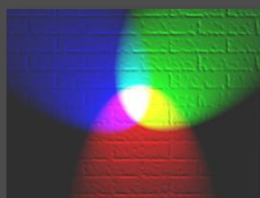
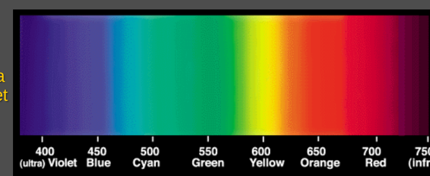
Color Theory



What is Color ?

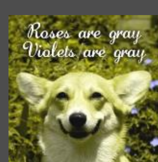
- Physical definition – visible electro-magnetic energy
  - Different wavelength – different color
  - Small portion of the electro-magnetic spectrum
    - Pure *monochromatic* colors
      = wavelengths 390nm (violet) to 750nm (red)

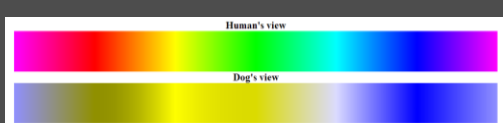


2

How to Represent Color?

- Use the wavelength?
  - Doesn't span all possible colors
  - Hard to generate monochromatic colors
  - Color is a visual **perceptual** property
    - Depends on the observer!

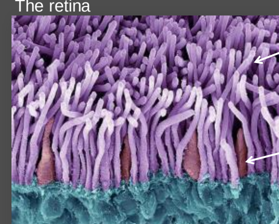




3

Human Color Perception

The retina

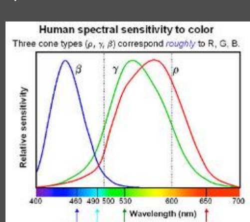


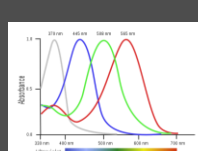
Why are cockpit lights red?

4

Human Color Perception

- Cone is a photoreceptor cell
- Three types of cones: respond to different regions in the spectrum





Bird has 4 types of cones

- Color-blind humans?

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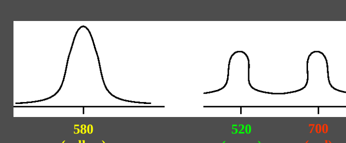
Color Representation

- Can represent colors using a small number of *primaries*



- Same way the retina does

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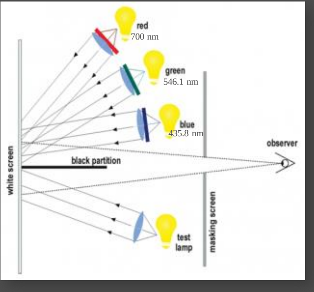
Wright & Guild RGB Experiment



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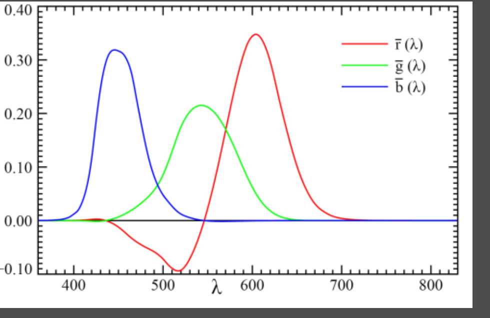
RGB Color Matching Functions



$$\int_0^\infty \bar{r}(\lambda)d\lambda = \int_0^\infty \bar{g}(\lambda)d\lambda = \int_0^\infty \bar{b}(\lambda)d\lambda$$

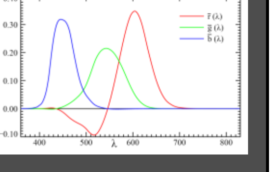
8

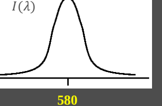
Reproducing a Color

- Given a distribution $I(\lambda)$

  $1 = \int_0^\infty I(\lambda)d\lambda$

- The ***tristimulus values:***
  - $R = \int_0^\infty I(\lambda)\bar{r}(\lambda)$
  - $G = \int_0^\infty I(\lambda)\bar{g}(\lambda)$
  - $B = \int_0^\infty I(\lambda)\bar{b}(\lambda)$





