Siggraph '97

Stereo Computer Graphics for Virtual Reality

Course Notes

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ACM SIGGRAPH '97

Stereoscopic Computer Graphics for Virtual Reality

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Welcome & Overview

- Introduction to depth perception & stereo graphics terminology
- Methods to generate stereoscopic images
- Stereo input/output techniques including head mounted displays
- Algorithms in stereoscopic computer graphics

Speaker Biographies:

David F. McAllister received his BS in mathematics from the University of North Carolina at Chapel Hill in 1963. Following service in the military, he attended Purdue University, where he received his MS in mathematics in 1967. He received his Ph. D. in Computer Science in 1972 from the University of North Carolina at Chapel Hill. Dr. McAllister is a professor in the Department of Computer Science at North Carolina State University. He has published many papers in the areas of 3D technology and computer graphics and has given several courses in these areas at SPIE, SPSE, Visualization and SIGGRAPH. He is the editor of a book on Stereo Computer Graphics published by Princeton University Press.

Lou Harrison received his BS in Computer Science from North Carolina State University in 1987 and his MS in Computer Science, also from NCSU, in 1990. Mr. Harrison has taught courses in Operating Systems and Computer Graphics at NCSU and is currently Manager of Operations for the Department of Computer Science at NCSU while pursuing his Ph. D. He has done research in the area of "Surface Generation for Computer Aided Milling." Mr. Harrison is a member of ACM, SIGGRAPH, and SPIE. He is a contributor to "Stereo Computer Graphics and Other True 3D Technologies" edited by David F. McAllister and published by Princeton University Press.

Martin Dulberg received his BA in Computer Science from Queens College, City University of New York, in 1993, his MS in Computer Science from North Carolina State University in 1996, and is currently pursuing his Ph.D. in Computer Science, also at North Carolina State University. Mr. Dulberg has done research in the area of "Simulation and Scientific Visualization of Precision Optical Fabrication Processes" and has experience with head mounted displays and various input devices. He is a member of ACM and SIGGRAPH.

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Stereo Computer Graphics for Virtual Reality

Introduction to depth perception and stereo graphics terminology

Lou Harrison

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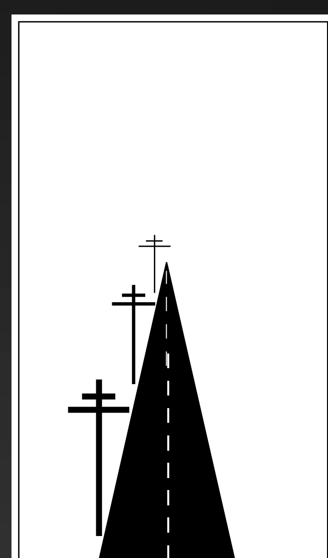
Depth Cues

- Psychological
- Physiological

Psychological Depth Cues

- Linear perspective

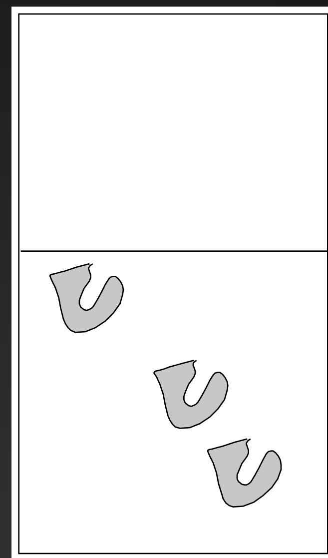
Size of the image of an object on the retina changes in inverse proportion to its change in distance.



Psychological Depth Cues

- Height in the field of view

Objects that rest on a surface below the horizon and are higher in the field of view are usually seen as being more distant.



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Psychological Depth Cues

- Aerial perspective

Objects further away tend to become less distance, cloudy or hazy.

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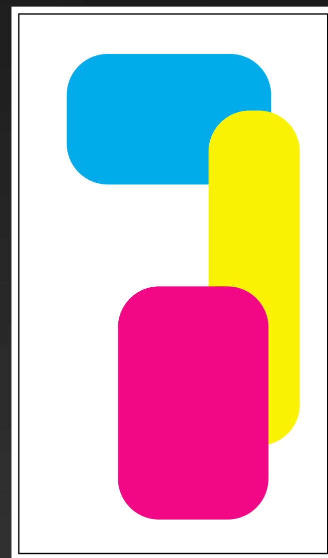
Psychological Depth Cues

- Interposition

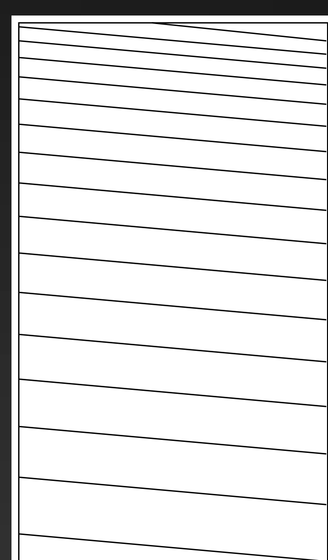
One object occludes, hides or overlaps another.



Psychological Depth Cues

- Texture Gradient

The pattern formed by a regular textured surface that extends away from the observer.



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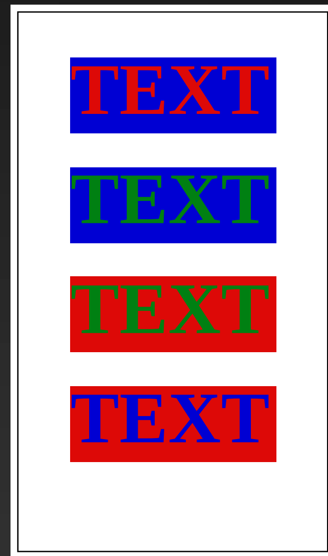
Psychological Depth Cues

- Color

Fluids in the eye cause refraction. Reds appear closer than blues. Bright objects appear closer than dull ones.

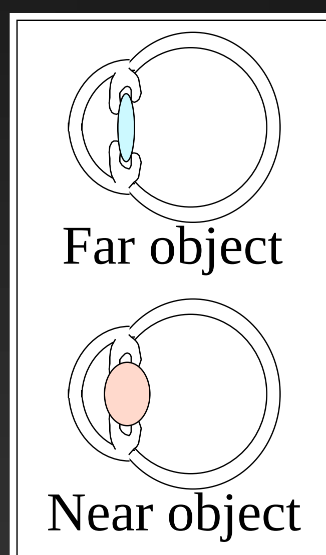
(chromostereopsis)



Physiological Depth Cues

- Accomodation

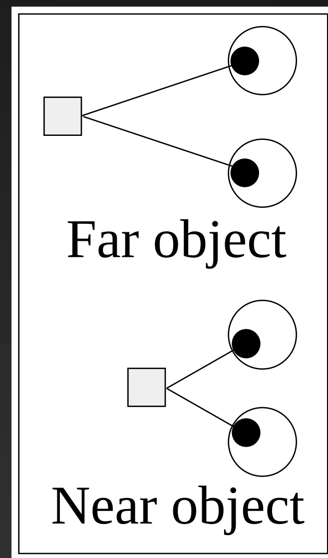
Change in focal length of the lens due to a change in tension from the ciliary muscle.



Physiological Depth Cues

- Convergence (Vergence)

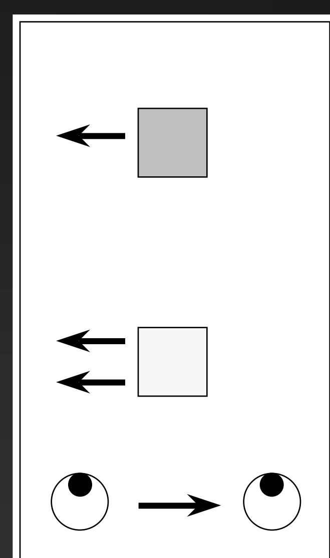
Rotation of the eyes inward to focus on objects as they move closer to the observer.



Physiological Depth Cues

- Motion parallax

As an observer moves, nearby objects appear to move rapidly while far objects appear to move more slowly.



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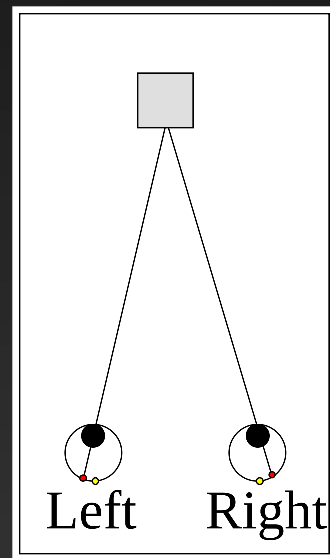
Physiological Depth Cues

- Binocular Disparity (Stereopsis)

Difference in the images projected on the left and right eyes when viewing a 3D scene.



Depth Cues

- Cues are usually additive
- Some cues are more powerful
- Cues may produce conflicting depth information

Depth Cues

- Stereo Blindness

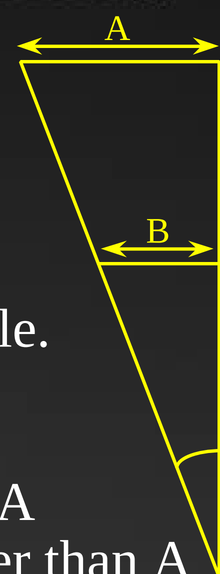
Approximately 10% of the population cannot see the depth in stereo images.

Emmert's Law

- Size constancy

The ratio of perceived size to perceived distance is constant for a given visual angle.

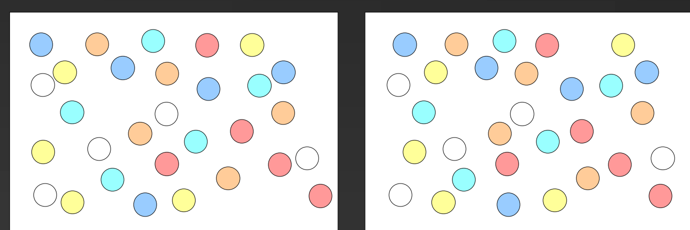
Given the same retinal angle, B is perceived as smaller than A because B is perceived as closer than A



Emmert's Law

- An example:

All the circles are the same size, but binocular disparity tells you they are at different depths, so the further back they appear, the larger they appear.



Emmert's Law

- The moral:

If you are going to have objects moving around in three dimensions in stereo, make sure they obey the laws of linear perspective.

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Terminology

Some terminology you are likely to see in the rest of the course

Terminology

- Horizontal Parallax (Binocular disparity or Binocular parallax)

When the retinal images of an object fall on disparate points on the two retinas. These points only differ in their horizontal position.

Value given by R - L.

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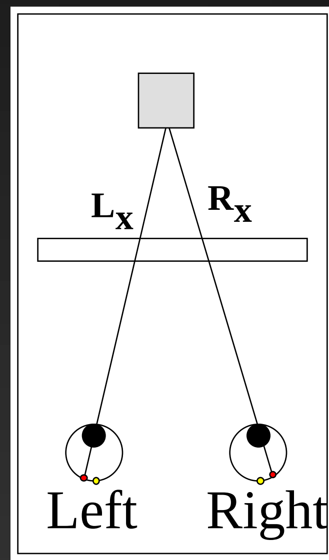
Terminology

- Stereo window (Plane)

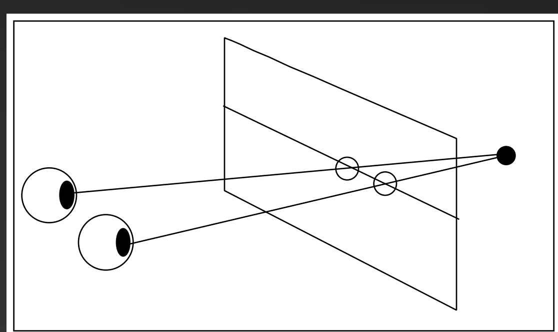
The point at which there is no difference in parallax between the two eye views.
Usually at the same depth as the monitor surface.



Terminology

- Homologous Points

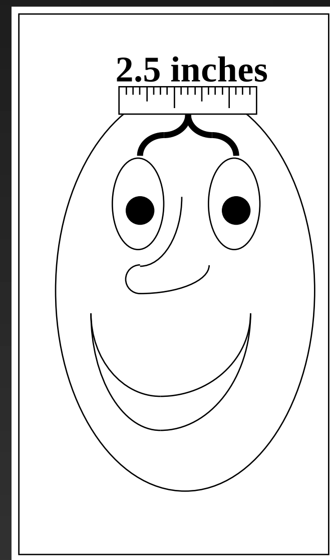
Points which correspond to each other in the seperate eye views.



Terminology

- Interocular Distance

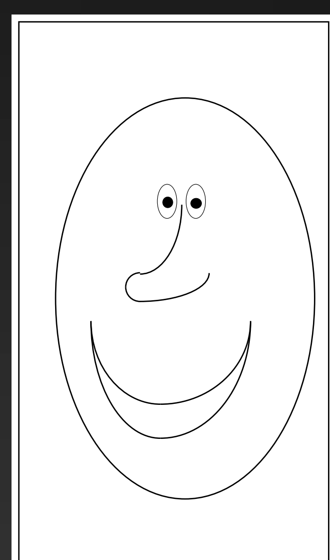
The distance between the left and right eyes. Usually about 2.5 inches.



Terminology

- Hypostereo

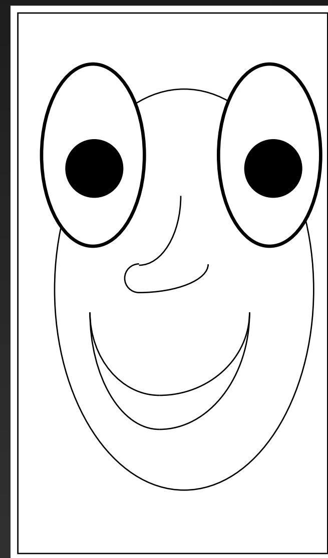
Decreasing the distance between the left and right eyes to show stereoscopic detail on small items.



Terminology

- Hyperstereo

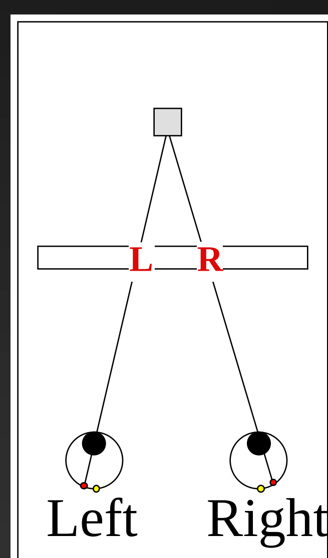
Increasing the distance between the left and right eyes to show stereoscopic detail in large scenes.



Terminology

- Positive Parallax

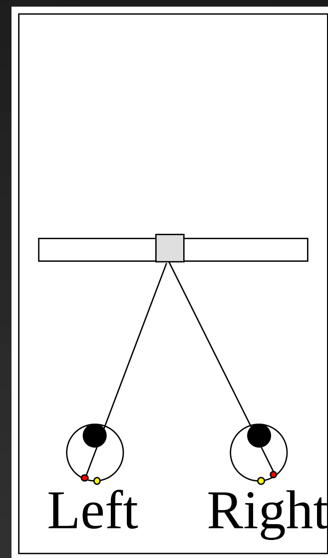
The point lies behind the stereo window. (On the opposite side from the observer)



Terminology

- Zero Parallax

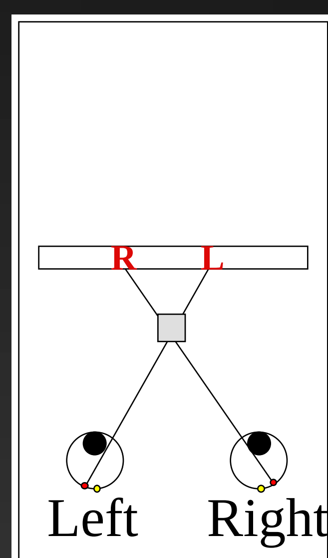
The point is at the same depth as the stereo window. (Both eyes see the same image.)



Terminology

- Negative Parallax

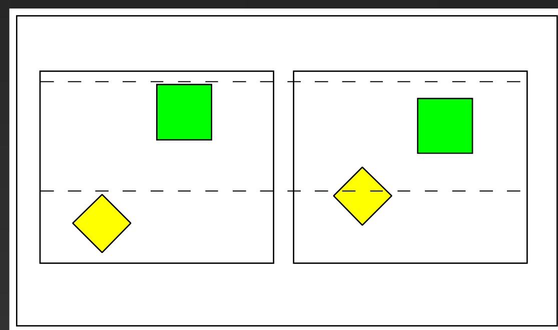
The point lies in front of the stereo window. (On the same side as the observer)



Terminology

- Vertical Displacement

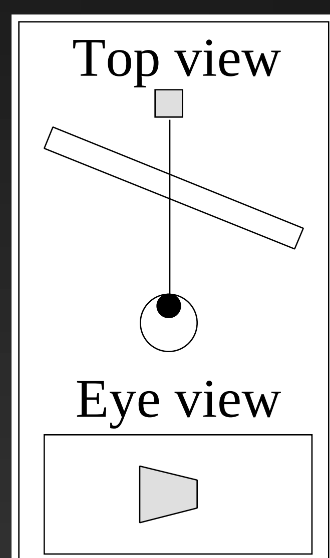
Vertical parallax between homologous points.



Terminology

- Keystoning

Image warping, may be due to indirect projection.



Terminology

- Interocular Crosstalk (Ghosting)

Each eye should only see it's view but sometimes it can see part of the other eye view as well. This is distracting and causes eye fatigue.

Stereo Output Techniques

- How to view stereo pairs

We want to be able to see stereo on a computer monitor, or in hardcopy form.

