CSC 317/2504: Computer Graphics

Course web site (includes all course information):
https://github.com/dilevin/computer-graphics-csc317/

Lectures: Monday 11:00-13:00 LEC101/LEC2001 BA1180
Slides and many lecture topic videos are available ahead of time.

Prof. Karan Singh
karan@dgp.toronto.edu
Office hours: open door or upon request by email.

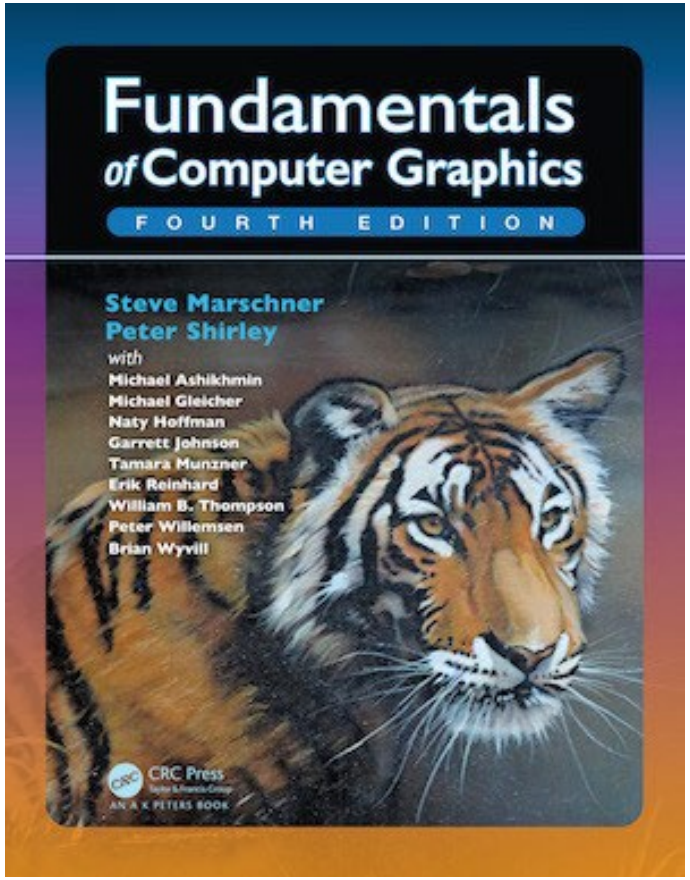
Tutorials: Wednesday 11:00-12:00 LEC101/LEC2001 BA1180

Questions:
on Assignments: Github issues pages
on Administrative stuff: Quercus https://q.utoronto.ca/courses/354220

Textbooks: Fundamentals of Computer Graphics
OpenGL Programming Guide & Reference

You will need:

- A computer to install and program the assignments.
- An internet connection for online material and to join any occasional zoom meetings.
- Availability during class and tutorial times.
- The textbook for required readings



Schedule (on the webpage)

Week	Topic / Event
1	Introduction, tutorial, Assignment 1 (Raster Images) **waitlisted ? zip assignment and email to TAs** due 17/09
2	Lecture 2, Assignment 2 Ray Casting due 24/09
3	Lecture 3, Assignment 3 Ray Tracing due 01/10
4	Lecture 4, Assignment 4 Bounding Volume Hierarchy due 8/10
5	Lecture 5, Assignment 5 Meshes due 22/10
6	**No Lecture, Thanksgiving**
	First In-Tutorial Test October 16th
7	Lecture 6, Assignment 6 Shader Pipeline due 5/11
8	**No Lecture, Reading Week !**
9	Lecture 7, Assignment 7 Kinematics due 12/11
10	Lecture 8, Assignment 8 Mass-Spring Systems due 19/11
11	Lecture 9, Assignment on Generative AI due 26/11
12	Second In-Class Test December 3rd

Marking Scheme (on the webpage)

%	Item
64	Assignments (best 8 of 9)
12	4 Quizzes (Online)
12	In Tutorial Test
12	In Class Test

Academic Honesty Policy is on the webpage and is mandatory reading!

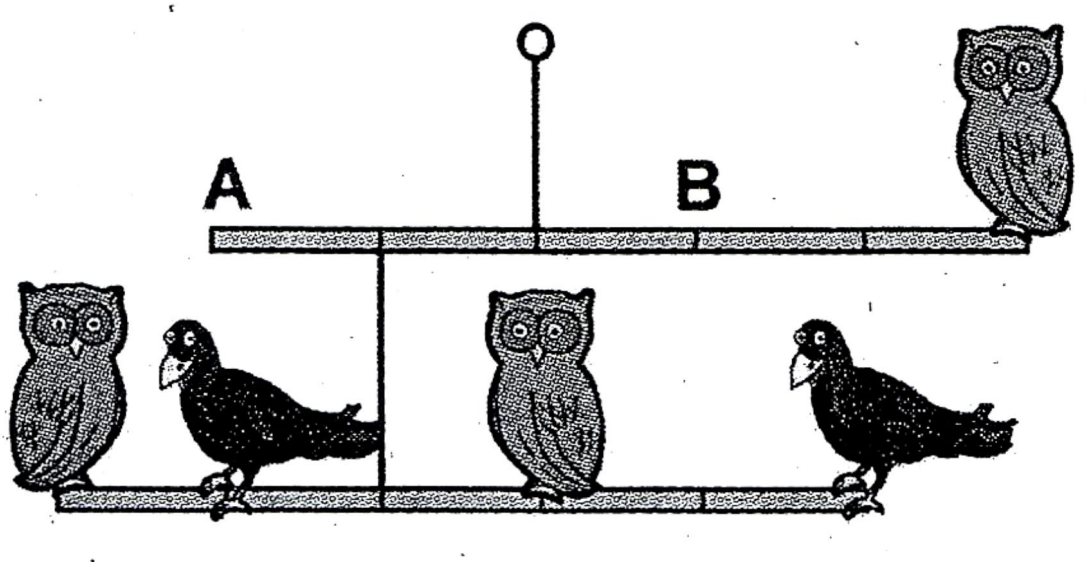
Tutorials sessions will be invaluable for the assignments.

Prerequisites (pre-test)

Background in math, CS and programming is required for this course.

A quick self-monitored pre-test (15-20 mins should be enough to do it)

1. Show you the mathematical background expected and your readiness for this course.
2. Show you what you need to brush up on. Questions about these math operations will not be answered by either Professors or TAs, we expect you to know this stuff.



Discrete Math

Q1: What is the intersection of the interval $\mathcal{A} = [-1, 3]$ and $\mathcal{B} = [0, 4]$? $\mathcal{A} \cap \mathcal{B} =$

Q2: In a balanced binary tree with n leaf nodes, how many internal nodes are there?

Q3: In a balanced binary tree with n leaf nodes, how deep is the tree?
(i.e., number of nodes on a shortest path from root to leaf)

Q4: What is 5! (five factorial)?

Q5: How many different ways are there to choose k items from a set of n items?

Linear Algebra

Q6: What size is the result of multiplying a 2×3 matrix and a 3×4 matrix?

Q7: What is the dot product between the vector $\mathbf{a} = [1, 2, 3]$ and $\mathbf{b} = [4, 5, 6]$? $\mathbf{a} \cdot \mathbf{b} =$

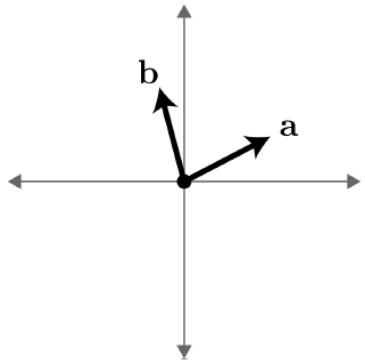
Q8: What is the cross product between the vector $\mathbf{a} = [4, 0, 0]$ and $\mathbf{b} = [0, 0, -2]$? $\mathbf{a} \times \mathbf{b} =$

Q9: What is the matrix product of the matrix $\mathbf{A} = \begin{pmatrix} 1 & 0 & 4 \\ 0 & 2 & 1 \\ 0 & -3 & 0 \end{pmatrix}$ and the vector $\mathbf{b} = \begin{pmatrix} -4 \\ 5 \\ 6 \end{pmatrix}$?

$\mathbf{A}\,\mathbf{b} =$

Q10: Using matrices, express the solution to the following system of equations:
$3x_1 + 2x_2 - 1x_3 = 10$, $2x_1 - 10x_3 = 0$, $-9x_1 + 9x_2 = -1$. (Form the system, but do not solve).

Q11: *Sketch* the results of $\mathbf{c} = \mathbf{a} + \mathbf{b}$ and $\mathbf{d} = \mathbf{b} - \mathbf{c}$ on the plot:



Mappings

Q12: Suppose we have a $f : \mathcal{A} \to \mathcal{B}$, what needs to be true to call f a *well-defined function*?

Q13: Is $f(x) = x^2$ invertible? Why (not)?

Q14: If x and y are real numbers, what sets are the domain and range of $f(x, y) = x^2 + y^2$? (use $\mathbb{R}$)

Logarithms

Q15: Express $\log(a^b)$ in terms of $\log a$ and b. $\log(a^b) =$

Q16: Express $\log(ab)$ in terms of $\log a$ and $\log b$. $\log(ab) =$

Trigonometry

Q17: Express $\cos(a + b)$ in terms of $\cos a$ and $\cos b$. $\cos(a + b) =$

Q18: Given a triangle with side lengths a, b, c and opposite angles A, B, C, express $\sin A$ in terms of a, b, and $\sin B$.

$\sin A =$

Q19: Given a right triangle with acute angles A and B, express the following in terms of opposite side length a and b:

$\sin A =$ $\cos A =$ $\tan A =$

Quadratic equation

Q20: How many real-value solutions for x are possible to an equation of the form $ax^2 + bx + c = 0$?
A) zero; **B)** one; **C)** two; **D)** three; **E)** zero, one or two; *or* **F)** zero, one, two or three.

Q21: Identify the solution(s), if any, to $x^2 - 4x - 5 = 0$.

Linear interpolation

Q22: What is *the* linear function $f : [0, 1] \to \mathbb{R}$, so that $f(0) = a$ and $f(1) = b$?

Q23: What is *the* linear *vector-valued* function $f : [0, 1] \to \mathbb{R}^3$, so that $f(0) = \mathbf{a}$ and $f(1) = \mathbf{b}$?

Derivatives

Q24: What is the derivative of the function $f(t) = 3t^2$? $\frac{df}{dt} =$

Q25: What is the second derivative of the function $f(t) = 3t^2$? $\frac{d^2 f}{dt^2} =$

Q26: What is the partial derivative of the function $f(x, y) = 3x^2 - 3y^2$ with respect to y? $\frac{df}{dy} =$

Q27: Given a function $f : \mathbf{R}^3 \to \mathbf{R}$, how many dimensions does its gradient have?

Q28: Using partial derivative and vector notations express the gradient of a function $f(x, y, z) : \mathbf{R}^3 \to \mathbf{R}$.

$\nabla f =$

C++ Programming

Q29: We want to call `func` on `x`, what should be written in place of the question mark in the following C++ code?
A) `*`; **B)** `&`; *or* **C)** nothing.

```
bool func(double & x);
...
int main()
{
  double * x = new double();
  func( ? x);
}
```

Geometry

Q30: What is the volume of a sphere with radius r?

Today

1. Introduction to Computer Graphics.
2. Preview of Assignments.
3. Raster Images.

Introduction to Computer Graphics

What is Computer Graphics?

Computers:

accept, process, transform and present information.

Computer Graphics:

accept, process, transform and present information

in a visual form.

Ok but… what is the course really about?

The science of turning the rules of geometry, motion and physics into (digital) pictures.

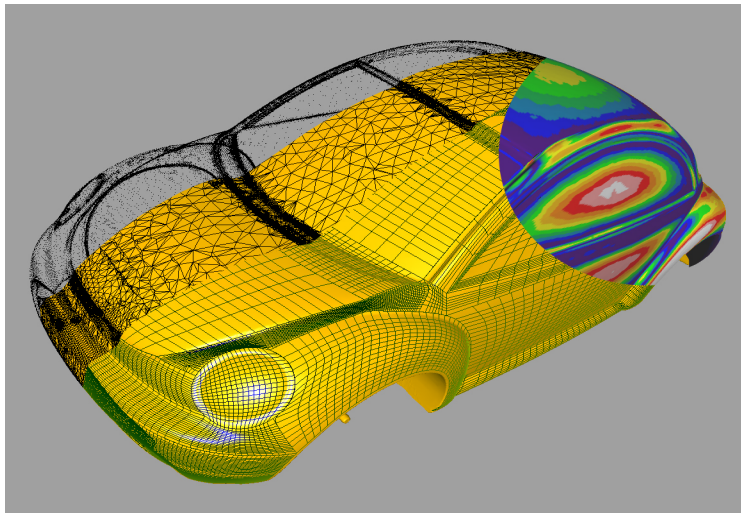
What its not about?

Photoshop, AutoCAD, Maya, Blender, Renderman, Graphics APIs.

Evan Pan (CSC 317 alumnus)

“Core” Areas of Computer Graphics

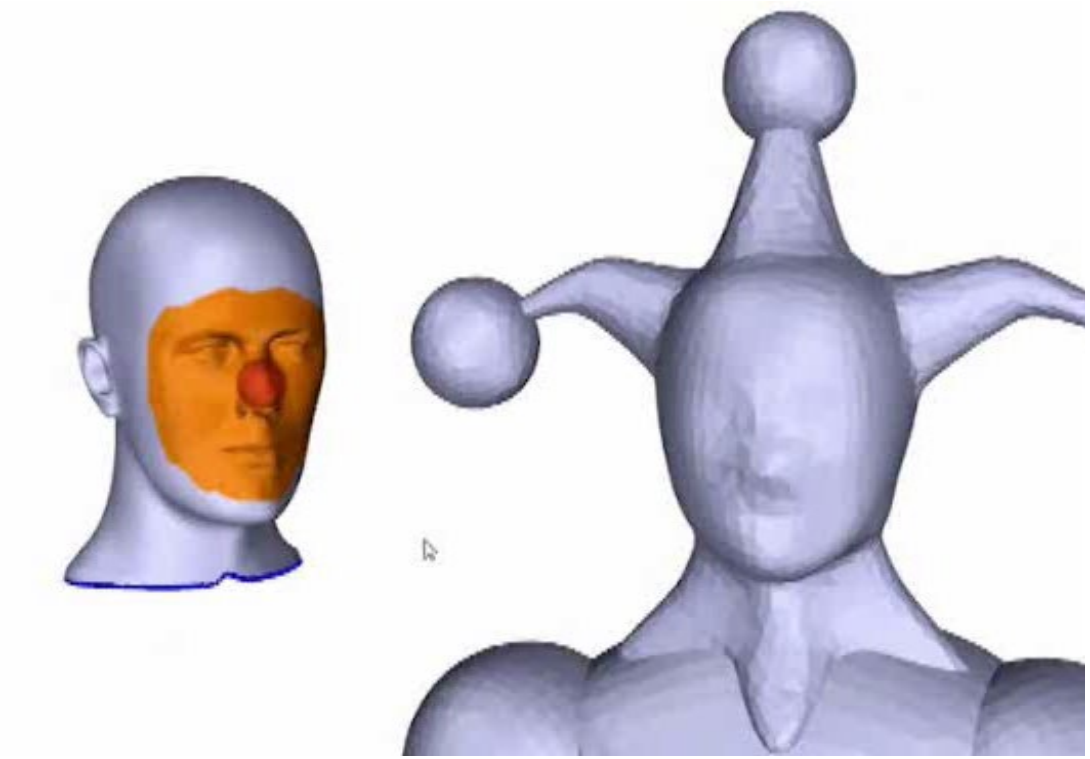
- Form (modeling)
  - How do we represent (2D or 3D) objects & scenes?
  - How do we build these representations?



