University of British Columbia
CPSC 314 Computer Graphics
May-June 2005

Tamara Munzner

Intro, Math Review, OpenGL Pipeline

Week 1, Tue May 10

http://www.ugrad.cs.ubc.ca/~cs314/Vmay2005

Introduction

Expectations

- hard course!
  - heavy programming and heavy math
- fun course!
  - graphics programming addictive, create great demos
- programming prereq
  - CPSC 216 (Program Design and Data Structures)
  - course language is C++/C
- math prereq
  - MATH 200 (Calculus III)
  - MATH 221/223 (Matrix Algebra/Linear Algebra)

Course Structure

- 45% programming projects
  - 9% project 1 (building beasties with cubes and math)
  - 9% project 2 (flying)
  - 9% project 3 (shaded terrain)
  - 18% project 4 (create your own graphics game)
- 25% final
- 15% midterm (week 4, Tue 5/31)
- 15% written assignments
  - 5% each HW 1/2/3
- programming projects and homeworks synchronized

Programming Projects

- structure
  - C++, Linux
    - OK to cross-platform develop on Windows
  - OpenGL graphics library
  - GLUT for platform-independent windows/UI
  - face to face grading in lab
- Hall of Fame
  - project 1: building beasties
    - previous years: elephants, birds, poodles
  - project 4: create your own graphics game

Late Work

- 3 grace days
  - for unforeseen circumstances
  - strong recommendation: don't use early in term
  - handing in late uses up automatically unless you tell us
- otherwise: 25% per 24 hours
  - no work accepted after solutions handed out
- exception: severe illness or crisis, as per UBC rules
  - let me know ASAP (in person or email)
  - must also turn in form with documentation

http://www.ugrad.cs.ubc.ca/~cs314/Vjan2005/illness.html

Regrading

- to request assignment or exam regrade
  - must submit detailed written explanation of why you think the grader was incorrect for the particular problem that you are disputing
- I may regrade entire assignment
  - thus even if I agree with your original request, your score may end up higher or lower

Course Information

- course web page is main resource
  - http://www.ugrad.cs.ubc.ca/~cs314/Vmay2005
  - updated often, reload frequently
- newsgroup is ubc.courses.cpsc.414
  - note old course number still used
  - readable on or off campus
- (no WebCT)

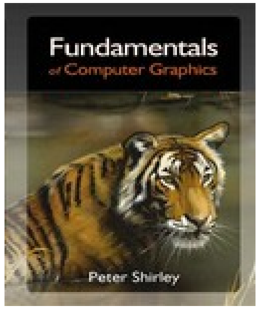
Labs

- attend two labs per week, 3 sessions each
  - Tue/Thu 11-12, 3-4, 4-5
    - Thursday afternoon better than Thu morning
  - Tuesdays: example problems in spirit of written assignments and exams
  - Thursdays: help with programming projects
  - no deliverables
  - strongly recommend that you attend

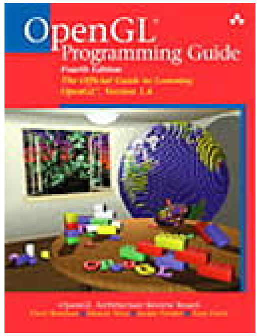
Teaching Staff

- instructor: Dr. Munzner
  - tmm@cs.ubc.ca
  - office hrs in CICSR 011
    - Mon 4:30-5:30
- TAs: Warren Cheung, Greg Kempe
  - wcheung@cs.ubc.ca
  - kempe@cs.ubc.ca
- use newsgroup not email for all questions that other students might care about

Required Reading



- Fundamentals of Computer Graphics
  - Peter Shirley, AK Peters



- OpenGL Programming Guide, v 1.4
  - OpenGL Architecture Review Board
  - v 1.1 available for free online

- readings posted on schedule page

Learning OpenGL

- this is a graphics course using OpenGL
  - not a course *on* OpenGL
- upper-level class: learning APIs mostly on your own
  - only minimal lecture coverage
    - basics, some of the tricky bits
  - OpenGL Red Book
  - many tutorial sites on the web
    - nehe.gamedev.net

Plagiarism and Cheating

- don’t cheat, I will prosecute
  - insult to your fellow students and to me
- programming and assignment writeups must be individual work
  - exception: project 3 can be team of two
  - can discuss ideas, browse Web
  - but cannot just copy code or answers
- you must be able to explain algorithms during face-to-face demo
  - or no credit for that part of assignment, possible prosecution

Citation

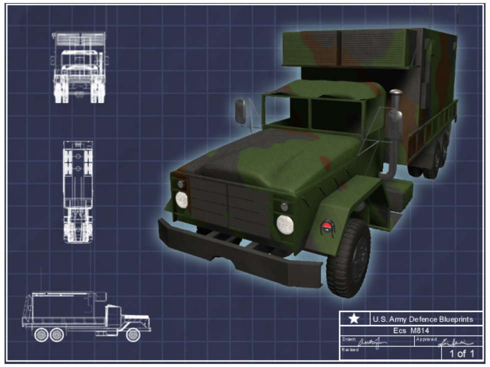
- cite all sources of information
  - web sites, study group members, books
  - README for programming projects
  - end of writeup for written assignments
  - http://www.ugrad.cs.ubc.ca/~cs314/Vmay2005/policies.html#plag

What is Computer Graphics?

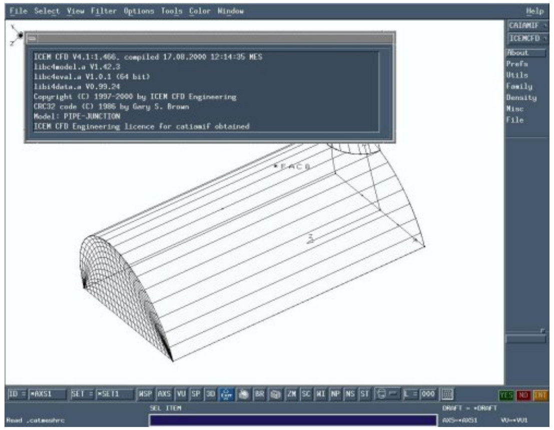
- create or manipulate images with computer
  - this course: algorithms for image generation

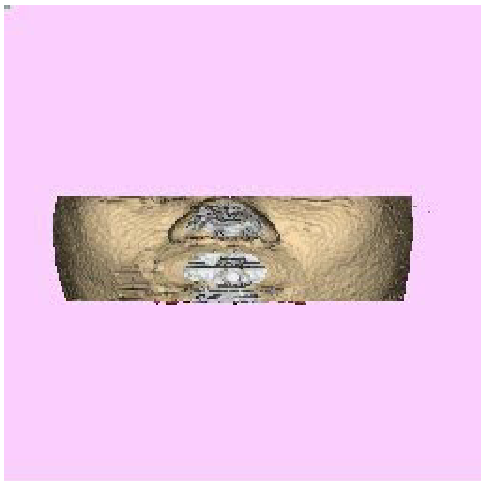
What is CG used for?

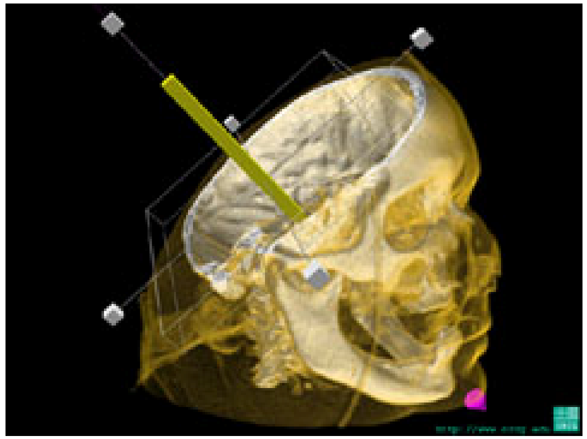
- graphical user interfaces
  - modeling systems
  - applications



- simulation & visualization







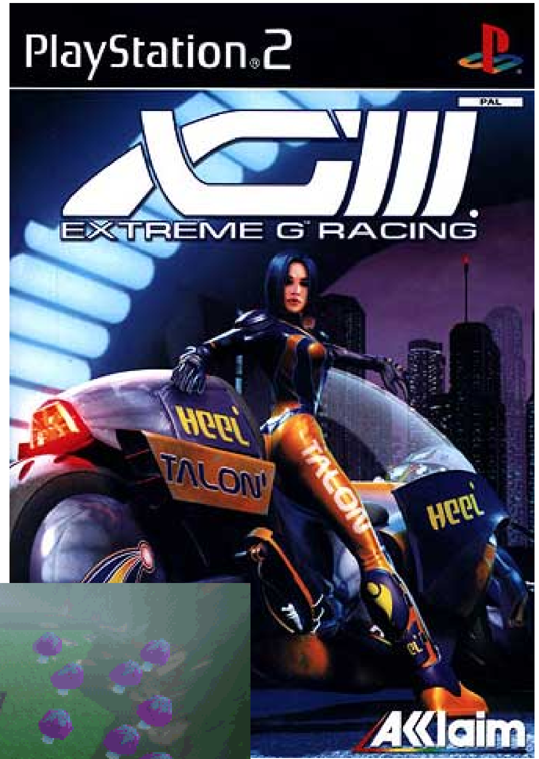
What is CG used for?

- movies
  - animation
  - special effects

Inspector Gadget © 1999 Walt Disney Pictures.
Visual Effects by Dream Quest Images.

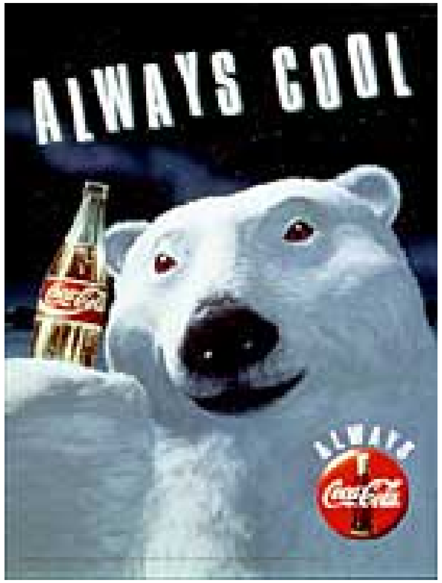
What is CG used for?

- computer games



What is CG used for?

- images
  - design
  - advertising
  - art



What is CG used for?

- virtual reality / immersive displays

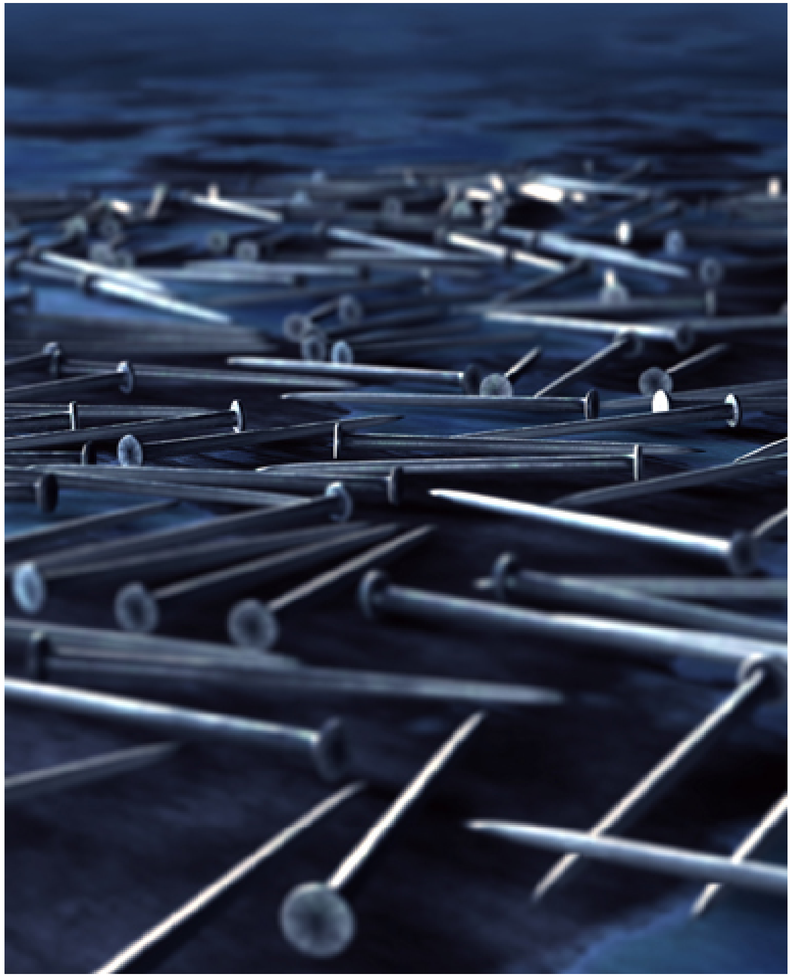
Real or CG?

http://www.alias.com/eng/etc/fakeorfoto/quiz.html

1

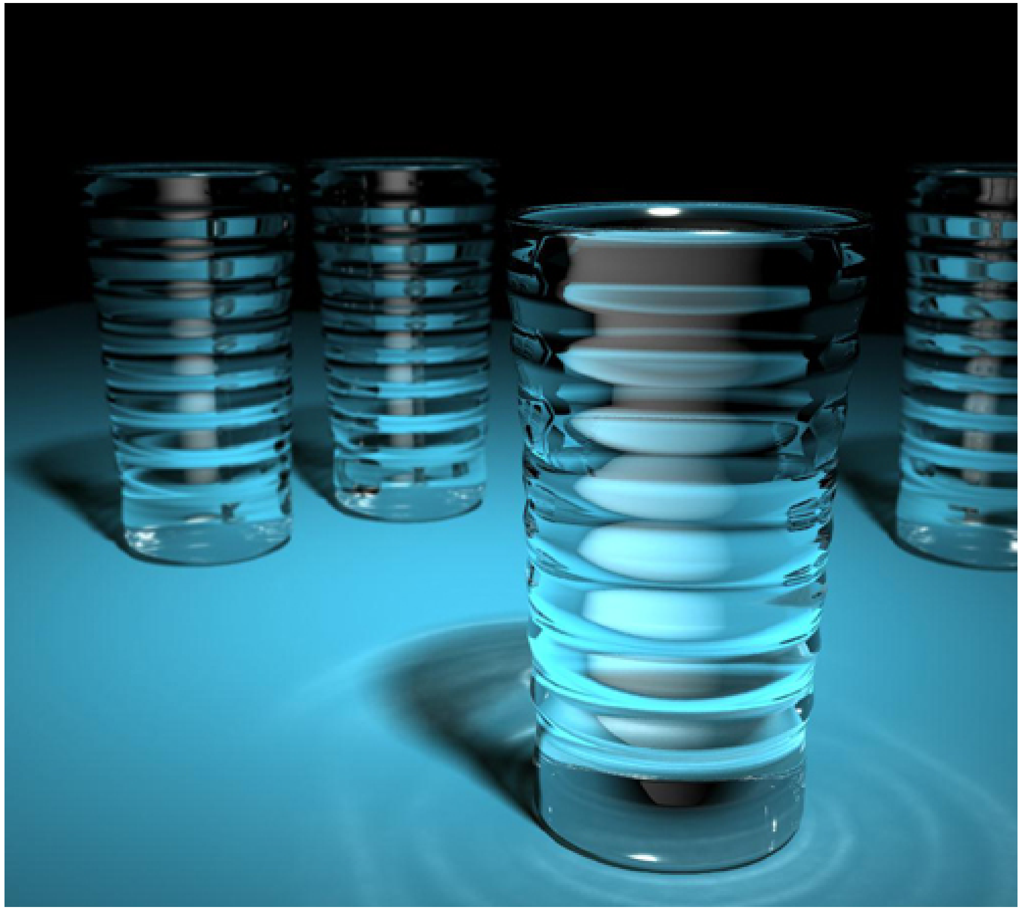
Real or CG?

2



Real or CG?

3



Real or CG?

4

This Course

- we cover
  - basic **algorithms** for
    - rendering – displaying models
    - (modeling – generating models)
    - (animation – generating motion)
  - programming in OpenGL, C++
- we do not cover
  - art/design issues
  - commercial software packages

Other Graphics Courses

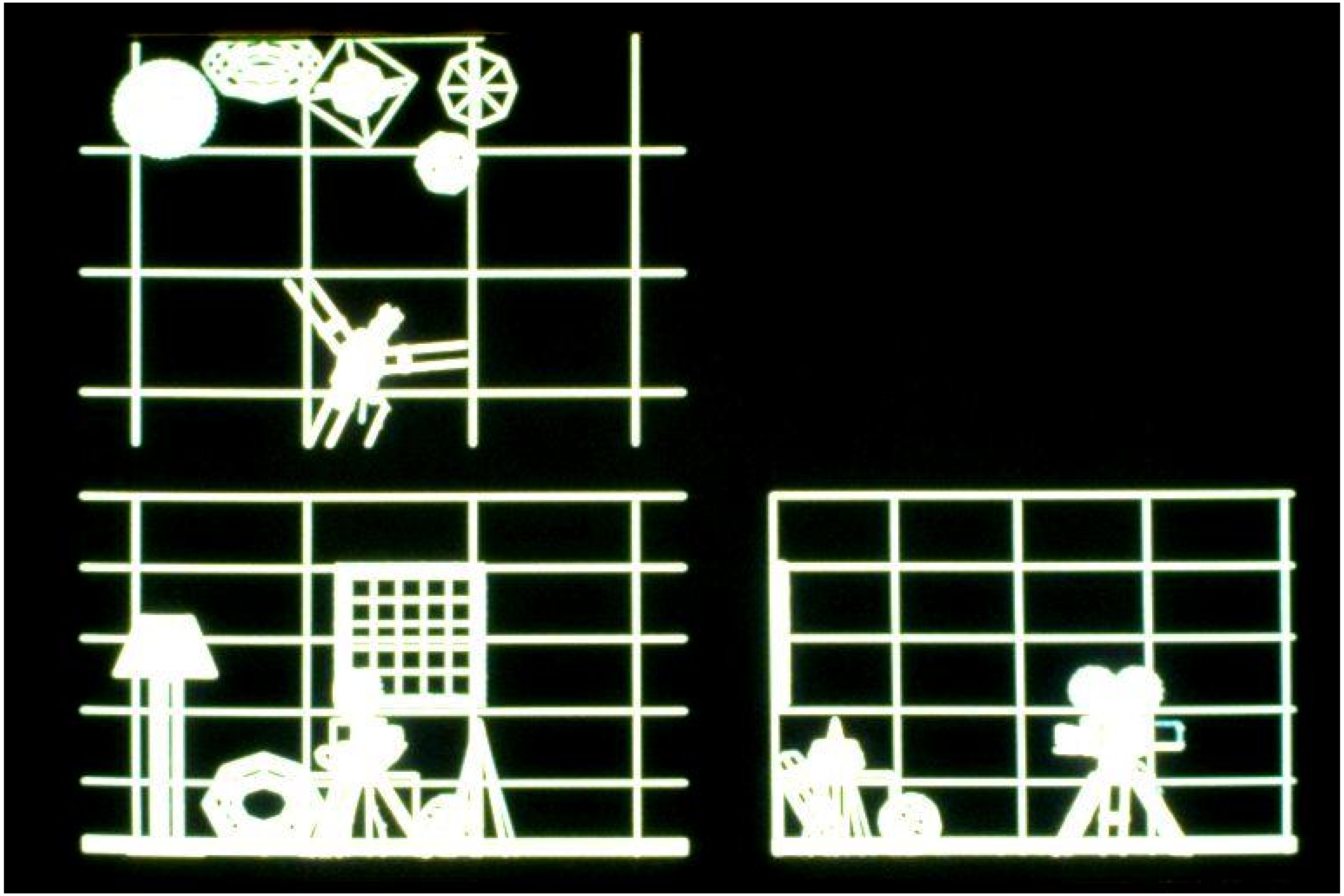
- CPSC 424: Geometric Modeling
- CPSC 426: Computer Animation