Stereo Output Techniques

- Time multiplexed (field sequential)

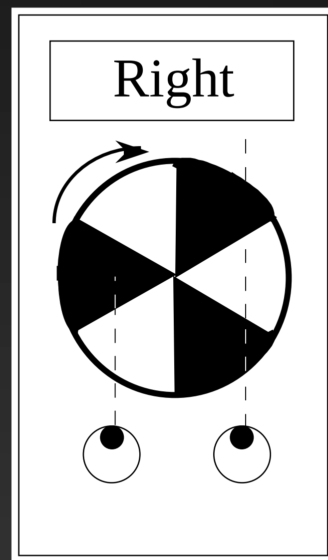
Different eye views alternately shown on a CRT. Some device must be used to make sure that each eye sees only the view it is supposed to see.

Each eye view should be refreshed often enough to avoid flicker. Newer CRTs operate at 120Hz, 60Hz for each eye.

Stereo Output Techniques

- Time multiplexed

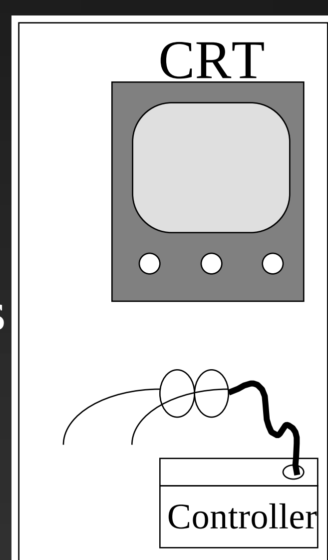
Early systems used a rotating metal plate synchronized with the screen.



Stereo Output Techniques

- Time multiplexed

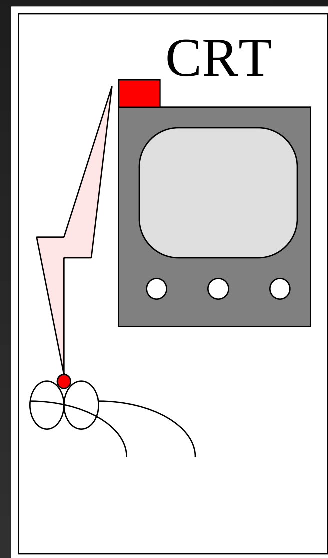
Later systems use active shutter glasses worn by observer. These shutters were originally made from PLZT ceramics. Newer ones are made from liquid crystals.



Stereo Output Techniques

- Time multiplexed

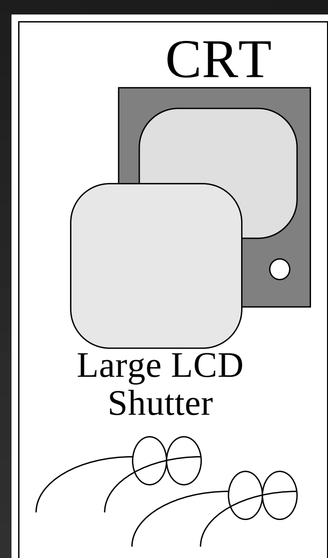
Newest systems use battery powered LCD glasses with an IR receiver and an IR transmitter hooked to the monitor.



Stereo Output Techniques

- Time multiplexed

Large polarizing LCD panels make it possible for observers to wear passive polarizing glasses (circular polarizers).



Stereo Output Techniques

- Time parallel

Present seperate left and right eye views simultaneously . This may be done by using two displays or a single display and some sort of optical splitting apparatus.

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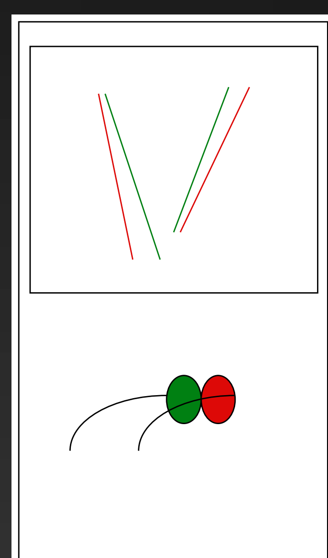
Stereo Output Techniques

- Time parallel

Two simultaneous views are displayed in complimentary colors and viewed through filtered glasses. (Anaglyphs)



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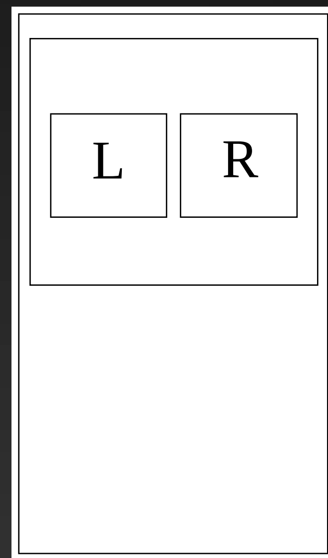
Stereo Output Techniques

- Time parallel

Viewer displays show the left and right eye views side by side on a CRT and the observer looks through an optical viewer.



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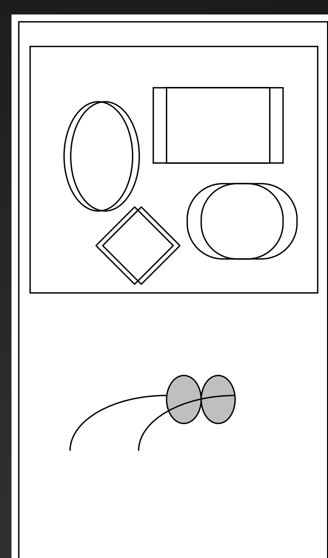
Stereo Output Techniques

- Time parallel

Two simultaneous views can be generated on seperate CRTs (or slide projectors) and projected through opposing polarizing filters.



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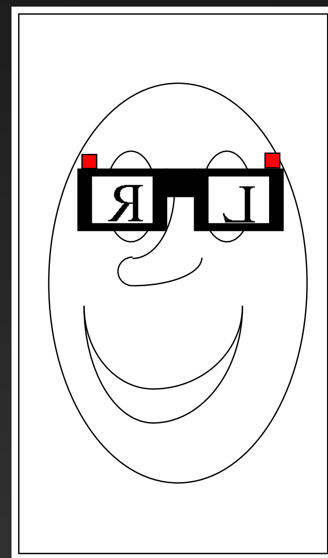
Stereo Output Techniques

- Time parallel

Head mounted displays consist of two small CRTs attached to the head with some display optics and a head tracking device .



Stereo Output Techniques

- Random Dot Stereograms

Provide an observer with binocular depth cues while eliminating all other cues.

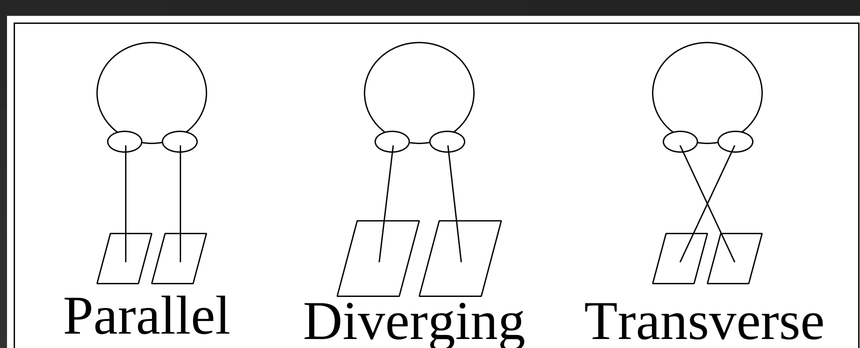
Taxonomy of Technologies

3D HARDCOPY

- **AUTOSTEREOSCOPIC**
  - **Holographic**
  - **Non-Holographic**
    - **Free View Prints**
    - Fully Computed
    - **Parallax Barrier**
    - Multiplexed
    - **Lenticular Screen**
- **APPARATUS NEEDED**
  - **Static**
    - Printed Images
    - Slides
    - Vectograph
  - **Dynamic**
    - Video Tape
    - Cinema

Stereo Output Techniques

- Free viewing.



Walleyed

Stereo Output Techniques

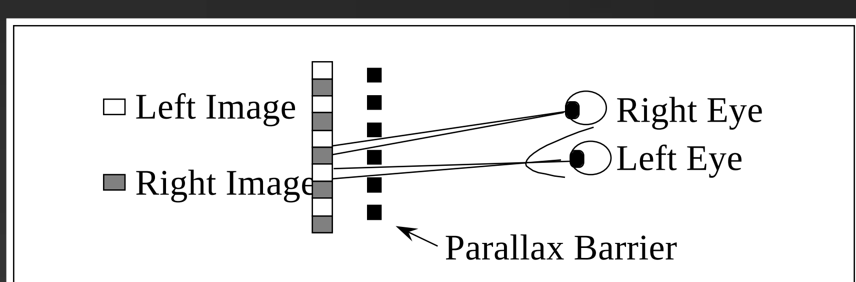
- Psuedo stereo

If a stereo pair is set up to be free viewed parallel and you view it transverse (or vice versa), all the depth information will be reversed.

Stereo Output Techniques

- Parallax barrier methods

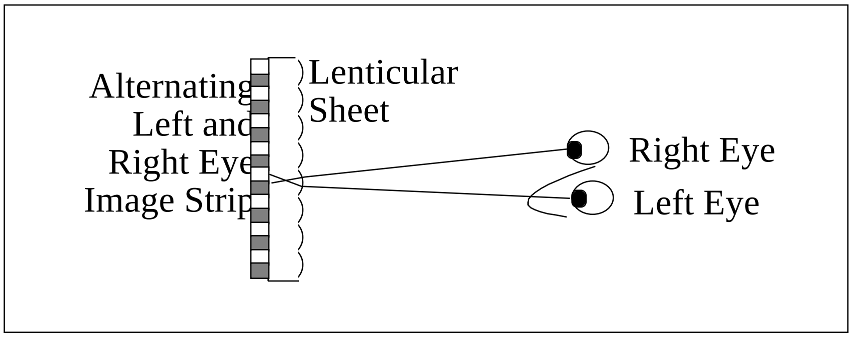
A vertical slit plate placed in front of a specially prepared image made of strips of alternating left and right eye views.



Stereo Output Techniques

- Lenticular sheets

Need no special viewing equipment.
Made from strips of cylindrical lenses.



Stereo Output Techniques

- Hi-Lo Stereo Fusion
  [Proffitt, Siggraph '96 Visual Proceedings]

Presents a fully rendered image to one eye and a reduced resolution rendering to the other.

When viewed, depth and details are fused.

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Stereo Output Techniques

- Pulfrich technique
  Neutral density filter over one eye.
  Movement required.

- Chromostereopsis
  prisms to create binocular disparity
  in color.

Stereo Output Techniques

- Alternating Pairs (VisiDep)

- Advantages
  - Autostereoscopic
  - Depth with only one eye
  - Uses standard video

- Disadvantages
  - Rocking motion in image
  - Objects separate into planar images
  - Depth perceived function of information in scene
  - Not amenable for photogrammetric work
    (measurement)

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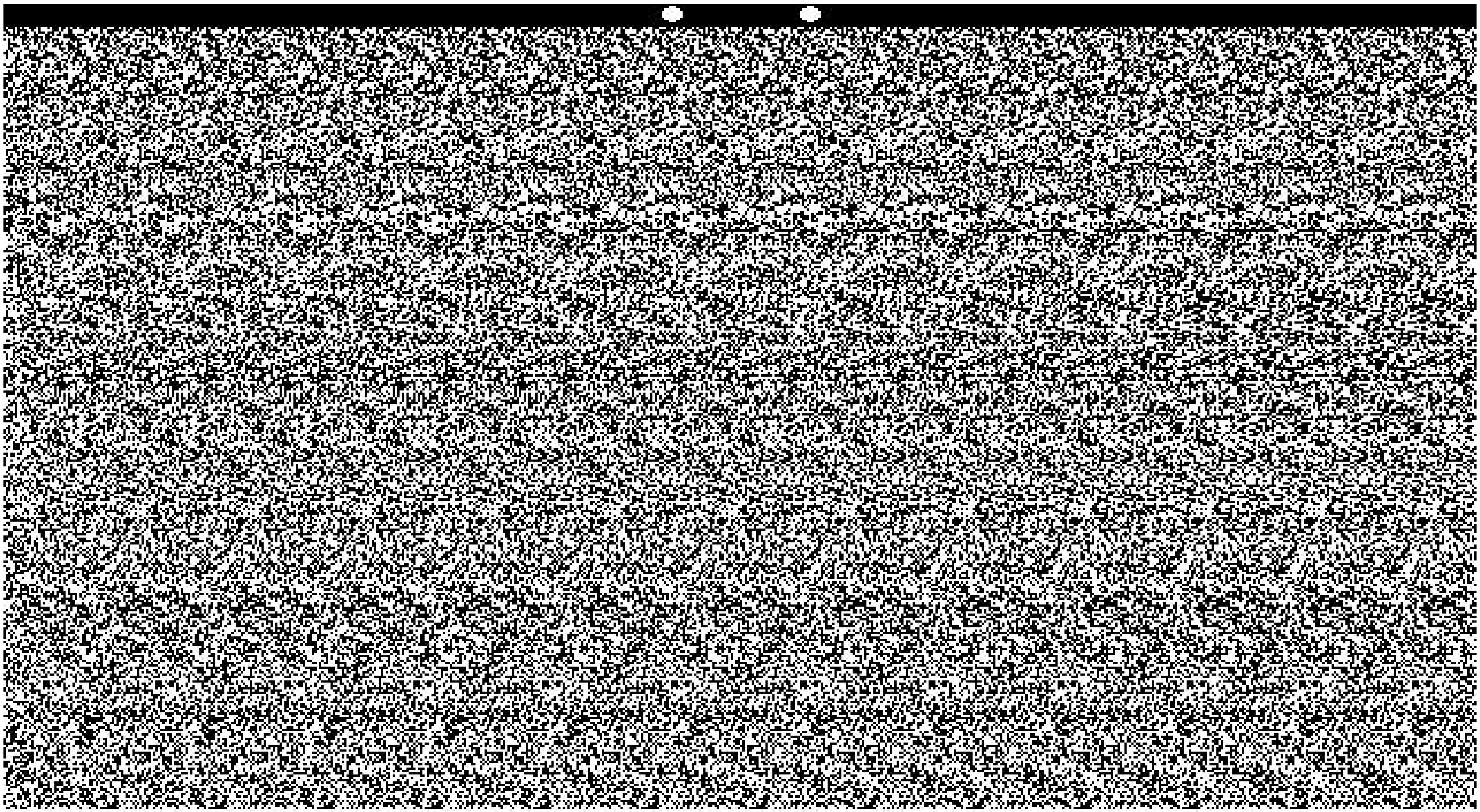
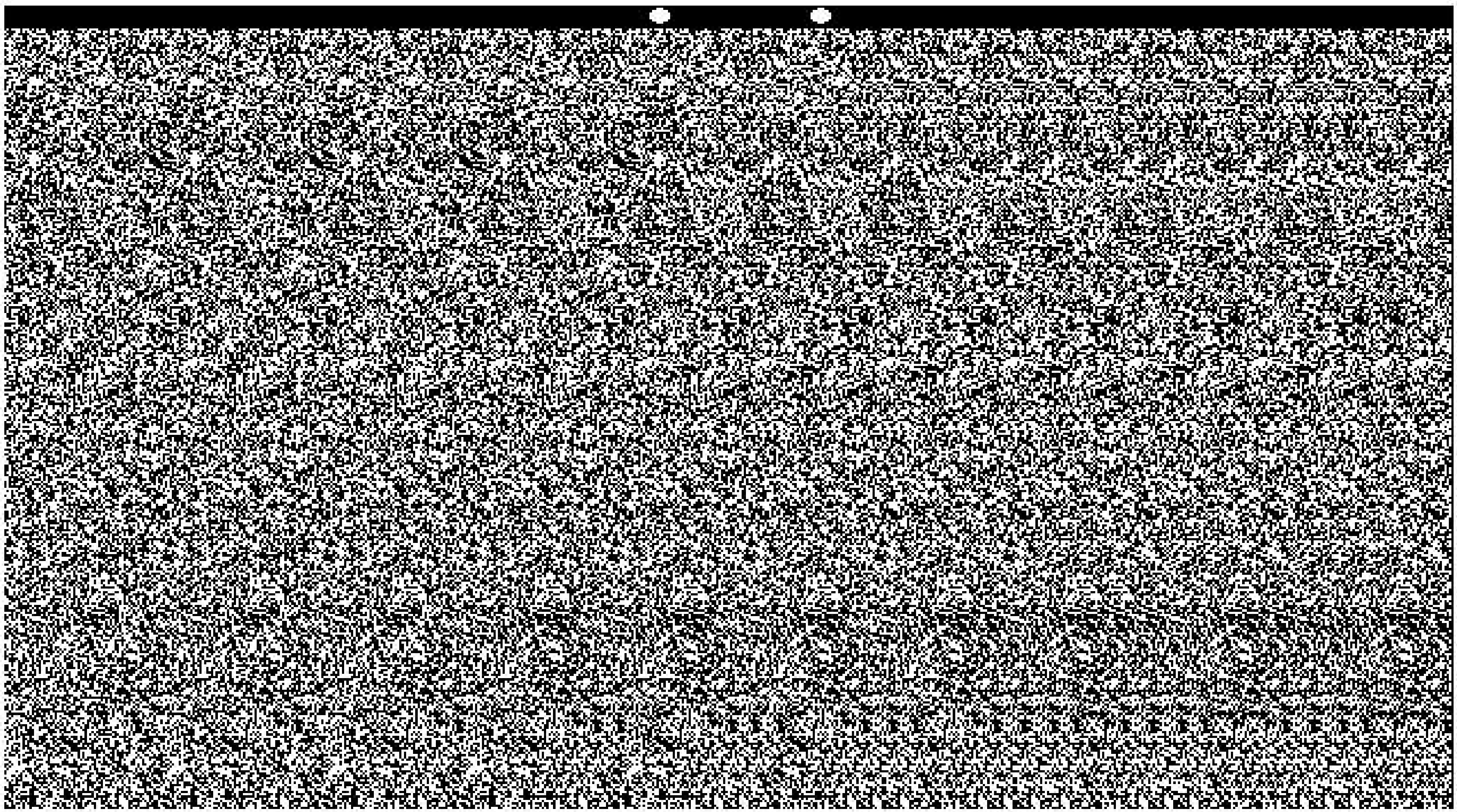
Stereo Output Techniques

- Autostereoscopic Displays

Random dot stereograms can be created so they "fuse" with themselves to form a stereo image. Cross or diverge your eyes until you see four dots instead of two. Concentrate on overlapping the center two. Let your eyes scan down the image. Practice and keep trying!