- Function, Behavior (animation)
  - How do we represent the way objects move?
  - How do we define & control their motion?

- Appearance (rendering)
  - How do we represent the appearance of objects?
  - How do we simulate the image-forming process?

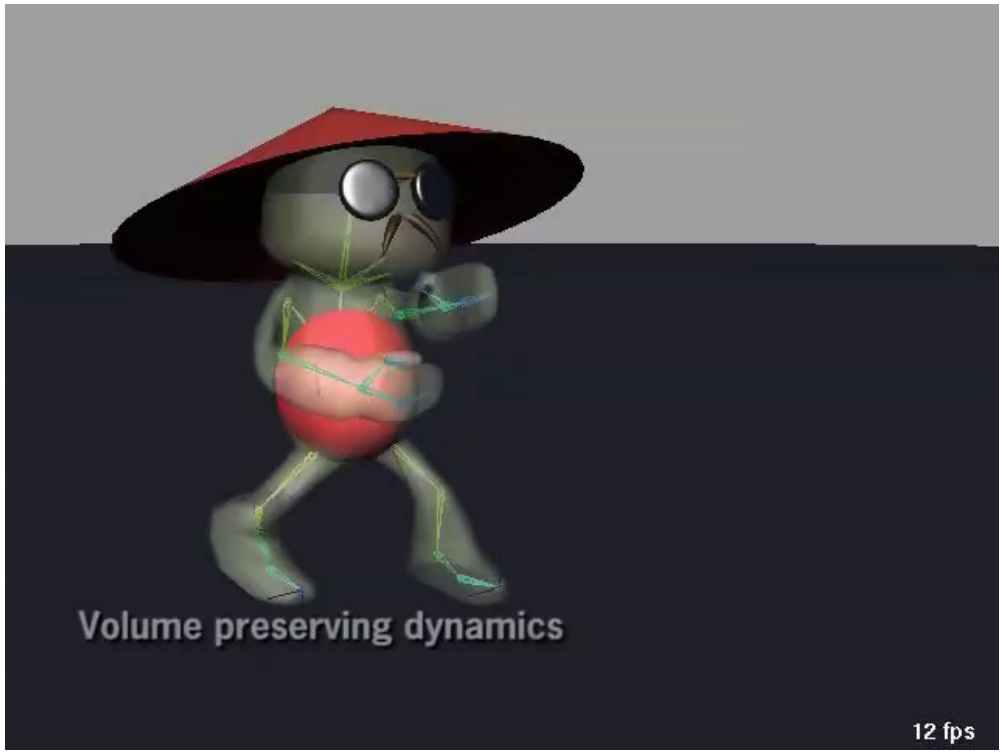
Modeling



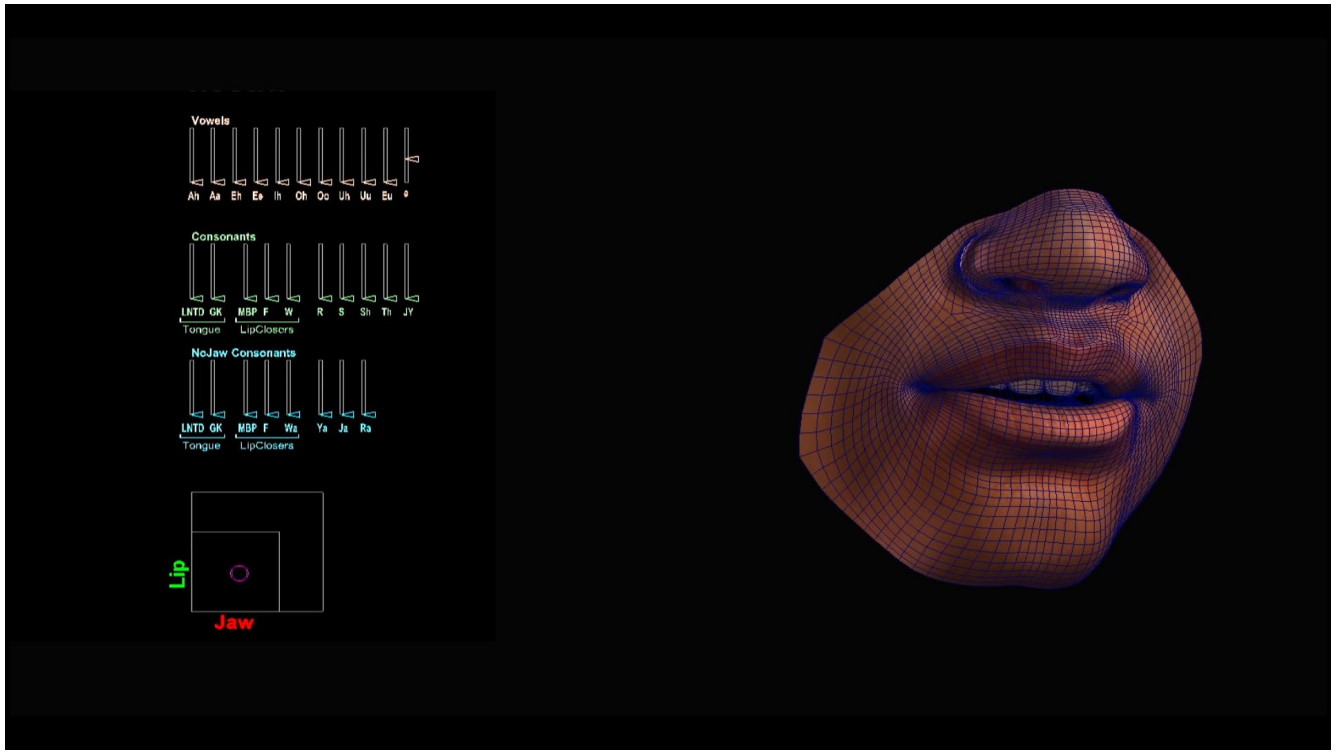
[MeshMixer. Schmidt, Singh, *SIGGRAPH 2010*]
www.meshmixer.com (acquired by Autodesk Inc.)

[Face-Extrusion Quadmeshes. Pandey, Baerentzen ,Singh, *SIGGRAPH 2022*]

Animation

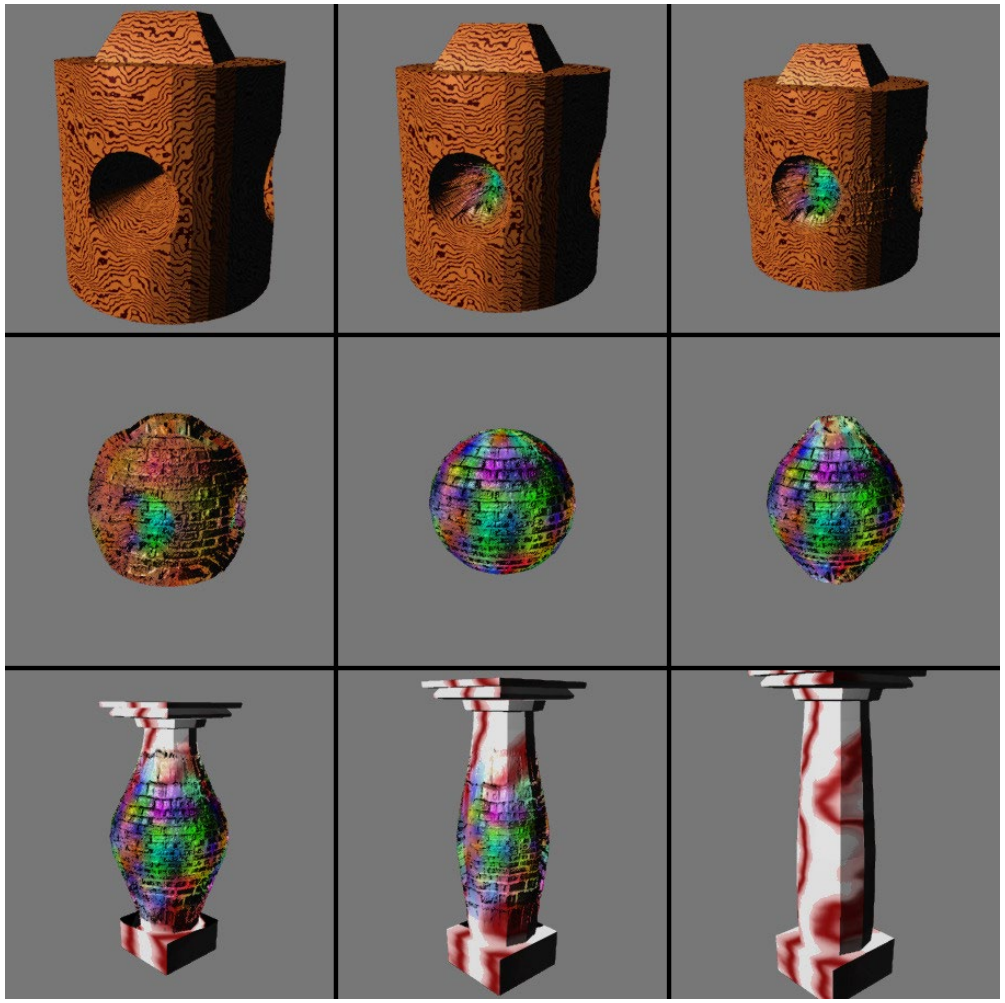


[Kinodynamic skinning using volume-preserving deformations, Angelidis, Singh, *ACM SCA 2007*]



[Visemenet: Zhou et al. *SIGGRAPH 2018*]

Rendering



[Singh, around *1992*]

[Weta Digital *2022*]

Other Areas of Computer Graphics

User Interaction

Virtual Reality

Visualization

Image Processing

3D Scanning and Fabrication

Computational Photography

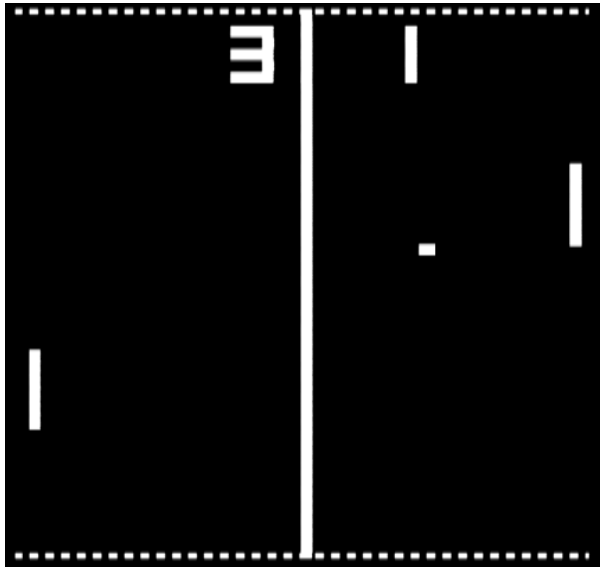
Movies

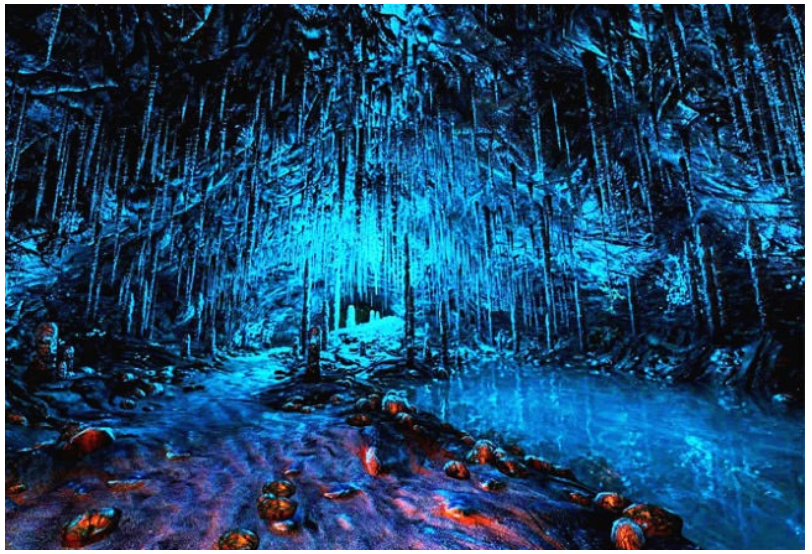
Drive new directions in CG
Set quality standards for CG

