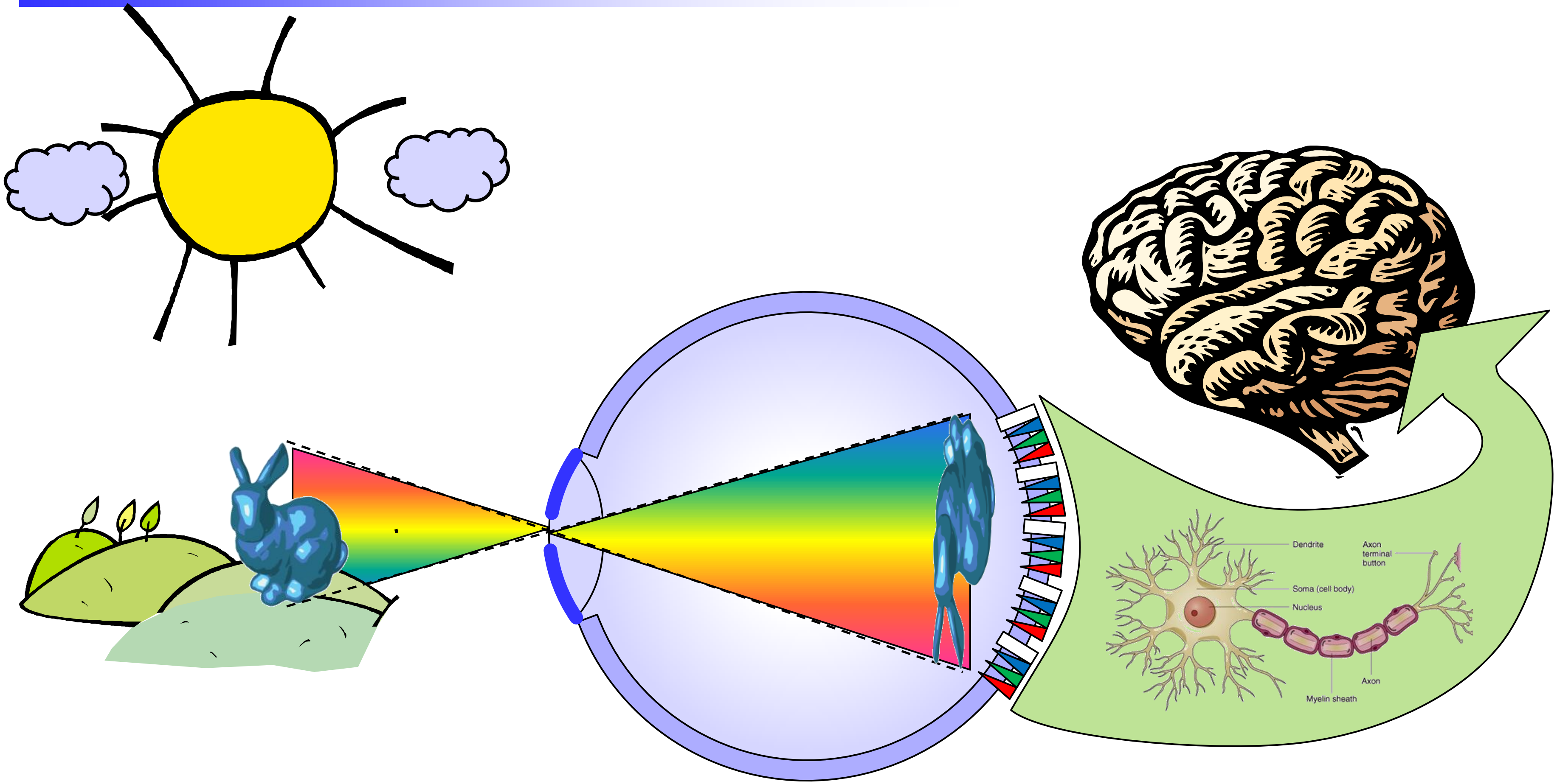
Color

John C. Hart

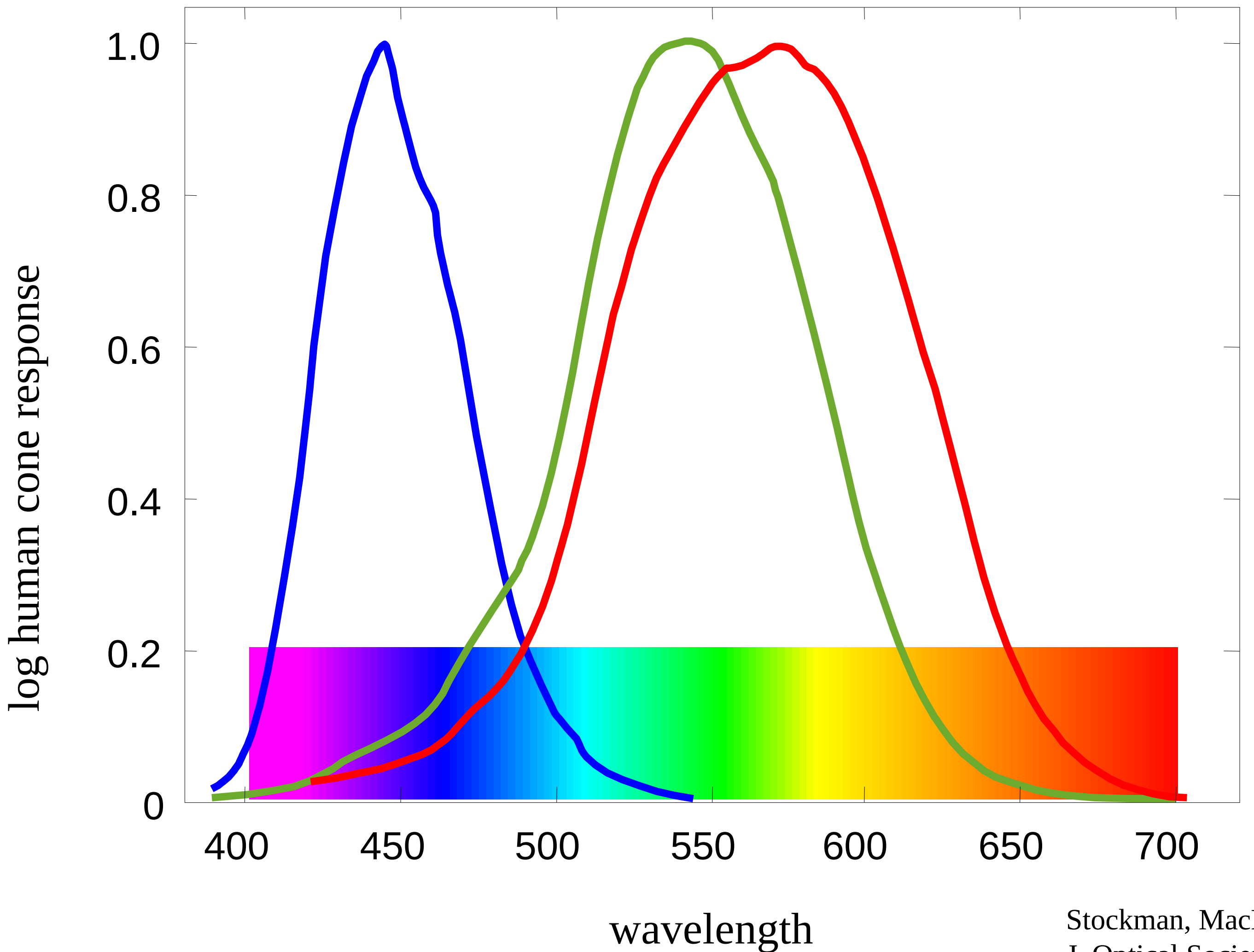
CS 418

Intro to Computer Graphics

Light Spectrum

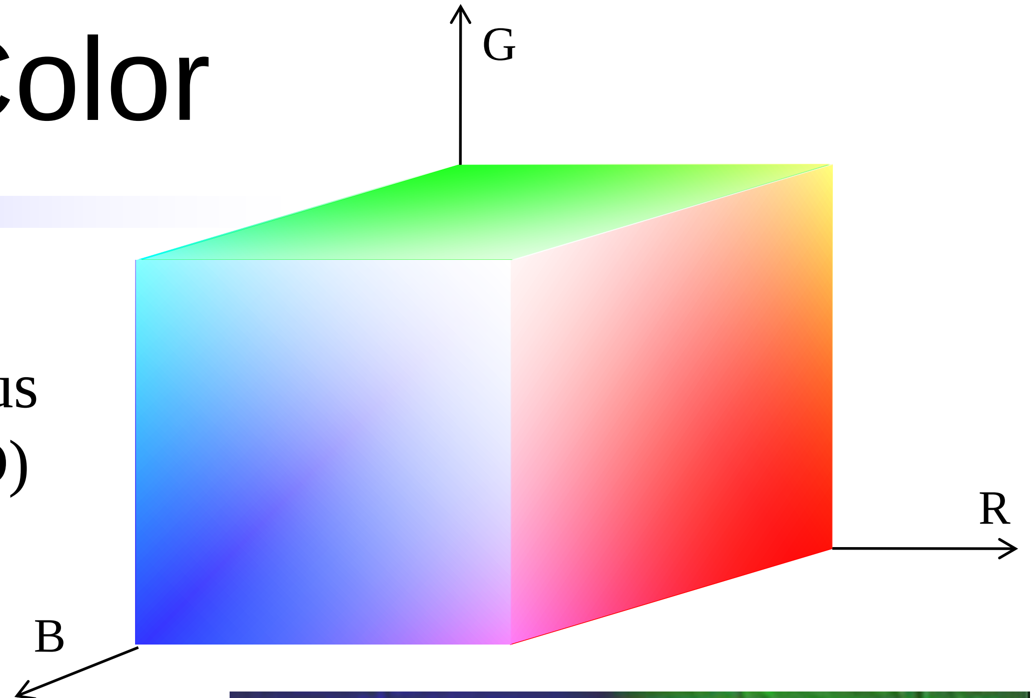


Cone Response

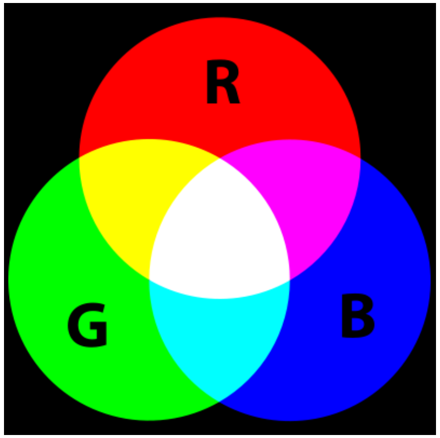


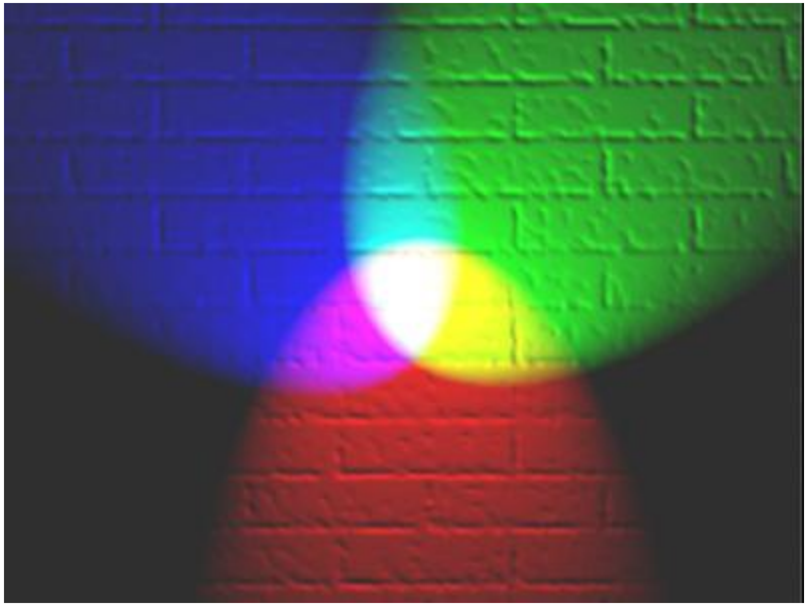
Stockman, MacLeod & Johnson (1993)
J. Optical Society of America A, 10,
2491-2521, via Wikipedia

RGB Additive Color



- Red, Green, Blue
- Color model used in luminous displays (CRT, plasma, LCD)
- Physically linear
- Perceptually logarithmic
- Additive
- Designed to stimulate each kind of cone





