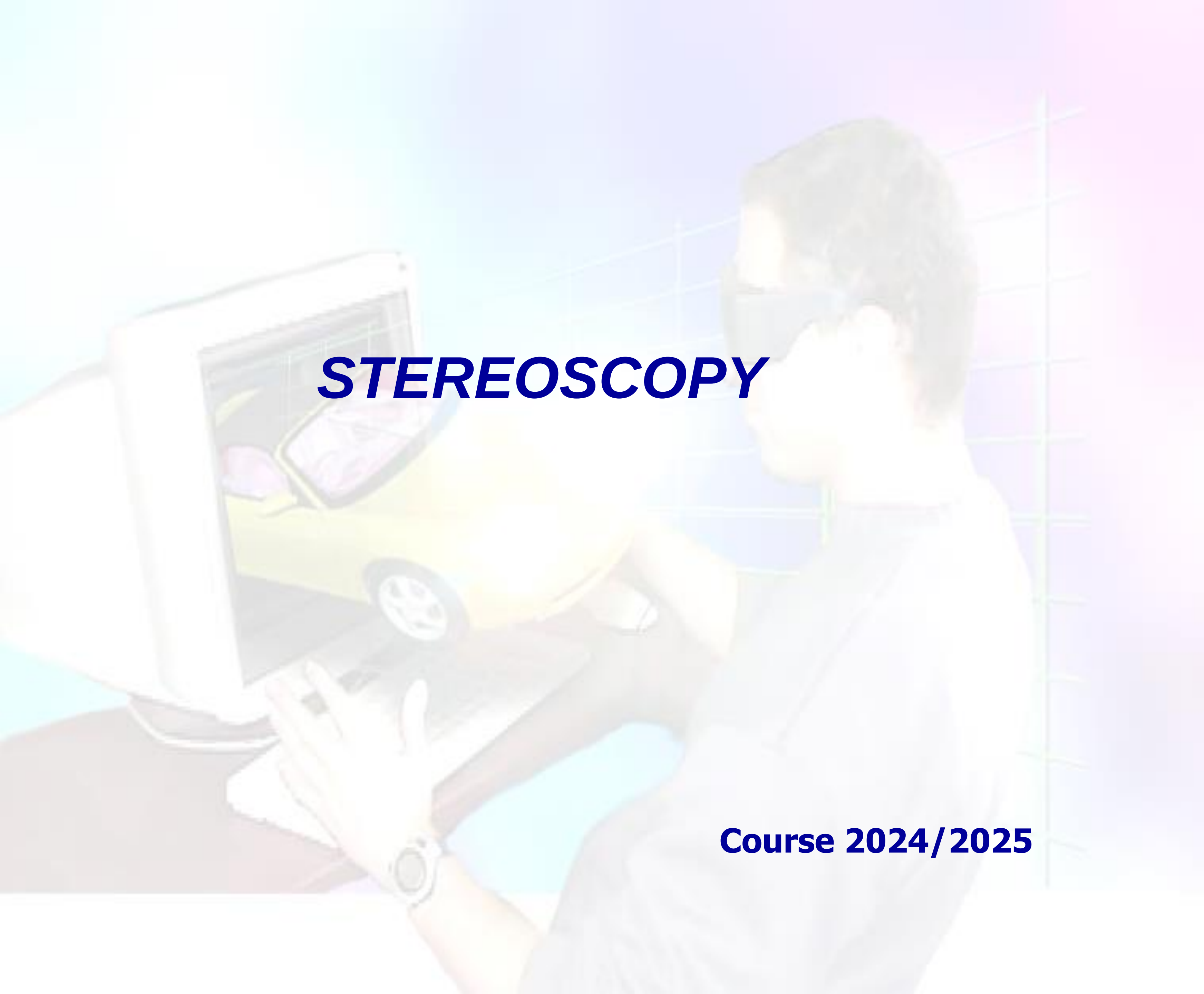


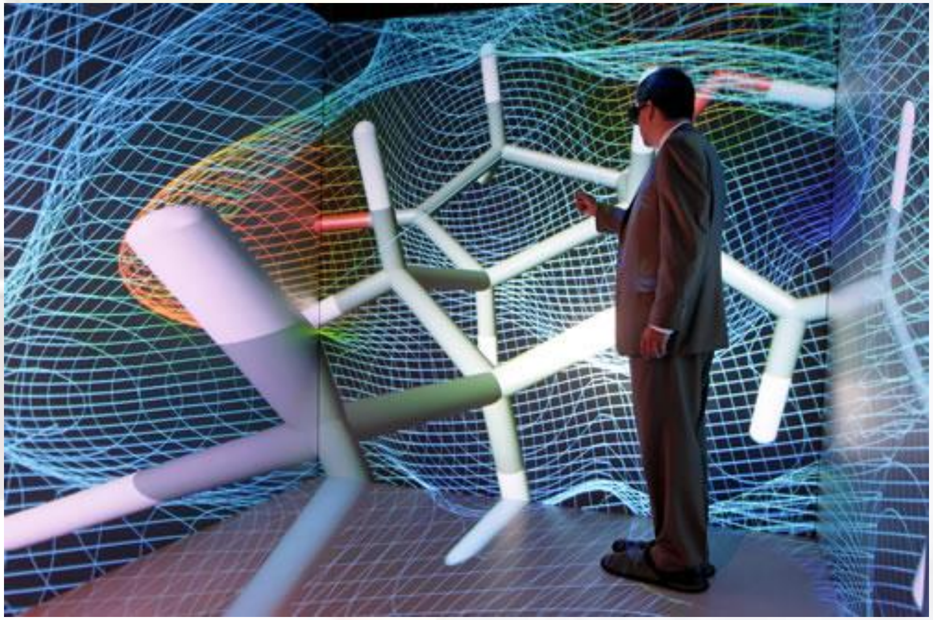
STEREOSCOPY

Course 2024/2025

Motivation

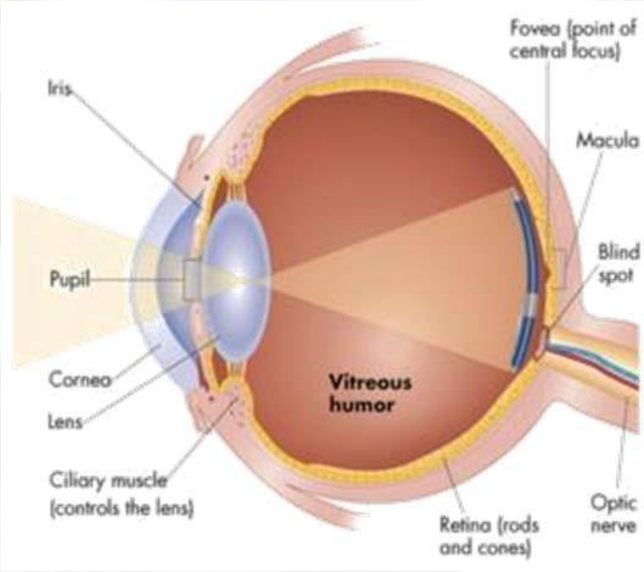
About stereoscopy

- One of the most important depth cues
- Key in all VR applications
- Influences both software and hardware
- Closely related to Human Visual System (HVS)



Depth perception

- Our retinas only capture **planar images**
- But the HVS is able to recover depth information by combining multiple **depth cues**.
- Depth cues = image features that help the HVS obtain depth information.

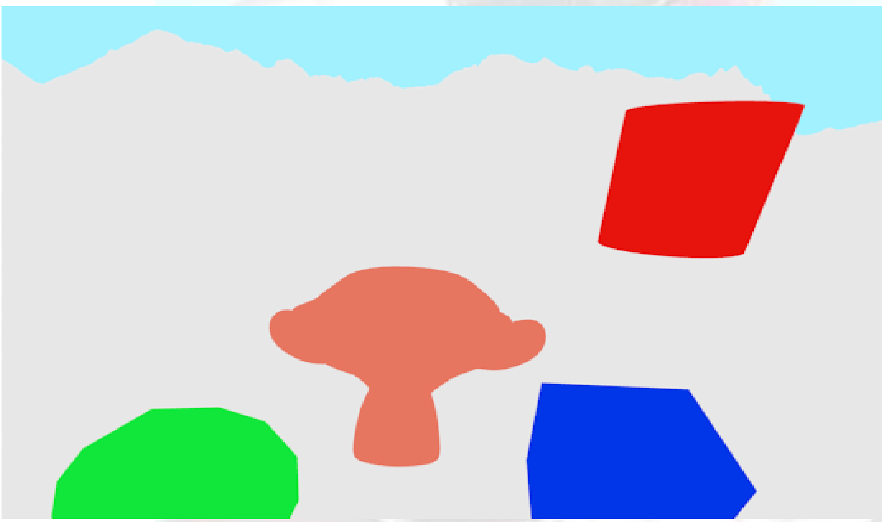


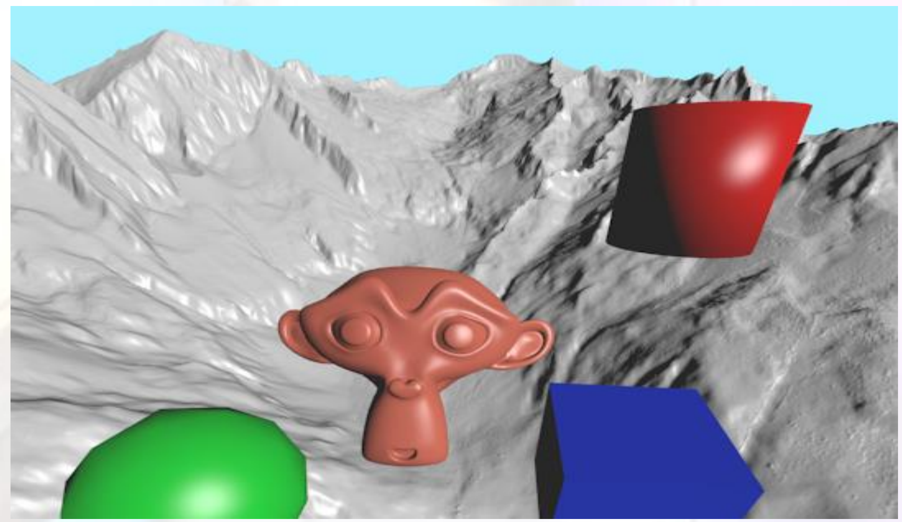
Depth cues

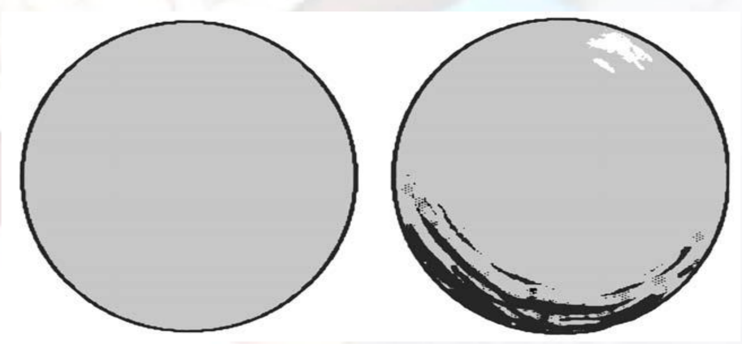
- In the real-world, all depth cues agree.
- In VR, some depth cues might disagree!
- Depth cue classification
  - Monocular
    - Shading, Shadows, Relative size, Perspective,Texture gradient, Atmospheric perspective, Motion parallax, Occlusion, Accommodation
  - Binocular
    - Convergence, retinal disparity

Shading / lighting

Shading provides shape and depth information because it largely depends on the surface orientation