- CPSC 514: Image-based Modeling and Rendering
- CPSC 526: Computer Animation
- CPSC 533A: Digital Geometry
- CPSC 533B: Animation Physics
- CPSC 533C: Information Visualization

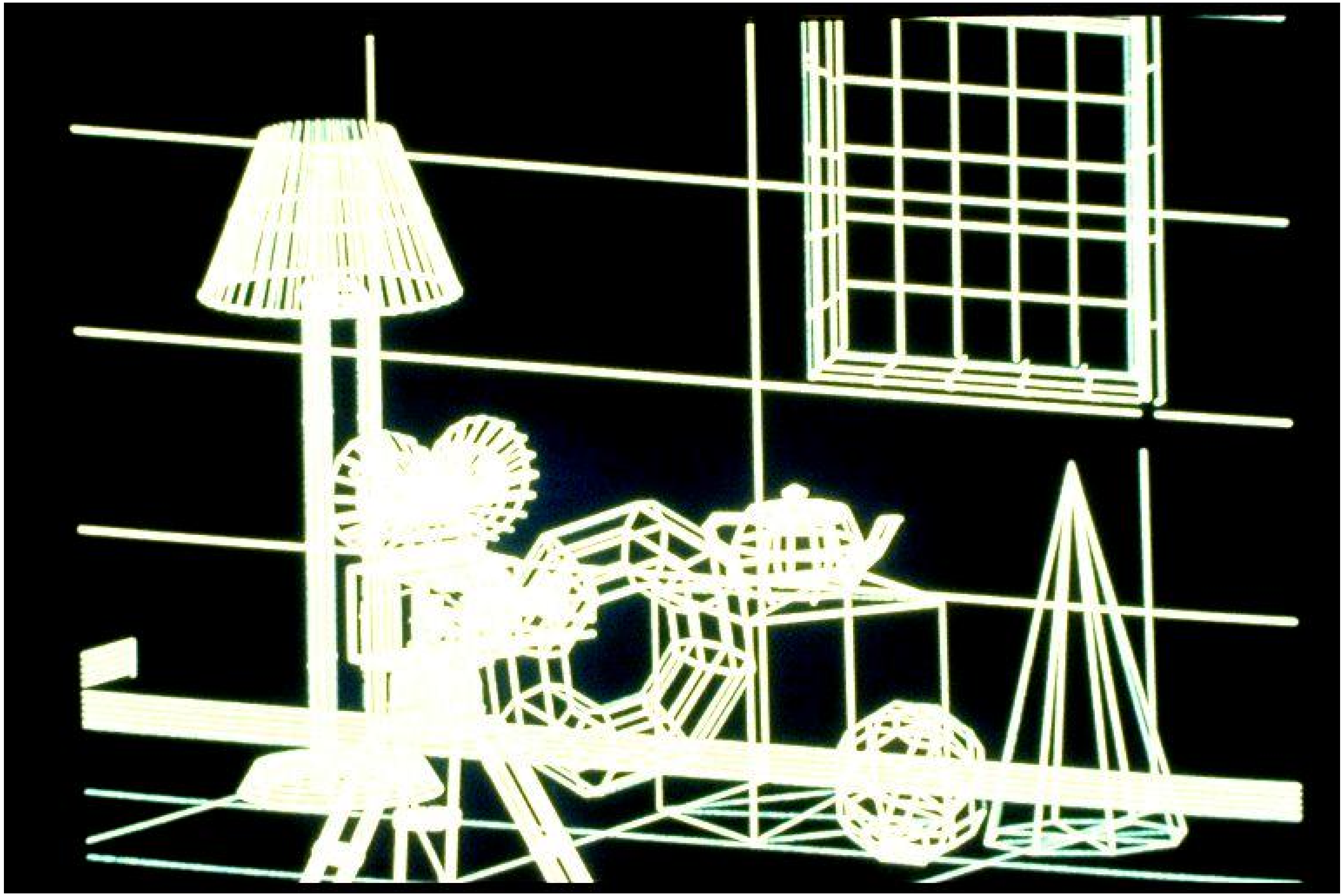
Rendering

- creating images from models
  - geometric objects
    - lines, polygons, curves, curved surfaces
  - camera
    - pinhole camera, lens systems, orthogonal
  - shading
    - light interacting with material
- Pixar Shutterbug series
  - Williams and Siegel using Renderman, 1990
  - www.siggraph.org/education/ materials/HyperGraph/shutbug.htm

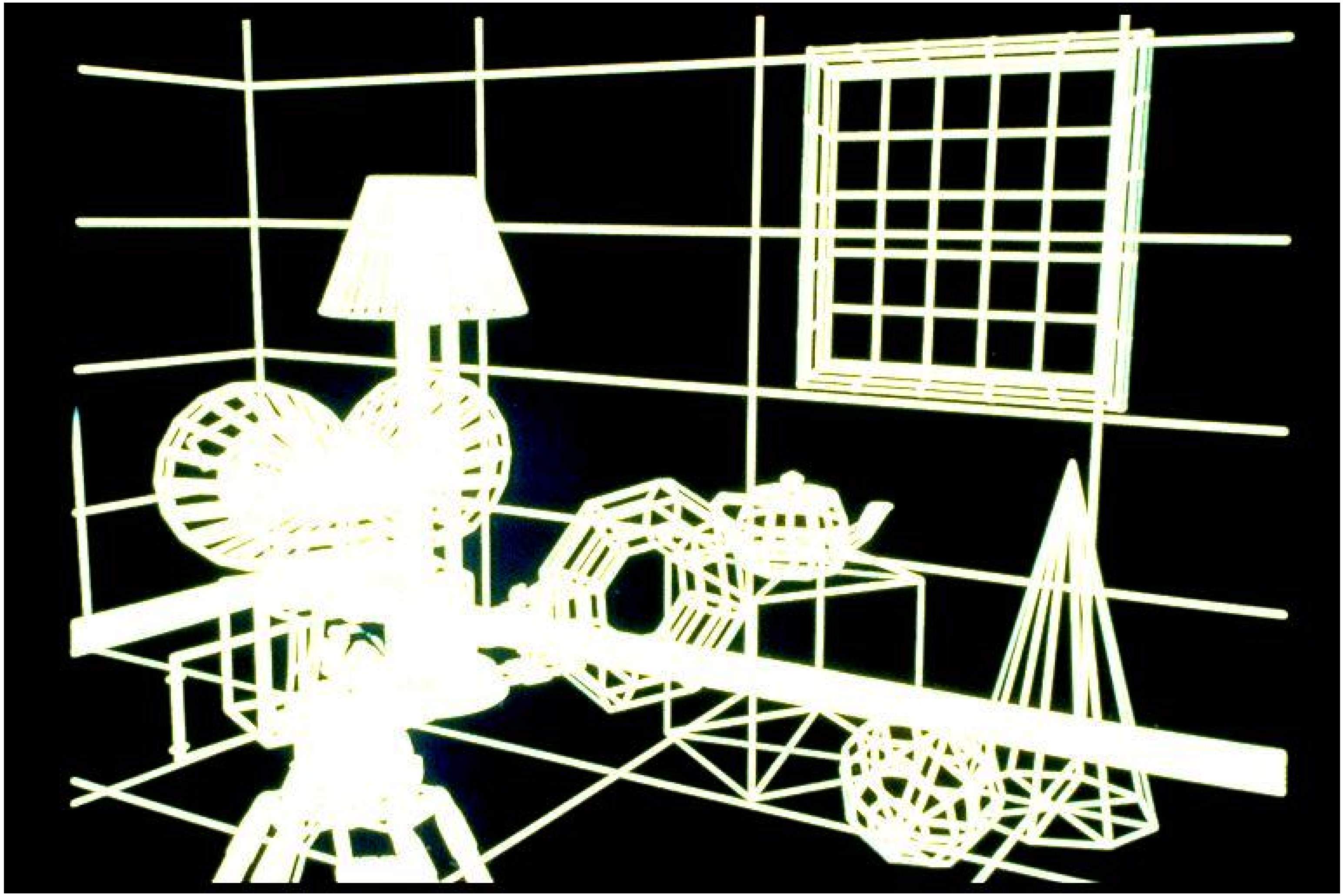
Modelling Transformation: Object Placement



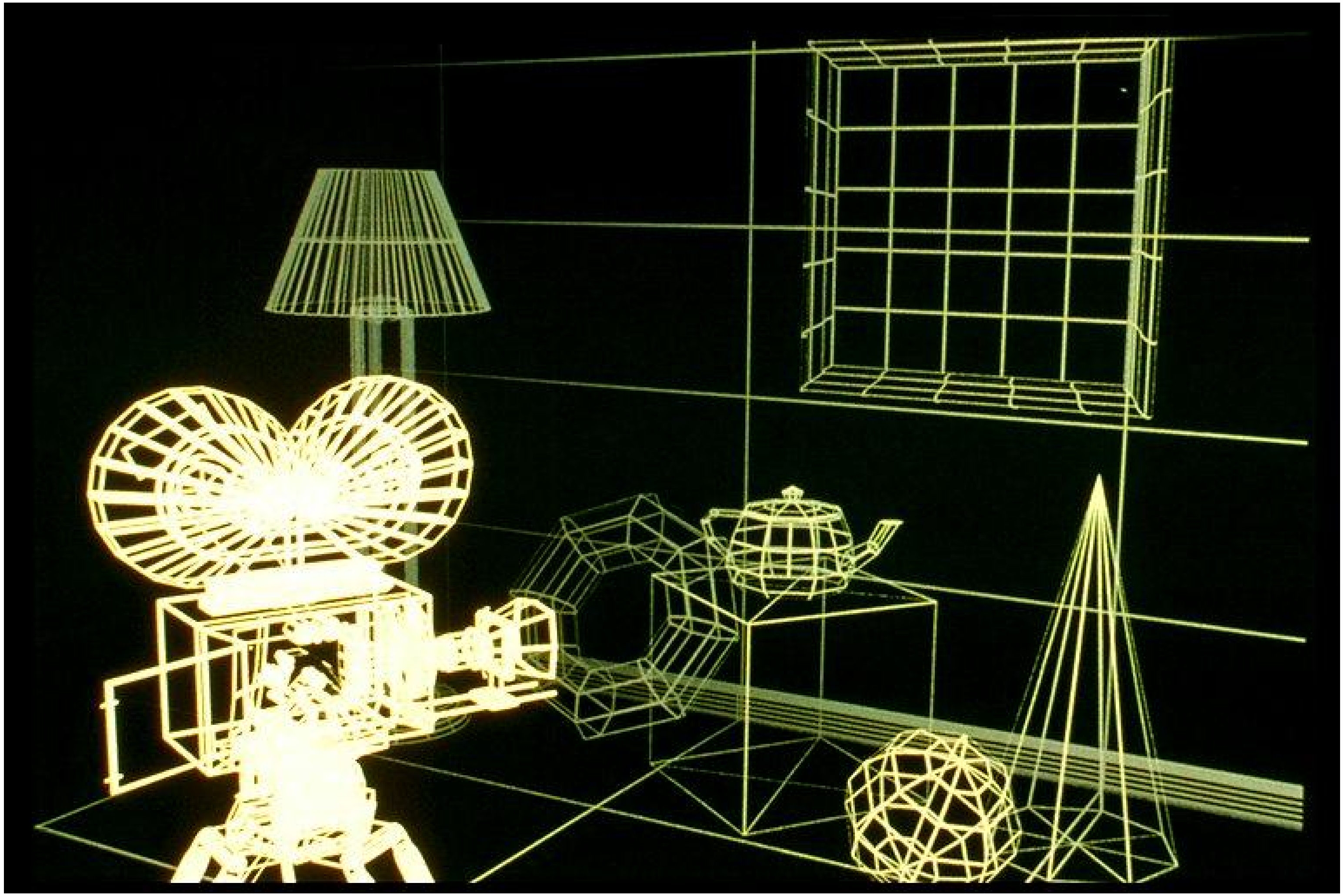
Viewing Transformation: Camera Placement