Geoff Martin

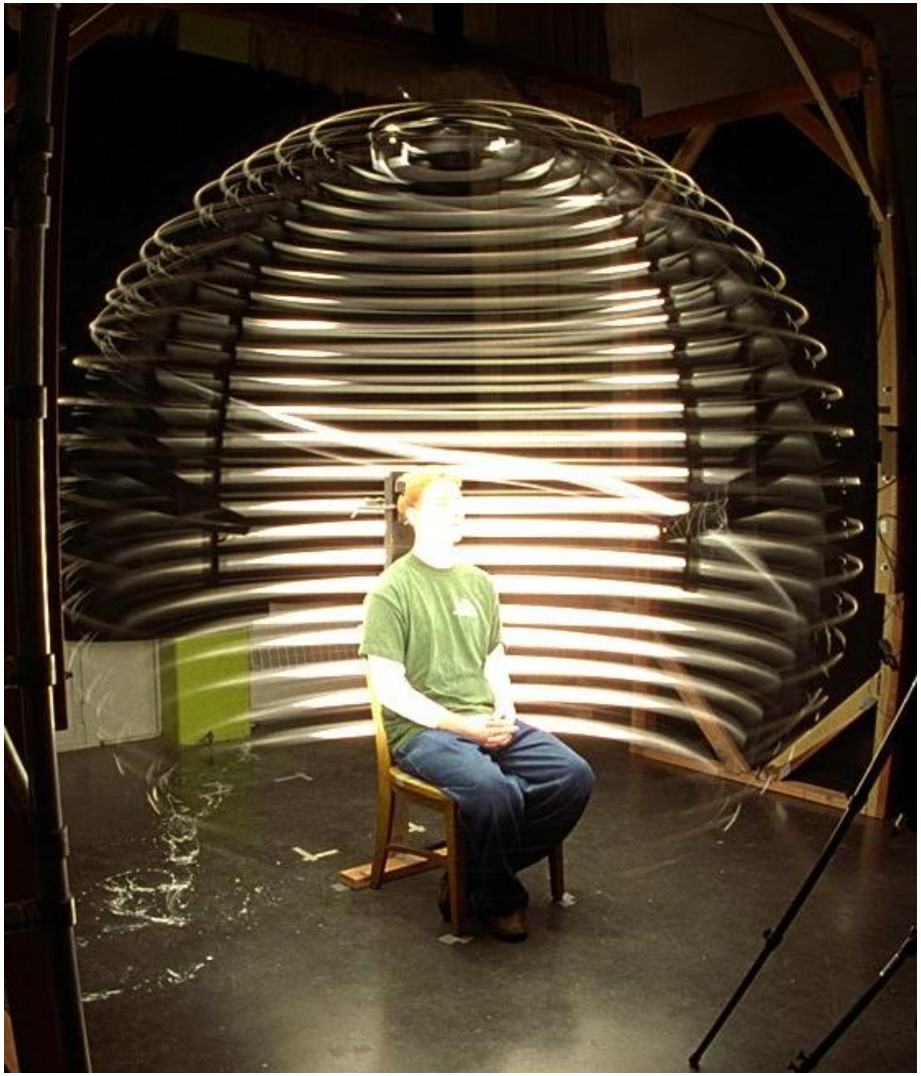
Light Adds

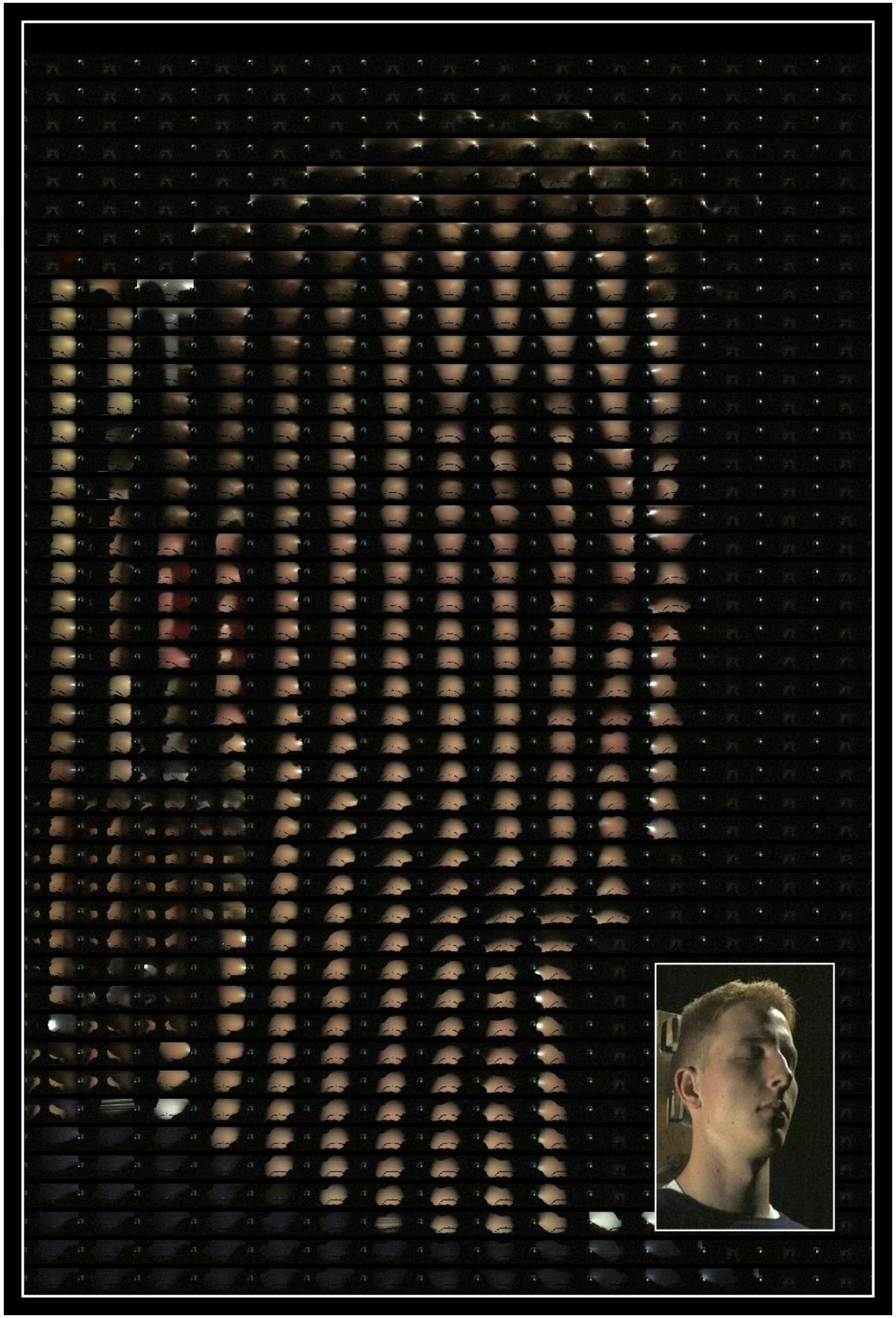
$$R(L_1) + R(L_2) = R(L_1 + L_2)$$

+

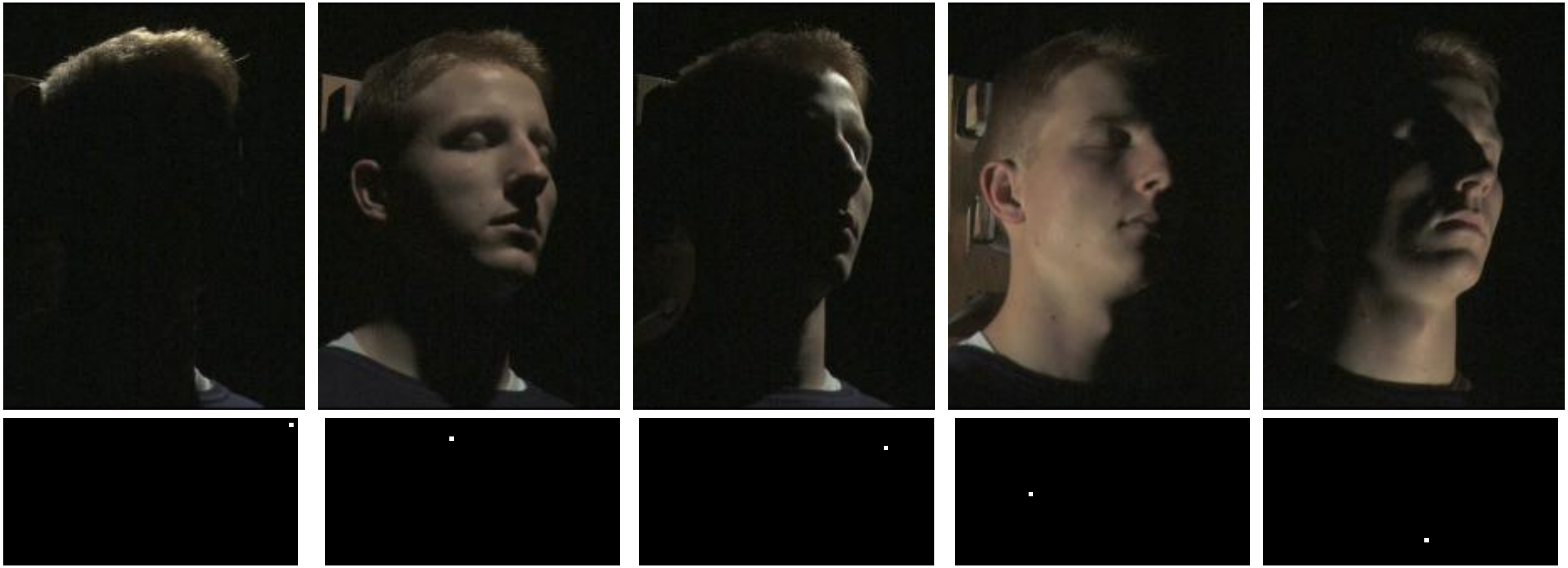
=

Light Stage





Point Light Sources

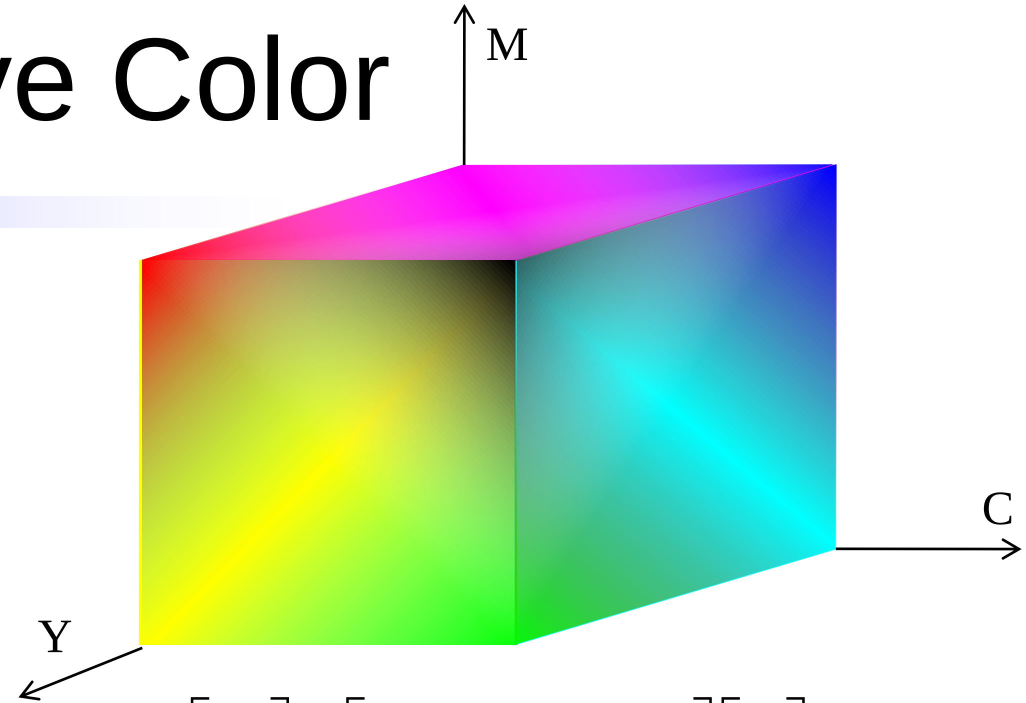


Debevec et al., Acquiring the Reflectance Field of a Human Face, Proc. SIGGRAPH 2000

Environment Lighting

Debevec et al., Acquiring the Reflectance Field of a Human Face, Proc. SIGGRAPH 2000

CMY Subtractive Color



- Cyan, Magenta, Yellow
- Color model used in pigments and reflective materials (ink,paint)
- Grade school color rules

  Blue + Yellow = Green?

