Digital Halftoning

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Gray-Scale Image Halftoning

Objective

- Use black-white (two-tone) images to render gray-level images
- Why called halftoning?
  - Normalize intensities of gray-level images to [0,1]
  - Need to find a threshold to split it into two values – 0 or 1
  - How to do thresholding?
  - Fixed thresholding does not work properly

Halftoning by Simple Thresholding

Gray-Level Image Halftoning Example

Digital halftoning: A process that converts from 8bpp to 1bpp

1bpp: 0/1, 1: black ink -> dark, 0: no ink -> white (background color)

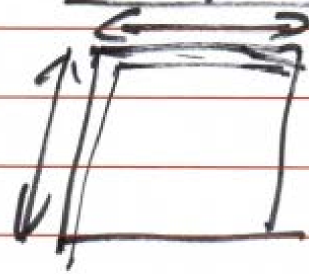
Why: paper printing versus screen display

Document Printing

Printing

Ink. → dpi dots per inch

300
600
1200



PDF

~~dot~~

dark black dots

(brightness) paper color

no ink

Goal and Methods

Goal: Rendering the illusion of gray-level images on two-tone display devices, e.g. printers.

A darker region ⟷ denser black pixels per area.

A whiter region ⟷ sparser black pixels per area.

2 commonly used methods

- Dithering
- Error Diffusion

Software versus Hardware

How to measure the performance of different algorithms?

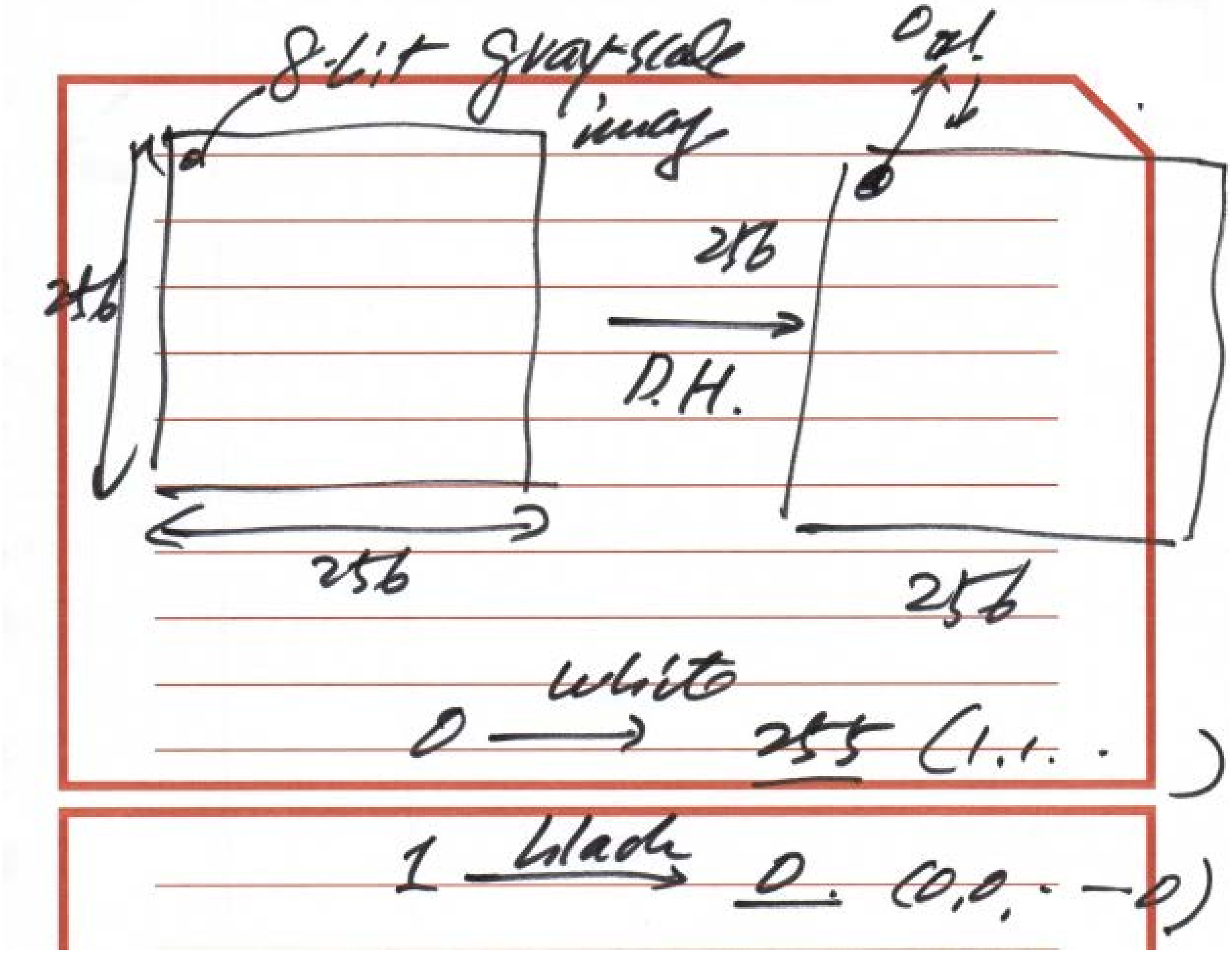
Good HW. → higher dpi

The performance gap between good and poor halftoning algorithms is small.

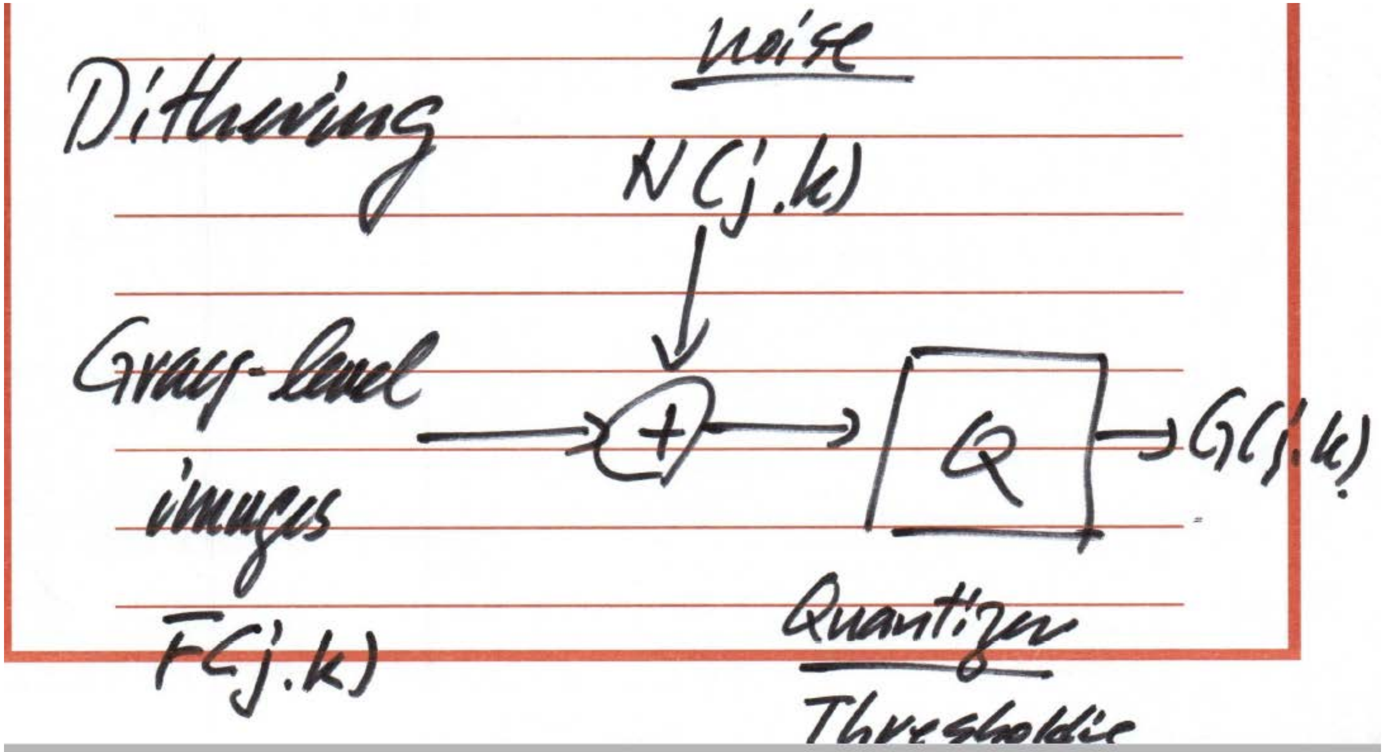
Poor HW. → low dpi.