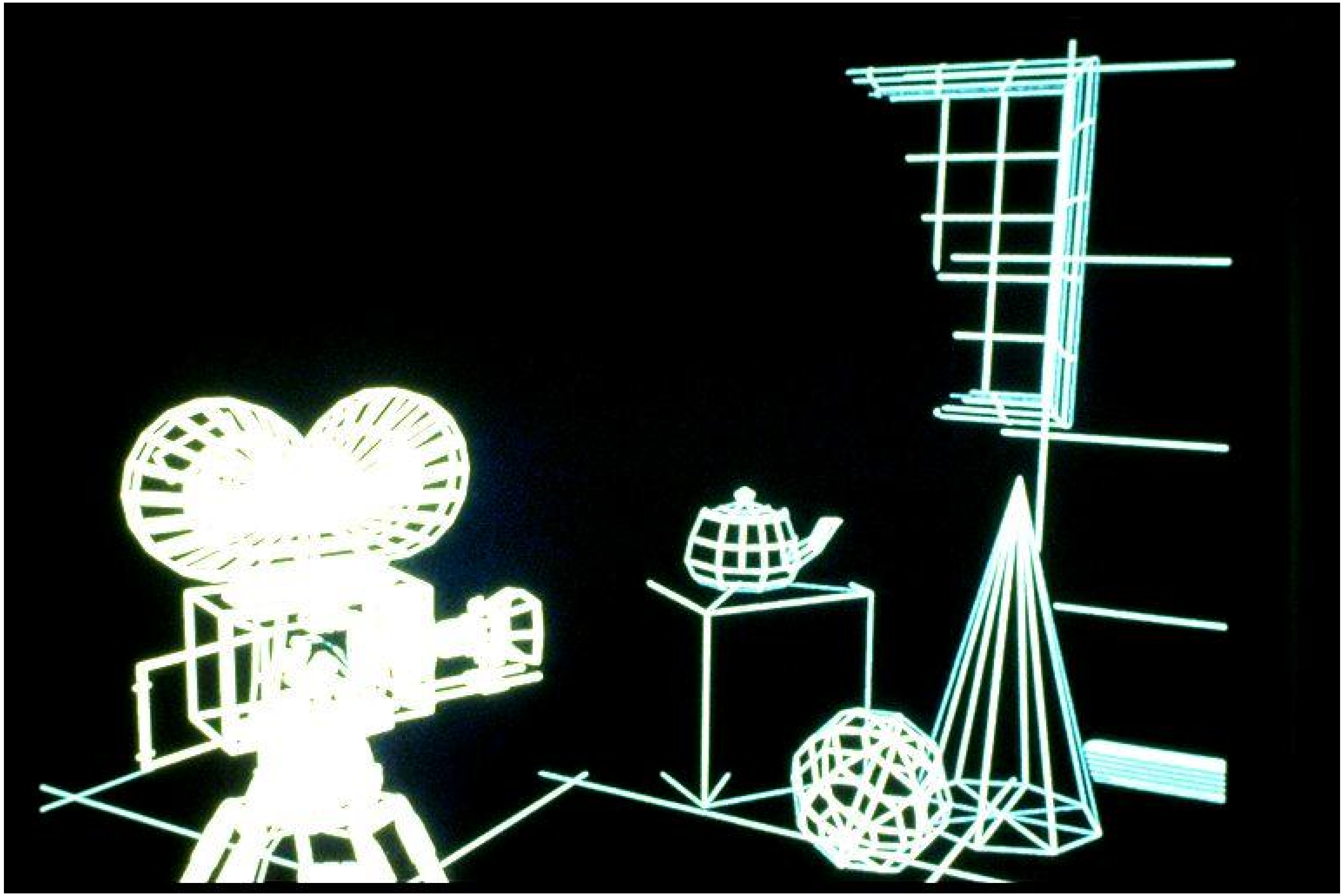
Perspective Projection



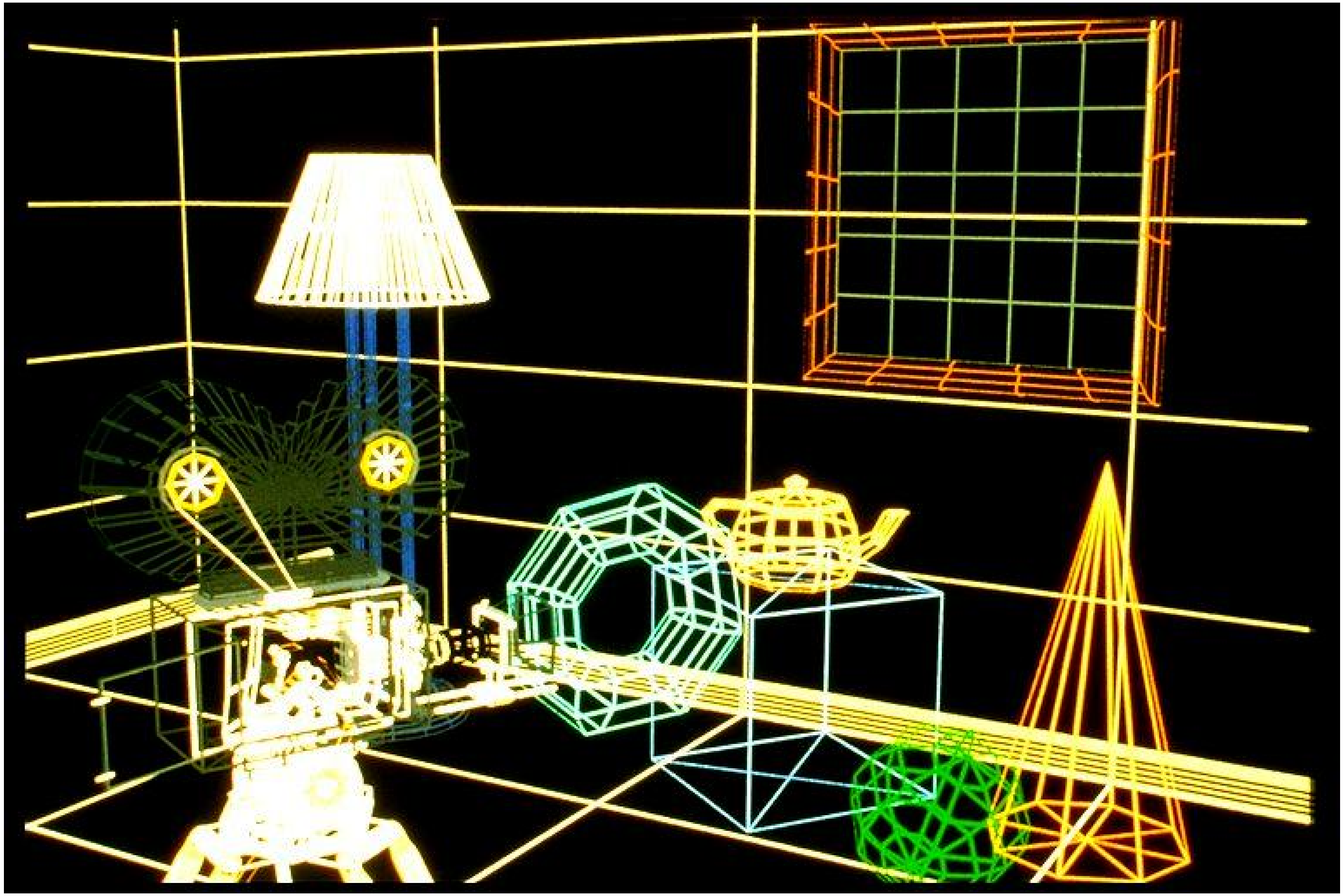
Depth Cueing



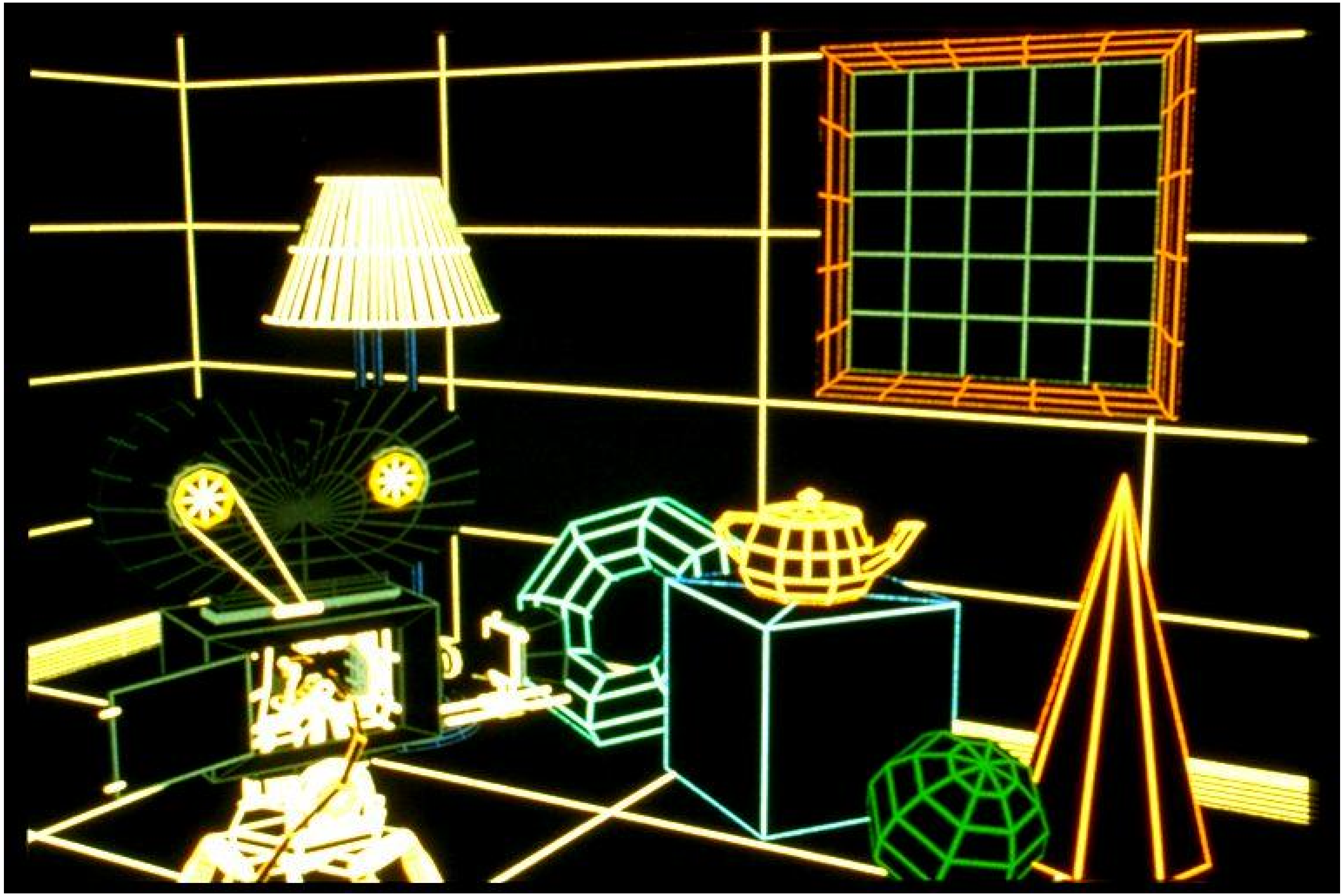
Depth Clipping



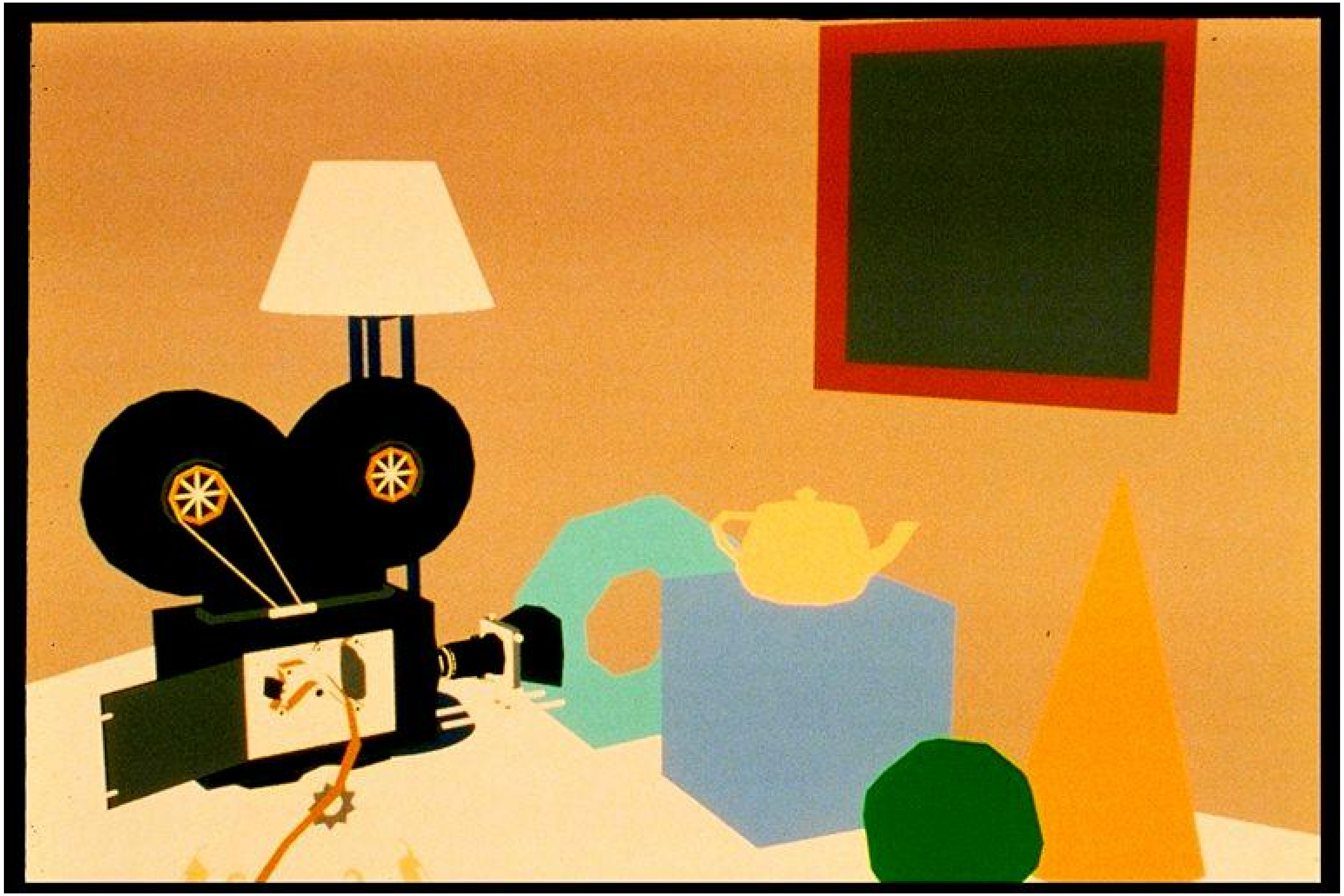
Colored Wireframes



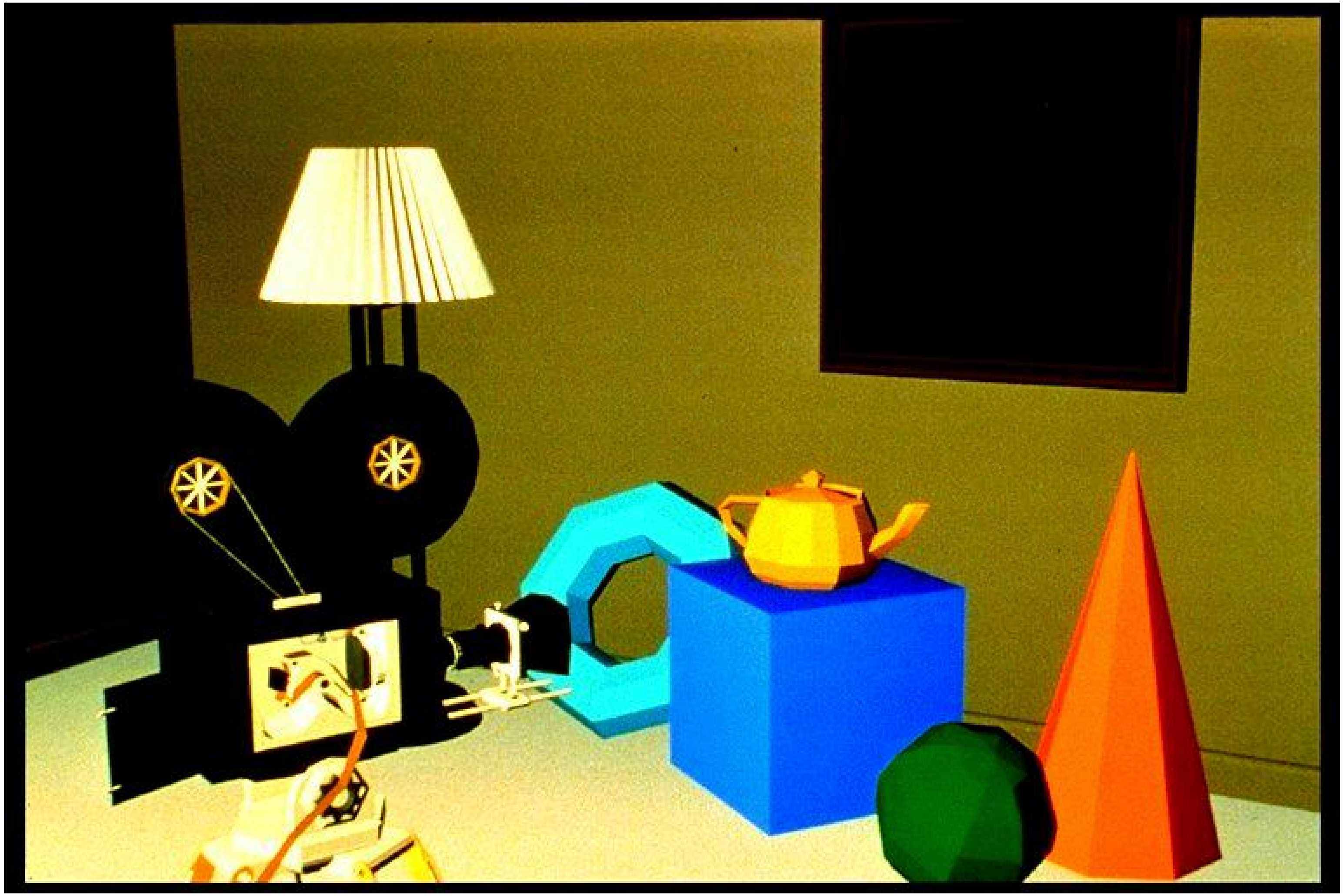
Hidden Line Removal



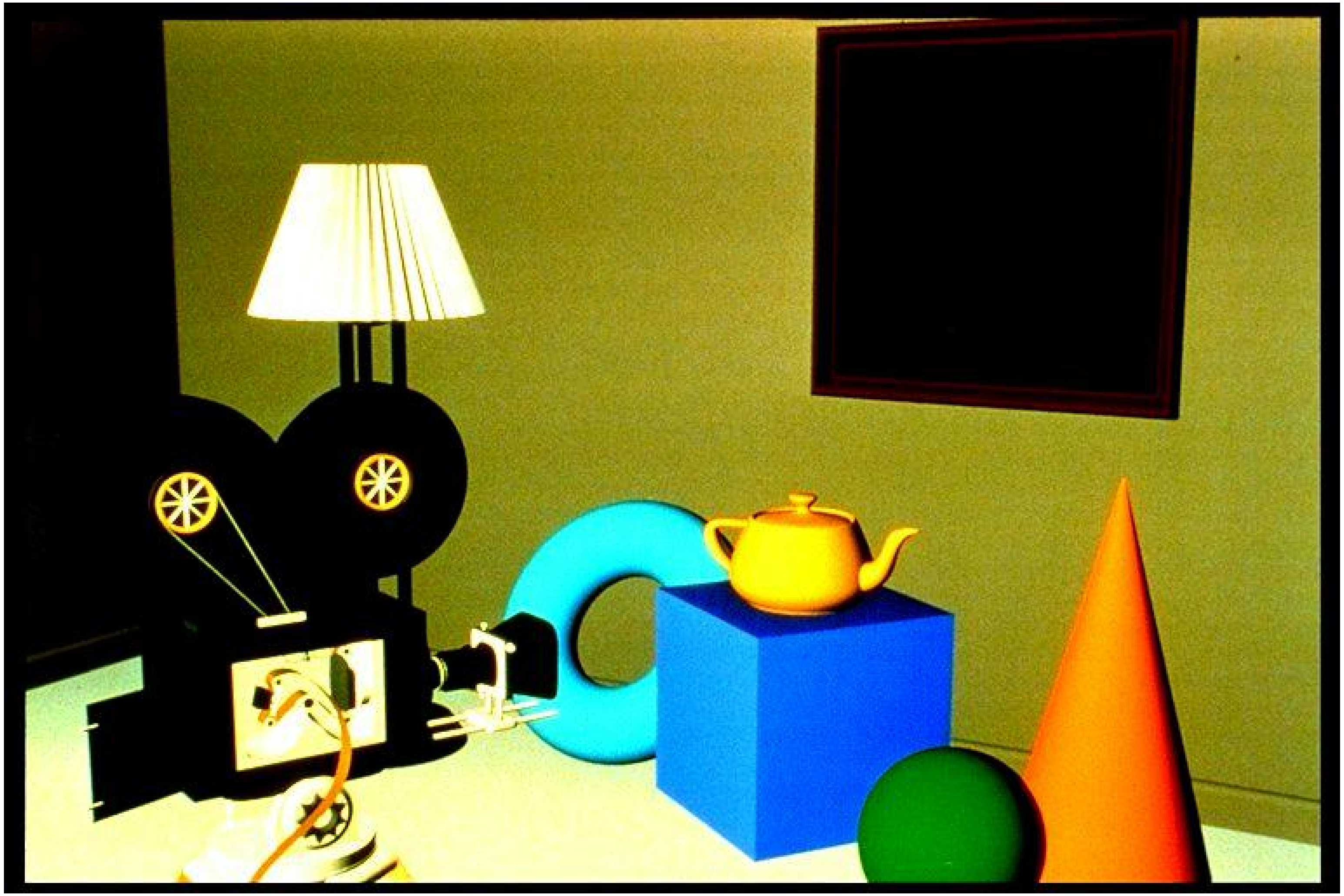
Hidden Surface Removal



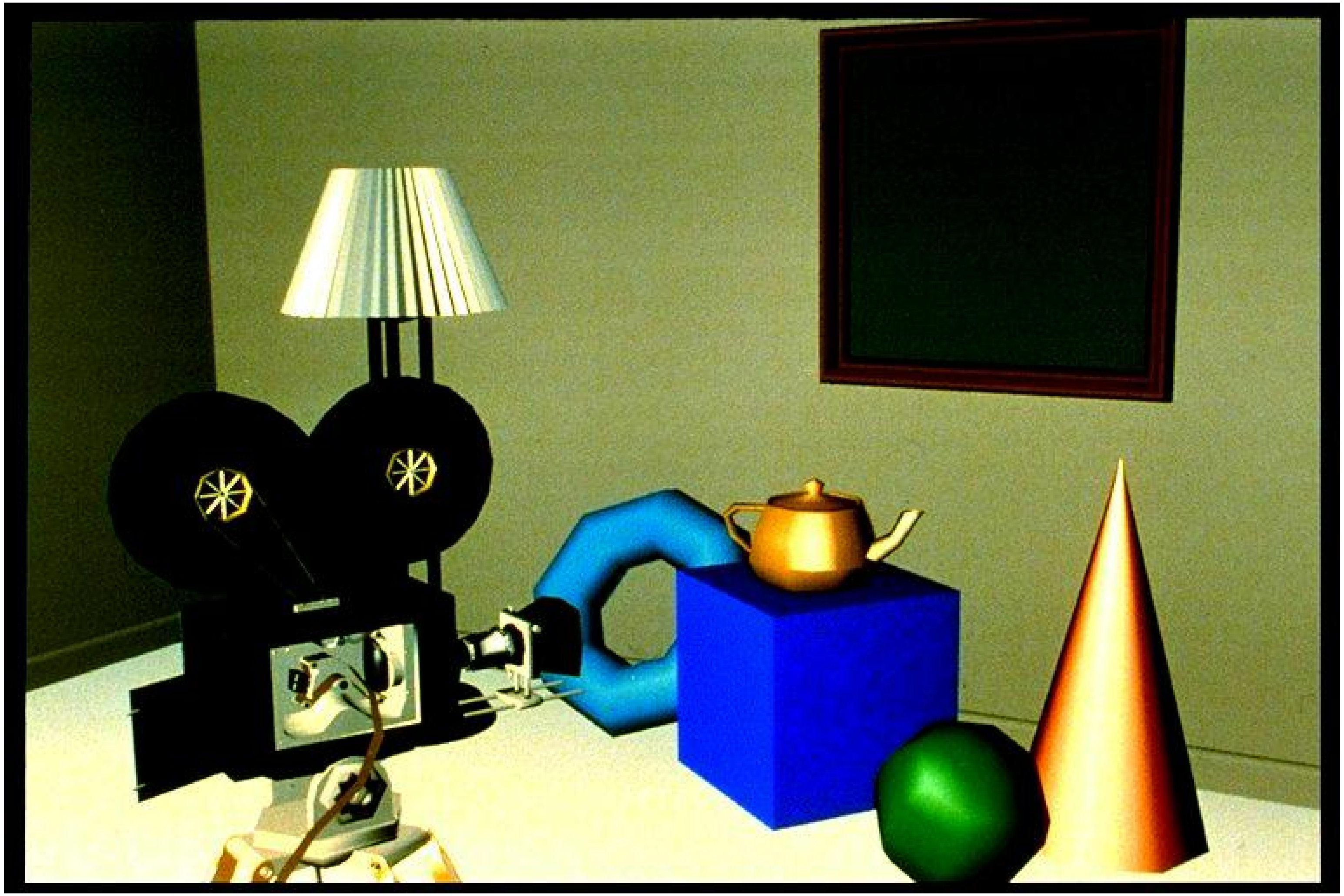
Per-Polygon Shading



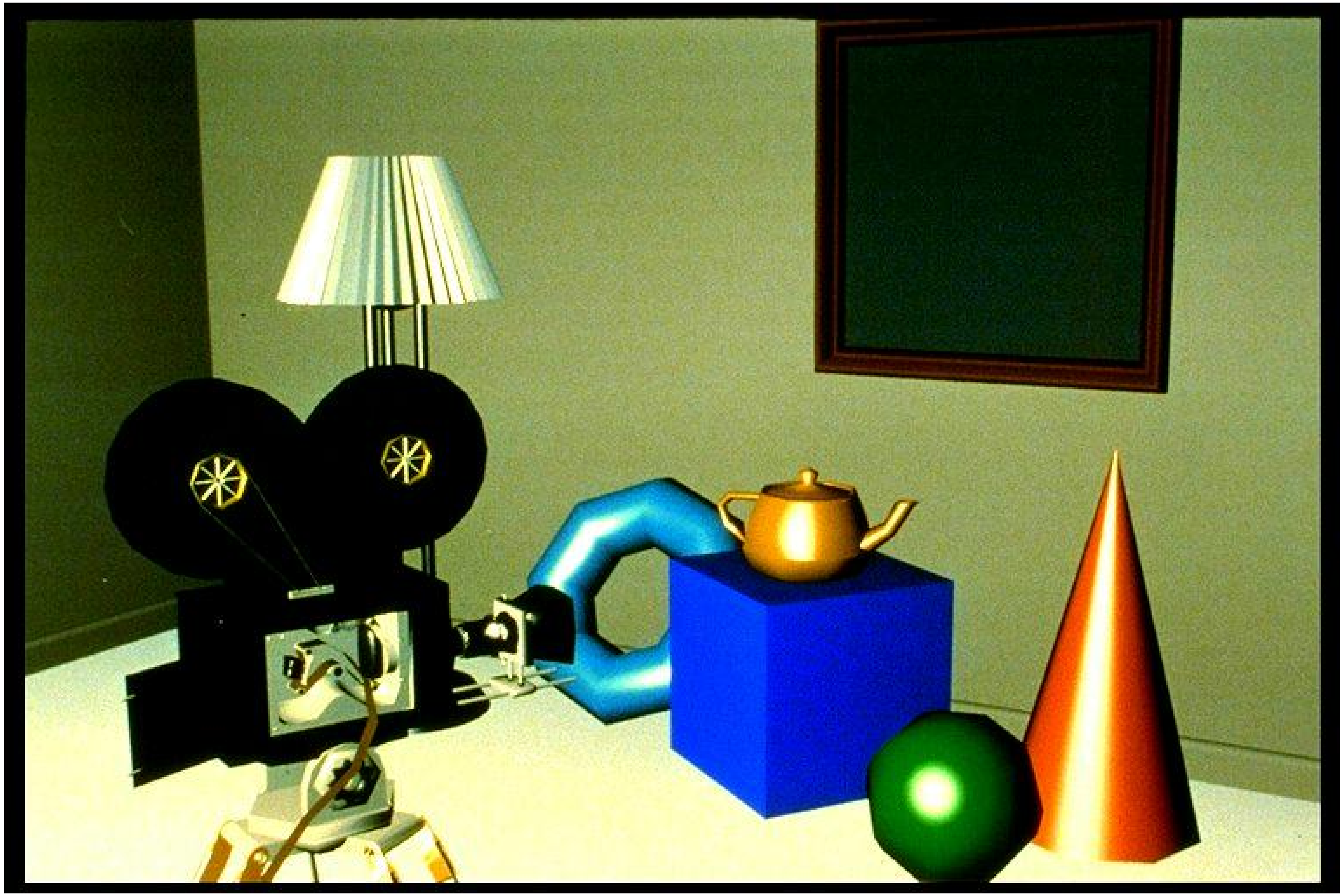
Gouraud Shading



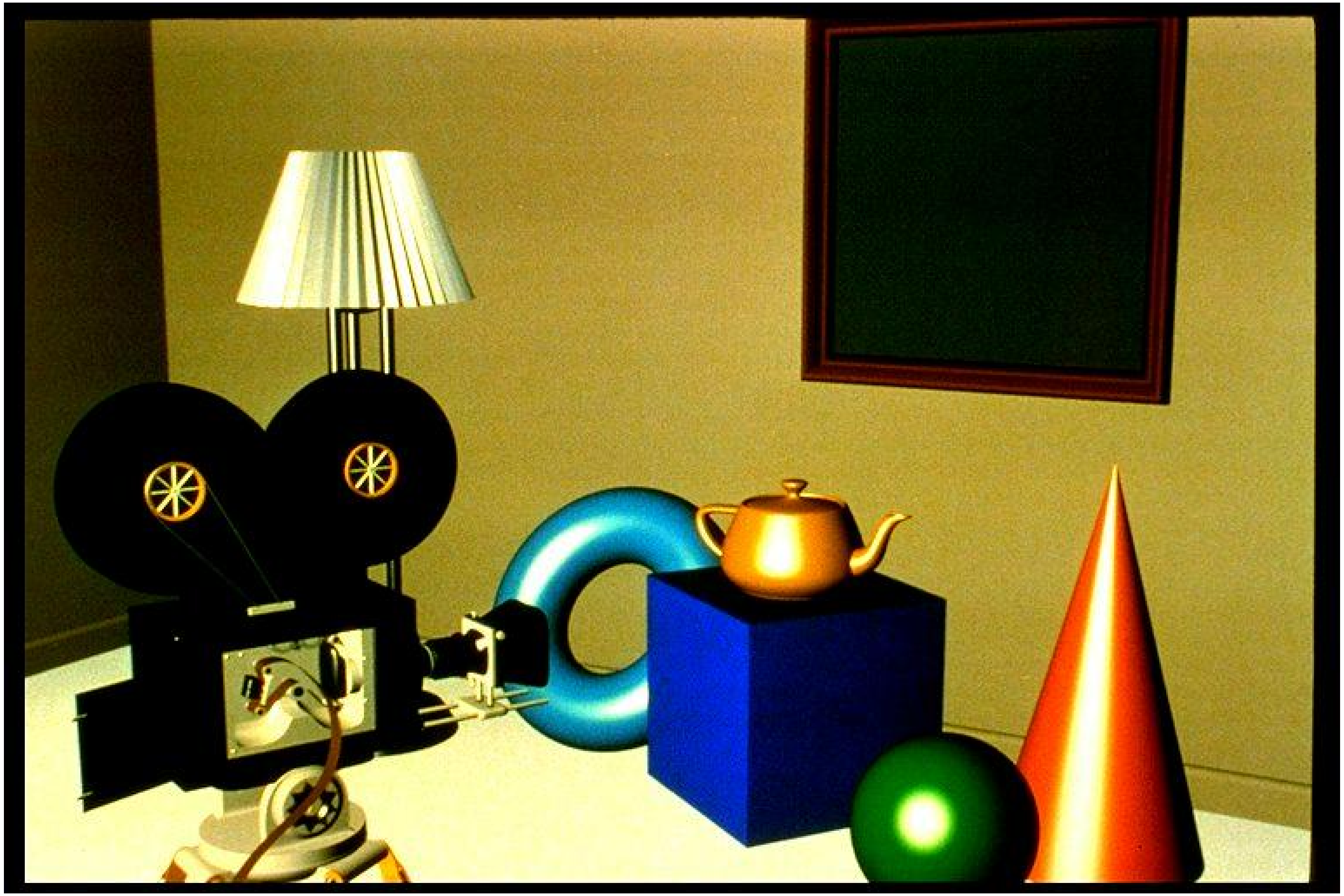
Specular Reflection



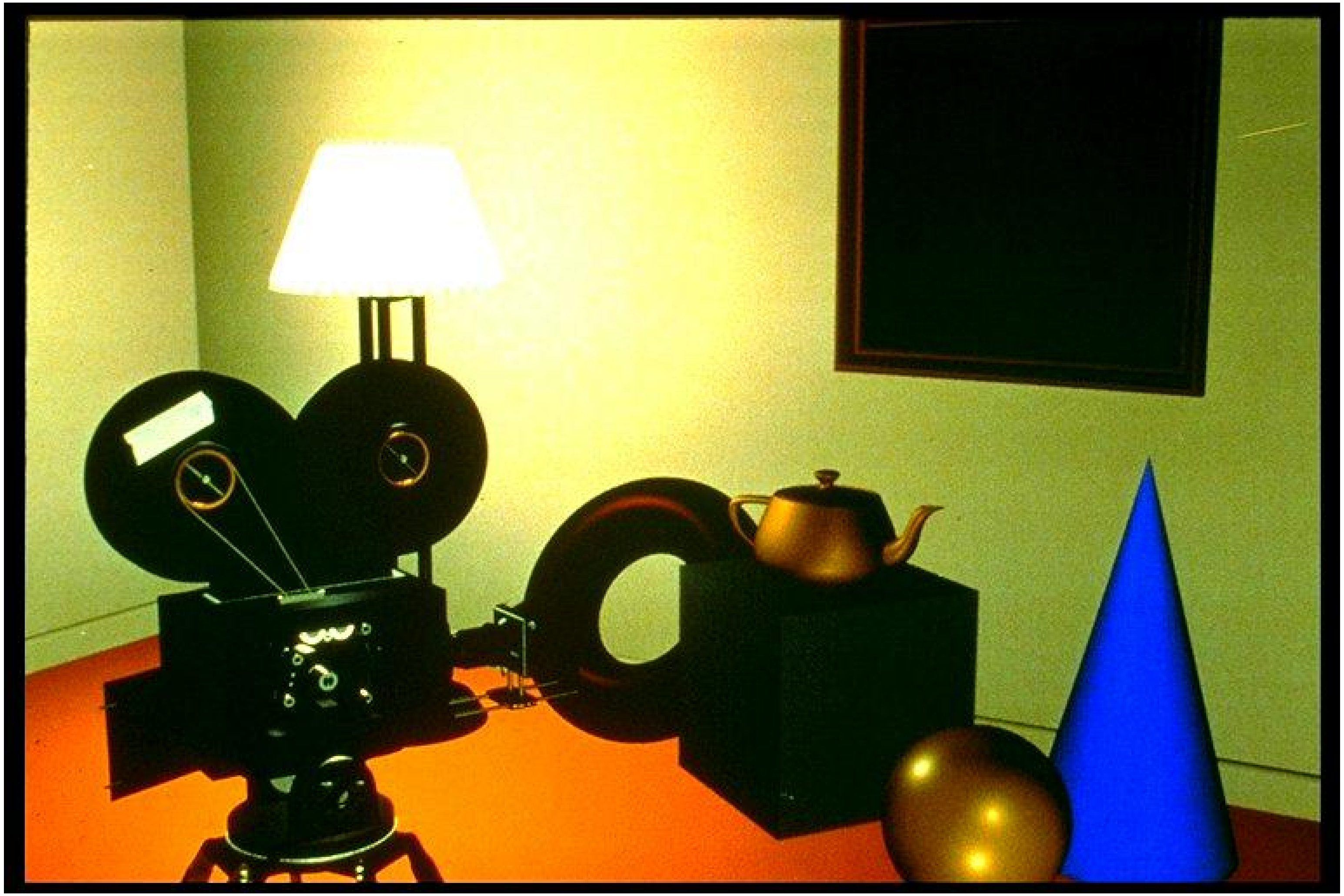
Phong Shading



Curved Surfaces



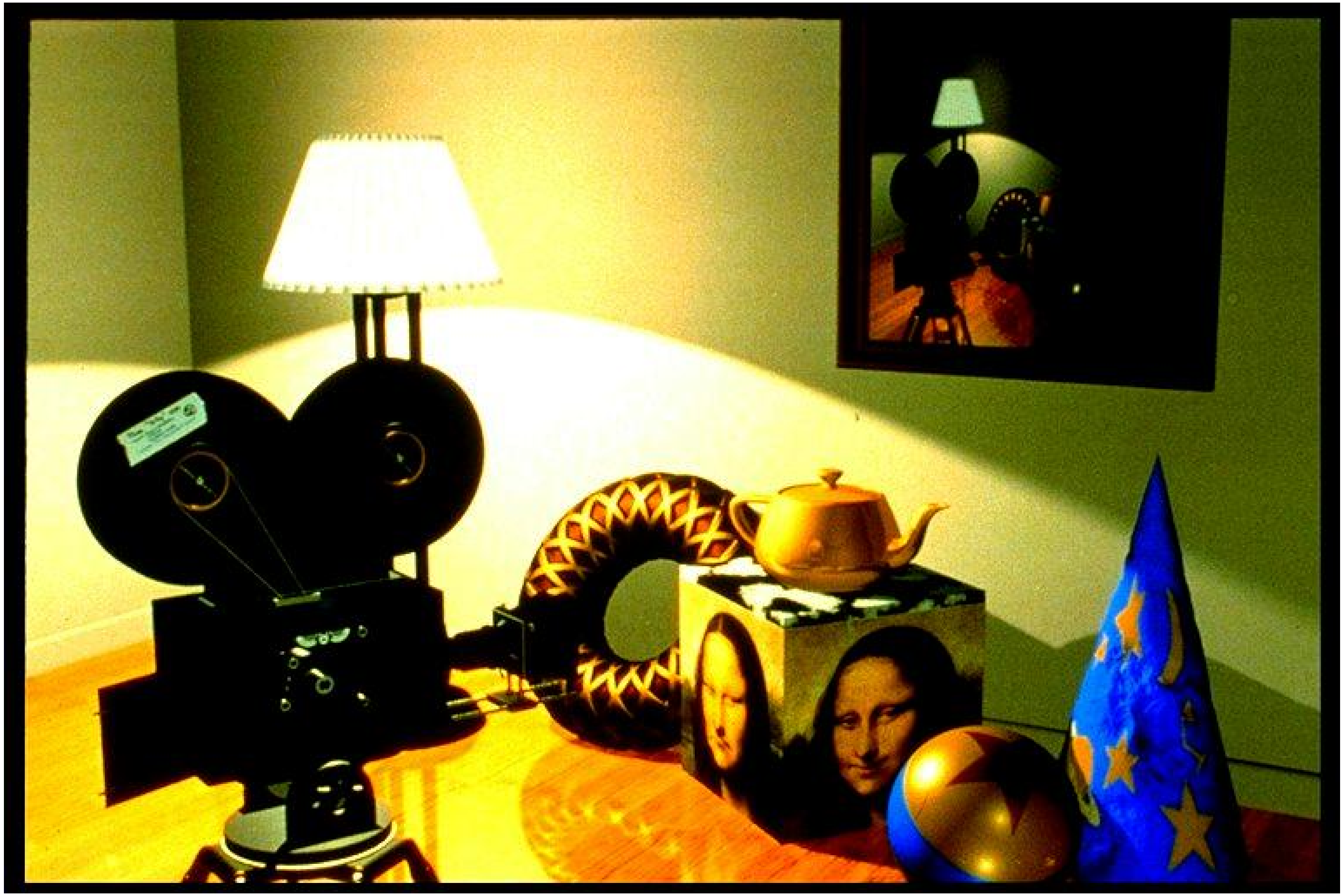
Complex Lighting and Shading



Texture Mapping

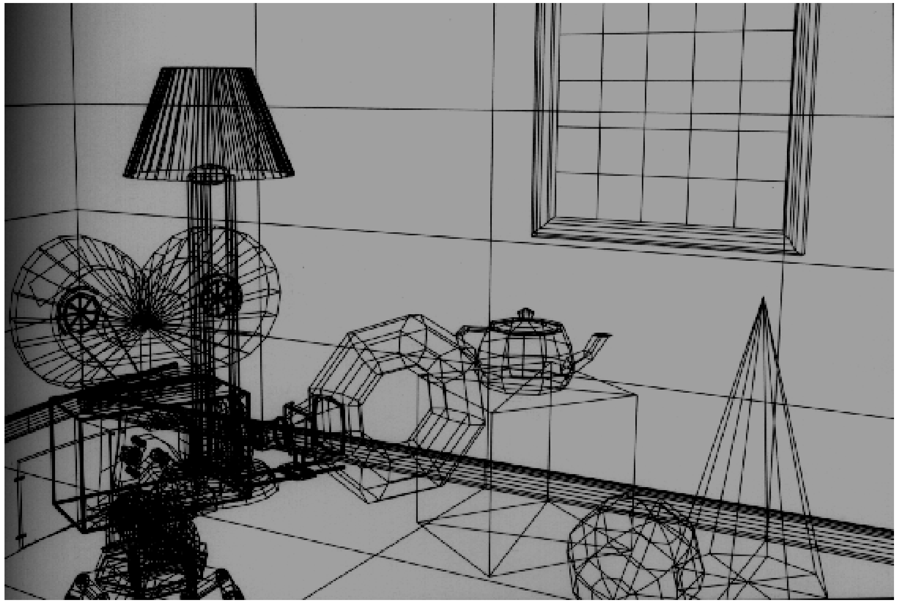
Displacement Mapping

Reflection Mapping



Modelling

- generating models
  - lines, curves, polygons, smooth surfaces
  - digital geometry



Animation

- generating motion
  - interpolating between frames, states

Math Review

Reading

- FCG Chapter 2: Miscellaneous Math
  - except for 2.11 (covered later)
  - skim 2.2 (sets and maps), 2.3 (quadratic eqns)
  - important: 2.3 (trig), 2.4 (vectors), 2.5-6 (lines) 2.10 (linear interpolation)
    - skip 2.5.1, 2.5.3, 2.7.1, 2.7.3, 2.8, 2.9
- FCG Chapter 4.1-4.25: Linear Algebra
  - skim 4.1 (determinants)
  - important: 4.2.1-4.2.2, 4.2.5 (matrices)
    - skip 4.2.3-4, 4.2.6-7 (matrix numerical analysis)

Textbook Errata

- list at http://www.cs.utah.edu/~shirley/fcg/errata
  - p 29, 32, 39 have potential to confuse

Notation: Scalars, Vectors, Matrices

- scalar
  - (lower case, italic)
- vector
  - (lower case, bold)
- matrix
  - (upper case, bold)

