# Virtual Reality

## VR Displays & Stereo Rendering


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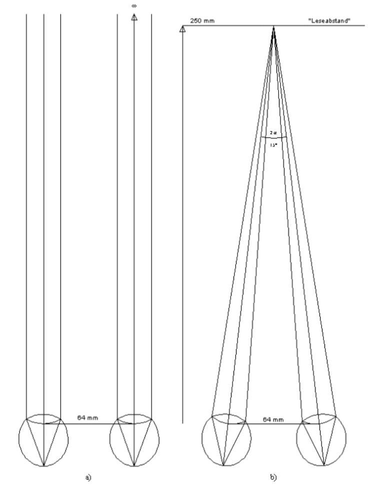
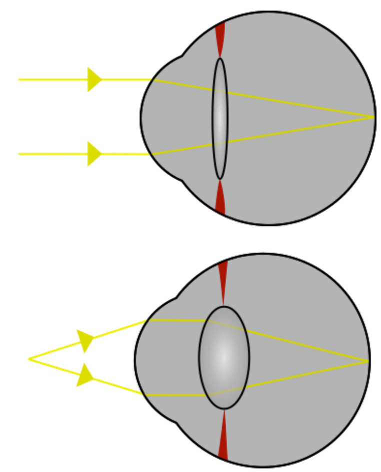
# Depth Cues

- Motion parallax: apparent motion of objects relative to each other, when observer moves
- Stereopsis (binocular/stereo vision)
  - Important, but not the most important depth cue
- Occlusion
- Perspective (see CG1)
- Lighting & shading
- Relative size / Familiar size
- Accommodation / Convergence
- Texture gradient
- Defocus blur

# Binocular / Stereoscopic Vision / Stereopsis

- Convergence = counterrotating eye movement (around the vertical axis), so that the optical axes of the eyes intersect at some point (fixation point)
  - So that the fixated object appear on the center of the retina (has highest resolution)
- Focus = adjustment of the eyes' lenses to adapt to different distances
  - So that the fixated object appears sharp on the retina
  - A.k.a. accomodation
- Two important terms that get confused very easily

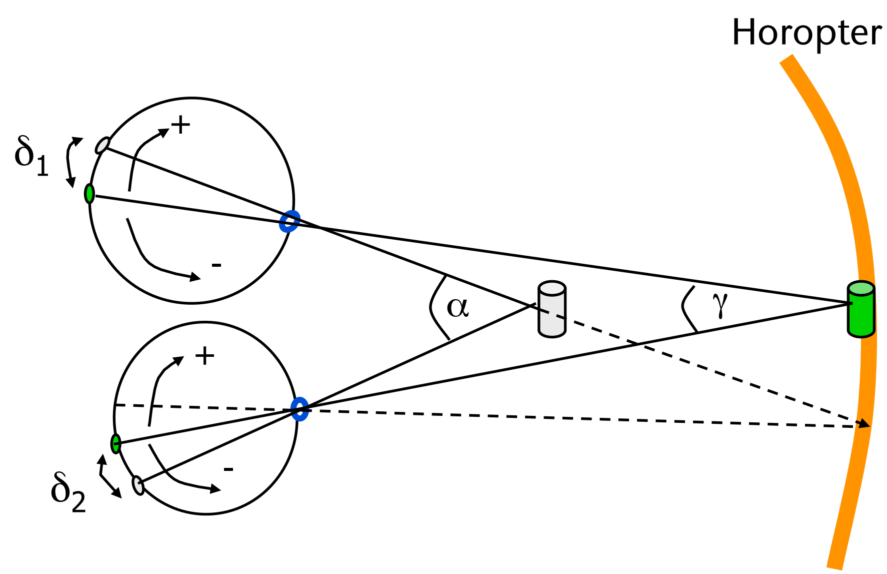




- Stereoscopic vision works just up to a few meters (< 6 m, ca.)
- Causes disparity between corresponding points on the retinas:

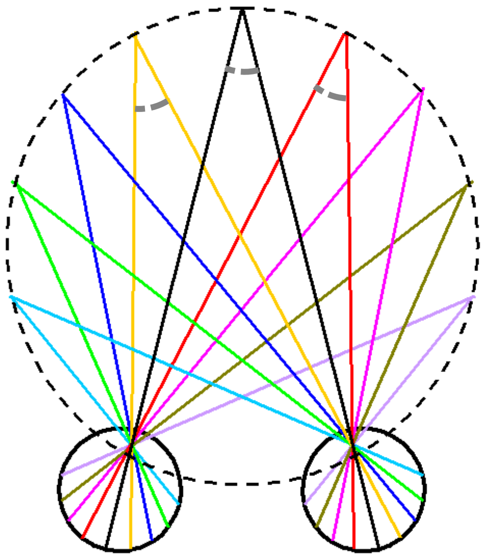
$$\delta = \delta_2 - \delta_1 = \gamma - \alpha$$

- Horopter = locus of points in space with same apparent depth as the fixated object = point with 0-disparity

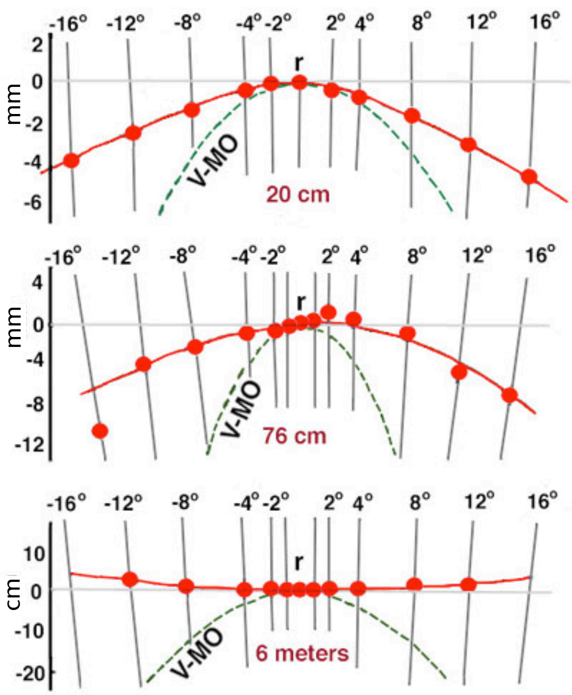


# Measuring the Horopter

- First of all: not measuring it, but *constructing* it → Vieth-Müller Circle = theoretical locus of points in space that stimulate corresponding retinal points

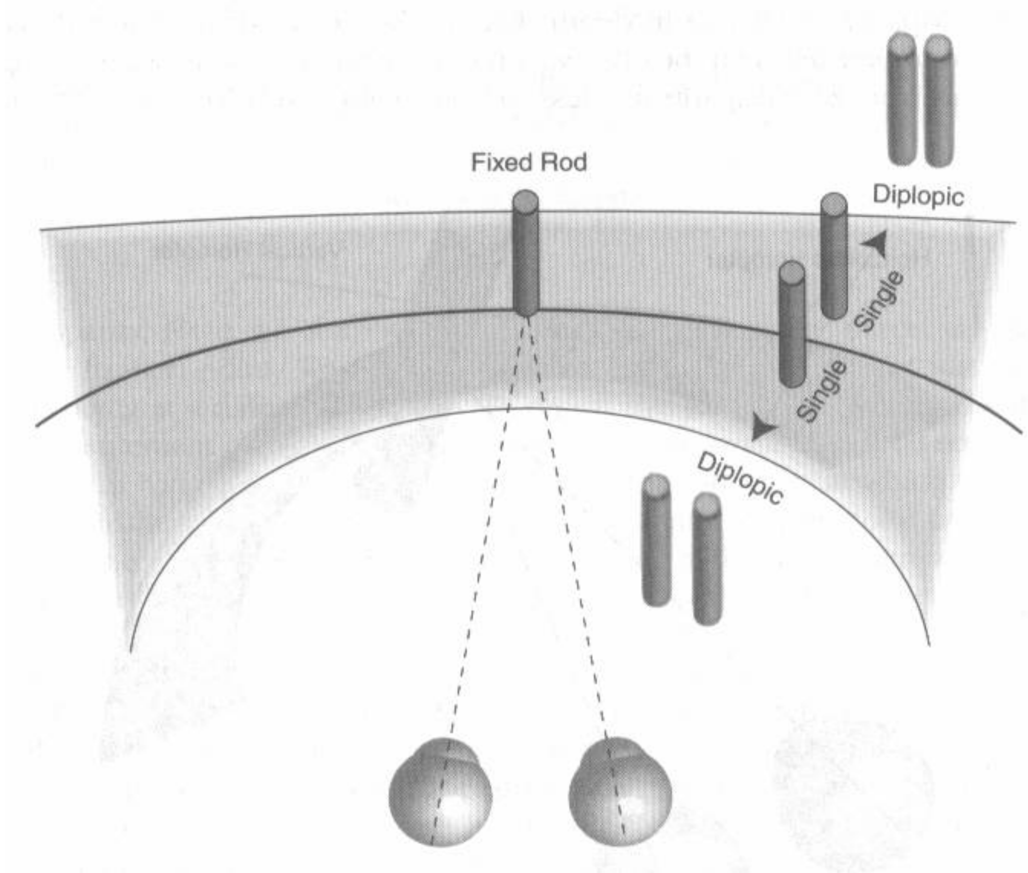


- Measuring the Horopter with the "Apparent Fronto-Parallel Plane" method:
  - Subject is asked to arrange a series of objects so that there appears to be no depth difference between them



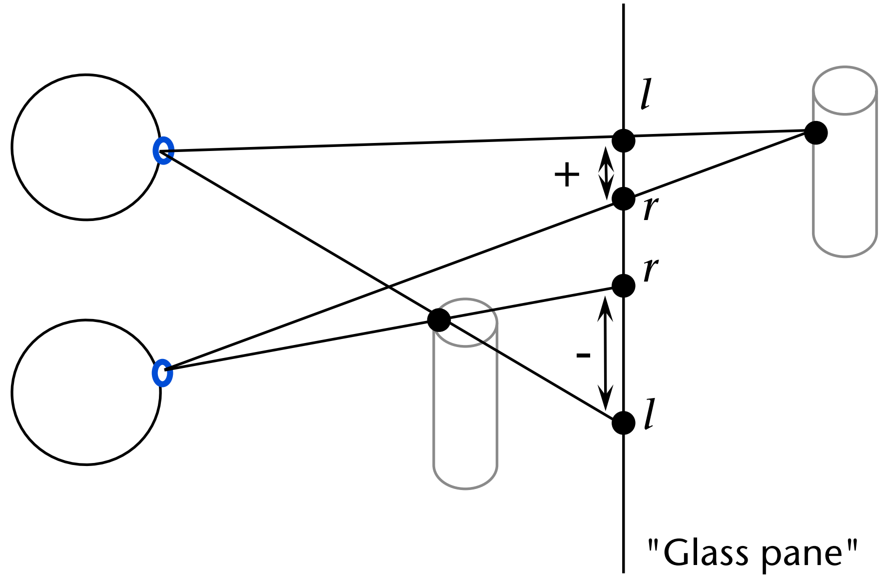
# Panum's Fusional Area

- There is a zone/range of depth around the horopter, where the brain is able to fuse the double image of an object
  → Panum's Area of Fusion



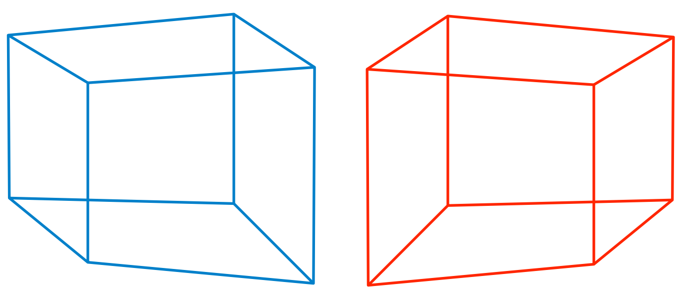
# Stereo Projection

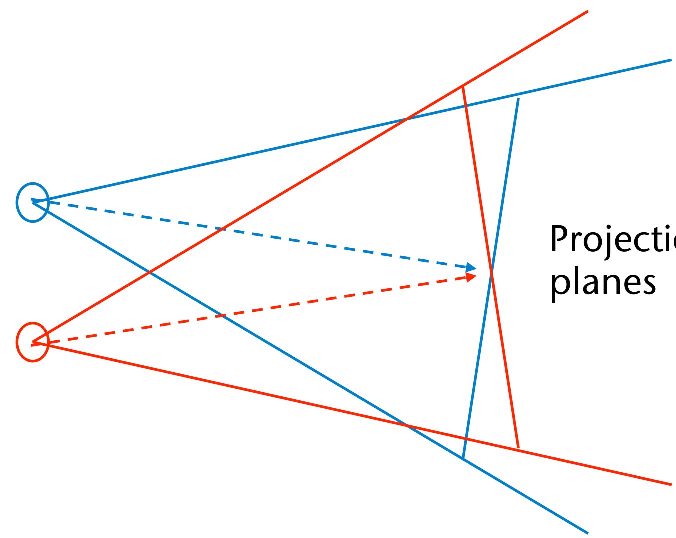
- Parallax on the screen
  → disparity in eye




- Wrong: converging view vectors

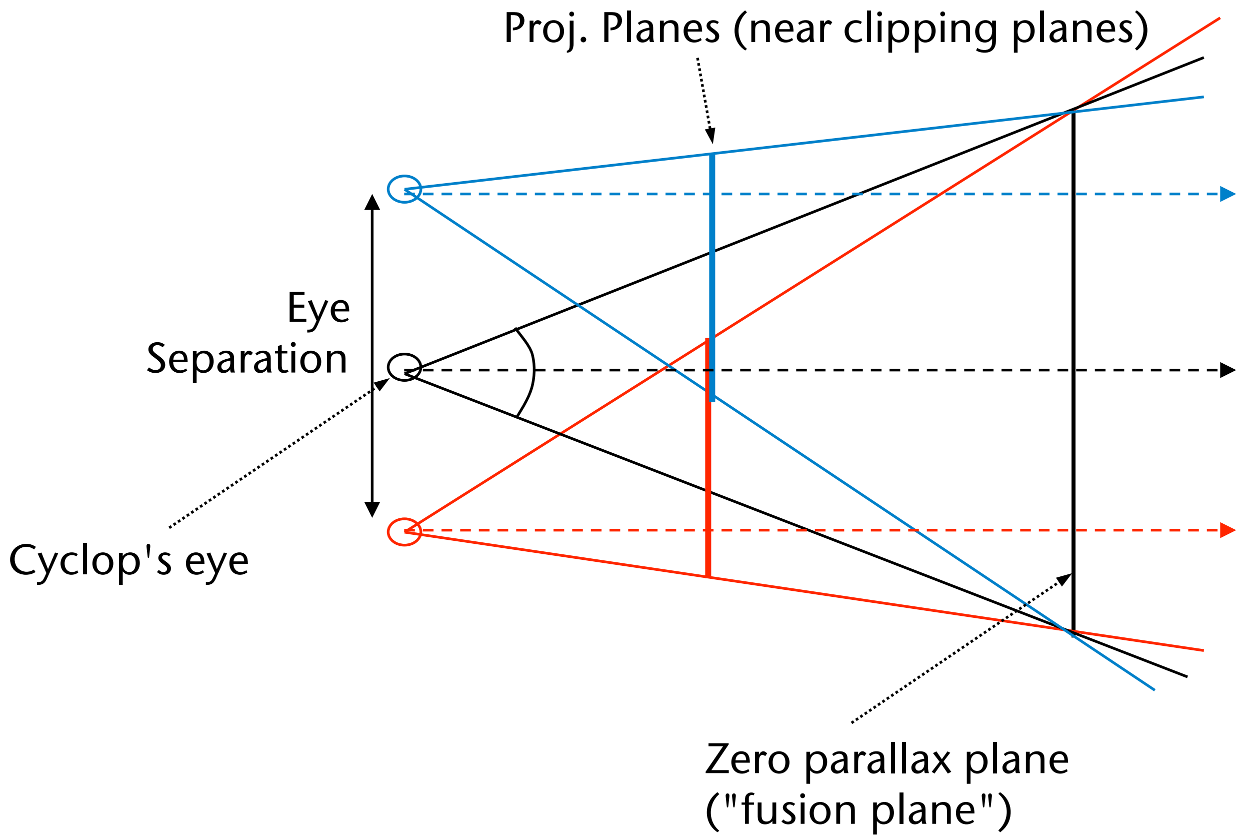
- Problem: vertical parallax!