~~the~~ The performance gap is larger.

Performance Evaluation



Dithering (1)



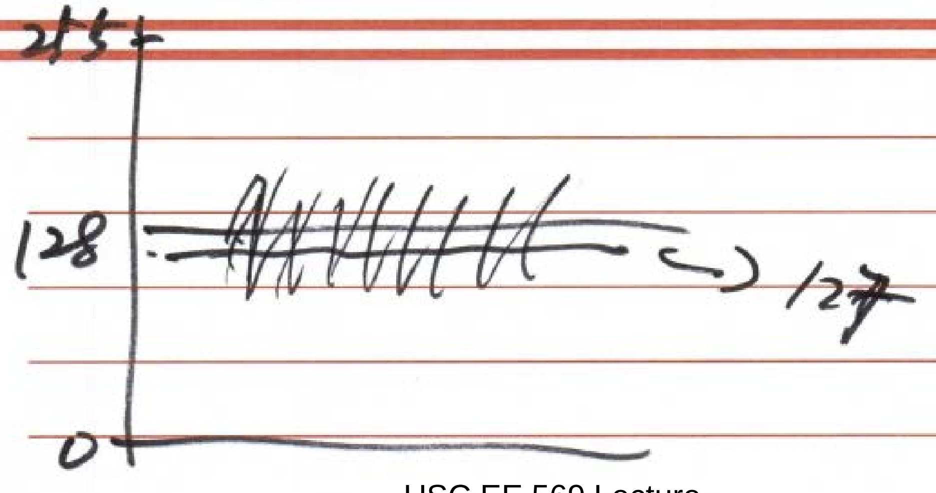
Why noise N(j,k) is needed?

Dithering (2)

Gray-scale value at a pixel

→ mean.

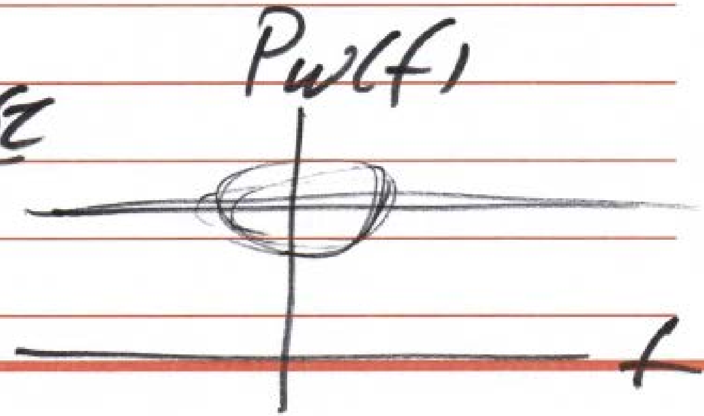
noise → random variable.
(zero-mean)