Games

Drive interactivity and AI in CG

Push CG hardware to its limits



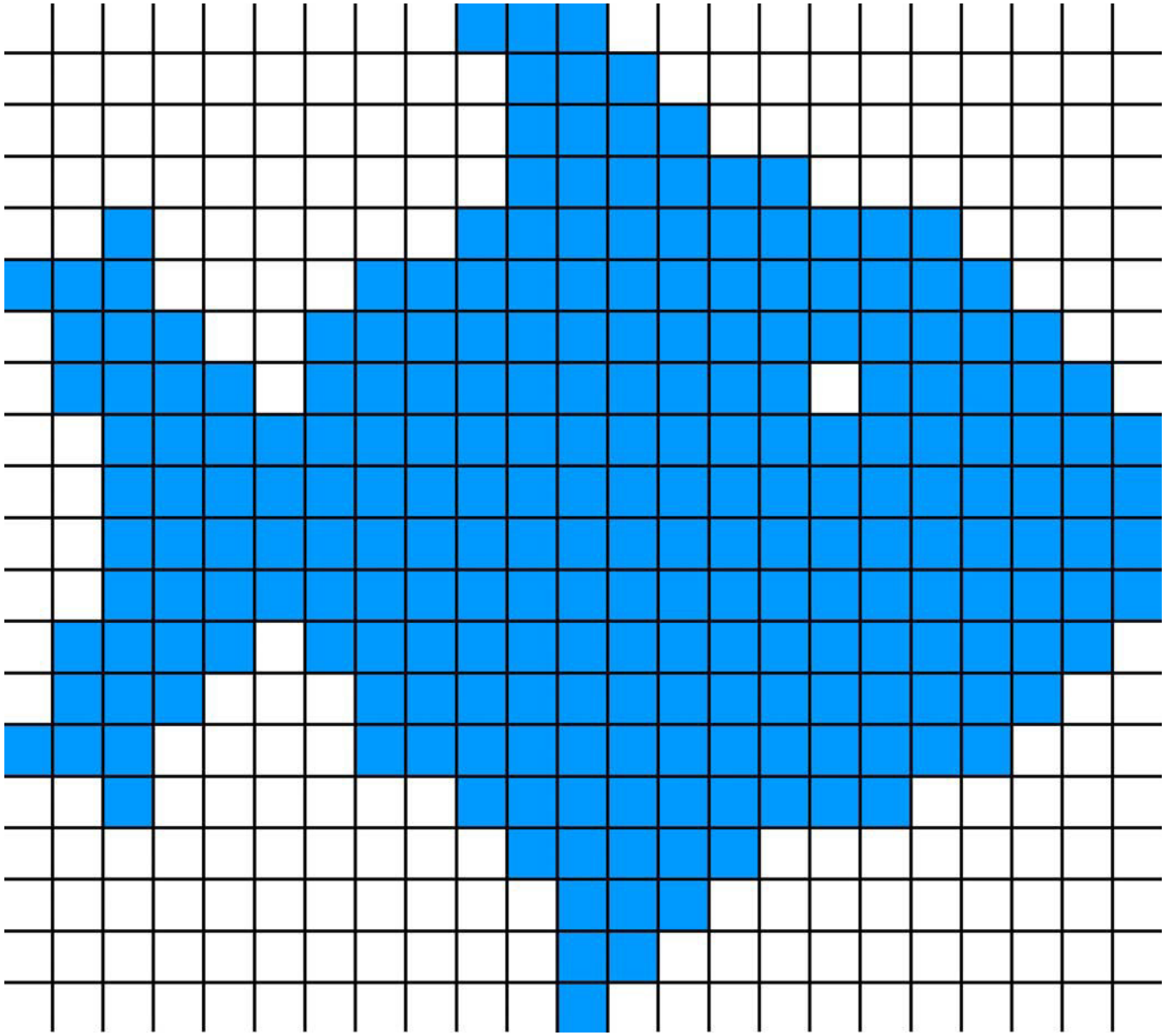



Miasma Chronicles
The Bearded Ladies
Jali

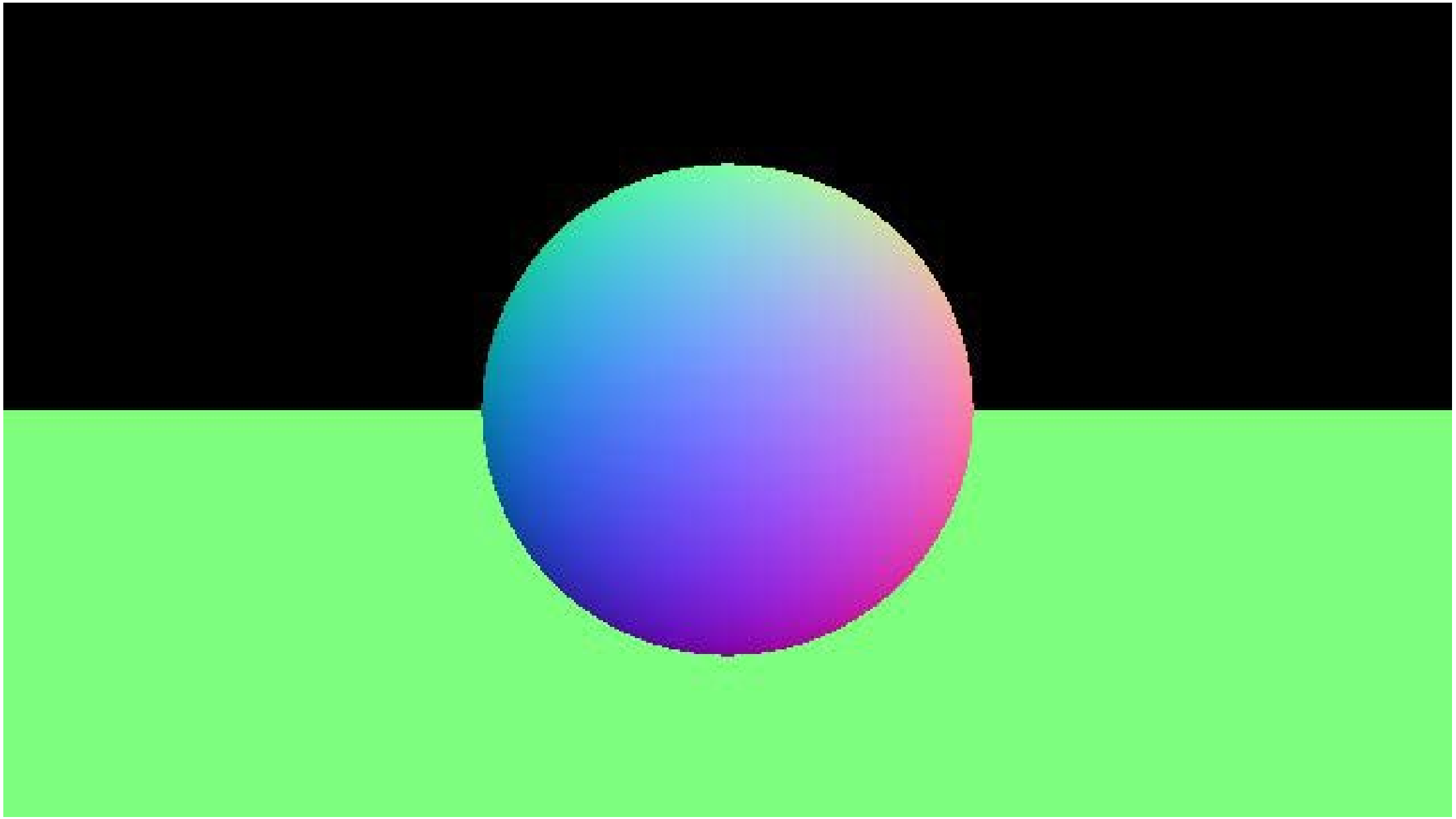
Assignment Previews

1. Raster Images
2. Ray Casting
3. Ray Tracing
4. Boundary Volume Hierarchies
5. Meshes
6. Shaders
7. Kinematics
8. Mass-Springs
9. Generative AI