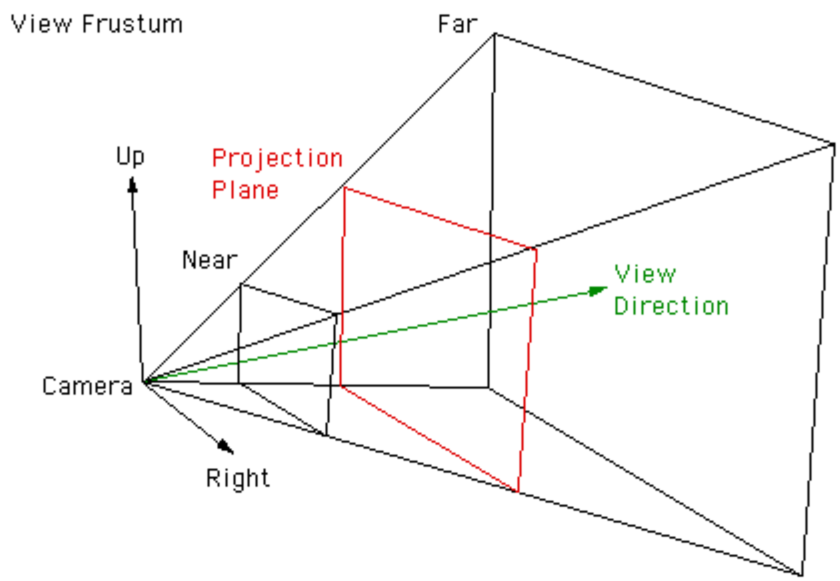


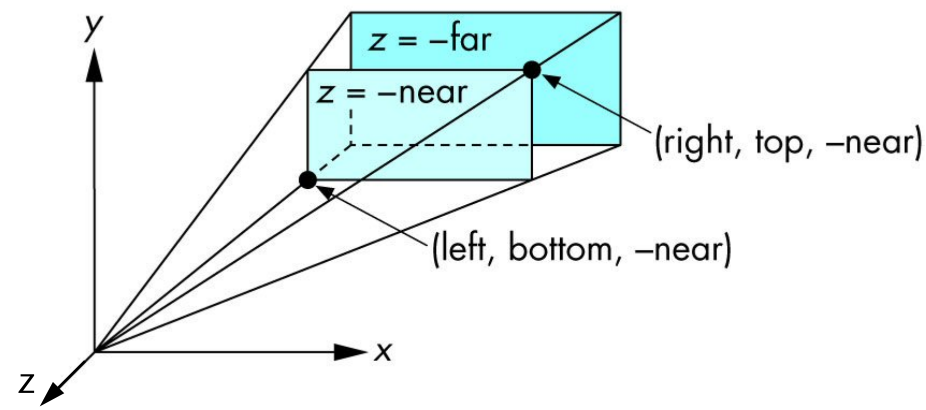
# Correct Stereoscopic Projection

- Right: parallel viewing vectors
  → *off-axis perspective projection*



# Recap: Perspective Projection in OpenGL



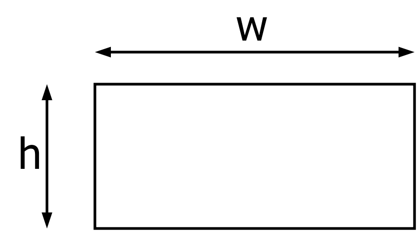




$$M_{proj} = \begin{pmatrix} \frac{2n}{r-l} & 0 & \frac{r+l}{r-l} & 0 \\ 0 & \frac{2n}{t-b} & \frac{t+b}{t-b} & 0 \\ 0 & 0 & \frac{-(f+n)}{f-n} & \frac{-2fn}{f-n} \\ 0 & 0 & -1 & 0 \end{pmatrix}$$

$n = |near|$ ,
$f = |far|$

```
glFrustum( left, right,
           bottom, top,
           near, far );
```

- Given *i*, aspect ratio *w/h*, horizontal FoV $\alpha$, near plane *n* , zero-parallax depth $z_0$
- Determine *left/right/top/bottom* for **`glFrustum`**()
- Assumption: no head tracking, i.e., cyklop's eye is in front of the center of the zero parallax plane
- *top* and *bottom* are as usual:



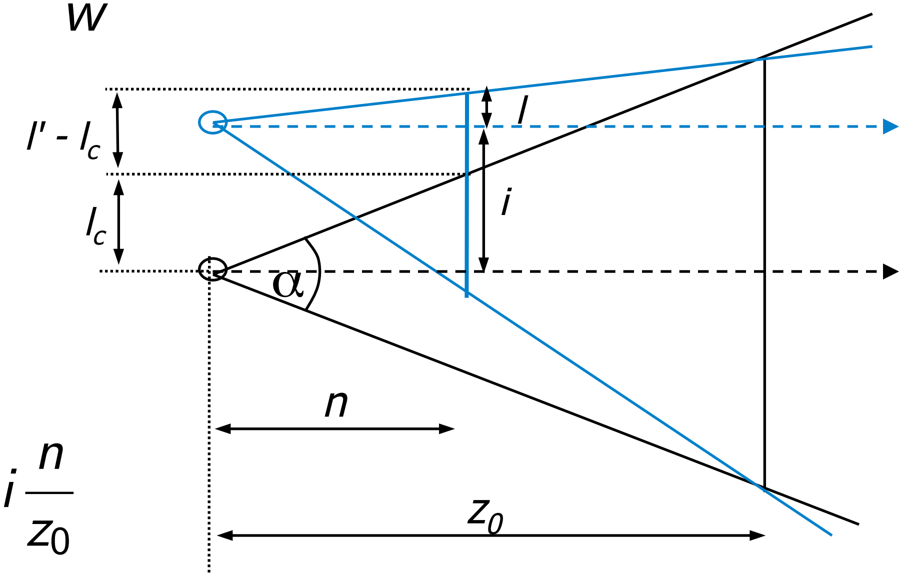

$$t = \frac{h}{w} l$$

- Example: *left* for left eye:

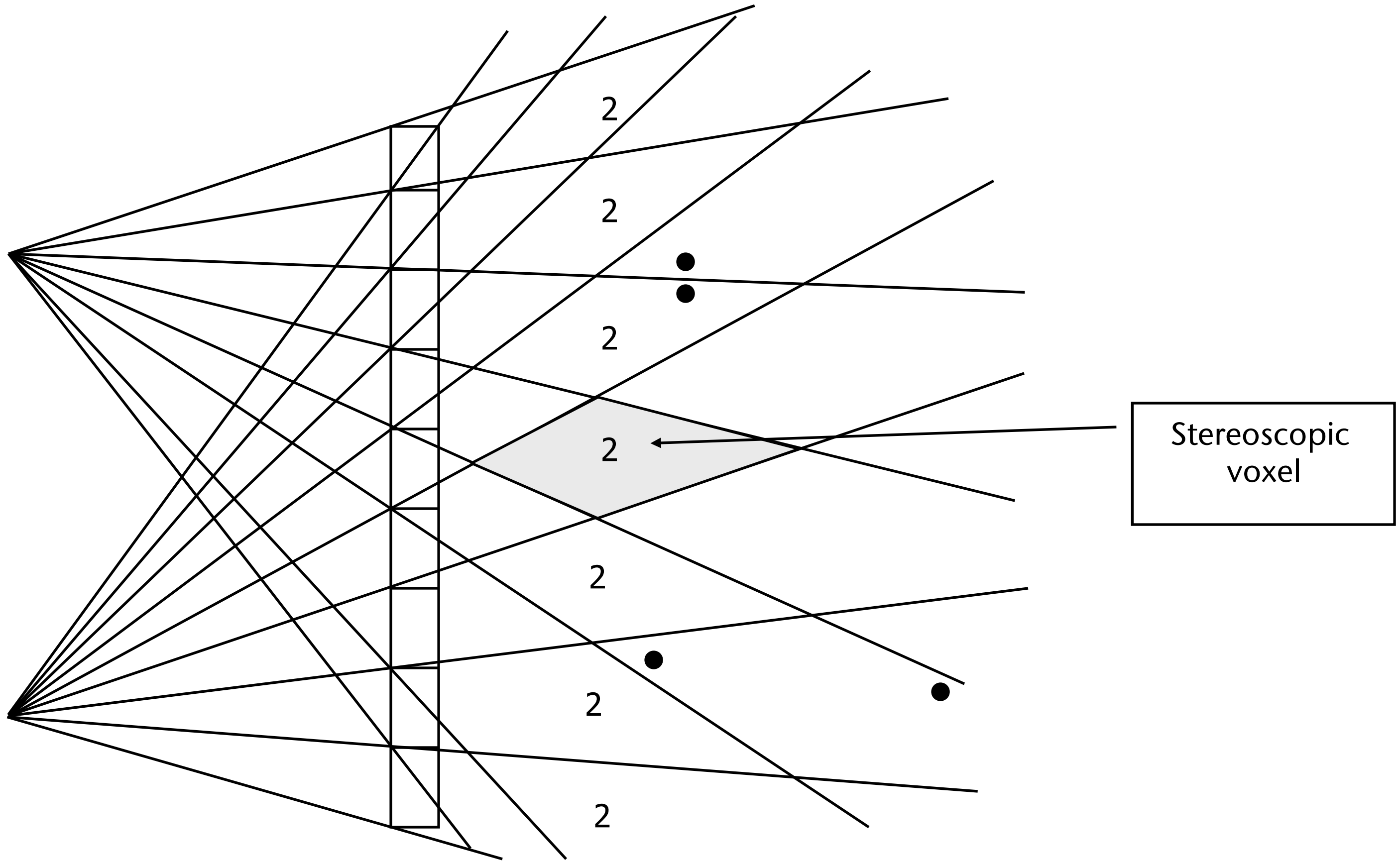
$$l_c = n \tan \frac{\alpha}{2}$$

$$l' - l_c = i \frac{z_0 - n}{z_0}$$

$$l = l_c + (l' - l_c) - i = l_c - i \frac{n}{z_0}$$



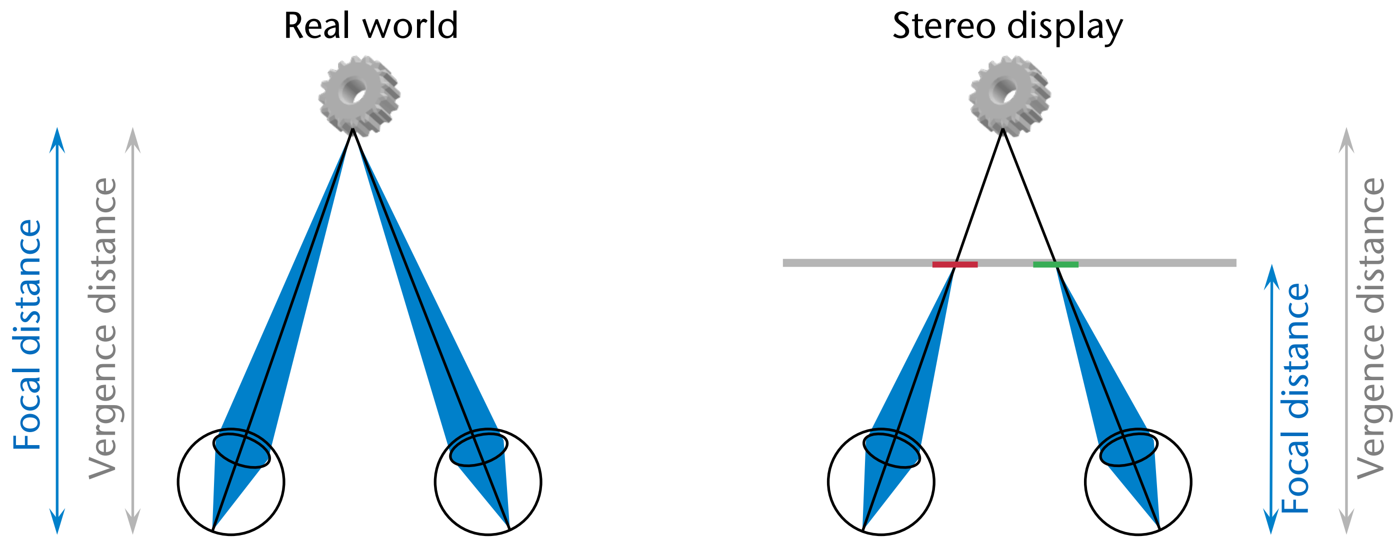
# Problems with Stereo Rendering: Depth aliasing




- This effect would occur, even if the Z-buffer was continuous!

# The Problem With Convergence-Focus Incongruity

- Experimental evidence shows: the brain computes a weighted average of multiple depth cues, including focal depth
- With stereoscopic displays, our eyes receive inconsistent depth cues:

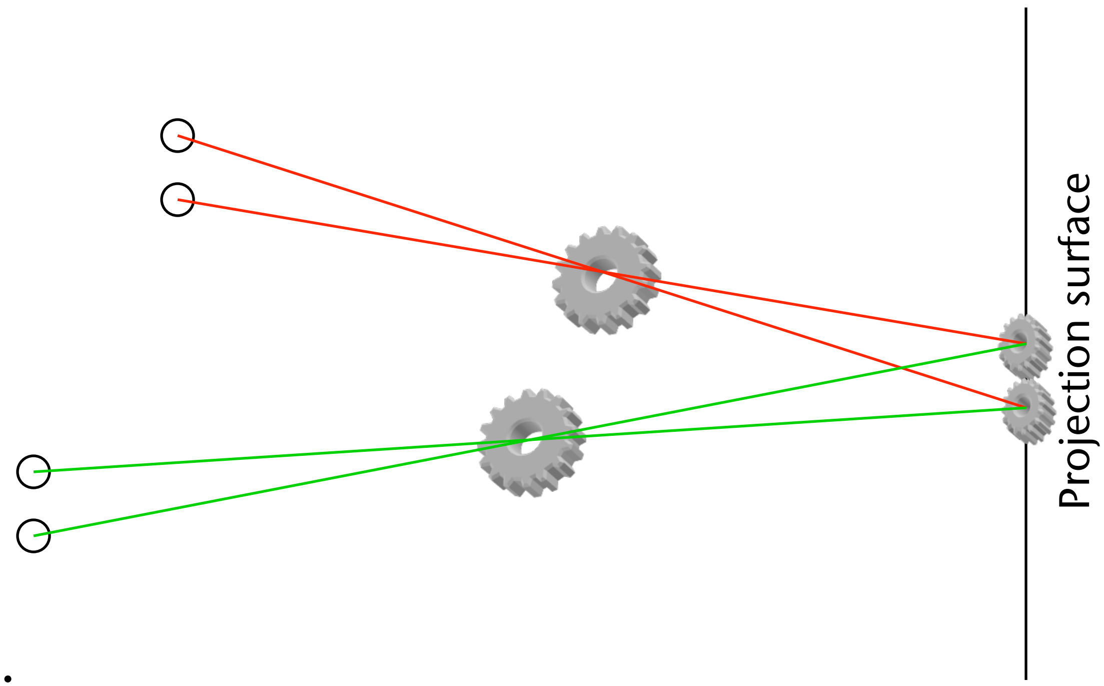



- Effect: in a Cave or Powerwall, near objects appear more distant than they are

Watt, Akeley, Ernst, Banks: "Focus cues affect perceived depth", J. of Vision, 2005]

# Stereo is (Usually) a "*One Man Show*"

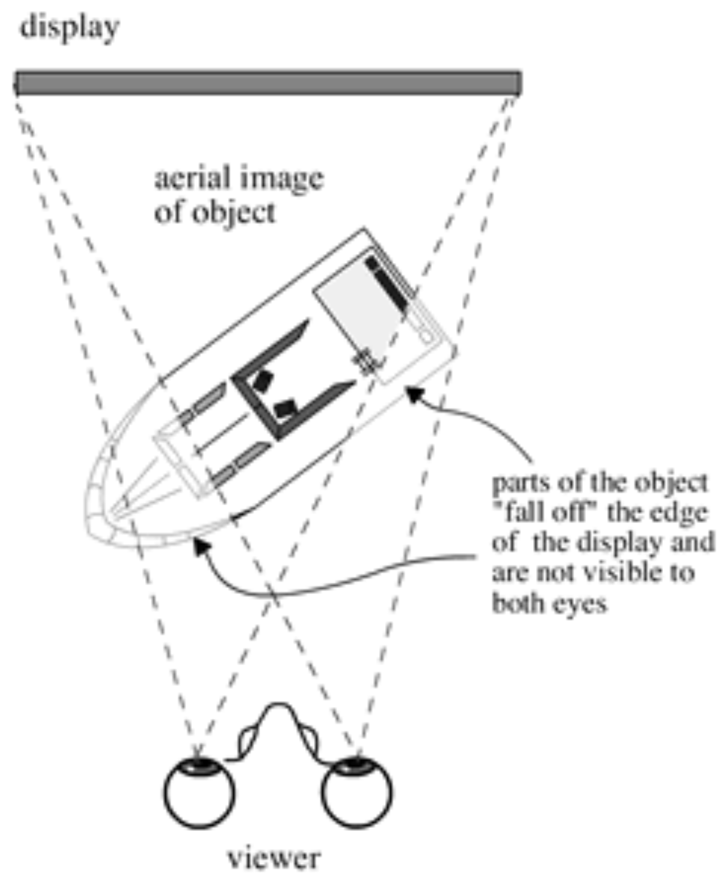
- Why are stereoscopic images correct only for 1 viewpoint?