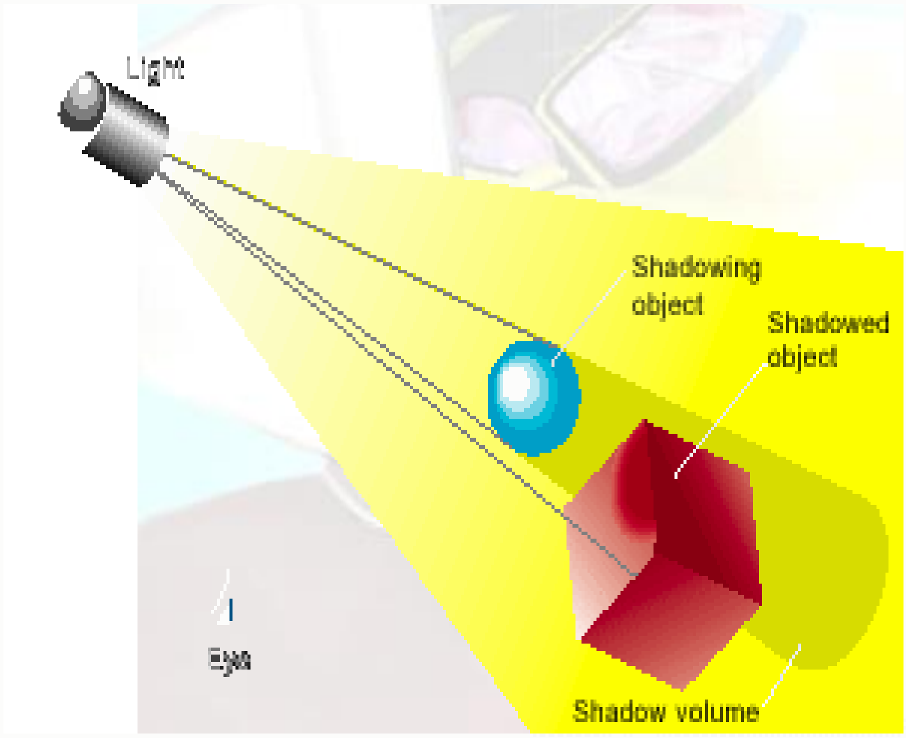




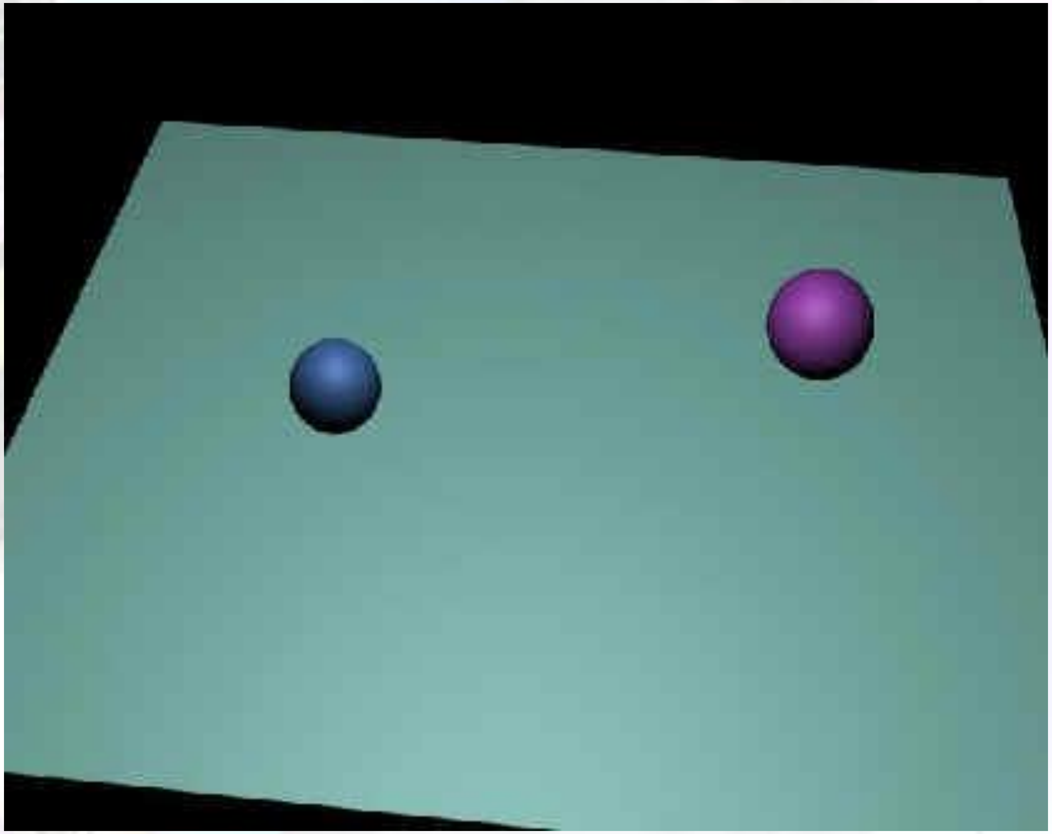


Shadows

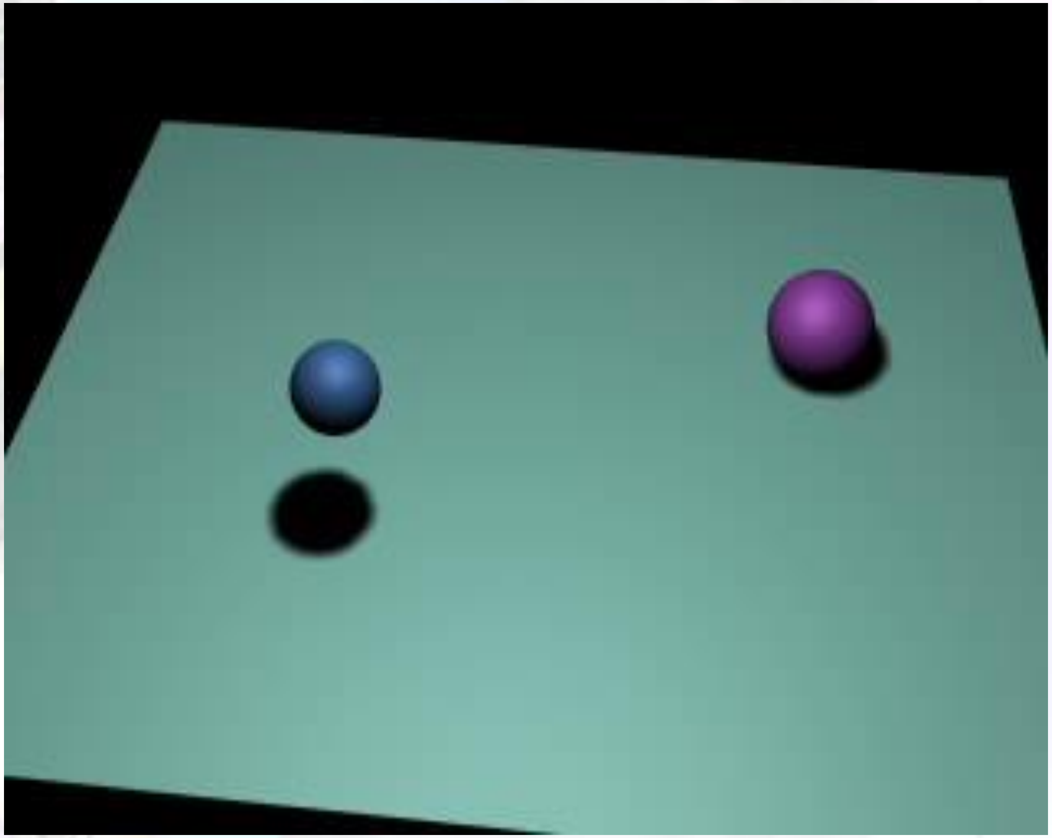
Shadows cast by objects play an important role in depth perception



Shadows

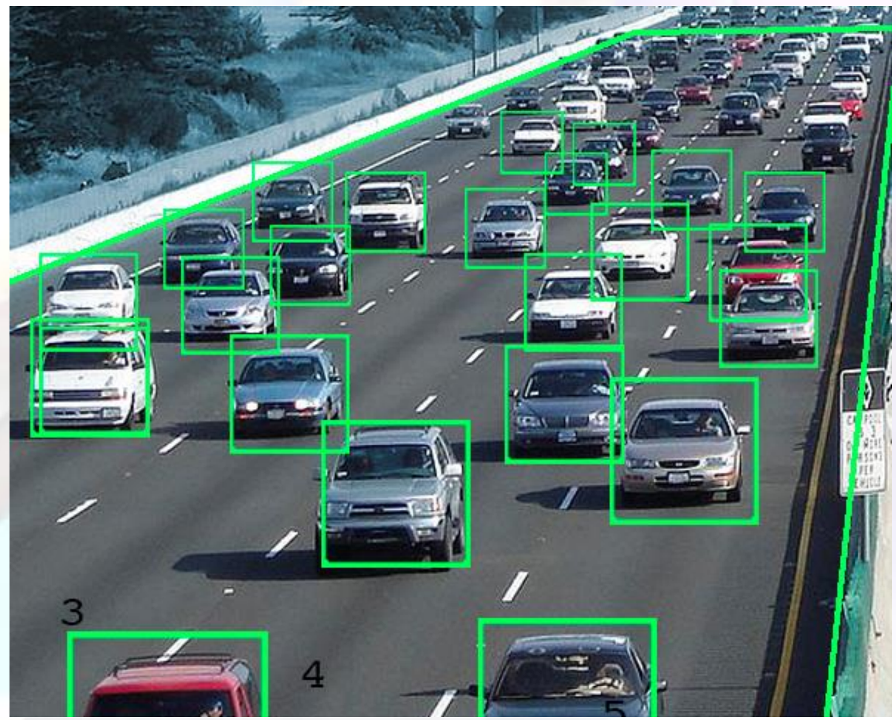


Shadows



Retinal image size

The visual system exploits the relative size of familiar objects to judge distance.



Perspective (linear perspective)

- As objects become more distant, they appear smaller because their visual angle decreases.
- Parallel lines appear to be meeting at a distant point (the vanishing point) on the horizon.

Texture gradient

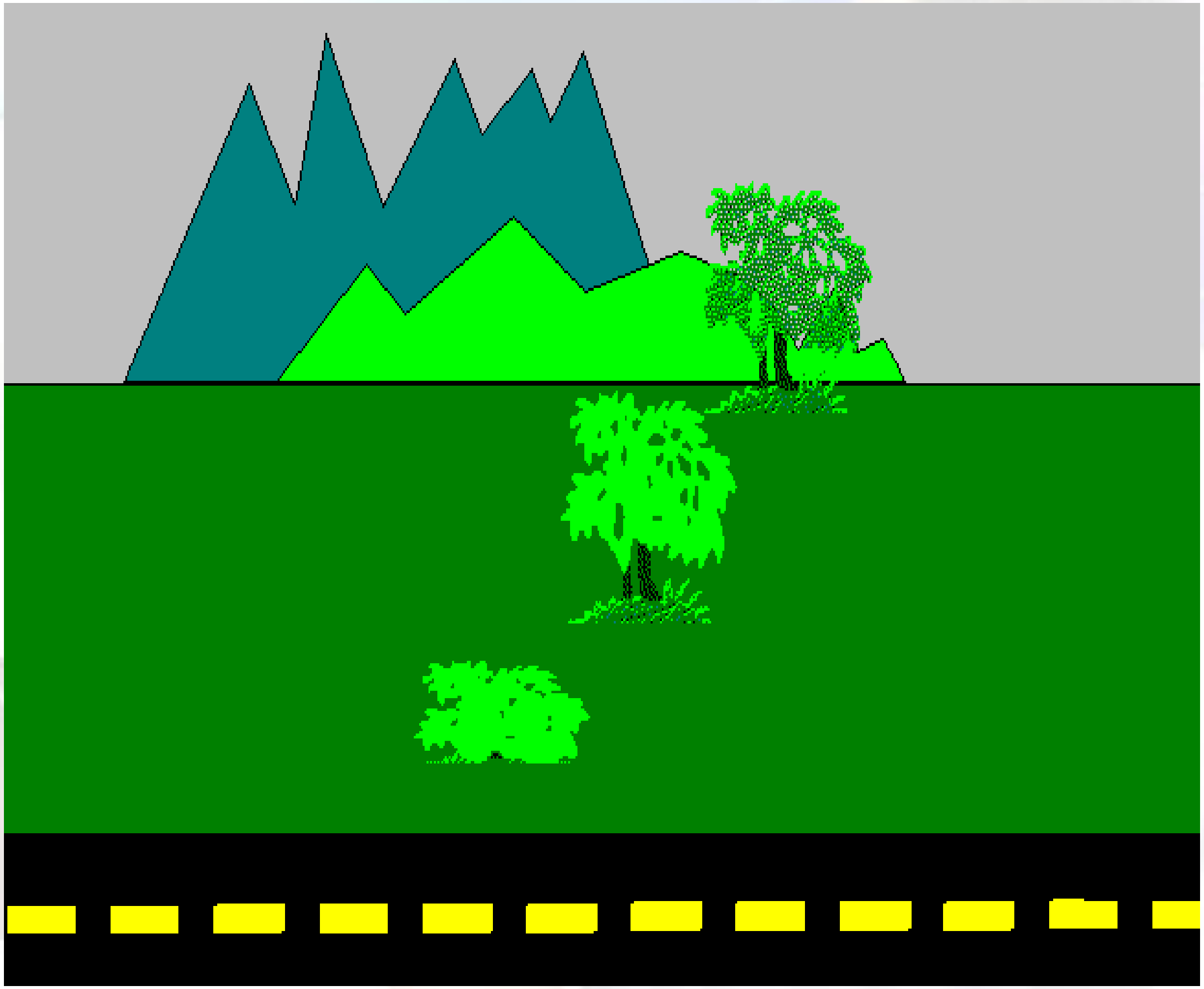
The further apart an object, the higher the spatial frequency of its texture