Dithering via Additive White Noise

white noise

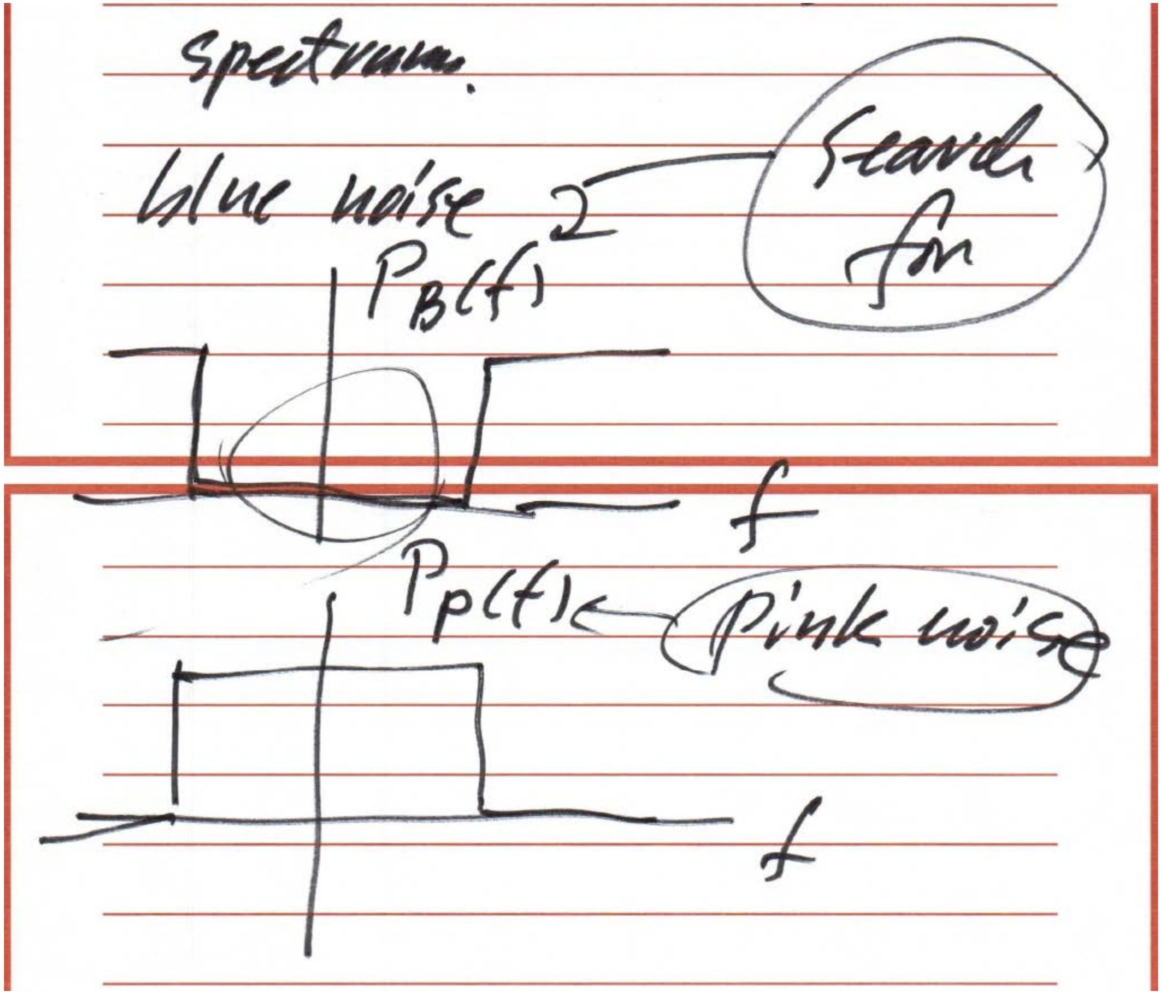
uncorrelated noise



Granularity patterns

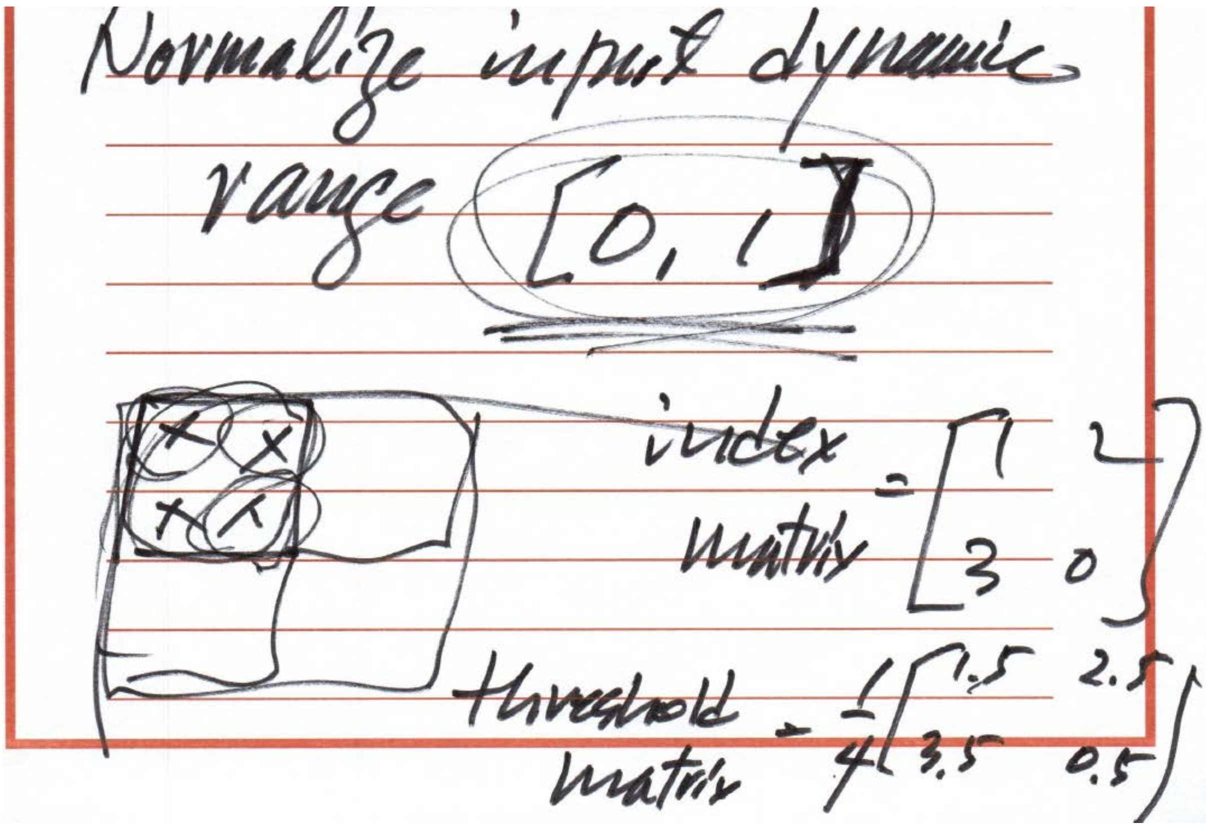
due to the low freq. power spectrum.

Dithering via Additive Blue Noise



Practical Dithering Algorithm (1)

- Instead of using additive noise, adopt adaptive thresholding



Practical Dithering Algorithm (2)

$$I_{2n}(i,j) = \begin{bmatrix} 4 \times I_n(i,j) + 1 & 4 \times I_n(i,j) + 2 \\ 4 \times I_n(i,j) + 3 & 4 \times I_n(i,j) \end{bmatrix}$$

$$I_2(i,j) = \begin{bmatrix} 1 & 2 \\ 3 & 0 \end{bmatrix}$$

$$\left[\begin{array}{cc|cc} 4+1 & 8+1 & 4+2 & 8+2 \\ 12+1 & 0+1 & 12+2 & 0+2 \\ 4+3 & 8+3 & 4 & 8 \\ 12+3 & 0+3 & 12 & 0 \end{array}\right]$$

Practical Dithering Algorithm (3)

- Summary

Dithering: $2^n \times 2^n$ window.