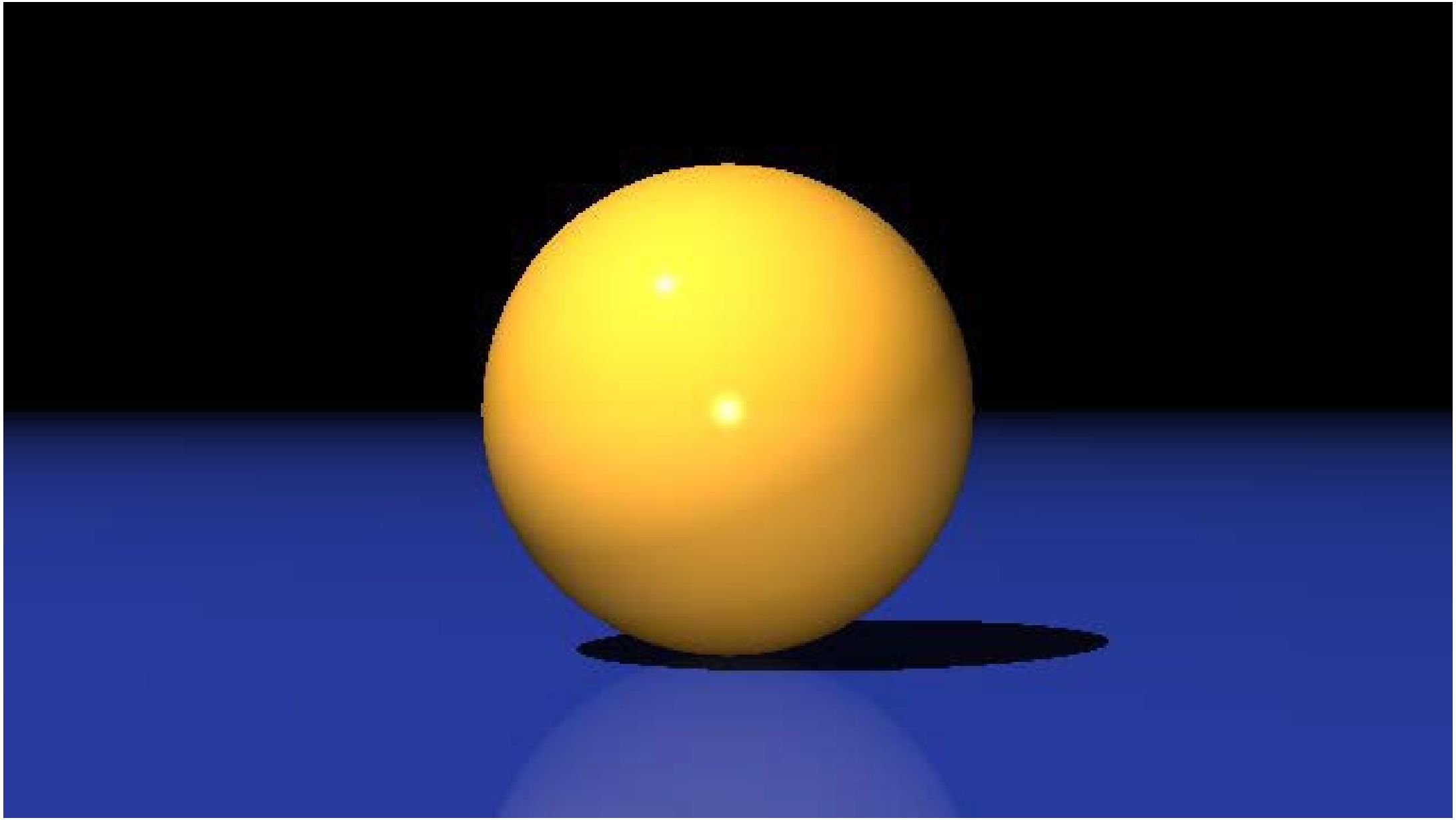
Raster Images



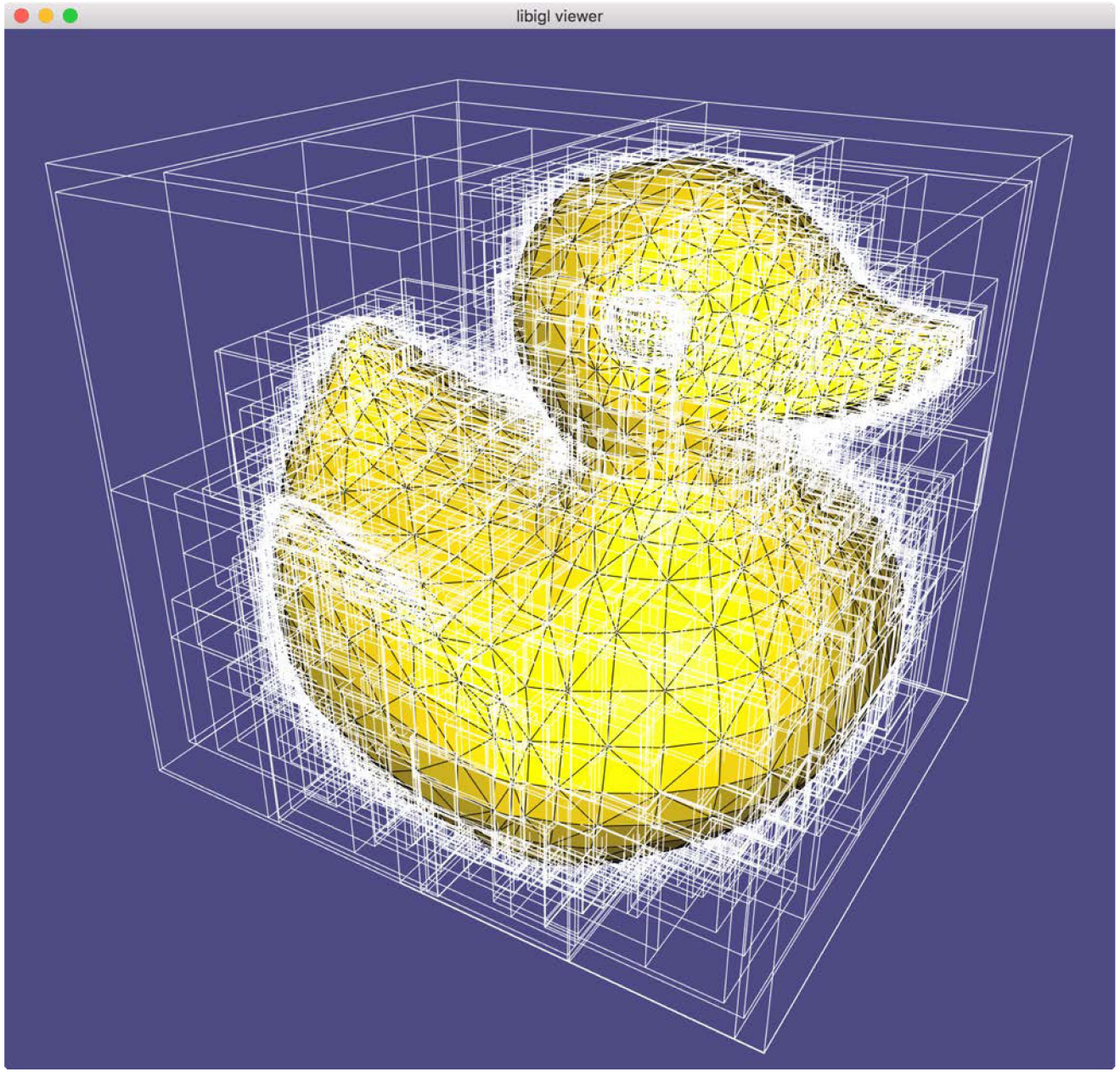
Ray Casting



Ray Tracing

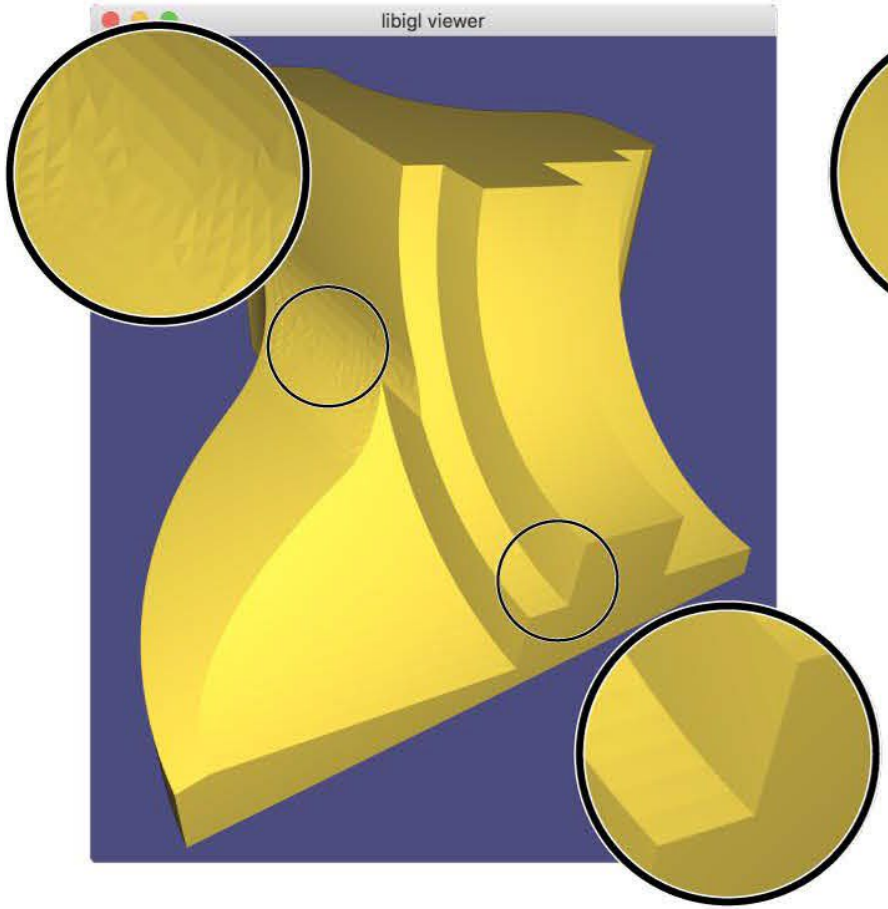


Boundary Volume Hierarchies

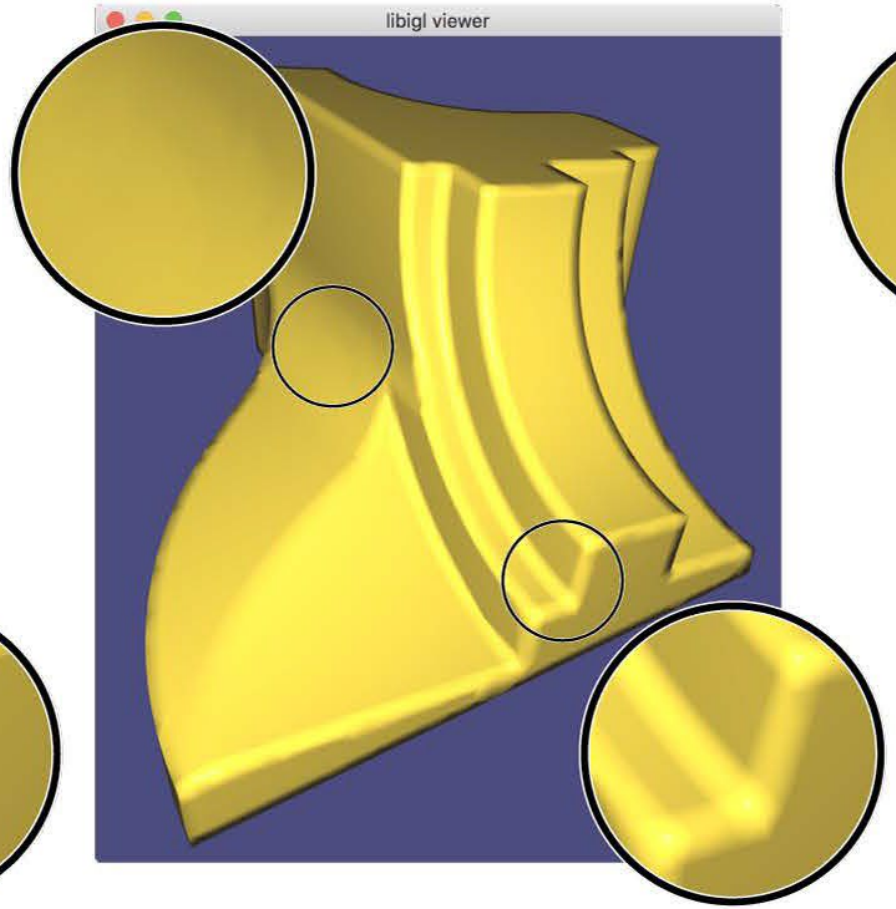


Meshes

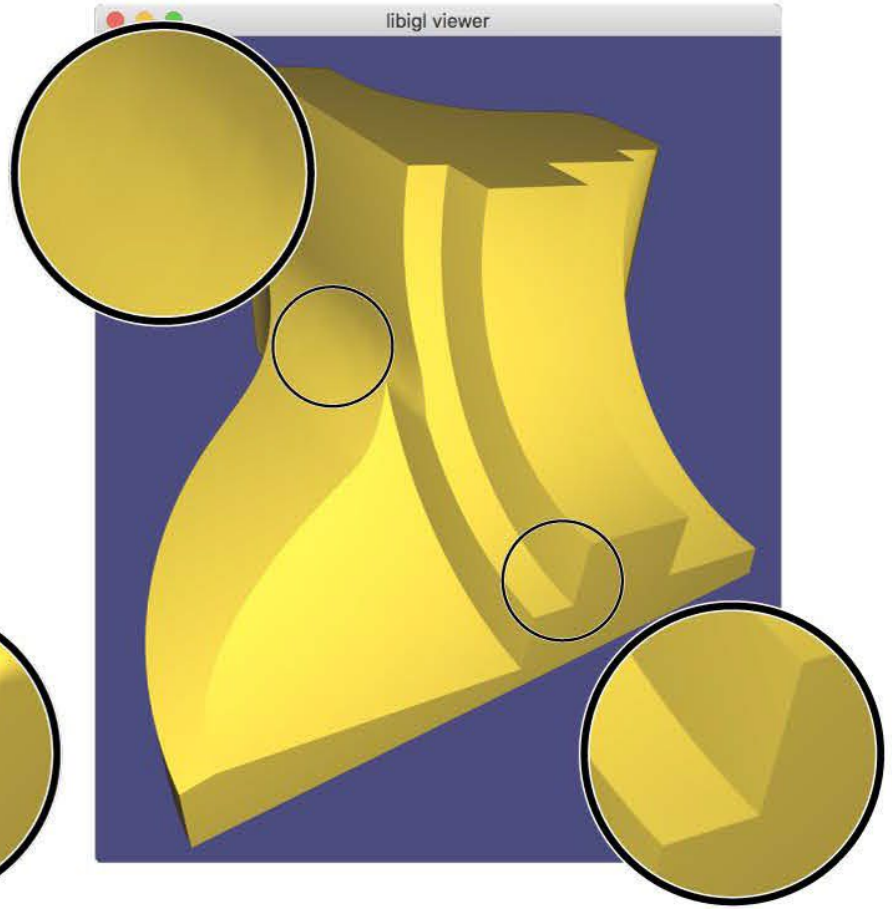
Per-face normals



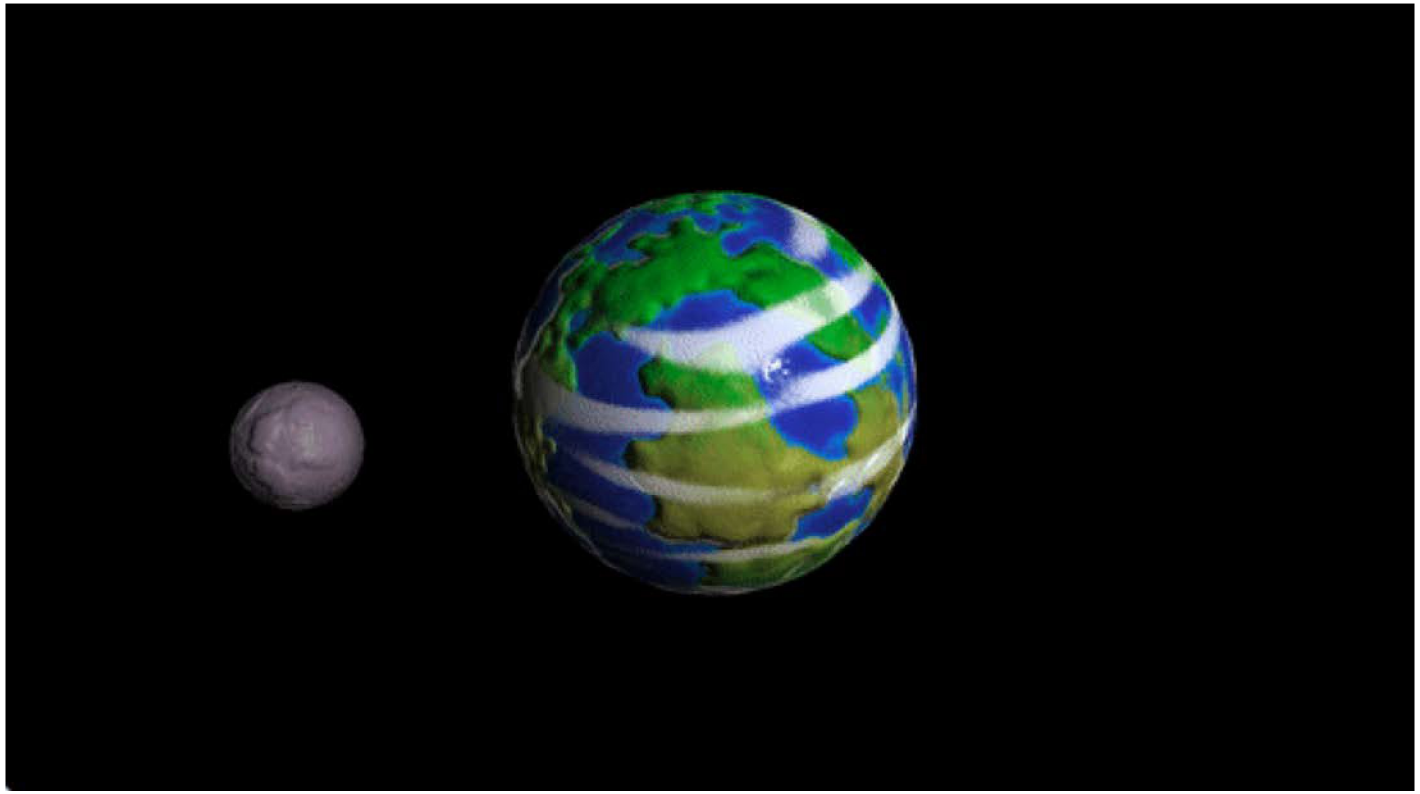
Per-vertex normals



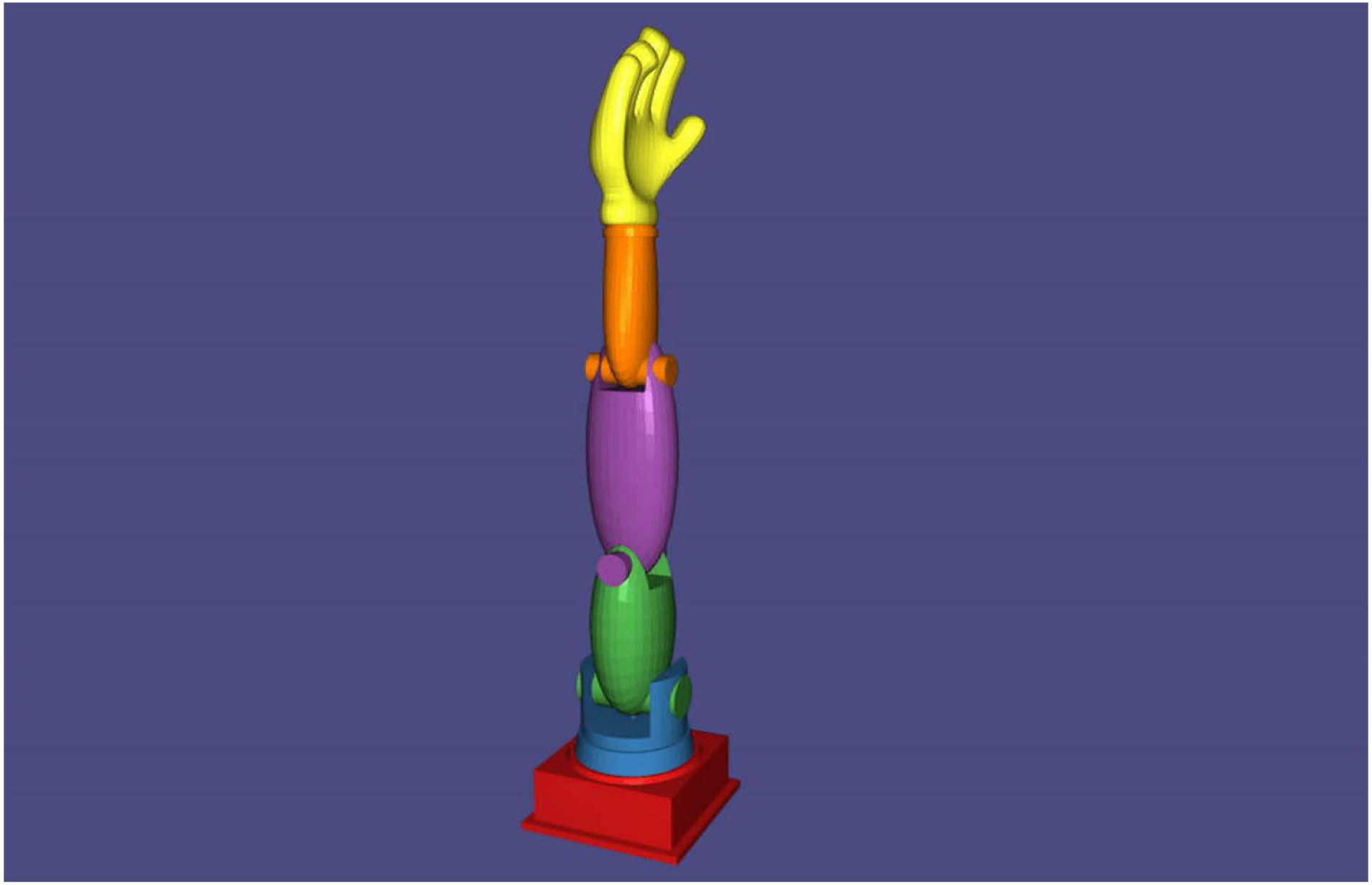
Per-corner normals



Shaders



Kinematics



Mass-Springs

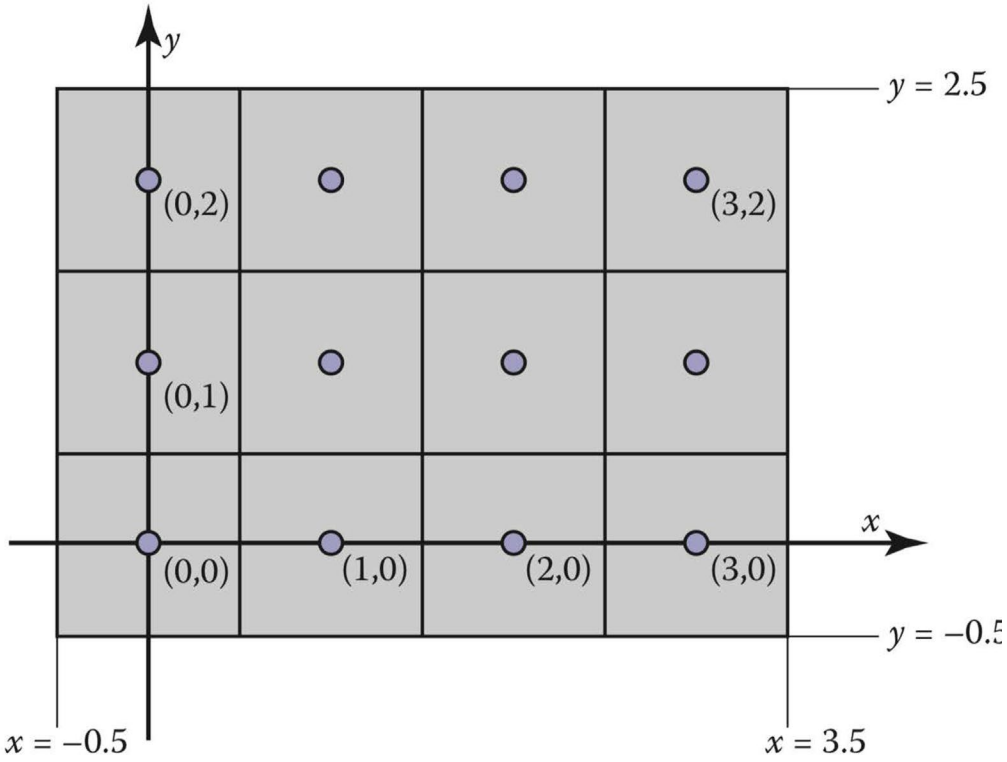
Raster Images

What is an Image?

