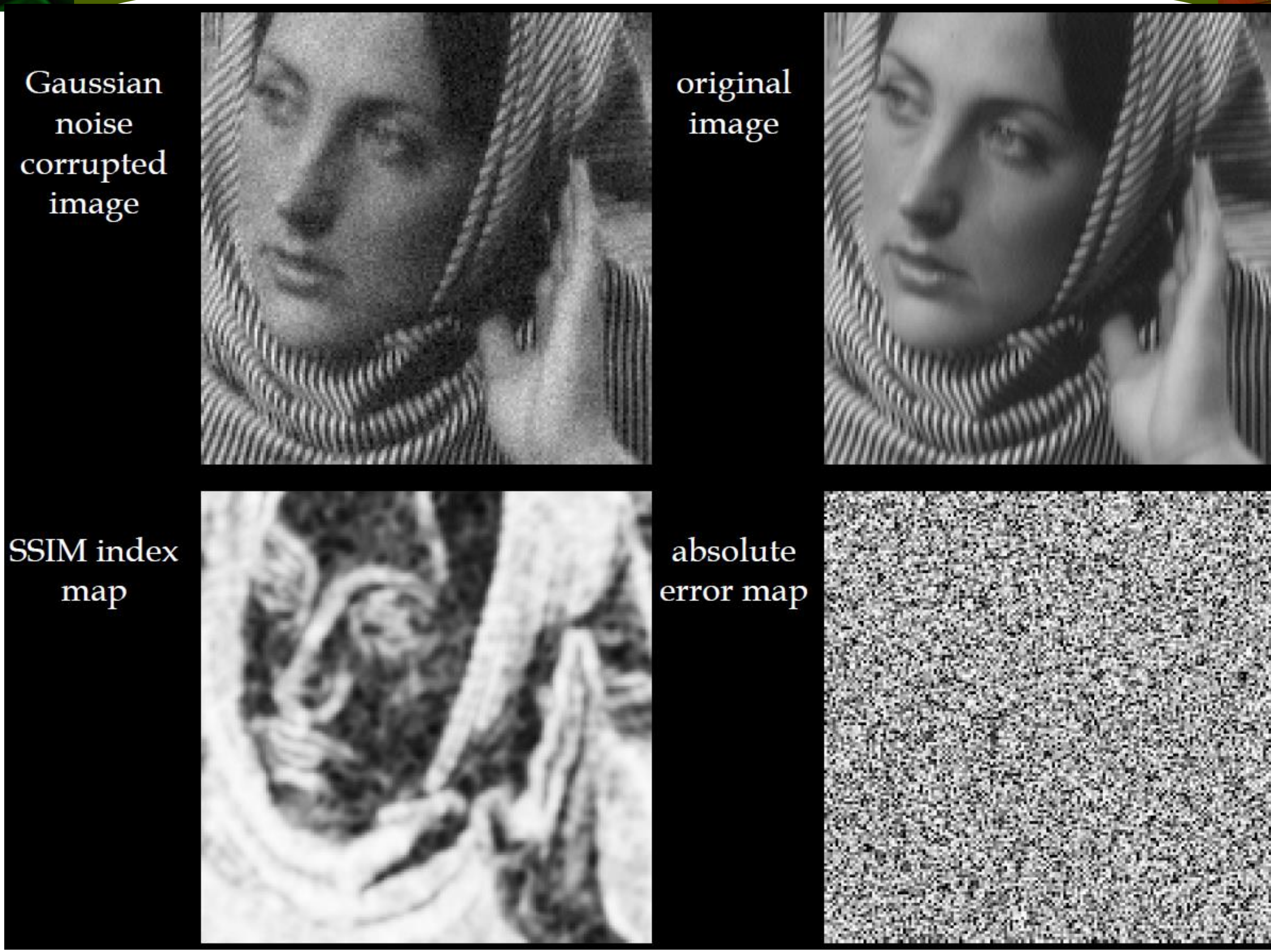

MSE=0, MSSIM=1
MSE=225, MSSIM=0.949
MSE=225, MSSIM=0.989
MSE=215, MSSIM=0.671
MSE=225, MSSIM=0.688
MSE=225, MSSIM=0.723

original image
initial distorted image
best SSIM for fixed MSE
worst SSIM for fixed MSE
best MSE for fixed SSIM
worst MSE for fixed SSIM
786

Correlation (1)



Correlation (2)



Conclusion

- For evaluation of image similarity
  - **PSNR: MSE**
  - **SSIM: intensity+contrast+structure**
    - Local mean and variance
- MSSIM is a bit better than PSNR.
- Usually, two measures should be considered for image similarity!