Atmospheric perspective (fog)

Objects that are a great distance away look hazier due to light scattering by the atmosphere

Atmospheric perspective (fog)

Motion parallax



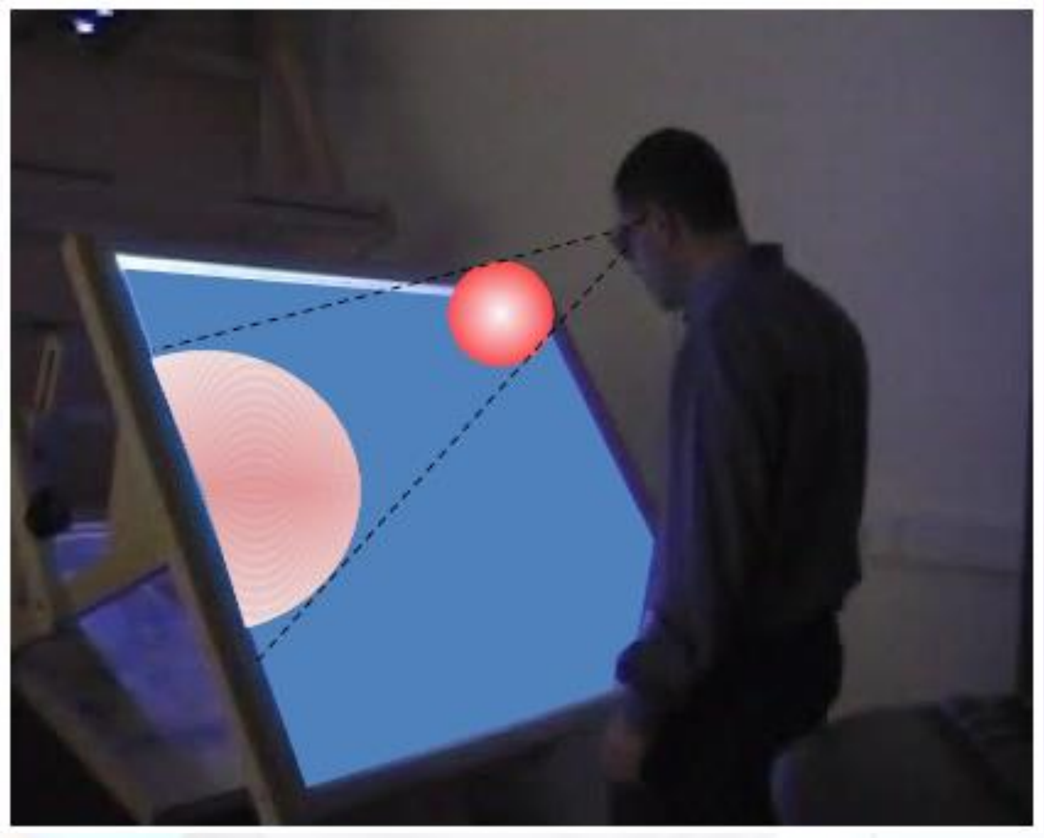
Occlusion (interposition)

Objects that block other objects appear to be closer.

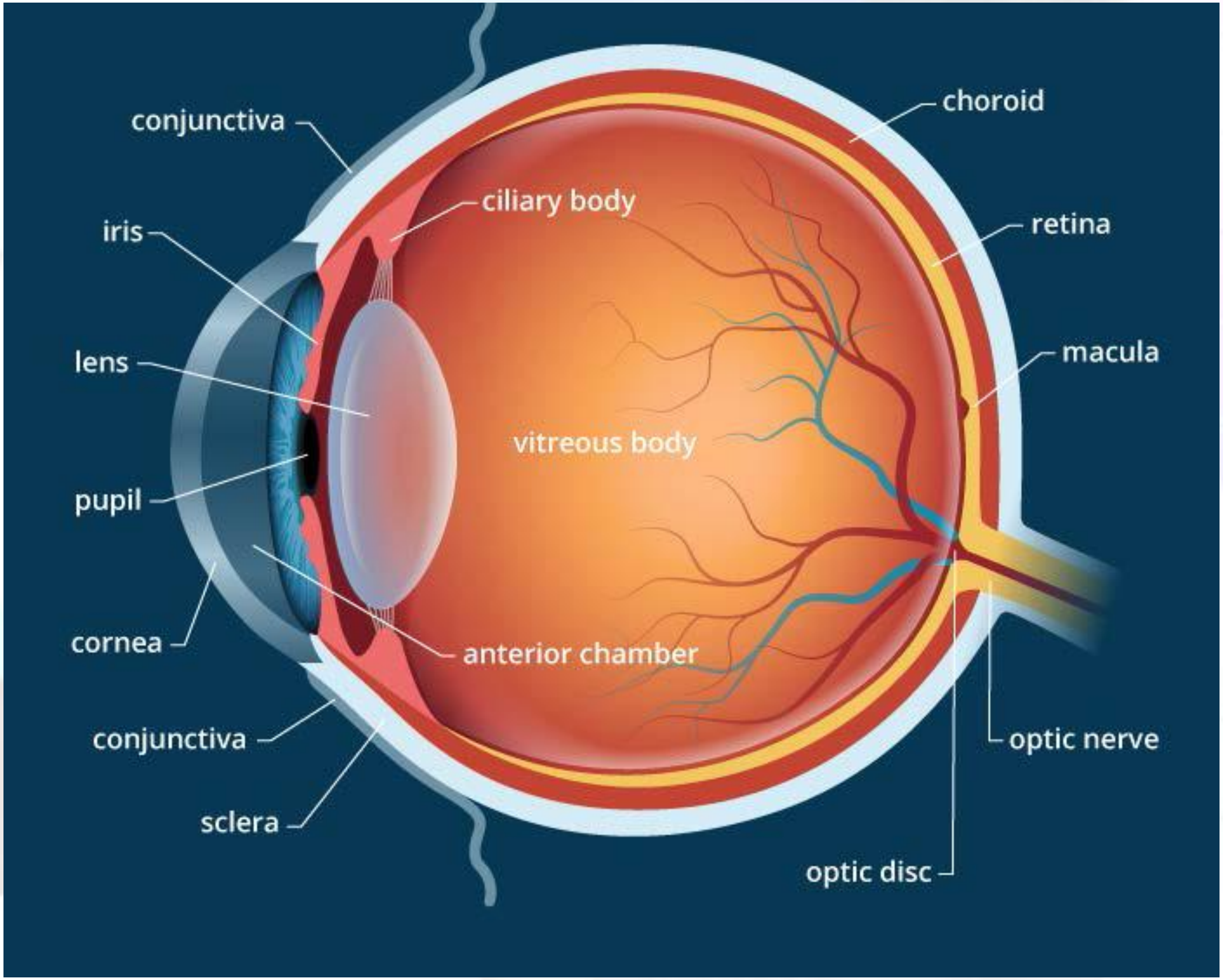
Occlusion – screen surround

Occlusion – screen surround

Occlusion – screen surround

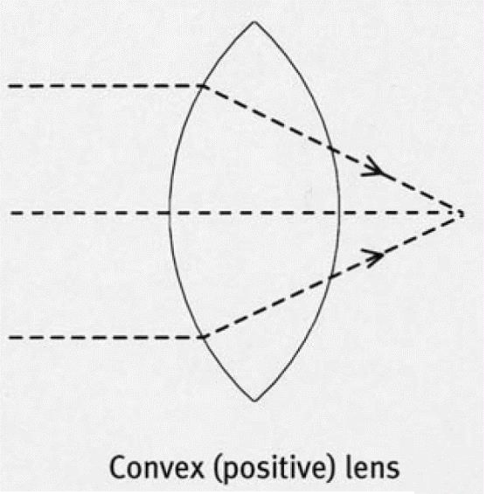


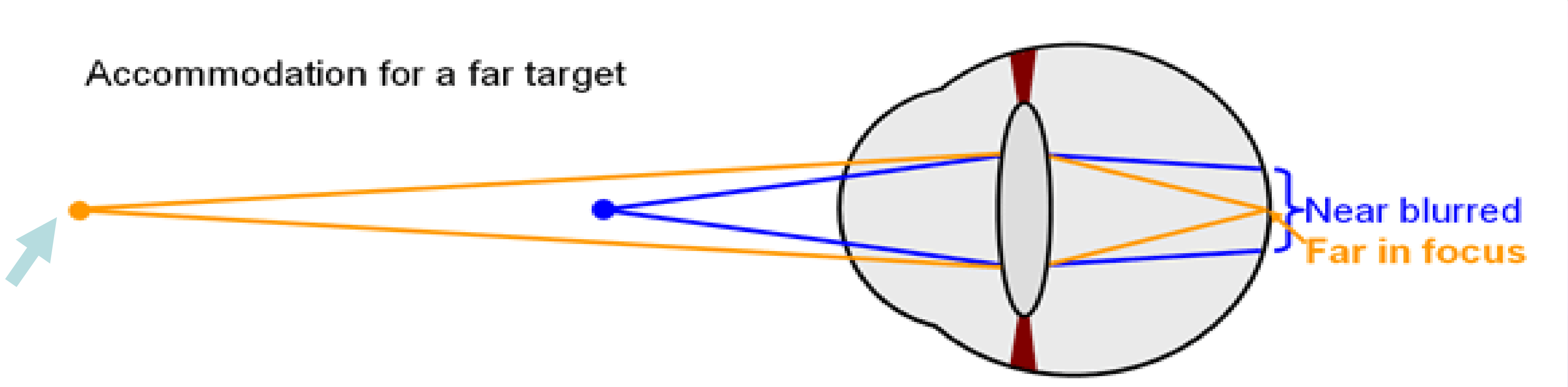
Human eye

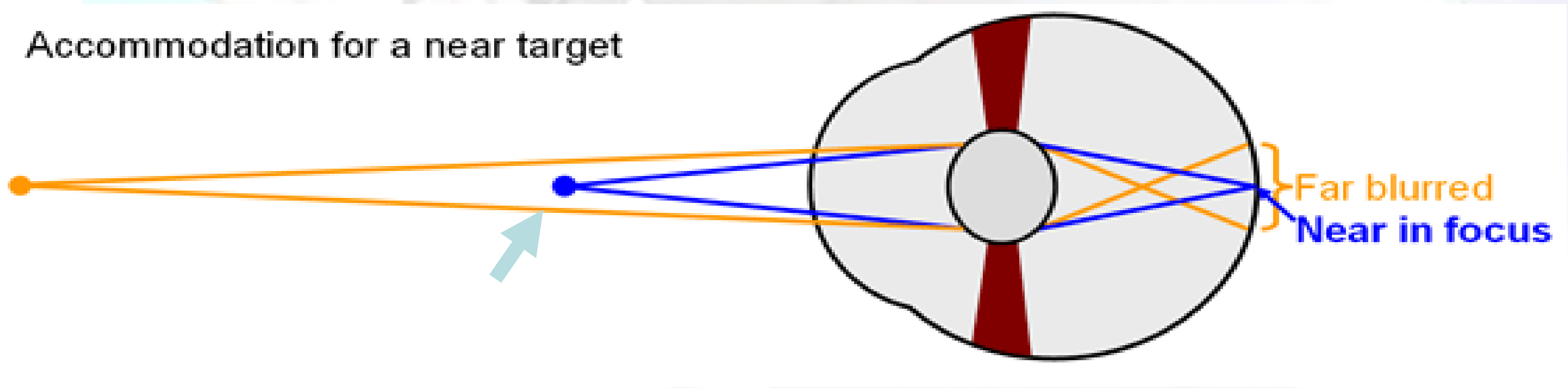

conjunctiva
iris
lens
pupil
cornea
conjunctiva
sclera
ciliary body
vitreous body
anterior chamber
choroid
retina
macula
optic nerve
optic disc