Image = distribution of light energy on 2D “film”
Digital images represented as rectangular arrays of **pixels**

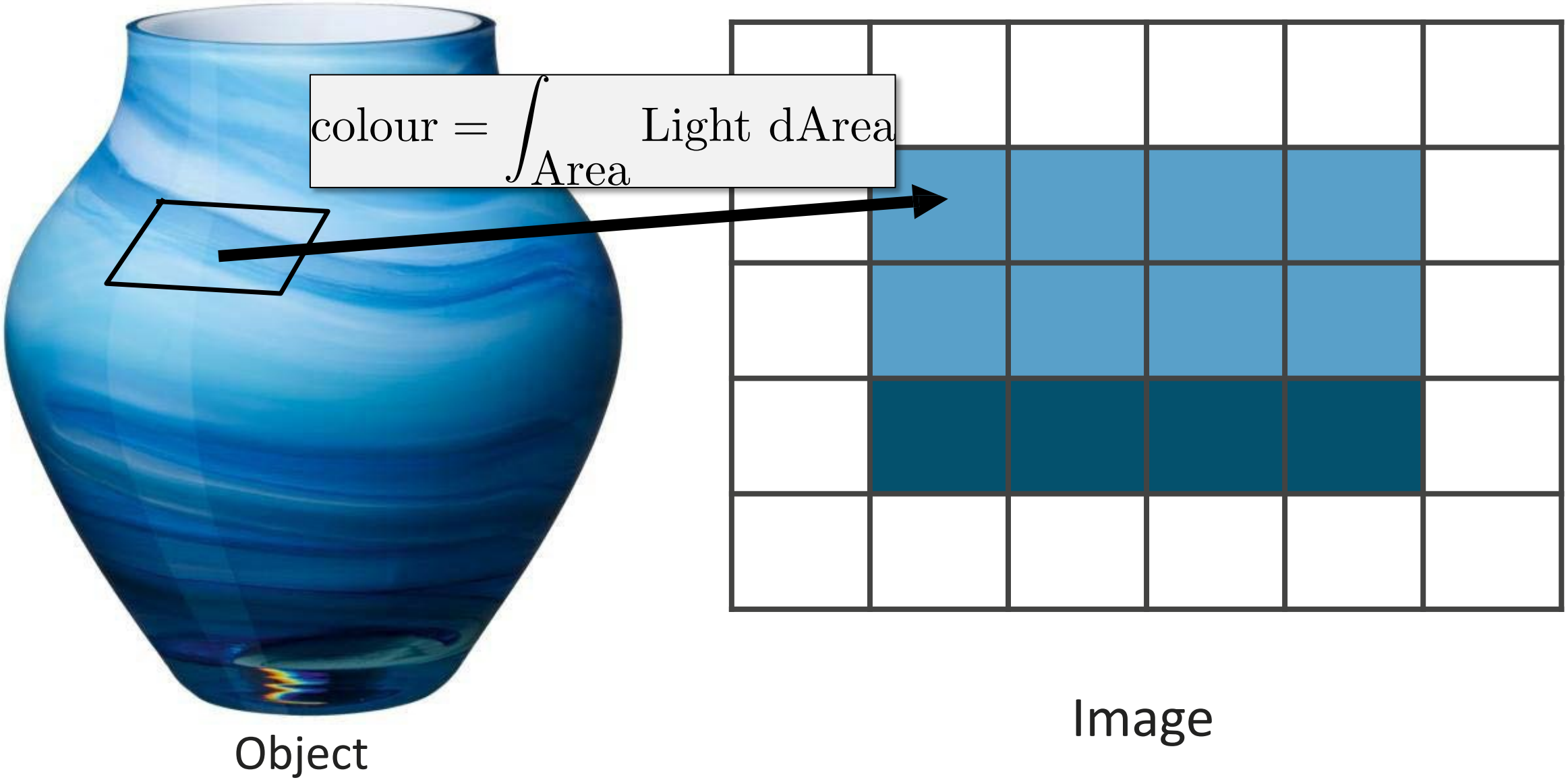
Image = a function defined for an array of pixels

$$I(x, y) : \mathbb{R}^2 \rightarrow \mathbb{R}^{+n}$$



Pixel Co-ordinates

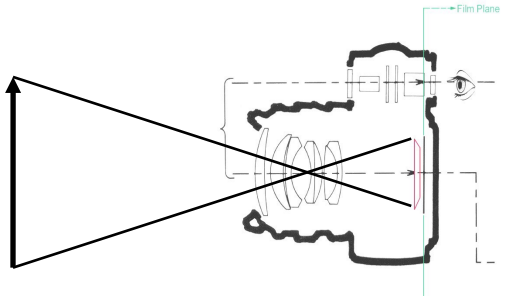
A Pixel in 3D need not be 'square'

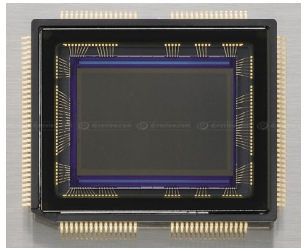


Raster Devices and pixels

- Input (scanners, cameras)

  2D array sensor: digital camera

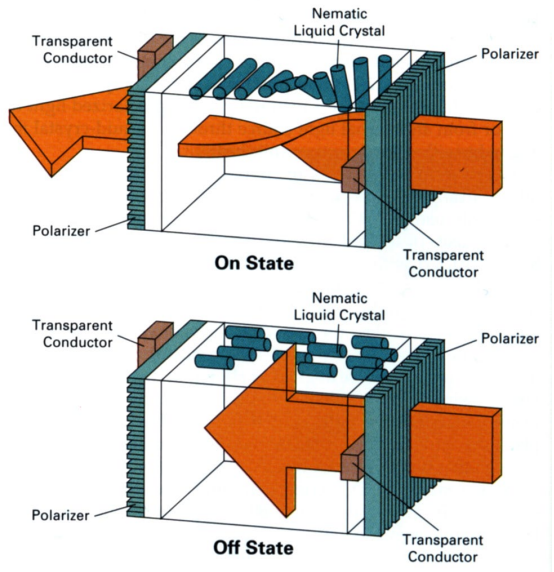




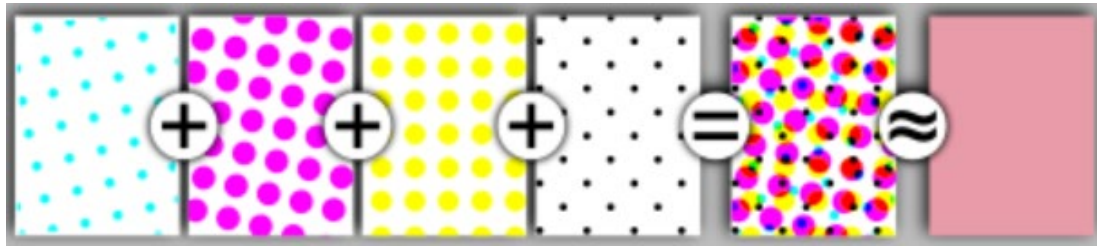
- Output (printers, displays)

  Emissive: light-emitting diode (LED)

  Transmissive: liquid crystal display (LCD)

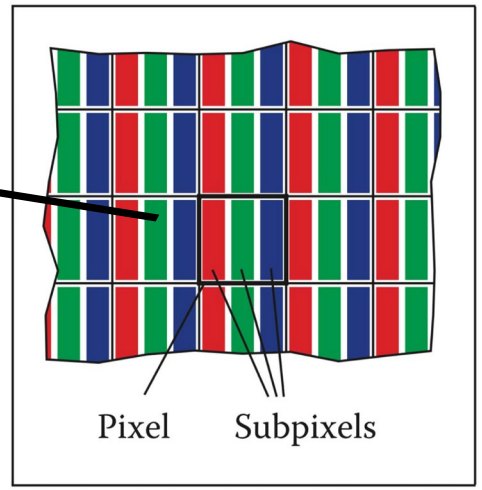


  Ink-jet printer

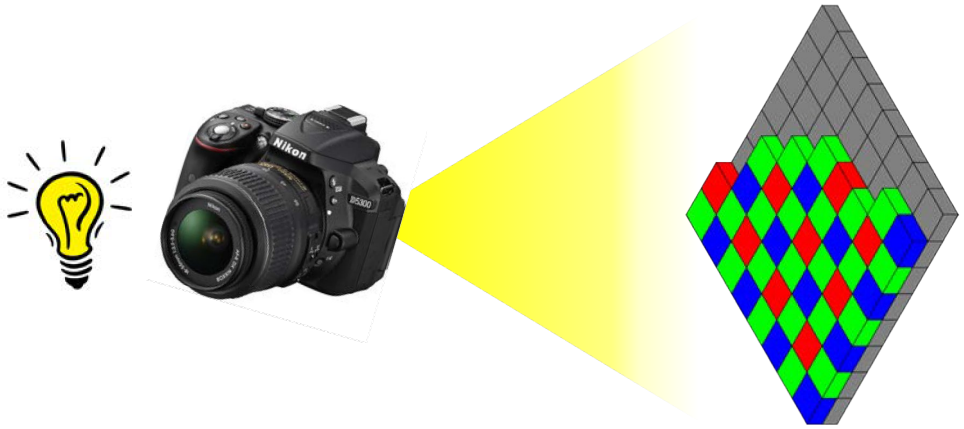


Raster Input/Output

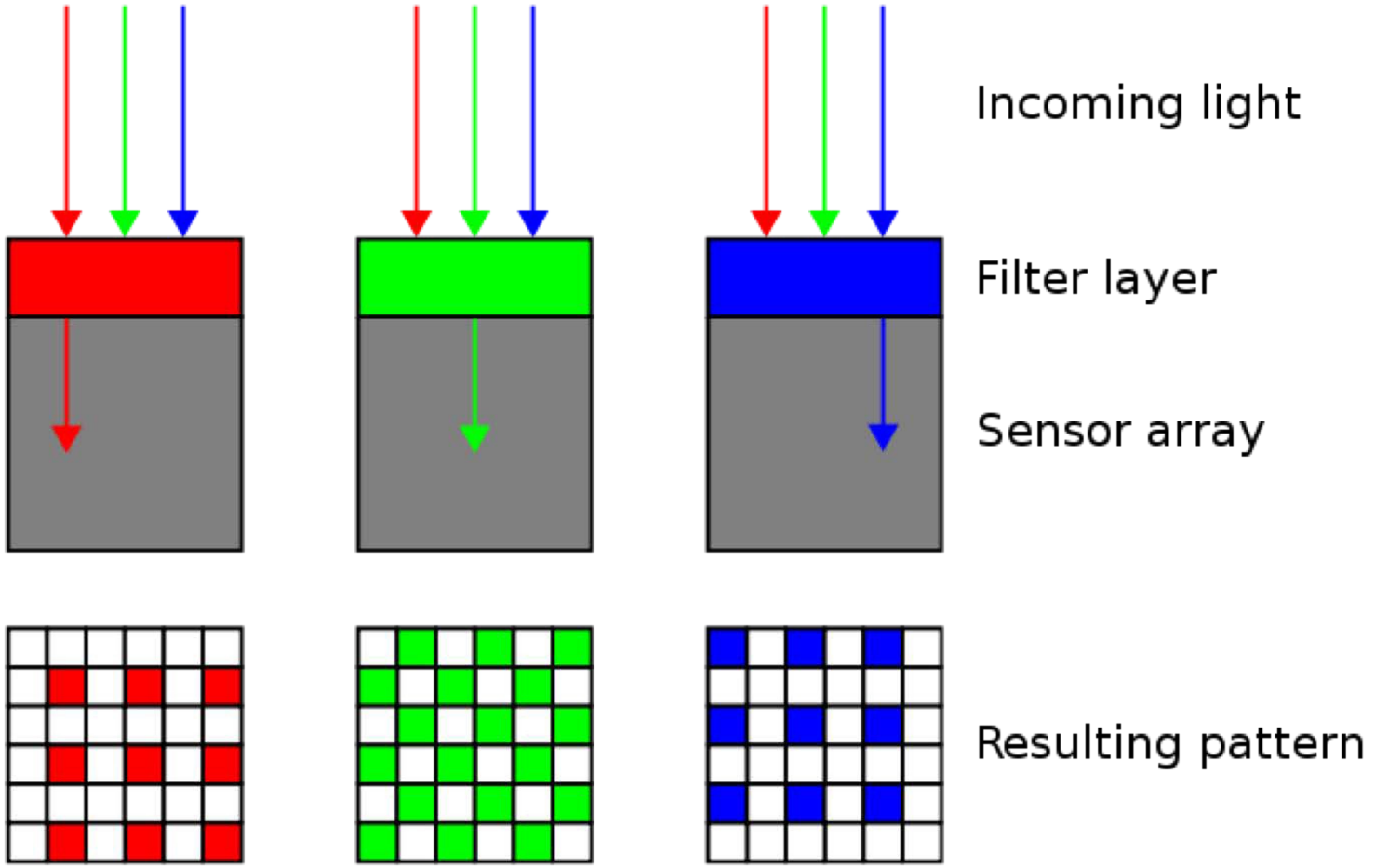
Bayer Filter



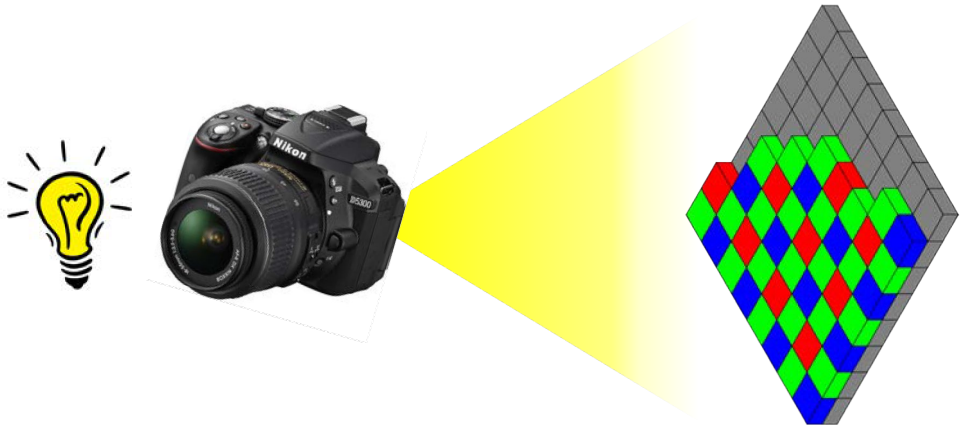
Raster Input Devices



$$i = 0.2126r + 0.7152g + 0.0722b.$$

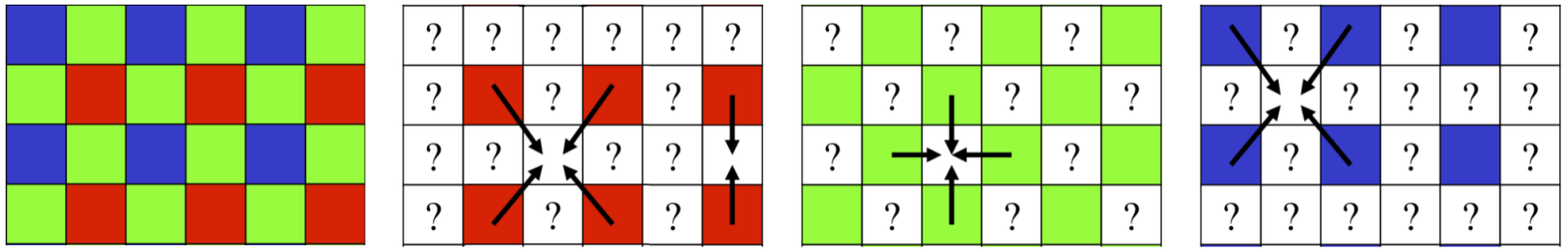


Why more ‘green’ than ‘red’ or ‘blue’?