- Solution:
  - For 2 viewers: render 4 images; or
  - True holographic/volumetric displays

# Stereo Violation

- 2 effects that can occur together:
  - *Clipping*
  - Depth from stereoscopic image
  - Object is clipped, although *in front of* the projection surface
  - Consequence: conflicting *depth cues* → *stereo violation*
- Example: lower left corner of the anaglyph mars image



# The Model of a User's Head

$M_e$ = viewpoint transformation

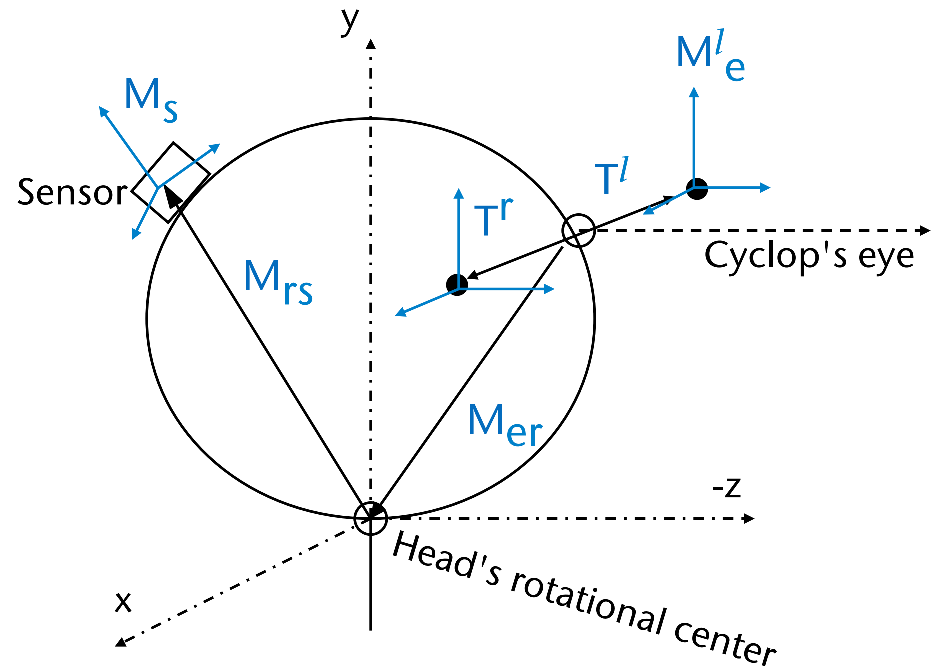
$M_s$ = current sensor reading, relative to ist zero calibration

$M_{rs}$ = transform. from head'srotational center to sensor

$M_{er}$ = transform. from "cyclop's eye" to head'srotational center

$T^l | T^r$ = translation to left/right eye

$$\mathbf{M}_e = \mathbf{T}_{l|r} \mathbf{M}_{er} \mathbf{M}_{rs} \mathbf{M}_s$$



# Relevant OpenGL Commands

- Initialization:

```
glutInitDisplayMode(GLUT_DOUBLE|GLUT_RGB|GLUT_DEPTH |
GLUT_STEREO);
```

- Rendering:

```
glDrawBuffer(GL_BACK_LEFT);
glClear(..)
glFrustum(...)
traverse scene graph ..
glDrawBuffer(GL_BACK_RIGHT);
glClear(..)
glFrustum(...)
traverse scene graph ..
```

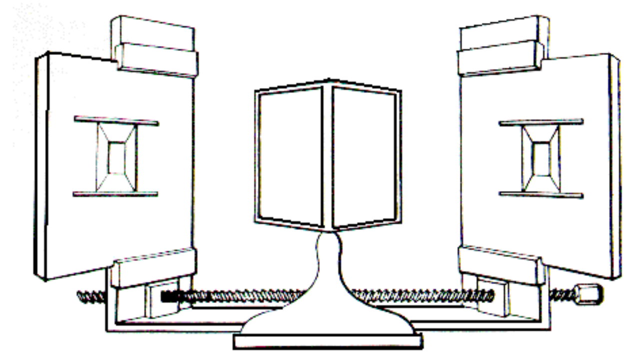
- Or: render with 2 different threads into 2 different graphics cards
- Or: side-by-side stereo (2 openGL viewports in one big window)

# Guidelines for Stereo Rendering

1. Make parallax not too big! (common error of novices)
   $\pm 1.6° \sim$ parallax $\leq 0.03 \cdot$ (distance to projection wall)
2. Single object → put zero-parallax plane at its center
3. Complete VE → 1/3 negative parallax, 2/3 positive parallax
4. Keep objects with negative parallax away from the border of the projection surface

# The History of Stereo Images

- Euklid (4th century BC)
- Sir Charles Wheatstone (1838 )



- 1860: 1 million Stereoscopes sold

- 1950-ies:

- Today (demo):

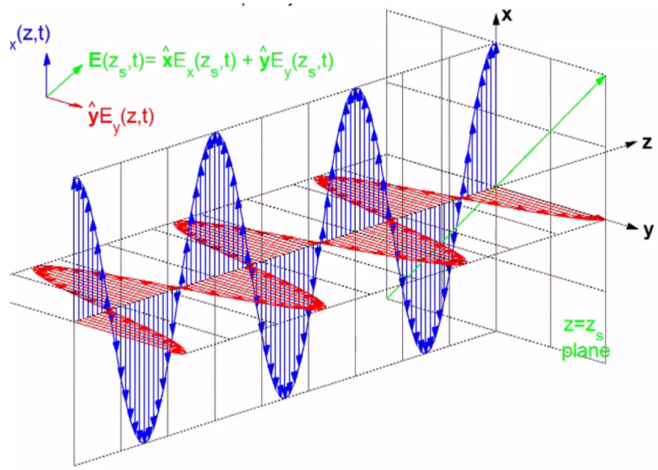
# How to Project Stereo with only *one* Display Surface?

- Need some kind of *Multiplexing*

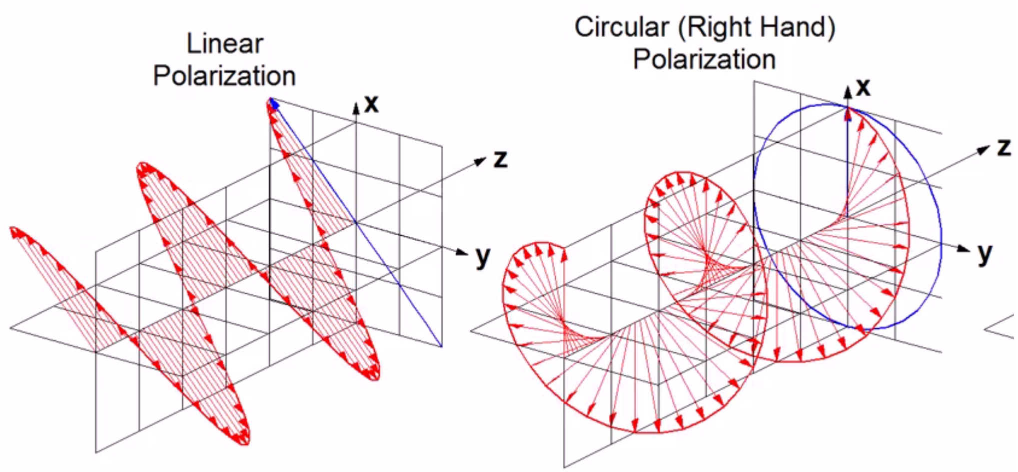
1. Temporal Multiplexing ("active stereo"):
   - Typically 1 projector (e.g. monitor)
   - Project/render alternatingly left/right image
   - Synchronously, switch left/right glass of *shutter glasses* to pass-through
   - Shutter glasses run with 120 Hz → 60 Hz framerate

2. Multiplexing by polarization ("passive stereo"):
   - Usually 2 projectors displaying on same surface
   - Project left/right simultaneously but with different Polarization of the light
   - Polarization glasses let only left/right images pass, resp.

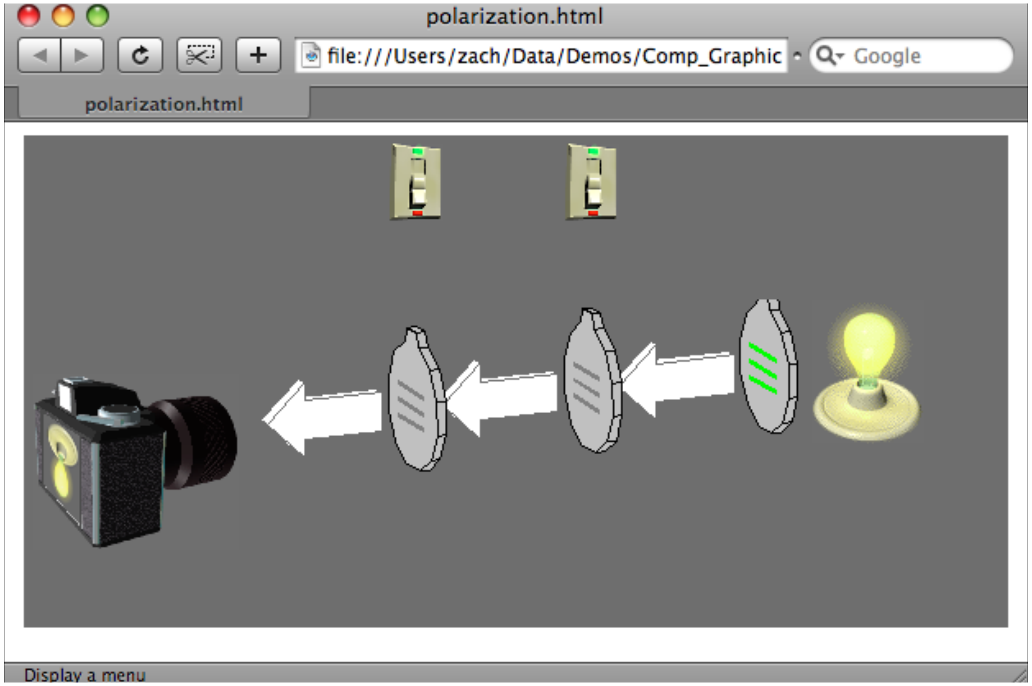
- Kinds of polarization:
  1. Linear polarization:
     - Any direction perpendicular to direction of travel of light