index matrix

lowest index → lower threshold

$\{0, 1, \ldots, 4^n - 1\}$

$n=1.$ $0, 1, \ldots 3$

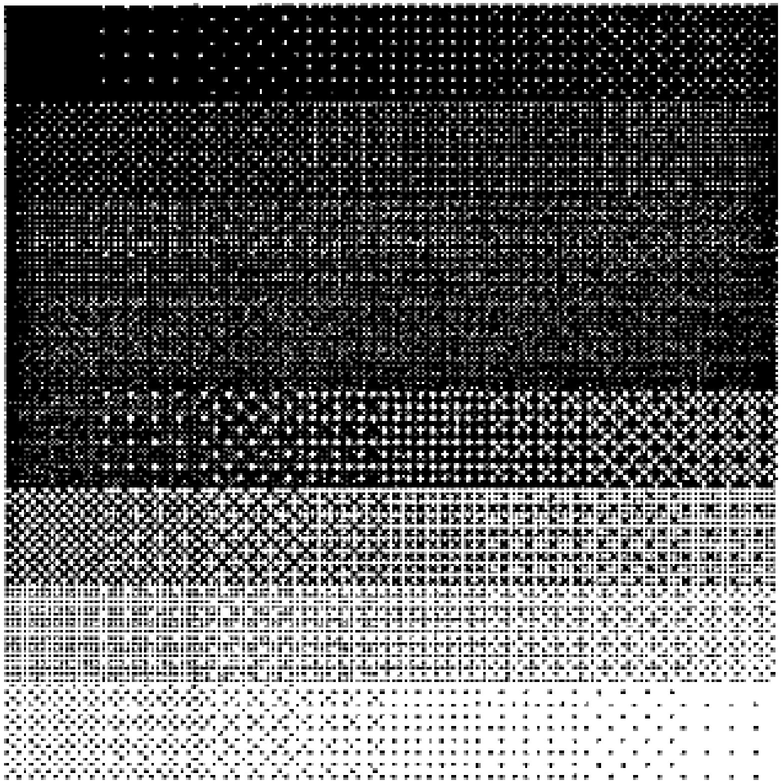
$n=2$ $0, 1, \ldots, 15$

Threshold matrix

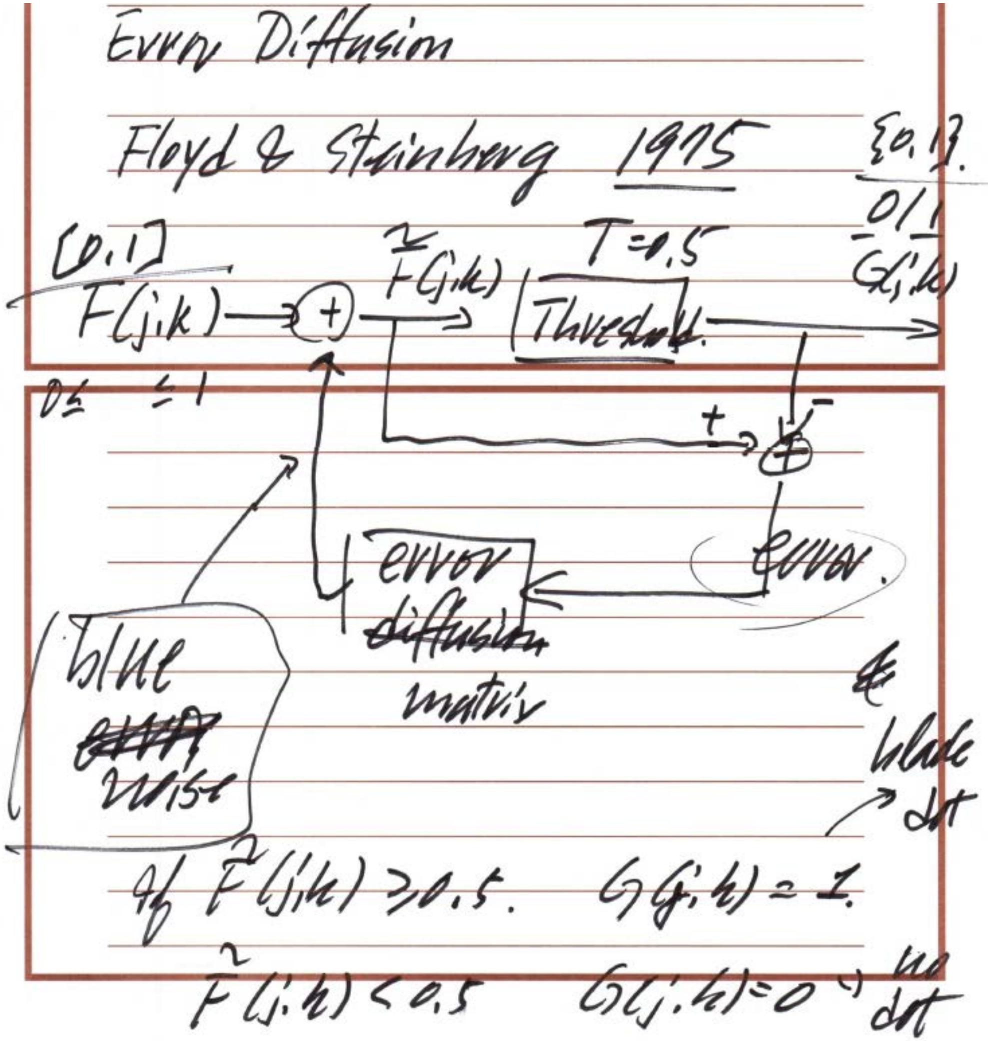
$$\frac{\text{index value} + 0.5}{4^n}.$$

Shortcomings of Dithering

- Texture-like visual patterns



Error Diffusion (1)



Error Diffusion (2)

$$E(j,k) = \tilde{F}(j,k) - G(j,k)$$

feed back to neighboring pixels

Error Diffusion mask.

Floyd-Steinberg (1975)

$$\frac{1}{16}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 7 \\ 3 & 5 & 1 \end{pmatrix}$$

Error Diffusion (3)

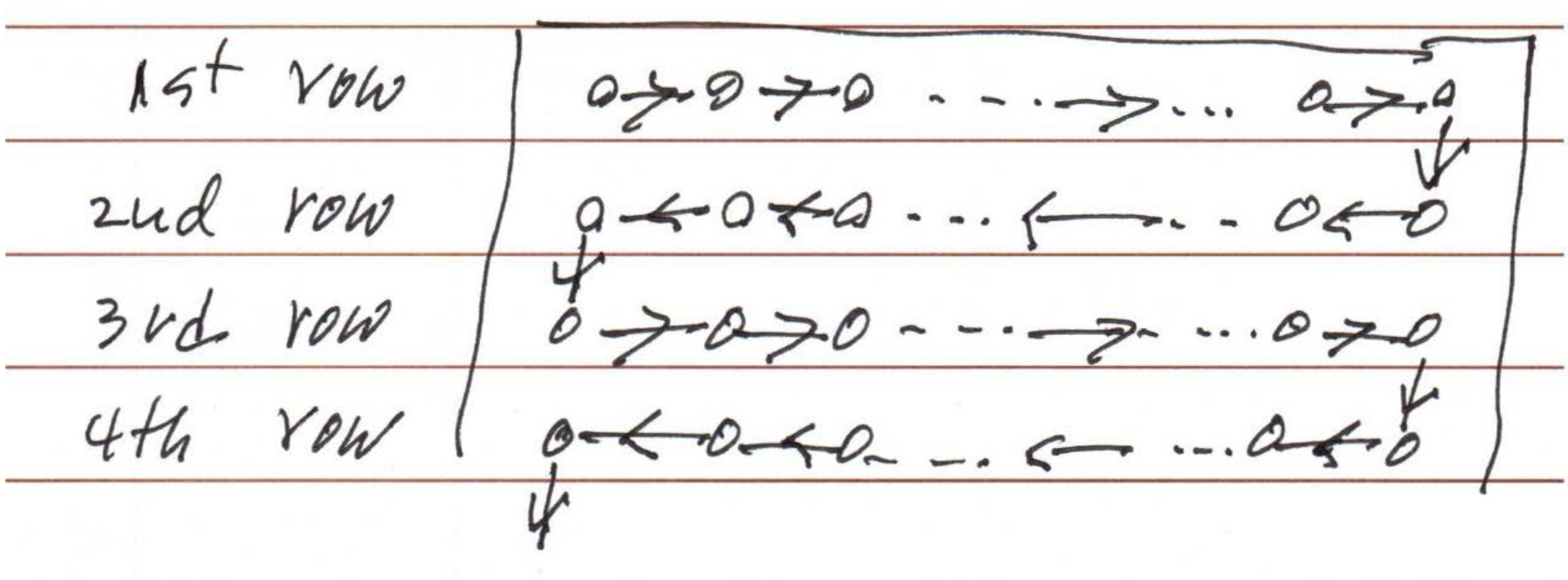
- Error diffusion filter

Jarvis et al. (1976)

$$\frac{1}{48}\begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 7 & 5 \\ 3 & 5 & 7 & 5 & 3 \\ 1 & 3 & 5 & 3 & 1 \end{pmatrix}$$

Error Diffusion with Serpentine Scanning

- The first, third, fifth, … rows
  - Left-to-right scanning
- The second, fourth, sixth, … rows
  - Right-to-left scanning



Error Diffusion Filters

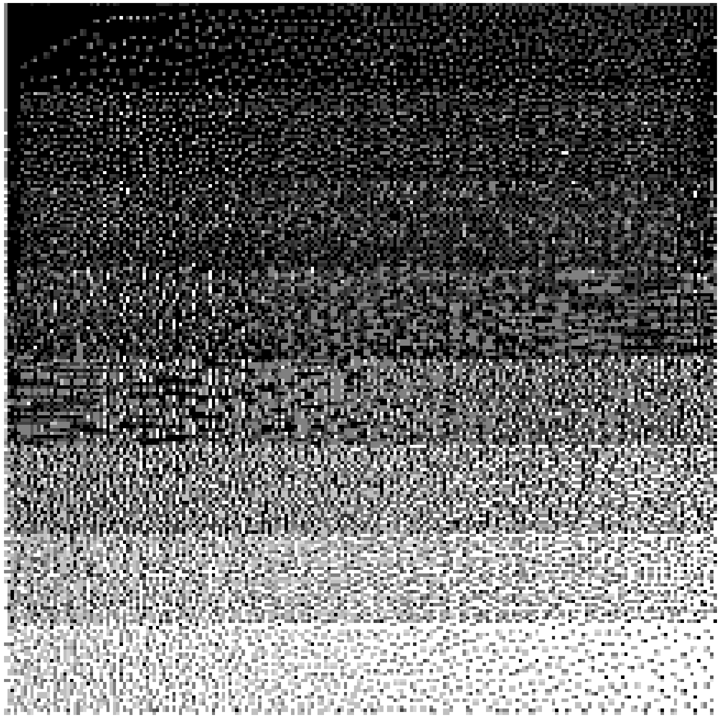
right-to-left

$$\frac{1}{16}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 7 \\ 3 & 5 & 1 \end{pmatrix}$$

left-to-right

$$\frac{1}{16}\begin{pmatrix} 0 & 0 & 0 \\ 7 & 0 & 0 \\ 1 & 5 & 3 \end{pmatrix}$$