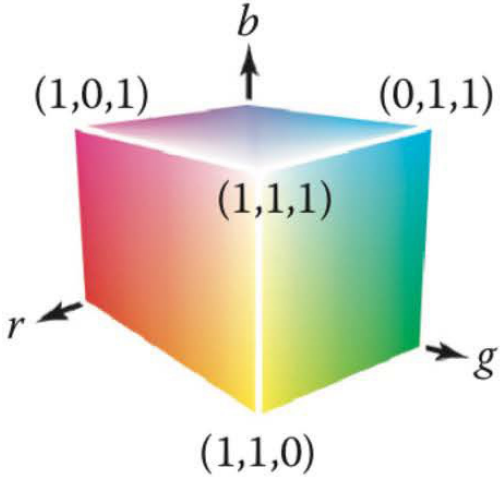


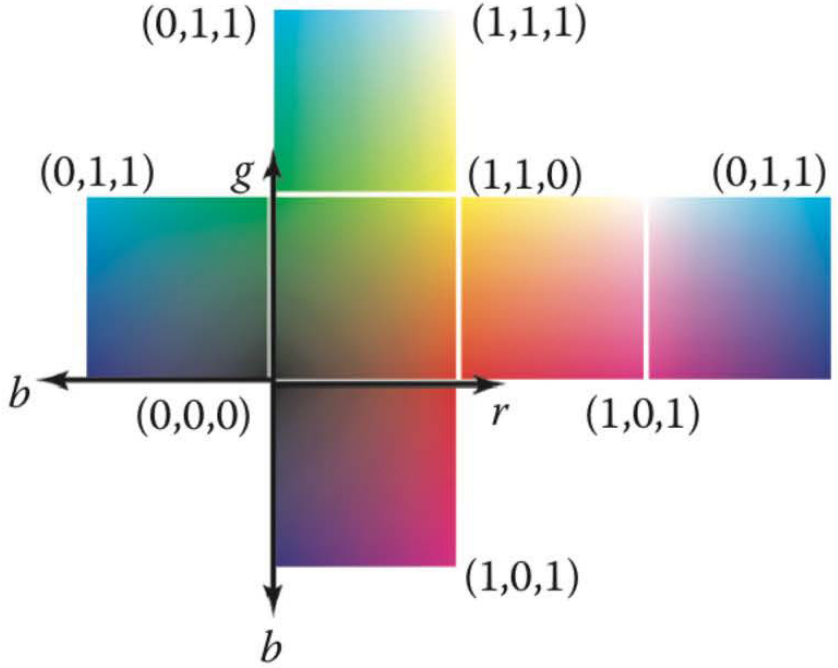
$$i = 0.2126r + 0.7152g + 0.0722b.$$

Demosaicing an image

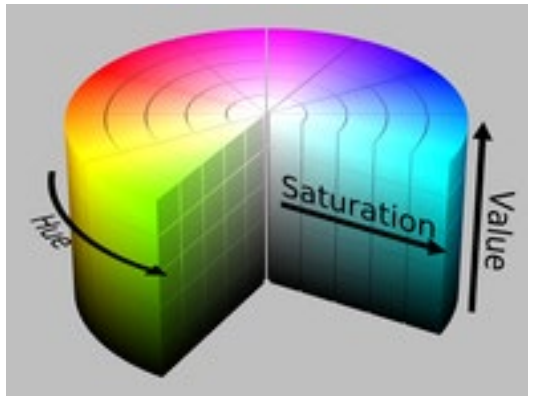


RGB Images

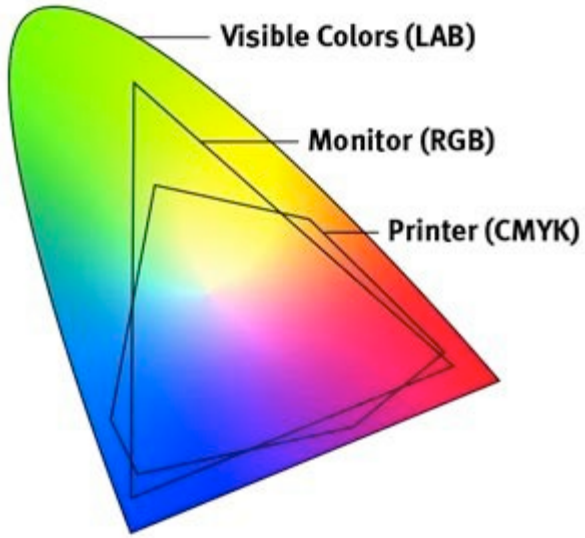




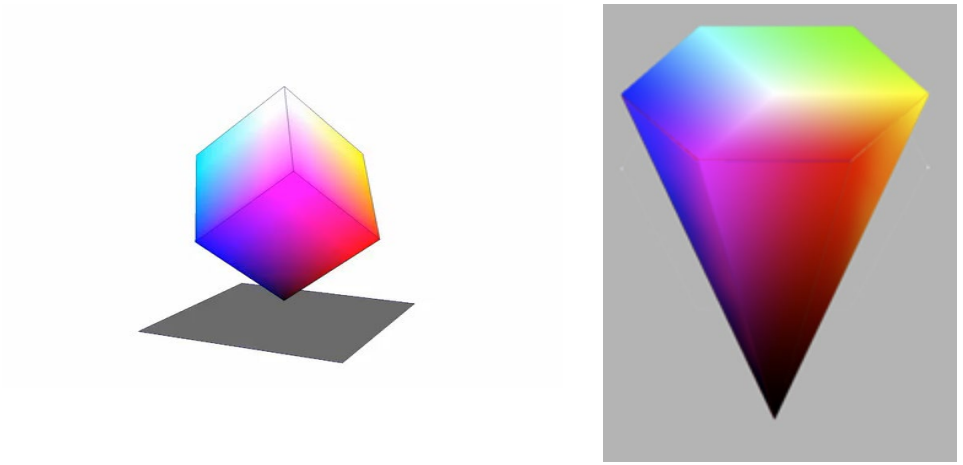
$$\begin{aligned}
\text{black} &= (0,0,0),\\
\text{red} &= (1,0,0),\\
\text{green} &= (0,1,0),\\
\text{blue} &= (0,0,1),\\
\text{yellow} &= (1,1,0),\\
\text{magenta} &= (1,0,1),
\end{aligned}$$

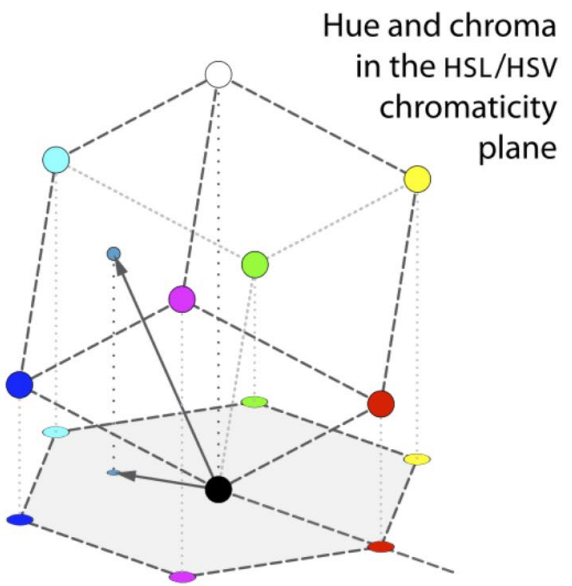


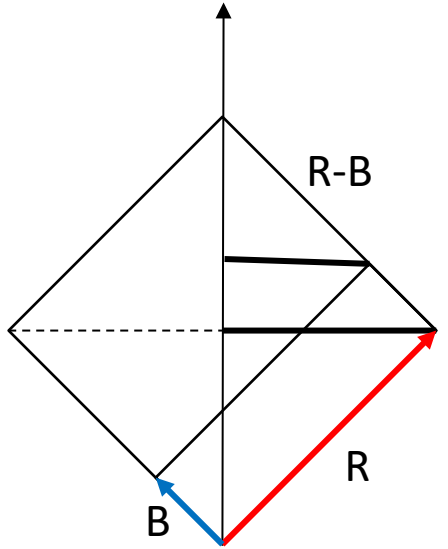
HSV



HSV <=> RGB







V=R

S=(R-B)/R

chroma $M = \max(R, G, B)$

$m = \min(R, G, B)$

$C = \text{range}(R, G, B) = M - m$

$$V = \max(R, G, B) = M$$

$$S_V = \begin{cases} 0, & \text{if } V = 0 \\ \frac{C}{V}, & \text{otherwise} \end{cases}$$

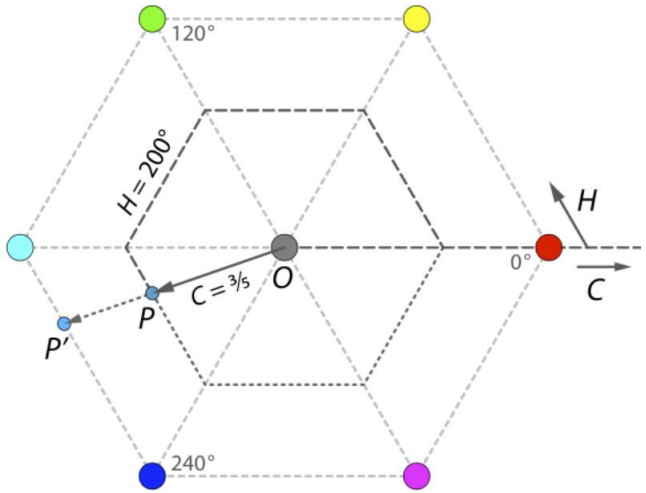
$$H' = \begin{cases} \text{undefined}, & \text{if } C = 0 \\ \frac{G-B}{C} \bmod 6, & \text{if } M = R \\ \frac{B-R}{C} + 2, & \text{if } M = G \\ \frac{R-G}{C} + 4, & \text{if } M = B \end{cases}$$

$$H = 60^\circ \times H'$$

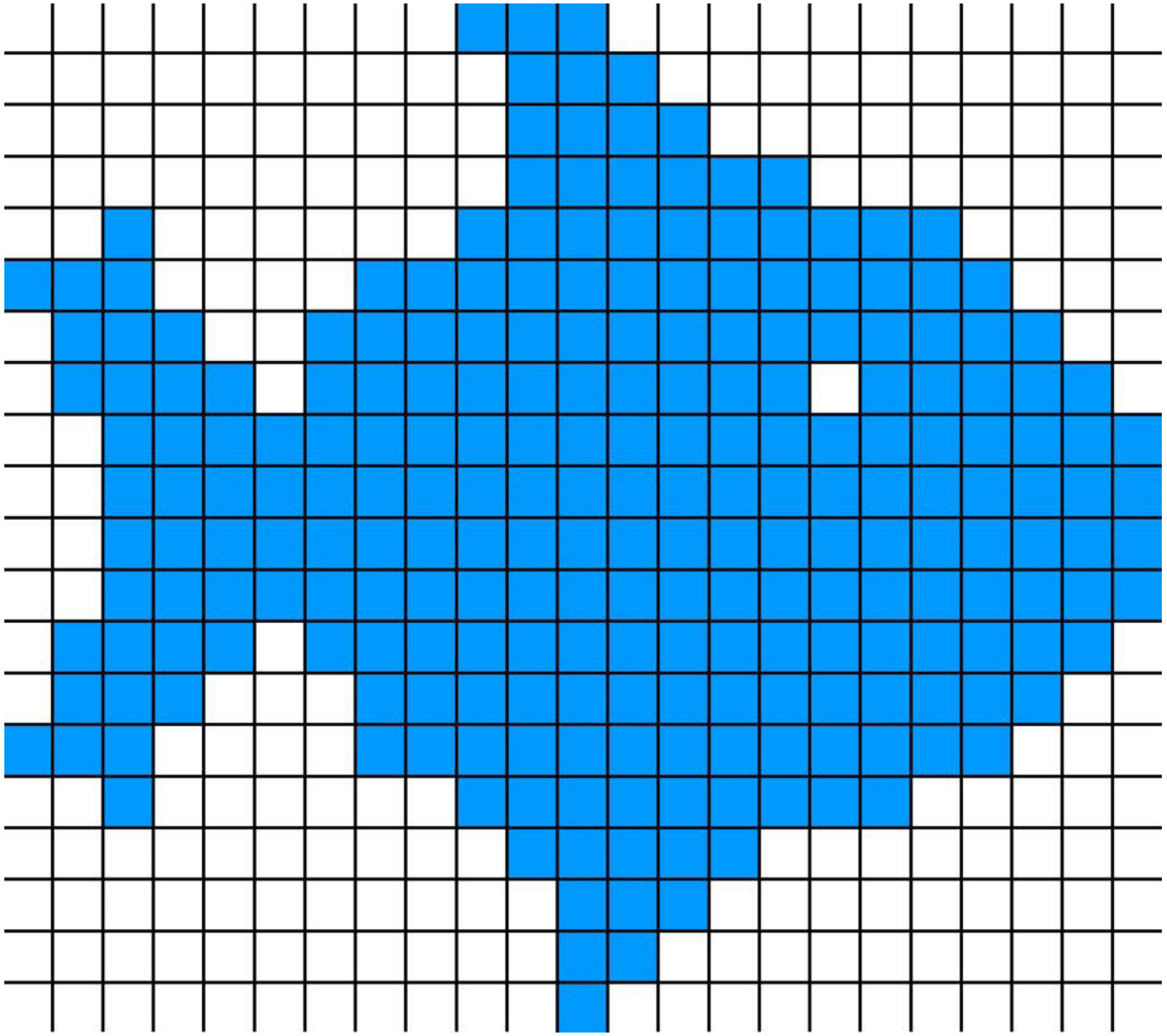
$R = 1/5$
$G = 3/5$
$B = 4/5$

$C = \frac{OP}{OP'} = B - R = 4/5 - 1/5 = 3/5 = .6$

$H = 60° \times \left(4 + \frac{R-G}{C}\right) = 60° \times (4 - 2/3) = 200°$



Raster Image



Data Types for Raster Images

Storage for 1024x1024 image (1 megapixel) = $2^{10} \times 2^{10}$ pixels

bitmap 1 bit per pixel (bpp) : 2^7KB or 128KB (2^3 pixels per byte)

grayscale 8bpp: 1MB

grayscale 16bpp: 2MB

color RGB 24bpp: 3MB

Q: Suppose you have a 767 X 772 rgb image stored in an array called `data`. How would you access the green value at the pixel on the 36th row and 89th column?