Random Dot StereoGrams courtesy of Rob Malick and Rob's Multimedia Lab



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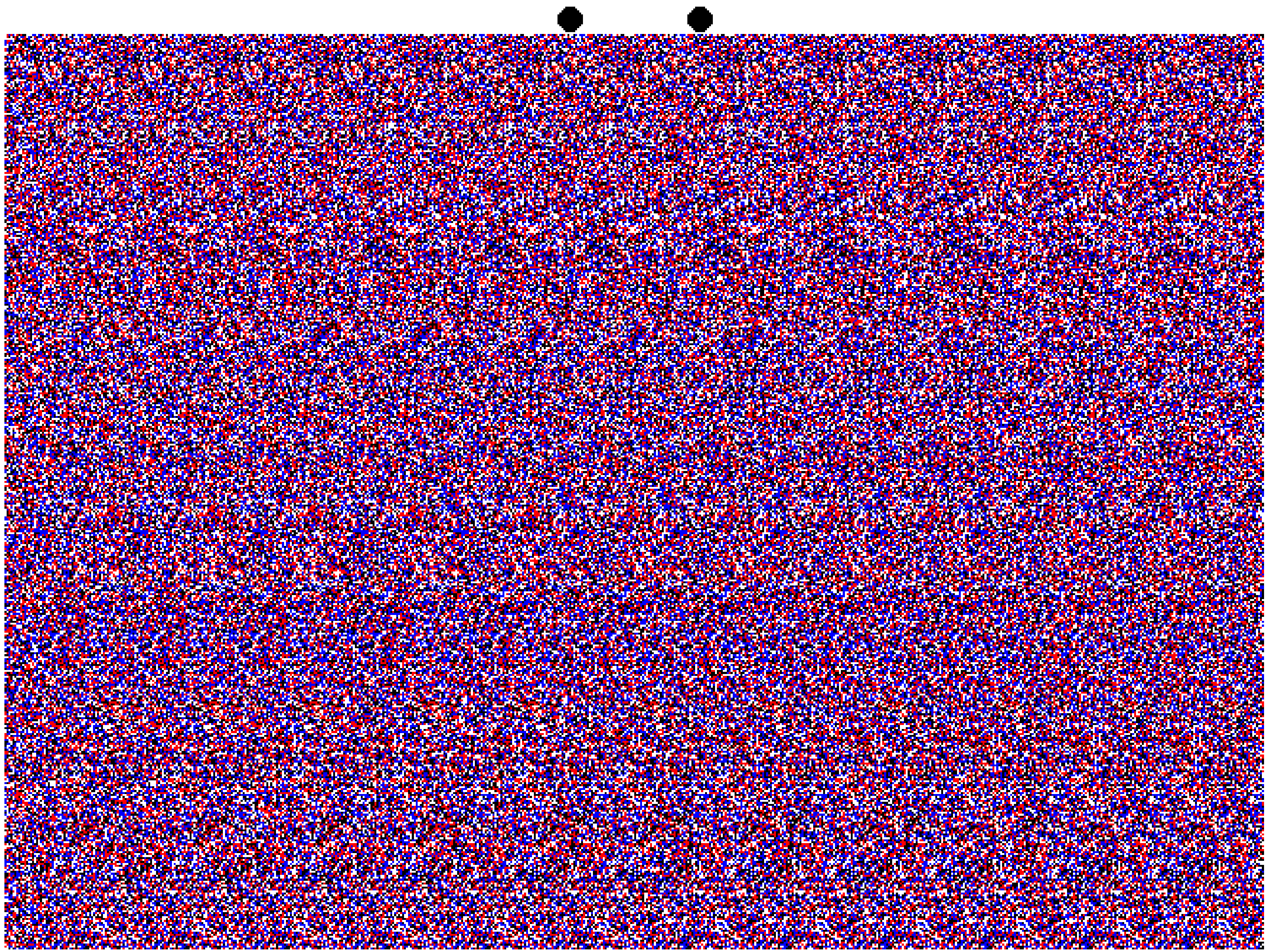

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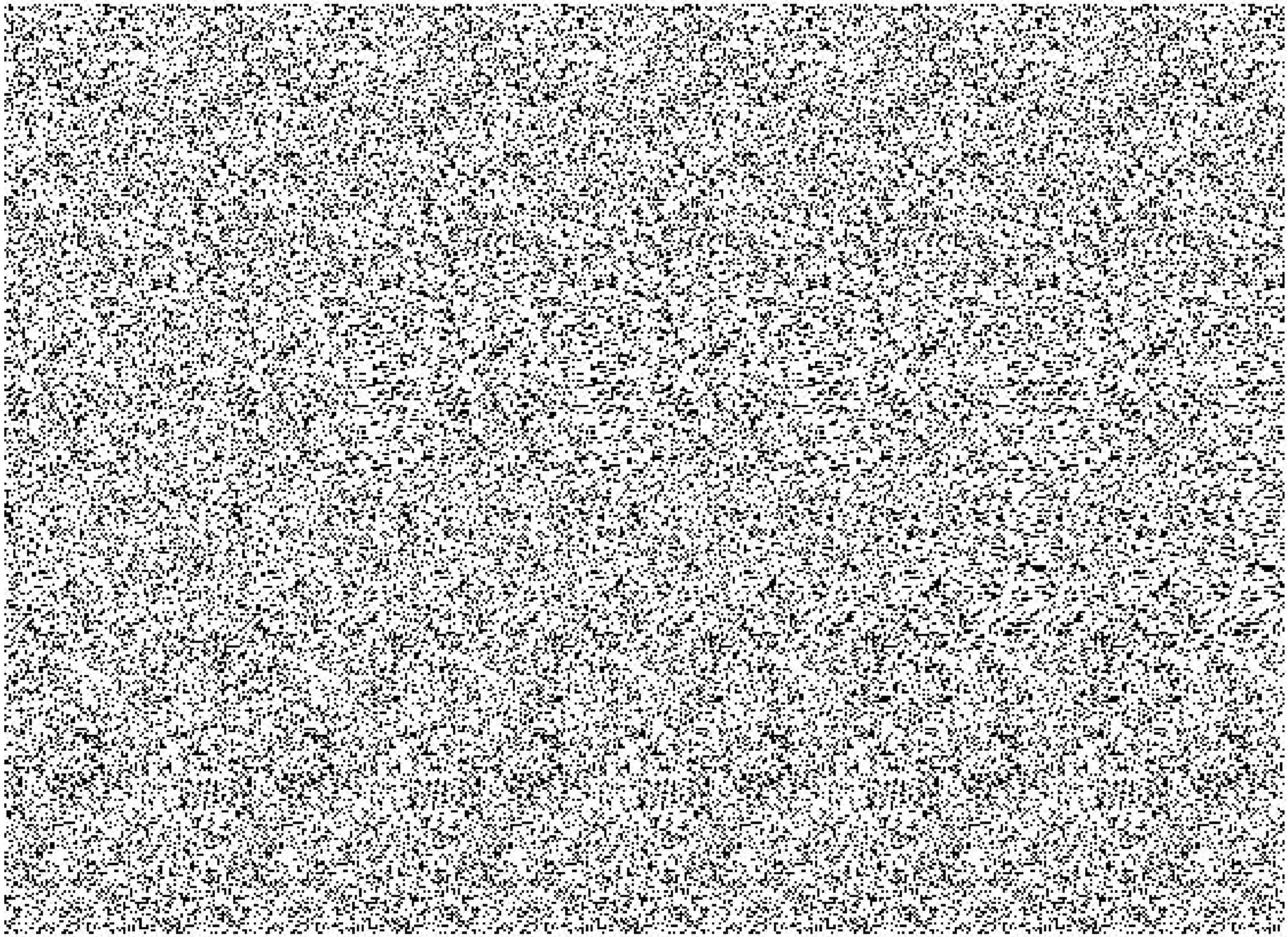

Random Dot StereoGrams courtesy of Rob Malick and Rob's Multimedia Lab

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Stereo Computer Graphics for Virtual Reality

Methods to generate stereoscopic images

David McAllister

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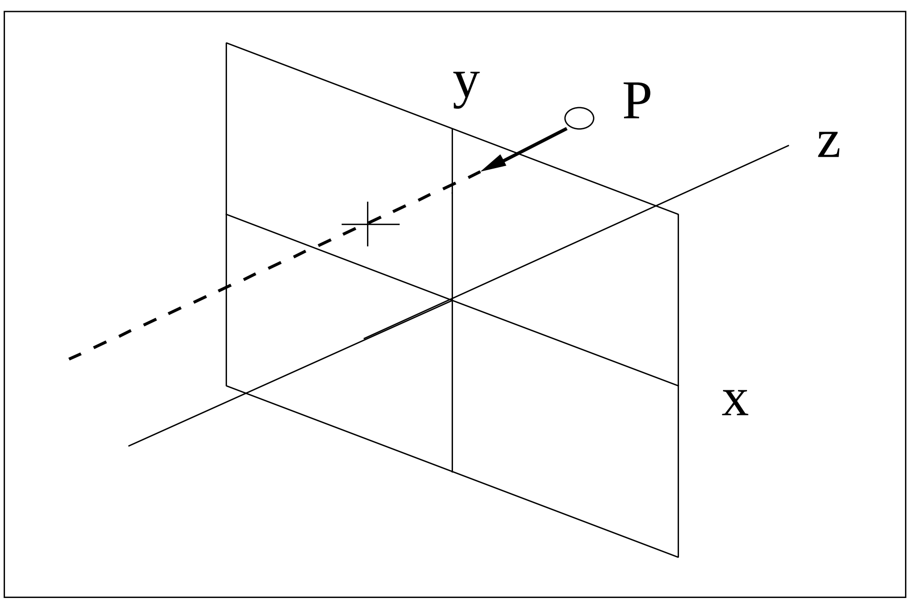
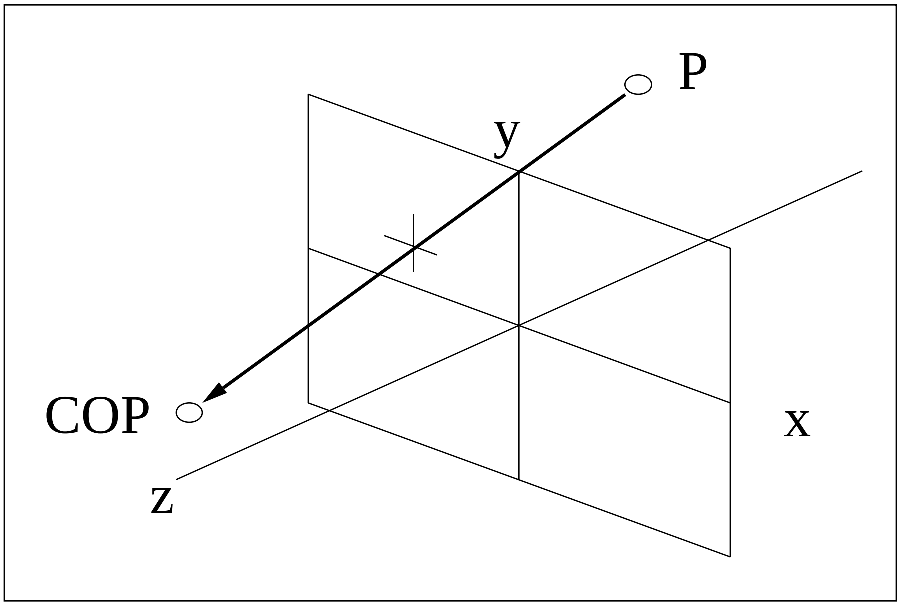
Computational Models

- Rotation
  - perspective projection
  - parallel projection
- Off Axis Perspective Projection
- Keystoning

Parallel Projection



Persepective Projection



Stereo Window

Recall:

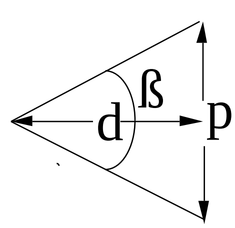
- Stereo window = locus of points where horizontal parallax H = 0
- Locus depends on method for computing stereo pairs
- Stereo window ≠ view plane

Heuristics for display of stereo pairs

- Corresponding points in the left & right eye views should have no vertical parallax.
- The primary objects of interest in a scene should be located at or near the stereo plane.
- Left and right images should match as closely as possible in terms of brightness, focus, size and color.
- Objects which appear in front of the stereo window should be placed near the center of the screen.
- Horizontal parallax should not exceed interocular distance (approximately 2.5 inches)*or maximum visual angle*

Visual Angle

- Too large - walleyed, difficult to fuse
- Too small - loss of depth



$$p = 2d \tan(\beta/2)$$

Visual Angle

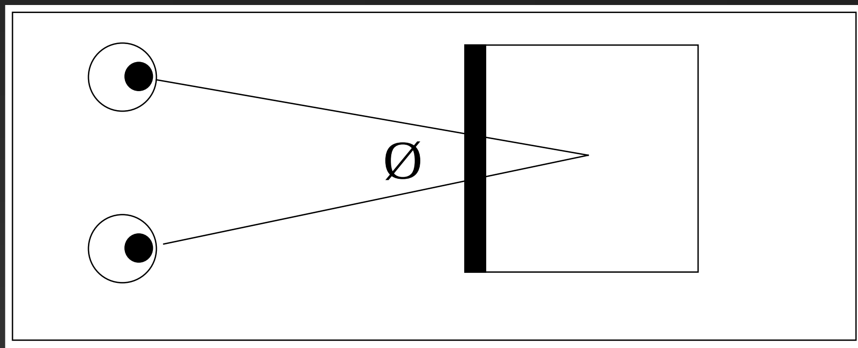
Recommendations (d=30")

- Valyes - 1.6 degrees uncrossed p=.028d = .84"
- Yeh and Silverstein - 27 min arc (interocular distance = .008d), p = .21" crossed, 24 min arc (interocular distance = .007d) uncrossed
- Hodges - 1.5 degrees (interocular distance = .026d), p = .78"

- p = 2.5: ß = 4.77 degrees,too large

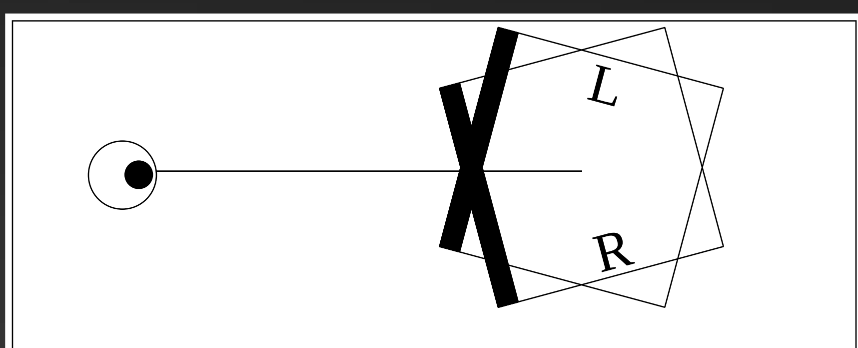
Rotations

- Ø is the angle of convergence.



Rotations

- This gives each eye a different projection plane.



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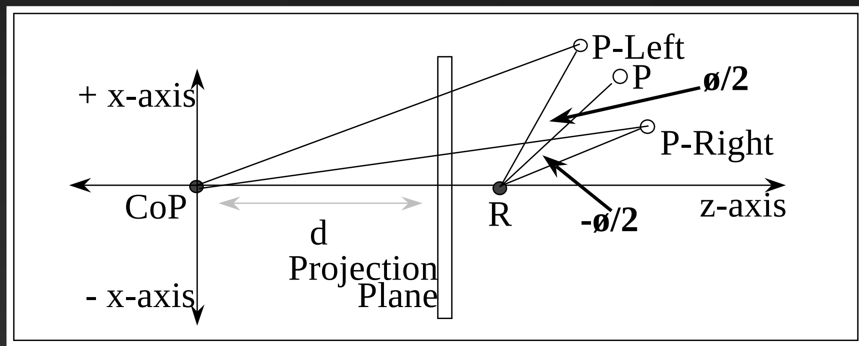
Rotations w/ Perspective Projection

- A commonly used technique



To get left eye view:
rotate about R through angle ø/2 and project
To get right eye view:
rotate about R throught angle -ø/2 and project

Rotations w/ Perspective Projection

- For a point P = (x, y, z) after the rotations about the y-axis:

xr = x cos(ø/2) - (z -R) sin(ø/2)
zr = (z -R) cos(ø/2) + x sin(ø/2) +R
and
xl = x cos(ø/2) + (z -R) sin(ø/2)
zl = (z -R) cos(ø/2) - x sin(ø/2) +R

yl = yr = y

Rotations w/ Perspective Projection

- After rotations and the perspective transformations we have:

$$xrw = \frac{d[x\cos(ø/2)-(z-R)\sin(ø/2)]}{[(z-R)\cos(ø/2)+x\sin(ø/2)+R]}$$

$$yrw = \frac{d\,y}{[(z-R)\cos(ø/2)+x\sin(ø/2)+R]}$$

Rotations w/ Perspective Projection

- Similarly:

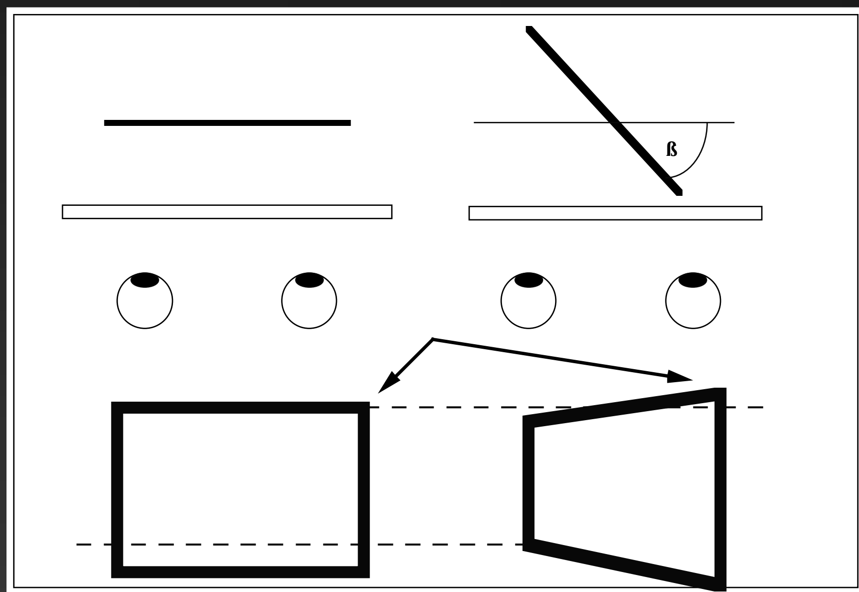
$$xlw = \frac{d[x\cos(ø/2)+(z-R)\sin(ø/2)]}{[(z-R)\cos(ø/2)-x\sin(ø/2)+R]}$$

$$ylw = \frac{d\,y}{[(z-R)\cos(ø/2)-x\sin(ø/2)+R]}$$

Let $x = 0, H = xr - xl, Hw = xrw - xlw$

$$\lim_{z\to\infty} H = \infty \qquad \lim_{z\to\infty} Hw = 2d\tan(\phi/2)$$

Rotations w/ Perspective Projection



Rotations w/ Perspective Projection

- Vertical Parallax, (V= ylw - yrw) is given by:

$$V = \frac{2dxy \sin(ø/2)}{[(z-R)\cos(ø/2) + R]^2 - x^2 \sin(ø/2)^2}$$

Vertical Parallax (disparity) can cause nausea and headaches. It should be limited to no more than six minutes of arc and viewed over limited time periods.