Examples of Error Diffusion



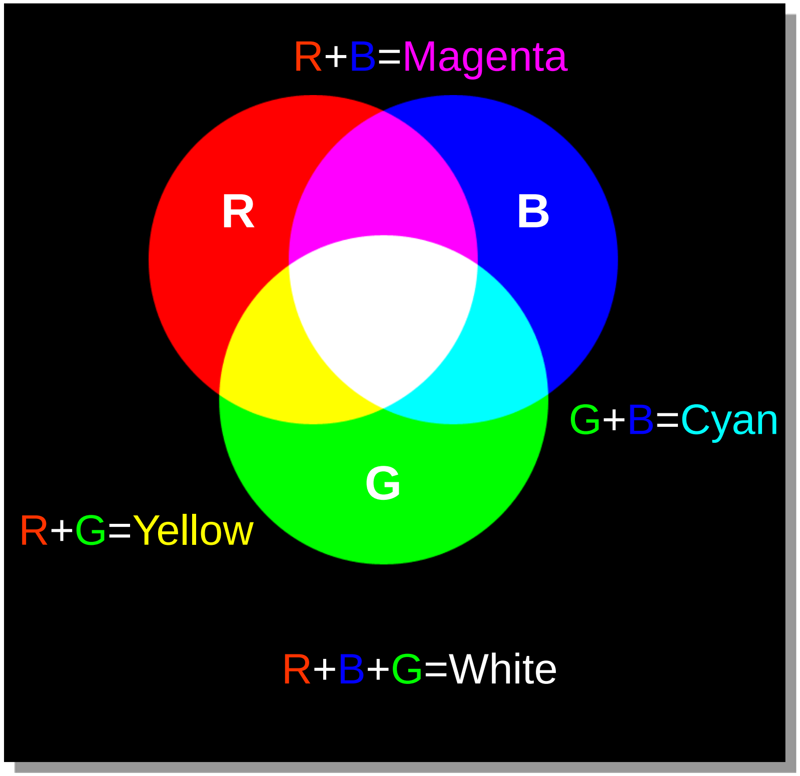
Basic Color Science

Color Mixing

- Get more colors based on the primary colors
  - Additive color mixing
    - RGB
  - Subtractive color mixing
    - CMY

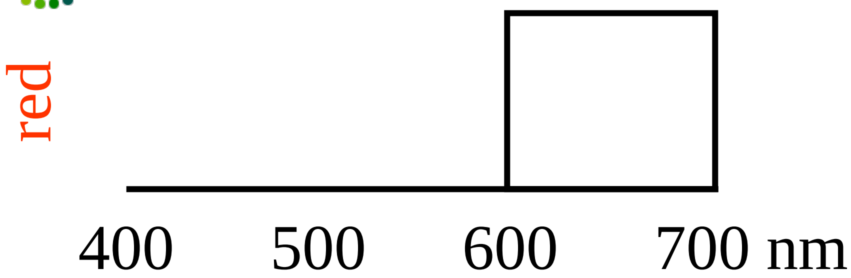
Additive Color Mixing

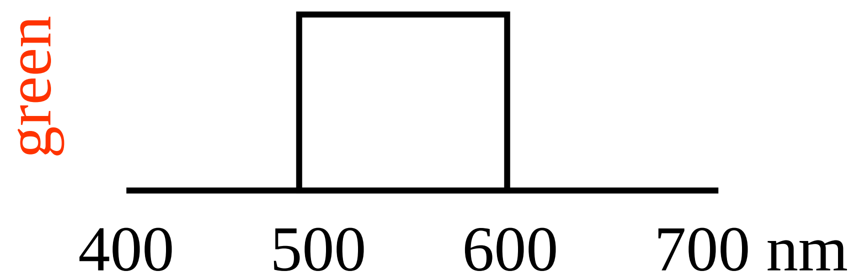
- Additive mixture
  - Overlap Spotlights in dark rooms
  - Primary colors
    - Red – long wavelengths
    - Green – middle wavelengths
    - Blue – short wavelengths
  - Secondary colors
    - Magenta
    - Cyan
    - Yellow
  - Applications
    - CRT phosphors
    - multiple projectors aimed at a screen
    - Polachrome slide film

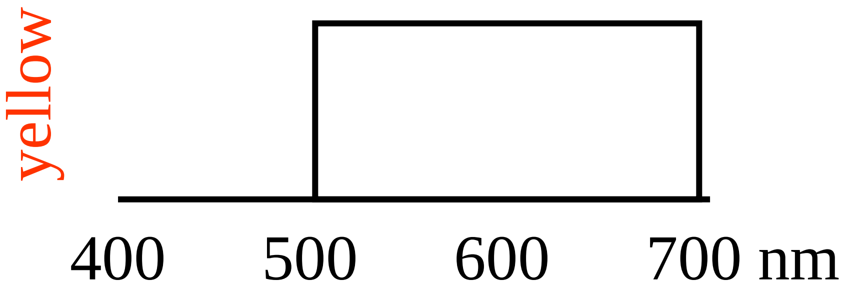


Additive color mixing with red, green, blue primary colors

Additive color mixing



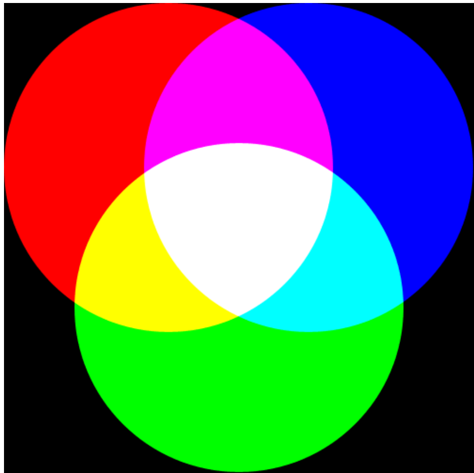




When colors combine by **adding** the color spectra. Example color displays that follow this mixing rule: CRT phosphors, multiple projectors aimed at a screen, Polachrome slide film.

Red and green make…

Yellow!