  2. Circular polarization:
     - Left-handed / right-handed polarization



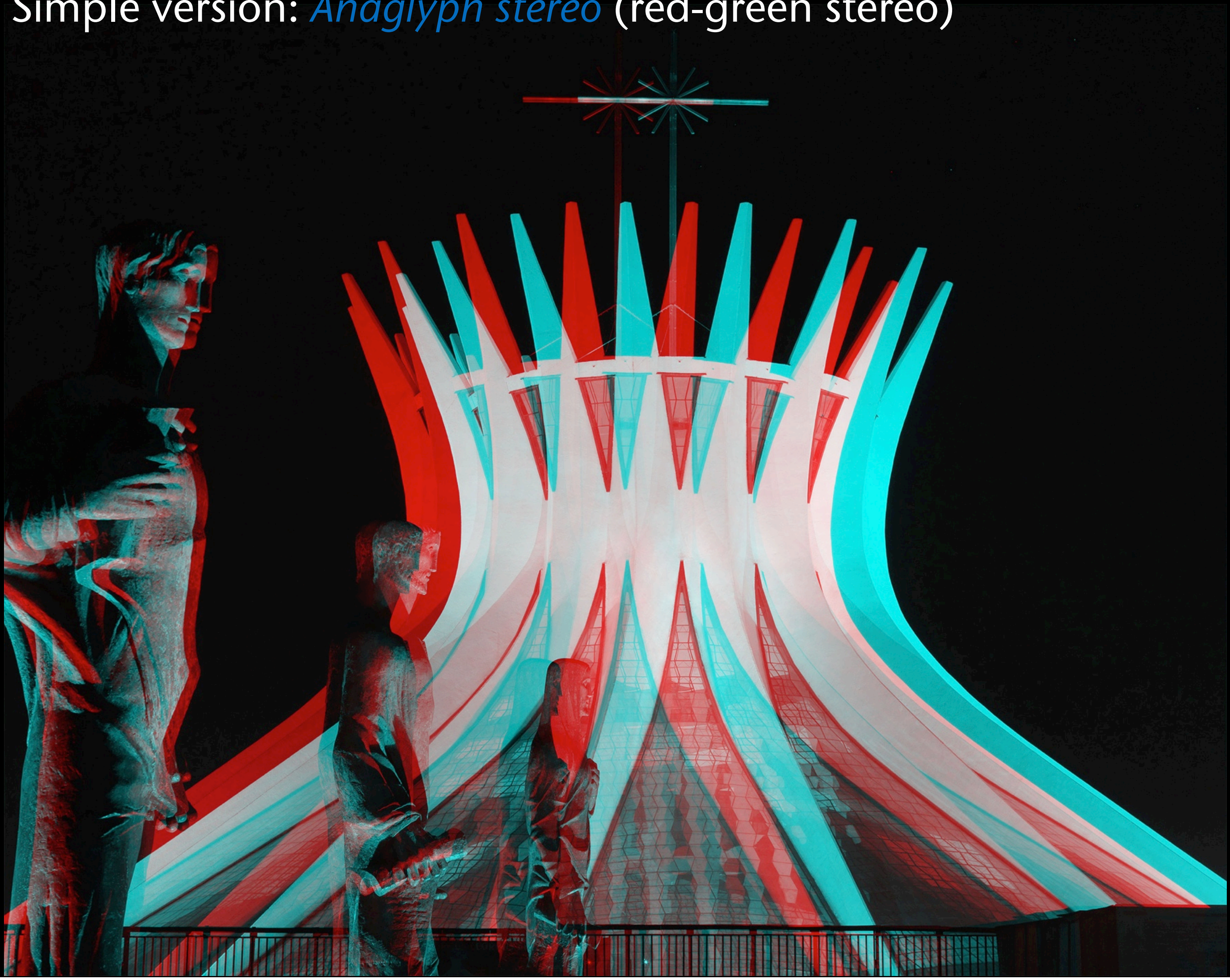
# Demo

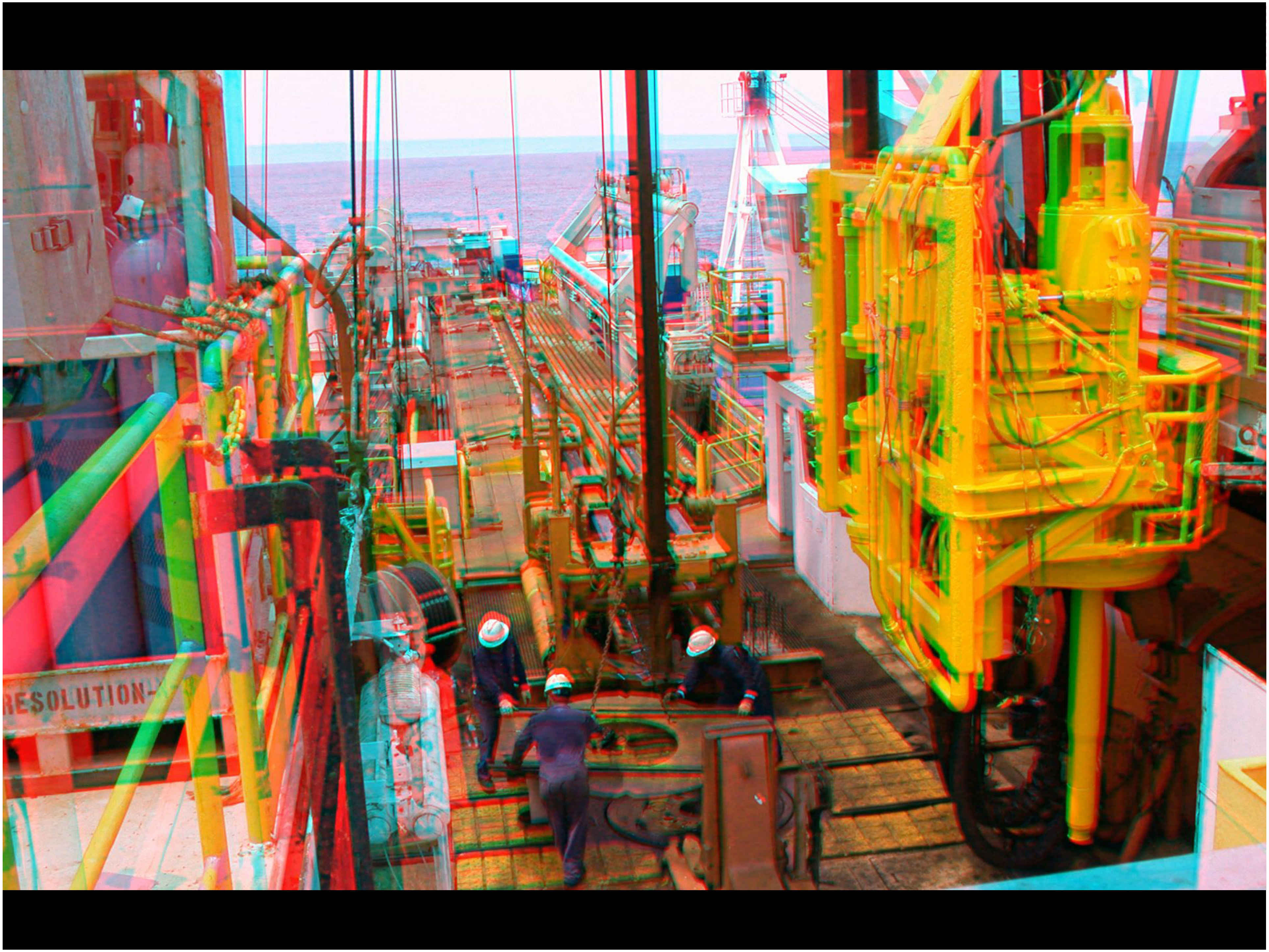


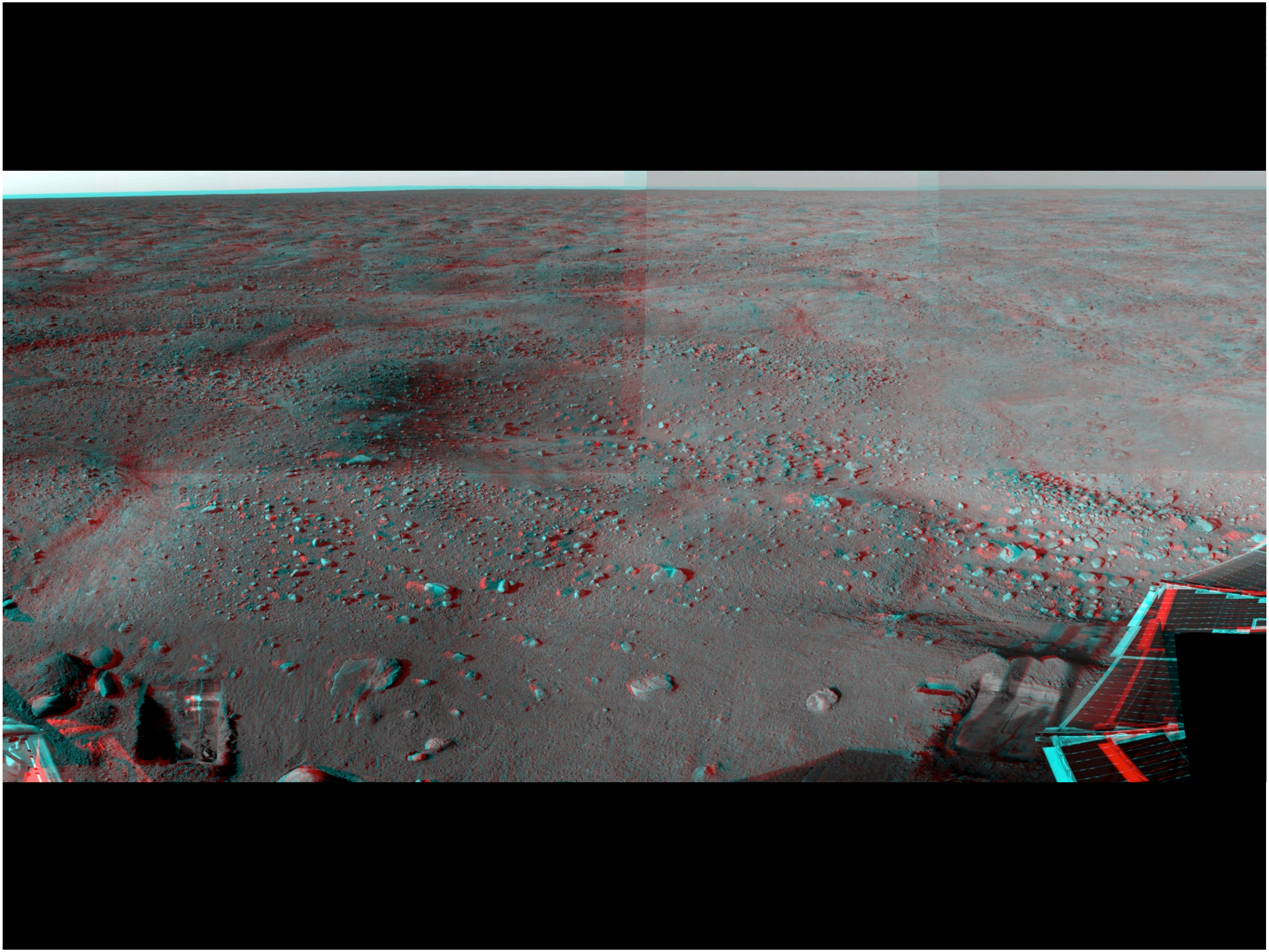

http://www.colorado.edu/physics/2000/applets/polarization.html

# "Color Multiplexing"

- Simple version: *Anaglyph stereo* (red-green stereo)

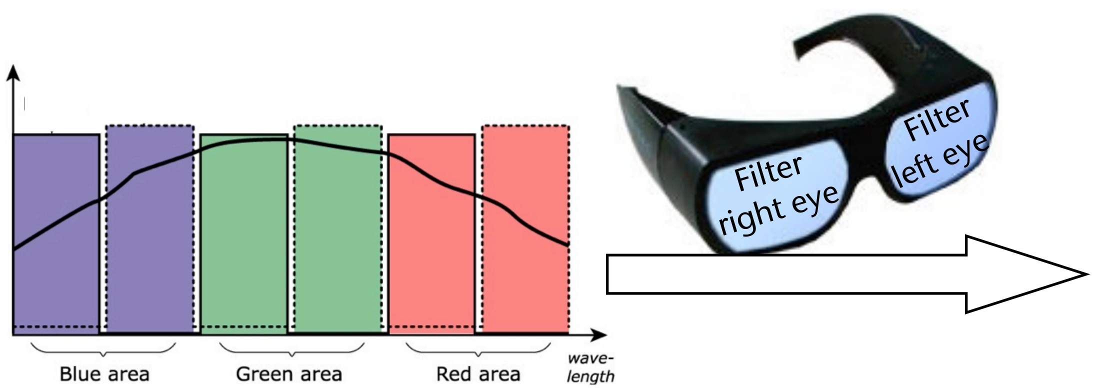


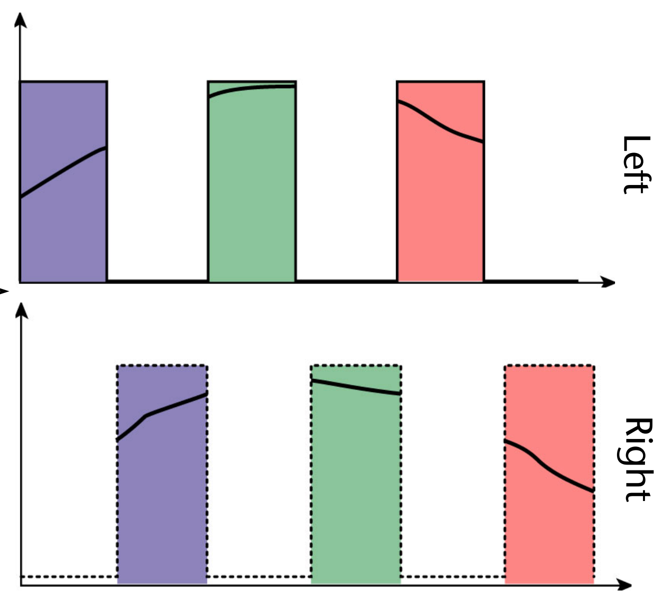

RESOLUTION-



# Wavelength Multiplexing (Infitec)

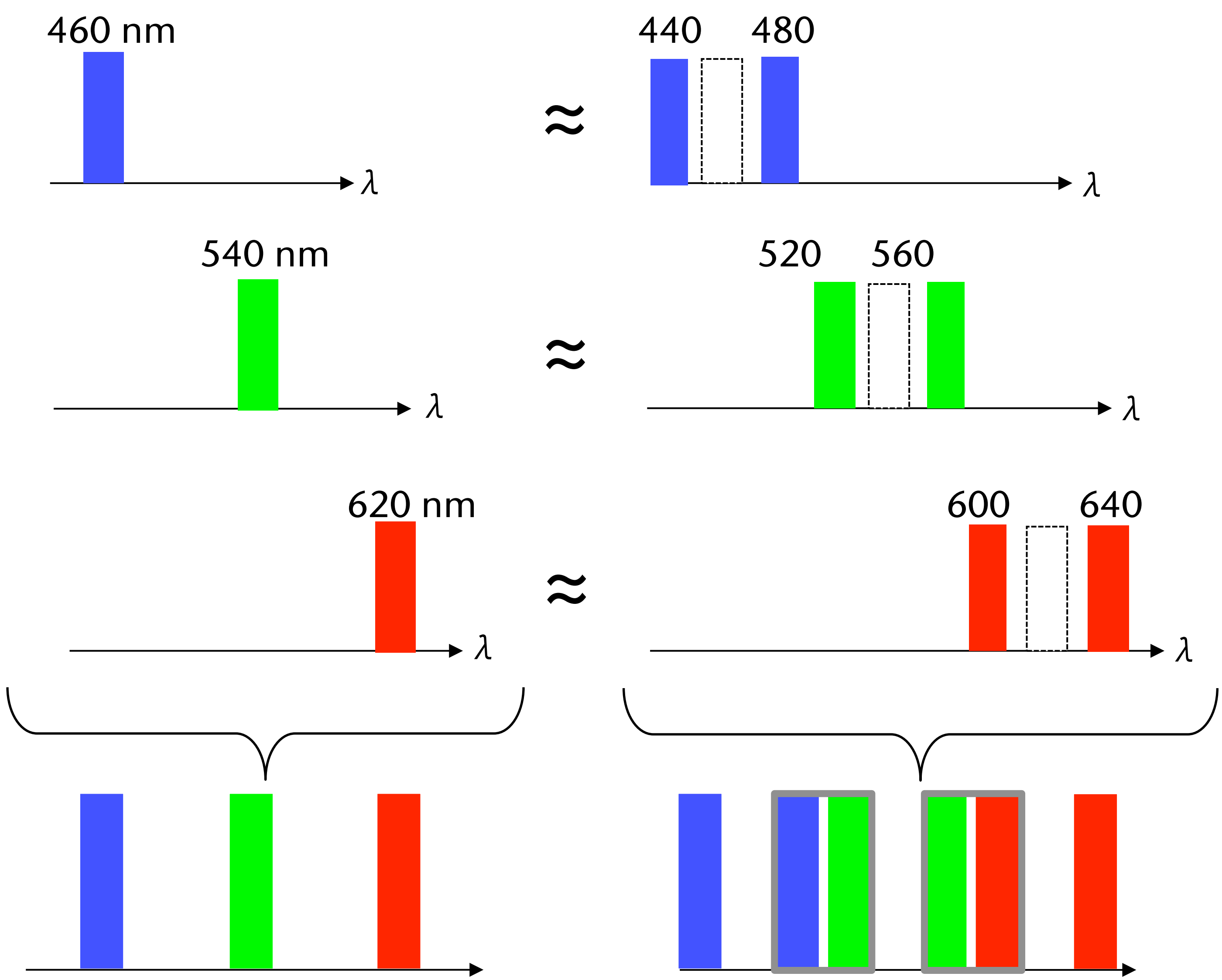
- Generalization of  anaglyph stereo:
  - Each of the primary colors must pass through a narrow band pass filter
  - Left & right eye get filters with interleaving band passes
  - Other names: Dolby3D, spectral comb filter




- Problem:
  - Color fidelity

# Improvement: utilize color metamerism

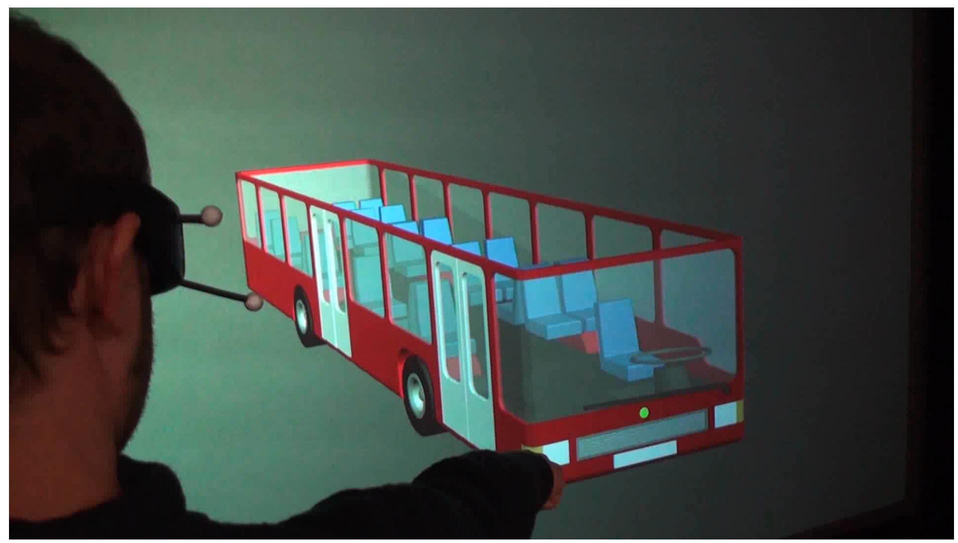



Courtesy Infitec (infitec.net)

# The Problem of Multiple Users and a Single Display

- Problem with a single-tracked projection (stereo or mono): only the viewpoint of the tracked users is correct, only she will see a correct image!
- Example:

Image's perspective is correct for the user



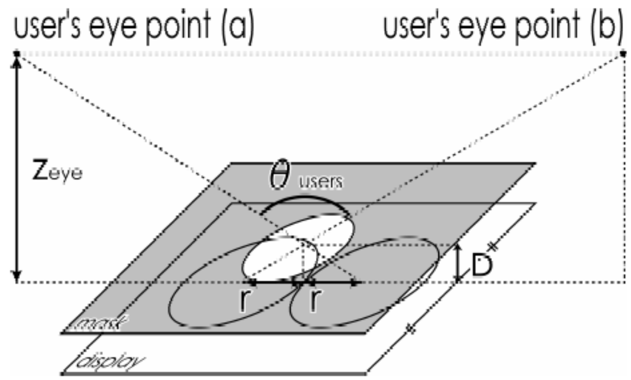
Image's perspective is correct for the (real) camera

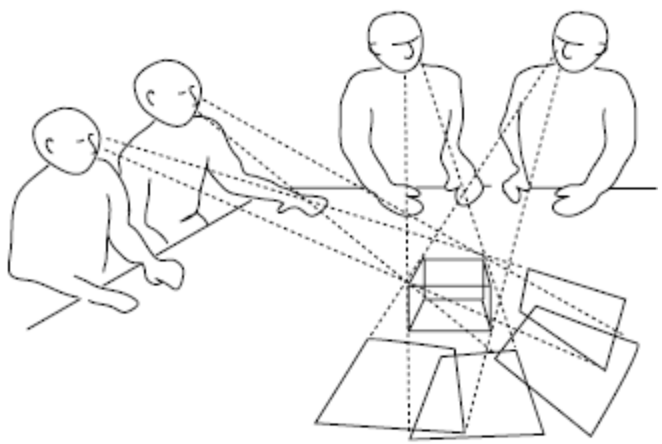
# Correct (Stereo-)Projection for Multiple Users

