The Rendering Pipeline – A First Look

Your Tasks Until Monday

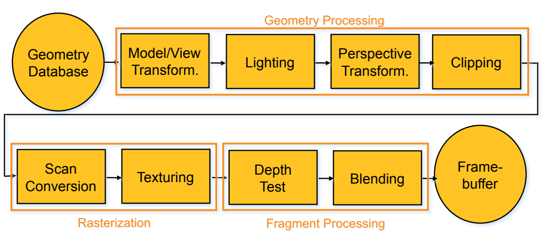
Assignment 0

- Refresher of linear algebra
- Set up programming environment on lab computers

Reading (in Shirley: Introduction to CG)

- Math refresher: Chapters 2, 4
  - *Optional (for now): 2.5-2.9*
- Background on graphics: Chapter 1

The Rendering Pipeline



The Rendering Pipeline

What is it? All of this:

- Abstract model for sequence of operations to transform a geometric model into a digital image
- An abstraction of the way graphics hardware works
- The underlying model for application programming interfaces (APIs) that allow the programming of graphics hardware
  - *OpenGL*
  - *Direct 3D*

Actual implementations of the rendering pipeline will vary in the details

Rendering Pipeline

Advantages of a pipeline structure

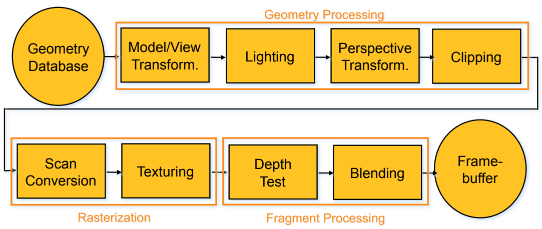
- Logical separation of the different components, modularity
- Easy to parallelize:
  - *Earlier stages can already work on new data while later stages still work with previous data*
  - *Similar to pipelining in modern CPUs*
  - *But much more aggressive parallelization possible (special purpose hardware!)*
  - *Important for hardware implementations!*
- Only local knowledge of the scene is necessary

Rendering 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*

The Rendering Pipeline



Geometry Database

Needs to represent models for

- Geometric primitives
- Relations between different primitives (transformations)
- Object materials
- Light sources
- Camera

Geometric Primitives

Different philosophies:

- Collections of complex shapes
  - *Spheres, cones, cylinders, tori, …*
- One simple type of geometric primitive
  - *Triangles or triangle meshes*
- Small set of complex primitives with adjustable parameters
  - *E.g. "all polynomials of degree 2"*
  - *Splines, NURBS (details in CPSC 424)*
  - *Fractals*

Geometric Primitives

Mathematical representations:

- Explicit functions
- Parametric functions
- Implicit functions

Explicit Functions

Curves:

- *y* is a function of *x*: $y := \sin(x)$
- Only works in 2D

Surfaces:

- *z* is a function of *x* and *y*: $z := \sin(x) + \cos(y)$
- Cannot define arbitrary shapes in 3D

Parametric Functions

Curves:

- 2D: x and y are functions of a parameter value t
- 3D: x, y, and z are functions of a parameter value t

$$C(t) := \begin{pmatrix} \cos(t) \\ \sin(t) \\ t \end{pmatrix}$$

Parametric Functions

Surfaces:

- Surface *S* is defined as a function of *parameter values s, t*
- *Names of parameters can be different to match intuition:*

$$S(\phi,\theta) := \begin{pmatrix} \cos(\phi)\cos(\theta) \\ \sin(\phi)\cos(\theta) \\ \sin(\theta) \end{pmatrix}$$

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Geometry Database

Implicit Surfaces:

- Surface is defined implicitly via the roots of a function
- E.g:

$$S(x,y,z): x^2 + y^2 + z^2 - 1 = 0$$

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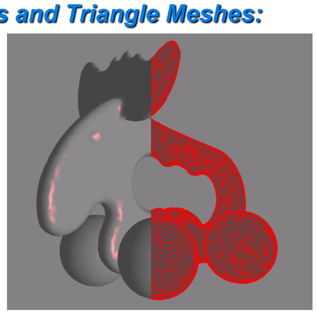
Geometry Database

Triangles and Triangle Meshes:



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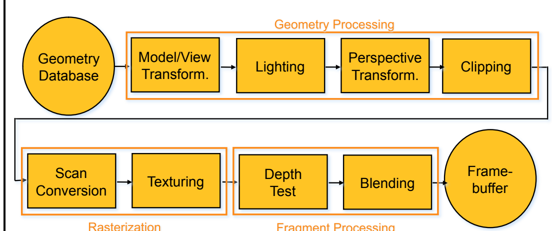
The Rendering Pipeline



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Modeling and Viewing Transformation

Modeling transformation:

- Map points from *object coordinate system* to *world coordinate system*
- *Same a placing objects*

Viewing transformation:

- Map points from *world coordinate system* to *camera* (or *eye*) *coordinate system*
- *Same as placing camera*

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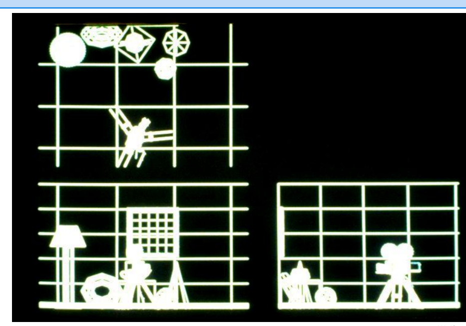
Modeling Transformation: Object Placement



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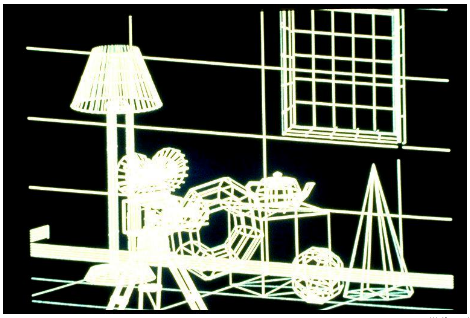
Viewing Transformation: Camera Placement

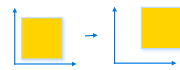


Modeling and Viewing Transformation

Types of transformations:

- *Rotations, scaling, shearing*

- *Translations*



- *Other transformations (not handled by rendering pipeline):*
  - Freeform deformation

Modeling and Viewing Transformation

Linear transformations

- Rotations, scaling, shearing
- Can be expressed as a *3x3* matrix
- E.g. rotation:

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \cos(\phi) & -\sin(\phi) & 0 \\ \sin(\phi) & \cos(\phi) & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

Modeling and Viewing Transformation

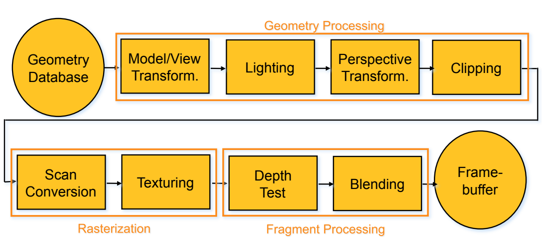
Affine transformations

- Linear transformations + translations
- Can be expressed as a *3x3* matrix + *3* vector
- E.g. rotation + translation:

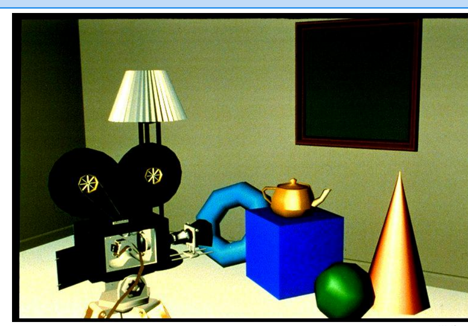
$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \cos(\phi) & -\sin(\phi) & 0 \\ \sin(\phi) & \cos(\phi) & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} + \begin{pmatrix} t_x \\ t_y \\ t_z \end{pmatrix}$$

- Another representation: *4x4 homogeneous matrix*

The Rendering Pipeline



Lighting



Complex Lighting and Shading

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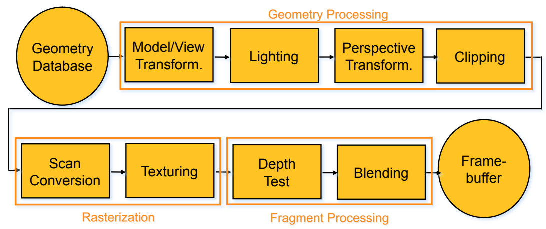
The Rendering Pipeline



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Perspective Transformation

Purpose:

- Project 3D geometry onto a 2D image plane
- Simulates a camera

Camera model:

- Pinhole camera
- Other, more complex camera models also exist in computer graphics, but are less common
  - *Thin lens cameras*
  - *Full simulation of lens geometry*

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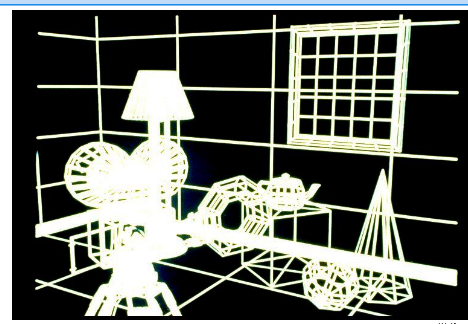
Perspective Projection



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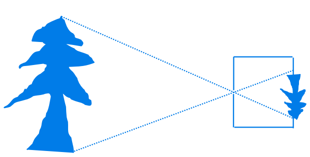
Perspective Transformation

Pinhole Camera:

- Light shining through a tiny hole into a dark room yields upside-down image on wall



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Perspective Transformation

Pinhole Camera

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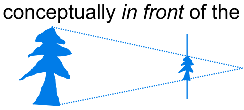
Pinhole Camera - Camera Obscura

Perspective Transformation

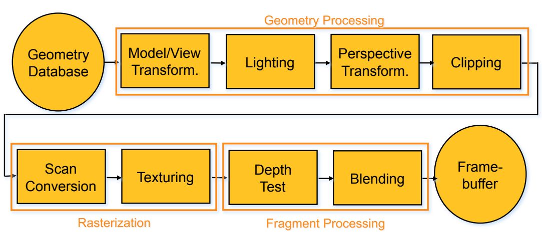
In computer graphics:

- Image plane is conceptually *in front* of the center of projection

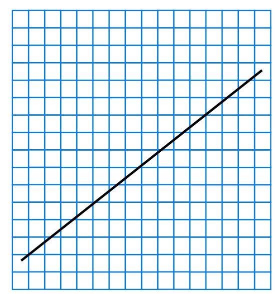


- Perspective transformations belong to a class of operations that are called *projective transformations*
- Linear and affine transformations also belong to this class
- *All* projective transformations can be expressed as *4x4* matrix operations

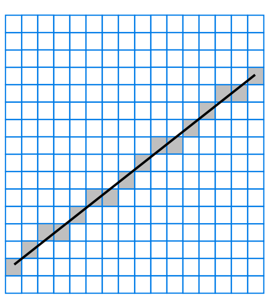
The Rendering Pipeline



Scan Conversion



Scan Conversion

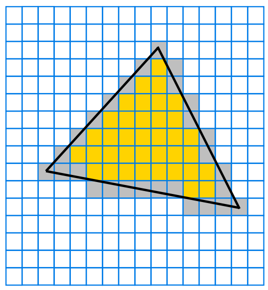


Scan Conversion

Problem:

- Line is infinitely thin, but image has finite resolution
- Results in steps rather than a smooth line
  - *Jaggies*
  - *Aliasing*
- One of the fundamental problems in computer graphics

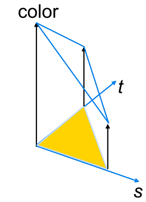
Scan Conversion



Scan Conversion

Color interpolation

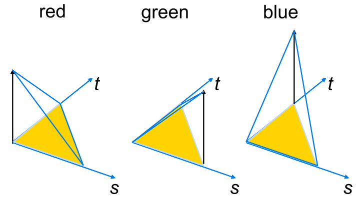
- Linearly interpolate per-pixel color from vertex color values
- Treat every channel of RGB color separately

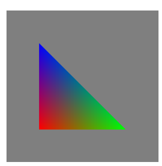


Scan Conversion

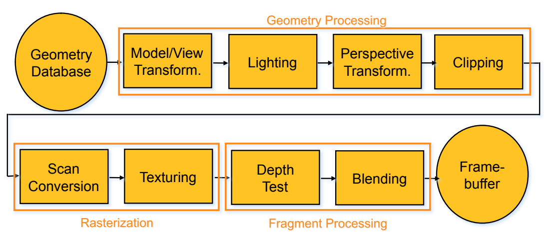
Color interpolation

- Example:

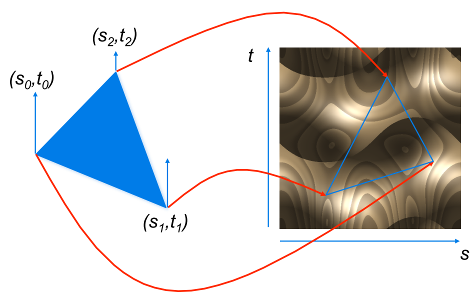




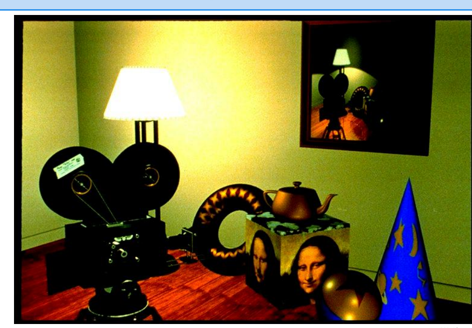
The Rendering Pipeline



Texturing



Texture Mapping



Displacement Mapping

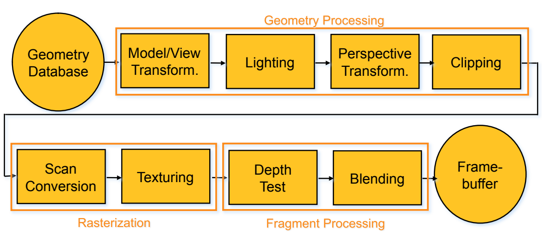
Reflection Mapping

Texturing

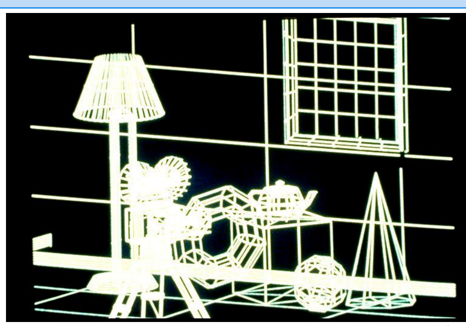
Issues:

- How to map pixel from texture (*texels*) to screen pixels
  - *Texture can appear widely distorted in rendering*
  - *Magnification / minification of textures*
- Filtering of textures
- Preventing aliasing (anti-aliasing)

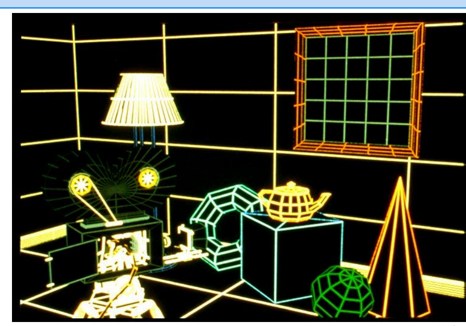
The Rendering Pipeline



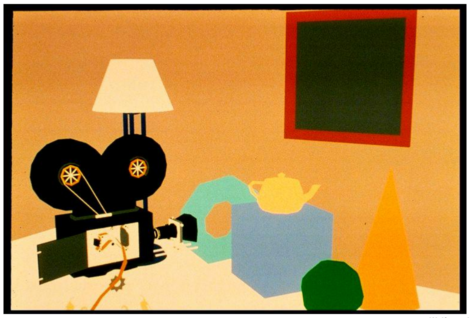
Without Hidden Line Removal



Hidden Line Removal



Hidden Surface Removal



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Depth Test / Hidden Surface Removal

Remove invisible geometry

- Parts that are hidden behind other geometry

Possible Implementations:

- Per-fragment decision
  - *Depth buffer*
- Object space decision
  - *Clipping polygons against each other*
  - *Sorting polygons by distance from camera*

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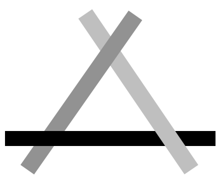
Depth Test / Hidden Surface Removal



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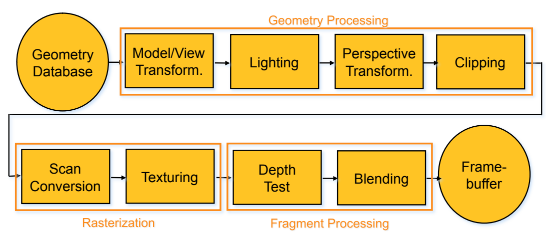
The Rendering Pipeline