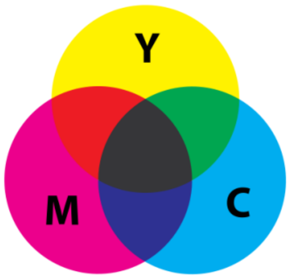
  Cyan + Yellow = Green
- Also CMYK (blacK)

  C + M + Y = Brown?

  C + M + Y = Black (in theory)

  C + M + Y = Gray (in practice)

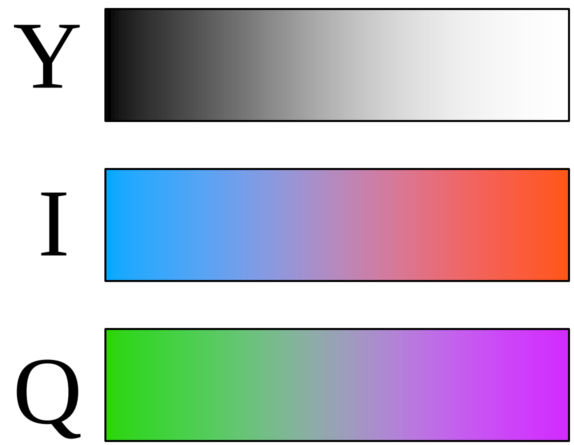
$$\begin{bmatrix} C \\ M \\ Y \\ 1 \end{bmatrix} = \begin{bmatrix} -1 & & & 1 \\ & -1 & & 1 \\ & & -1 & 1 \\ & & & 1 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \\ 1 \end{bmatrix}$$



$$\begin{bmatrix} C \\ M \\ Y \\ K \end{bmatrix} = \begin{bmatrix} 1 & & & -\min(C,M,Y) \\ & 1 & & -\min(C,M,Y) \\ & & 1 & -\min(C,M,Y) \\ & & & \min(C,M,Y) \end{bmatrix} \begin{bmatrix} C \\ M \\ Y \\ 1 \end{bmatrix}$$

NTSC TV Colors

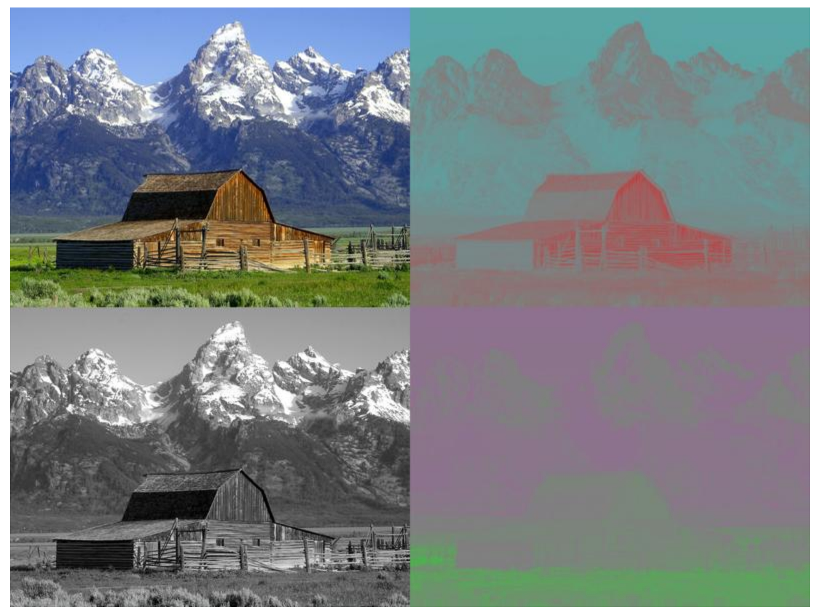
- YIQ
  - Yluminance = 59%G + 30%R + 11%B
  - Intermodulation (or In-Phase)
  - Quadrature
- Flesh tones in I given more bandwidth than Q, but not as much as luminance
- Luminance resolution of NTSC video is about 500 pixels
- Full-color resolution of NTSC video is about 160 pixels (limited by Q's carrier)



$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.595716 & -0.274453 & -0.321263 \\ 0.211456 & -0.522591 & 0.311135 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 0.9563 & 0.6210 \\ 1 & -0.2721 & -0.6474 \\ 1 & -1.1070 & +1.7046 \end{bmatrix} \begin{bmatrix} Y \\ I \\ Q \end{bmatrix}$$

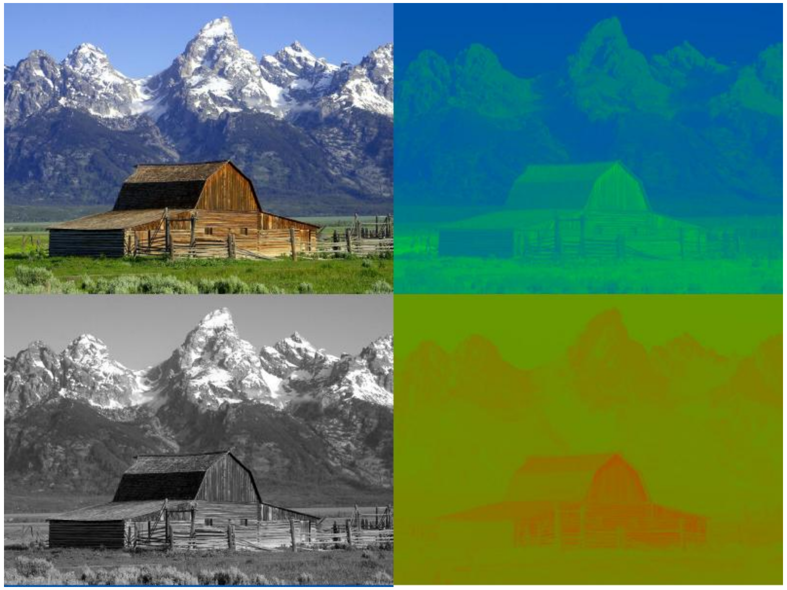
$$R, G, B, Y \in [0,1], \quad I \in [-0.5957, 0.5957], \quad Q \in [-0.5226, 0.5226]$$



Example by Wikipedia user: (3ucky(3all

Digital Video Colors

- YUV
  - yLuminance
  - U ≅ B – Y
  - V ≅ R – Y
- Aka YPbPr (analog) and YCbCr (digital)
- YUV422 transmits pixel pairs with individual luminance but shared chrominance

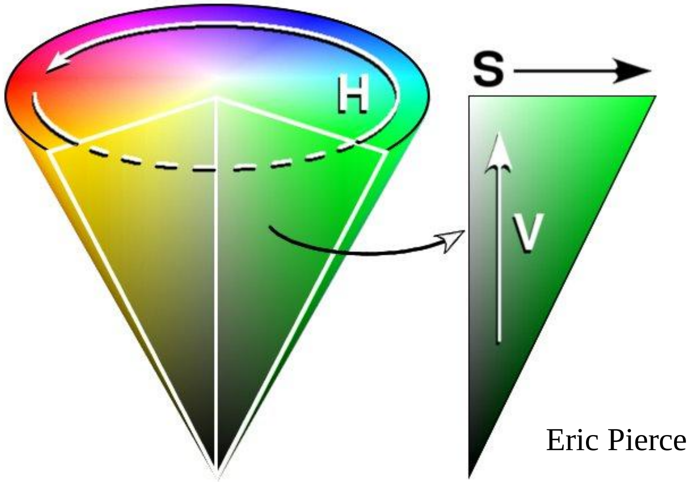


$$Y \in [0,1], \quad U \in [-0.436, 0.436], \quad V \in [-0.615, 0.615]$$

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

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

Selecting Colors



HSV = Hue, Saturation, Value

- 1978, Alvy Ray Smith
- Hue [0,360] is angle about color wheel

  0° = red, 60° = yellow, 120° = green,

  180° = cyan, 240° = blue, 300° = magenta
- Saturation [0,1] is distance from gray