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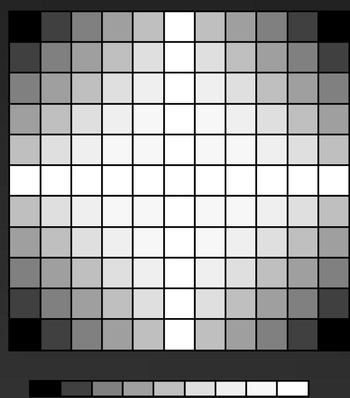
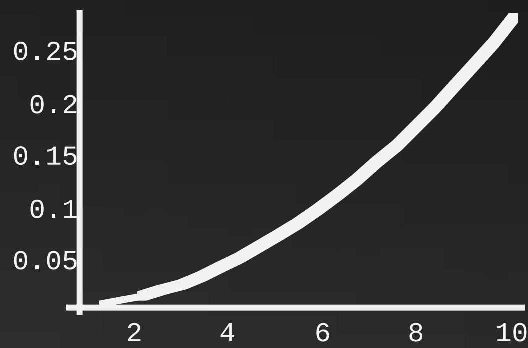
Rotations w/ Perspective Projection

Vertical Parallax On Normalized Screen



Greatest Vertical Parallax — No Vertical Parallax



ø = 4.7 degrees, d = R= z = 30",
x=y, V ≤ .052"

Rotations w/ Perspective Projection

- Location of the stereo window

The horizontal parallax, H= xlw - xrw

At the stereo window, H = 0

Solving for the equation of the stereo window:

$$x^2+[(z-R)+(R \sin ø/2)/\sin ø]^2 = \{(R\sin ø/2)/\sin ø\}^2$$

Rotations w/ Perspective Projection

Which is the equation for a circle in the x-z plane with center:

(0,0, R [1 - (sin ø/2) / sin ø)])

and radius:

(R sin ø/2) / sin ø.

Semi-cylindrical stereo window.

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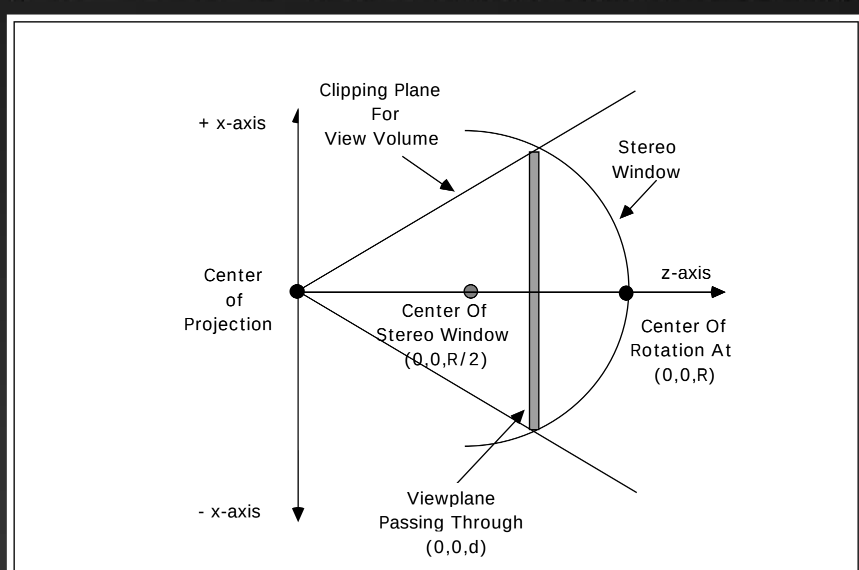
Rotations w/ Perspective Projection



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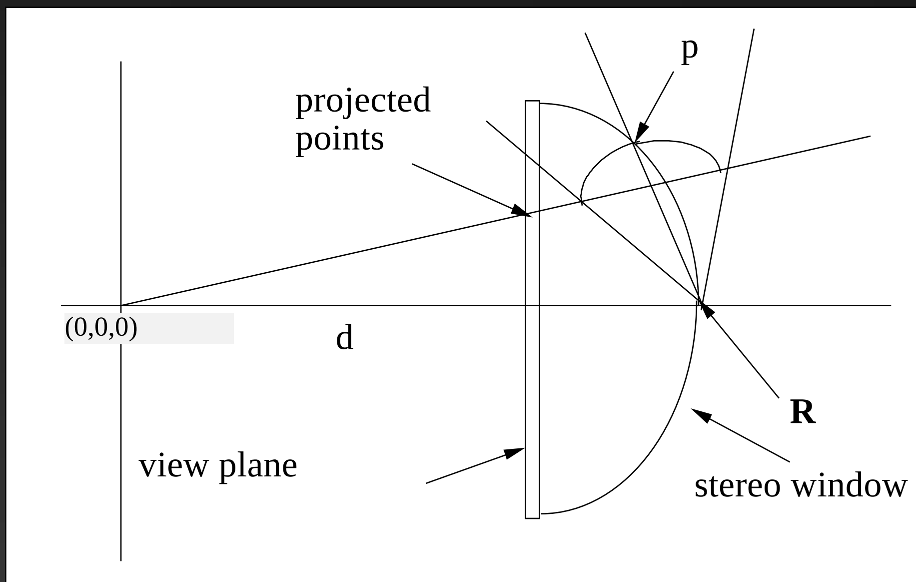
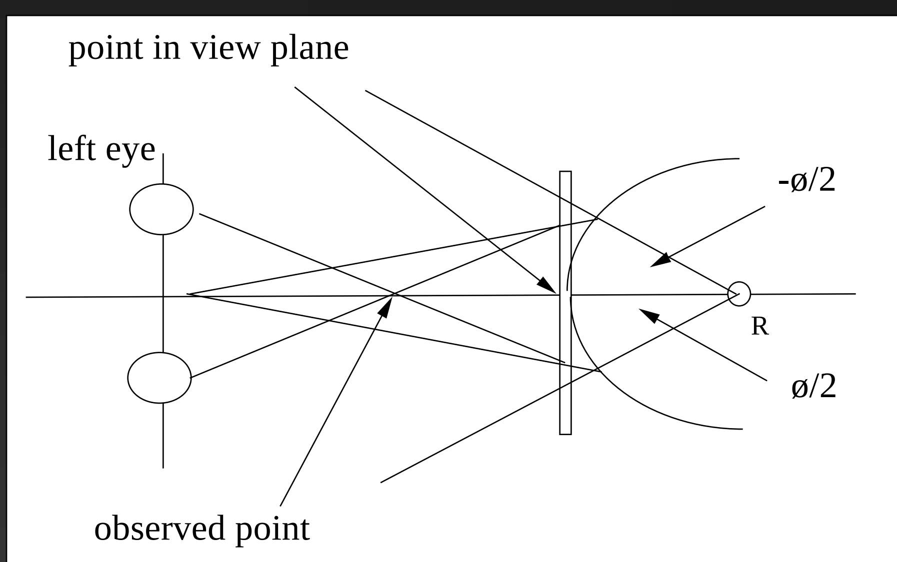
Rotation w/ Perspective Projection



Rotation w/ Perspective Projection



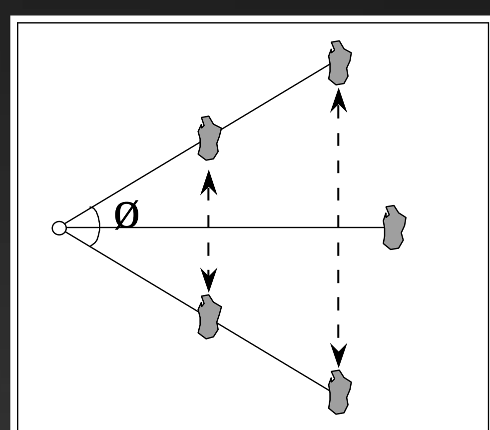
Rotations w/ Parallel Projection

- Planar stereo window as opposed to the semi-cylindrical stereo window.
- No problem with vertical parallax.
- No foreshortening effect
- Inverse perspective effect (Emmert's Law).
- Unbounded parallax.

Rotations w/ Parallel Projection

- Unbounded Parallax effect

The further an object is from the center of rotation, the larger the parallax will be.



Rotations

Rotations Always Create Artifacts

• With Perspective Projection
  Vertical Parallax
  Spatial Distortions on flat screens

• With Parallel Projection
  Inverse perspective effect
  Unbounded parallax

Rotation

WHY BOTHER?

CAD programs make it easy!

Mathematica

Interface permits easy rotation of scene

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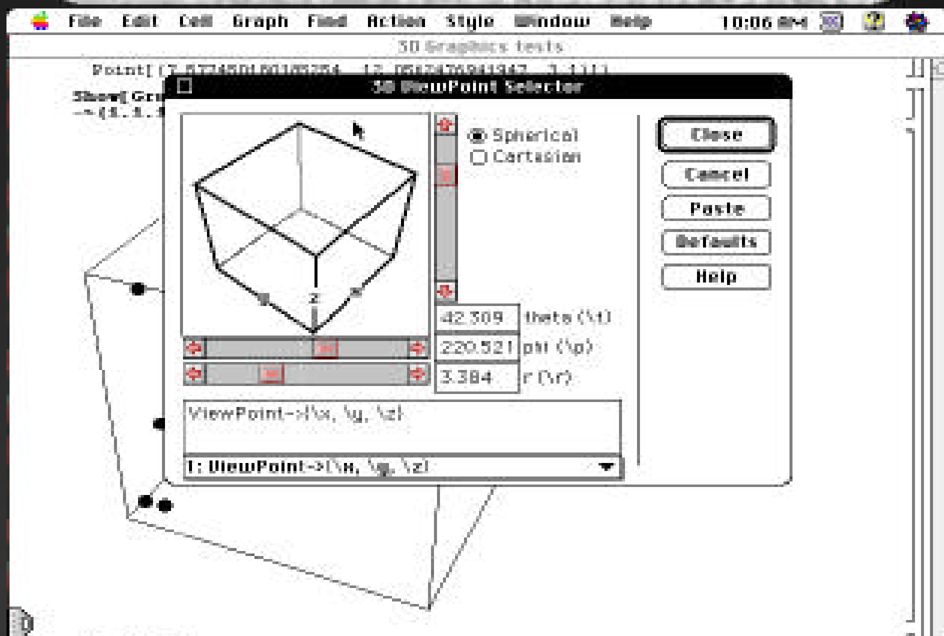
Mathematica Interface



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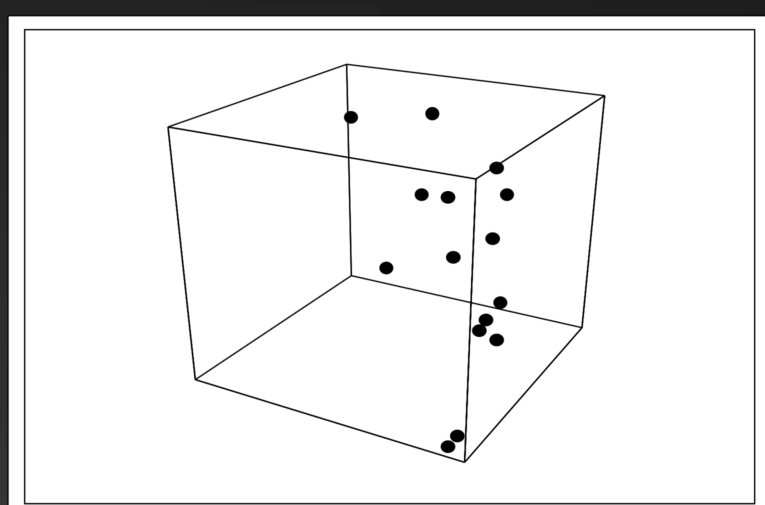
Example

Monoscopic View of Scattered Data



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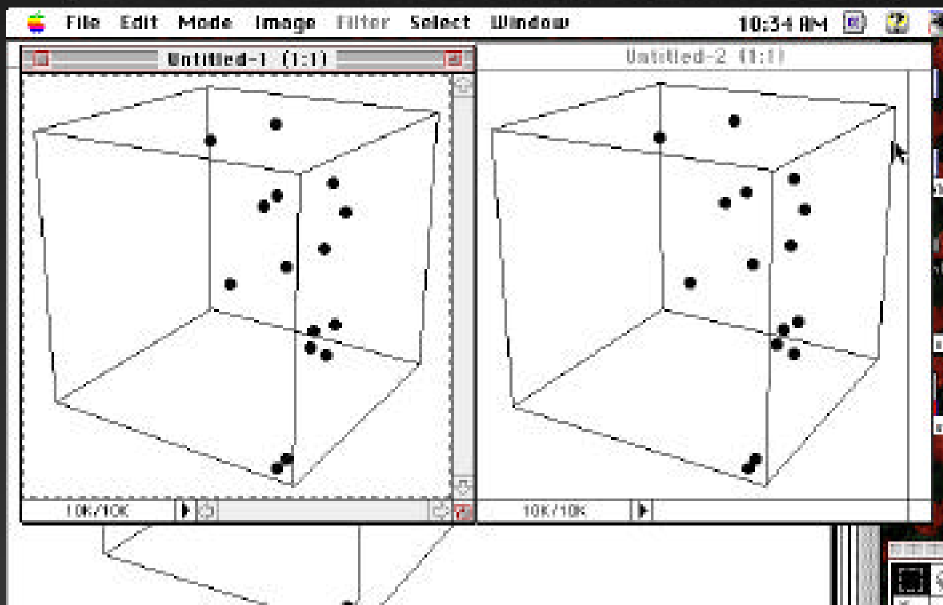
Cross Viewing

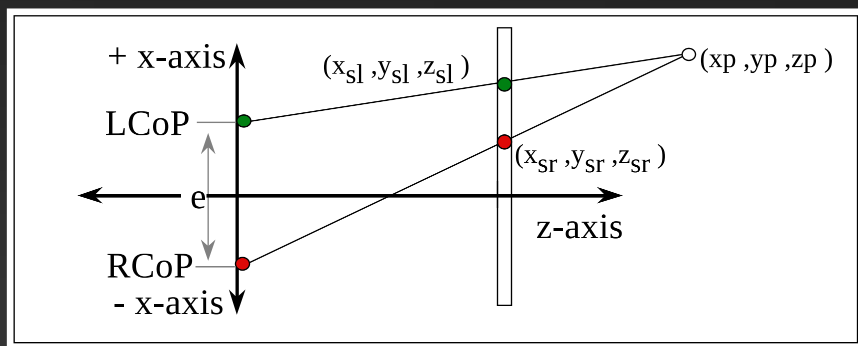


Quicktime VR

- Stitch 2D images together
- Easy construction of left eye/right eye pairs

Using Two Centers of Projection

- Planar stereo window
- No vertical parallax
- Proper perspective effect



Using Two Centers of Projection

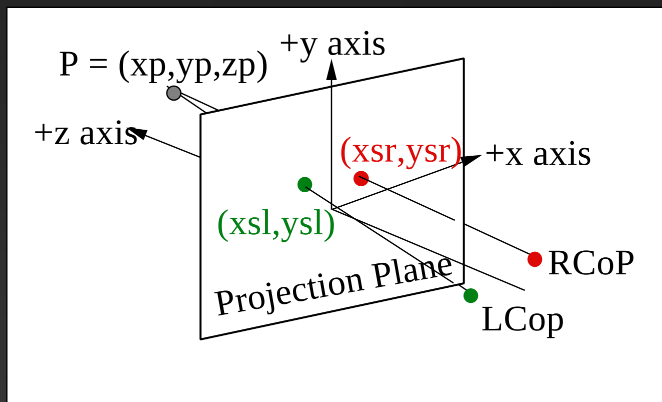
$x_{sl} = xd/z - ed/2z + e/2$ $\qquad y_{sl} = yd/z$

$x_{sr} = xd/z + ed/2z - e/2$ $\qquad y_{sr} = yd/z$

Note: The projected y values are equal.
No Vertical Parallax!