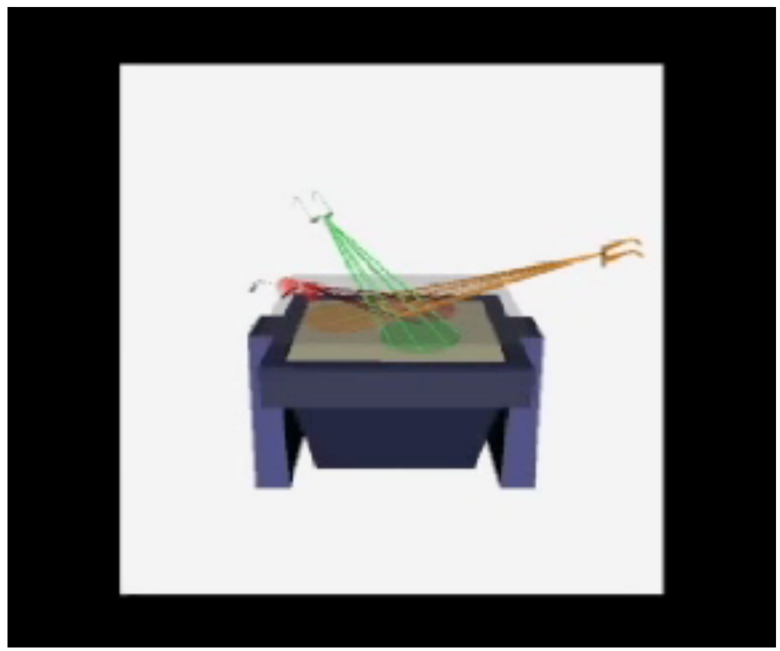
- Probably only possible for a small number of users
- *Temporally multiplexed*:
  - Framerate for multi-user stereo = Framerate for mono * 2 · #User
- Infitec for several users:
  - Each user gets glasses with slightly shifted comb filters
  - With *n* users we need 2*n* different comb filters → extremely narrow bands
- *Spatially multiplexed*
- Combination of the above

# Spatial Multiplexing

- Proj. surface is partitioned among users
- Consequence: interdependence between
  - Size of the *view frustum*
  - Working volume of users
  - D & radius of hole
- Example:



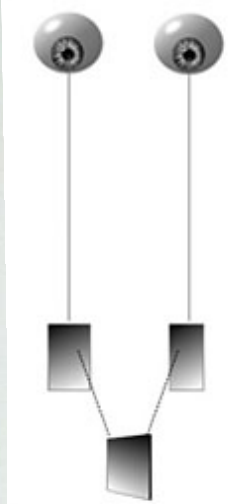





IllusionHole @ Siggraph 2001

# Example Stereogram

- The following image appears to be 3-dimensional, if you can decouple focus (=accomodation) and convergence (you have to scale the slides so that the statues are about 5 cm apaprt)

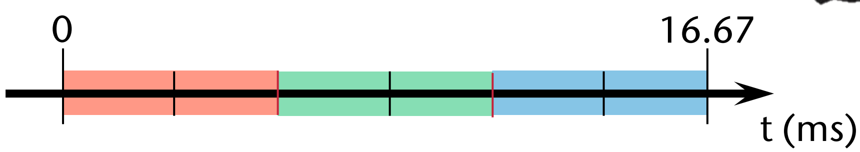



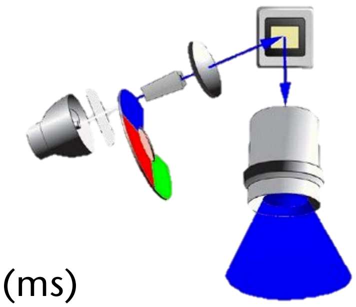
Postcard from 1868

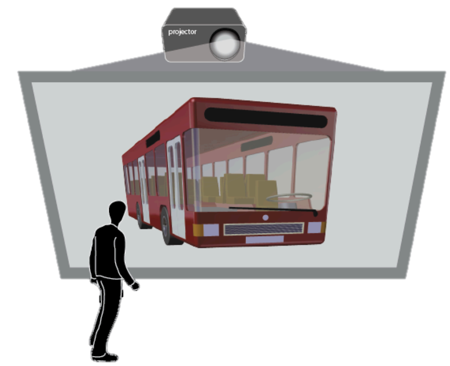
# Stereo for 6 Users

[2011]

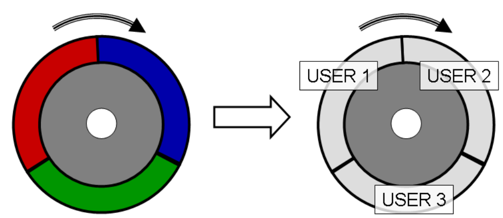
- Combination of active and passive stereo, plus ingenious utilization of time-sequential projectors
- Recap from CG1: time-sequential RGB with DLPs





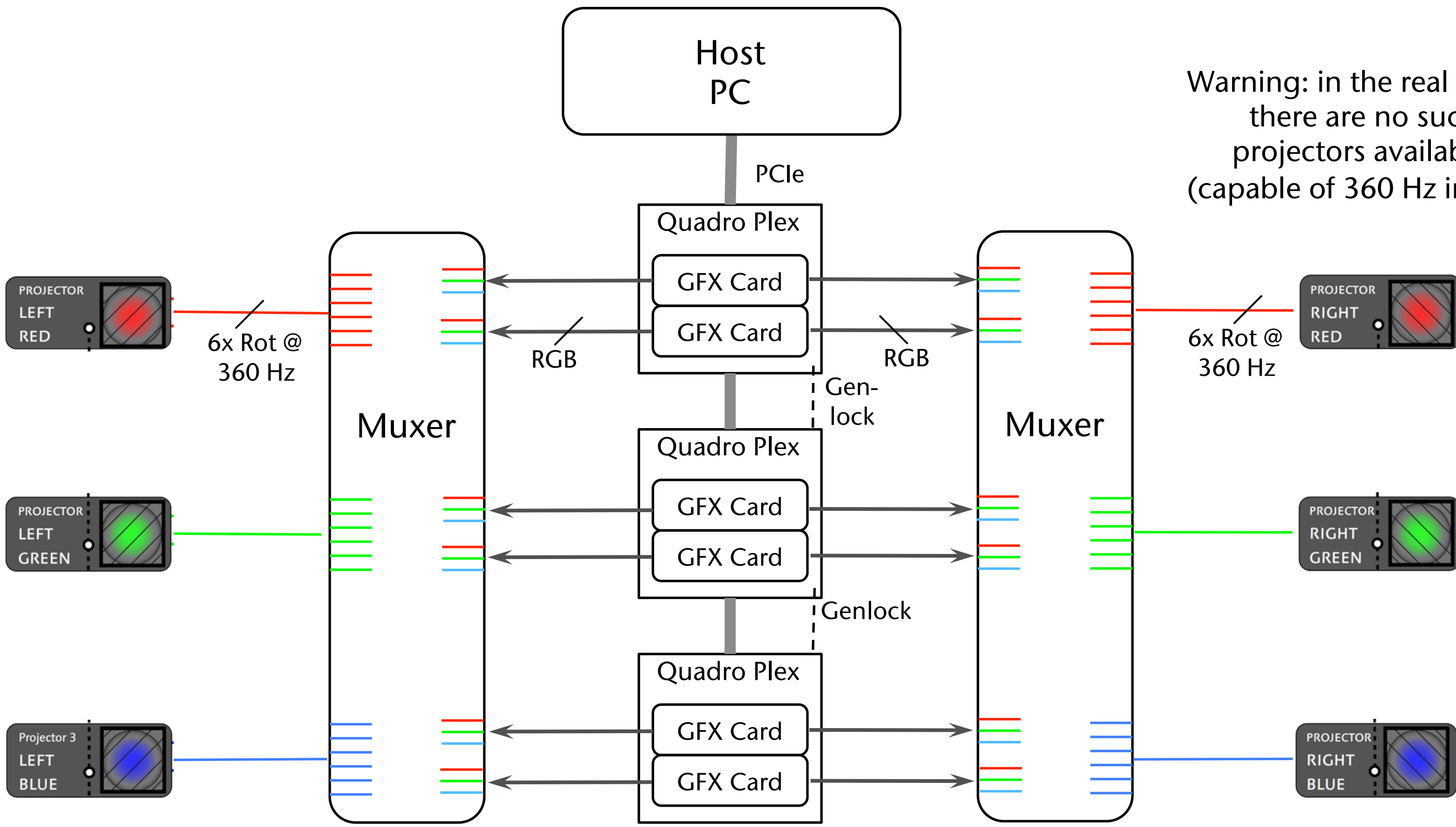
1. Modification: remove color wheel
2. Modification: each user gets shutter glasses that additionally has left/right polarization filters
   - Must be fast enough to prevent cross-talk!





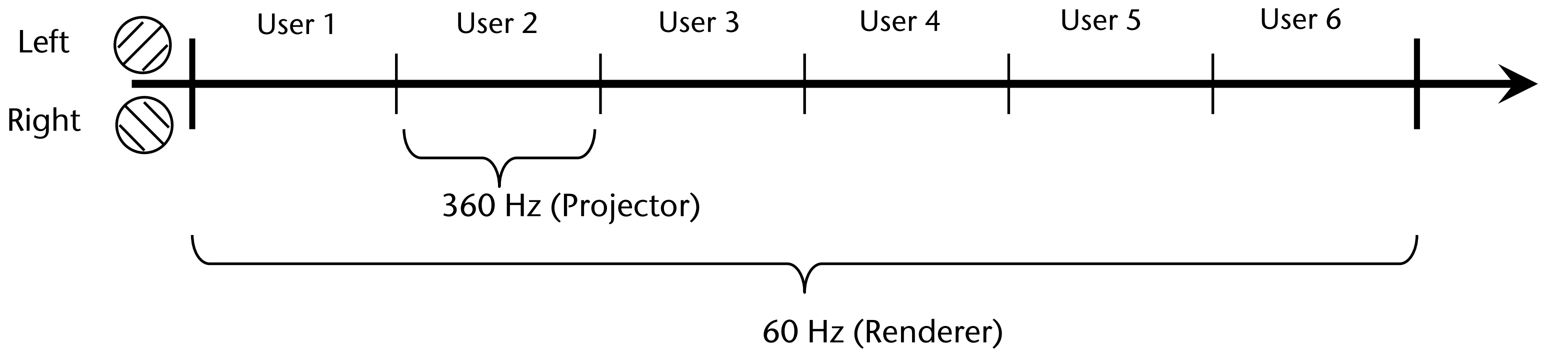
# The Hardware in *Principle*

- 6 stereo video streams are generated by 6 graphics cards in 1 PC
- Distribution of the video streams to 6 projectors via multiplexers




Warning: in the real world, there are no such projectors available! (capable of 360 Hz inputs)

- Timing:



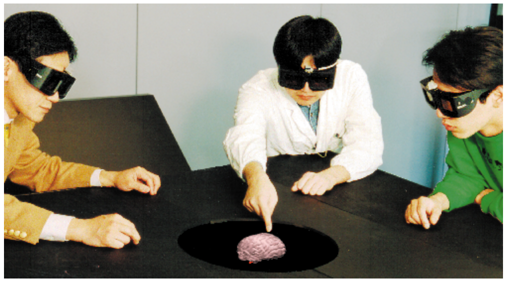

- Video:

# Outlook

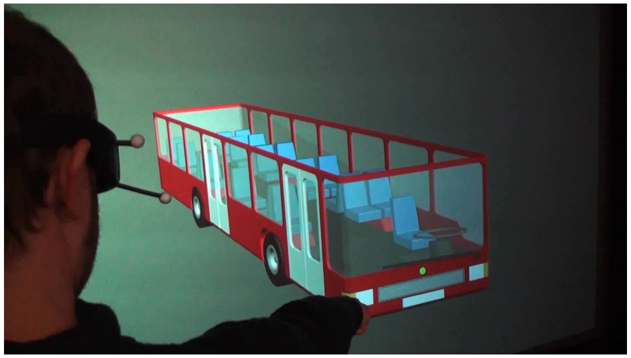
- With *perspectively correct* projections for *each* user, the shared 3D space will become coherent for all users
- Consequence: direct communication (including *pointing!*) in co-located CSCW is possible

Agrawala et al. 1997


Arthur et al. 1998

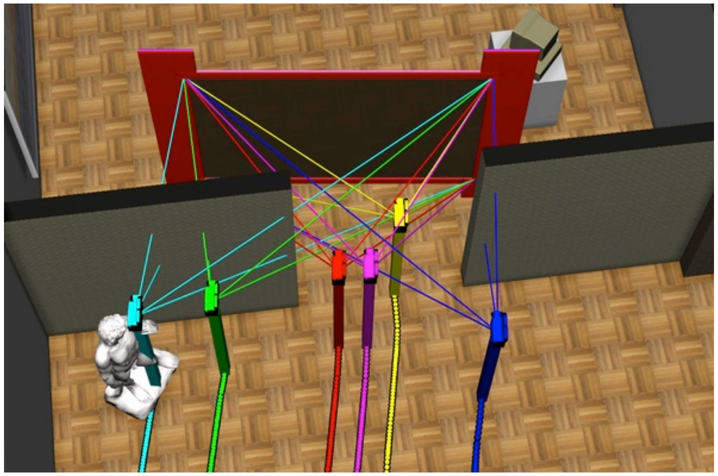

Kitamura et al. 2001

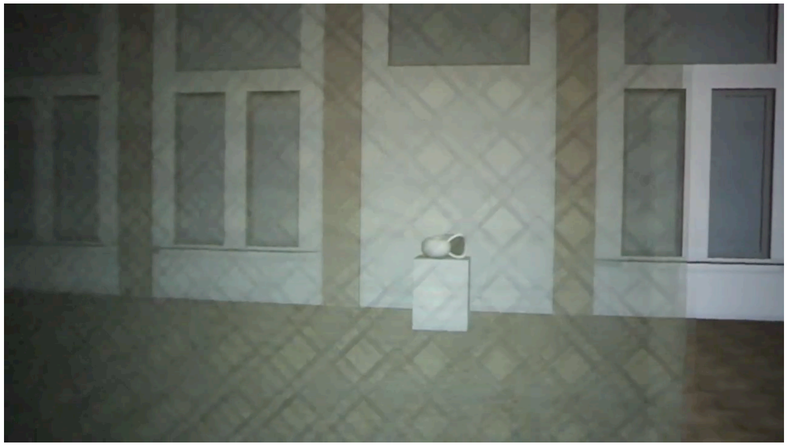

Agócs et al. 2006



# Interaction Issue with Multi-User-Stereo

- Navigation: the "navigator" controls the path for all users (and he sees only his own viewpoint!)
- Problem: the other users' viewpoint goes through walls
- Solution:
  - Adjust the paths of the other users automatically to bring them closer to the navigator's viewpoint
  - Fade away obstacles in the path of each user





# Autostreogram (Single Image Stereogram)

- "Magic Eye" images are constructed patterns such that corresponding points convey depth

Underlying "depth image"

# Stereoscopic Effect Based on the Pulfrich-Effect

- See slide "Pulfrich Effekt" in *Optische Täuschungen*

## Der Pulfrich-Effekt

- 1922 entdeckt von Carl Pulfrich, deutscher Physiker
- Basis: dunkle Lichtreize lösen etwas später ein Signal aus als helle
- Beispiel: Video mit einer Sonnenbrille über *einem* Auge betrachten

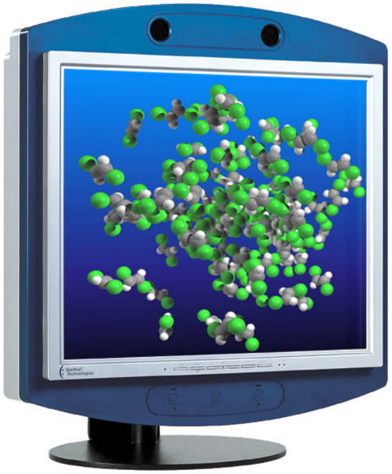

http://www.youtube.com/watch?v=1mnWl_u_zBg

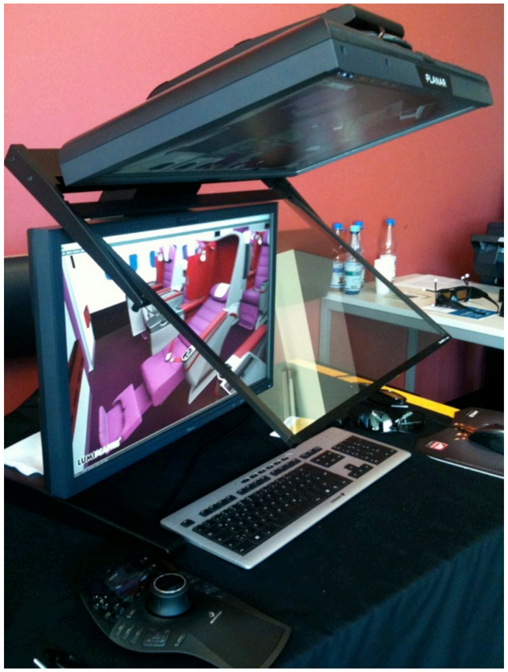
# The Kinds of Immersive Displays

- Autostereo Monitor
- *Head-Mounted* Displays (HMDs)
- *Head-Coupled* Displays (HCDs)
- *Immersive projection* displays (IPDs)
  - *"Powerwall"*
  - *Workbench*
  - *Cave*
- "Exotic" displays:
  - Retinal displays
  - Holographic displays
  - ...