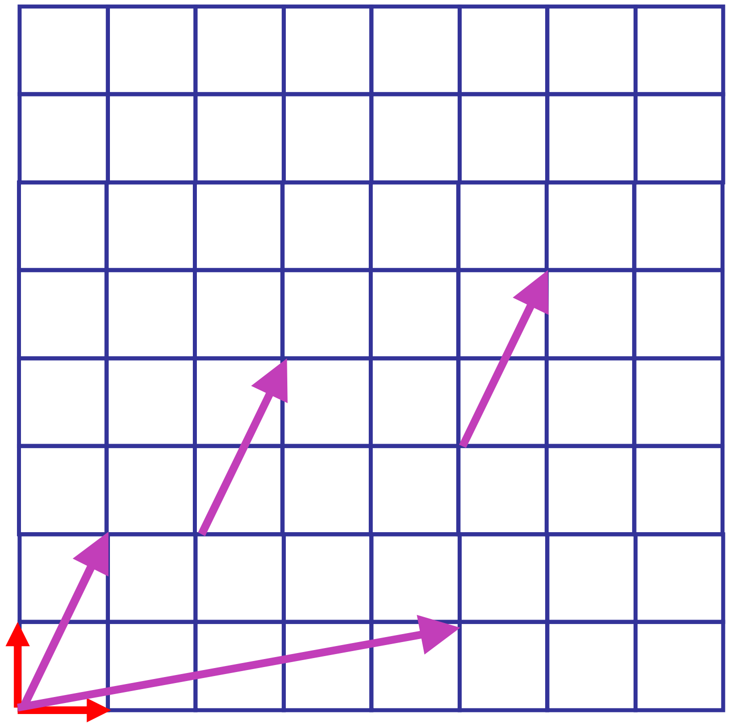
$$a$$

$$\mathbf{a} = \begin{bmatrix} a_1 & a_2 & \dots & a_n \end{bmatrix}$$

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

Vectors

- arrow: length and direction
  - oriented segment in nD space
- offset / displacement
  - location if given origin



Column vs. Row Vectors

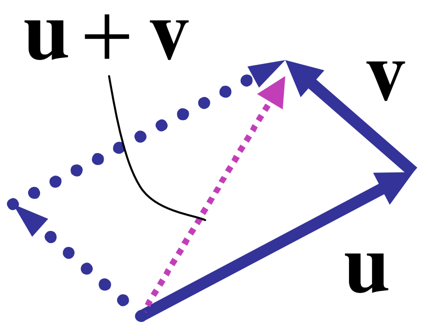
- row vectors $$\mathbf{a}_{row} = \begin{bmatrix} a_1 & a_2 & \dots & a_n \end{bmatrix}$$
- column vectors $$\mathbf{a}_{col} = \begin{bmatrix} a_1 \\ a_2 \\ \dots \\ a_n \end{bmatrix}$$
- switch back and forth with transpose

$$\mathbf{a}_{col}^T = \mathbf{a}_{row}$$

Vector-Vector Addition

- add: vector + vector = vector
- parallelogram rule
  - tail to head, complete the triangle

geometric



algebraic

$$\mathbf{u}+\mathbf{v}=\begin{bmatrix} u_1+v_1 \\ u_2+v_2 \\ u_3+v_3 \end{bmatrix}$$

examples:

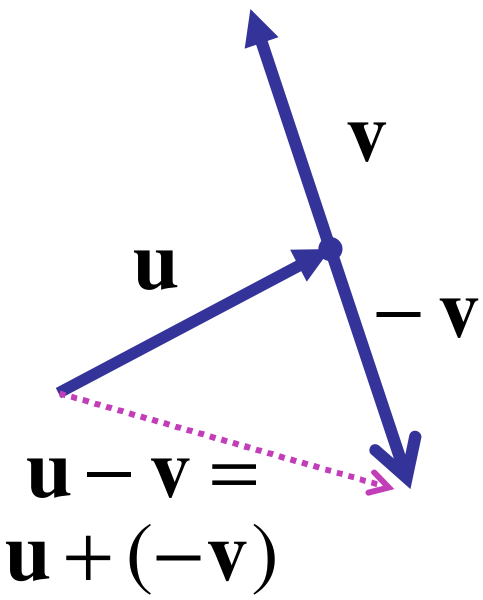
$$(3,2)+(6,4)=(9,6)$$

$$(2,5,1)+(3,1,-1)=(5,6,0)$$

Vector-Vector Subtraction

- subtract: vector - vector = vector

$$\mathbf{u}-\mathbf{v}=\begin{bmatrix} u_1 - v_1 \\ u_2 - v_2 \\ u_3 - v_3 \end{bmatrix}$$



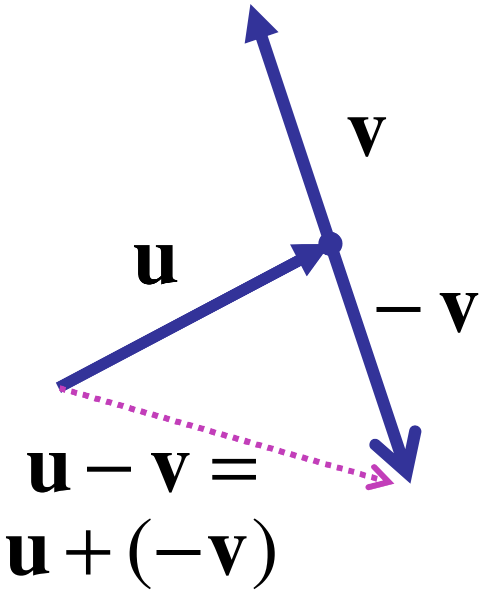
$$(3,2)-(6,4)=(-3,-2)$$

$$(2,5,1)-(3,1,-1)=(-1,4,0)$$

Vector-Vector Subtraction

- subtract: vector - vector = vector

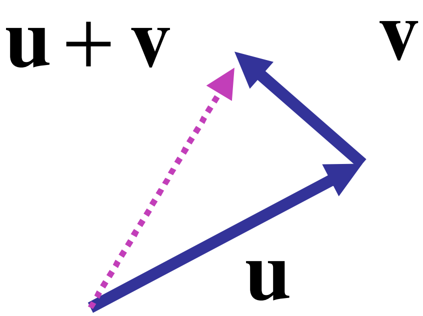
$$\mathbf{u} - \mathbf{v} = \begin{bmatrix} u_1 - v_1 \\ u_2 - v_2 \\ u_3 - v_3 \end{bmatrix}$$

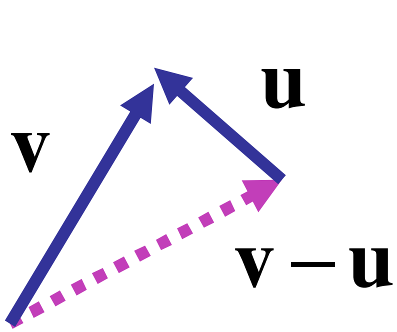


$$(3,2) - (6,4) = (-3,-2)$$

$$(2,5,1) - (3,1,-1) = (-1,4,0)$$

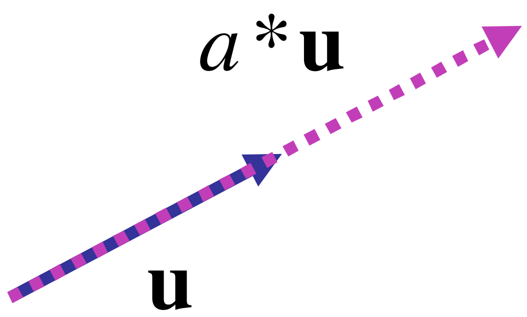
argument reversal





Scalar-Vector Multiplication

- multiply: scalar * vector = vector
  - vector is scaled



$$a * \mathbf{u} = (a * u_1, a * u_2, a * u_3)$$

$$2 * (3,2) = (6,4)$$

$$.5 * (2,5,1) = (1,2.5,.5)$$

Vector-Vector Multiplication

- multiply: vector * vector = scalar
- dot product, aka inner product

$$\mathbf{u} \bullet \mathbf{v}$$

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \bullet \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = \left(u_1 * v_1\right) + \left(u_1 * v_2\right) + \left(u_3 * v_3\right)$$

Vector-Vector Multiplication

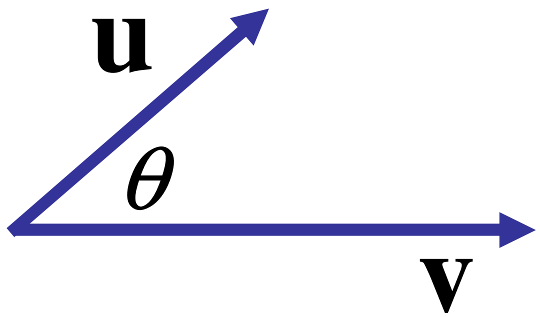
- multiply: vector * vector = scalar
- dot product, aka inner product

$$\mathbf{u} \bullet \mathbf{v}$$

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \bullet \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = (u_1 * v_1) + (u_1 * v_2) + (u_3 * v_3)$$

$$\mathbf{u} \bullet \mathbf{v} = \|\mathbf{u}\| \|\mathbf{v}\| \cos\theta$$

- geometric interpretation
  - lengths, angles
  - can find angle between two vectors

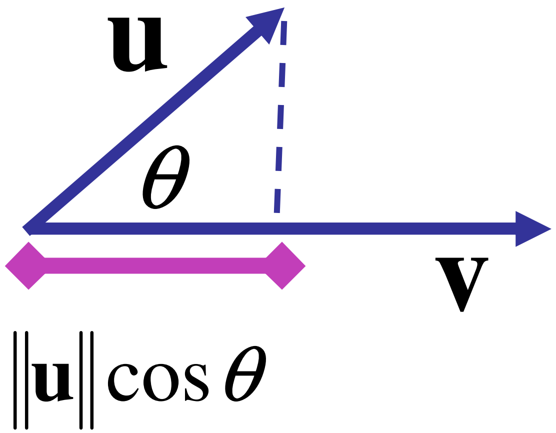


Dot Product Geometry

- can find length of projection of u onto v

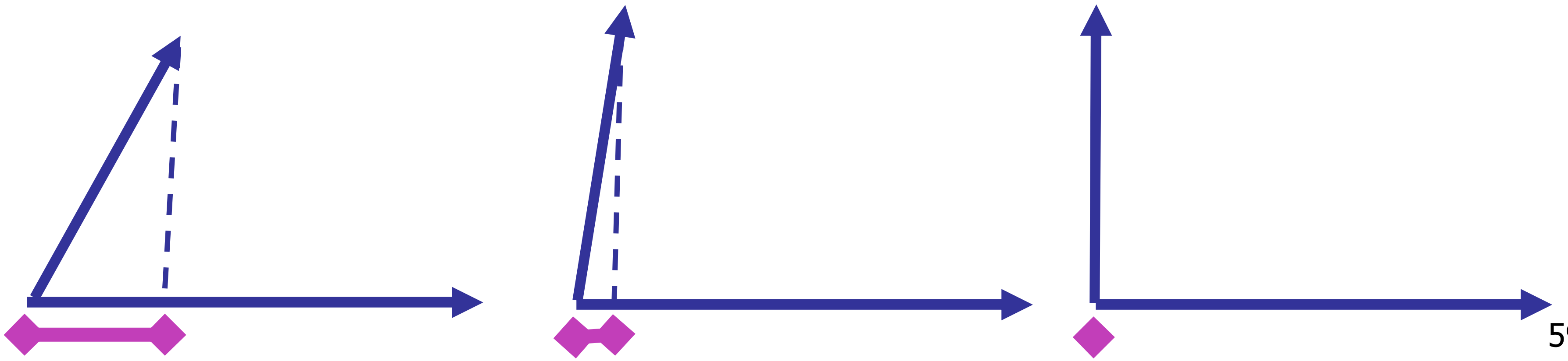
$$\mathbf{u} \bullet \mathbf{v} = \|\mathbf{u}\| \|\mathbf{v}\| \cos\theta$$

$$\|\mathbf{u}\| \cos\theta = \frac{\mathbf{u} \bullet \mathbf{v}}{\|\mathbf{v}\|}$$



- as lines become perpendicular,

$$\mathbf{u} \bullet \mathbf{v} \rightarrow 0$$



Dot Product Example

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \bullet \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = \left(u_1 * v_1\right) + \left(u_1 * v_2\right) + \left(u_3 * v_3\right)$$

$$\begin{bmatrix} 6 \\ 1 \\ 2 \end{bmatrix} \bullet \begin{bmatrix} 1 \\ 7 \\ 3 \end{bmatrix} = (6*1) + (1*7) + (2*3) = 6 + 7 + 6 = 19$$

Vector-Vector Multiplication, The Sequel

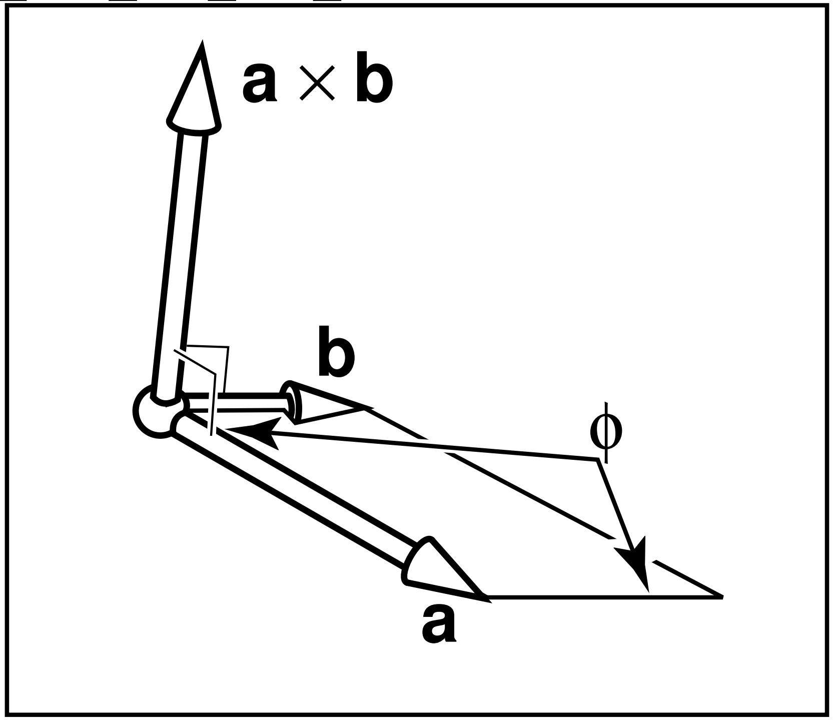
- multiply: vector * vector = vector
- cross product
  - algebraic

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \times \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = \begin{bmatrix} u_2 v_3 - u_3 v_2 \\ u_3 v_1 - u_1 v_3 \\ u_1 v_2 - u_2 v_1 \end{bmatrix}$$

  - geometric

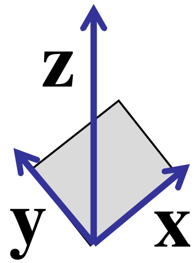
$$\|\mathbf{a} \times \mathbf{b}\| = \|\mathbf{u}\| \|\mathbf{v}\| \sin\theta$$

    - $\|\mathbf{a} \times \mathbf{b}\|$ parallelogram area
    - $\mathbf{a} \times \mathbf{b}$ perpendicular to parallelogram



RHS vs LHS Coordinate Systems

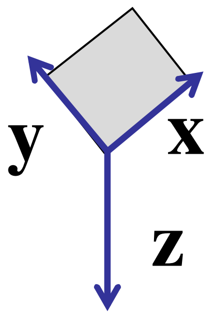
- right-handed coordinate system convention



right hand rule:
index finger x, second finger y;
right thumb points up

$$\mathbf{z} = \mathbf{x} \times \mathbf{y}$$

- left-handed coordinate system



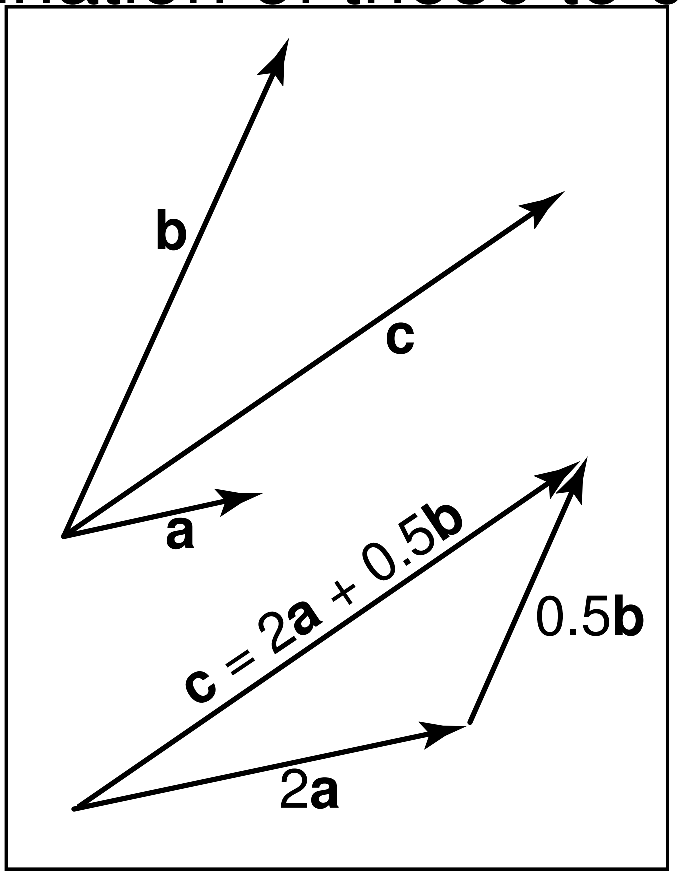
left hand rule:
index finger x, second finger y;
left thumb points down

$$\mathbf{z} = \mathbf{x} \times \mathbf{y}$$

Basis Vectors

- take any two vectors that are linearly independent (nonzero and nonparallel)
  - can use linear combination of these to define any other vector:

$$\mathbf{c} = w_1\mathbf{a} + w_2\mathbf{b}$$



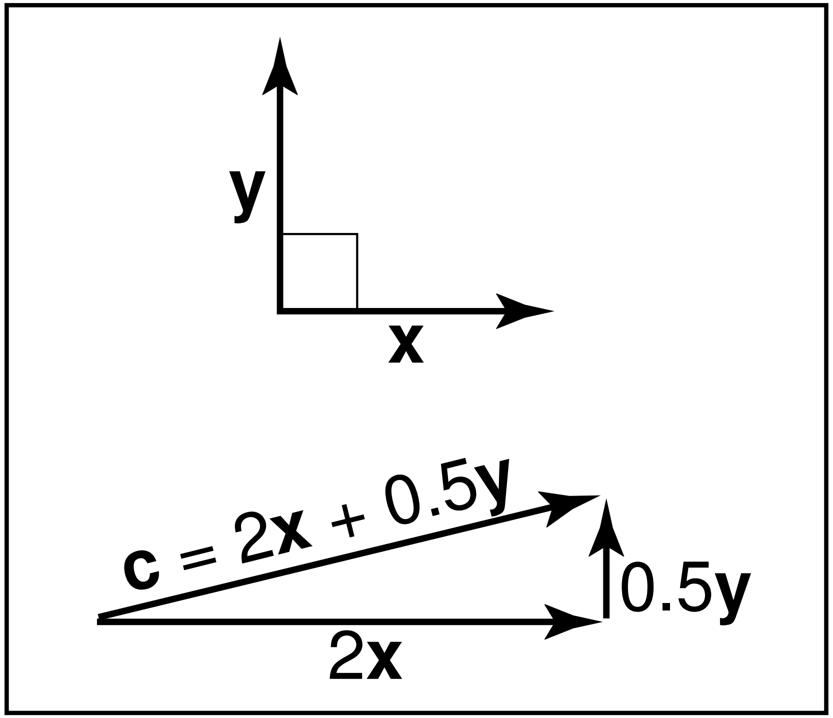
Orthonormal Basis Vectors

- if basis vectors are orthonormal (orthogonal (mutually perpendicular) and unit length)
  - we have Cartesian coordinate system
  - familiar Pythagorean definition of distance

orthonormal algebraic properties

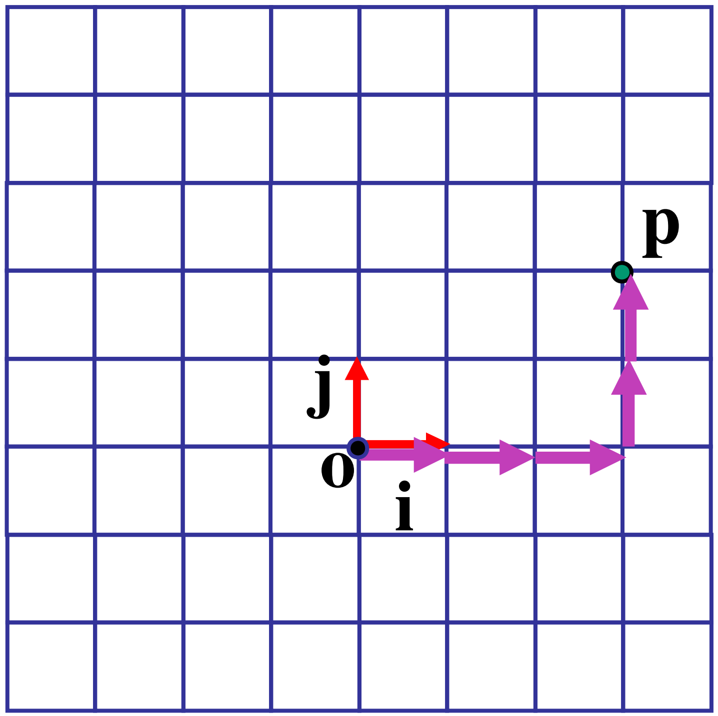
$$\|\mathbf{x}\| = \|\mathbf{y}\| = 1,$$

$$\mathbf{x} \bullet \mathbf{y} = 0$$



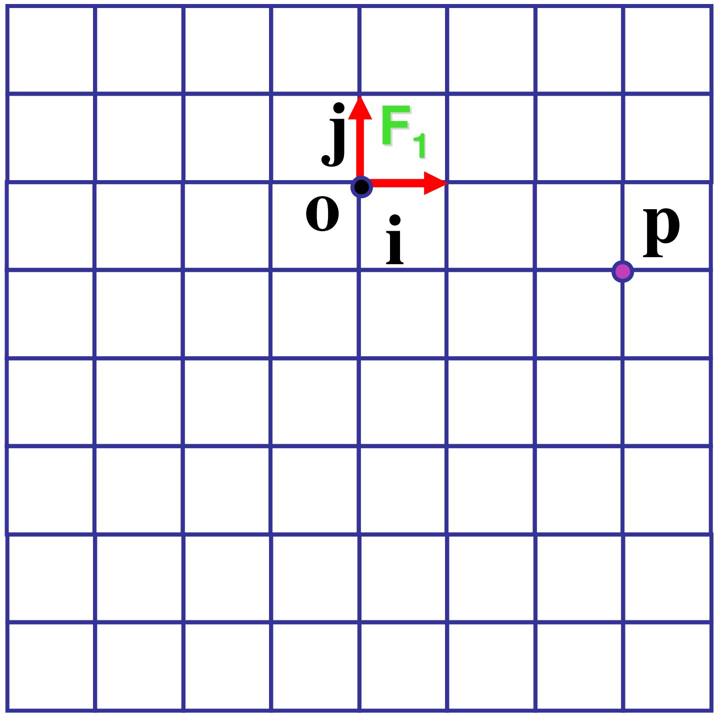
Basis Vectors and Origins

- coordinate system: just basis vectors
  - can only specify offset: vectors
- coordinate frame: basis vectors and origin
  - can specify location as well as offset: points



$$\mathbf{p} = \mathbf{o} + x\mathbf{i} + y\mathbf{j}$$

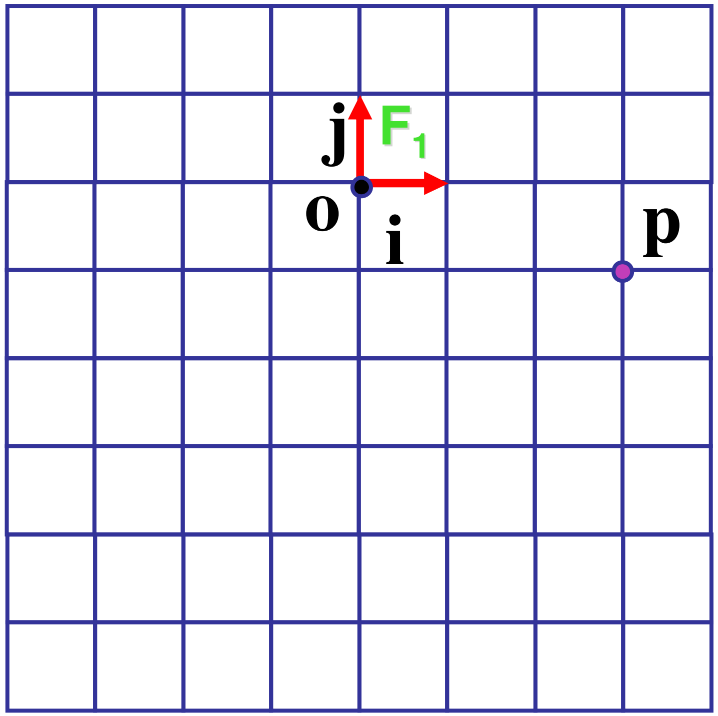
Working with Frames



$$\mathbf{p} = \mathbf{o} + x\mathbf{i} + y\mathbf{j}$$

F_1

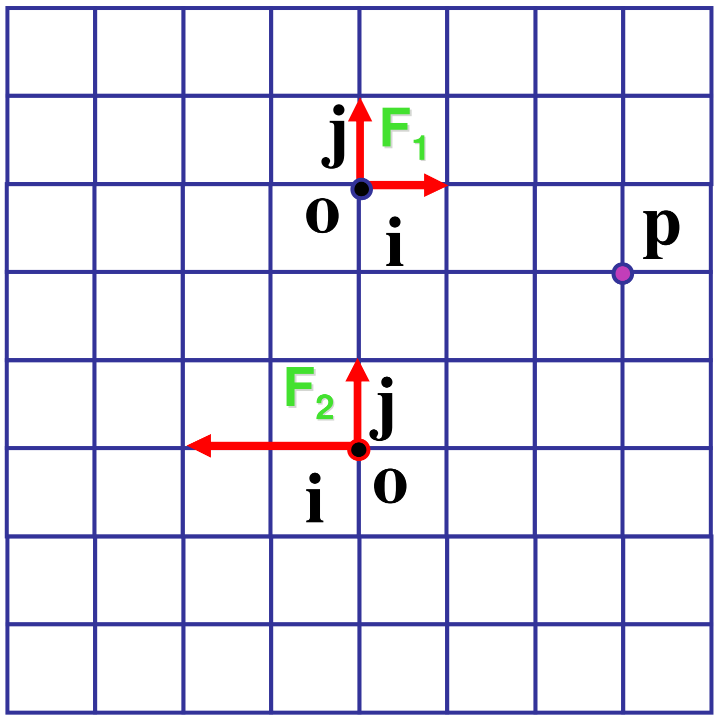
Working with Frames



$$\mathbf{p} = \mathbf{o} + x\mathbf{i} + y\mathbf{j}$$

F_1 p = (3,-1)

Working with Frames

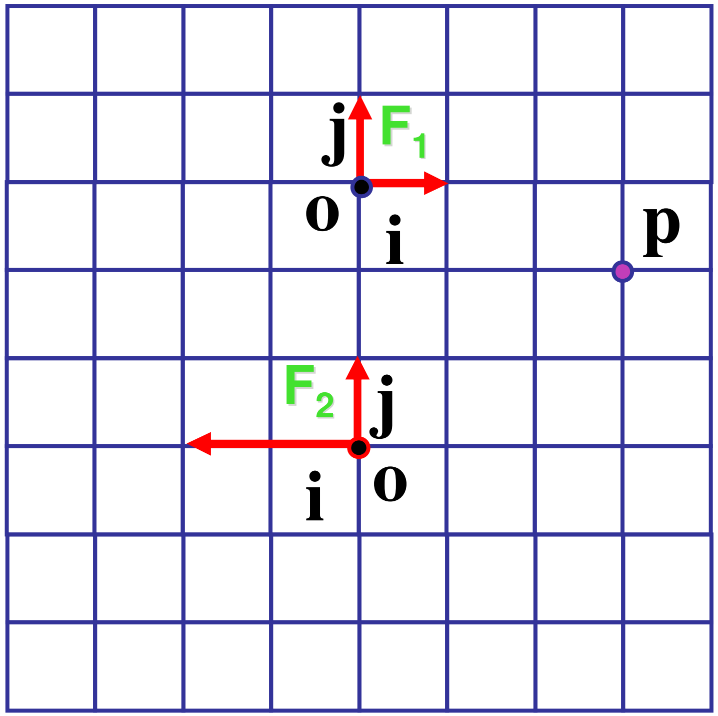


$$\mathbf{p} = \mathbf{o} + x\mathbf{i} + y\mathbf{j}$$

F_1 **p = (3,-1)**

F_2

Working with Frames

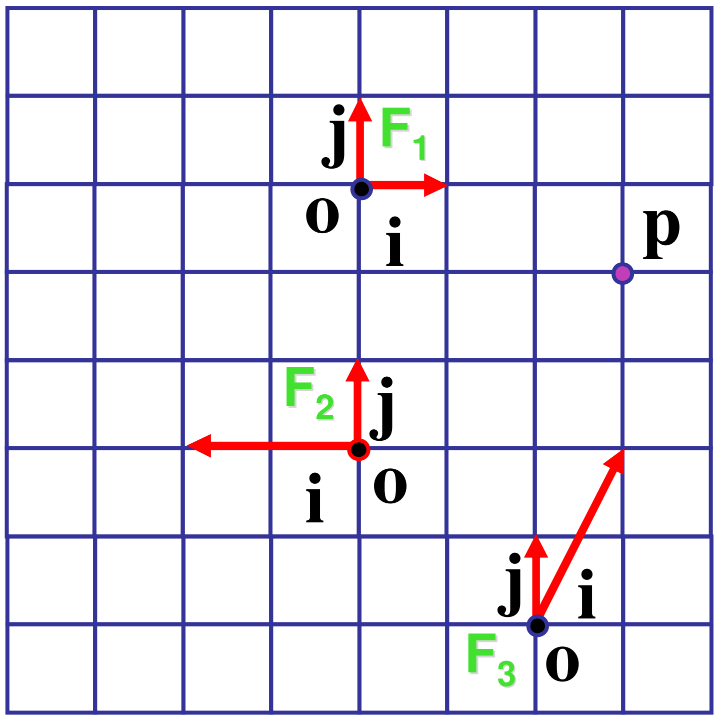


$$\mathbf{p} = \mathbf{o} + x\mathbf{i} + y\mathbf{j}$$

F_1 p = (3,-1)

F_2 p = (-1.5,2)

Working with Frames



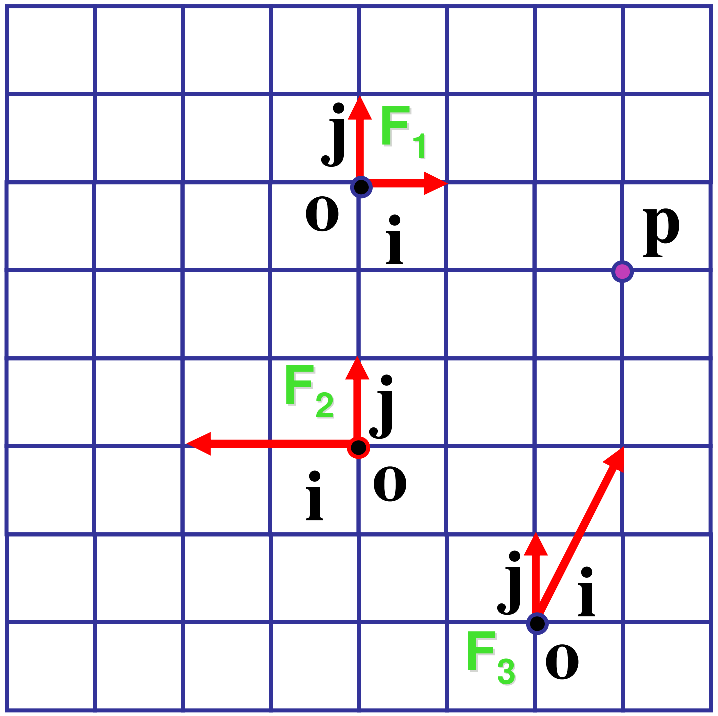
$$\mathbf{p} = \mathbf{o} + x\mathbf{i} + y\mathbf{j}$$

F_1 p = (3,-1)

F_2 p = (-1.5,2)

F_3

Working with Frames



$$\mathbf{p} = \mathbf{o} + x\mathbf{i} + y\mathbf{j}$$

F_1 $\quad$ $p = (3,-1)$

F_2 $\quad$ $p = (-1.5,2)$

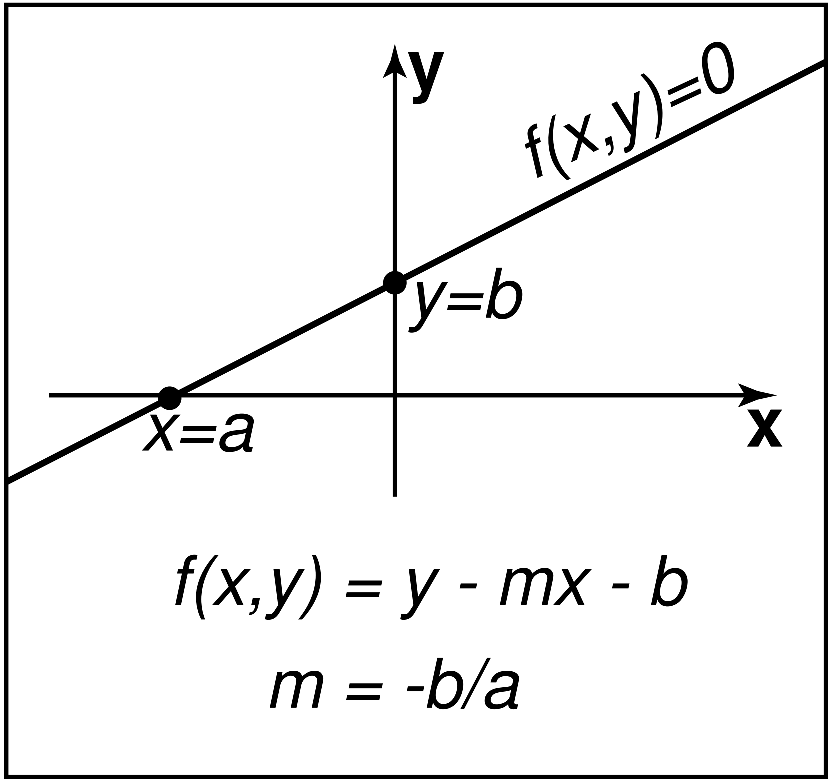
F_3 $\quad$ $p = (1,2)$

Named Coordinate Frames

- origin and basis vectors $\mathbf{p} = \mathbf{o} + a\mathbf{x} + b\mathbf{y} + c\mathbf{z}$
- pick canonical frame of reference
  - then don't have to store origin, basis vectors
  - just $\mathbf{p} = (a, b, c)$
  - convention: Cartesian orthonormal one on previous slide
- handy to specify others as needed
  - airplane nose, looking over your shoulder, ...
  - really common ones given names in CG
    - object, world, camera, screen, ...