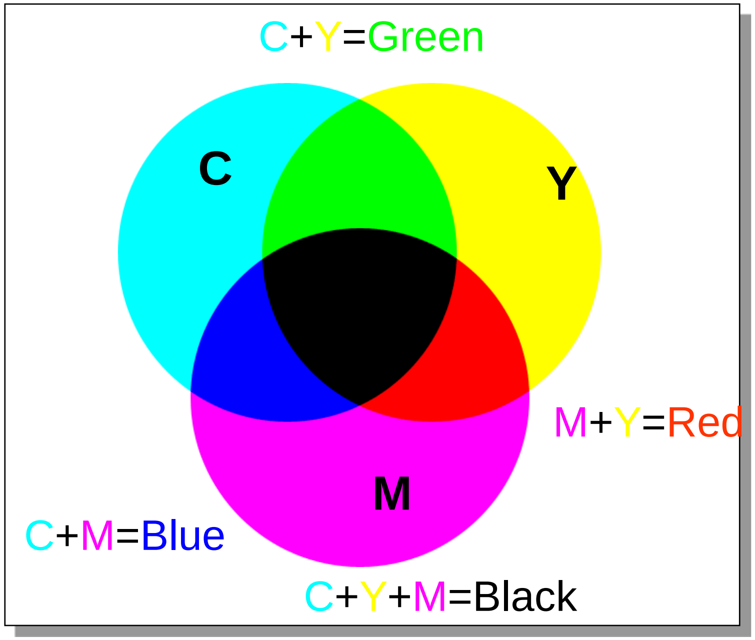


Subtractive Color Mixing

- Subtractive color mixing
  - Employed with paints and pigments
  - Primary colors
    - Yellow – white light subtracts blue (short wavelengths)
    - Magenta – white light subtracts green (middle wavelengths)
    - Cyan – white light subtracts red (long wavelengths)
  - All lights are subtracted - black

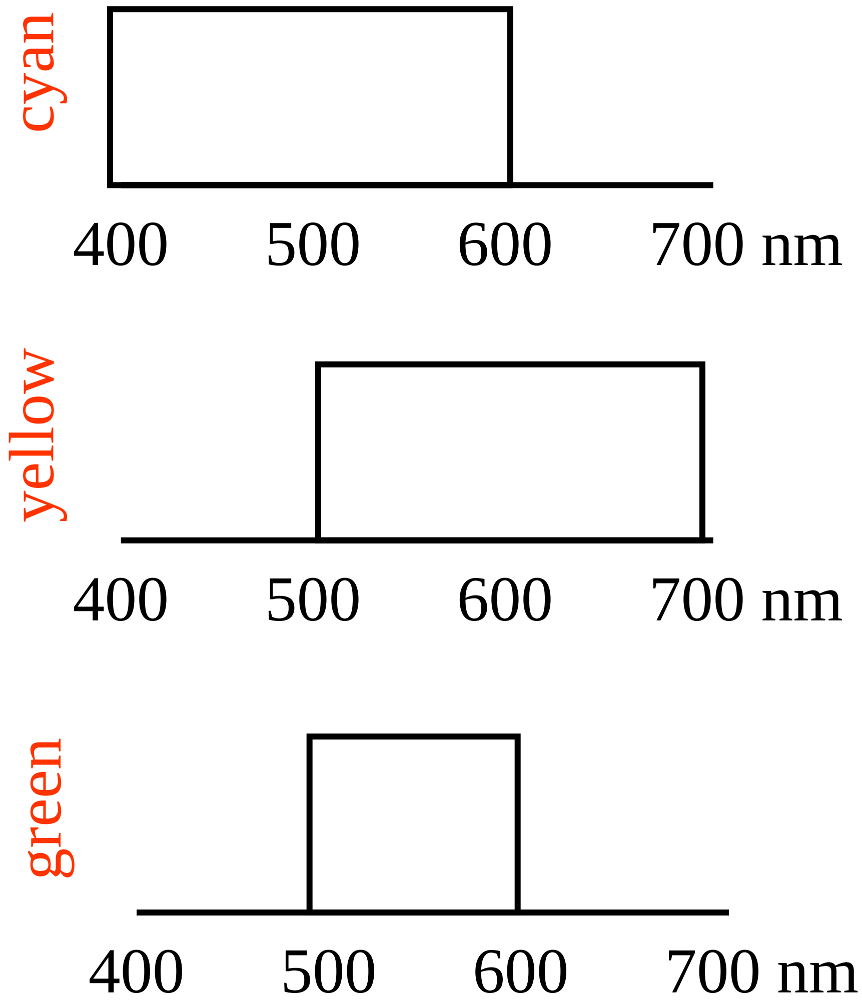
Demo

Ink Color	Absorbs	Reflects	Appears
C	Red light	Green and Blue light	Cyan
M	Green light	Red and Blue light	Magenta
Y	Blue light	Red and Green light	Yellow
M + Y	Green & Blue light	Red light	Red
C + Y	Red and Blue light	Green light	Green
C + M	Red and Green light	Blue light	Blue



Color subtraction with primary filters

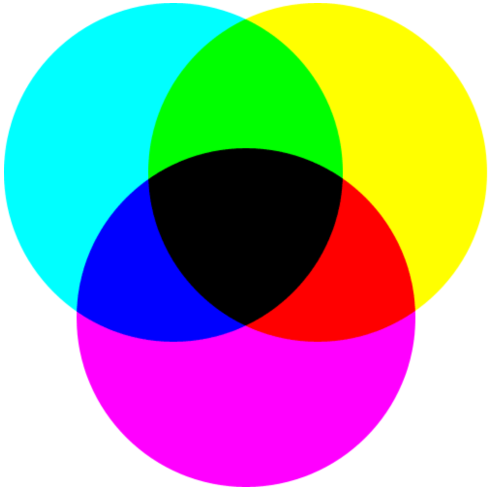
Subtractive color mixing



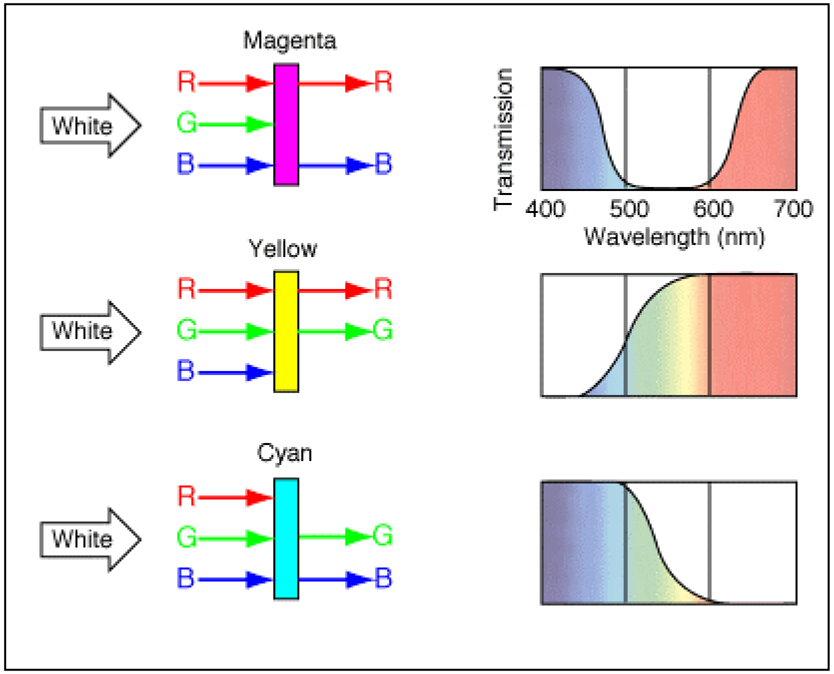
When colors combine by *multiplying* the color spectra. Examples that follow this mixing rule: most photographic films, paint, cascaded optical filters, crayons.