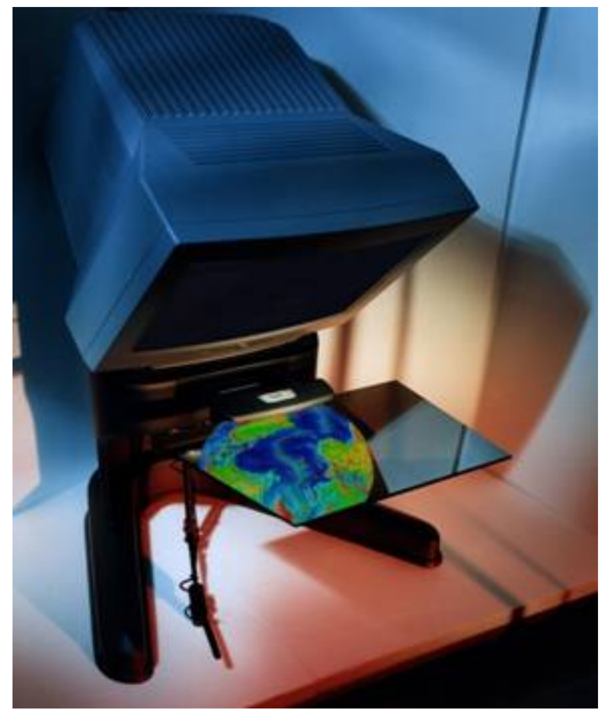
# Stereo Monitor (mostly Autostereo)

- Sometimes called "*Fishtank VR*"
- Advantages:
  - Inexpensive
  - Resolution up to 1900 x 1600
  - Well accepted by users
  - No special requirements on the environment/setting
  - Some 3D capabilities
- Disadvantages:
  - Small Field-of-View (FoV)
  - No immersion
  - Very limited working volume
  - "*Stereo frame violation*" is very common

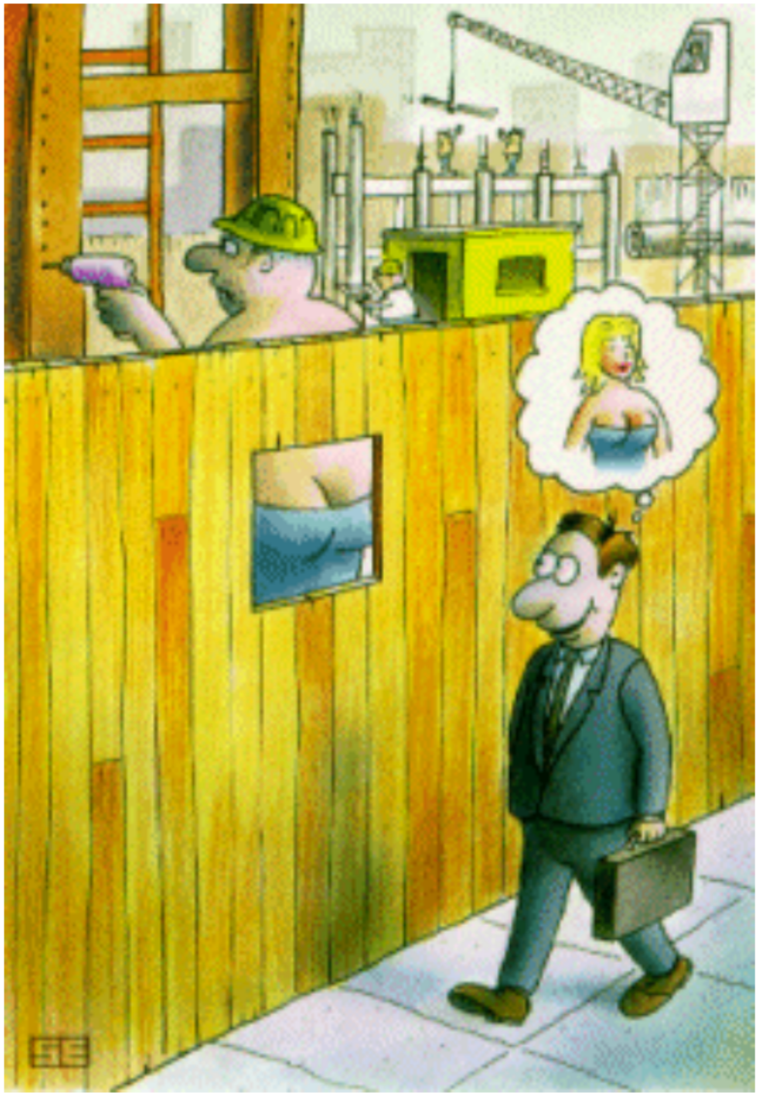




- Interesting things you can do with a simple monitor: the "Reachin-Idea"

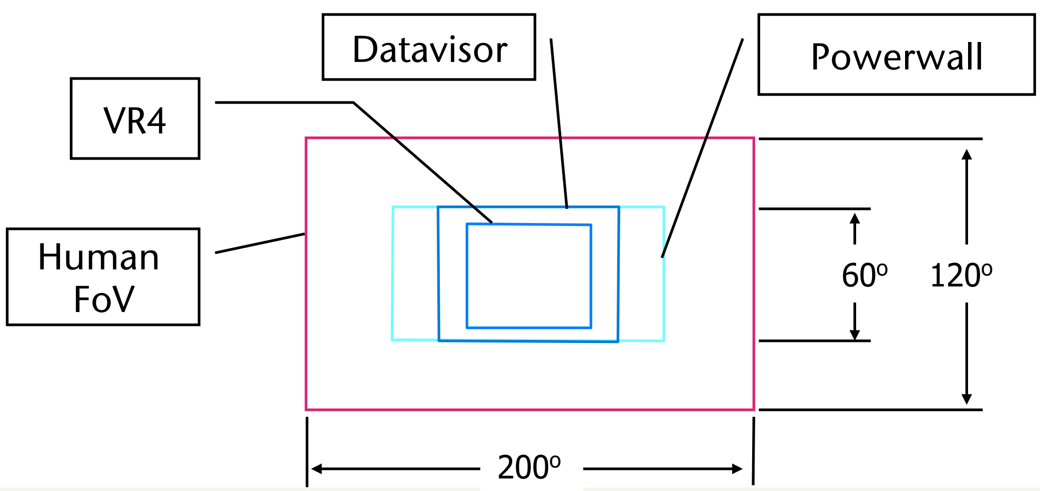
- The problem with a small FoV: there is no immersion!



# Head-Mounted Diplays (HMD)

- First "true" VR display
- Technologies / characteristics:
  - HMDs using LCDs (sometimes CRTs)
  - Weight:
    - Small FoV → lightweight; large FoV → heavy
- Advantages:
  - Kind of "surround display"
  - Very good immersion
  - No "*stereo frame violation*"
  - Large working volume
  - *Low-end models* are inexpensive
  - Almost no special requirements on the working environment

- Disadvantages:
  - Uncomfortable when used for a prolonged time ("*invasive interface*")
  - Distortions
  - Real environment is shut off (good for immersion, bad for collaboration and self-embodiment)
  - Manipulation of real controls is difficult (e.g., in mockup of cockpit)
  - Every participant needs an HMD (bad: expensive, good: everybody has correct perspective in VE)
- Actually, HMDs hve been invented a long time before "VR"

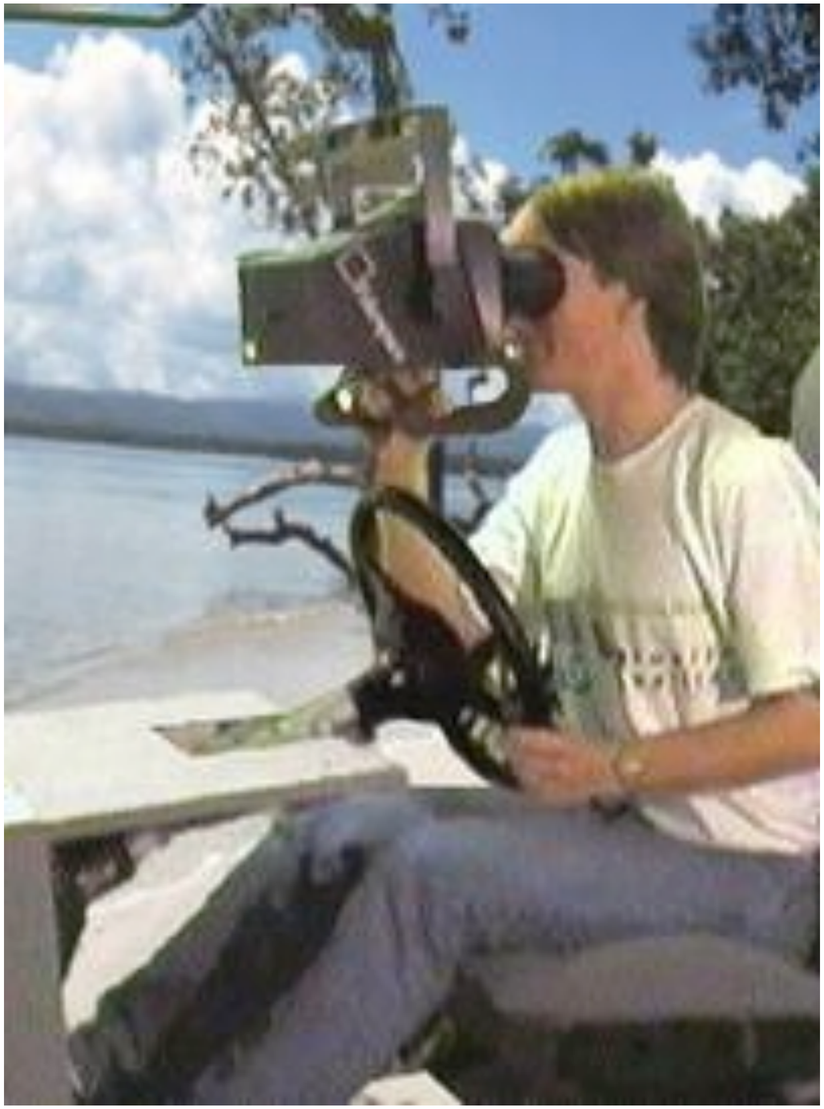



*Bell Helicopter, 1967*

# Head Coupled Displays (HCD)

- HCD = HMD mounted on a "boom"
- Advantage of HCDs over HMDs:
  - Possible to quickly "take the display off" for a moment; or users can just take a "quick peek" into the VE
  - Low weight on the head
  - Extremely good tracking comes built-in
- Disadvantages compared to HMDs:
  - Smaller working volume
  - One hand is always occupied
  - Inertia

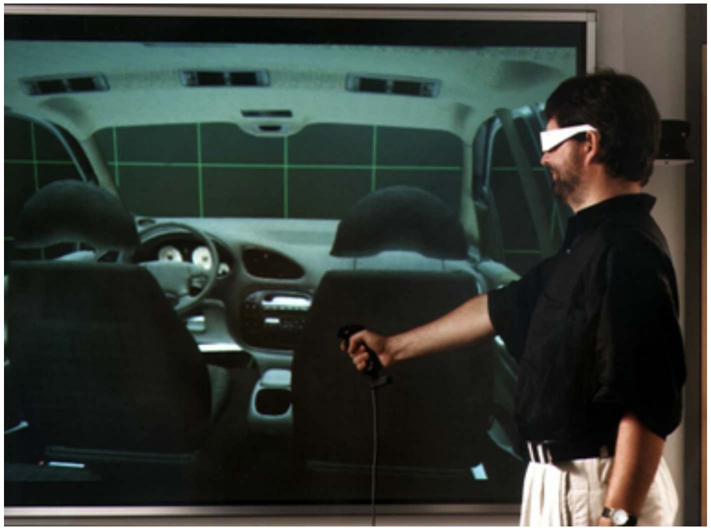
→ Failed to gain market share



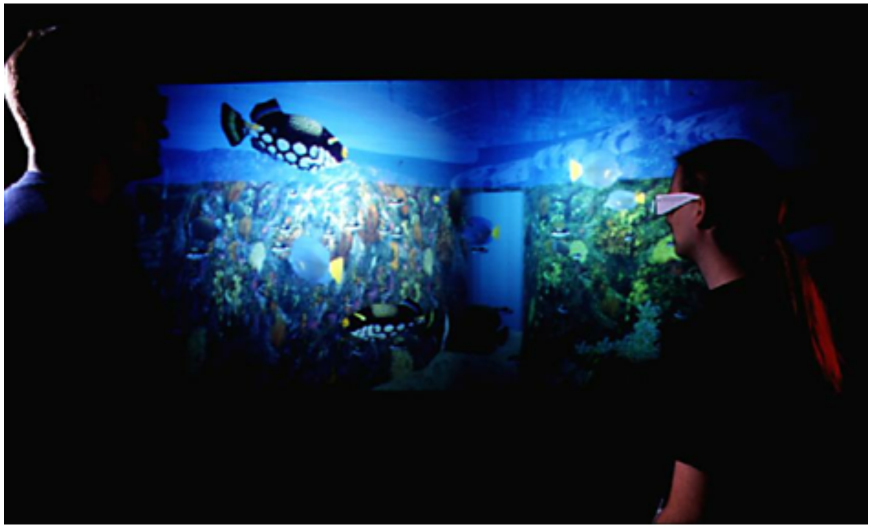
# Immersive Projection Displays / Technology (IPD / IPT)

- Idea is (somewhat) similar to cinema theaters
- Setup: 1–6 walls on which VE is projected
- *Powerwall* = 1 wall (e.g., 3x6 meters)
- *Workbench* = 1 horizontal display surface (table)
- *Holobench, L-Shape* = 2 display surfaces, 1 vertical, 1 horizontal
- *Cave* = 3–6 walls

