The Rendering Pipeline –
A First Look

Wolfgang Heidrich

Your Tasks Until Monday

Assignment 0

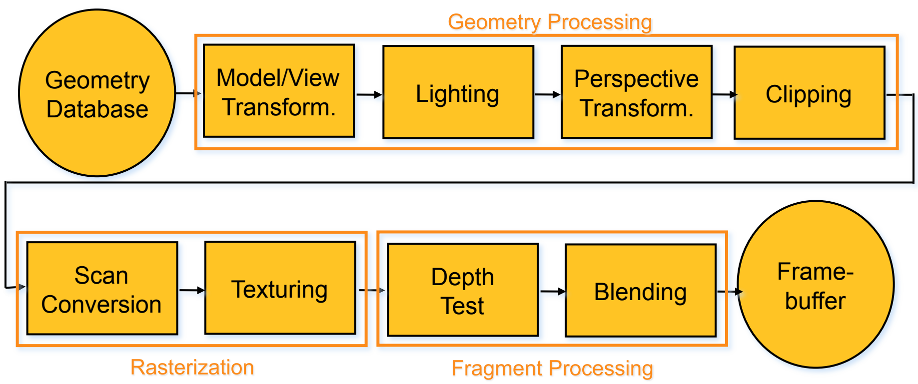
- Refresher of linear algebra
- Set up programming environment on lab computers

Reading (in Shirley: Introduction to CG)

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

Wolfgang Heidrich

The Rendering Pipeline



Wolfgang Heidrich

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

Wolfgang Heidrich

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

Wolfgang Heidrich

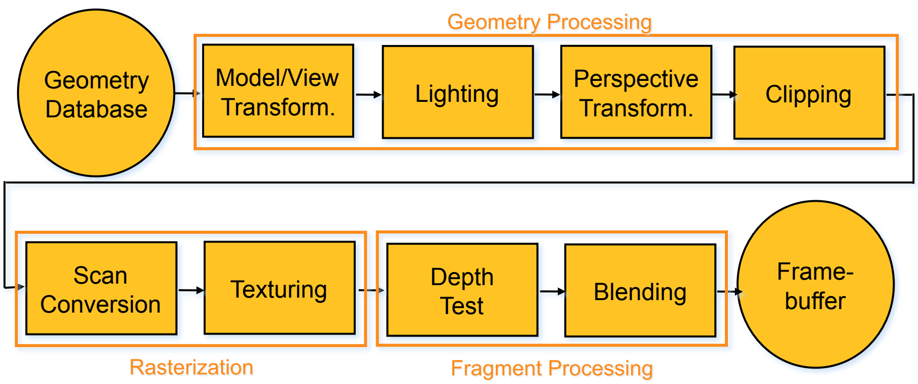
Rendering Pipeline

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*

Wolfgang Heidrich

The Rendering Pipeline



Wolfgang Heidrich

Geometry Database

Needs to represent models for

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

Wolfgang Heidrich

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

Wolfgang Heidrich

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

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

Wolfgang Heidrich

Parametric Functions

Surfaces:

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

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

Wolfgang Heidrich

Geometry Database

Implicit Surfaces:

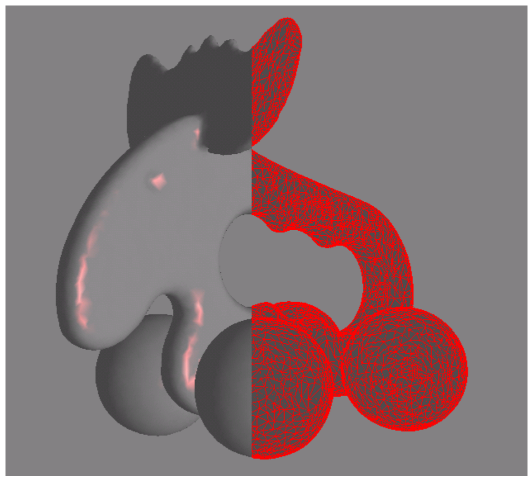
- Surface is defined implicitly via the roots of a function
- E.g:

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

Wolfgang Heidrich

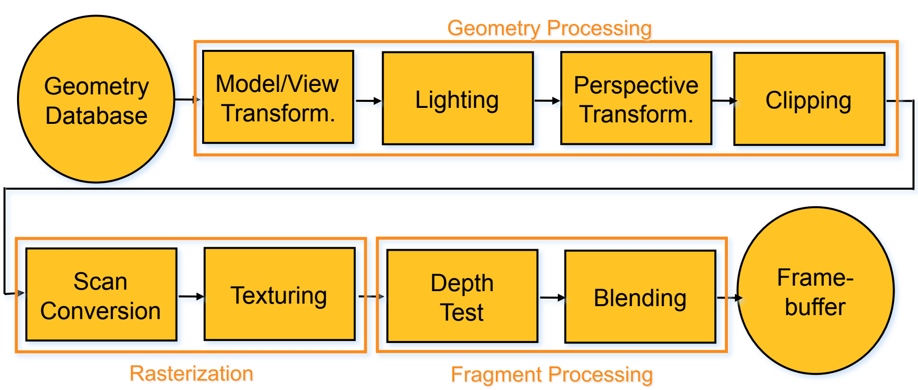
Geometry Database

Triangles and Triangle Meshes:



Wolfgang Heidrich

The Rendering Pipeline



Wolfgang Heidrich

Modeling and Viewing Transformation

Modeling transformation:

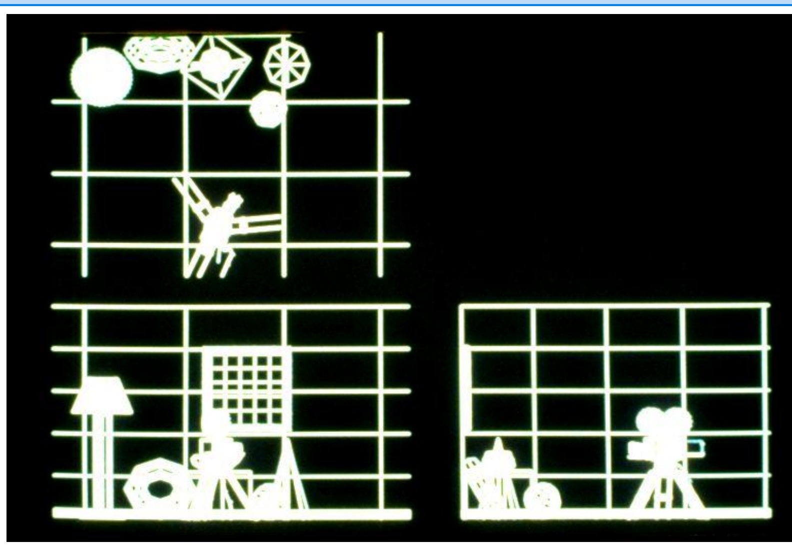
- Map points from *object coordinate system* to *world coordinate system*
- *Same a placing objects*

Viewing transformation:

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

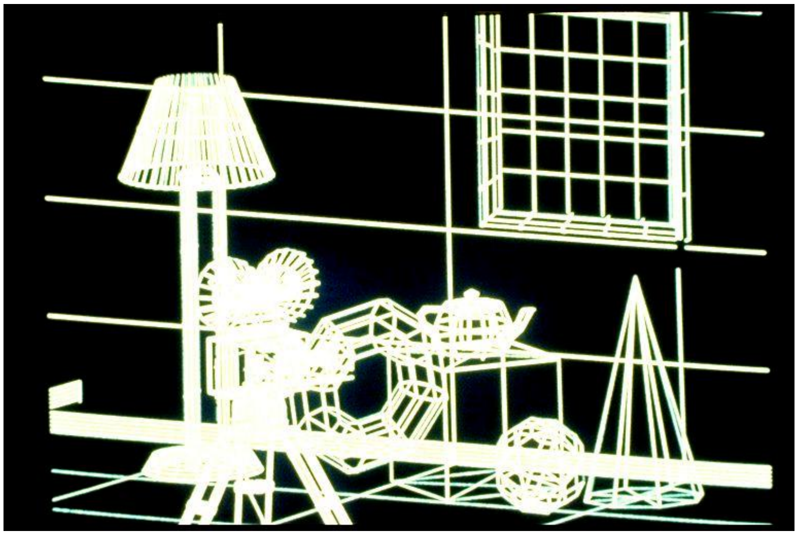
Wolfgang Heidrich

Modeling Transformation: Object Placement



Wolfgang Heidrich

Viewing Transformation: Camera Placement

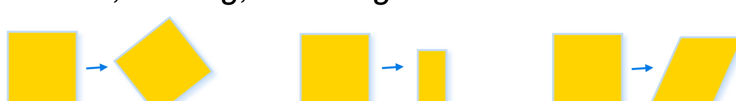


Wolfgang Heidrich

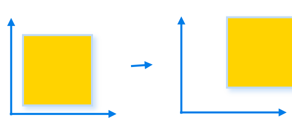
Modeling and Viewing Transformation

Types of transformations:

- *Rotations, scaling, shearing*



- *Translations*



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

Wolfgang Heidrich

Modeling and Viewing Transformation

Linear transformations

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

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

Wolfgang Heidrich

Modeling and Viewing Transformation

Affine transformations

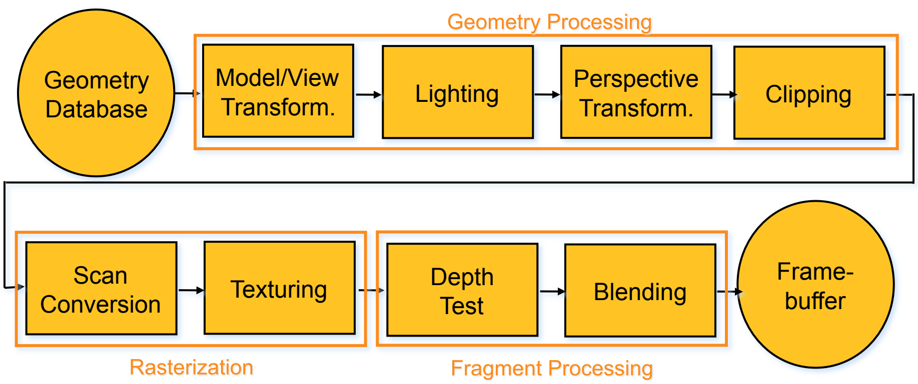
- Linear transformations + translations
- Can be expressed as a *3x3* matrix + *3* vector
- E.g. rotation + translation:

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

- Another representation: *4x4 homogeneous matrix*

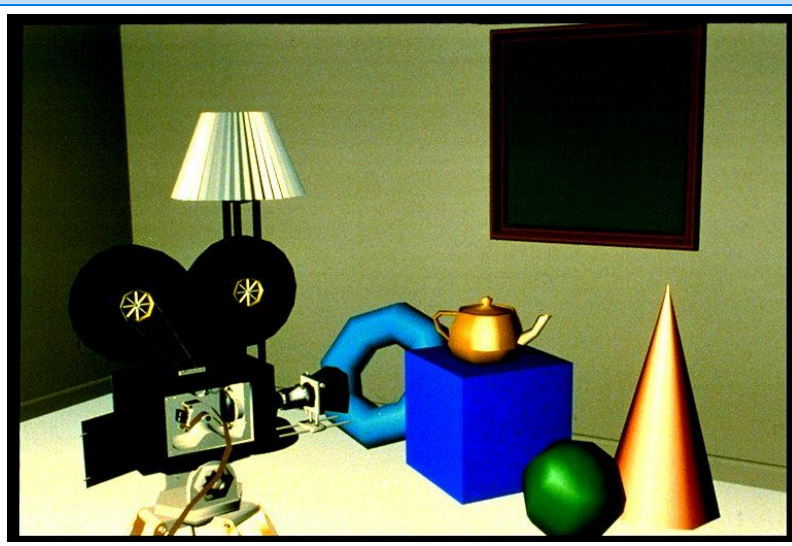
Wolfgang Heidrich

The Rendering Pipeline



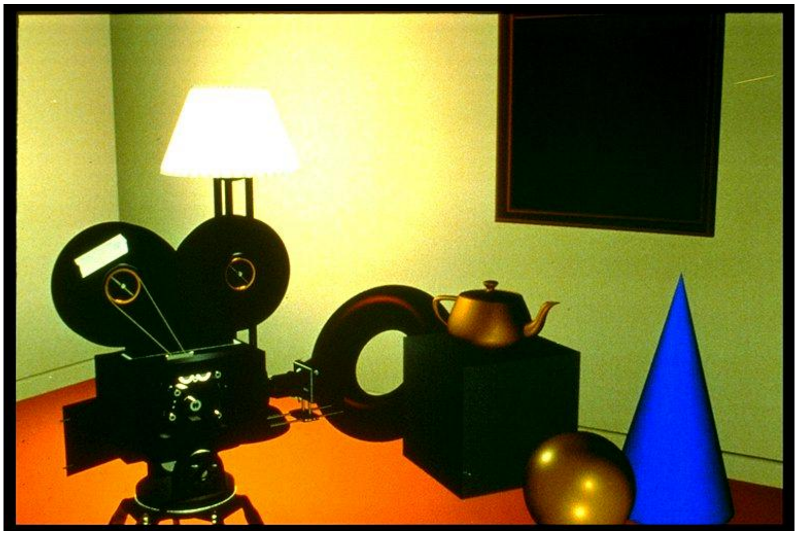
Wolfgang Heidrich

Lighting



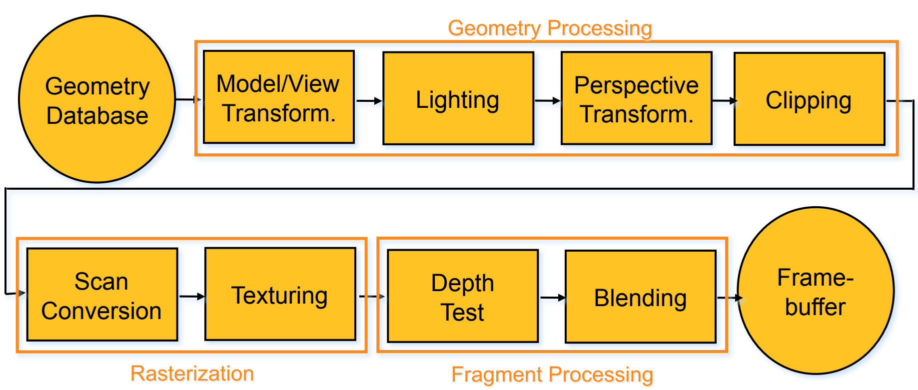
Wolfgang Heidrich

Complex Lighting and Shading



Wolfgang Heidrich

The Rendering Pipeline



Wolfgang Heidrich

Perspective Transformation

Purpose:

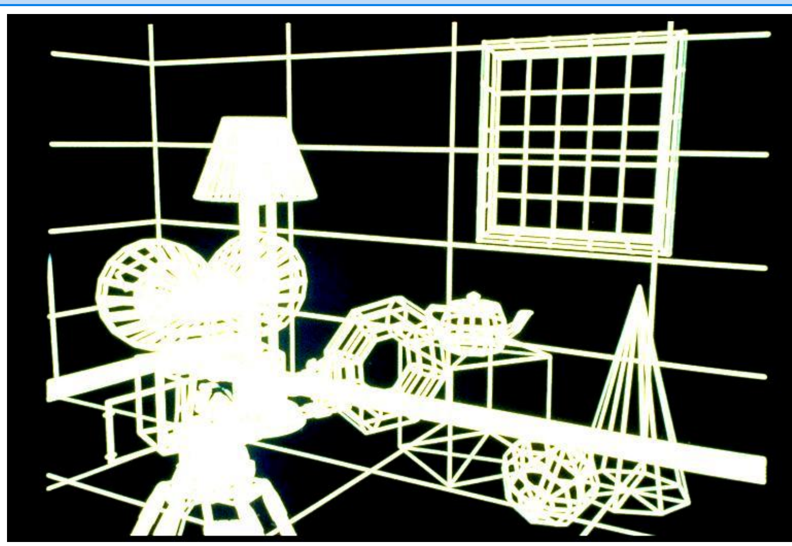
- Project 3D geometry onto a 2D image plane
- Simulates a camera

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*

Wolfgang Heidrich

Perspective Projection

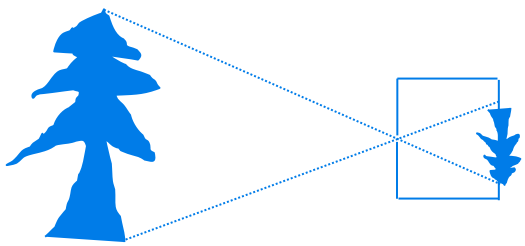


Wolfgang Heidrich

Perspective Transformation

Pinhole Camera:

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



Wolfgang Heidrich

Perspective Transformation

Pinhole Camera

Wolfgang Heidrich

Pinhole Camera - Camera Obscura

Wolfgang Heidrich

Perspective Transformation

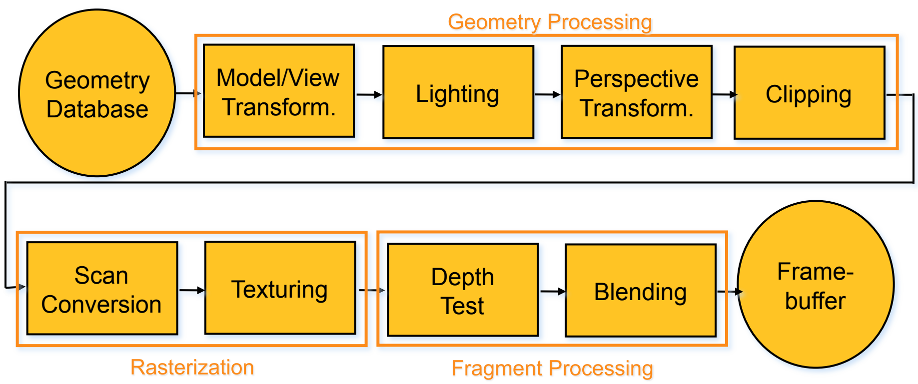
In computer graphics:

- 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

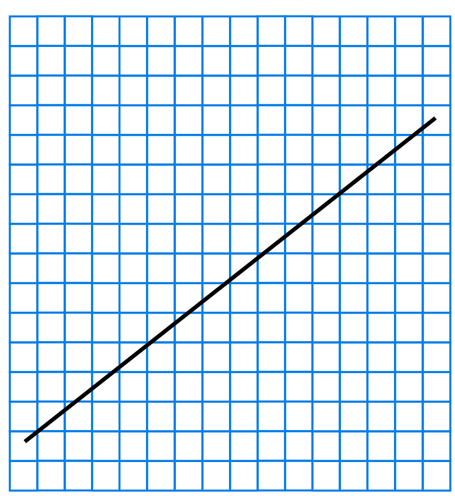
Wolfgang Heidrich

The Rendering Pipeline



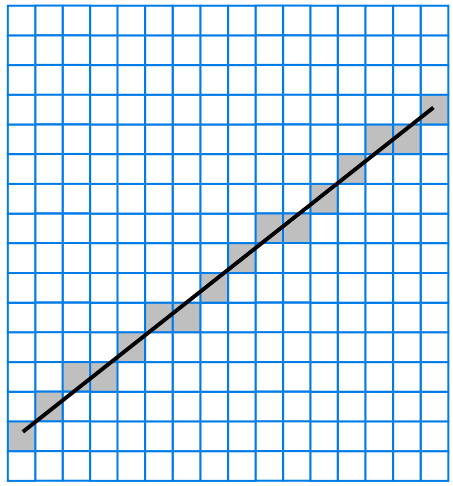
Wolfgang Heidrich

Scan Conversion



Wolfgang Heidrich

Scan Conversion



Wolfgang Heidrich

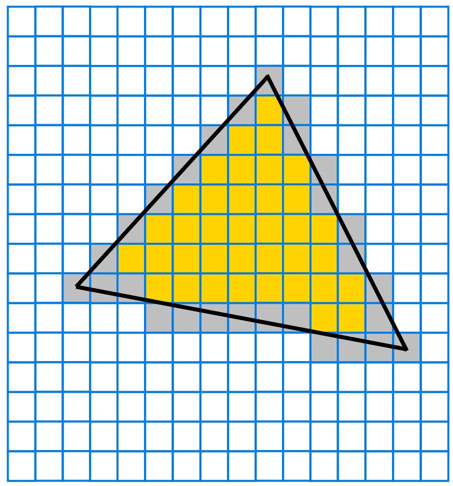
Scan Conversion

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

Wolfgang Heidrich

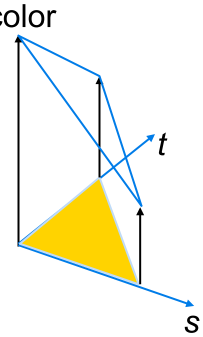
Scan Conversion



Scan Conversion

Color interpolation

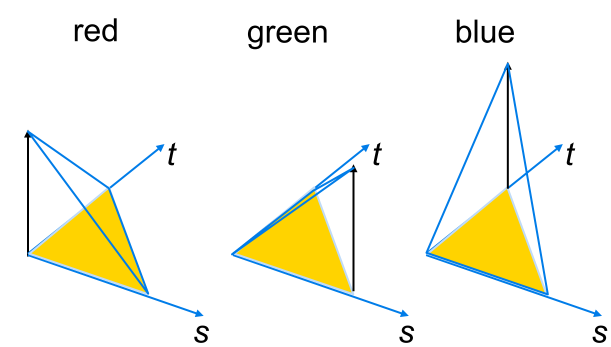
- Linearly interpolate per-pixel color from vertex color values
- Treat every channel of RGB color separately

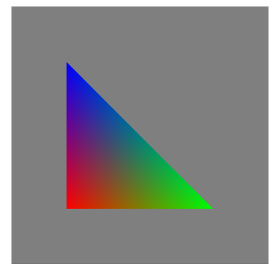


Scan Conversion

Color interpolation

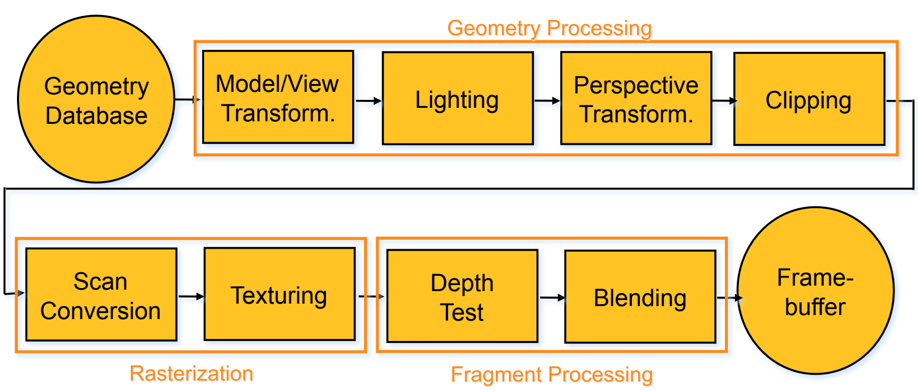
- Example:





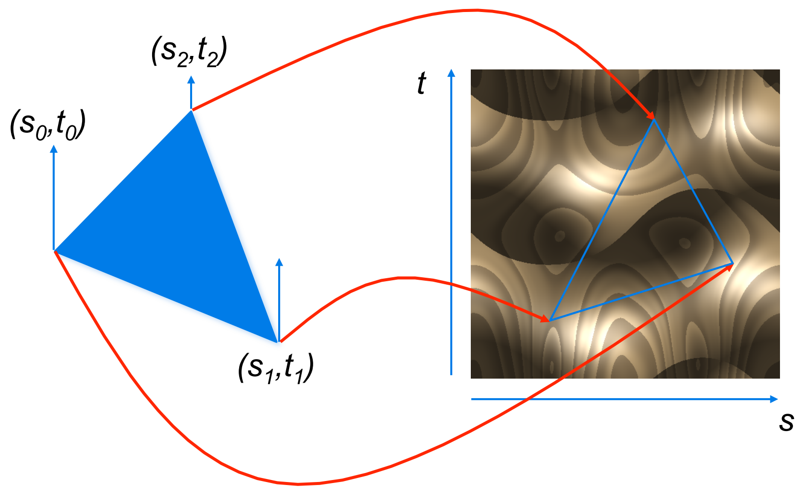
Wolfgang Heidrich

The Rendering Pipeline



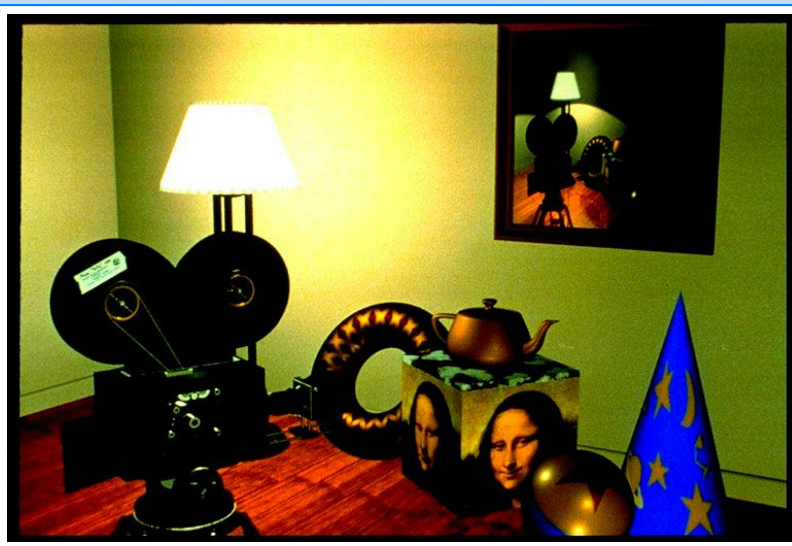
Wolfgang Heidrich

Texturing



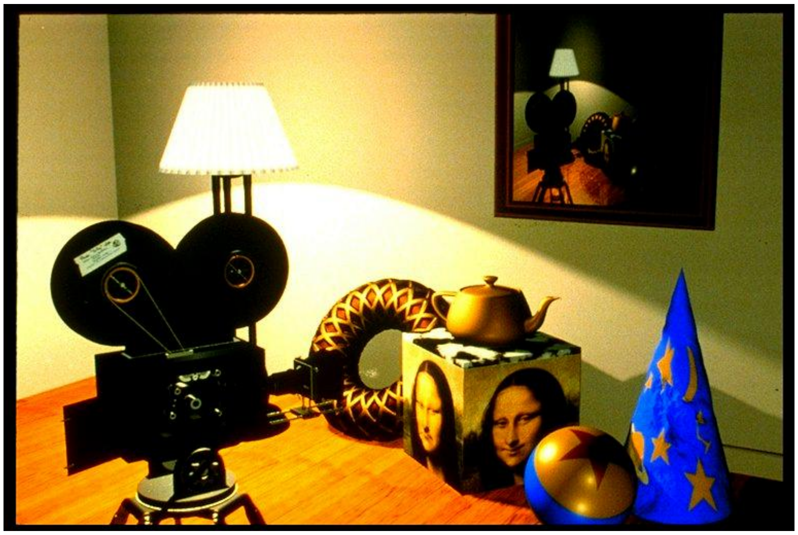
Wolfgang Heidrich

Texture Mapping



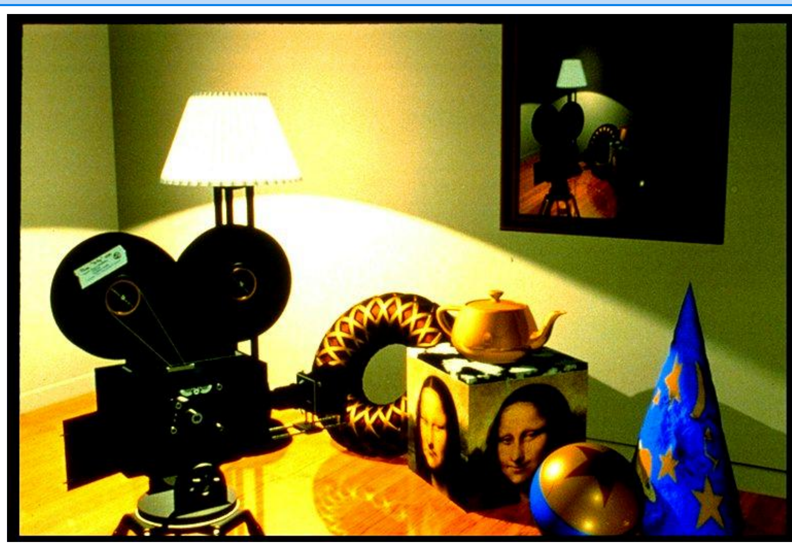
Wolfgang Heidrich

Displacement Mapping



Wolfgang Heidrich

Reflection Mapping



Wolfgang Heidrich

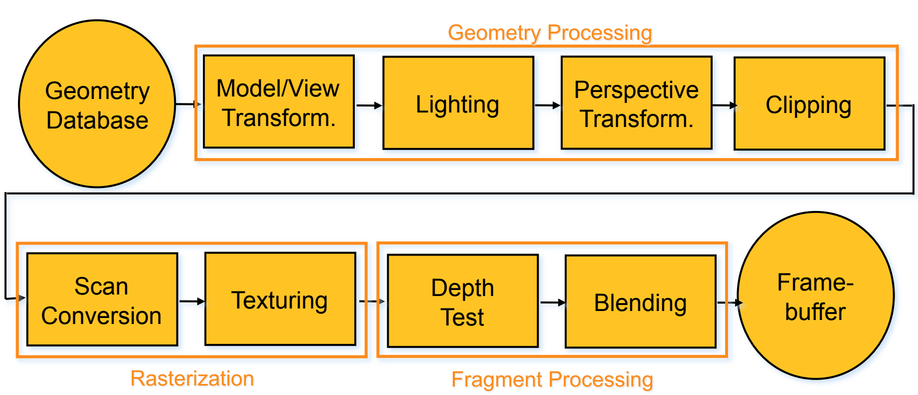
Texturing

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)