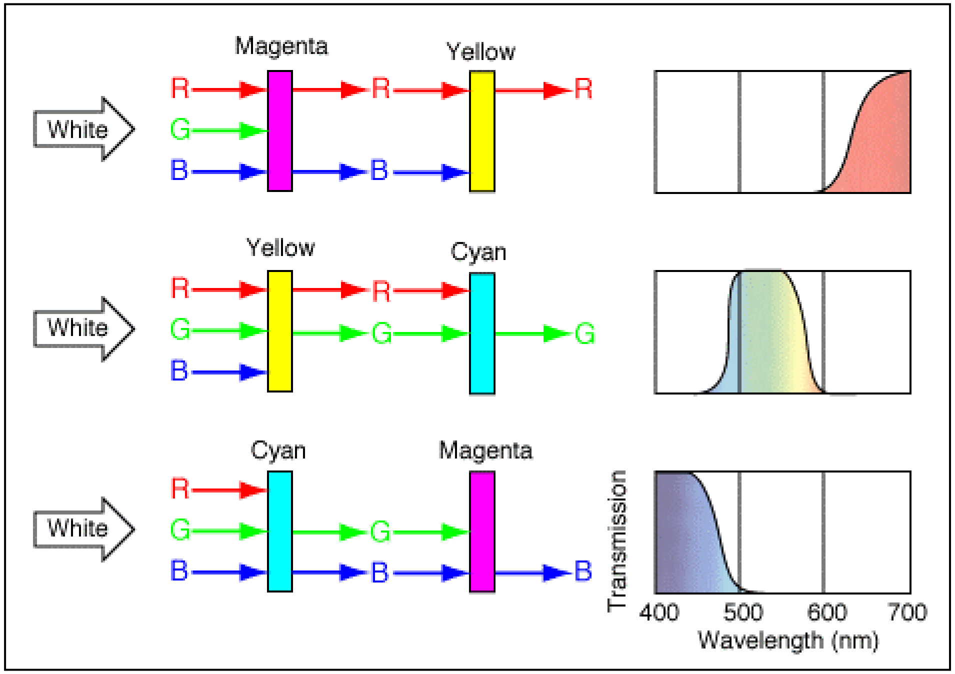
Cyan and yellow (in crayons, called "blue" and yellow) make…

Green!



Subtractive Color Mixing - Example





Illuminate colored filters with white light from behind*

*Image source: *HyperPhysics*

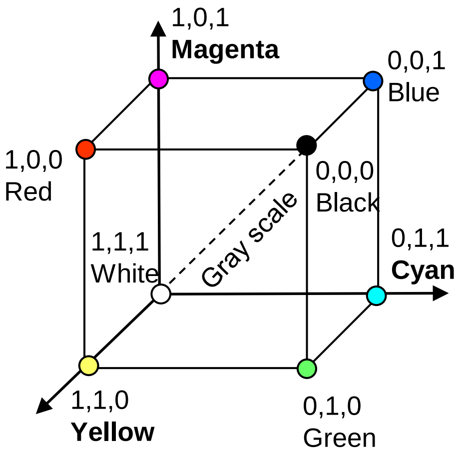
Demo

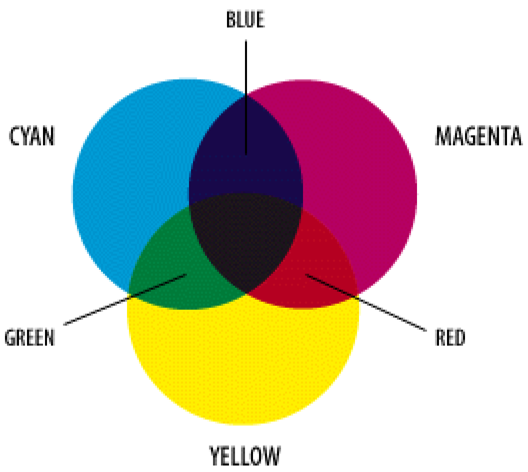
CMY (or CMYK)

- CMY is used for printing (subtractive color mixing)
- CMYK models adds pure black (K) to the mix – a richer black and less ink consumption
- Directly specifying colors in CMY is complicated, but conversion from RGB model is simple
  - Some corrections are required when converting CRT-colors RGB to ink-colors CMY
  - To produce more colors, tricks like halftoning and dithering must be used

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Ideally, CMY model is simply transposition of RGB Model





Color Models (or Spaces)

- Three types of cones suggests color is a 3D quantity
- A color model is a 3D (or N-D) unique representation of a color
- What to use is application oriented
- Example
  - RGB – TV monitors, cameras, computer graphics, etc.
  - CMY (or CMYK) – color printing
  - YIQ / YUV – TV broadcasting

  hardware-oriented

  - HSI / HSV – color image manipulation → user-oriented
  - CIE L*u*v* / CIE L*a*b* – Image retrieval → equal visual variance

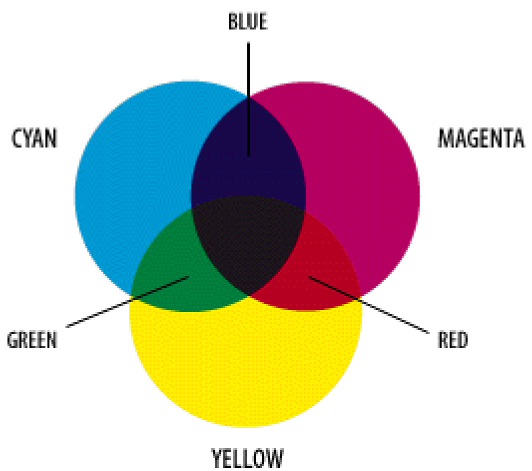
Color Image Halftoning

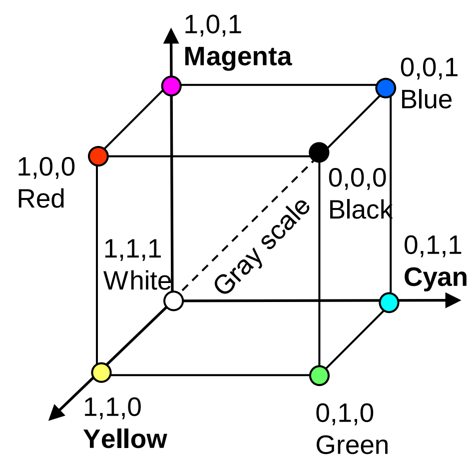
Color Image Halftoning Example

Digital color halftoning: A process that converts from 24bpp to 8 options

Color cartridge: cyan, magenta, yellow (CMY)
Cyan: 0/1 -> one dot of a cyan ink
Magenta: 0/1 -> one dot of a magenta ink
Yellow: 0/1 -> one dot of a yellow ink

CMY (or CMYK) Color Space





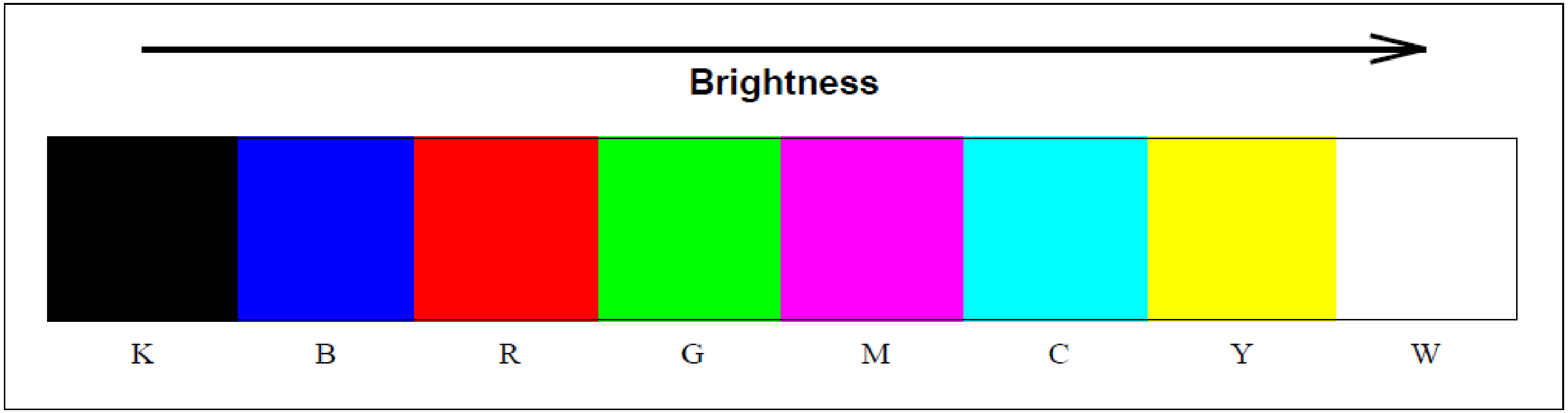
$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