  S = (maxRGB – minRGB)/maxRGB
- Value [0,1] is distance from black

  V = maxRGB

Δ = maxRGB – minRGB

maxRGB = R → H = (G – B)/Δ

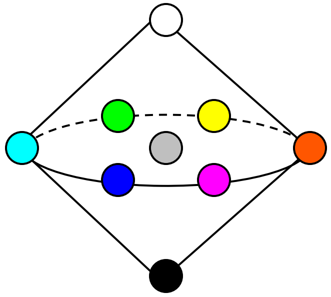
maxRGB = G → H = 2+(B – R)/Δ

maxRGB = B → H =4+ (R – G)/Δ

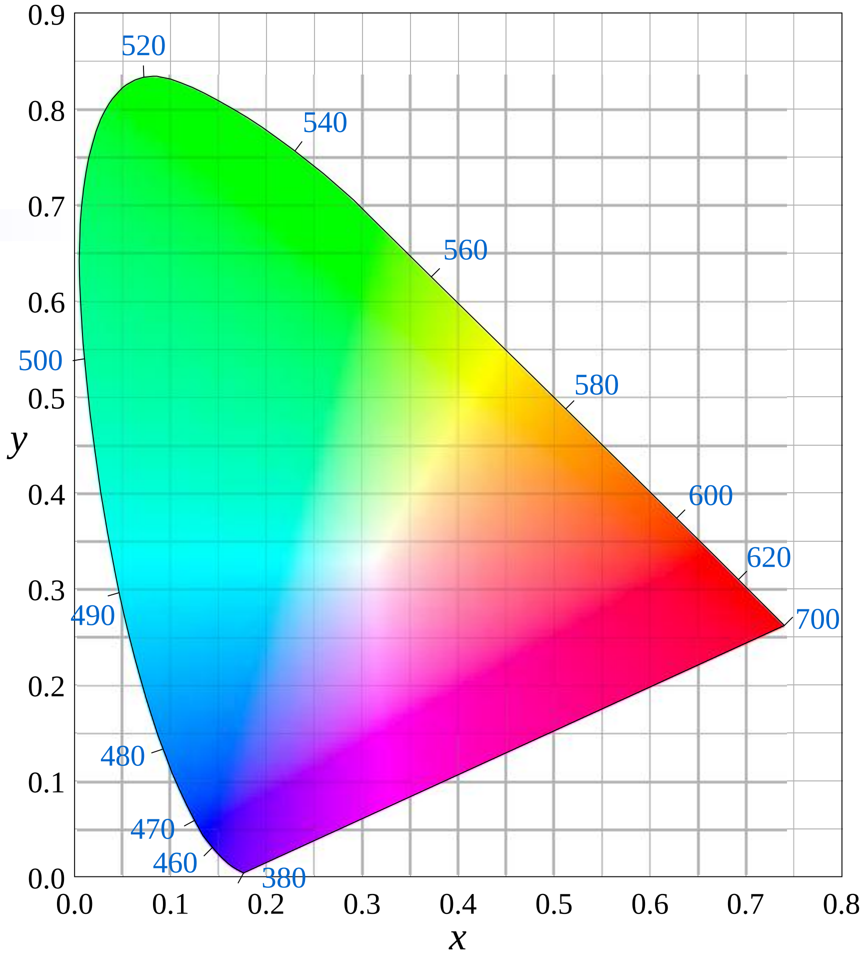
H = (60*H) mod 360

HLS = Hue, Saturation, Lightness

- Double cone, saturation in middle



CIE XYZ



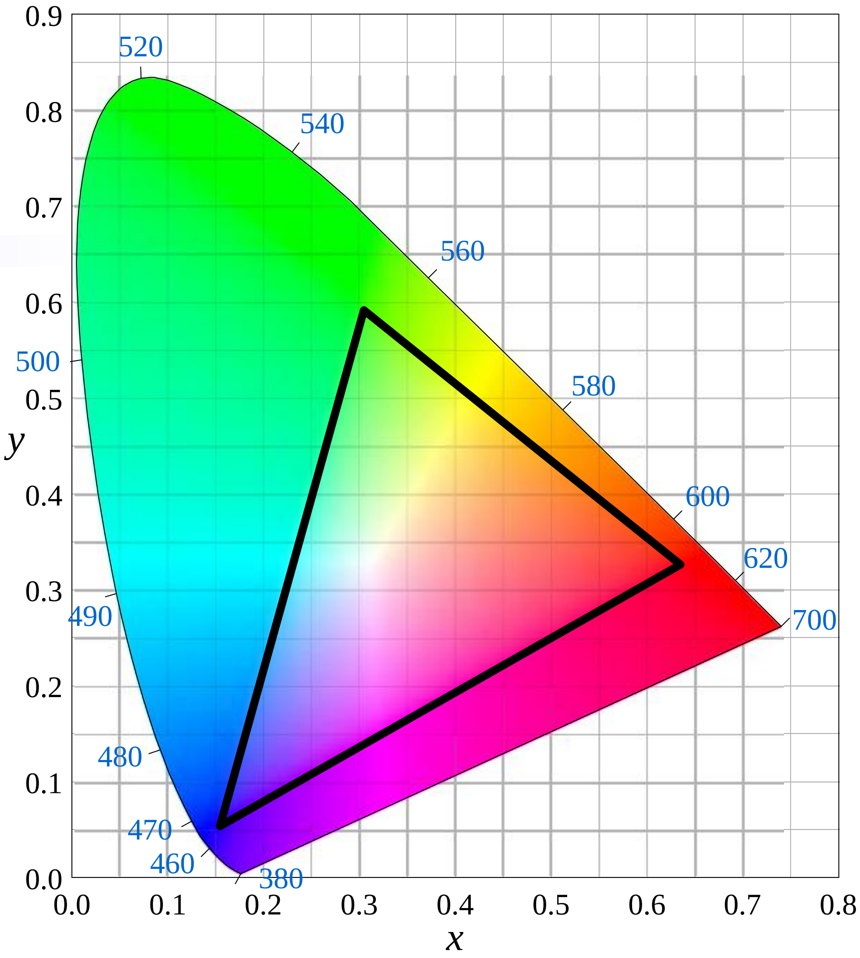
- CIE: International Commission on Illumination
- 3-D space defined by three color-matching functions
  - X ≅ R, Y ≅ G, Z ≅ B
  - Y indicates brightness
- Projected to 2-D using

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

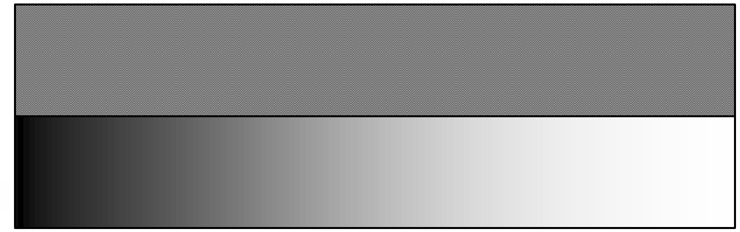
  $y = Y/(X + Y + Z)$
- Perceptually designed
- L,a*,b* space measures perceptual distance between colors

Gamut

- Portion of the spectrum reproduced by a given color space
- TV’s (even HDTV’s) can only display a small portion of perceivable colors
- Printers can display a slightly different portion of colors



Gamma

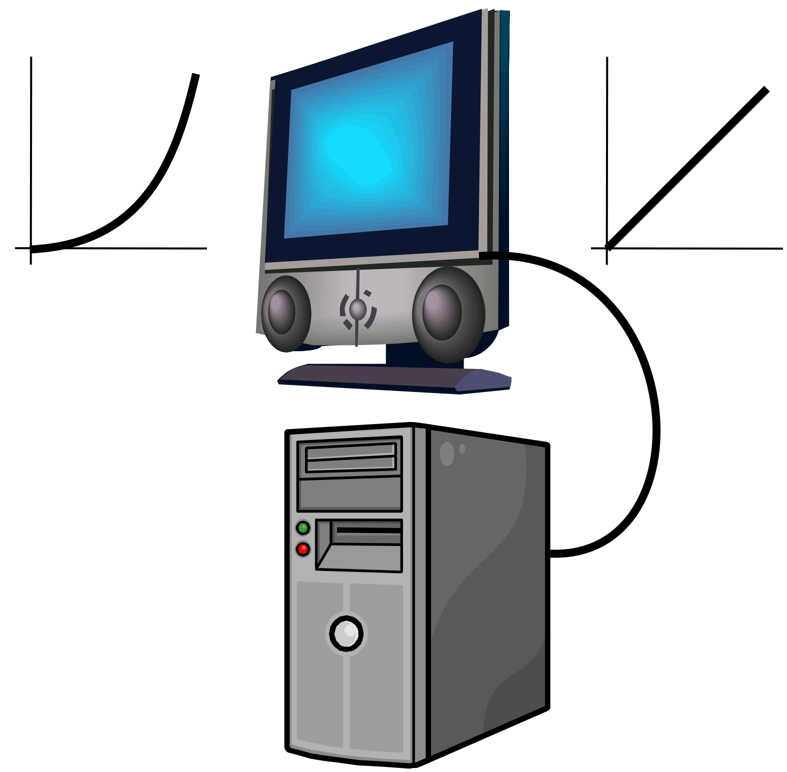


- We perceive differences in intensity more carefully for darker shades
- Monitors accommodate this feature