580
(yellow)

9

Some Crayola Colors

- *Black, Brown, Orange, Violet, Blue, Green, Red, Yellow, Blizzard Blue, Laser Lemon, Screamin' Green, Wild Watermelon, Green, Mulberry, Raw Umber, Burnt Orange, Goldenrod, Navy Blue, Sepia, Cadet Blue, Indian Red, Plum, Sky Blue, Apricot, Gold, Orange, Silver, Bittersweet, Gray, Spring Green, Tan, Green Blue, Orchid, Thistle, Blue Green, Green Yellow, Periwinkle, Turquoise Blue, Blue Violet, Lemon Yellow, Pine Green, Violet (Purple), Brick Red, Magenta, Prussian Blue, Violet Blue, Mahogany, Violet Red, Burnt Sienna, Maize, Red Orange, White, Carnation Pink, Maroon, Red Violet, Yellow, Cornflower, Melon, Salmon, Yellow Green, Flesh, Olive Green, Sea Green, Yellow Orange, Asparagus, Macaroni and Cheese, Razzmatazz, Timber Wolf, Cerise, Mauvelous, Robin's Egg Blue, Tropical Rain Forest, Denim, Pacific Blue, Shamrock, Tumbleweed, Granny Smith Apple, Purple Mountain's Majesty, Tickle Me Pink, Wisteria Almond, Canary, Fern, Pink Flamingo, Antique Brass, Caribbean Green, Fuzzy Wuzzy Brown, Purple Heart, Banana Mania, Cotton Candy, Manatee, Shadow, Beaver, Cranberry, Mountain Meadow, Sunset Orange, Blue Bell, Desert Sand, Outer Space, Torch Red, Brink Pink, Eggplant, Pig Pink, Vivid Violet, Electric Lime, Purple Pizzazz, Razzle Dazzle Rose, Unmellow Yellow, Magic Mint, Radical Red, Sunglow, Neon Carrot, Chartreuse, Ultra Blue, Ultra Orange, Ultra Red, Hot Magenta, Ultra Green, Ultra Pink, Ultra Yellow, Atomic Tangerine, Hot Magenta, Outrageous Orange, Shocking Pink*

(252,137,172)

(206,255,29)

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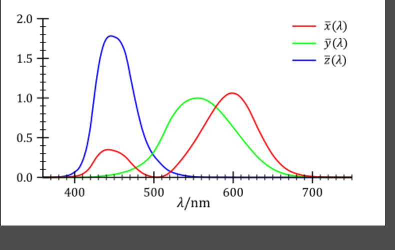
CIE Color Matching Functions



X, Y, Z do not correspond to visible colors !

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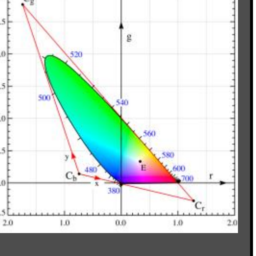
CIE Chromaticity Diagram
(1931)

- Universal standard (**C**ommission **I**nternationale de l'**E**clairage = International Commission on Illumination)

$$r = \frac{R}{R+G+B}$$

$$g = \frac{G}{R+G+B}$$



- What did we lose by normalizing?
- What colors are not in the diagram?