Accommodation

- **Deformation of the eye lens** (*cristalino*)
- Allows to **focus objects** at some distance

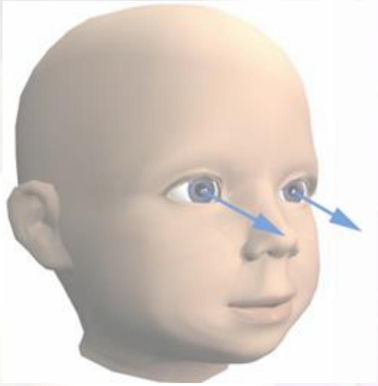


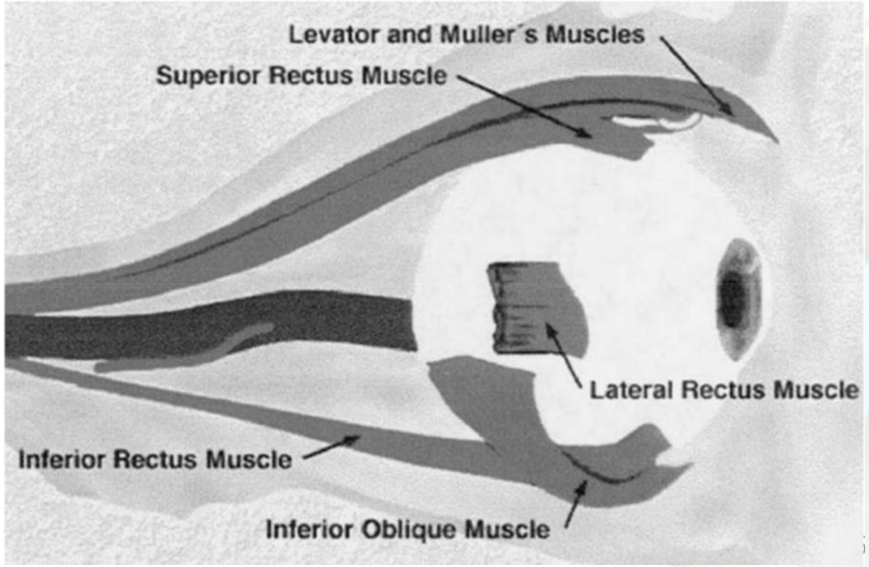


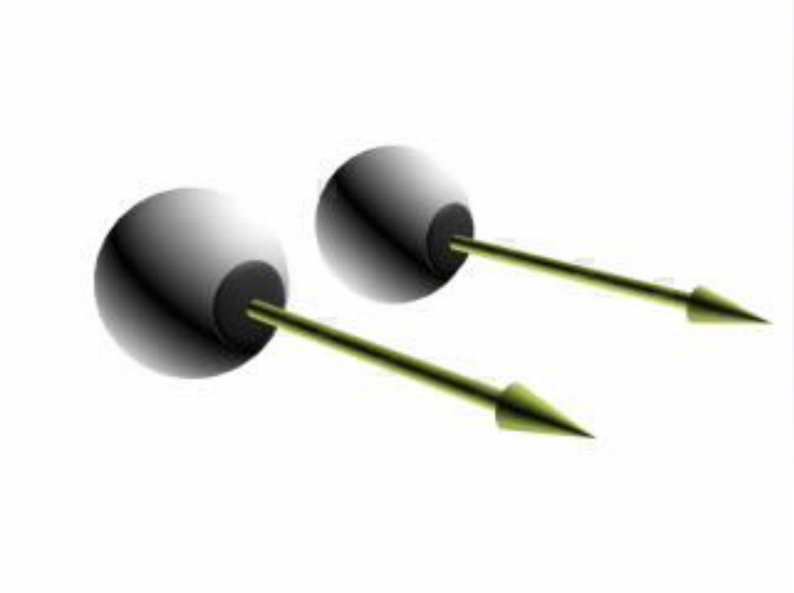


Convergence

- **Rotation of the eye balls**
- Allows to **center the object we are looking at on the fovea.**







Accommodation & convergence

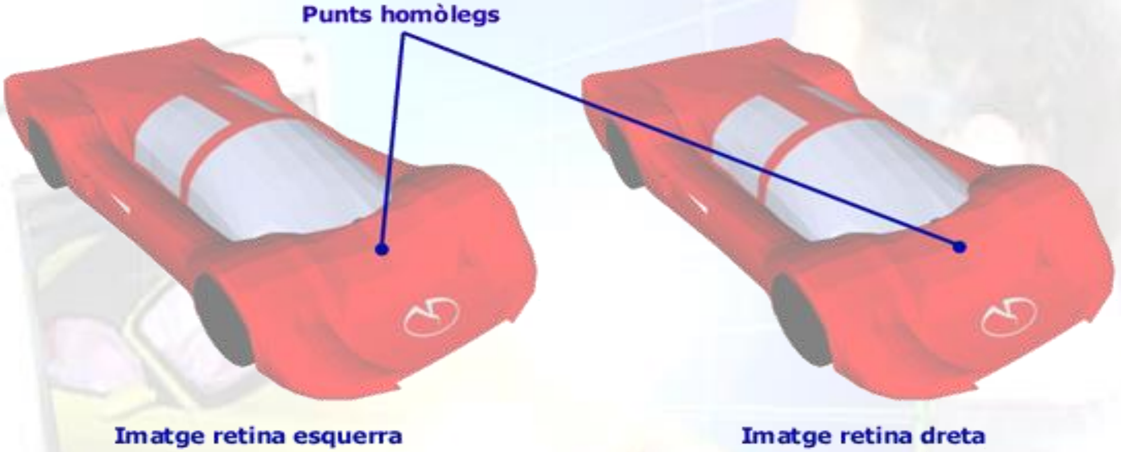
Points in common:

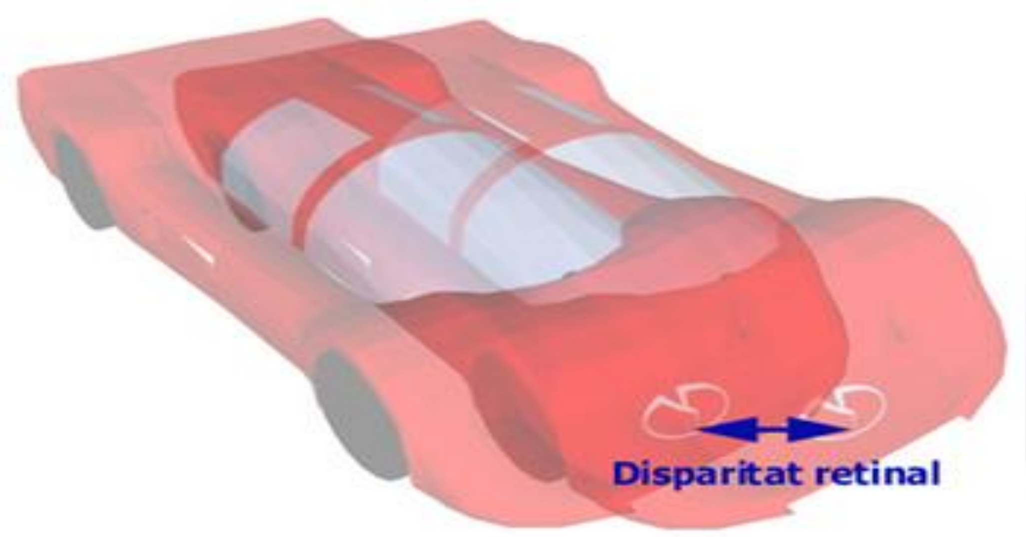
- Both depend on the object depth
- There is a natural relationship between accomodation and convergence.
- In most VR stereo displays, this relationship is broken → **vision decoupling**

Retinal disparity

Difference in the L/R images of an object due to the eyes' horizontal separation

Retinal disparity (informally)





Fusion and stereopsis

- The human brain is able to **combine two images with disparity into a single image with depth**.
- This ability is called **fusion** and the resulting sense is called **stereopsis**.


+

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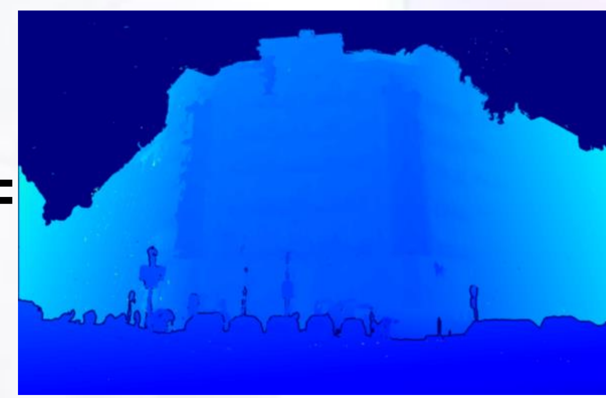
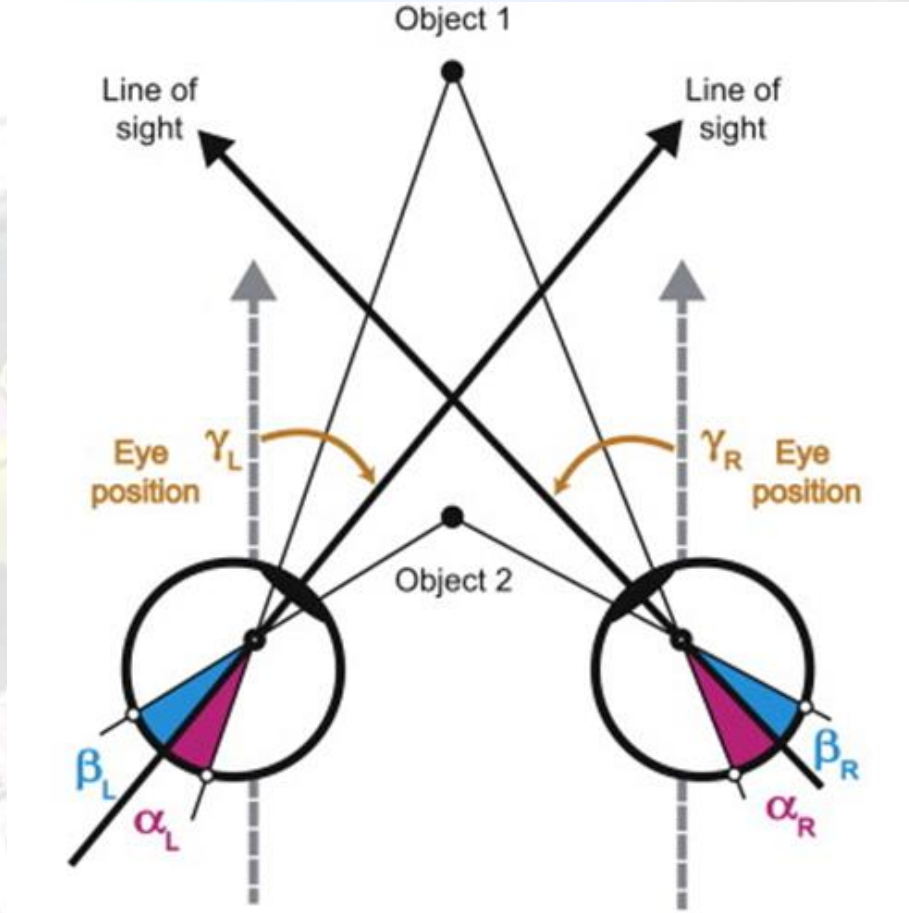