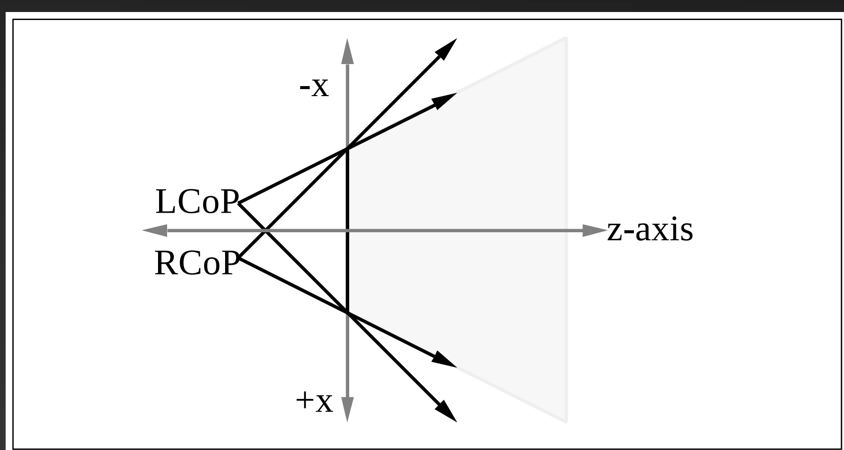
Off Axis Projection

Viewplane located at z = 0
LCoP at (-e/2, 0, -d) RCoP at (e/2, 0 , -d)
xsl = (xp(d) - zpe/2)/(d + zp) ysl = yp(d)/(d + zp)
xsr = (xp(d) + zpe/2)/(d + zp) ysr = yp(d)/(d + zp).



Off Axis Projection

- Move the center of projection.



On Axis Projection

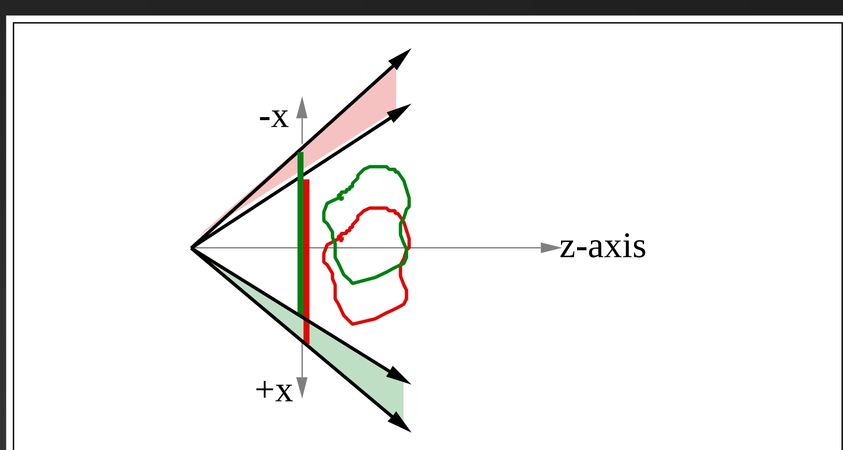
xsl = d(xp + e/2)/(d + zp) - e/2
xsr = d(xp - e/2)/ (d + zp) + e/2

1. Translation
2. Standard perspective projection
3. Pan

$$Parallax = Hs = xsr - xsl = \frac{ez_p}{d + z_p}$$

On Axis Projection

- Move the data.



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Stereo Projection Transformation

- (x,y,z) are the coordinates of a point to be projected.
- using homogeneous coordinates
- right-handed coordinate system.

the stereo projection transformation is

$$(x_w, y_w) = (x'/w,\ y/w)$$

Stereo Projection Transformation

where (x', y, z, w) = (x, y, z, 1)S
and S =

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \alpha\mu\Omega/d & 0 & 1 & 1/d \\ -\alpha\Omega & 0 & 0 & 0 \end{pmatrix}$$

Stereo Projection Transformation

where:

- d is the location of the stereo window in world coordinates when $\mu = 1$.
- μ is an optional scaling factor which moves the stereo window to $z = d/\mu$.
- Ω equals 5/2W, where W is the width of the CRT screen on which the stereo pair is to be displayed.
- $\alpha = +1$ to compute the left-eye perspective view
  -1 to compute the right-eye perspective view.

The optimal viewing distance between the observer and the CRT screen is equal to $\mu dW/2$.

Stereo Projection Transformation

This transformation may be decomposed into a translation along the x axis a distance $-\alpha\Omega$, followed by a perspective projection, followed by a translation along the x-axis a distance $\alpha\mu\Omega$. The transformation matrices are shown below in the same order:

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\alpha\Omega & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1/d \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \alpha\mu\Omega & 0 & 0 & 1 \end{pmatrix}$$

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Stereo Projection Transformation

Conclusions

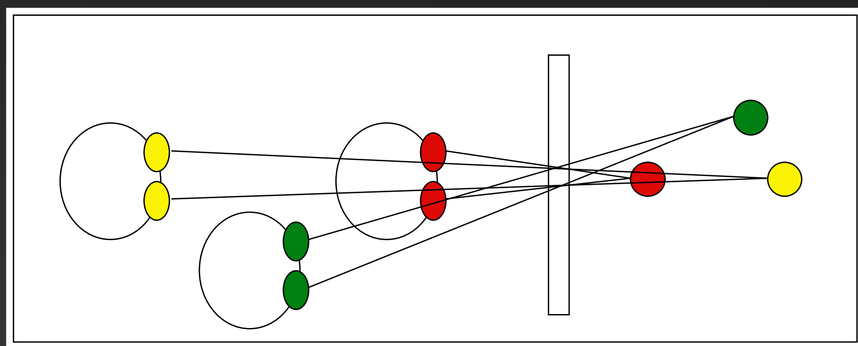
Rotations always have undesirable side effects when viewed over long periods of time.

The best method for generating stereo views is with two centers of projection.

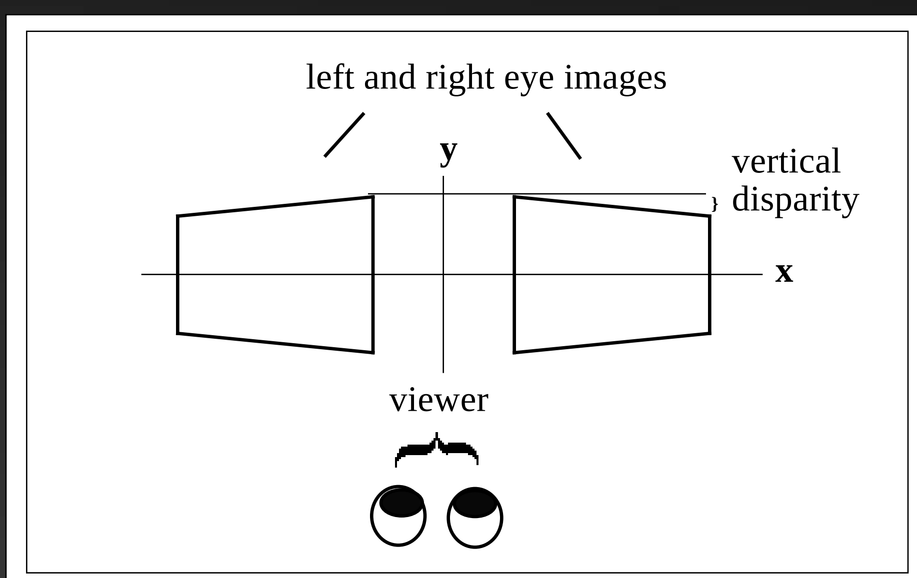
This method can be efficiently implemented using a translation, perspective projection and pan.

Image scaling & distortion

- There is a best distance and location to view a stereoscopic display.

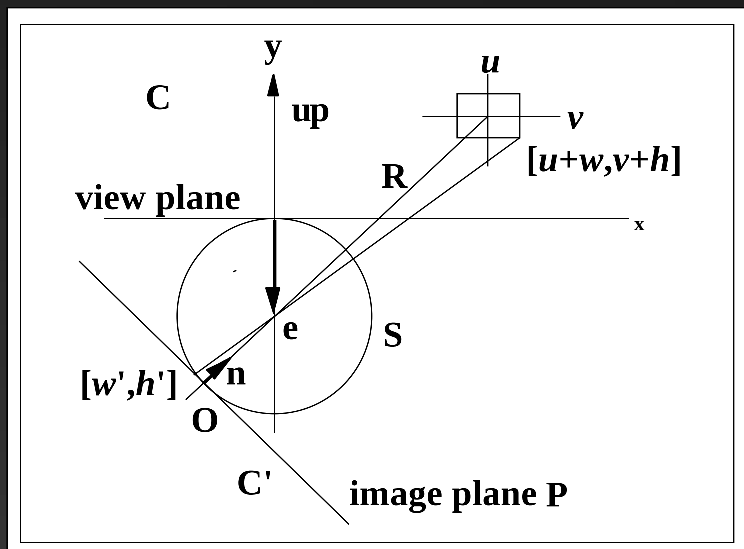


Keystoning - Parallel Views



Eye view - Projection

Geometric Model



Forward Projection Map

$$w'(u,v,w,h) = \frac{we^2\sqrt{u^2+v^2+e^2}}{\sqrt{u^2+e^2}\,(u^2+v^2+e^2+vh+uw)}$$

$$h'(u,v,w,h) = \frac{e((u^2+e^2)h-uvw)}{\sqrt{u^2+e^2}\,(u^2+v^2+e^2+vh+uw)}$$

Projection Warp

homogeneous coordinates

$$[\,\omega' w', \omega' h', \omega'\,] = [w, h, 1]\mathbf{B}$$

$$\mathbf{B} = \begin{bmatrix} A & G & D \\ B & H & E \\ C & I & F \end{bmatrix}$$

$$A = e^2\sqrt{u^2+v^2+e^2},\ B = 0,\ C = 0,$$

$$D = u\sqrt{u^2+e^2},\ E = v\sqrt{u^2+e^2},\ F = \sqrt{u^2+e^2}\,(u^2+v^2+e^2)$$

$$G = euv, H = e(u^2+e^2), I = 0$$

2D Texture Map

$$w' = f_1(w,h) = \frac{Aw + Bh + C}{Dw + Eh + F}$$

$$h' = f_2(w,h) = \frac{Gw + Hh + I}{Dw + Eh + F}$$

ratio of linear forms

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Special Cases

v = 0

$$w'(u,0,w,h) = \frac{we^2}{(u^2 + e^2 + uw)}$$

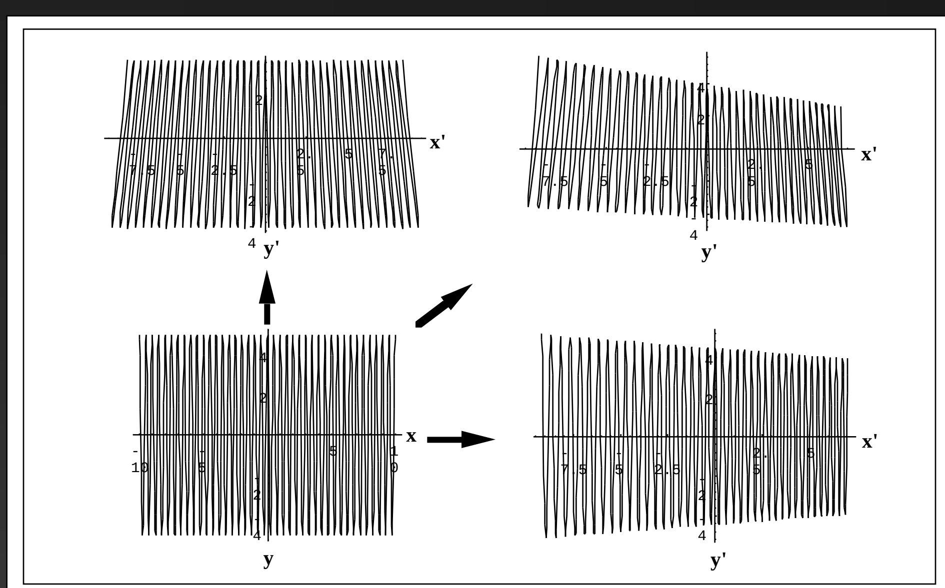
$$h'(u,0,w,h) = \frac{e\sqrt{u^2 + e^2}\,h}{(u^2 + e^2 + uw)}$$

u = 0

$$w'(0,v,w,h) = \frac{we\sqrt{v^2 + e^2}}{v^2 + e^2 + vh}$$

$$h'(0,v,w,h) = \frac{e^2 h}{v^2 + e^2 + vh}$$

Projection Warps



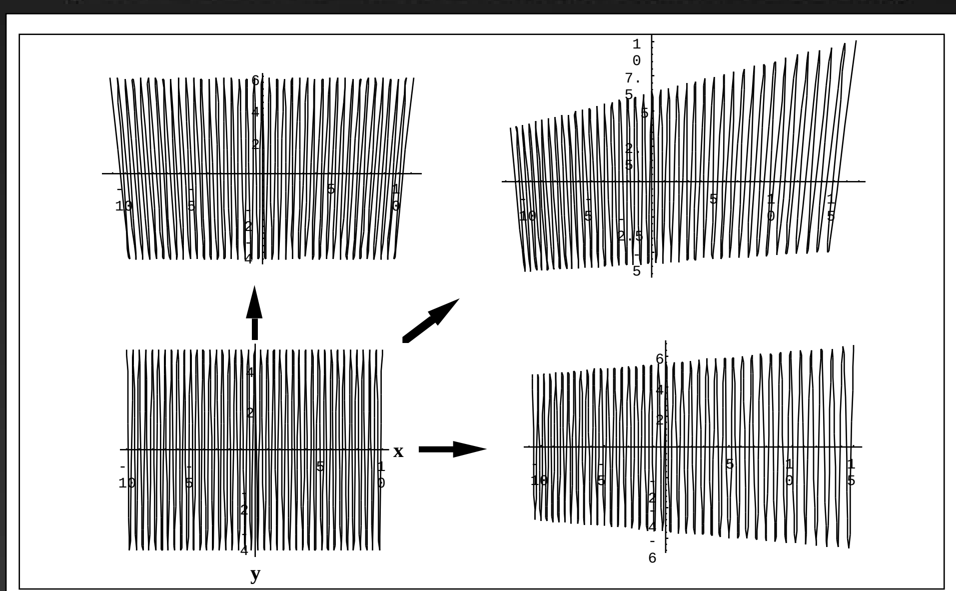
Inverse Transformation

$$w = g_1(w', h') = \frac{(FH - EI)w' + (CE - BF)h' + (BI - CH)}{(EG - DH)w' + (BD - AE)h' + (AH - BG)}$$

$$h = g_2(w', h') = \frac{(DI - FG)w' + (AF - CD)h' + (CG - AI)}{(EG - DH)w' + (BD - AE)h' + (AH - BG)}$$

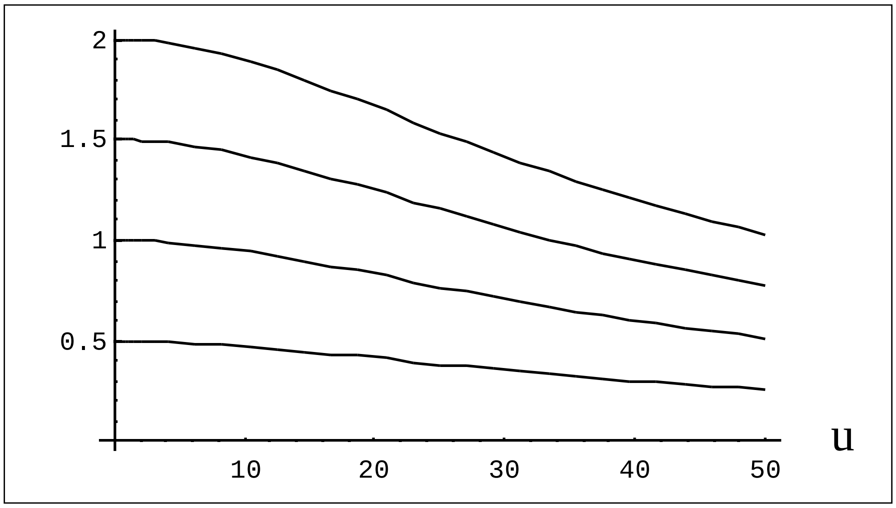
also a ratio of linear forms

Inverse or Pre-Warp



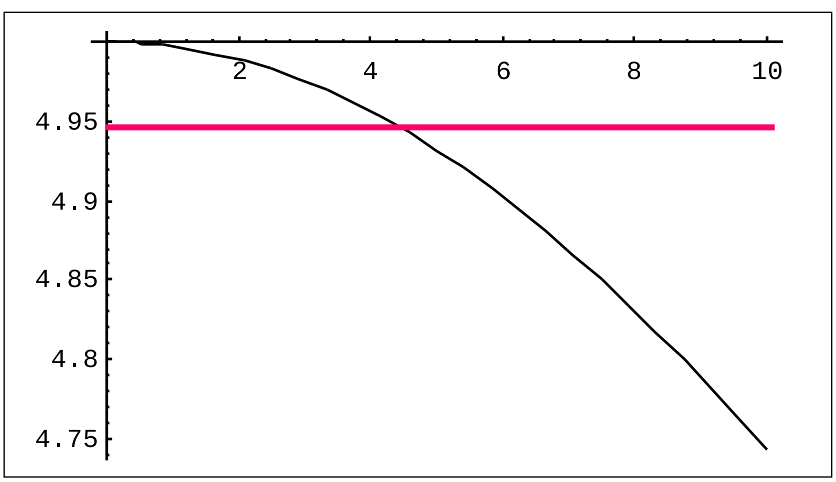
How bad can it be?

h' for v = 0, w = 0, h = .5, 1. 1.5, 2



Keystoning Example, d=30"

h' for h = 5, w = 0 max = .052



Keystoning

Conclusion:

Prewarp images for time parallel viewing

Use texture maps

Siggraph '97

Stereo Computer Graphics for Virtual Reality

Stereo input/output techniques including head mounted displays

Martin Dulberg

Multimedia Lab
Department of Computer Science
North Carolina State University

Virtual Reality Overview

- Overview
- Input Devices
- Output Devices
- Head Tracking
- Interaction Styles

Virtual Reality Overview

- What is Virtual Reality? Anything from an action game to a "holodeck"
- How immersive is the virtual world?
- How many senses are engaged?