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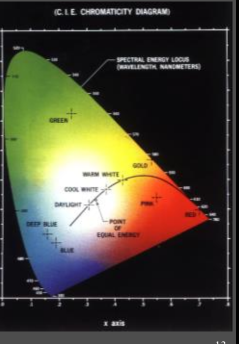
CIE Chromaticity Diagram
(1931)

- Linear transformation from rg space to xy space so that visible region is inside simplex and white is (1/3,1/3).
- Visible colors contained in horse-shoe region
- Pure colors (*hues*) located on boundary of the region



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The CIE Diagram

- Color "white" is point W=(1/3,1/3)
- Any visible color C is blend of a hue C' and W
- Purity of color measured by its *saturation*:

$$\text{saturation}(C) = \frac{d_1}{d_1 + d_2}$$

- When does Saturation(C) = 1? =0 ?
- *Complement* of C is (the unique) other hue D on line through C' and W
- Any line through W defines complementary colors

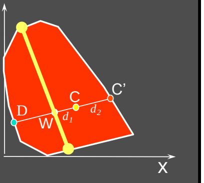

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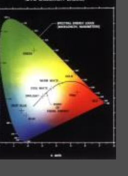
Image Enhancement



- Increase the saturation of the colors
- Move them towards the boundary of the visible region


unsaturated


saturated

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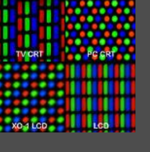
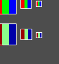
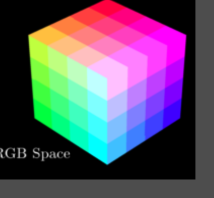
The RGB Color Model

- Common in describing *emissive* color displays
- Primaries are Red, Green and Blue
- Color (including intensity) described as combination of primaries







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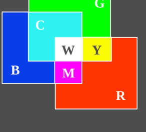
The RGB Color Model



Lighthouse demo

Col = rR + gG + bB *r,g,b*∈[0, 1]

- Yellow = Red+Green (1, 1, 0)
- Cyan = Green+Blue (0, 1, 1)
- Magenta = Red+Blue (1, 0, 1)
- White = Red+Green+Blue (1, 1, 1)
- Gray = 0.5 Red+0.5 Blue+0.5 Green (0.5, 0.5, 0.5)
- Main diagonal of RGB cube represents shades of gray

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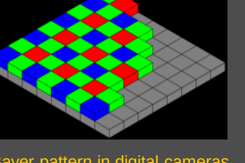
RGB Sensors


Bayer pattern in digital cameras

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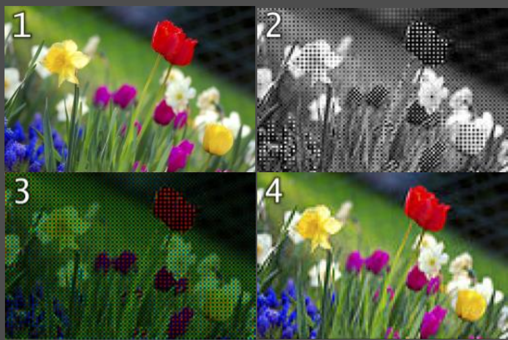
Demosaicing



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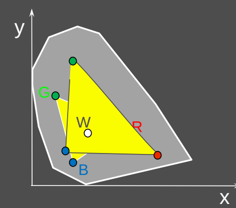
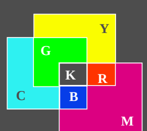
Color Gamuts

- Not every color output device is capable of generating all the visible colors in the CIE diagram
- Usually a color is generated as a *convex* combination of three *primaries* R,G,B
- The possible colors are bounded by a triangle (the *gamut*) in XYZ space, whose vertices are R,G,B
- Different devices have different gamuts



The CMY Color Model

- Used mainly in color printing, where the primary colors are subtracted from the background white.
- Cyan, Magenta and Yellow primaries are the complements of Red, Green and Blue
- Primaries (dyes) subtracted from white paper which absorbs no energy
  - Red = White-Cyan = White-Green-Blue (0, 1, 1)
  - Green = White-Magenta = White-Red-Blue (1, 0, 1)
  - Blue = White-Yellow = White-Red-Green (1, 1, 0)
  - (r,g,b) = (1-c,1-m,1-y)