# Powerwall

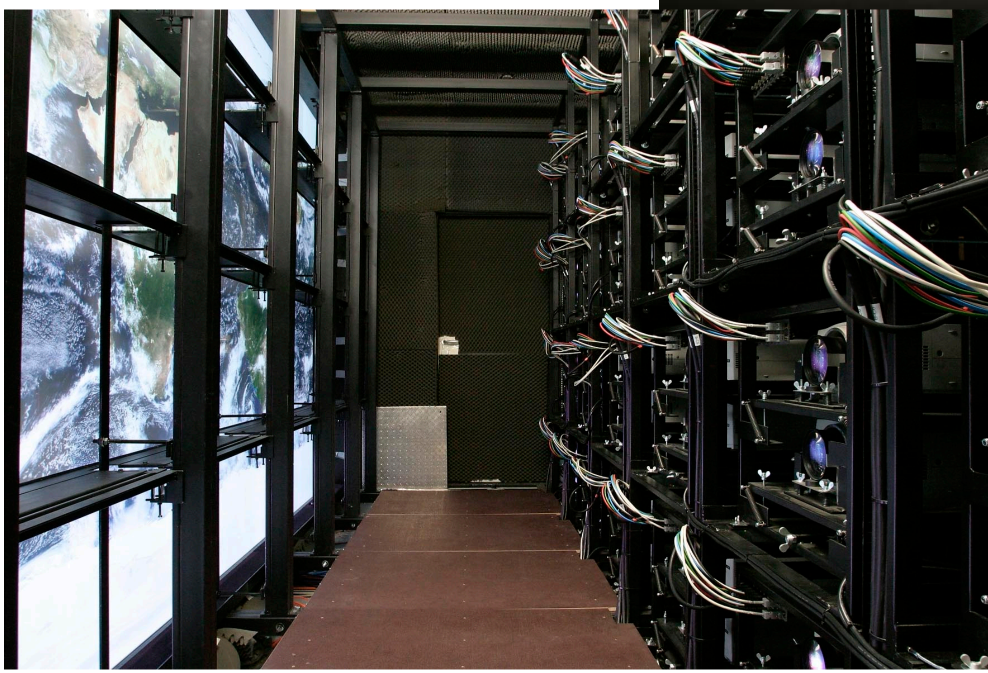


*Powerwall with back projection*

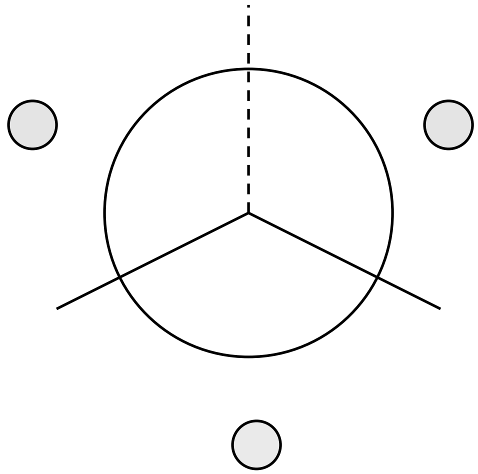


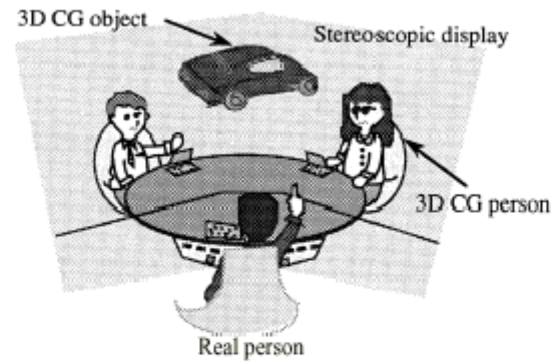
*Powerwall with front projection,*
*(problems with that: edge blending, hot spots)*

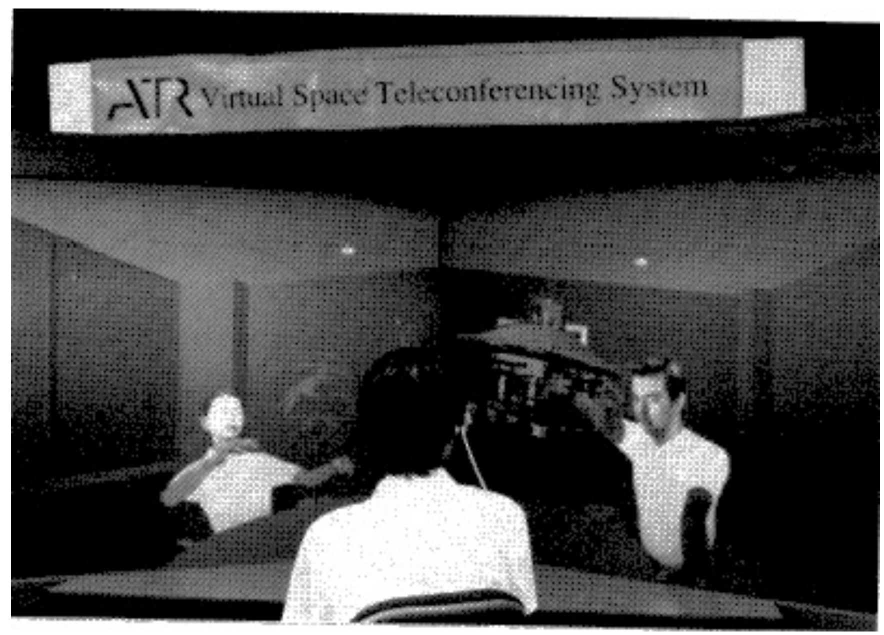
- "*HeyeWall*", Darmstadt:
  - 24 tiles, 48 PCs
  - Total resolution: 18 Mio pixels (6144 x 3072) in stereo



# Example Application: Virtual Conference Room





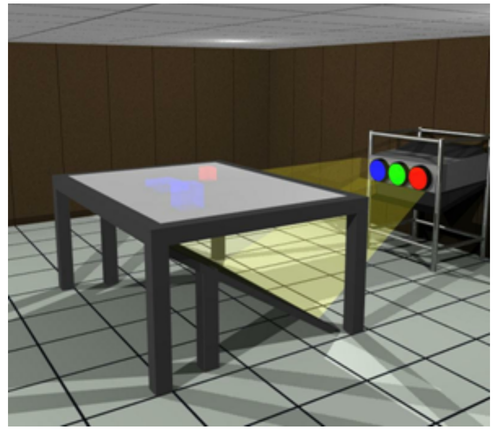




Result: *1 shared workspace*,
by way of coherently adjoining
"desktop IPD"

# Workbench, L-Shape, etc.

*Workbench*

*Principle of the workbench*

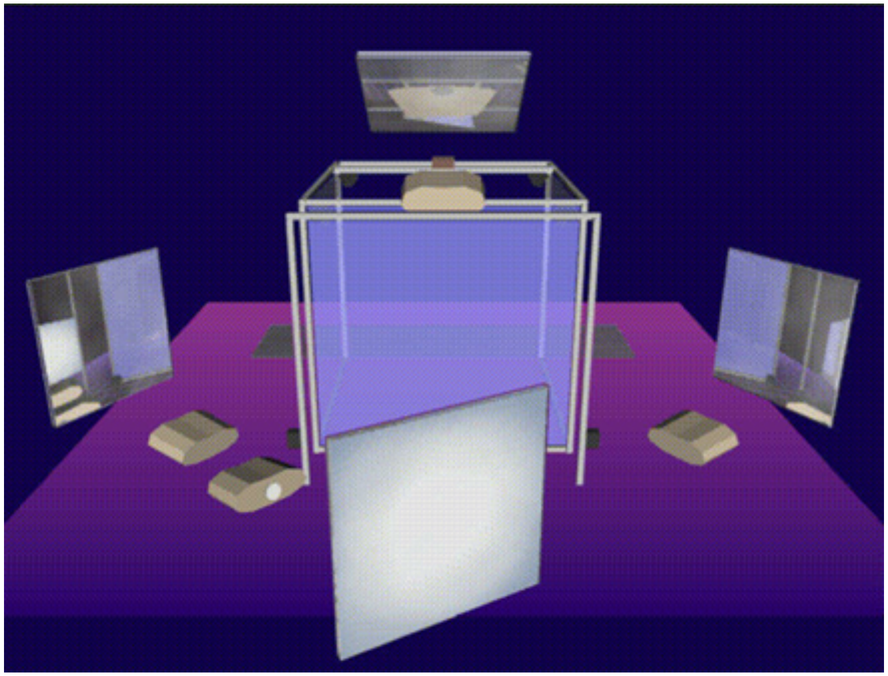


*Tilting "workbench"*

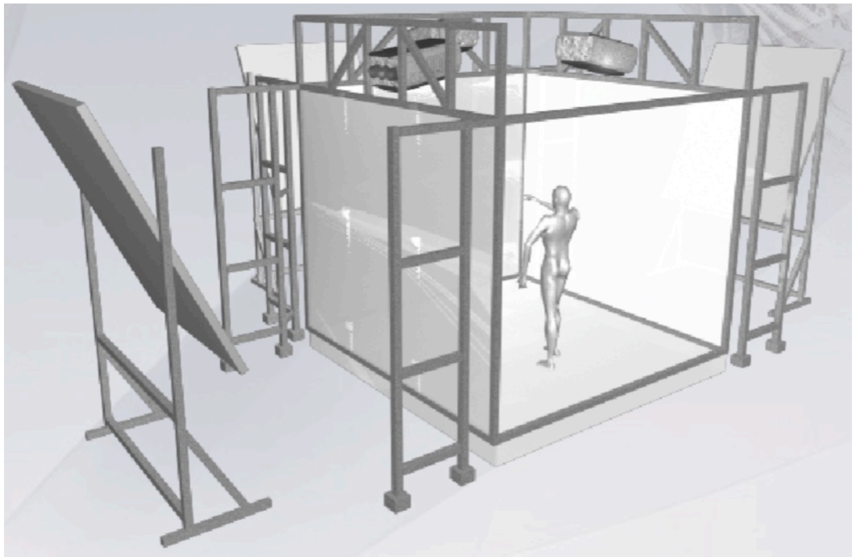

*Holobench*

# Cave

*3-wall cave*



*Schematic of the arrangement of the mirrors*

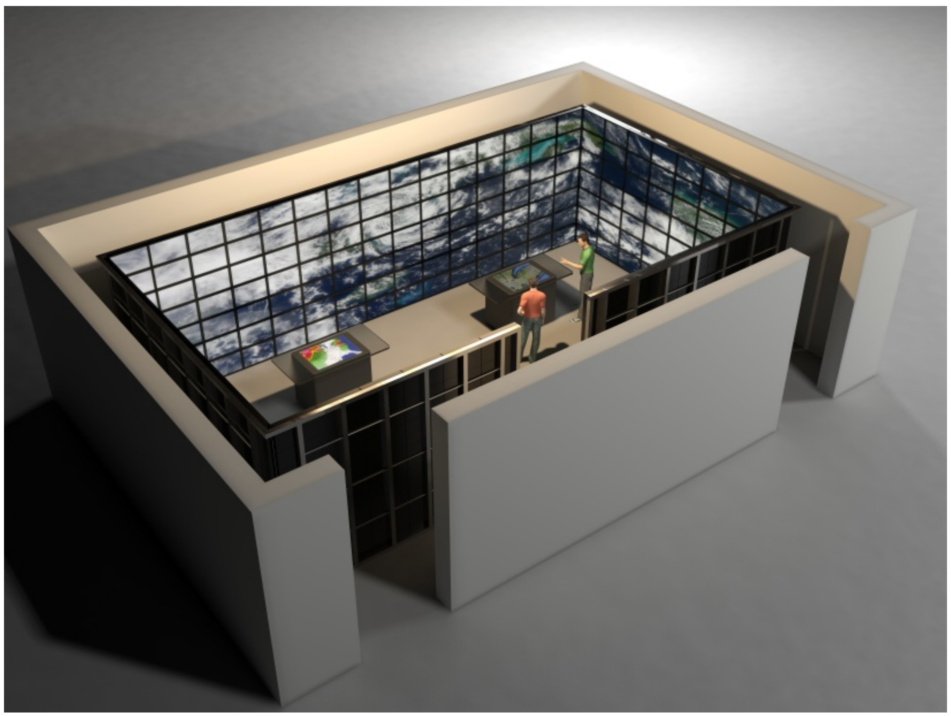


5-wall cave, FhG-IGD, Darmstadt

6-wall cave, Alborg, DK

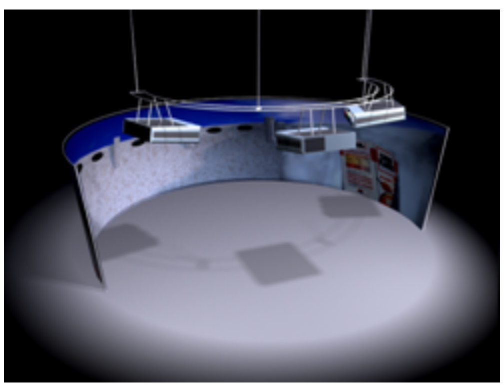
# RealityDeck - Immersive Giga-Pixel Display

- 308 x 30" LCD displays
- 2560x1600 resolution per display
- 1.5 Giga pixels of resolution in total
- 40'x30'x11' physical dimensions
- 85 dual quad-core, dual-GPU cluster nodes



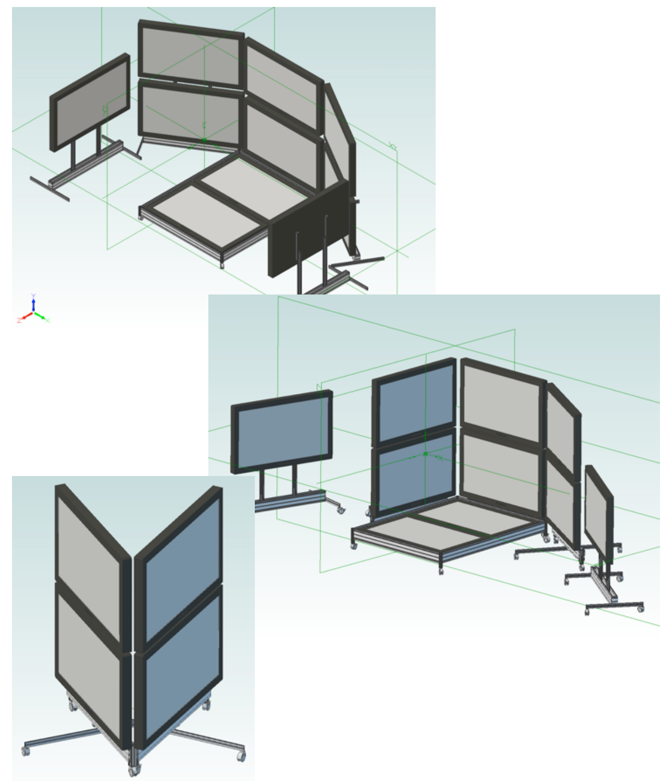
http://www.cs.stonybrook.edu/~realitydeck/

# Curved Screens



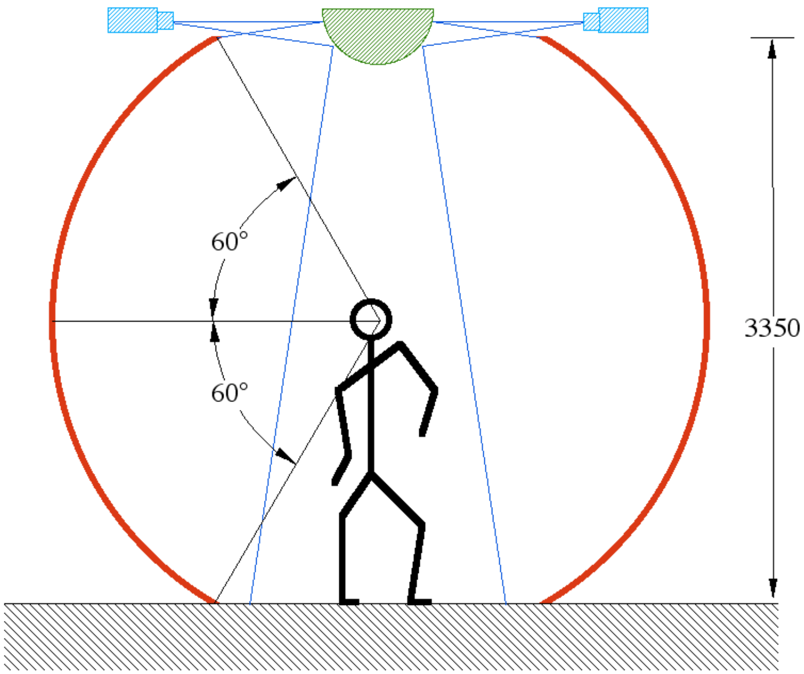
# Curved Screen made out of 3D-TVs

- Idea: construct the walls of a Cave out of a (small) number of 3D TVs
- Advantage: reconfigurable relatively easily (just put the walls on wheels)



# Personal Domes

- Example: Wii + Dome + MacBook Pro




Source: Paul Bourke, University of Western Australia, http://local.wasp.uwa.edu.au/~pbourke/

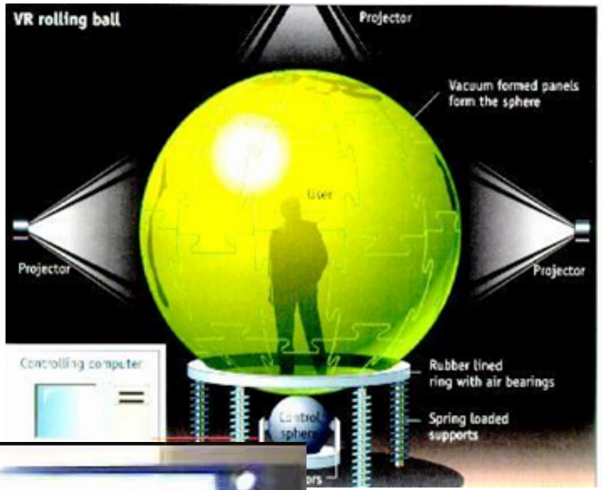

GIZMODO

- A modern "Sensorama":