The CMY model is the complementary of the RGB Model

Color Digital Halftoning

- Conversion from the RGB color space to the CMY color space
- Baseline:
  - Perform digital halftoning on C, M, Y channels separately
    - Quantization and error diffusion on C, M, Y channels individually
  - The quality does not look good
  - Why?
- Improvement
  - Minimal Brightness Variation Criterion (MBVC)
    - To reduce halftone noise, select from within all halftone sets by which the desired color may be rendered, the one whose brightness variation is minimal

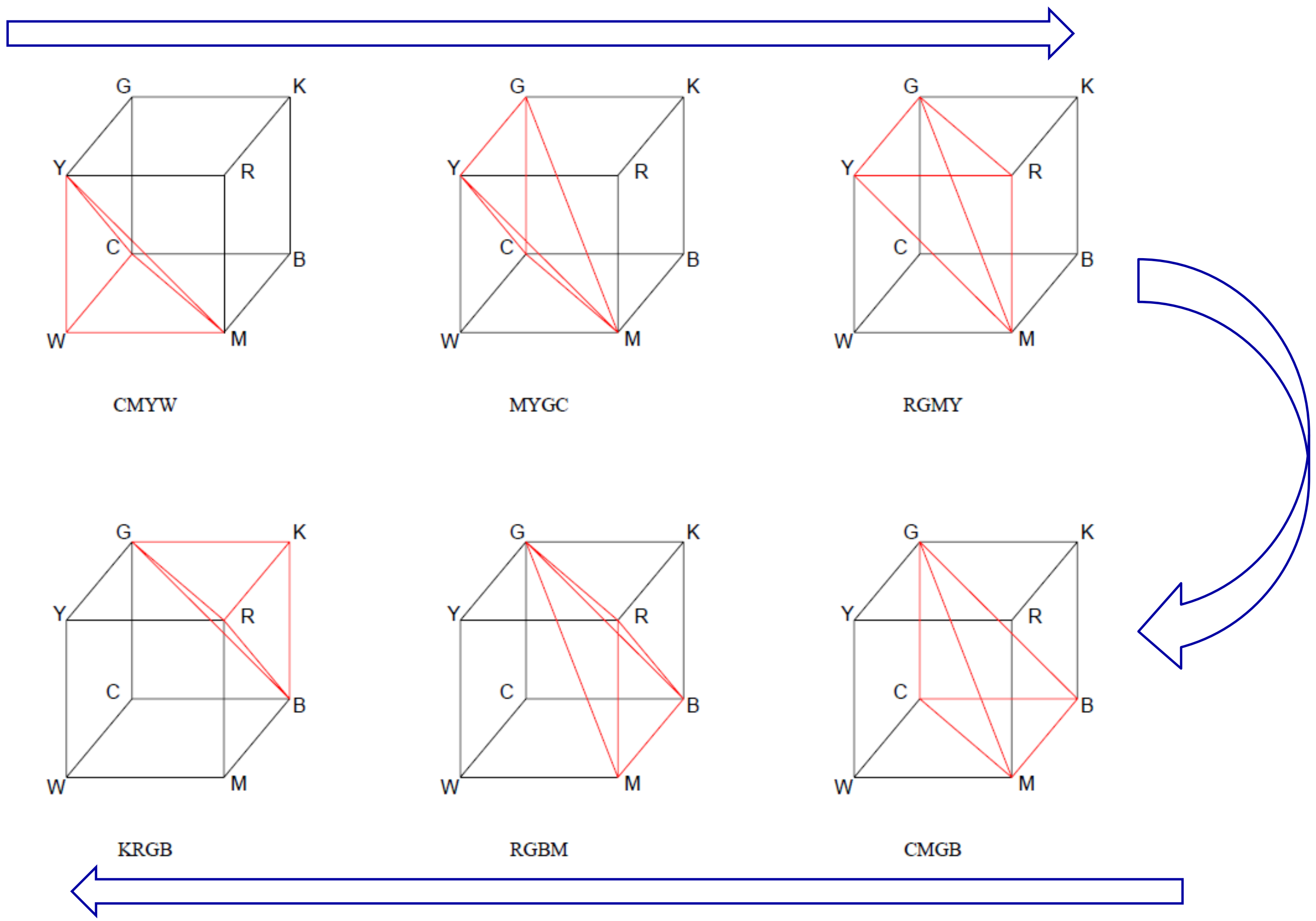
MBVC



The brightness scale of eight basic colors

Color Space Partitioned Into 6 Tetrahedral Volumes

Brightest

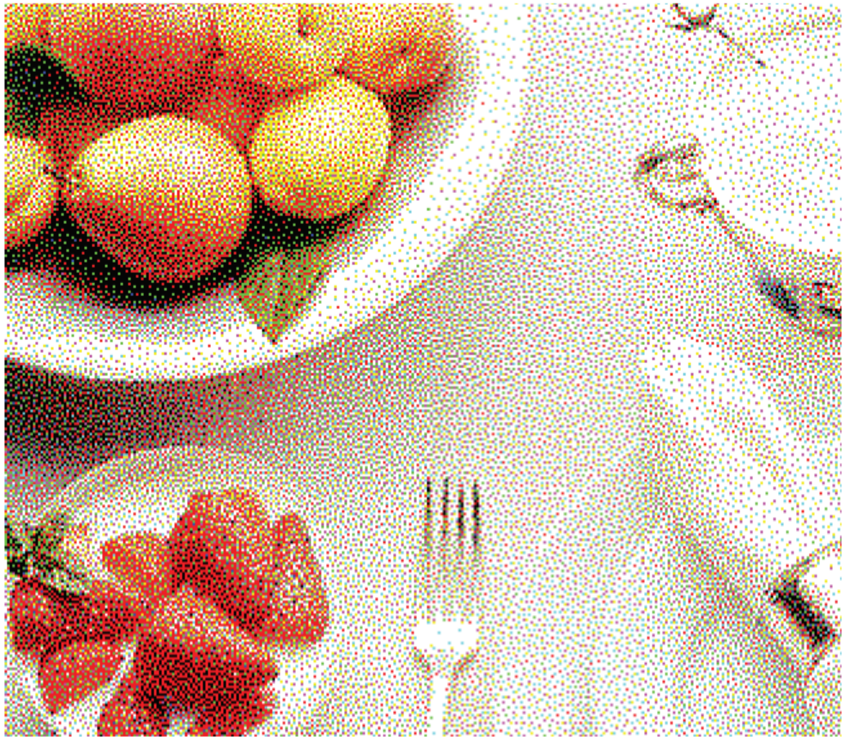


Darkest

MVBC Color Halftoning

- Algorithm
  - Find the corresponding tetrahedral volume for a given pixel
  - Quantize its color to that of its nearest corner
  - Diffuse the error to its neighboring pixels in C, M, Y channels

Another Algorithm: DBS



[FIG7] Halftone generated by the colorant-based DBS algorithm. The image is printed at 100 dpi.

Zoom-In on Strawberries