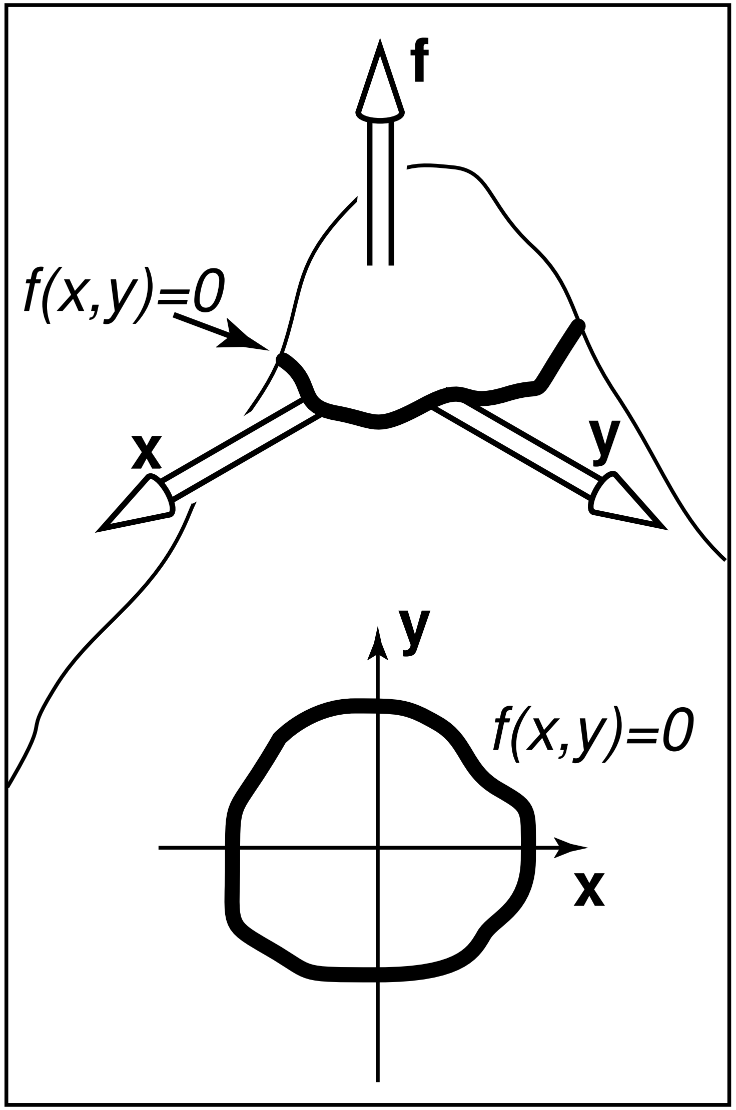
Lines

- slope-intercept form
  - $y = mx + b$
- implicit form
  - $y - mx - b = 0$
  - $Ax + By + C = 0$
  - $f(x,y) = 0$



Implicit Functions

- find where function is 0
  - plug in (x,y), check if
    - 0: on line
    - < 0: inside
    - > 0: outside
- analogy: terrain
  - sea level: f=0
  - altitude: function value
  - topo map: equal-value contours (level sets)



Implicit Circles

- $f(x, y) = (x - x_c)^2 + (y - y_c)^2 - r^2$
  - circle is points (x,y) where f(x,y) = 0
- $p = (x, y), c = (x_c, y_c) : (\mathbf{p} - \mathbf{c}) \bullet (\mathbf{p} - \mathbf{c}) - r^2 = 0$
  - points **p** on circle have property that vector from **c** to **p** dotted with itself has value r^2
- $\|\mathbf{p} - \mathbf{c}\|^2 - r^2 = 0$
  - points points **p** on the circle have property that squared distance from **c** to **p** is r^2
- $\|\mathbf{p} - \mathbf{c}\| - r = 0$
  - points **p** on circle are those a distance *r* from center point **c**

Parametric Curves

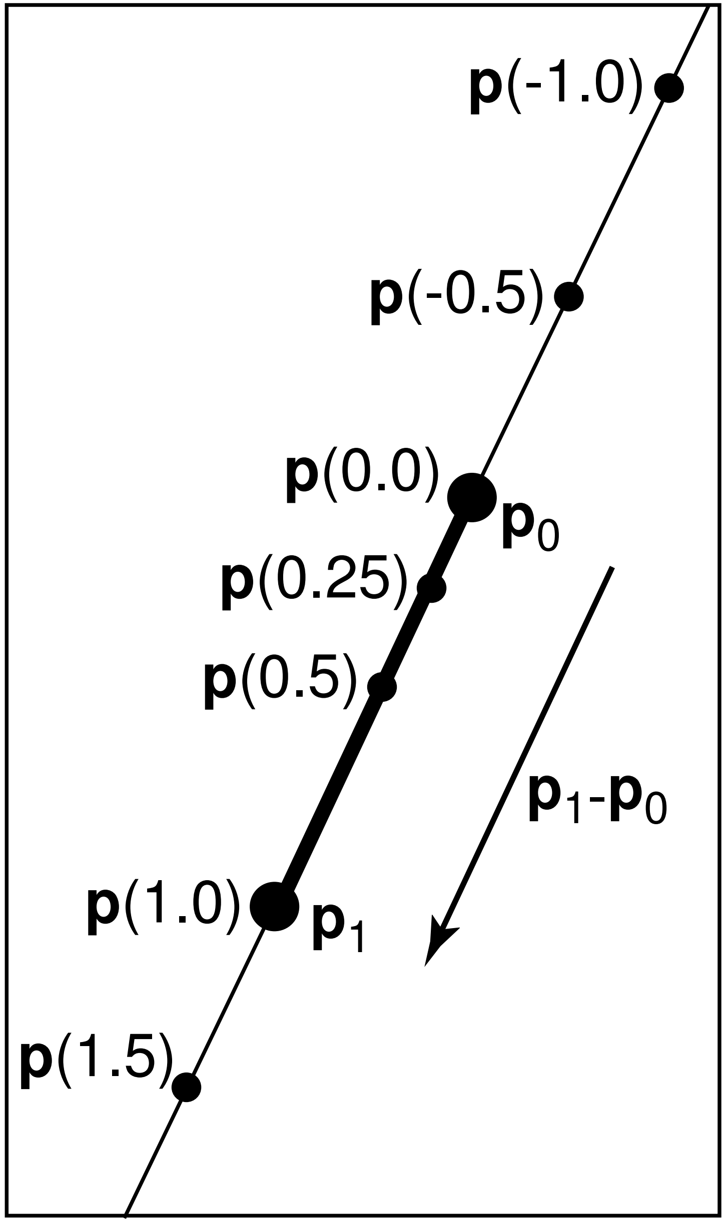
- parameter: index that changes continuously
  - (x,y): point on curve
  - t: parameter

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} g(t) \\ h(t) \end{bmatrix}$$

- vector form
  - $\mathbf{p} = f(t)$

2D Parametric Lines

- $$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} x_0 + t(x_1 - x_0) \\ y_0 + t(y_1 - y_0) \end{bmatrix}$$
- $\mathbf{p}(t) = \mathbf{p}_0 + t(\mathbf{p}_1 - \mathbf{p}_0)$
- $\mathbf{p}(t) = \mathbf{o} + t(\mathbf{d})$
- start at point $\mathbf{p}_0$,
  go towards $\mathbf{p}_1$,
  according to parameter t
  - $\mathbf{p}(0) = \mathbf{p}_0$, $\mathbf{p}(1) = \mathbf{p}_1$



Linear Interpolation

- parametric line is example of general concept
  - $\mathbf{p}(t) = \mathbf{p}_0 + t(\mathbf{p}_1 - \mathbf{p}_0)$
  - interpolation
    - **p** goes through **a** at $t = 0$
    - **p** goes through **b** at $t = 1$
  - linear
    - weights t, $(1-t)$ are linear polynomials in t

Matrix-Matrix Addition

- add: matrix + matrix = matrix

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} + \begin{bmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \end{bmatrix} = \begin{bmatrix} n_{11}+m_{11} & n_{12}+m_{12} \\ n_{21}+m_{21} & n_{22}+m_{22} \end{bmatrix}$$

- example

$$\begin{bmatrix} 1 & 3 \\ 2 & 4 \end{bmatrix} + \begin{bmatrix} -2 & 5 \\ 7 & 1 \end{bmatrix} = \begin{bmatrix} 1+(-2) & 3+5 \\ 2+7 & 4+1 \end{bmatrix} = \begin{bmatrix} -1 & 8 \\ 9 & 5 \end{bmatrix}$$

Scalar-Matrix Multiplication

- multiply: scalar * matrix = matrix

$$a\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} a*m_{11} & a*m_{12} \\ a*m_{21} & a*m_{22} \end{bmatrix}$$

- example

$$3\begin{bmatrix} 2 & 4 \\ 1 & 5 \end{bmatrix} = \begin{bmatrix} 3*2 & 3*4 \\ 3*1 & 3*5 \end{bmatrix} = \begin{bmatrix} 6 & 12 \\ 3 & 15 \end{bmatrix}$$

Matrix-Matrix Multiplication

- row by column

$$\begin{bmatrix} \boxed{m_{11} \quad m_{12}} \\ m_{21} \quad m_{22} \end{bmatrix} \begin{bmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \end{bmatrix} = \begin{bmatrix} \boxed{p_{11}} & p_{12} \\ p_{21} & p_{22} \end{bmatrix}$$

$$p_{11} = m_{11}n_{11} + m_{12}n_{21}$$

Matrix-Matrix Multiplication

- row by column

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \end{bmatrix} = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix}$$

$$p_{11} = m_{11}n_{11} + m_{12}n_{21}$$

$$p_{21} = m_{21}n_{11} + m_{22}n_{21}$$

Matrix-Matrix Multiplication

- row by column

$$\begin{bmatrix} \boxed{m_{11} \quad m_{12}} \\ m_{21} \quad m_{22} \end{bmatrix} \begin{bmatrix} n_{11} & \boxed{n_{12}} \\ n_{21} & \boxed{n_{22}} \end{bmatrix} = \begin{bmatrix} p_{11} & \boxed{p_{12}} \\ p_{21} & p_{22} \end{bmatrix}$$

$$p_{11} = m_{11}n_{11} + m_{12}n_{21}$$

$$p_{21} = m_{21}n_{11} + m_{22}n_{21}$$

$$p_{12} = m_{11}n_{12} + m_{12}n_{22}$$

Matrix-Matrix Multiplication

- row by column

$$\begin{bmatrix} m_{11} & m_{12} \\ \boxed{m_{21} & m_{22}} \end{bmatrix} \begin{bmatrix} n_{11} & \boxed{n_{12}} \\ n_{21} & \boxed{n_{22}} \end{bmatrix} = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & \boxed{p_{22}} \end{bmatrix}$$

$$p_{11} = m_{11}n_{11} + m_{12}n_{21}$$

$$p_{21} = m_{21}n_{11} + m_{22}n_{21}$$

$$p_{12} = m_{11}n_{12} + m_{12}n_{22}$$

$$p_{22} = m_{21}n_{12} + m_{22}n_{22}$$

Matrix-Matrix Multiplication

- row by column

$$\begin{bmatrix} m_{11} & m_{12} \\ \boxed{m_{21} \quad m_{22}} \end{bmatrix} \begin{bmatrix} n_{11} & \boxed{n_{12}} \\ n_{21} & \boxed{n_{22}} \end{bmatrix} = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & \boxed{p_{22}} \end{bmatrix}$$

$$p_{11} = m_{11}n_{11} + m_{12}n_{21}$$

$$p_{21} = m_{21}n_{11} + m_{22}n_{21}$$

$$p_{12} = m_{11}n_{12} + m_{12}n_{22}$$

$$p_{22} = m_{21}n_{12} + m_{22}n_{22}$$

- noncommutative: **AB** != **BA**

Matrix Multiplication

- can only multiply if
  number of left rows = number of right cols
  - legal

$$\begin{bmatrix} a & b & c \\ e & f & g \end{bmatrix} \begin{bmatrix} h & i \\ j & k \\ l & m \end{bmatrix}$$

  - undefined

$$\begin{bmatrix} a & b & c \\ e & f & g \\ o & p & q \end{bmatrix} \begin{bmatrix} h & i \\ j & k \end{bmatrix}$$

Matrix-Vector Multiplication

- points as column vectors: postmultiply

$$\begin{bmatrix} x' \\ y' \\ z' \\ h' \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ h \end{bmatrix} \qquad \mathbf{p}' = \mathbf{M}\mathbf{p}$$

- points as row vectors: premultiply

$$\begin{bmatrix} x' & y' & z' & h' \end{bmatrix} = \begin{bmatrix} x & y & z & h \end{bmatrix} \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix}^T \qquad \mathbf{p}'^T = \mathbf{p}^T \mathbf{M}^T$$

Matrices

- transpose $\begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix}^T = \begin{bmatrix} m_{11} & m_{21} & m_{31} & m_{41} \\ m_{12} & m_{22} & m_{32} & m_{42} \\ m_{13} & m_{23} & m_{33} & m_{43} \\ m_{14} & m_{24} & m_{34} & m_{44} \end{bmatrix}$
- identity $\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
- inverse $\mathbf{A}\mathbf{A}^{-1} = \mathbf{I}$
  - not all matrices are invertible

Matrices and Linear Systems

- linear system of n equations, n unknowns

$$3x + 7y + 2z = 4$$
$$2x - 4y - 3z = -1$$
$$5x + 2y + z = 1$$

- matrix form **Ax**=**b**

$$\begin{bmatrix} 3 & 7 & 2 \\ 2 & -4 & -3 \\ 5 & 2 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 4 \\ -1 \\ -1 \end{bmatrix}$$

Rendering Pipeline

Reading

- RB Chap. Introduction to OpenGL
- RB Chap. State Management and Drawing Geometric Objects
- RB Appendix Basics of GLUT
  - (Basics of Aux in v 1.1)

Rendering

- goal
  - transform computer models into images
  - may or may not be photo-realistic
- interactive rendering
  - fast, but limited quality
  - roughly follows a fixed patterns of operations
    - rendering pipeline
- offline rendering
  - ray-tracing
  - global illumination

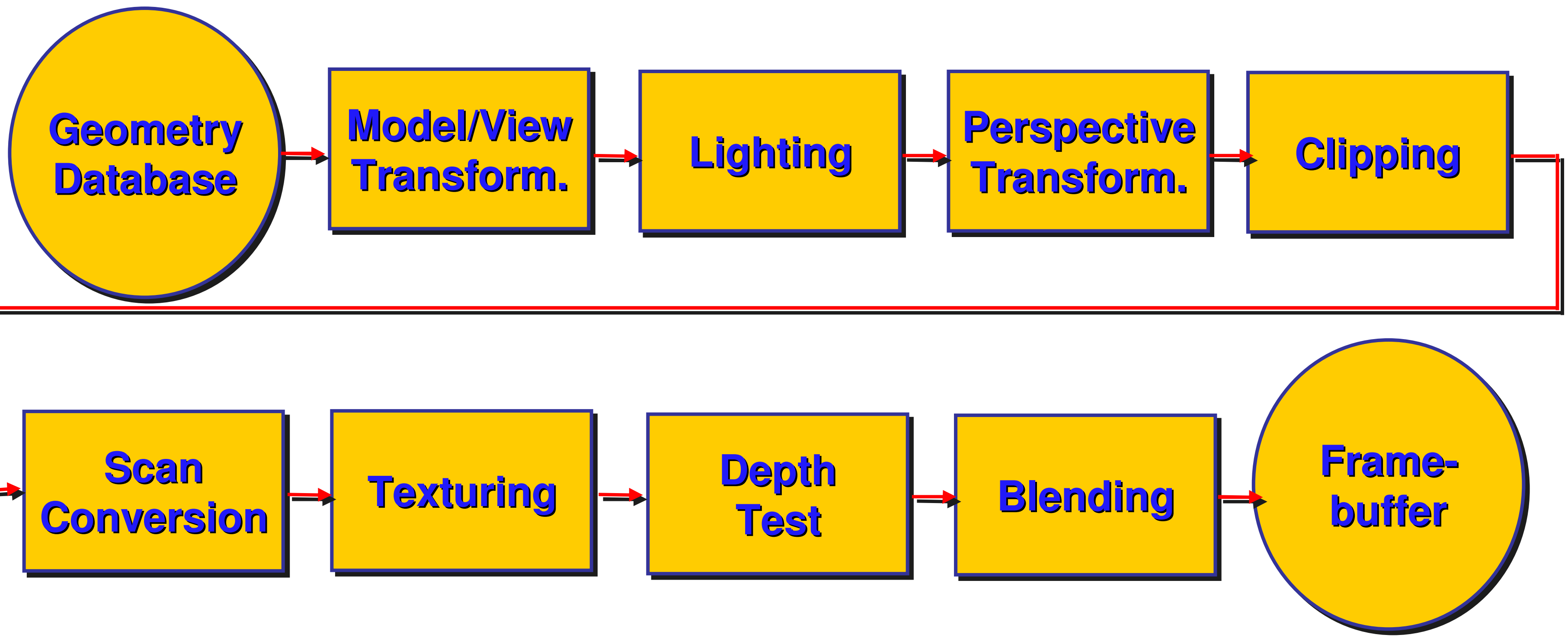
Rendering

- tasks that need to be performed
(in no particular order):
  - project all 3D geometry onto the image plane
    - geometric transformations
  - determine which primitives or parts of primitives are visible
    - hidden surface removal
  - determine which pixels a geometric primitive covers
    - scan conversion
  - compute the color of every visible surface point
    - lighting, shading, texture mapping

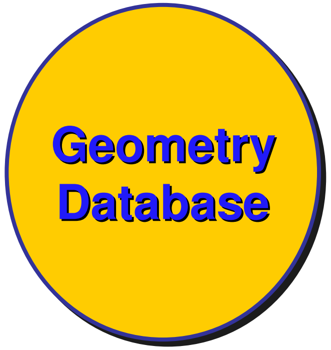
Rendering Pipeline

- what is the pipeline?
  - abstract model for sequence of operations to transform geometric model into digital image
  - abstraction of the way graphics hardware works
  - underlying model for application programming interfaces (APIs) that allow programming of graphics hardware
    - OpenGL
    - Direct 3D
- actual implementation details of rendering pipeline will vary

Rendering Pipeline

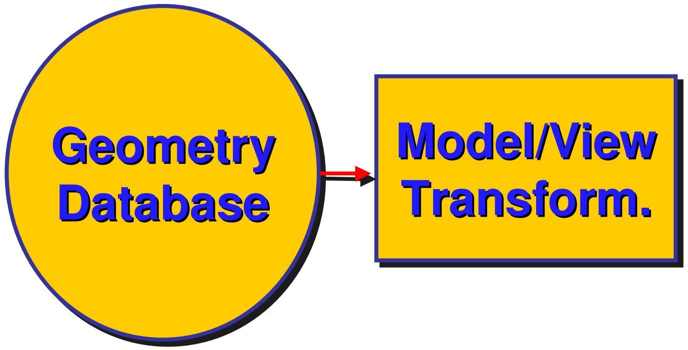


Geometry Database



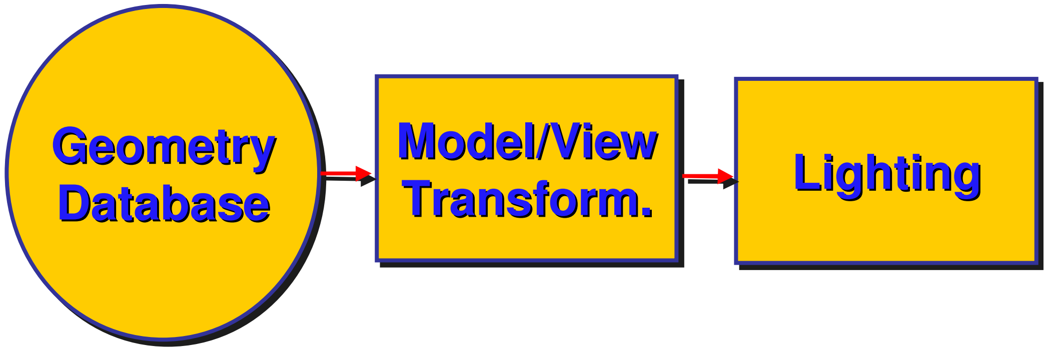
- geometry database
  - application-specific data structure for holding geometric information
  - depends on specific needs of application
    - triangle soup, points, mesh with connectivity information, curved surface