*Immersa-Dome* from Aardvark Applications

Bremen

# VirtuSphere




Studie


www.virtusphere.com

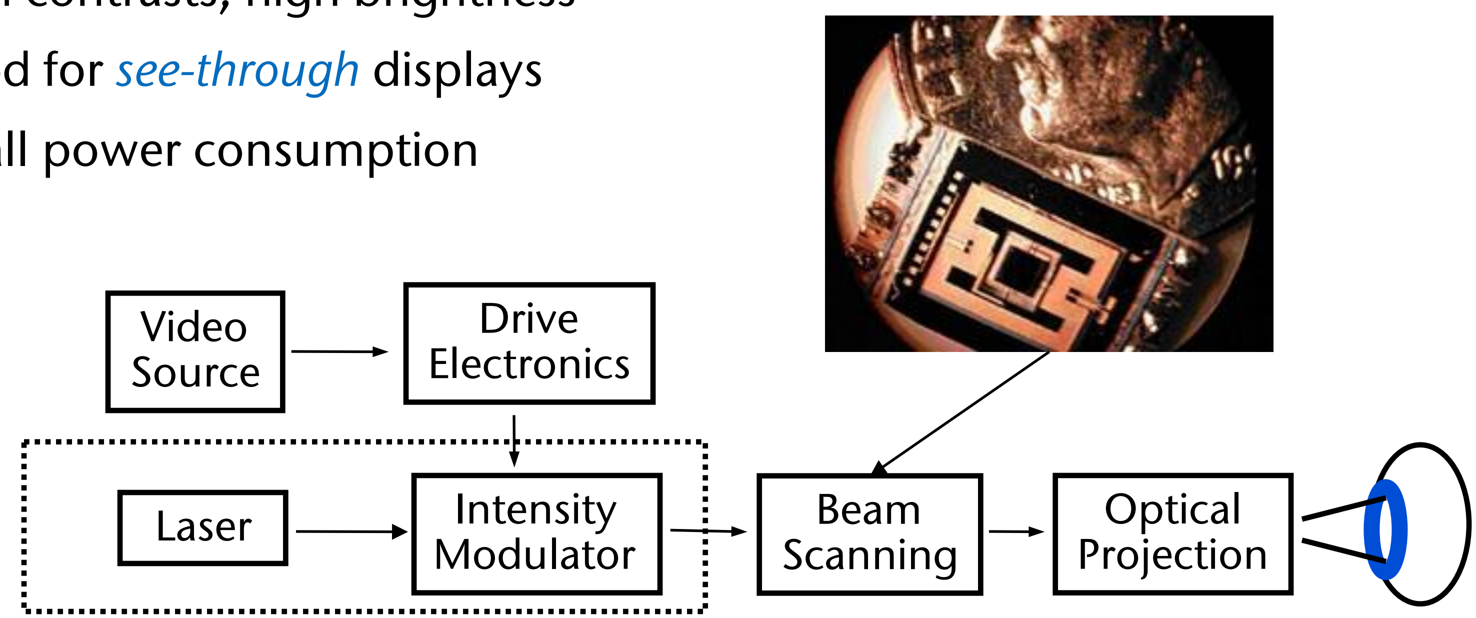

SPIEGEL ONLINE

# Advantages and Disadvantages of IPDs

- Advantages:
  - Large resolution
  - Large *field-of-view*
  - "*Non-invasive*"
  - No isolation of the real world
  - (Can accomodate Several Users)
  - *Cave*: turning the head results in small changes of the images
    → problem of latency is reduced / not so prominent
- Disadvantages:
  - Size
  - Price (lots of projectors, lots of graphics cards)
  - Precision, calibration
  - Potentially "*stereoscopic violation*"
  - Correct view only for one *viewer* (unless a massive amount of hardware is used)

# Retina Displays (retinal displays)

- Idea:
  - Use the human retina as the display surface (all images from the outer world end up there anyway)
  - Use a laser to write the image by scanlines into the eye
- Advantages:
  - Can be miniaturized (potentially)
  - High contrasts, high brightness
  - Good for *see-through* displays
  - Small power consumption



*Retinal display*


*Design study*

# Holographic / Volumetric Displays

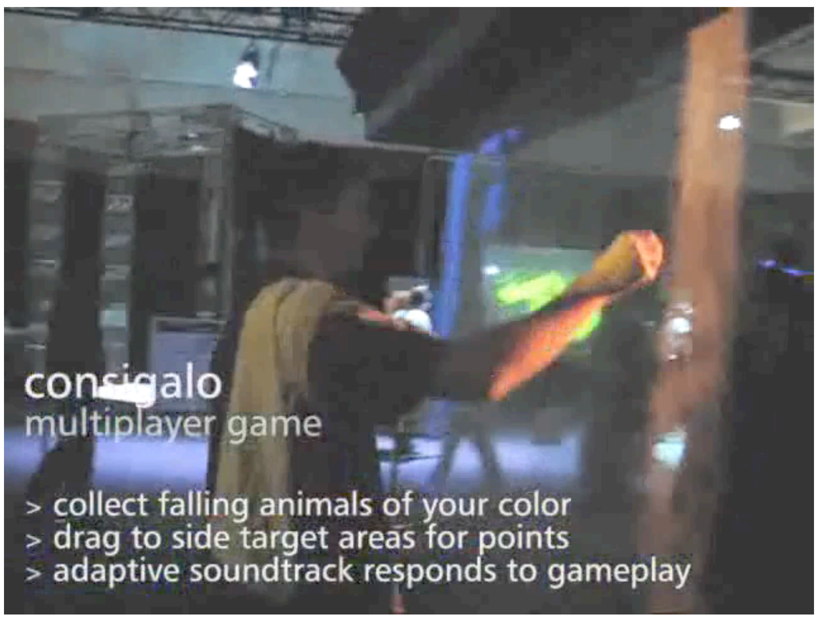
- Real 3-dimensional displays
- Advantages:
  - Provide correct perspective/view from *every* angle!
  - Coherence between accomodation and convergence
  - Depth of field (Tiefen(un-)schärfe)
- Holographic displays: algorithmic computation of holograms
- Problems:
  - Staggering amount of computational work
  - Colors
- Volumetric displays: voxel are projected into a volume (as opposed to a surface)
- Problems:
  - Size of data (e.g. 100 mega-voxels = 1000x1000x100 display resolution)
  - Occlusions?

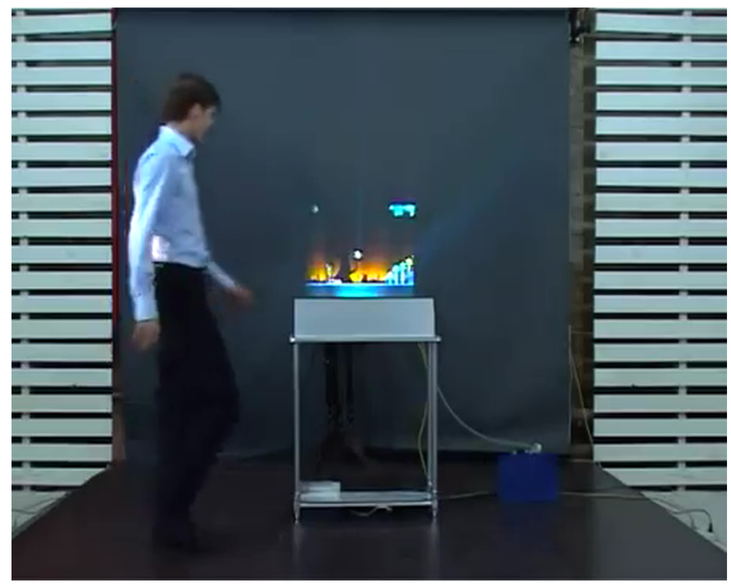
- Example volumetric display:
  - 198 x 768 x 768 ≈ 100 million voxels
  - Frame rate: 20 Hz

# Unusual Display Surfaces

- Fog ("fog screen"):
  - Laminar, non-turbulent air flow
  - Water droplets are "sandwiched" within the air flow
- DisplAir: dry fog

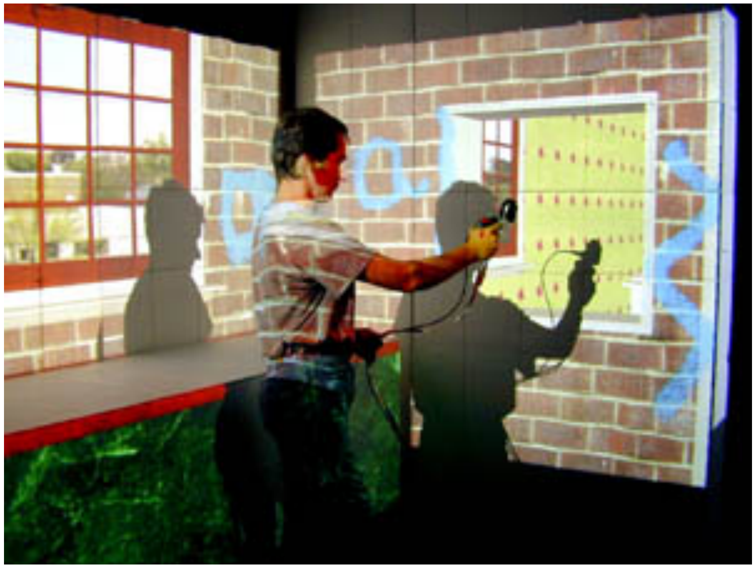
FogScreen



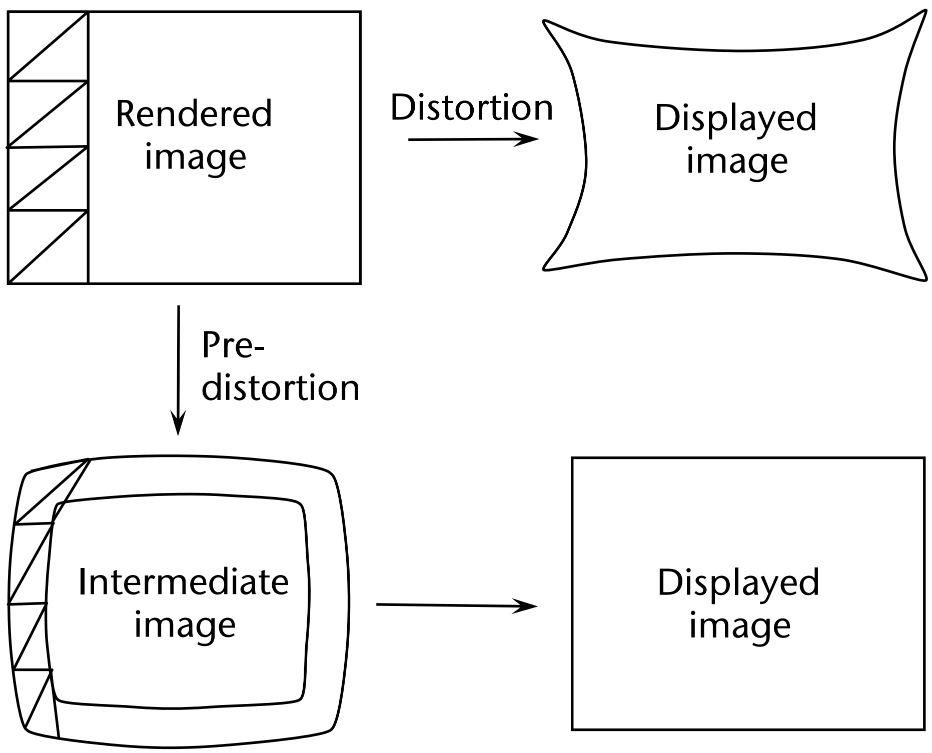
DisplAir

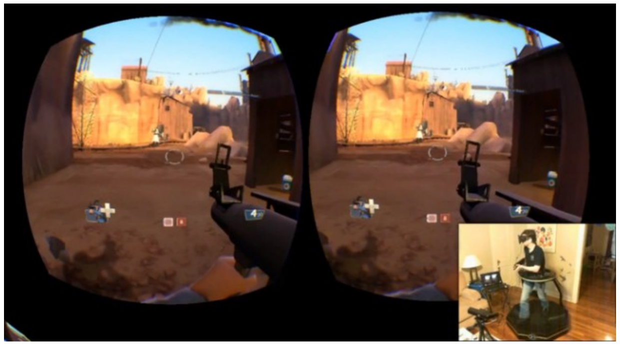
- "Everywhere displays":



# Rendering on HMDs

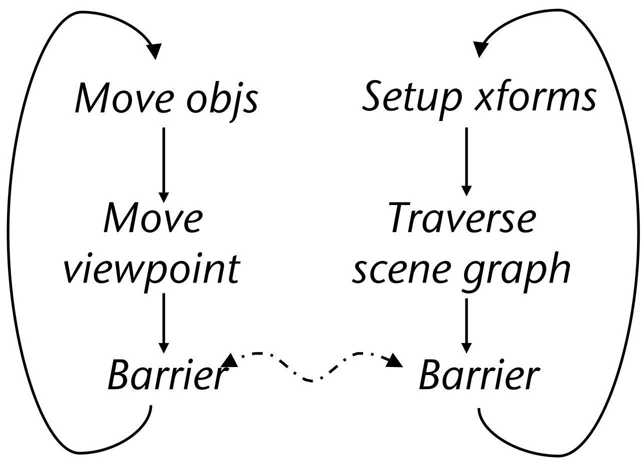
- Optics in HMDs usually cause some amount of distortion
  - Especially the Oculus Rift
- Idea: pre-distortion (using a texture)

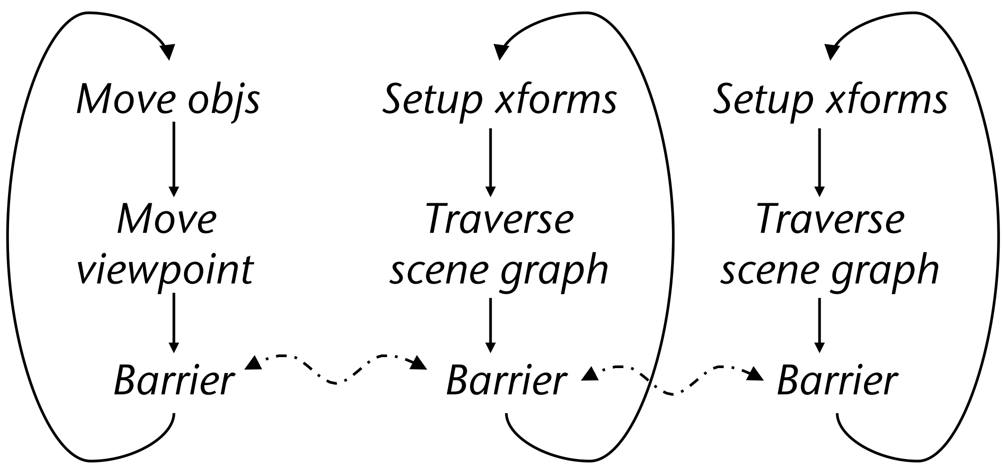


# System Overview: the Rendering Loop

- 1 processor → everything serial
- 2 processors → app and renderer in parallel
- Stereo → 2 render processes (3 proc)
- In general: *n* walls in stereo →
  - ≥ *n+1* processors, *n* render processes
  - Better *2n+1* processors



# Crosstalk (Ghosting)

- Crosstalk = if one eye (also) sees the image meant for the other eye
  - Amount of crosstalk depends on technology

# Simulator Sickness

- Simulator sickness = more or less of the following symptons (can sometimes occur with prolonged stay in flight simulators / virtual environments):
  - Nausea (including vomiting), eye strain, dizziness, drowsiness, blurred vision, headache, fatigue
- Cause is not entirely clear
- Common hypothesis: inconsistent sensory input to brain (e.g., mismatch between vision and vestibular organ (organ of equilibrium))
  - E.g., when staying below deck for a prolonged time
  - With latency between motion of platform and rendering in flight simulators
- Frequency: 20-40% with jet pilots
  - Occurs more frequently with experienced pilots than novices [sic]
- Other observations with mismatching sensory inputs:
  - In a rotating field when walking forward, people tilt their heads and feel like they are rotating in the opposite direction
  - If a person is walking on a treadmill holding onto a stationary bar and you change the rate the visuals are passing by, it will feel to the person like the bar is pushing or pulling on their hands