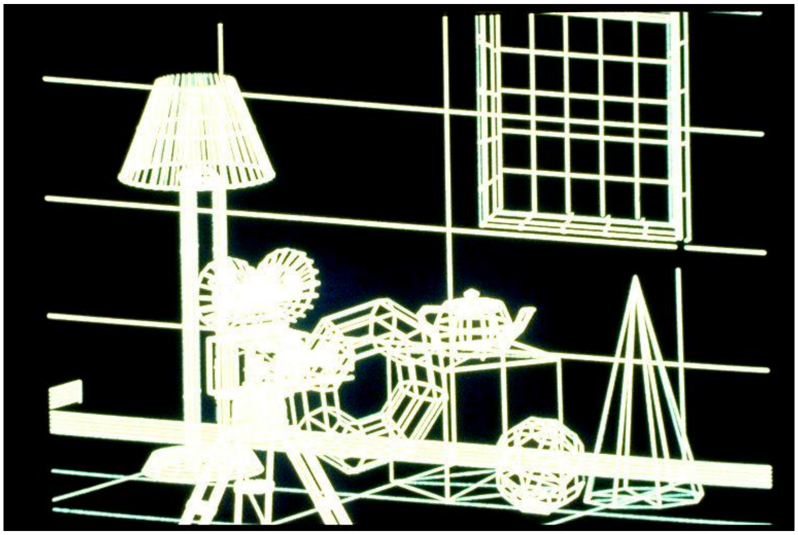
Wolfgang Heidrich

The Rendering Pipeline



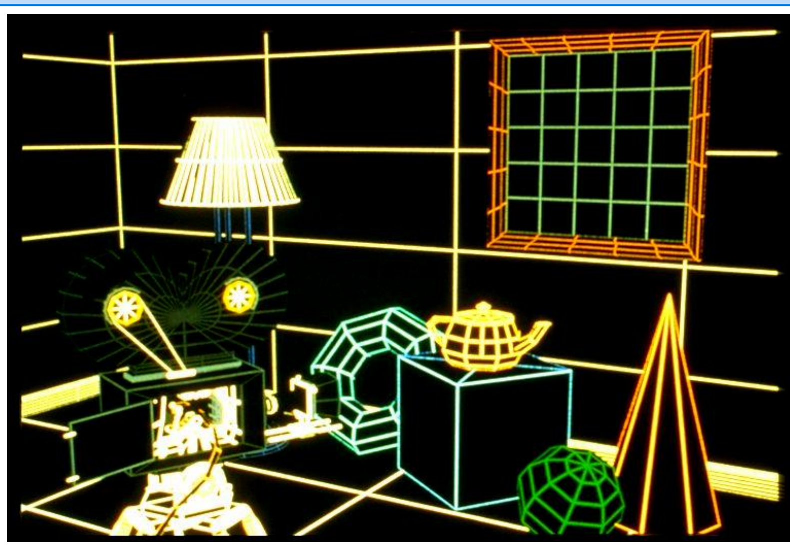
Wolfgang Heidrich

Without Hidden Line Removal



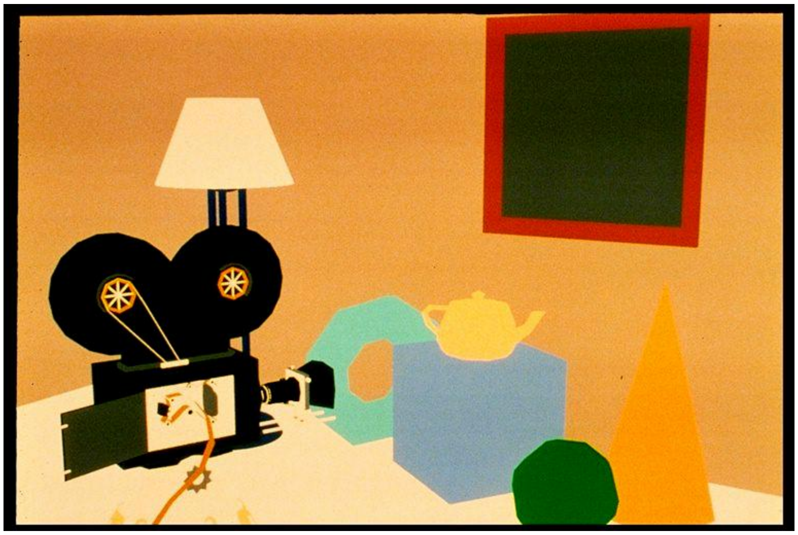
Wolfgang Heidrich

Hidden Line Removal



Wolfgang Heidrich

Hidden Surface Removal



Wolfgang Heidrich

Depth Test / Hidden Surface Removal

Remove invisible geometry

- Parts that are hidden behind other geometry

Possible Implementations:

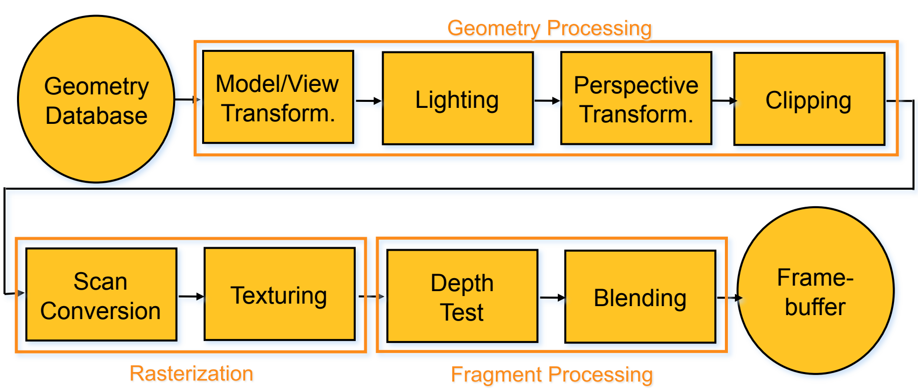
- Per-fragment decision
  - *Depth buffer*
- Object space decision
  - *Clipping polygons against each other*
  - *Sorting polygons by distance from camera*

Wolfgang Heidrich

Depth Test / Hidden Surface Removal

Wolfgang Heidrich

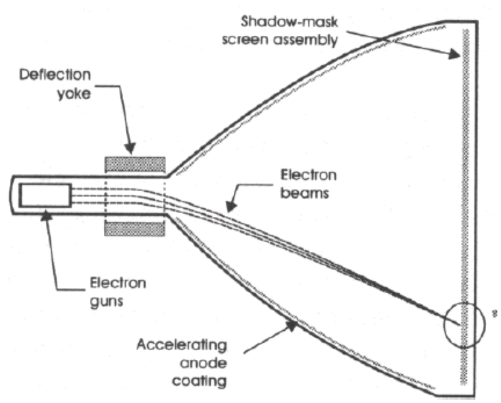
The Rendering Pipeline



Wolfgang Heidrich

Display Technology

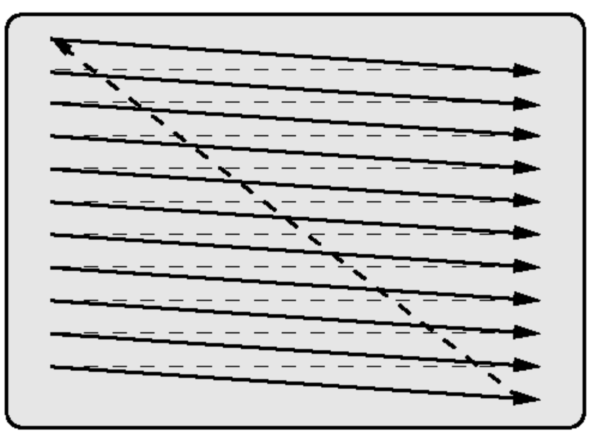
Cathod Ray Tubes (CRTs)