Retinal disparity (more formally)

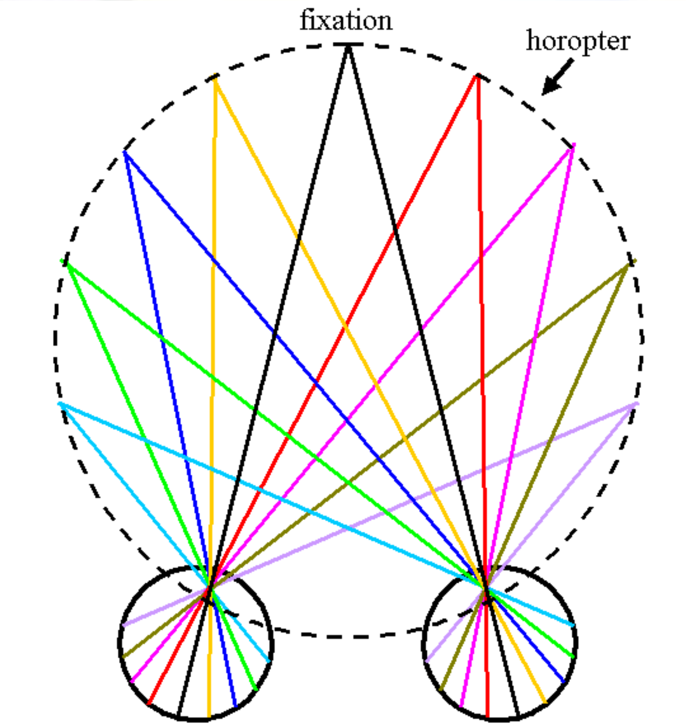


	Retinal Disparity
Object 1	$\alpha_L - \alpha_R$
Object 2	$\beta_L - \beta_R$

Positive angles

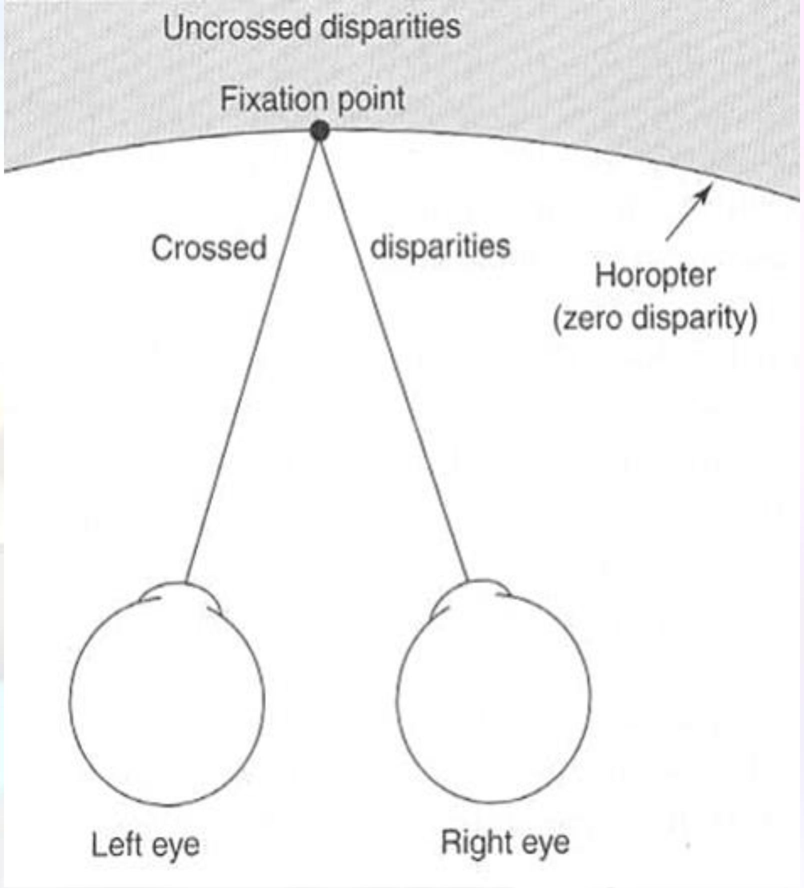
Retinal disparity (more formally)

Horopter: surface of points in space that, for a given convergence, are projected onto points with **no disparity**



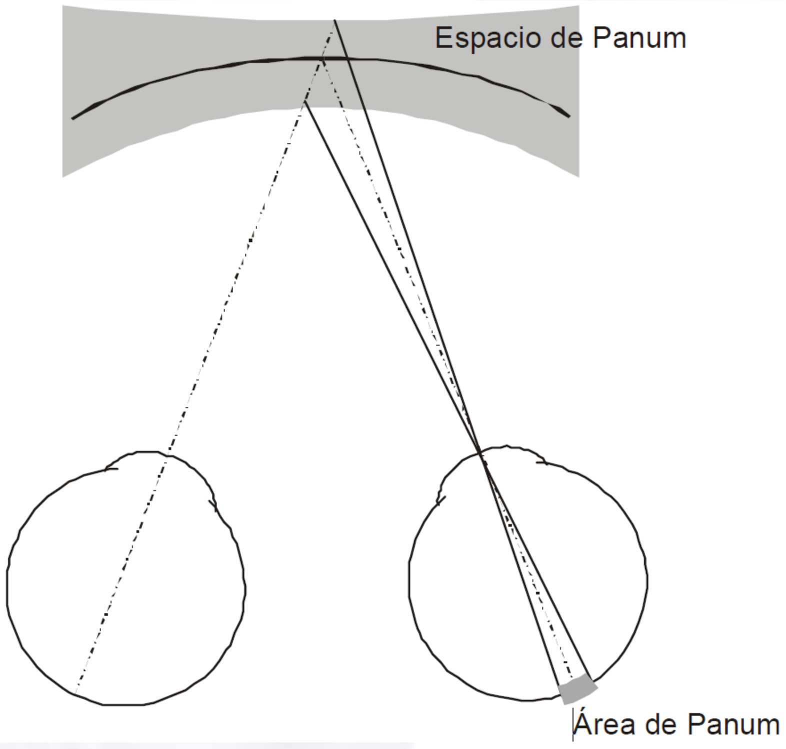
Retinal disparity (more formally)

- **Points closer** than the Horopter have **crossed disparity** (negative disparity)
- **Points farther** than the Horopter have **uncrossed disparity** (positive disparity)



Retinal disparity (more formally)

- **Panum's fusion area:** Space surrounding the horopter where fusion is feasible.
- **Within Panum's fusion area** points might have **non-zero disparity** but they can be fused (resulting in a single image with depth).
- **Outside Panum's fusion area** points have **a large disparity** and fusion fails, producing double images (diplopia).
- Near the fovea, the maximum binocular disparity resulting in fusion corresponds to a visual angle of about 10 minutes of arc **(1/6 of one degree).**



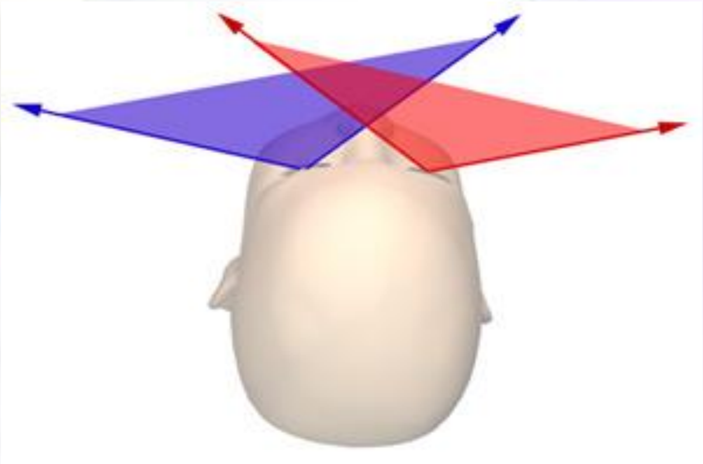
Retinal disparity

Remember:

- Every scene point has its own retinal disparity.
- If we change fixation point, we change retinal disparity!

Human eye fact sheet

- IOD (interocular or interpupillary distance): 5 - 7.5 cm
- Average IOD: 6.3 – 6.6 cm
- Eye field-of-view: 160º-180º hor x 130º vert
- Horizontal overlap: 140º



TAXONOMY of 3D displays

According to number of screens

Where are the L/R images projected onto?

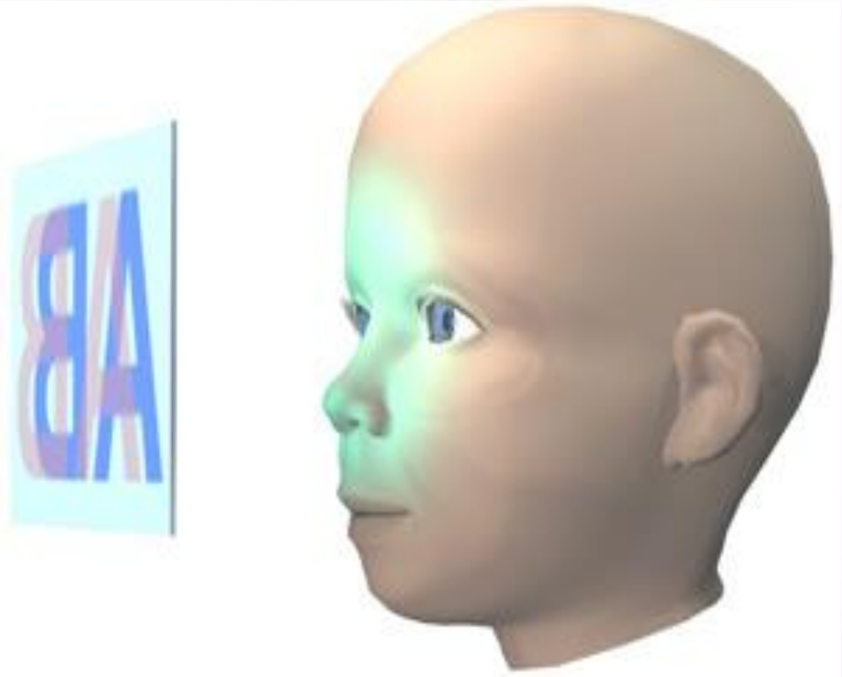
- Two independent screens (eg HMD)
- A single screen (3D TV, 3D cinema, CAVE…)
- Directly onto the retina (no screen)

Separate projections (two screens)

- Each eye can only see one screen (through optics)
- Used in HMD, HCD…

Superimposed projections

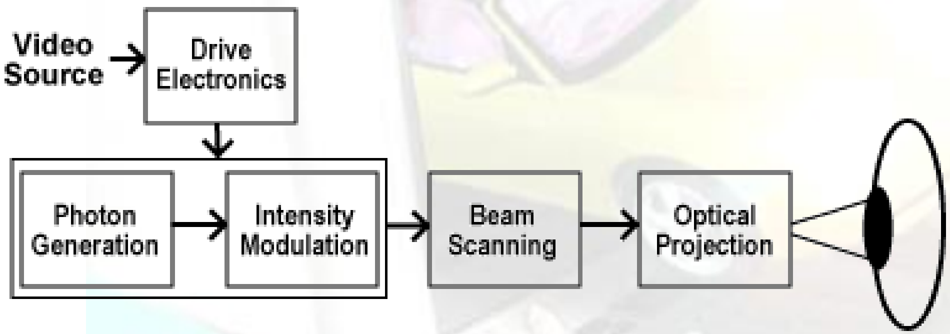
- Both eyes can see the screen
- Requires some **image separation technique** (eg polarization glasses, anaglyph…)
- Used in most projection-based equipment (CAVEs…)