$$I = cV^{\gamma}$$

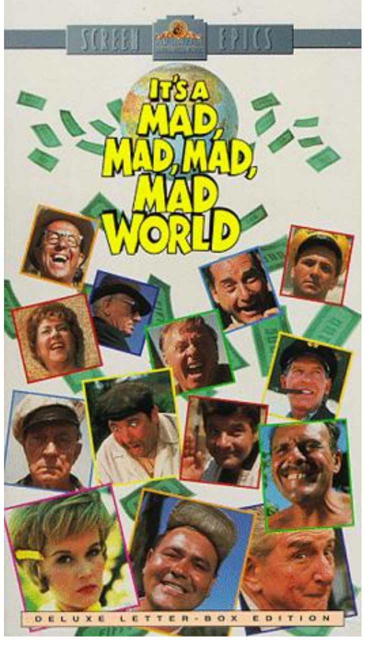
- Gamma usually between 2 and 2.5
- Need to correct pixel values so they display correct intensity

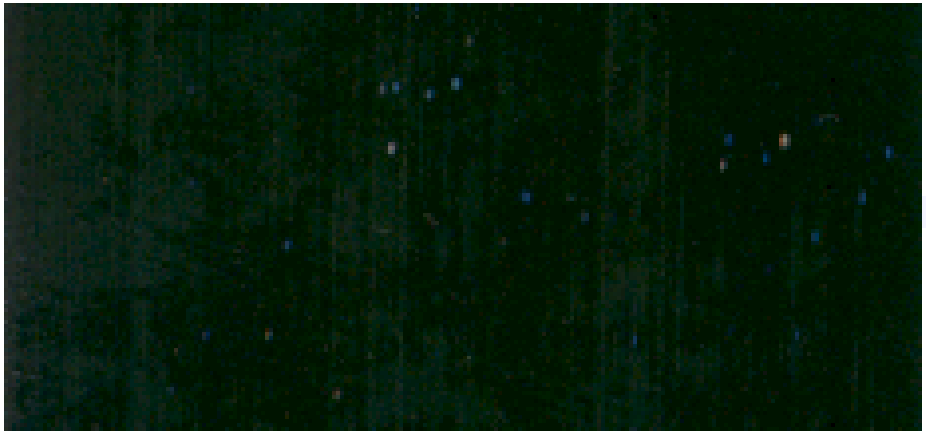
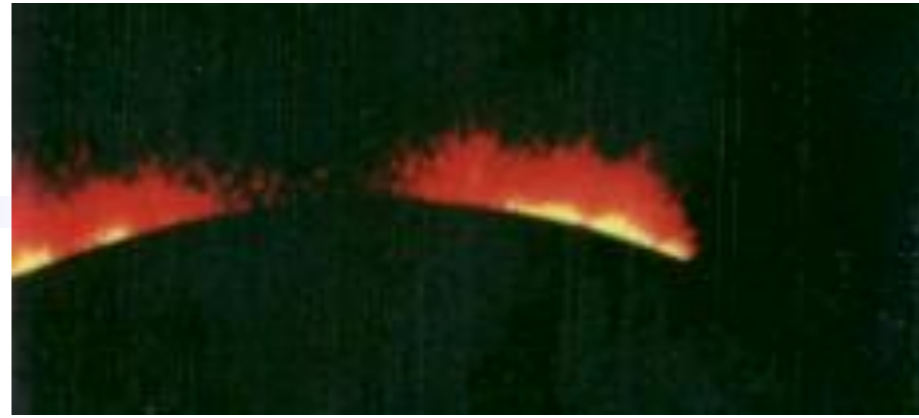
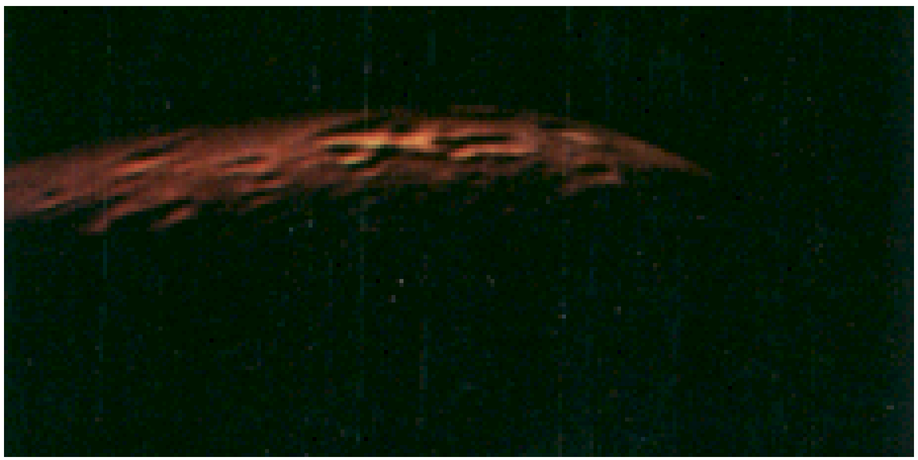
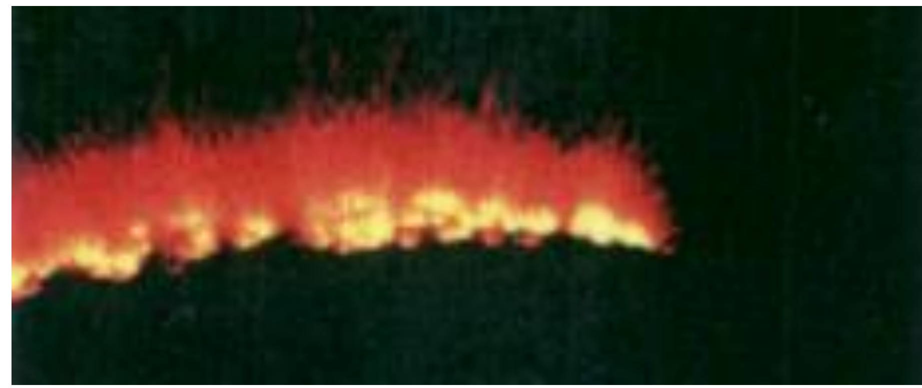
$$\log I = \log c + \gamma \log V$$



Lynwood Dunn (1904-1998)

- Visual effects pioneer
- Acme-Dunn optical printer



Academy of Motion Picture Arts & Sciences
Scientific and Engineering Award
To Alvy Ray Smith, Tom Duff, Ed Catmull and Thomas Porter
for their Pioneering Inventions in Digital Image
COMPOSITING.
PRESENTED MARCH 2, 1996

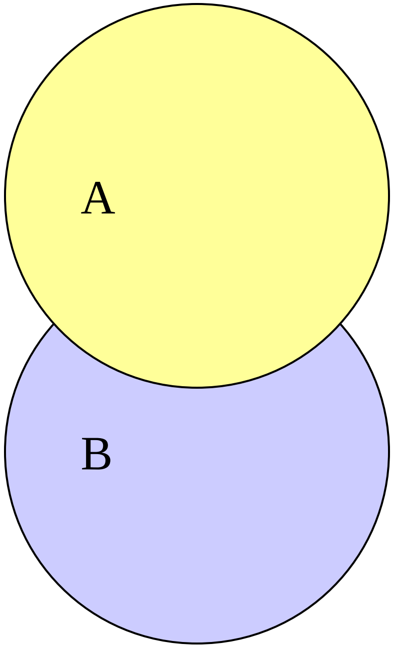
The Over Operator

- How to indicate which parts of front picture are clear and which are opaque
- Use alpha channel to indicate opacity [Smith]
- Over operator [Porter & Duff S'84]
- *A* over *B*:

$$C_{A \text{ over } B} = \alpha_A C_A + (1 - \alpha_A)\, \alpha_B C_B$$
$$\alpha_{A \text{ over } B} = \alpha_A + (1 - \alpha_A)\, \alpha_B$$

- Note that $\alpha_A C_A$ used in color equations, so store $\alpha_A C_A$ instead of C_A
- *A* over *B* w/premultiplied alpha

$$C_{A \text{ over } B} = C_A + (1 - \alpha_A)\, C_B$$
$$\alpha_{A \text{ over } B} = \alpha_A + (1 - \alpha_A)\, \alpha_B$$



$$C = (\alpha R\ \alpha G\ \alpha B\ \alpha)$$

Is Over Transitive?