Virtual Reality Overview

- Quality vs. quantity of visuals:
- Smoother motion or richer environment?
- How realistic is the simulation of reality?
- How well does the simulation mesh with our perception of reality?

Input Devices

- Degrees of Freedom

Can perform translations and/or rotations with respect to each of the three axes for a total of 6 possible degrees. The number available simultaneously determines the degrees of freedom of a given input device.

Input Devices

- Draw Volume

Some devices are limited to a certain physical area based upon sensor ranges. We'll call this area the draw volume. Stationary devices have no such limitation.

Input Devices

- Keyboard

Has a single degree of freedom since only one keystroke can be recognized at a time.

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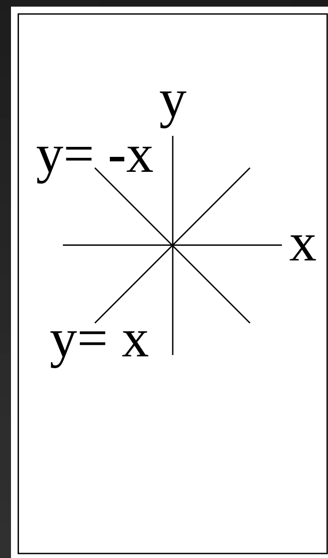
Input Devices

- Joystick

Appears to have two degrees of freedom, but actually only has one. Moves only in one of 8 different directions.



Input Devices

- Joystick

A button on the joystick (or attached keyboard) can toggle between rotations and translations.
Another button can toggle between the xy plane and the xz plane.

Input Devices

- Single button mouse

Two degrees of freedom.
Translations in xy plane. Can toggle to xz plane via a key on the keyboard. Can also toggle between translation and rotation.

Input Devices

- Single button mouse

Rotation about arbitrary axis possible but not intuitive. Usually involves at least 3 steps.

1) Align arbitrary axis with x axis
2) Do desired rotation
3) Reverse step 1

Input Devices

- Multi-button mouse

Also has two degrees of freedom, but toggling can be done more effectively with mouse buttons instead of having to redirect attention to a keyboard or menu.

Input Devices

- Track Ball

Similar in function to a mouse, except the base is stationary and the user rolls a ball within it. Also two degrees of freedom. Trackballs are sometimes used in systems to replace mice when desk space is limited.

Input Devices

- Force & Torque converters

Has six degrees of freedom. Usually a ball mounted to a post with internal sensors to measure pressures and pressure directions applied by a user. Allows an object to be rotated about any axis and translated in any direction simultaneously.

Input Devices

- Force & Torque converters

Usually has a selection button at the top of the ball. May also have user programmable function keys. Sensitivity is also adjustable. With practice, a user can drive a cursor over a curvilinear path with a high degree of accuracy.

Input Devices

- Force & Torque converters

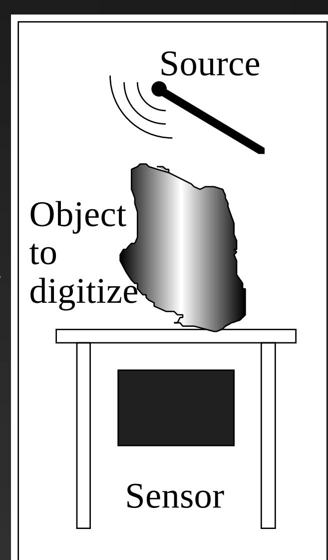
Many find it difficult to control both translations and rotations simultaneously, so the device is often limited to 3 degrees of freedom.

An example of such a device is the SpaceBall 2003.

Input Devices

- Magnetic Field devices

Six degrees of freedom. A magnetic source point activates a sensor mounted below a platform. Can be used to digitize 3D objects.



Input Devices

- Magnetic Field devices

Metallic objects can cause distortions in the magnetic field.

Examples are 3SPACE Digitizer and 3SPACE Isotrack by Polhemus.

Input Devices

- Magnetic Field devices

Each has a draw volume of 30" centered on the sensor. Can be extended to 60" at reduced accuracy. Normal accuracy is 0.1°

Digitizer supports models
18" x 18" x 10"

Input Devices

- Acoustic devices

Six degrees of freedom. Similar to magnetic devices but use an ultrasonic signal instead of magnetic waves.

Not subject to distortions from metallic objects.

Input Devices

- Acoustic devices

An example is the Logitech 2D/6D mouse. Can function as a normal mouse in 2D mode, but houses 3 receiving microphones.
Draw volume is a 2 foot cube with 200 dpi resolution or a 7 foot cube with 10 dpi resolution (for head tracking).

Input Devices

- Data Gloves

Allow you to get 6 degrees of freedom info for the users hand.
More sophisticated units are more accurate and provide more information about the flex of joints.
Data gloves allow the user to interact with the environment in interesting ways.

Input Devices

- Boom (by Fakespace Labs)

Six degrees of freedom
Has several joints and moves in a way similar to a human arm.

Designed to work like a head mounted tracking system, but it can be used as as an input device.

Input Devices

- Boom

Optical sensors on the joints provide high precision feedback.

Drawing volume limited only by the length of the arms of the device and is considerably larger than the volume of either of the previous two devices.

Input Devices

- Hybrid devices

Devices such as the Handle marketed by StereoGraphics fit a comfortable input device around either magnetic or acoustic sensors. Thus the user can switch between magnetic and acoustic devices as needed and keep the same input device feel.

Output Devices

- Head Mounted Displays

Technology: Color wheel, LCD, CRT
Resolution: 320x200 to 1280x1024
Contrast: Crisp Blacks, Bright Colors
Color Depth: 16 to 24bit
Video Input: VGA, NTSC, PAL
Try before you buy!!!!

Output Devices

- Head Mounted Display Purchase

Extended wear vs. many users.
External Light Blockage.
Weight, Balance, Airflow and Comfort.
Audio and Video Compatability.
Ease of Adjustability.
Durability, Price and Warranty.

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Output Devices

- Other Devices

LCD Shutter Glasses: work by alternating which eye is opaque or clear while you look at a monitor or other special display.
Boom: Like stereo binoculars.
The Cave: Immersive, multi-user environment. Participants wear shutter glasses.

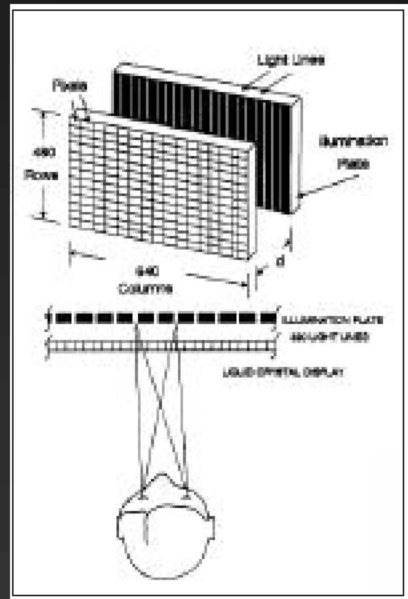
Output Devices

- Polarized Displays: VREX

Laptop display replaced with polarized LCD panel that alternates polarization for right and left eye views.
The user wears inexpensive glasses.
Limited but acceptable field of view.
User can't tilt their head while viewing.

Output Devices

- Parallax Illumination: Dimension Technologies



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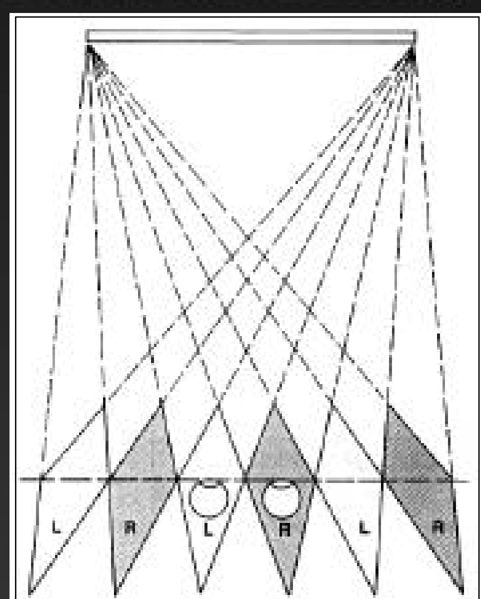
Output Devices

- Parallax Illumination: Dimension Technologies



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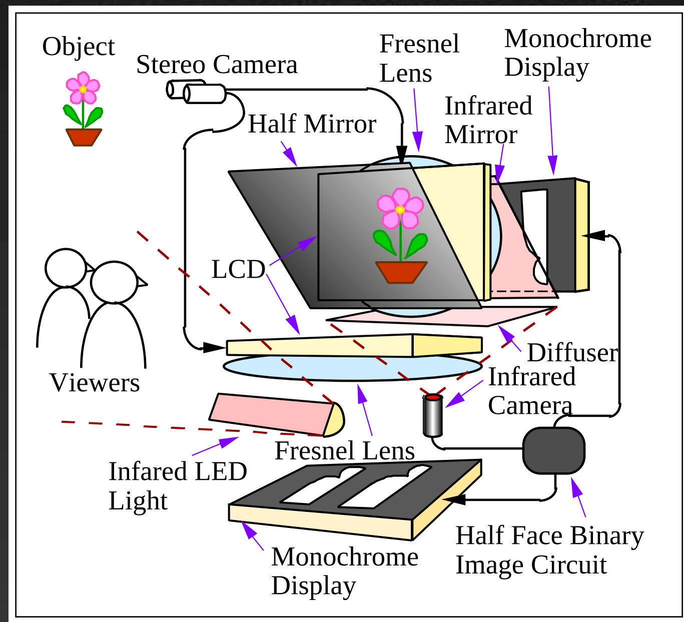
Output Devices

- LCD Multi-user Display Sea Phone Co., Ltd.



Output Devices

Look

Feel

Sound

Output Devices

- Most Virtual Reality Applications concentrate on the visual senses to the exclusion of all other.

Aural: Sound
Haptic: Touch
Olfactory: Smell

Output Devices

- Haptic Devices

Force Feedback: Now becoming popular in joy sticks. They allow the user to "feel" collisions and changes in terrain.
Research has been done with regard to feeling textures, remote operations and other areas.

Output Devices

- Three Dimensional Sound

Adds richness, realism, depth and motion cues to the environment.
Can be created by mixing left and right channels and varying volume and frequency of wav or other sound files.
Many headsets come with built in headphones.

Head Tracking

- Head Tracking Devices

Usually Magnetic Field or Acoustic devices.
Device transmits positional and rotational information to a base unit which is connected to a serial port.
Many devices have software for PC's but not for Unix machines.

Head Tracking

- Serial Interface

A record containing X, Yand Z position as well as the rotational angle about the X, Yand Z axis is sent N times per second to the serial port.
N may vary depending on the number of devices connected to the base unit.

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Head Tracking

- Jitter

The oscilation of frames due to the slight but continuous motion of the user.

Head Tracking

- Latency

The time required to correctly update the users position.
It is important to get the last complete record from the serial port to minimize latency.
This can be achieved by not buffering previous records.

Head Tracking

- Motion Sickness

A small percentage of the population gets sick from immersive VR. This percentage will increase as latency increases.

Head Tracking

- Tracking Motion: First Try

Update viewing transformation to the most recent record as quickly as possible.

Problem: Users never keep their head still. This will result in jitter.

Head Tracking

- Tracking Motion: Second Try

To avoid jitter, define a minimum change in orientation required before the view transformation is altered. These delta's will depend on the scale of your coordinate system.
What happens when users make sudden, quick movements?

Head Tracking

- Tracking Motion: Third Try

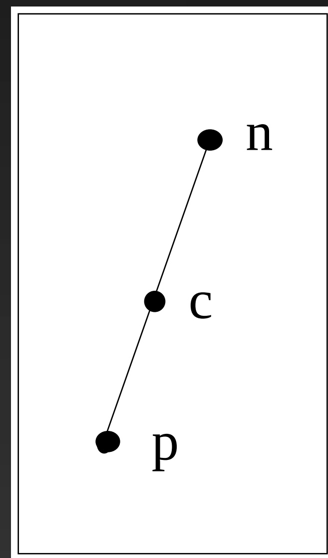
Smooth out motion

Interpolate between previous and current position

Head Tracking

- Linear Interpolation

Interpolate between previous and current position
2D:
cx=px+(nx-px)
cy=py+(ny-py)



Head Tracking

- Tracking Motion: Fourth Try

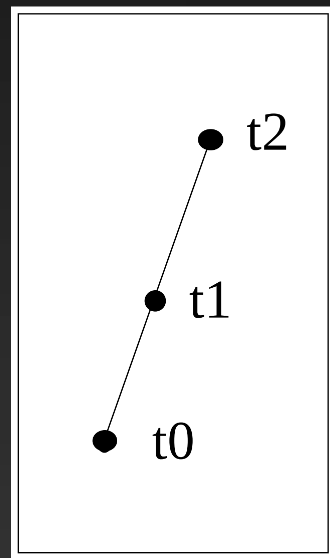
Try to predict where the head will be positioned.

Linear Extrapolation or Curve Fitting

Head Tracking

- Linear Extrapolation

Use the previous 2 positions to predict the current position
2D:
t2x=t1x+(t1x-t0x)
t2y=t1y+(t1y-t0y)



Head Tracking

- What to do?

The best solution is some combination of the previous 4 ideas.

There are other more sophisticated methods for dealing with the problem.

Interaction Styles

- Fish Tank Virtual Reality
- Walk Through
- Fly Through
- Part In Hand
- Collaborative
- Hybrid

Interaction Styles

- Fish Tank Virtual Reality

A monitor is used with perspective projection.
Head tracking may or may not be used.
Stereopsis may or may not be used.
Head tracking more effective than stereopsis at providing the illusion of immersion.

Interaction Styles

- Walk Through

Much like an action game.
The user navigates through the environment.
Positional and rotational data is fed into the perspective projection.
Collision detection may be used.
Best for small areas.

Interaction Styles

- Fly Through

The user remains on a particular path until they change their orientation much like a flight simulation.
Only the change in positional information is passed to the perspective projection.
Best for large environments.

Interaction Styles

- Part In Hand

A six degree of freedom sensor is embedded in an object.
The user manipulates the object to view it from different angles or distances.
The user remains stationary while the part moves.

Interaction Styles

- Collaborative

The cave allows multiple users to experience an environment together.
One person acts as the facilitator and is tracked to generate the perspective view.
The further you are from the facilitator the more skewed the view appears.

Interaction Styles

- Hybrid

The environment is composed of both real and computer generated objects. The Responsive Workbench: objects are projected onto a real workbench or desk.
More accurately adopted to the metaphor of everyday work.

Siggraph '97

Stereo Computer Graphics for Virtual Reality

Algorithms in stereoscopic computer graphics

David McAllister

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Final Session - Introduction

Overview

Cursors and view volumes

- properties
- problems
- conclusions

Rendering Problems and Shortcuts

- erasing
- picket fencing
- double images
- pixel shifting
- ray tracing
- clipping
- back face removal

Final Session - Introduction

Overview

Some Research Areas

- color quantization
- motion blur
- interfaces
- stereo from 2D images

Observations

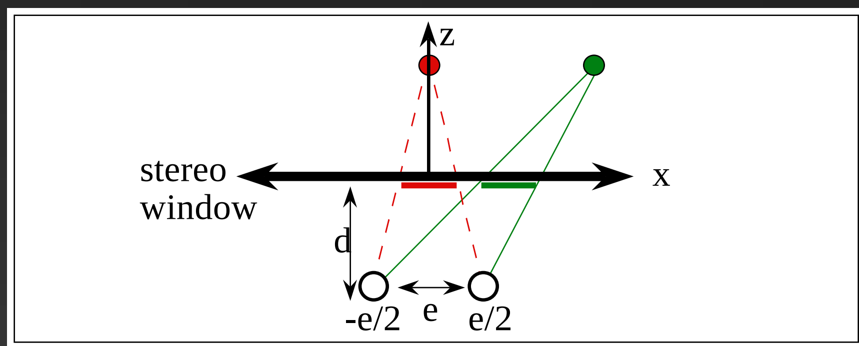
- Difficult for most stereo users to fuse abrupt changes in parallax.
- Rapid change in negative parallax will normally require a few seconds for a viewer to fuse images.

More observations

- Rendering of left and right eye views need not require twice the time of rendering a single frame
- Homologous points have equal y values.

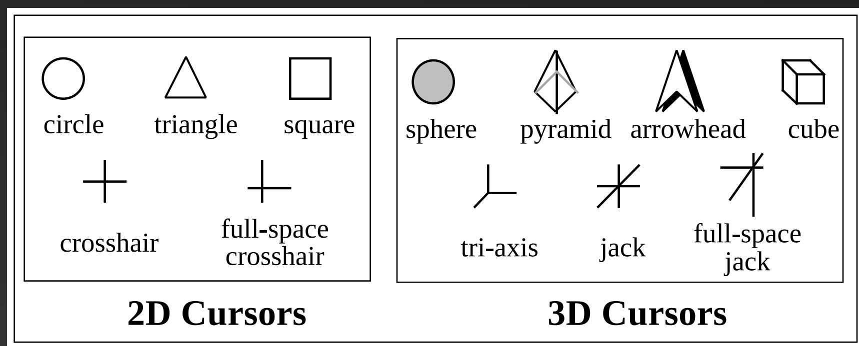
Parallax of points with the same z

- Parallax is a function of only the z coordinate and interocular distance. The y coordinate is fixed!