Wolfgang Heidrich

Display Technology

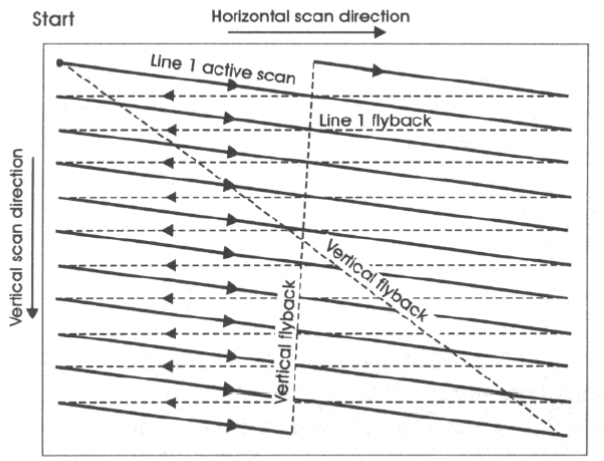
Raster Scan Electron Beam



Wolfgang Heidrich

Display Technology

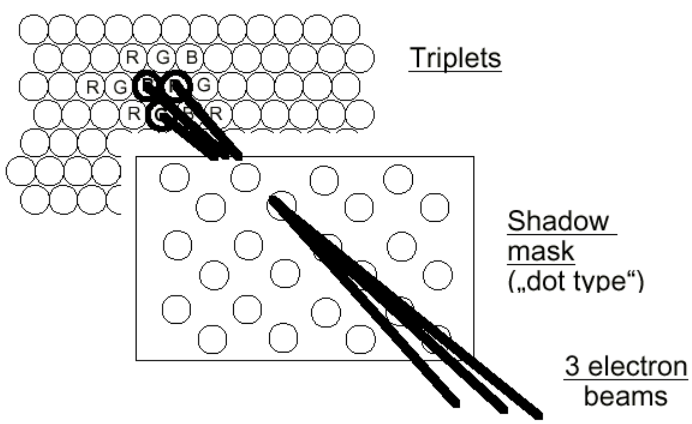
Interlaced Scanning



Wolfgang Heidrich

Display Technology

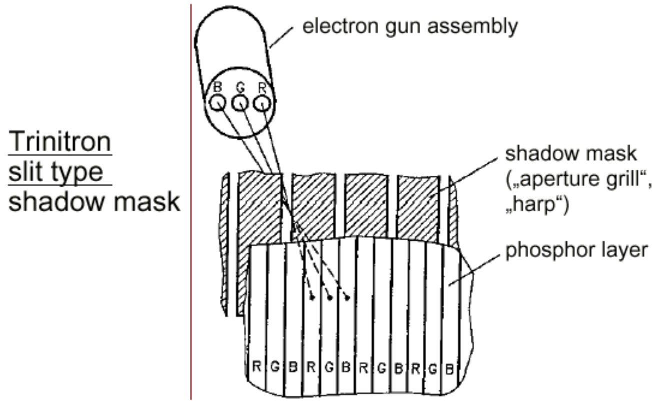
Color CRTs



Wolfgang Heidrich

Display Technology

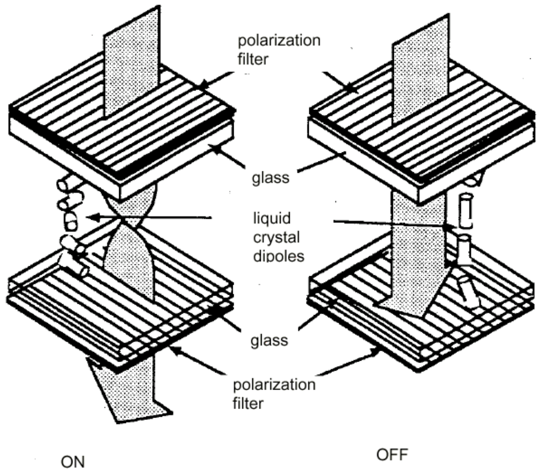
Trinitron CRTs



Wolfgang Heidrich

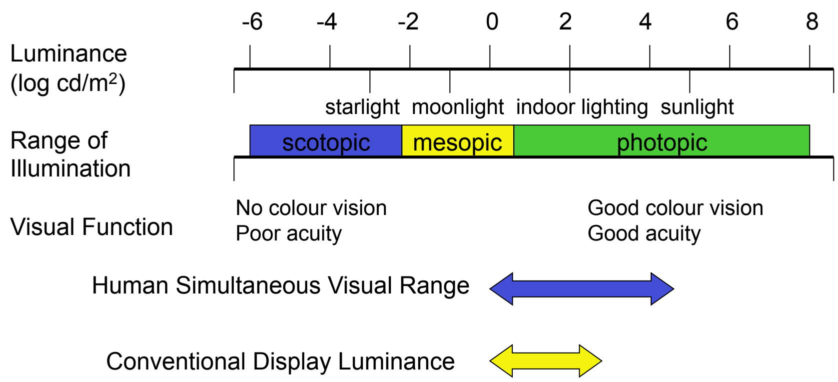
Display Technology

Liquid Crystal Displays (LCD)

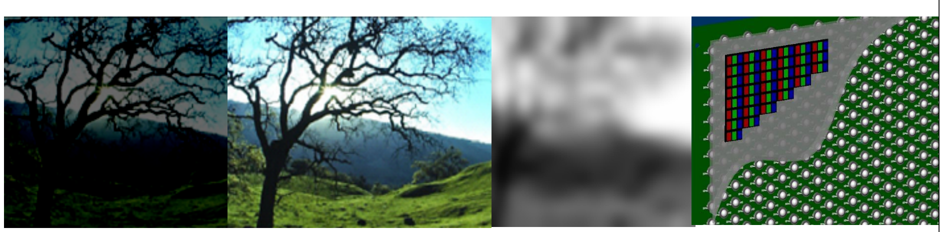


Wolfgang Heidrich

High Dynamic Range Displays



HDR Display Principle



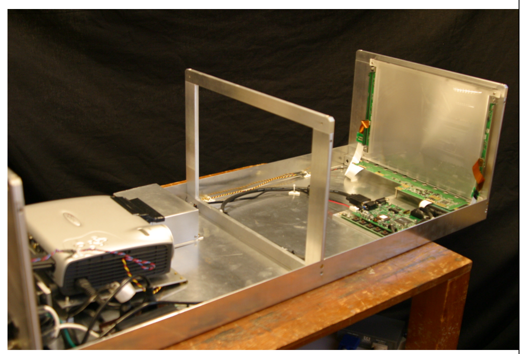
High resolution Colour Image | High Dynamic Range Display | Low resolution Luminance Modulated Second Image | Low resolution LED Array

- 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/m^2

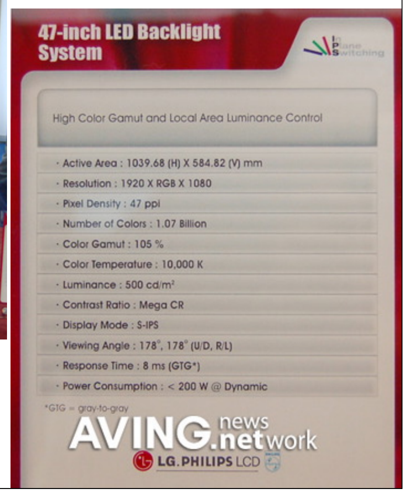
Wolfgang Heidrich

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)

Wolfgang Heidrich