- A over (B over C)

  $= C_A + (1-\alpha_A)(C_B + (1-\alpha_B)C_C)$

  $= C_A + (1-\alpha_A)C_B + (1-\alpha_A)(1-\alpha_B)C_C$

  $= C_{AB} + (1 - \alpha_A - (1-\alpha_A)\alpha_B)C_C$

  $= C_{AB} + (1-\alpha_{AB})\, C_C$

  $= (A$ over $B)$ over C

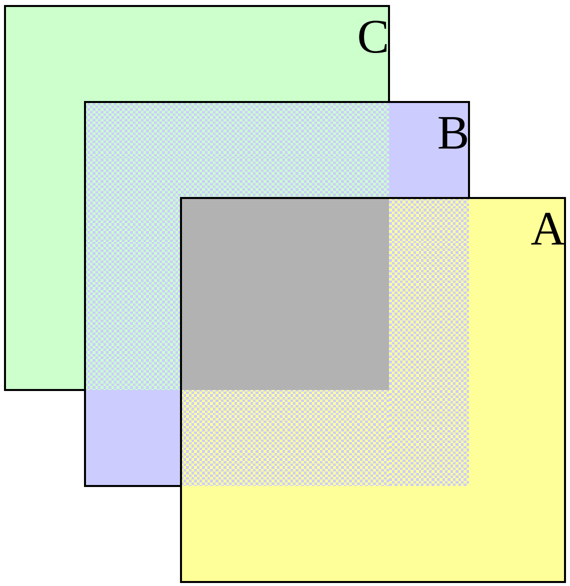
- What about α

  $= \alpha_A + (1-\alpha_A)\, \alpha_{BC}$

  $= \alpha_A + (1-\alpha_A)(\alpha_B + (1-\alpha_B)\, \alpha_C)$

  $= \alpha_A + (1-\alpha_A)\alpha_B + (1-\alpha_A)(1-\alpha_B)\alpha_C$

  $= \alpha_{AB} + (1-\alpha_{AB})\alpha_C$



Accumulating Opacity

- Depends on order of accumulation
- Back to front
  - Over operator

$$C_{out} = \alpha\, C + (1 - \alpha)\, C_{in}$$

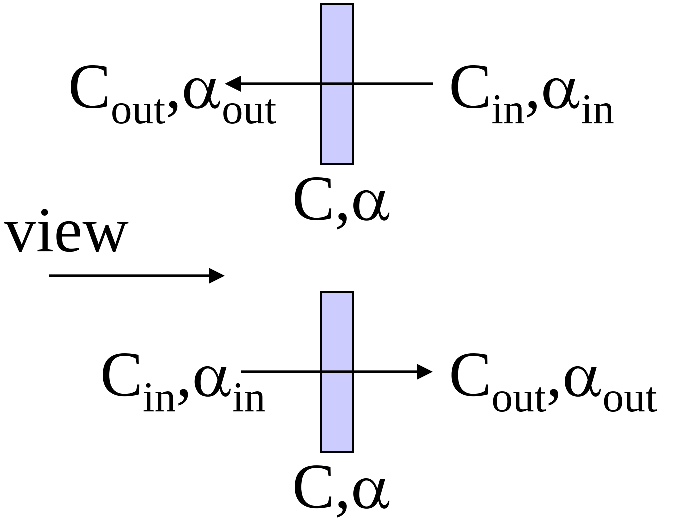
$$\alpha_{out} = \alpha + (1 - \alpha)\, \alpha_{in}$$

  - No need to maintain α
- Front to back
  - Under operator

$$C_{out} = \alpha_{in}\, C_{in} + (1 - \alpha_{in})\, C$$

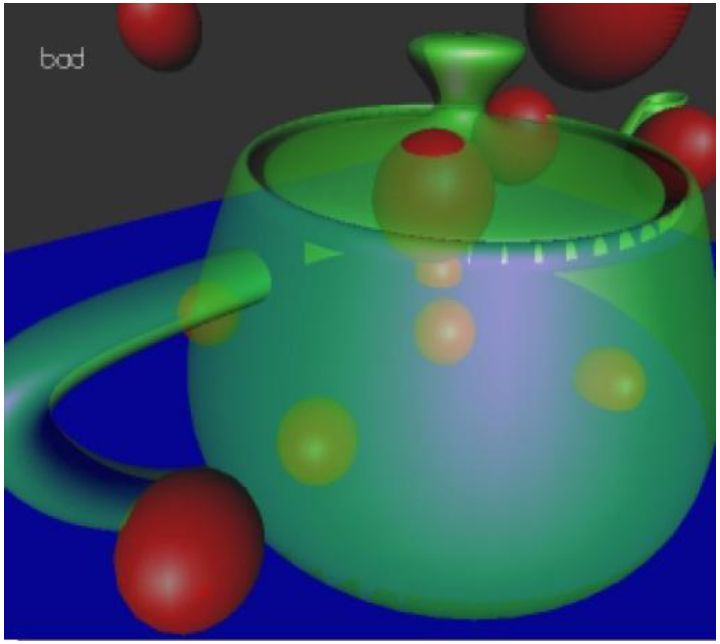
$$\alpha_{out} = \alpha_{in} + (1 - \alpha_{in})\, \alpha$$

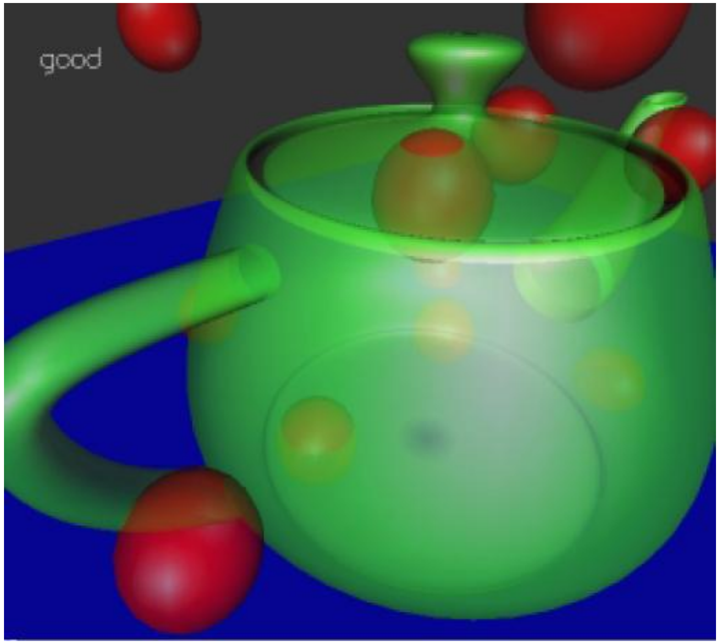
  - Need to maintain α



Order Independent Transparency

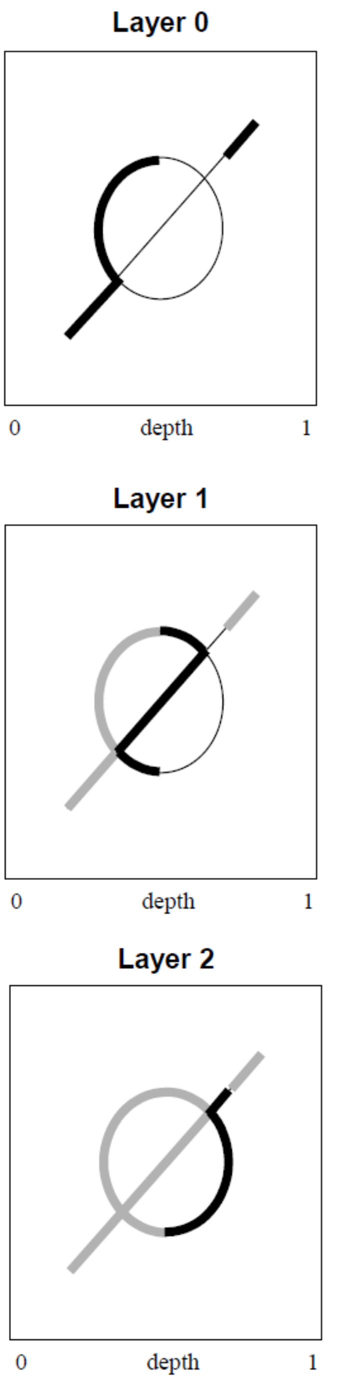
- Alpha blending works for sorted rendering
  - Front to back
  - Back to front
- Doesn’t work for out-of-order
  - Front, back, middle
- Would need to keep track separately of the front part and the back part
- Could keep a linked list at each pixel
  - A-buffer (Catmull)
  - Not practical for hardware