Model/View Transformation



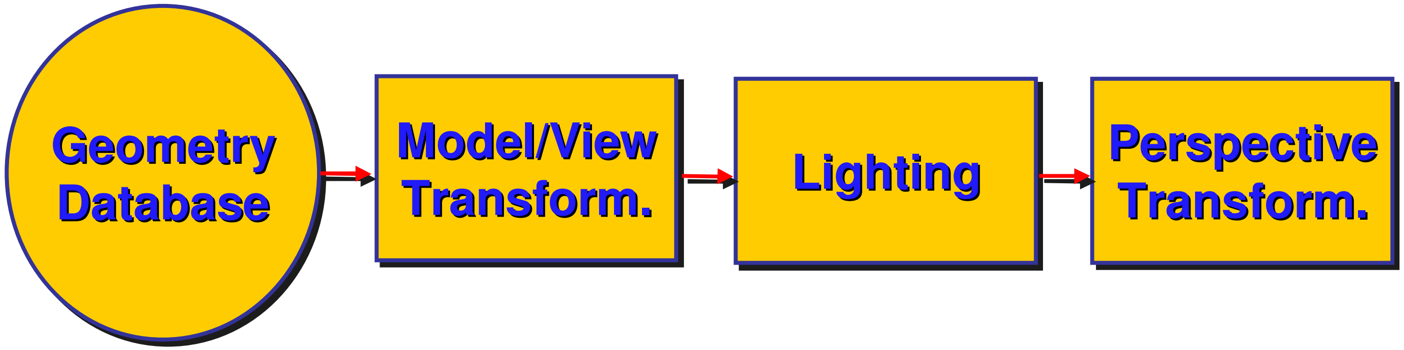
- modeling transformation
  - map all geometric objects from local coordinate system into world coordinates
- viewing transformation
  - map all geometry from world coordinates into camera coordinates

Lighting



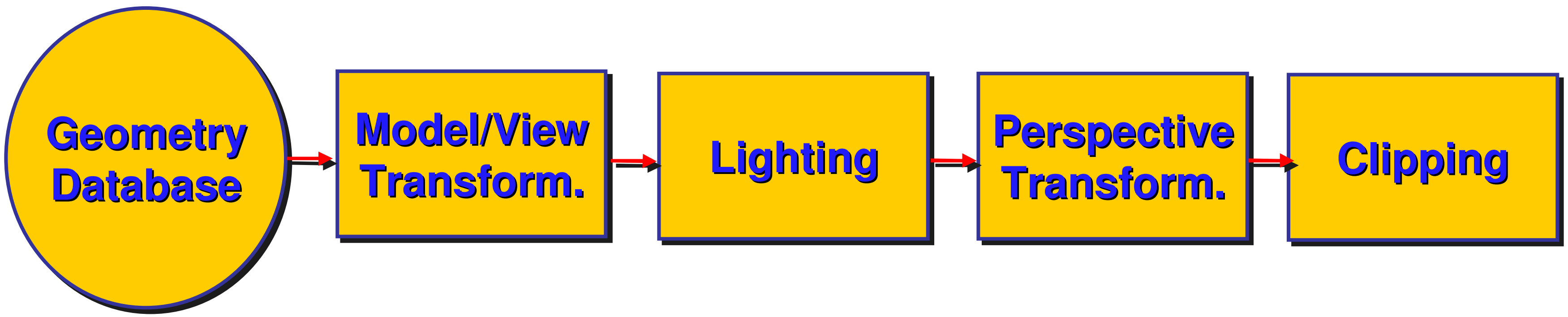
- lighting
  - compute brightness based on property of material and light position(s)
  - computation is performed *per-vertex*

Perspective Transformation



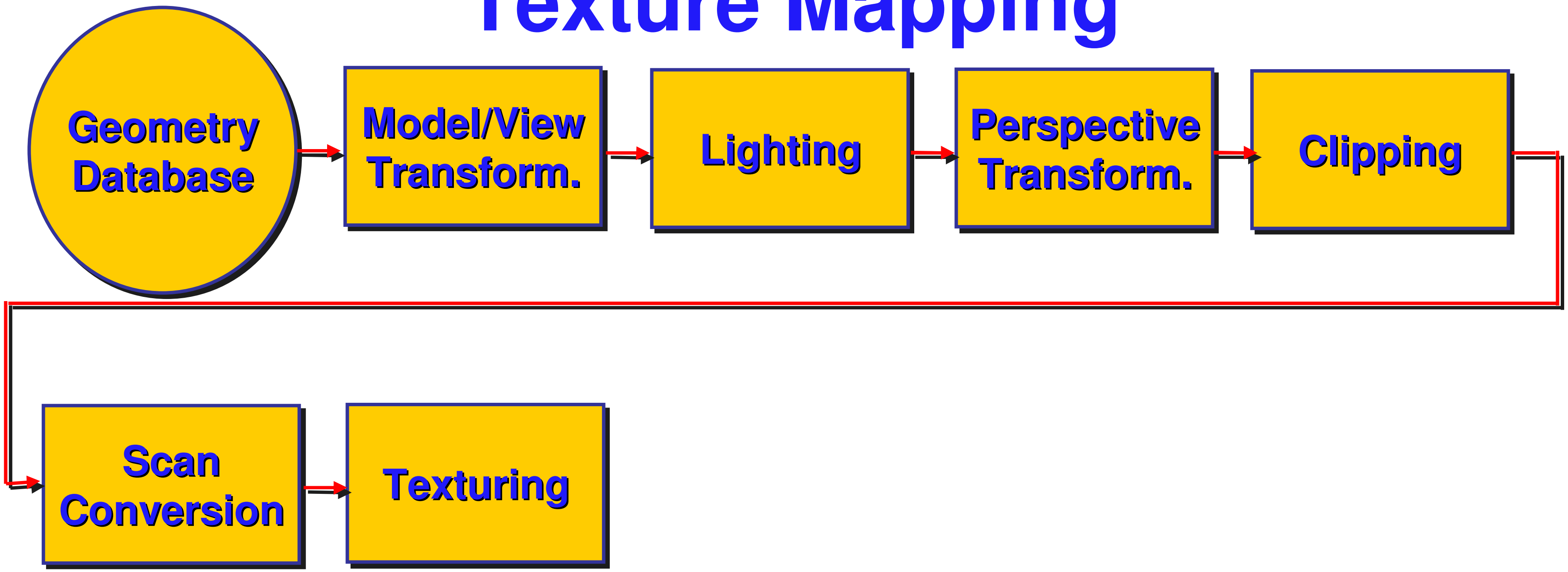
- perspective transformation
  - projecting the geometry onto the image plane
  - projective transformations and model/view transformations can all be expressed with 4x4 matrix operations

Clipping



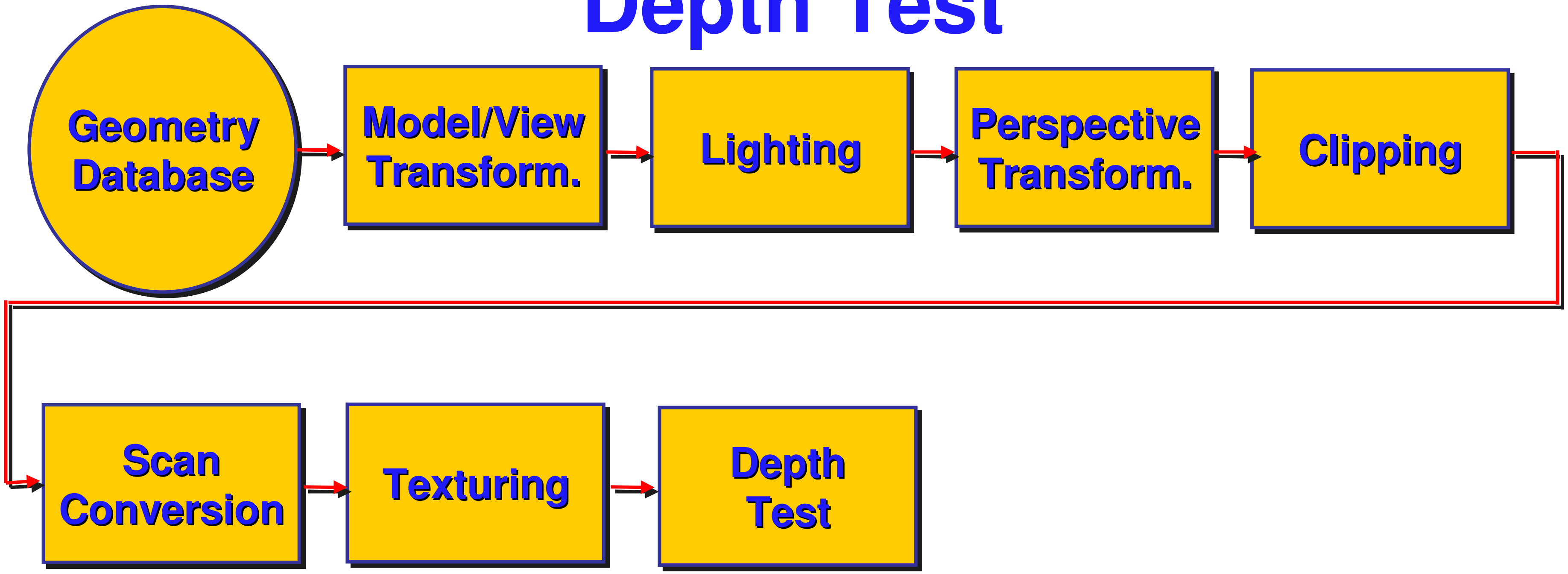
- clipping
  - removal of parts of the geometry that fall outside the visible screen or window region
  - may require *re-tessellation* of geometry

Texture Mapping



- texture mapping
  - “gluing images onto geometry”
  - color of every fragment is altered by looking up a new color value from an image

Depth Test



- depth test
  - remove parts of geometry hidden behind other geometric objects
  - perform on every individual fragment
    - other approaches (later)

Pipeline Advantages

- modularity: logical separation of different components
- easy to parallelize
  - earlier stages can already work on new data while later stages still work with previous data
  - similar to pipelining in modern CPUs
  - but much more aggressive parallelization possible (special purpose hardware!)
  - important for hardware implementations
- only local knowledge of the scene is necessary

Pipeline Disadvantages

- limited flexibility
- some algorithms would require different ordering of pipeline stages
  - hard to achieve while still preserving compatibility
- only local knowledge of scene is available
  - shadows
  - global illumination

OpenGL (briefly)

OpenGL

- started in 1989 by Kurt Akeley
  - based on IRIS_GL by SGI
- API to graphics hardware
- designed to exploit hardware optimized for display and manipulation of 3D graphics
- implemented on many different platforms
- low level, powerful flexible
- pipeline processing
  - set state as needed

Graphics State

- set the state once, remains until overwritten
  - glColor3f(1.0, 1.0, 0.0) → set color to yellow
  - glSetClearColor(0.0, 0.0, 0.2) → dark blue bg
  - glEnable(LIGHT0) → turn on light
  - glEnable(GL_DEPTH_TEST) → hidden surf.

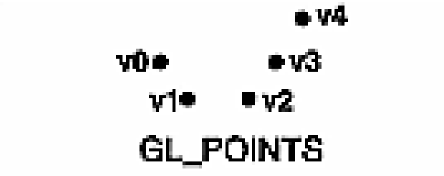
Geometry Pipeline

- tell it how to interpret geometry
  - glBegin(<*mode of geometric primitives*>)
  - *mode* = GL_TRIANGLE, GL_POLYGON, etc.

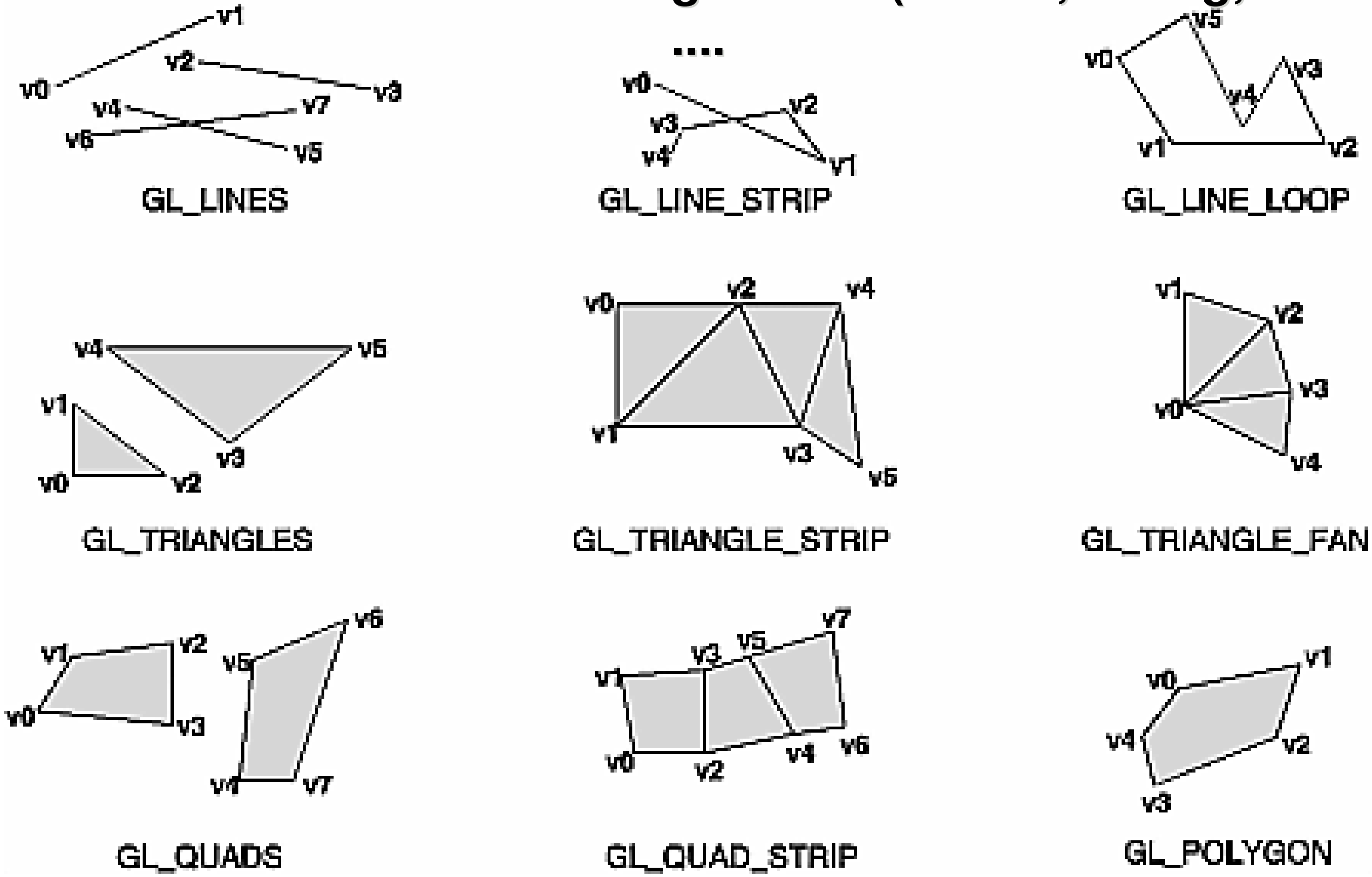
- feed it vertices
  - glVertex3f(-1.0, 0.0, -1.0)
  - glVertex3f(1.0, 0.0, -1.0)
  - glVertex3f(0.0, 1.0, -1.0)

- tell it you're done
  - glEnd()

Open GL: Geometric Primitives




```
glPointSize( float size);
glLineWidth( float width);
glColor3f( float r, float g, float b);
....
```



Code Sample

```
void display()
{
  glClearColor(0.0, 0.0, 0.0, 0.0);
  glClear(GL_COLOR_BUFFER_BIT);
  glColor3f(0.0, 1.0, 0.0);
  glBegin(GL_POLYGON);
    glVertex3f(0.25, 0.25, -0.5);
    glVertex3f(0.75, 0.25, -0.5);
    glVertex3f(0.75, 0.75, -0.5);
    glVertex3f(0.25, 0.75, -0.5);
  glEnd();
  glFlush();
}
```

- more OpenGL as course continues

GLUT

GLUT: OpenGL Utility Toolkit

- developed by Mark Kilgard (also from SGI)
- simple, portable window manager
  - opening windows
    - handling graphics contexts
  - handling input with callbacks
    - keyboard, mouse, window reshape events
  - timing
    - idle processing, idle events
- designed for small-medium size applications
- distributed as binaries
  - free, but not open source

GLUT Draw World

```
int main(int argc, char **argv)
{
      glutInit( &argc, argv );
      glutInitDisplayMode( GLUT_RGB |
                           GLUT_DOUBLE | GLUT_DEPTH);
      glutInitWindowSize( 640, 480 );
      glutCreateWindow( "openGLDemo" );
      glutDisplayFunc( DrawWorld );
      glutIdleFunc(Idle);
      glClearColor( 1,1,1 );
      glutMainLoop();

      return 0;       // never reached
}
```

Event-Driven Programming

- main loop not under your control
  - vs. procedural
- control flow through event callbacks
  - redraw the window now
  - key was pressed
  - mouse moved
- callback functions called from main loop when events occur
  - mouse/keyboard state setting vs. redrawing

GLUT Callback Functions

```
// you supply these kind of functions

void reshape(int w, int h);
void keyboard(unsigned char key, int x, int y);
void mouse(int but, int state, int x, int y);
void idle();
void display();


// register them with glut

glutReshapeFunc(reshape);
glutKeyboardFunc(keyboard);
glutMouseFunc(mouse);
glutIdleFunc(idle);
glutDisplayFunc(display);
```

```
void glutDisplayFunc (void (*func)(void));
void glutKeyboardFunc (void (*func)(unsigned char key, int x, int y));
void glutIdleFunc (void (*func)());
void glutReshapeFunc (void (*func)(int width, int height));
```

Display Function

```
void DrawWorld() {
      glMatrixMode( GL_PROJECTION );
      glLoadIdentity();
      glMatrixMode( GL_MODELVIEW );
      glLoadIdentity();
      glClear( GL_COLOR_BUFFER_BIT );
      angle += 0.05;                  //animation
      glRotatef(angle,0,0,1);         //animation
      ...  // redraw triangle in new position
      glutSwapBuffers();
}
```

- directly update value of angle variable
  - so, why doesn't it spin?
  - only called in response to window/input event!

Idle Function

```
void Idle() {
      angle += 0.05;
      glutPostRedisplay();
}
```

- called from main loop when no user input
- should return control to main loop quickly
  - update value of angle variable here
  - then request redraw event from GLUT
    - draw function will be called next time through
- continues to rotate even when no user action

Keyboard/Mouse Callbacks

- do minimal work
- request redraw for display
- example: keypress triggering animation
  - do not create loop in input callback!
    - what if user hits another key during animation?
  - shared/global variables to keep track of state
  - display function acts on current variable value

Labs

Thursday Lab

- labs start Thursday
  - 11-12: morning not ideal, it's before lecture
  - 3-4,4-5: better, try to attend afternoon if possible
- project 0
  - make sure you can compile OpenGL/GLUT
    - useful to test home computing environment
  - template: spin around obj files
  - todo: change rotation axis
  - do not hand in, not graded
  - http://www.ugrad.cs.ubc.ca/~cs314/Vmay2005/a0
- project 1
  - transformations
  - more on Thursday after transformations lecture

Remote Graphics

- OpenGL does not work well remotely
  - very slow
- only one user can use graphics at a time
  - current X server doesn't give priority to console, just does first come first served
  - problem: FCFS policy = confusion/chaos
- solution: console user gets priority
  - only use graphics remotely if nobody else logged on
    - with 'who' command, ":0" is console person
  - stop using graphics if asked by console user via email
  - or console user can reboot machine out from under you