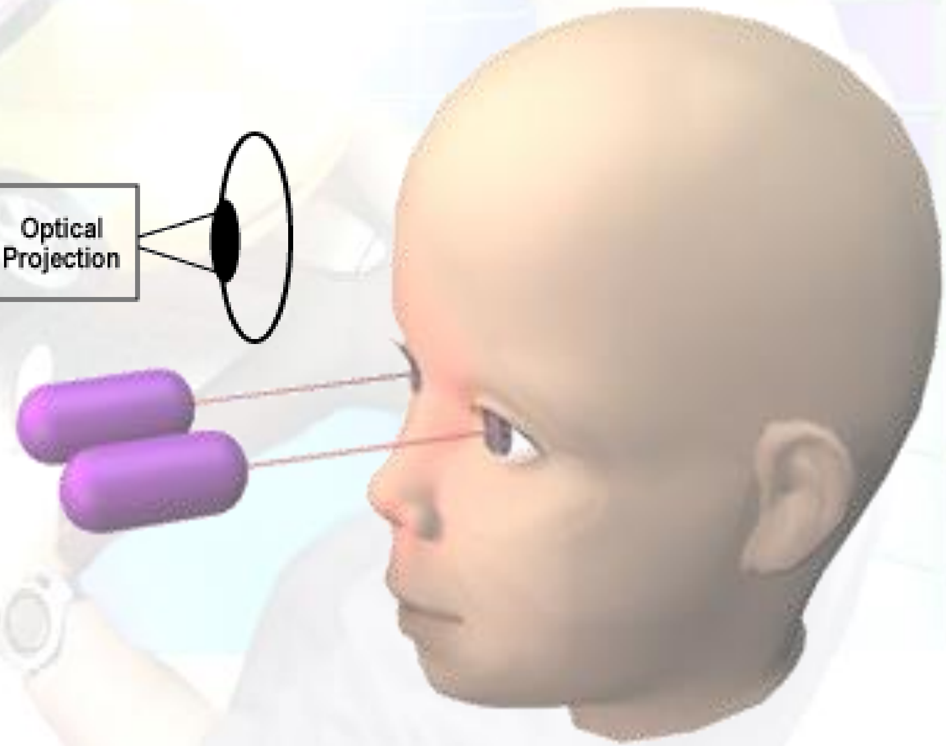


Direct projection into retinas

- Laser emitters
- Virtual Retinal Display, VRD

http://www.hitl.washington.edu/projects/vrd/project.html





Synthesis of stereo images

- Input: 3D model, tracking data, display system data
- Output: images with retinal disparity

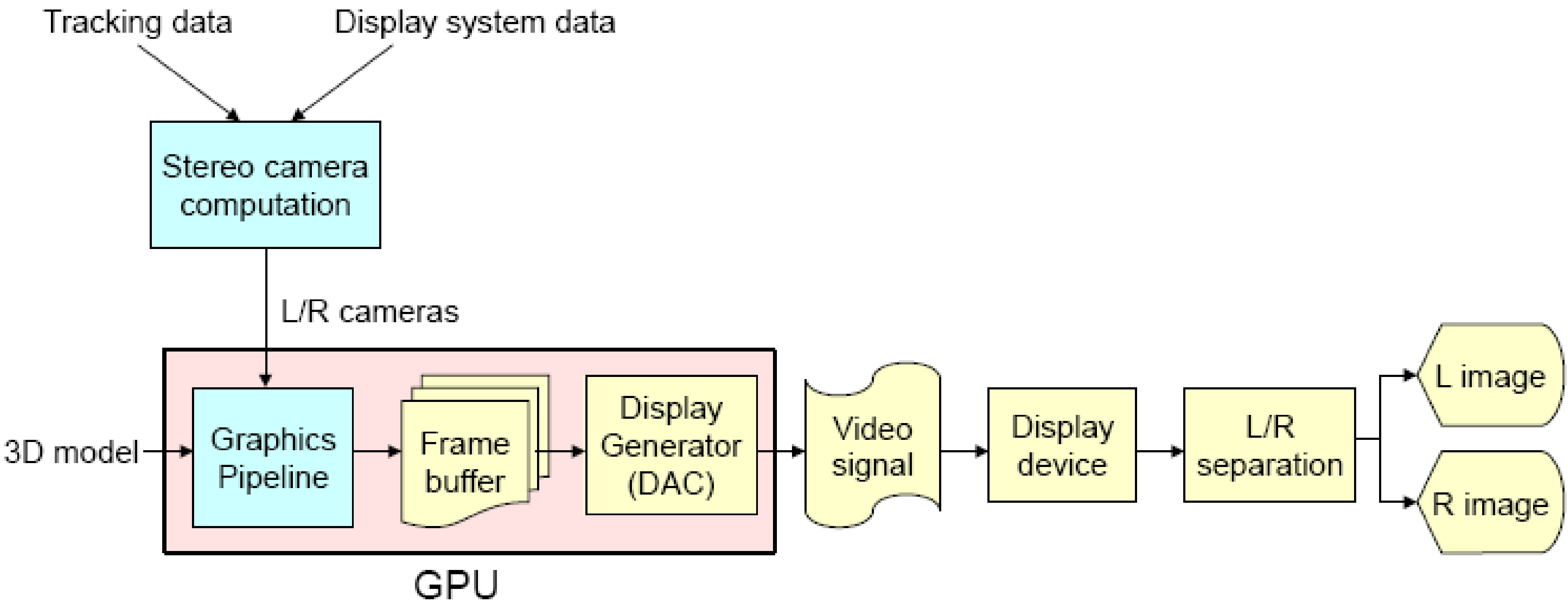


Image separation

- Separation ~ means for providing each eye with its needed image (and rejecting the unnecessary image).
- Required when a single screen contains both images.

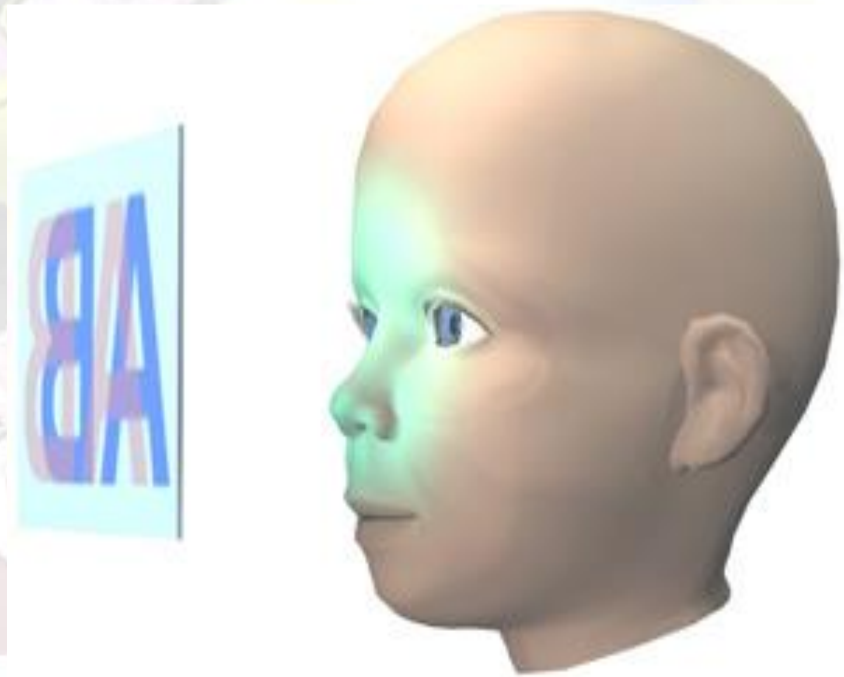


Image separation

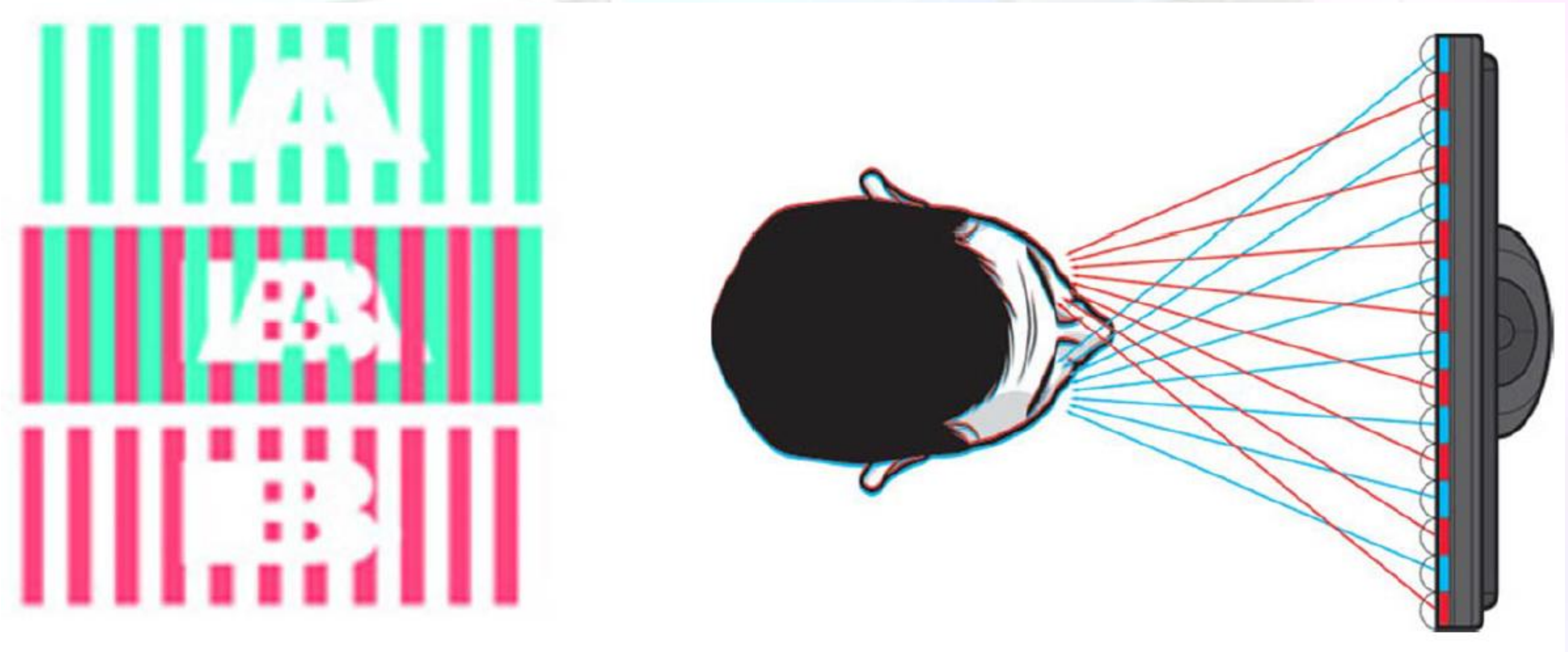
Classification

- Autostereoscopic displays
- Glasses
  - – Anaglyph glasses
  - – Infitec glasses
  - – Polarizing glasses
  - – Shutter-glasses