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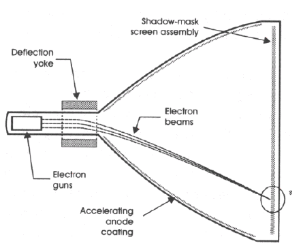
Display Technology

Cathod Ray Tubes (CRTs)



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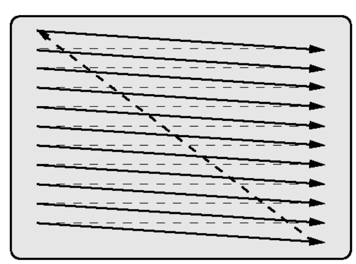
Display Technology

Raster Scan Electron Beam



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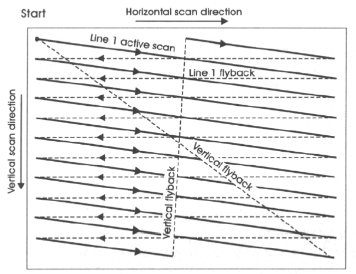
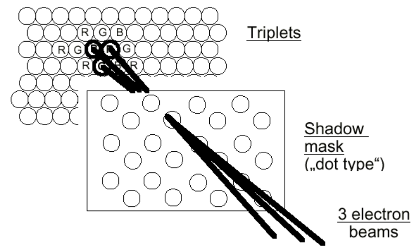
Display Technology

Interlaced Scanning



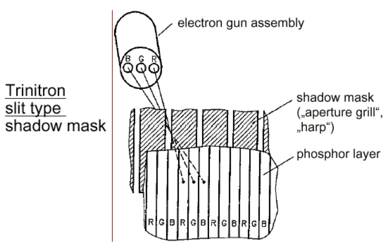
Display Technology

Color CRTs



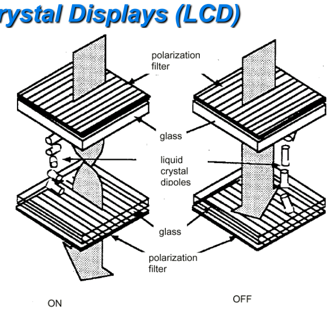
Display Technology

Trinitron CRTs

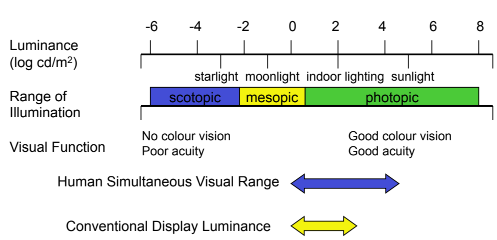


Display Technology

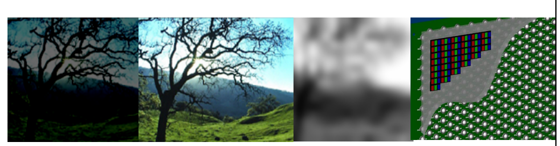
Liquid Crystal Displays (LCD)



High Dynamic Range Displays



HDR Display Principle



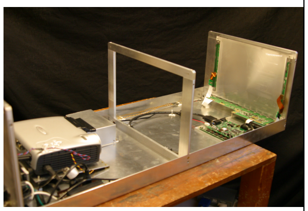
High resolution Colour Image | High Dynamic Range Display | Low resolution Luminance Modulated Second Image | Low resolution LED Array

- Modulated LED array
- Conventional LCD
- Image compensation

Prototype Setup: Projector/LCD Panel

Hardware setup:

- Remove backlight from LCD panel
- Shine image from video projector onto back of panel
  - *(Fresnel lens for focusing)*
- Multiplies dynamic range of LCD and projector



Measured:

- Contrast: 50,000:1
- Intensity: 2,700 cd/m²

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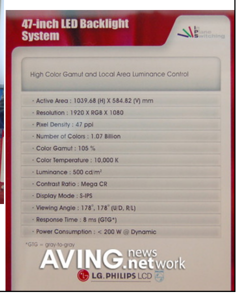
Brightside Technologies / Dolby Commercial Display

18'' prototype: Zeetzen 5

37'' commercial prototype DR-37P

LG Philips - "Local Area Luminance Control"



Coming Up…

Next week:

- Geometric Transformations (Affine, Perspective)

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