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color separation without black

color separation with black

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The YIQ Color Model

- Human eye more sensitive to changes in luminance (intensity) than to changes in hue or saturation
- Luminance useful for displaying grayscale version of color signal (e.g. B&W TV)
- Luminance Y – affine combination of R,G,B
- I & Q – null blend (zero sum) of R,G,B
- Conversion

$$(y,i,q)=(r,g,b)\begin{bmatrix}0.30 & 0.60 & 0.21\\ 0.59 & -0.28 & -0.52\\ 0.11 & -0.32 & 0.31\end{bmatrix}$$

- Green component dominates luminance value

Y∈[0,1]

I∈[-0.6,0.6]

Q∈[-0.52,0.52]

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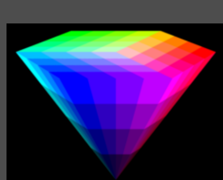
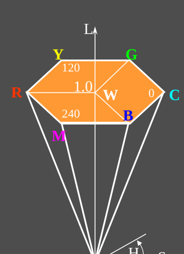
The HSL Color Model

- People naturally mix colors based on Hue, Saturation and Luminance
- Resulting coordinate system is cylindrical
- H – angle around axis
- S ∈ [0,1] – distance from axis
- L ∈ [0,1] – distance from apex





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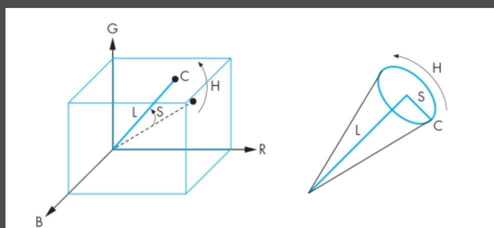
RGB to HSL



- L – lightness, distance from black
- S – Saturation, distance from diagonal
- H – Hue, direction where vector is pointing
- RGB to HSV

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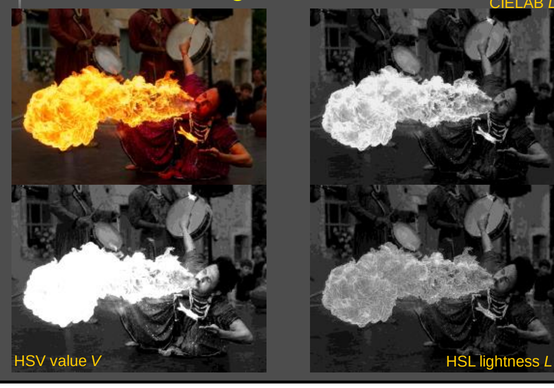
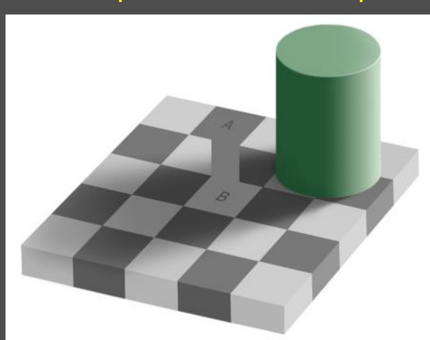
The Lightness Value



The Importance of Perception



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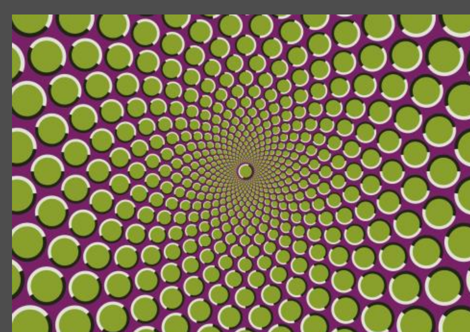
The Importance of Perception



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The Importance of Perception

- Spinning dancer

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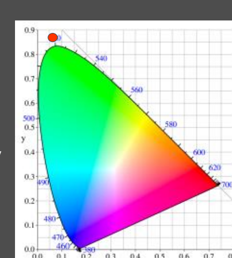
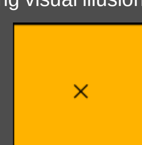
Impossible Colors