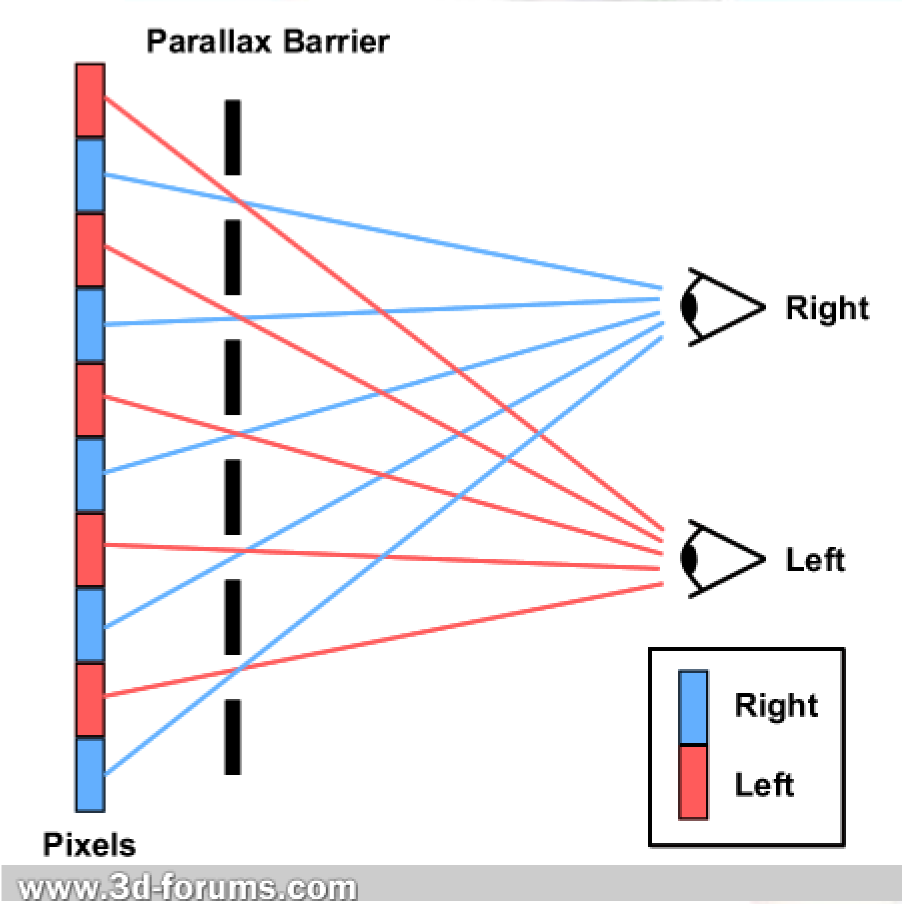
Passive stereo

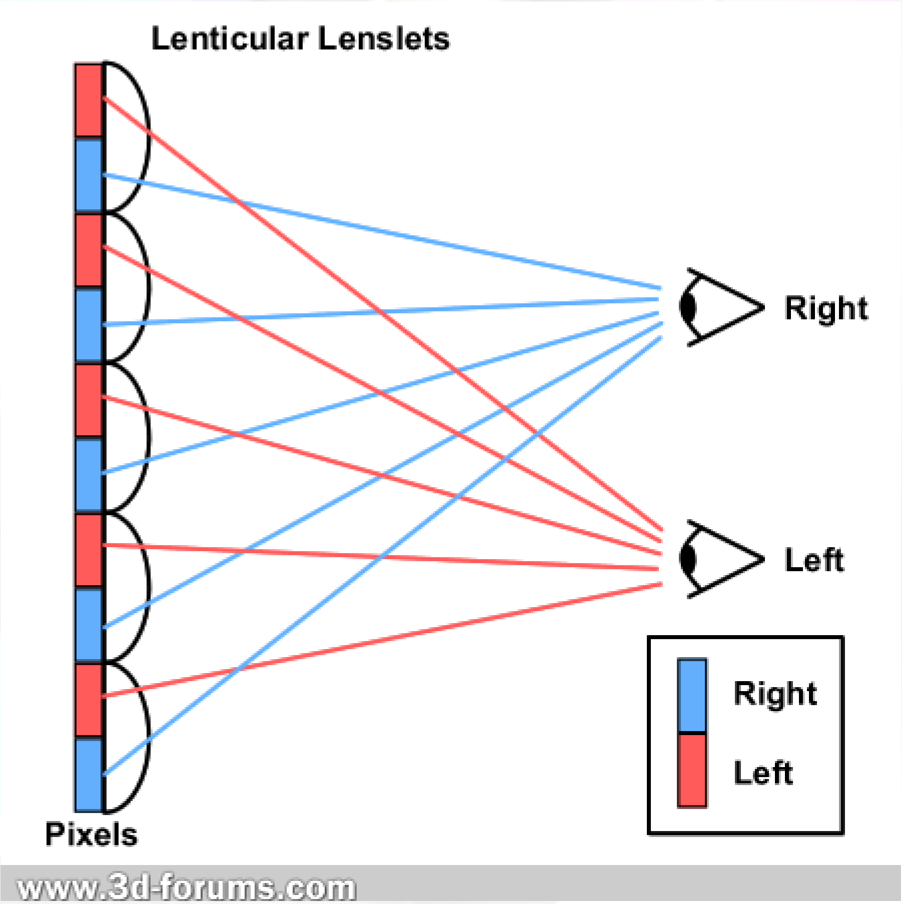
Active stereo

Autostereoscopic displays

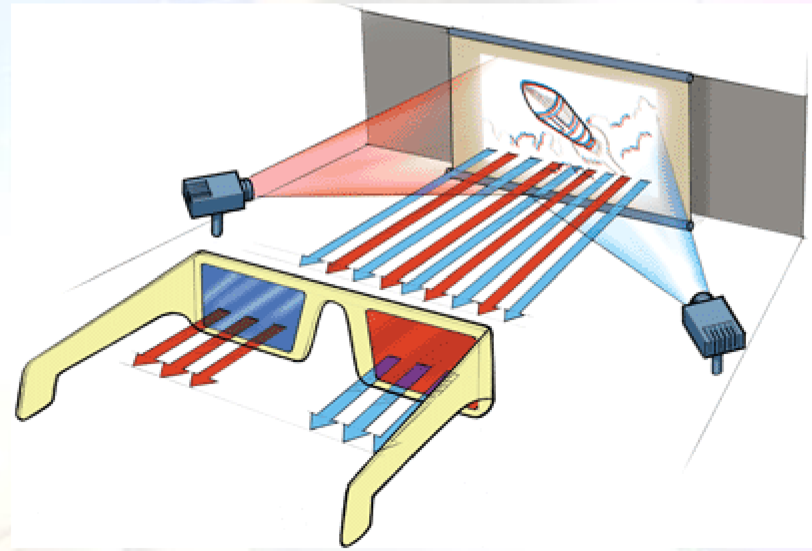


Autostereoscopic displays





Anaglyph filters

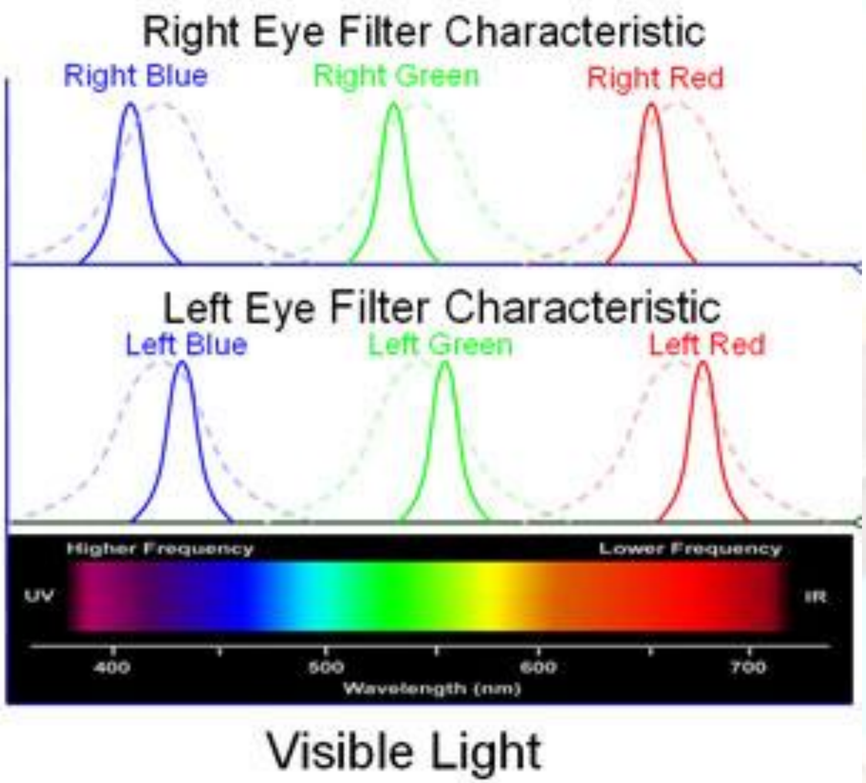


Anaglyph filters

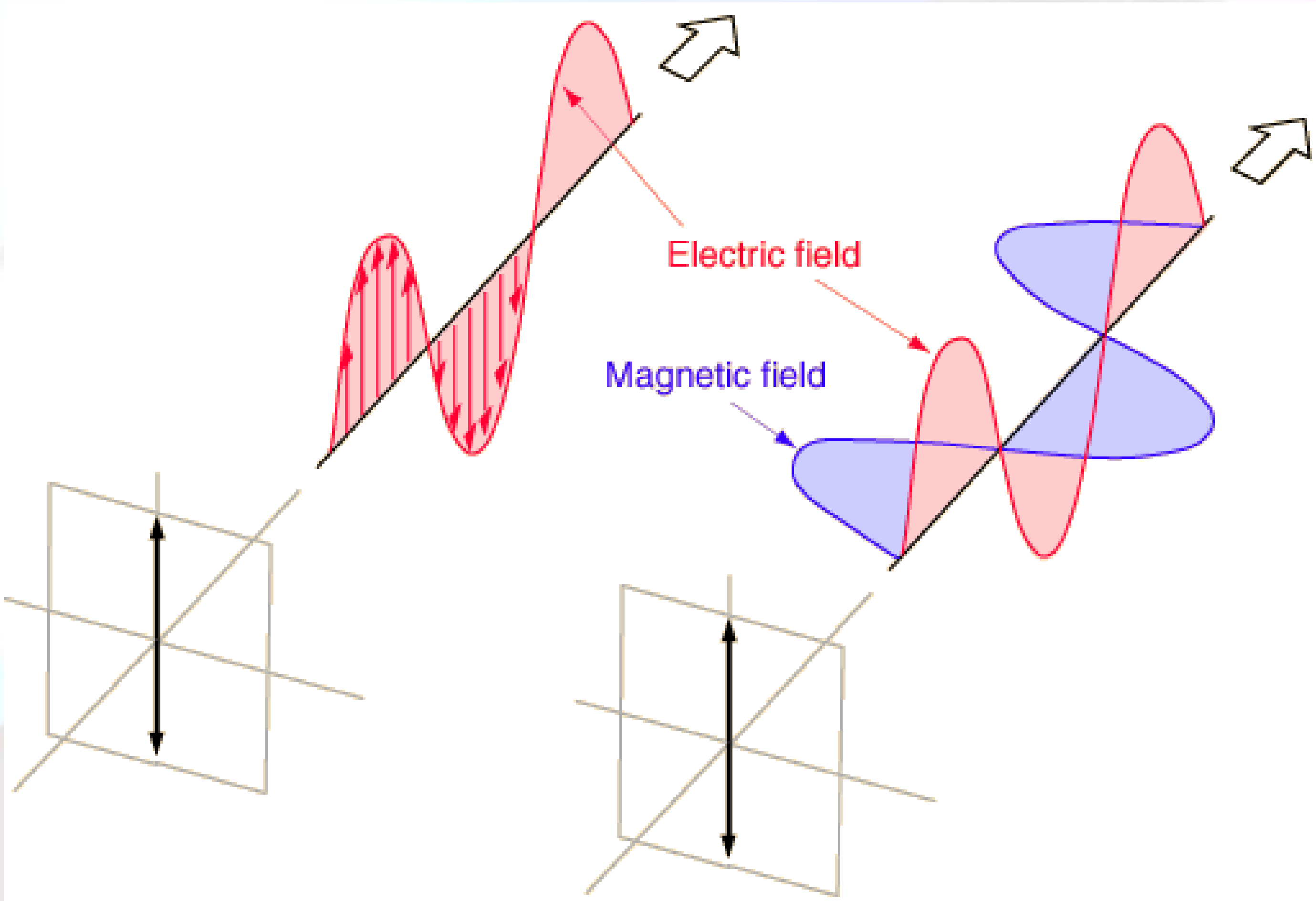
- Based on complementary colors:
  - R-GB, G-RB, B-RG
- Example: red-cyan, left filter blocks G and B; leaves R.
- Cheap
- Obvious color problems