A: `data[1 + 3*(88+767*35)]` (Remember C++ starts counting with `0`).

color + alpha (transparency) 32bpp: 4MB

floating-point HDR color: 12MB (each of 3 color channels is a 32bit float i.e. 4B)

Assignment #1 tasks

`src/reflect.cpp`

Horizontally reflect an image (like a mirror)

`src/rotate.cpp`

Rotate an image 90^\circ counter-clockwise

Assignment #1 tasks

`src/rgb_to_gray.cpp`

Convert a 3-channel RGB image to a 1-channel grayscale image.

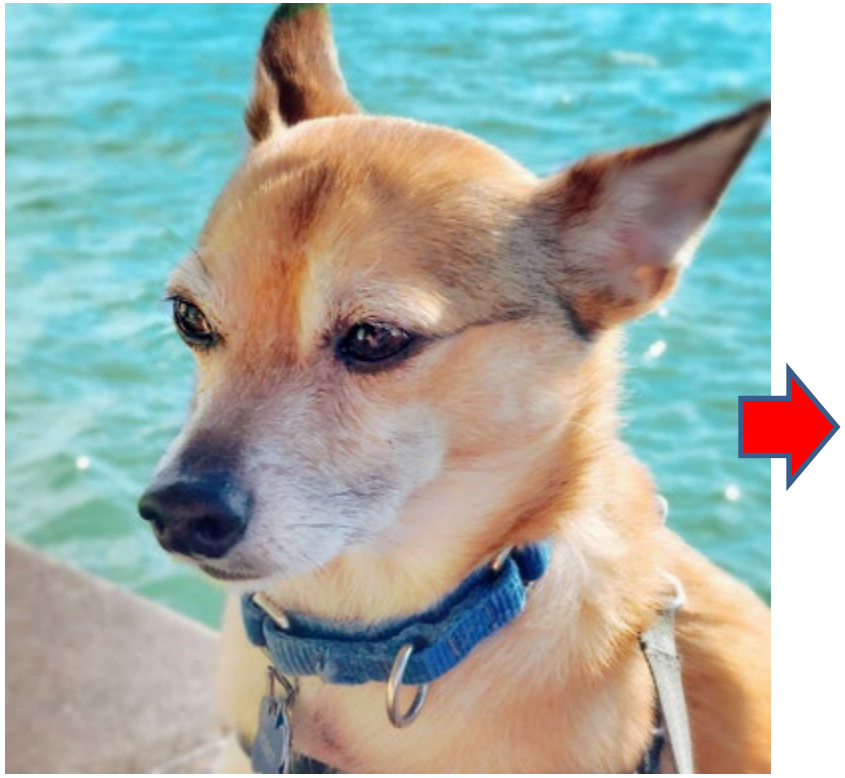
`src/demosaic.cpp`

Given a mosaiced image (interleaved GBRG colors in a single channel), created a 3-channel rgb image.

`src/simulate_bayer_mosaic.cpp`

Simulate an image acquired from the Bayer mosaic by taking a 3-channel rgb image and creating a single channel grayscale image composed of interleaved red/green/blue channels. The output image should be the same size as the input but only one channel.

Assignment #1 tasks



`src/rgb_to_hsv.cpp`

Convert a color represented by red, green and blue intensities to its representation using hue, saturation and value.

`src/hsv_to_rgb.cpp`

Convert a color represented by hue, saturation and value to its representation using red, green and blue intensities.

`src/hue_shift.cpp`

Shift the hue of a color rgb image.

Hint: Use your `rgb_to_hsv` and `hsv_to_rgb` functions.

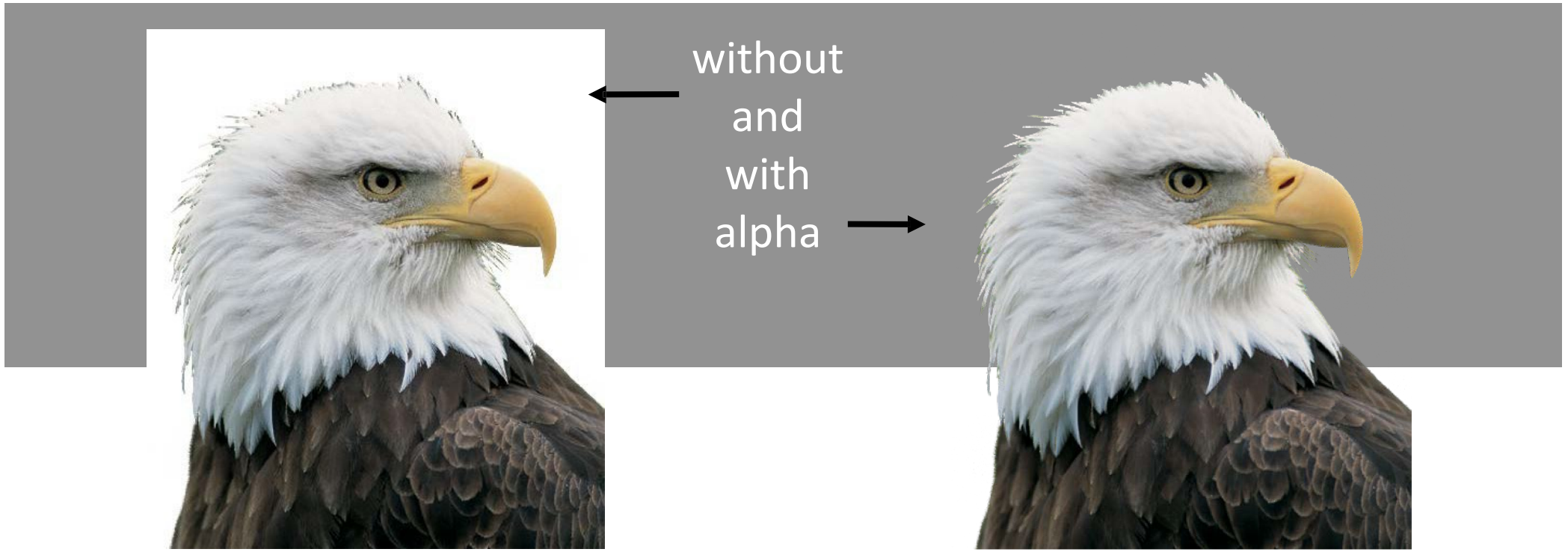
`src/desaturate.cpp`

Desaturate a given rgb color image by a given factor.

Hint: Use your `rgb_to_hsv` and `hsv_to_rgb` functions.

Transparency

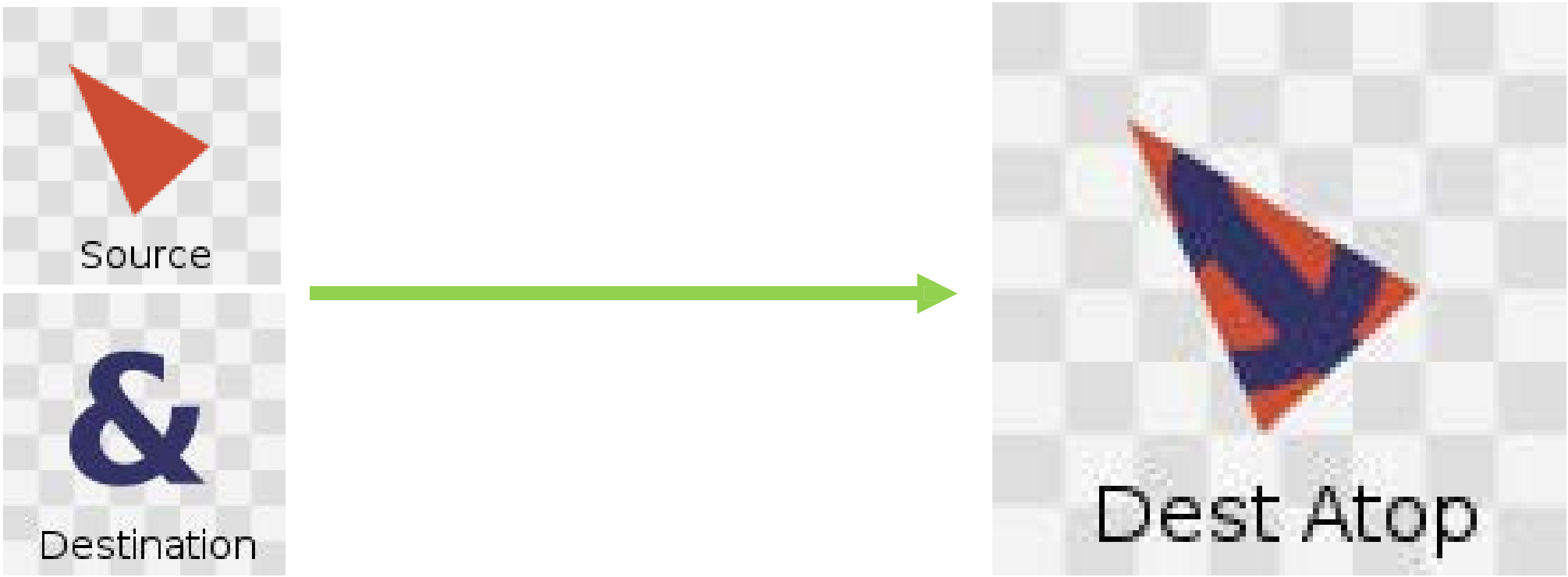
Append (Red, Green, Blue) to be (Red, Green, Blue, Alpha)



$$\mathbf{c} = \alpha \mathbf{c}_f + (1 - \alpha)\mathbf{c}_b.$$

Compositing

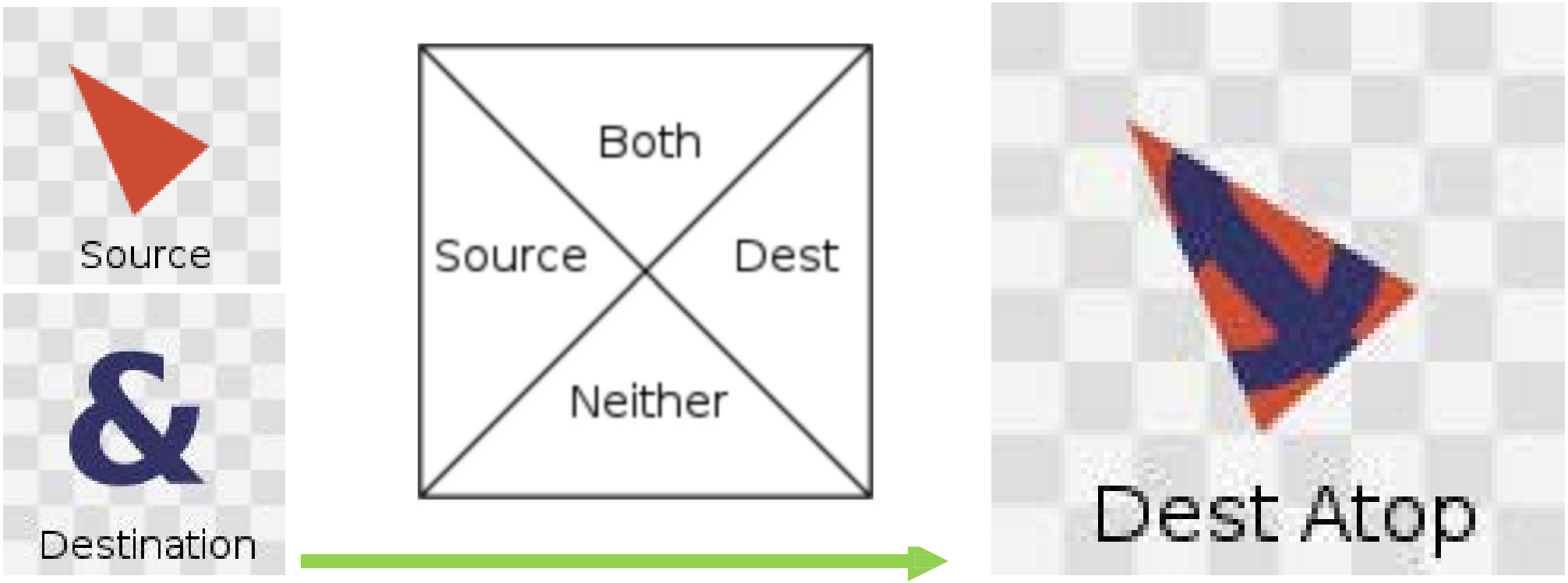
Compositing is about layering images on top of one another



http://ssp.impulsetrain.com/porterduff.html

Compositing

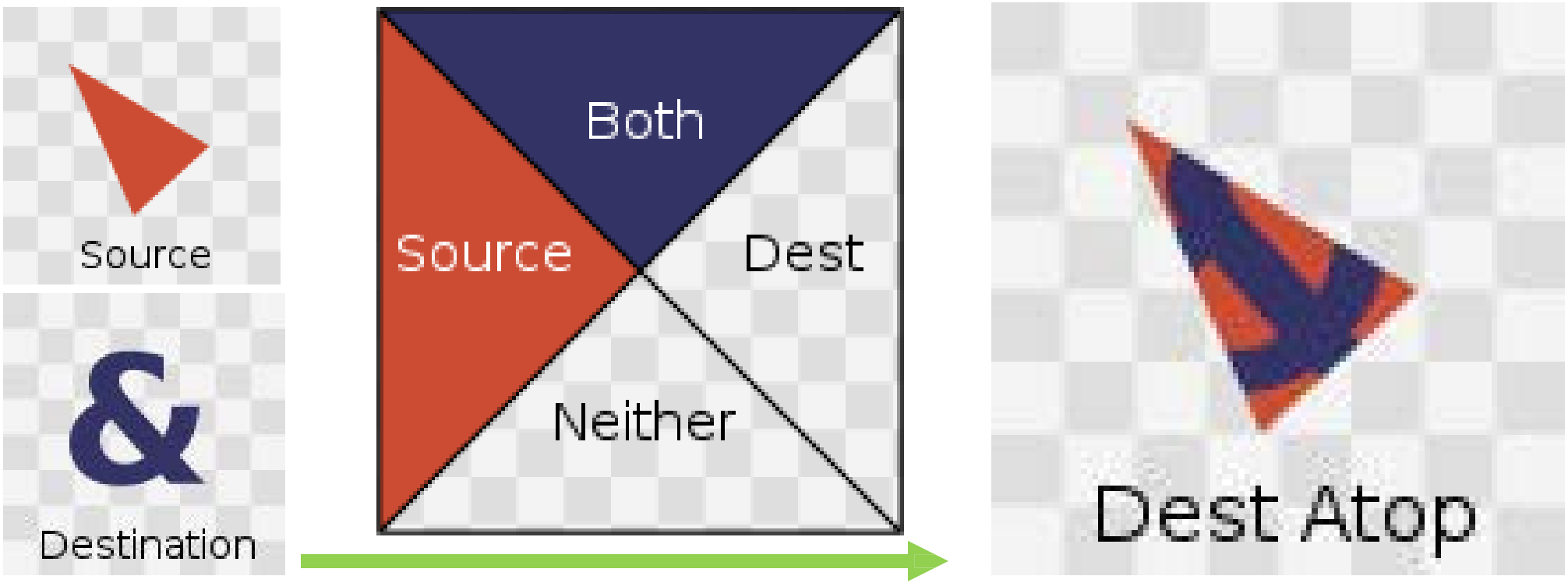
Compositing is about layering images on top of one another



http://ssp.impulsetrain.com/porterduff.html

Compositing

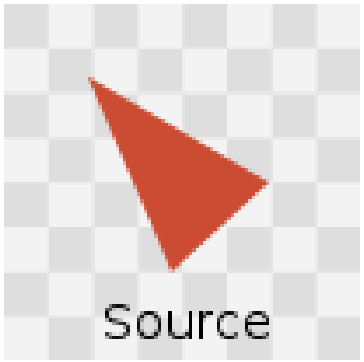
Compositing is about layering images on top of one another



http://ssp.impulsetrain.com/porterduff.html

Compositing

Compositing is about layering images on top of one another



$$A_{\text{src}} \cdot [s] + A_{\text{dest}} \cdot [d] + A_{\text{both}} \cdot [b]$$