- What are the "colors" outside the range?
  - Colors that cannot be seen normally by the human eye
  - E.g. hyper saturated
- Can be "seen" temporarily by using visual illusions





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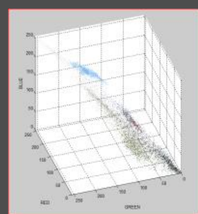
Color Quantization

Most images do not cover all of 24-bit RGB space

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Indexed Color

Replace (R,G,B) values with an index to a color table

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Color Quantization
Applications

- Displays with limited color resolution

ZX Spectrum (1988)
1-bit color for 8x8 blocks


These days - Embedded displays

- Image compression

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Color Quantization

256 colors

64 colors

16 colors

4 colors

Lighthouse demo

34

Color Quantization

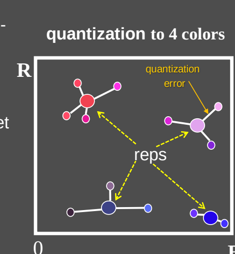
True color = 24bpp

256 colors = 8bpp

35

Color Quantization

- High-quality color resolution for images - 8 bits per primary = 24 bits = 16.7M different colors
- Reduce number of colors – select subset (colormap/pallete) and map all colors to this subset of *representatives*
- Used for devices capable of displaying limited number of different colors simultaneously. E.g. an 8 bit display.



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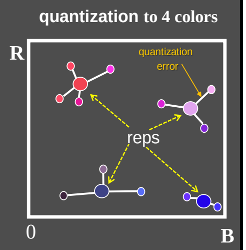
Color Quantization Issues

- How are the representative colors chosen?
  - Fixed representatives, image independent - fast
  - Image content dependent - slow
- Which image colors are mapped to which representatives?
  - Nearest representative - slow
  - By space partitioning - fast



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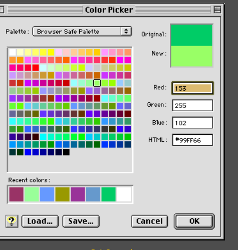
Standard Color Palettes



216 colors

16 colors

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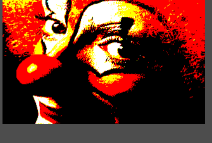
Color Quantization

256 colors



uniform

median-cut

8 colors

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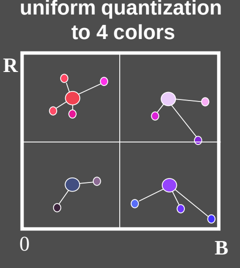
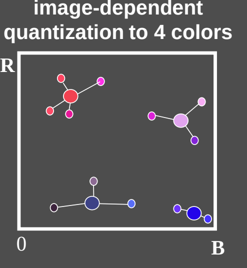
Choosing the Representatives



large *quantization error*

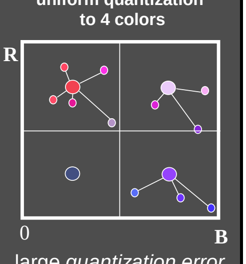


small *quantization error*

40

Uniform Quantization

- Fixed representatives - lattice structure on RGB cube
- Image independent - no need to analyze input image
- Some representatives may be wasted
- Fast mapping to representatives by discarding least significant bits of each component



large *quantization error*

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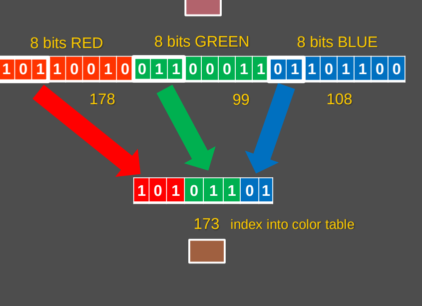
Uniform Quantization



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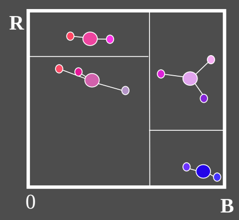
Median-Cut Quantization