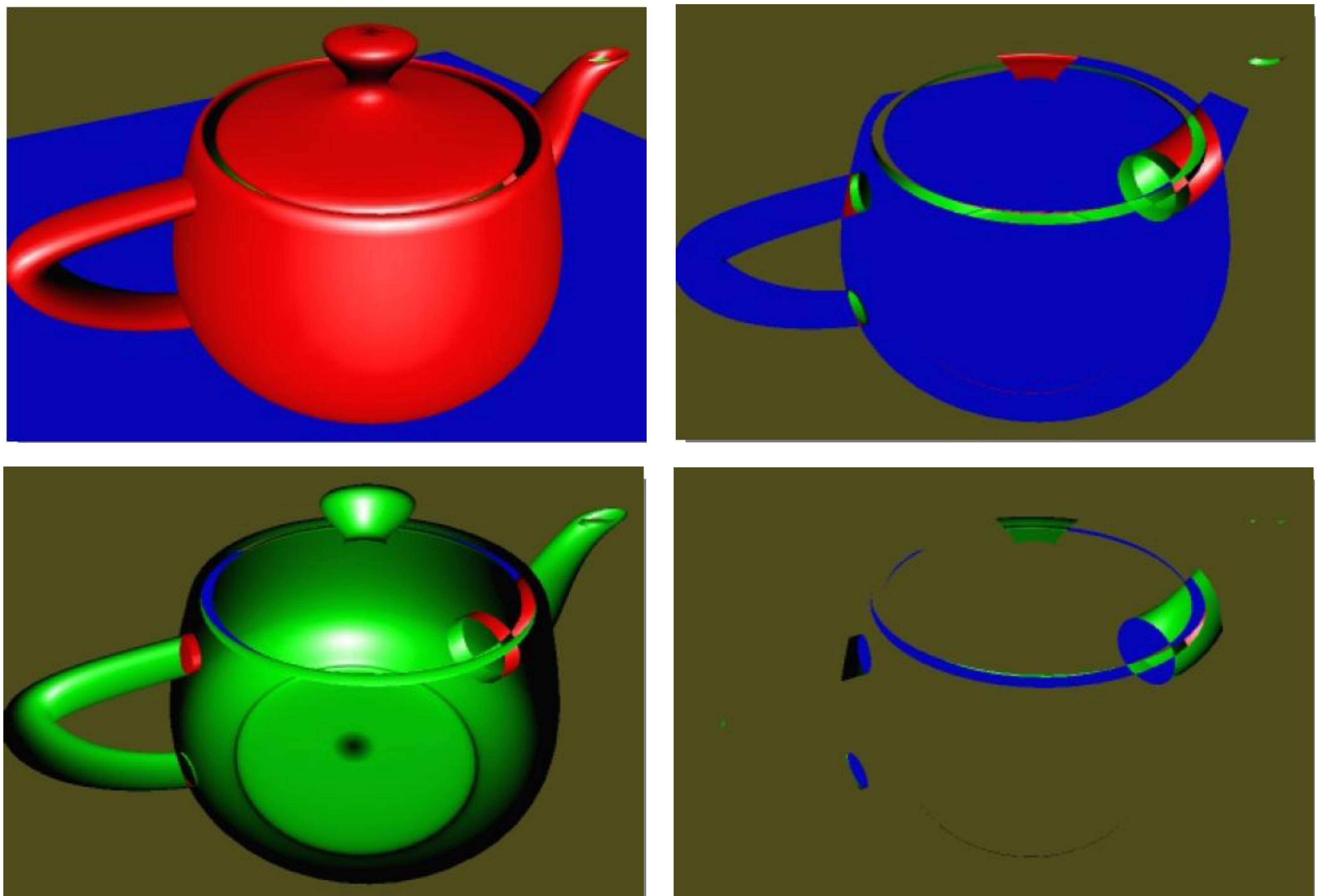


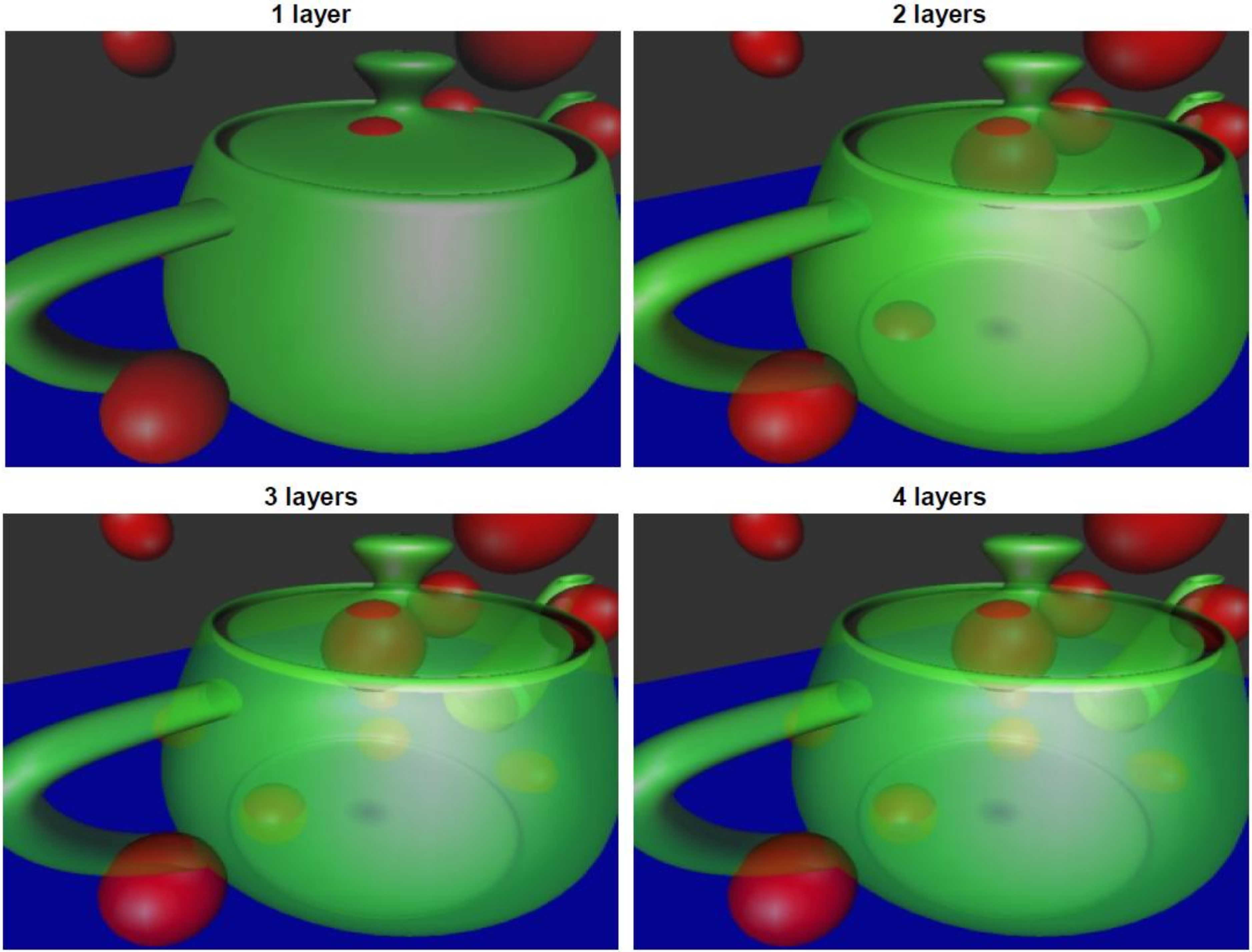
Depth Peeling

- Cass Everett, NVIDIA Tech Rep, 2001
- Needs 2 z-buffers (previous, current)
- One rendering pass per layer
- Fragment written to frame buffer if
  - Farther than previous z-buffer
  - Closer than current z-buffer
- After each pass, current z-buffer written to previous z-buffer
- Surviving fragment composited “under” displayed fragment



Depth Peels




1 layer
2 layers
3 layers
4 layers