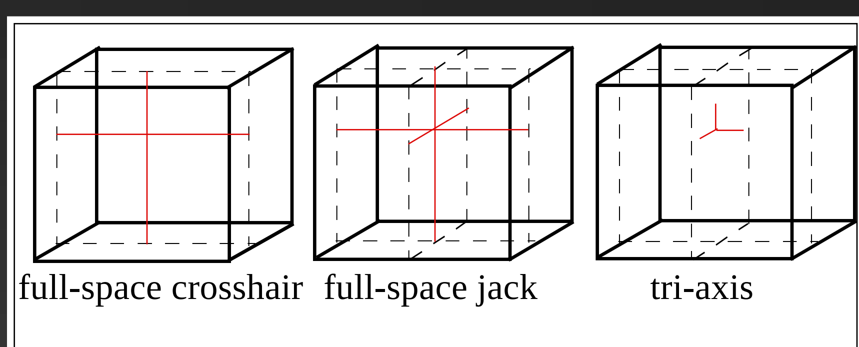
Cursors & Cursor Control (Barham)

Stereo cursors for interactive specification of B-spline space curves.



Cursors & Cursor Control (Barham)

Examples of full-space crosshair, full-space jack and tri-axis cursors.



Cursors & Cursor Control (Barham)

- Movement types
  - Spatial (no restrictions)
  - Planar (restricted to a plane)
  - Linear (x, y, or z direction)
- Tasks
  - Select and change a control point
  - Reproduce a curve

Cursors & Cursor Control (Barham)

- Limitations
  - No cursor rotations permitted
  - No gravity permitted
- Good cursor characteristics
  - Interposition
  - Ghost points - jacks & cursors
  - Grid on view volume - full-space
  - Tektronix anchored rubberband

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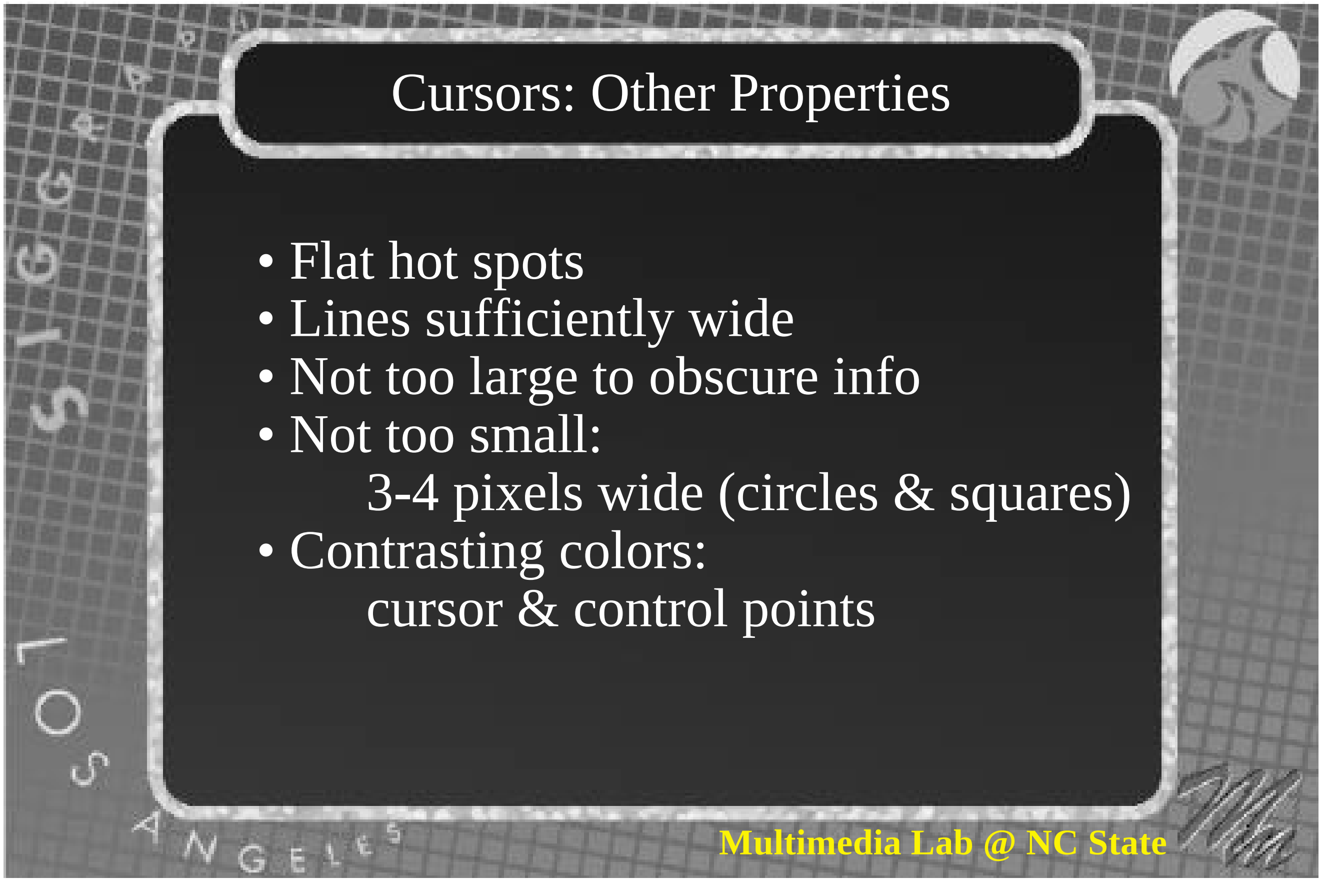
Cursors: Other Properties
• Flat hot spots
• Lines sufficiently wide
• Not too large to obscure info
• Not too small:
3-4 pixels wide (circles & squares)
• Contrasting colors:
cursor & control points
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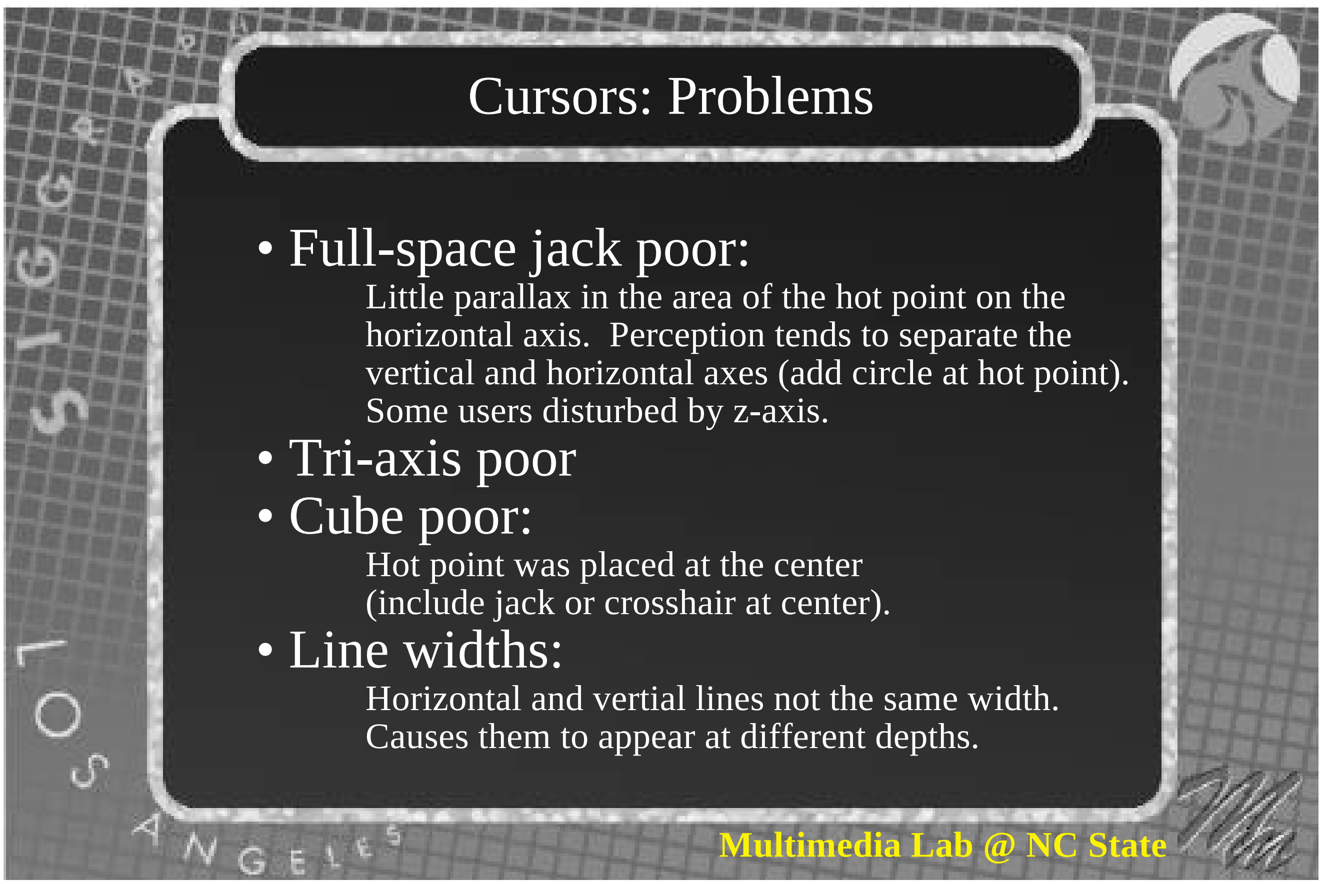
Cursors: Problems
• Full-space jack poor:
Little parallax in the area of the hot point on the horizontal axis. Perception tends to separate the vertical and horizontal axes (add circle at hot point). Some users disturbed by z-axis.
• Tri-axis poor
• Cube poor:
Hot point was placed at the center (include jack or crosshair at center).
• Line widths:
Horizontal and vertial lines not the same width. Causes them to appear at different depths.
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Cursors: Conclusions

- Good cursor choice:
  - Full-space jack with circular hot point at origin.
  - Include option to convert to full-space cross hair.
  - Include option to convert from full space.
- Gravity is a good option
  - Something always selected in a non-empty scene.
- Users showed no preference over unrestricted vs. linear movement.
- Little difference between 3D and 2D
  - For polygonal objects (small pyramid = small triangle)
  - 2D is faster to render.

Cursors: Conclusions

- Subjects used stereopsis and linear perspective for rapid and large depth changes

- Subjects used interposition for fine tuning.

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Rendering/Perception Problems

Erasing/Deleting

Picket fencing

Double images

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Research Areas

Compression

- JPEG
- MPEG
- Color Quantization

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Research Areas

Temporal Antialiasing

Motion Blur

2D methods not appropriate

- Supersampling
- Stochastic Sampling

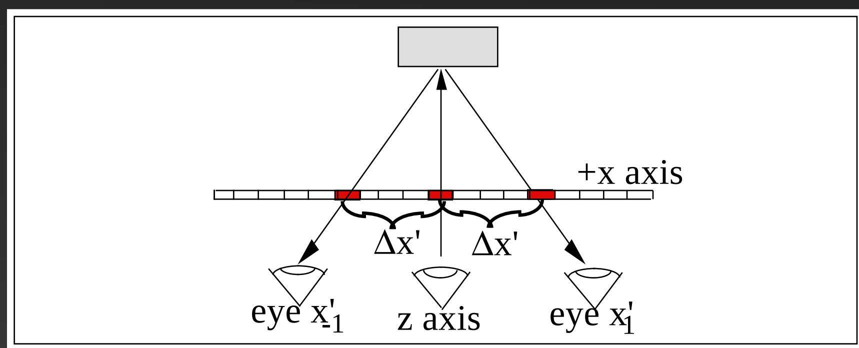
Research Areas

GUI Interfaces

Windowing Facilities

Pixel Shifting (Love)

- Uses projected z in z-buffer and interocular distance to "back compute" alternate eye points.



Pixel Shifting (Love)

- Scan line algorithm.
- Fill in holes using linear interpolation.
- Fast, inaccurate.
- Ignores hidden surfaces.

Pixel Shifting (Love)

- Love proposed using this method to speed up rendering of stereo animation by calculating the left eye view and back-computing the right for even frames and vice versa for odd frames.

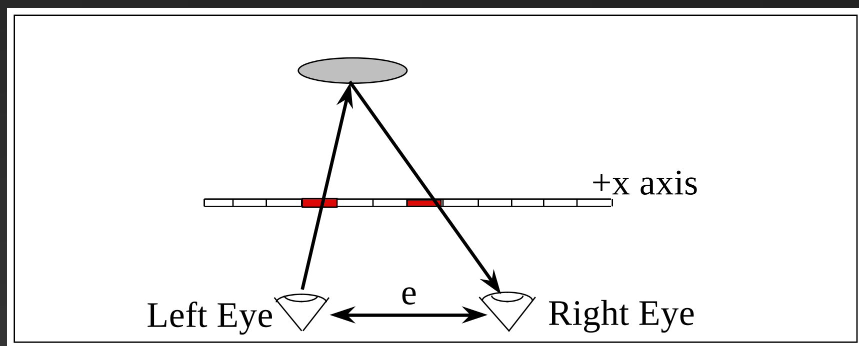
Frame	Left Eye	Right Eye
2n	Calculate	Back-comp
2n+1	Back-comp	Calculate

Ray Tracing (Adelson & Hodges)

- Avoid unnecessary ray intersection calculations.
- Ray trace left eye pixel
  if it intersects an object determine illumination (no reflection or transparency)
- Spawn ray from object to right eye (reprojection) Similar to Love's pixel shift.

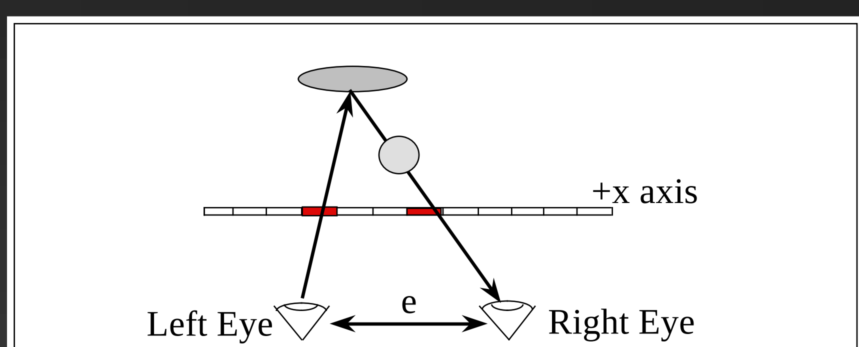
Ray Tracing (Adelson & Hodges)

- Determine if reprojected ray intersects another object. If not, set right pixel to same color (modulo specular reflection).



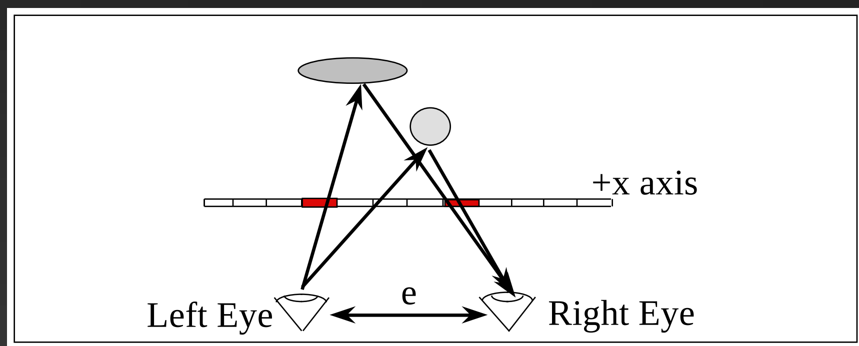
Ray Tracing (Adelson & Hodges)

- If it intersects another object, mark as bad, may need to raytrace in right eye view. (Bad pixel problem)



Ray Tracing (Adelson & Hodges)

- Overlapping pixel problem
  Two points reproject to the same pixel.



Ray Tracing (Adelson & Hodges)

- Solution for both problems, (and any missed pixels). Just raytrace these pixels in the right eye view as well.
- More recent work has studied reflection and transparency.
- More work is needed in combining this with radiosity.

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Scan line algorithms (Adelson et al)

- Use active edge list sorted by y value.
- Y value the same for both eyes.
- Can use a single active edge list for the pair and share all the work to maintain the edge list.
- Work along scan lines done separately for each eye.

Clipping (Adelson et al)

- Liang-Barsky clipping.
- Y value the same for both eyes.
- Y parametric equation need only be calculated once for the pair.
- Top and bottom calculations need only be calculated once for the pair (A major part of the calculation).

Backface Removal (Adelson et al)

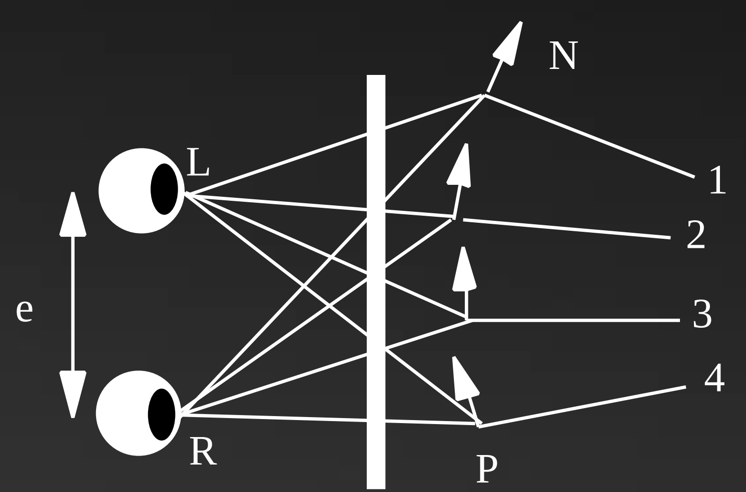
- Refresher:

  If Ax + By + Cz +D < 0, polygon is backface.

  If Ax + By + Cz +D ≥ 0, polygon is frontface.

- Conceptually, if the polygon is a backface for one eye, most likely it is for the other eye as well.
- Only a tough call if the polygon normal is near perpendicular to the line of sight.

Backface Removal (Adelson et al)



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Backface Removal (Adelson et al)

- If normal points generally in the positive x direction ($A > 0$), then:
- If left eye is backface ($A(x+e)+By+Cz+D<0$), Both are backfaces.
- If left not a backface, and $Ax+By+Cz+D<0$, Right eye is a backface.
- Else neither is a backface.