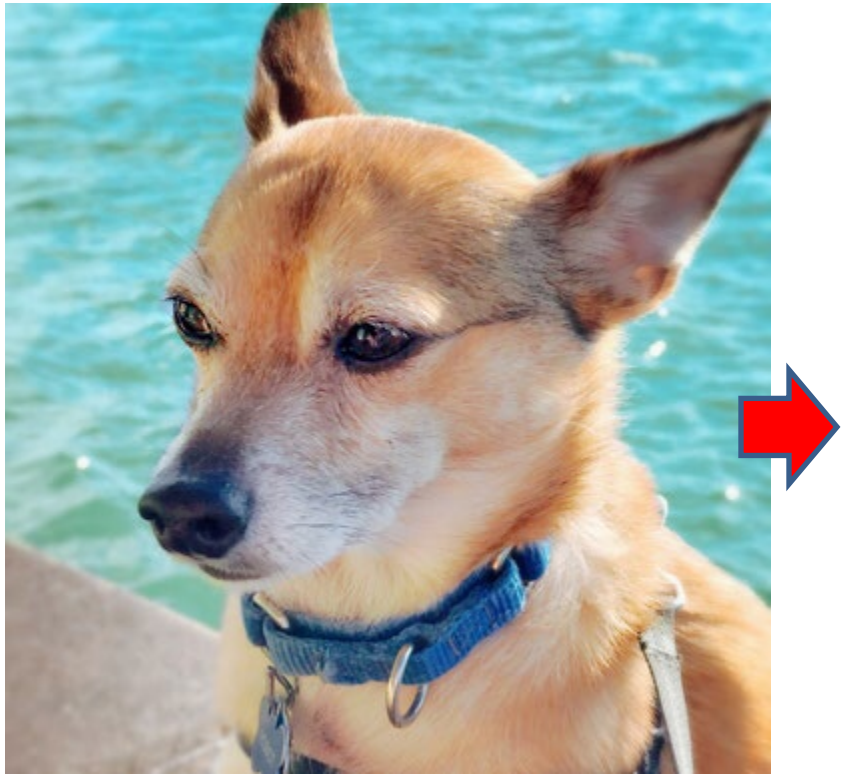
$B(s, d)$ for color blending

$$A_{\text{src}} = \alpha_{\text{s}} \cdot (1 - \alpha_{\text{d}})$$
$$A_{\text{dst}} = \alpha_{\text{d}} \cdot (1 - \alpha_{\text{s}})$$
$$A_{\text{both}} = \alpha_{\text{s}} \cdot \alpha_{\text{d}}$$

	[s]	[d]	[b]
Src	*s*	0	s
Atop	0	*d*	s
Over	*s*	*d*	s
In	0	0	s
Out	*s*	0	0
Dest	0	*d*	d
DestAtop	*s*	0	d
DestOver	*s*	*d*	d
DestIn	0	0	d
DestOut	0	*d*	0
Clear	0	0	0
Xor	*s*	*d*	0

http://ssp.impulsetrain.com/porterduff.html

Assignment #1 tasks



`src/over.cpp`

Compute C = A Over B, where A and B are semi-transparent rgba images and "Over" is the Porter-Duff Over operator.

Raster Image issues: Gamma Correction

Linear encoding V_S =	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Linear intensity I =	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0

Display intensity is nonlinear wrt input intensity

Raster Image issues: Gamma Correction

$$\text{displayed intensity} = (\text{maximum intensity})a^{\gamma}$$

gamma

… of display

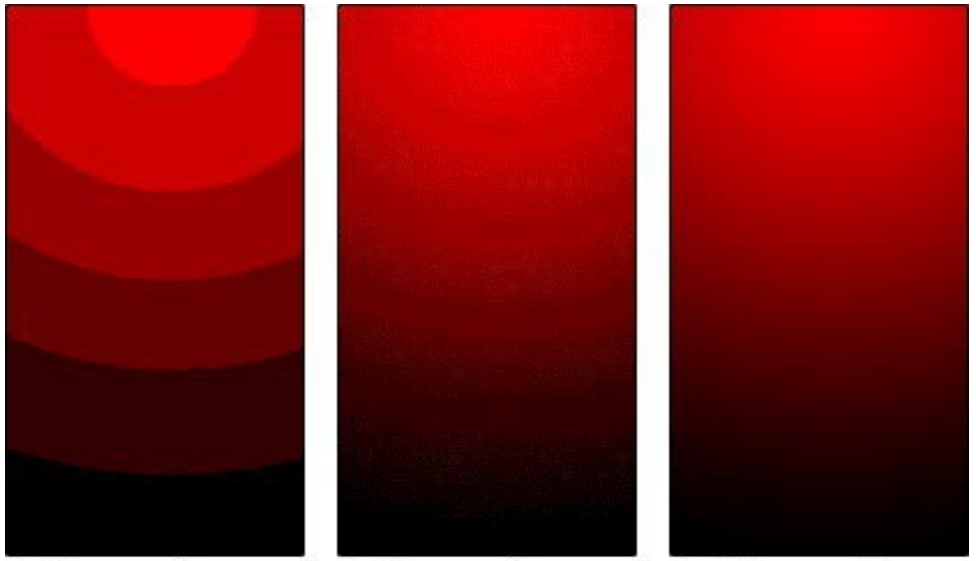
image amplitude [0,1]

Measuring Gamma for a display:

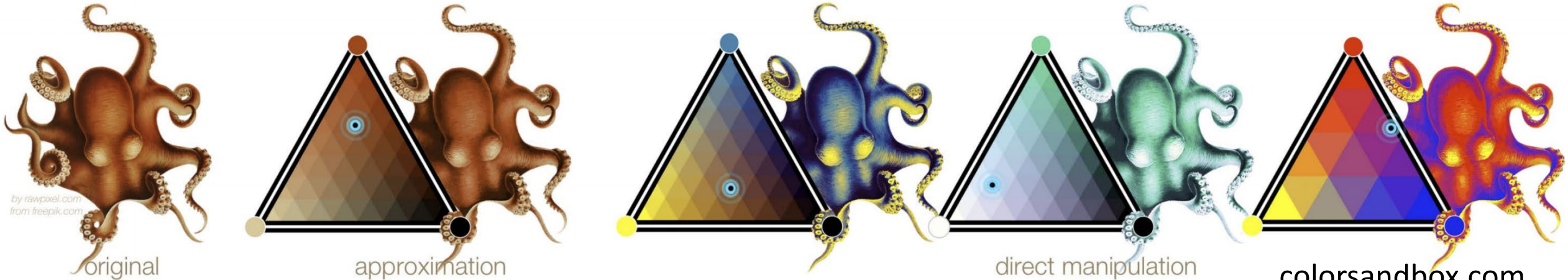
find image amplitude a for ½ display brightness => $\gamma = \frac{\ln 0.5}{\ln a}$

γ=0.25 γ=0.5 γ=1.0 γ=1.5 γ=2.0

Raster Image issues: Banding

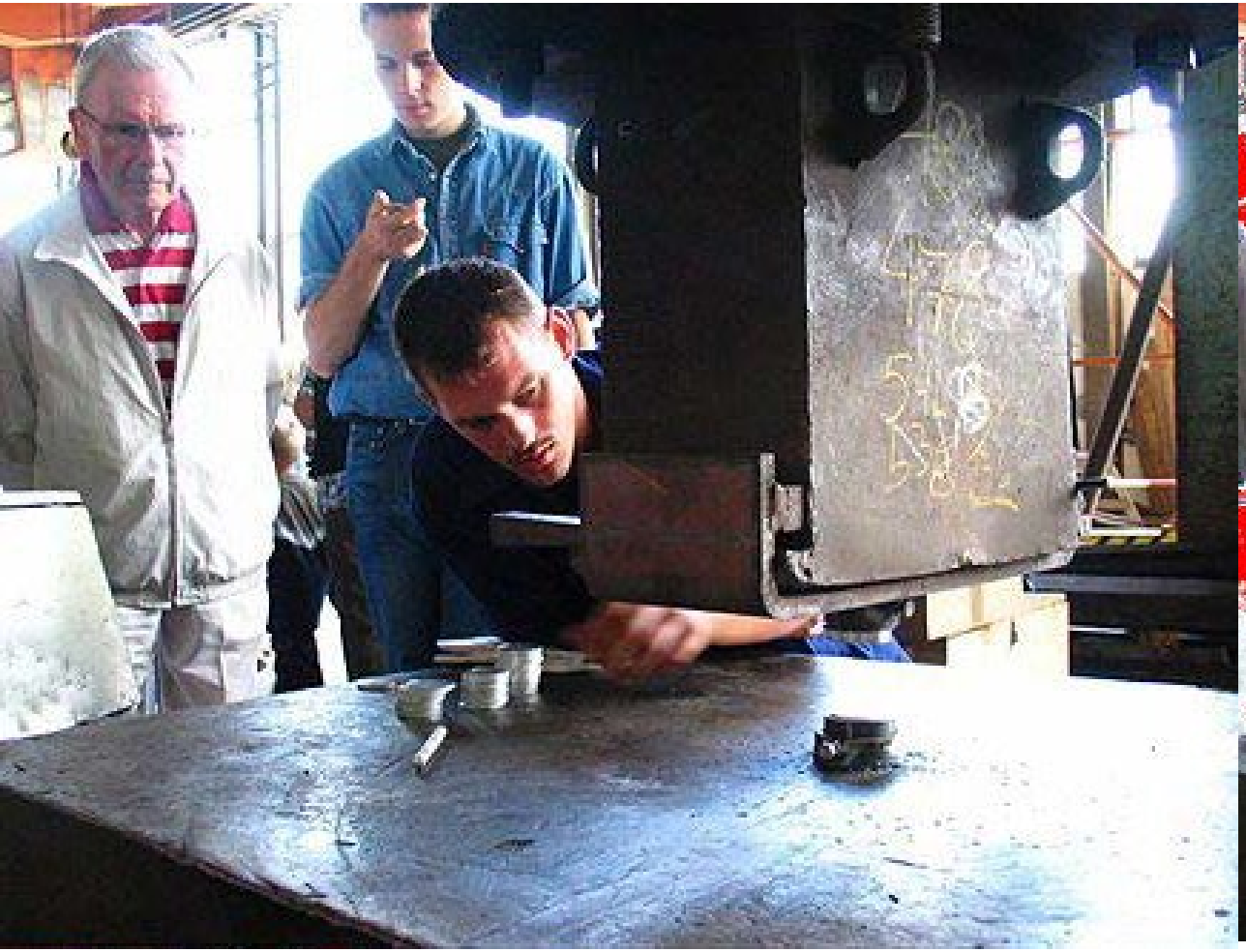


8-bit gradient | 8-bit gradient, dithered | 24-bit gradient



colorsandbox.com

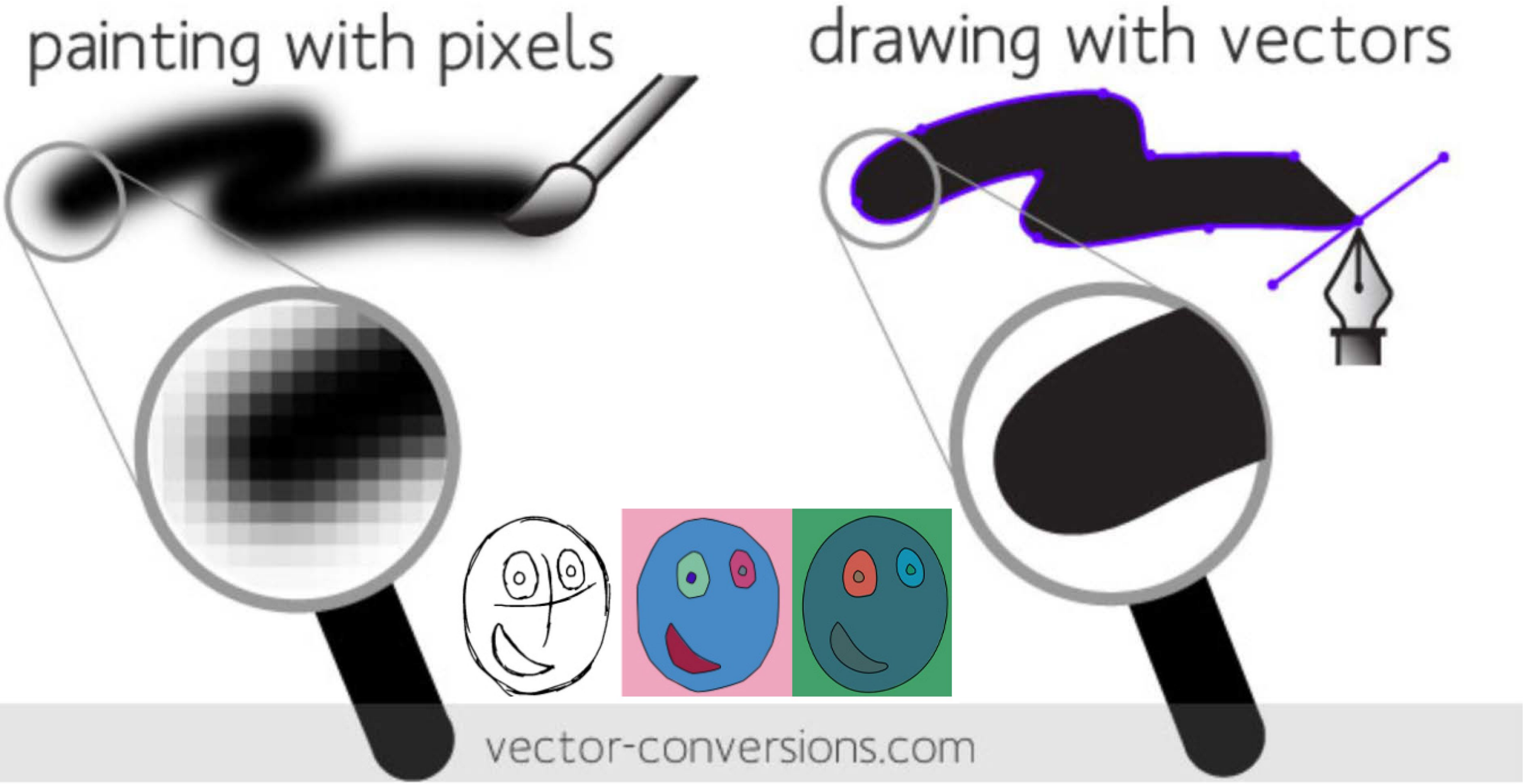
Raster Image issues: Clipping



Original

Clipped

Aside: More Than Just Raster Images



Assignment 1

Available Right Now

Next Week: Ray Casting