- Image colors partitioned into *n* cells, s.t. each cell contains approximately same number of image colors
- Recursive algorithm
- Image representatives - centroids of image colors in each cell
- Image color mapped to rep. of containing cell
  - not necessarily nearest representative (example?)

image-dependent quantization to 4 colors



small *quantization error*

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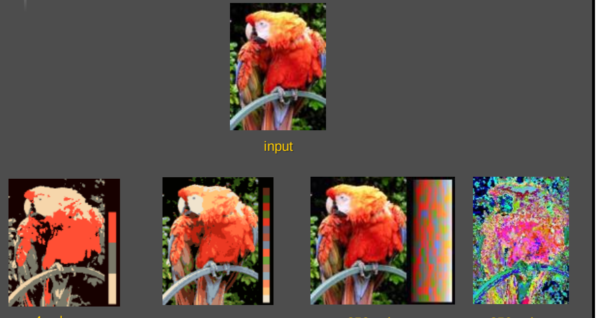
Median-Cut Quantization



input

4 colors | 16 colors | 256 colors | 256 colors (wrong palette)

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Dithering

- Newspapers have only 1 bit per color, black or white. How do they display shades of gray?

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Binary Dithering

- Improve quality of quantized image by distributing quantization error

original | threshold | dithered

46

Binary Dithering – B&W

- Threshold – map upper half of gray-level scale to white and lower half to black

If $I(i,j) > \frac{1}{2}$
$I(i,j) = 1;$
else
$I(i,j) = 0;$

- Each pixel produces some quantization error
- Distribute quantization error – use local threshold
- Use matrix of thresholds for each $n \times n$ pixels

If $I(i,j) > M(i \bmod n, j \bmod n)$
$I(i,j) = 1$
else
$I(i,j) = 0$
end;

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Ordered Dither Matrix

- For four level input use 2×2 matrix

$\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$ threshold $\quad \begin{bmatrix} 0 & 2 \\ 3 & 1 \end{bmatrix}$ dither

- For 16 level input 4×4 matrix

$$\begin{bmatrix} 0 & 8 & 2 & 10 \\ 12 & 4 & 14 & 6 \\ 3 & 11 & 1 & 9 \\ 15 & 7 & 13 & 5 \end{bmatrix}$$

- Can be generalized recursively to $2^k \times 2^k$ matrix

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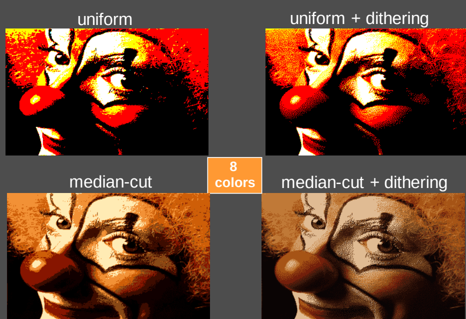
Quantization + Dithering



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Error Diffusion

- Reduce quantization error by propagating accumulated error from pixel to (some of) its neighbors
  - in scanline order before thresholding


```
FloydSteinberg(I)
For x := 1 to XMax do
  For y := 1 to YMax do
    err := I(x,y)-(I(x,y)>128)*256;
    I(x,y) := (I(x,y)>128)*256;
    I(x+1,y)    := I(x+1,y)+err*7/16;
    I(x-1,y+1) := I(x-1,y)+err*3/16;
    I(x,y+1)    := I(x,y+1)+err*5/16;
    I(x+1,y+1) := I(x+1,y+1)+err*1/16;
  end
end
```


error-diffusion

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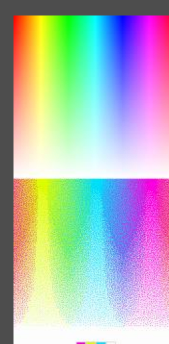
Error Diffusion (cont'd)



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