Backface Removal (Adelson et al)

- Similarly, if normal points generally in the negative x direction, then:
- If left is not backface ($A(x+e)+By+Cz+D \geq 0$), Neither is a backface.
- If left is a backface, and $Ax+By+Cz+D \geq 0$, Right eye is not a backface.
- Else both are backfaces.

2D - 3D

Techniques

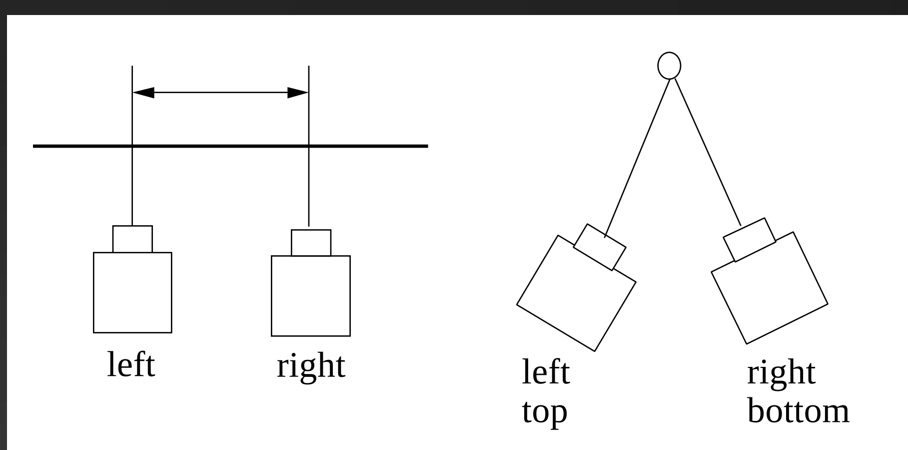
Motion parallax/Short term memory

Plenoptic Modeling

Linear Morphing

2D-3D

Camera alternatives



2D-3D

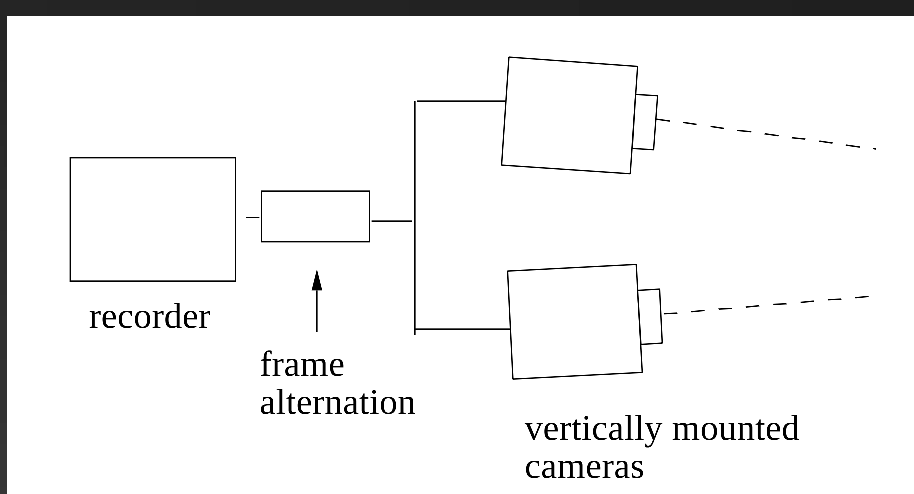
Time Delay Based Stereo

- Movement - motion parallax
- Short Term Memory

VISIDEP
Pulfrich Effect
Transvision

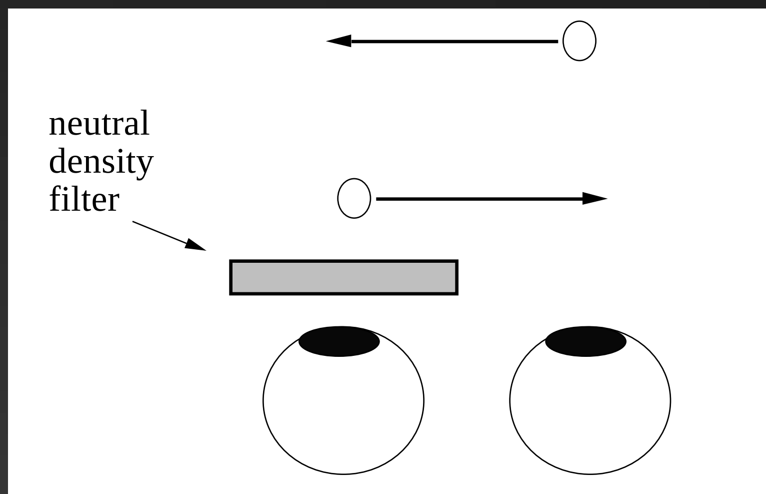
2D-3D

VISIDEP



2D-3D

Pulfrich Effect



2D-3D

SPATIO-TEMPORALLY INTERPOLATED STEREOSCOPY

Transvision - B. J. Garcia

- Single - lens (SLS)
- Temporal disparities
- Short term memory

2D-3D

SLS: ALGORITHMS

Utilize global and local image analysis to extract stereo cues

Global (whole frame) : fixed time delay between images presented to L, R eyes

E.g. delay = 1 field or 1 frame

Global adaptive: variable time delay, shift delay to L,R eye (motion-dependent)

2D-3D

Combined Global/Local (Sub-frame) Adaptive

Global analysis for *simple* cases
- linear horizontal object movement
- linear camera panning

Local analysis for *complex* cases
- objects and camera in motion
- multiple objects in motion

2D-3D

Enhanced viewer tolerance?

- not subject to classical stereo non-linearities

- still requires *parallax control*, ie. stereo disparities must be within <u>fusible</u> range

2D-3D

1974: Two seminal papers: J. Ross, C.W. Tyler (independently)

John Ross, Australia
Stereopsis by binocular delay, Nature, 248, Vol.2, 1974.

- Considered visual processes involved in motion-tracking

- Parts of the visual field are seen at different times by each eye, depending on motion

- Or, each eye sees the same visual field, but at different times

- Refutes classical view of *instantaneous binocular disparities*

2D-3D

- To maintain stereopsis, vision must use *short-term memory* resources

- Ross used random-dot stereograms (RDS's) to eliminate monocular form cues

Experimental Psychology

temporal characteristics of stereovision

Ross, Tyler, Morgan, Blake, Julesz, ...

2D-3D

C.W. Tyler, England
Stereopsis in dynamic visual noise,
Nature, Vol. 250, 1974.

-repeated Ross' experiments on interocular delay

- temporal disparities = spatial disparities

2D-3D

Dual visual processes

Process 1: Converting temporal disparities to spatial disparites by inter-ocular delay

Process 2: Creating coherent stereo perception by interpolation

2D-3D

Stereo Interpolation

Fundamental Tenet: *Vision interpolates*

Proof: Acuity of vision exceeds limits predicted from granular structure of retinal mosaic receptor cells

Example:

-Typical subject can align two bars in a vernier task with precision of 2 sec arc.

- Separation of cone receptors in retina at densest spacing is 20-30 sec arc

2D-3D

Image Based Rendering

Epipolar Geometries

L. McMillan/G. Bishop

- Avoid assumptions of geometry of objects in scene
- Move pixels consistent with camera movement
- Preserve visibility

2D-3D

Epipolar Geometry

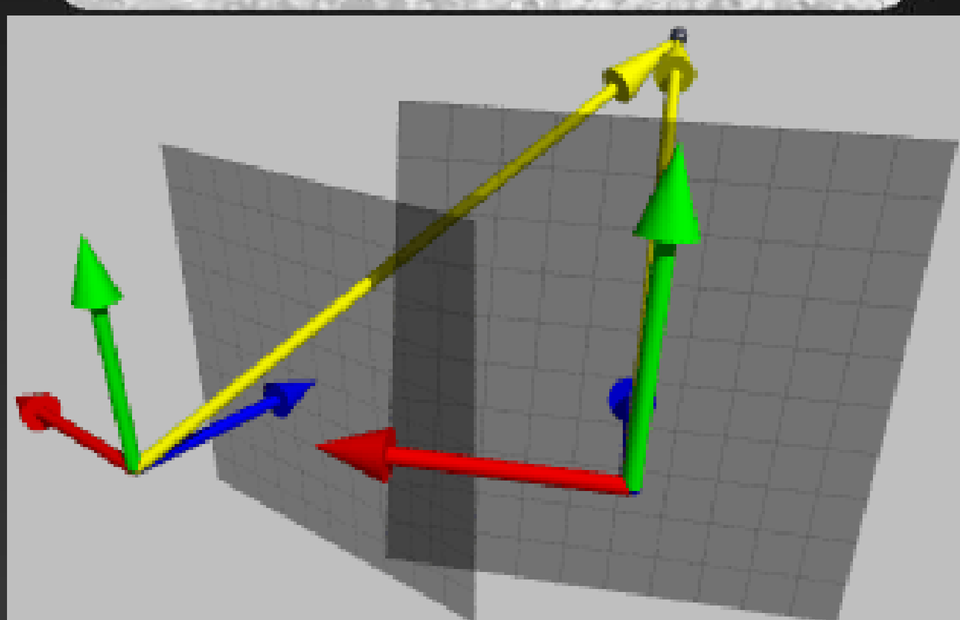
Changes of viewpoint introduces geometric relationships

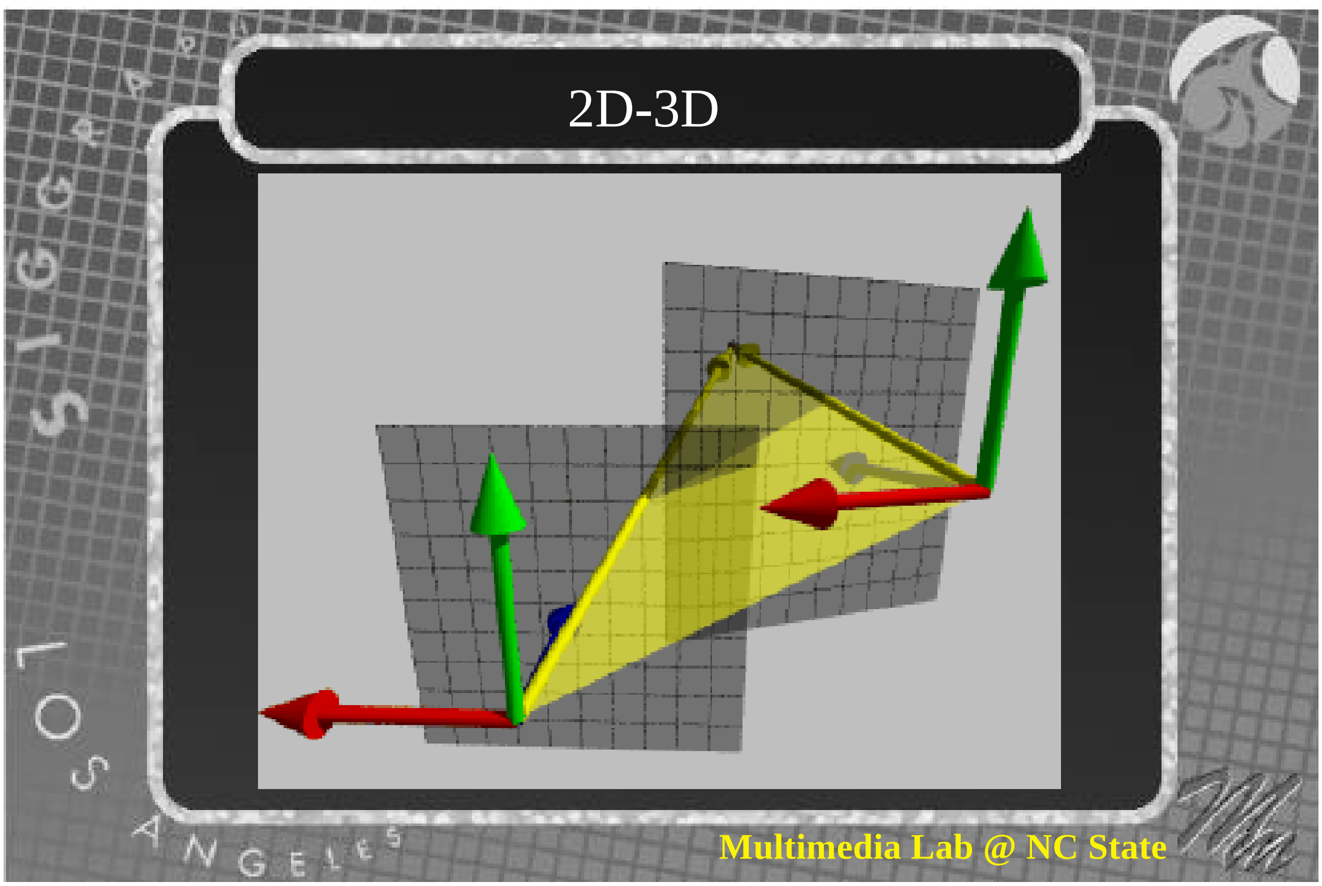
Purturbed Projective Geometry (texture mapping)

2D-3D

- As camera moves, points in image move along epipolar lines which are projections of rays from the epipole or COP in Camera 1 to point in image.
- Visibility handled by identifying quadrants determined by epipole in image of Camera 2.
- Separate quadrant rendering produces correct visibility.
- Holes in image result from hidden surfaces in original image.

2D-3D

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2D-3D

View Morphing

S. M. Seitz, C. R. Dyer

2D-3D

View Morphing

When does a linear 2D morph preserve 3D shape?

Intermediate views are correct views of the same scene

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2D-3D

Linear Interpolation or Blending

- *PI* is the initial pixel location - color,
- *PF* is the final pixel location - color,
- *P(s)* is the ‘tween’ pixel location - color,

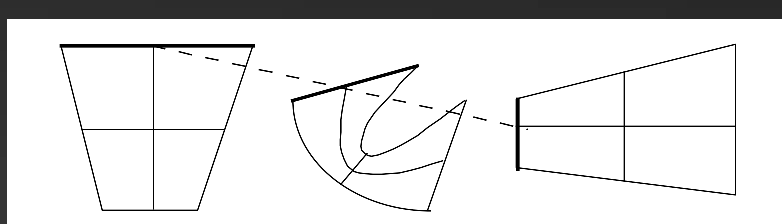
$$P(s) = sPI + (1-s)PF, \quad s \, \varepsilon \, [0, 1].$$

2D-3D

Projection Warps

- not preserved under linear interpolation - sum is ratio of quadratics

- lines are not preserved



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2D-3D

Shape Preserving Morphs

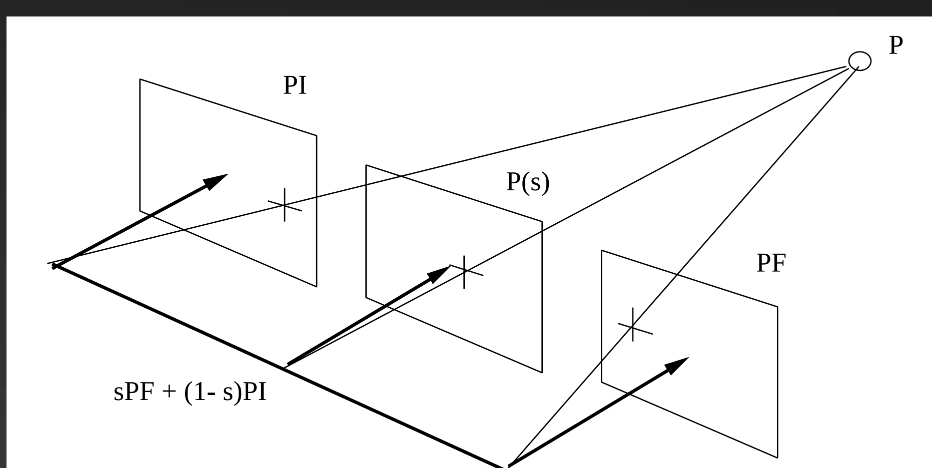
• *Prewarp* two images - brings image planes into alignment

• Compute a *linear morph* (corresponsdence maps, image warp and cross dissolve) - intermediate images with ***parallel*** image plane

• *Postwarp* inbetween images - produce desired inbetween image plane alignment

2D-3D

Linear morphing of <u>parallel</u> views preserves shape



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2D-3D

Extend to non-parallel views for which optical center of one camera in field of view for the other

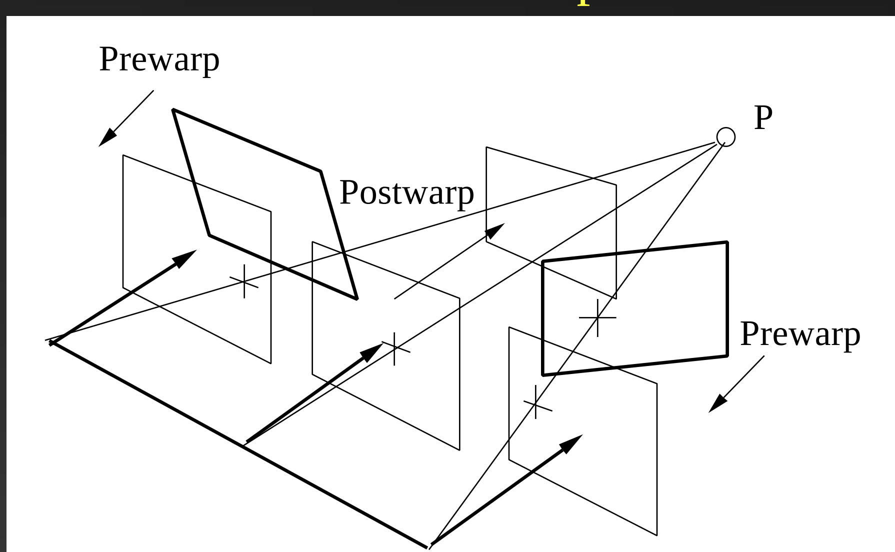
projection matrices need not be known

Any two projection matrices suffice that send correponding points to the same scan line

Constraint - visibility identical for both images

2D-3D

Pre/Post Warp



Siggraph '97

Stereo Computer Graphics for Virtual Reality

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