Infitec glasses (Dolby 3D digital cinema)

- Improved version of anaglyph glasses



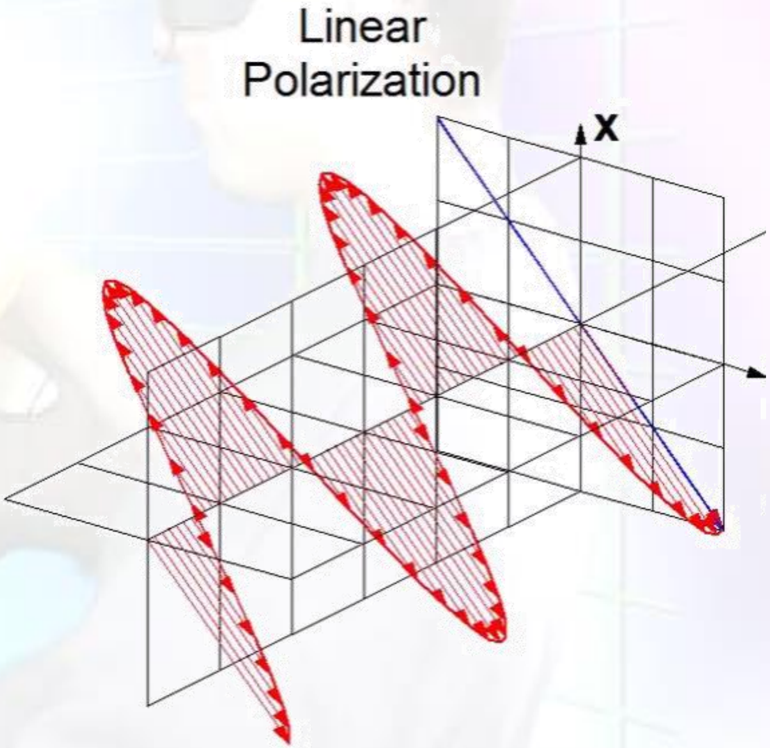
Polarization



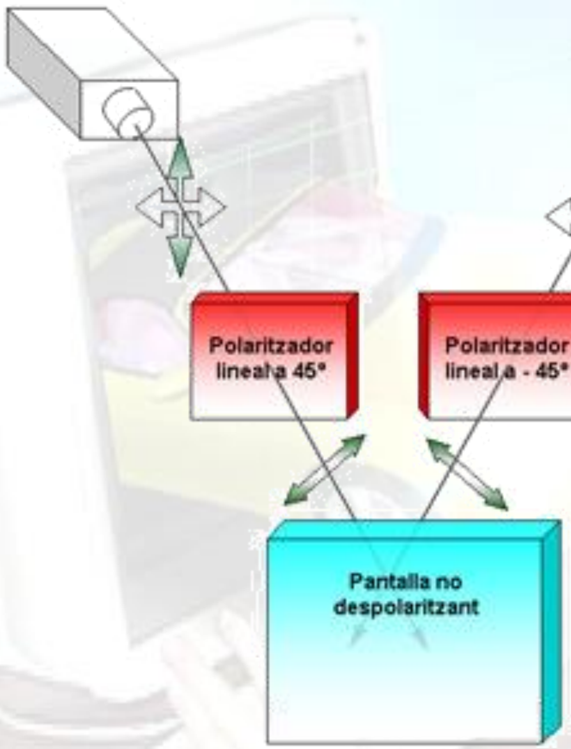
See this video: https://www.youtube.com/watch?v=8YkfEft4p-w

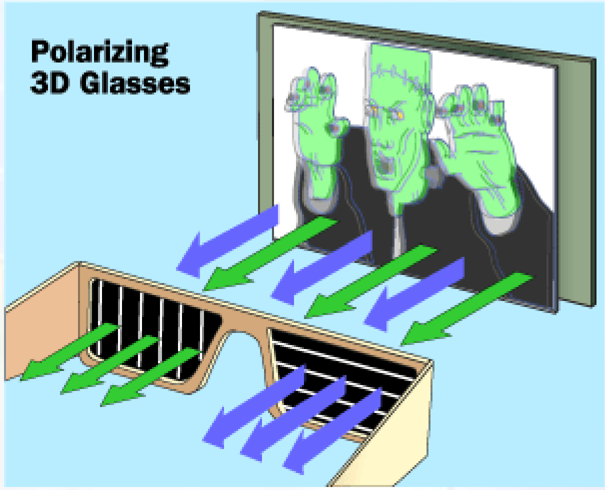
Linear polarizing glasses

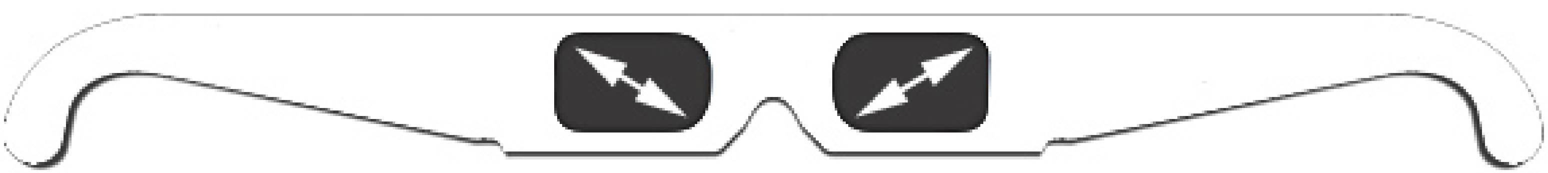
- Based on linear polarization filters
  - In the projectors
  - In the glasses
- Oriented at 90º
- Cheap
- Sensible to head tilt



Linear polarizing glasses



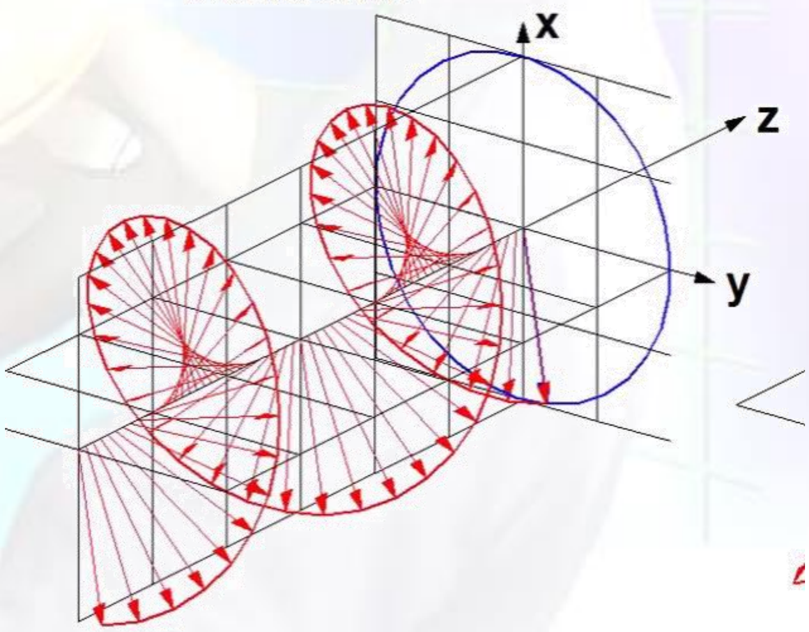




Circular polarizing glasses

- Based on circular polarization filters (projectors & glasses)
- Cheap
- Almost head-tilt insensible.

Circular (Right Hand) Polarization



Shutter glasses

- A LC shutter avoids light from going through each eye, syncronized with the video signal.
- In any given time, one filter is in a *transparent state* and the other is in an *opaque state*.
- Requires a display device running at >100 Hz
- Syncronization between graphics card and glasses:
  - Infrarred signal
  - Wired

Shutter glasses

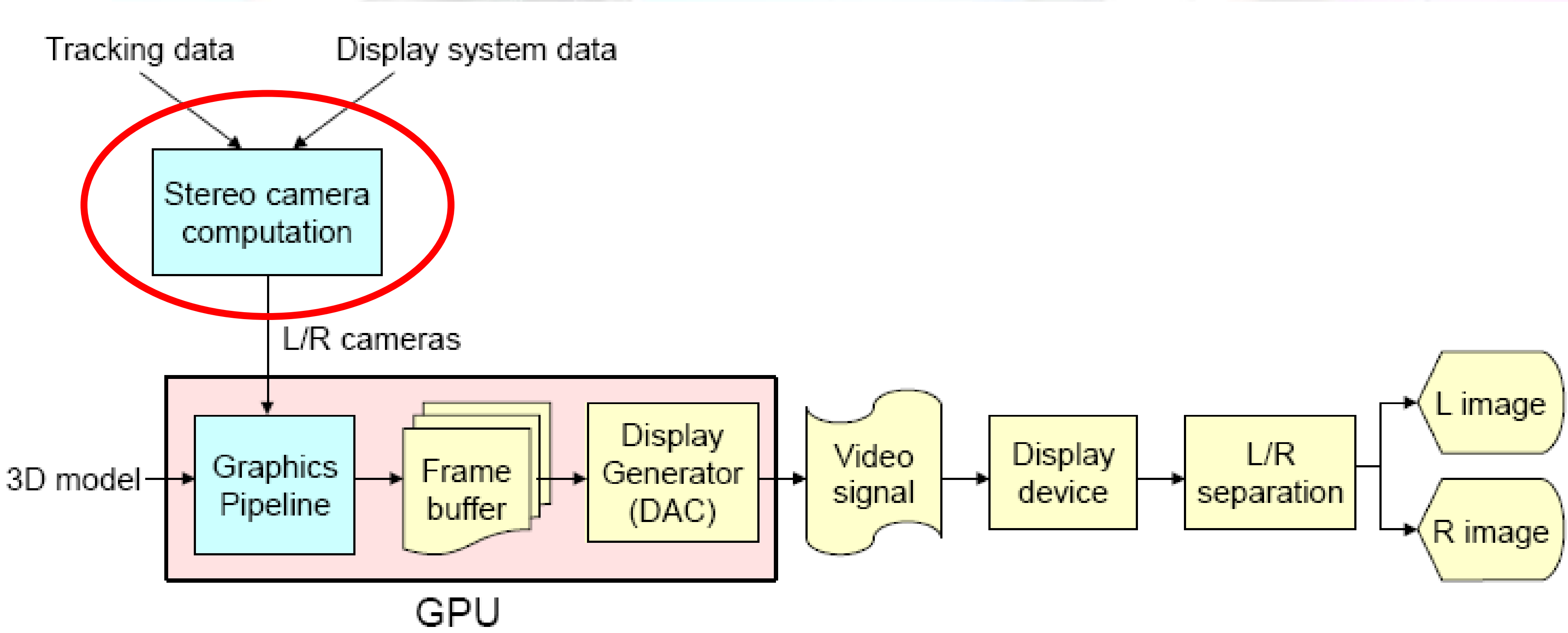
Sync source:

- Stereo-readycards
  - Dedicated signal (eg VESA mini DIN-3)
- Non-stereo-ready cards:
  - VGA connector (pass-through)

Comparison

Technology	Glasses	Head Pos	Head Tilt	Glasses Cost	Suitable for
Lenticular	No glasses	Y	Y	-	VR, TV
Anaglyph	Red/Cyan	N	N	Low	Press
Infitec	Infitec	N	N	High	VR, cinema
Passive stereo	Polarizing glasses	N	Y	Mid	VR, TV, cinema
Active stereo	Shutter glasses	N	N	High	VR, TV, cinema

Synthesis of stereo images



Stereo camera computation

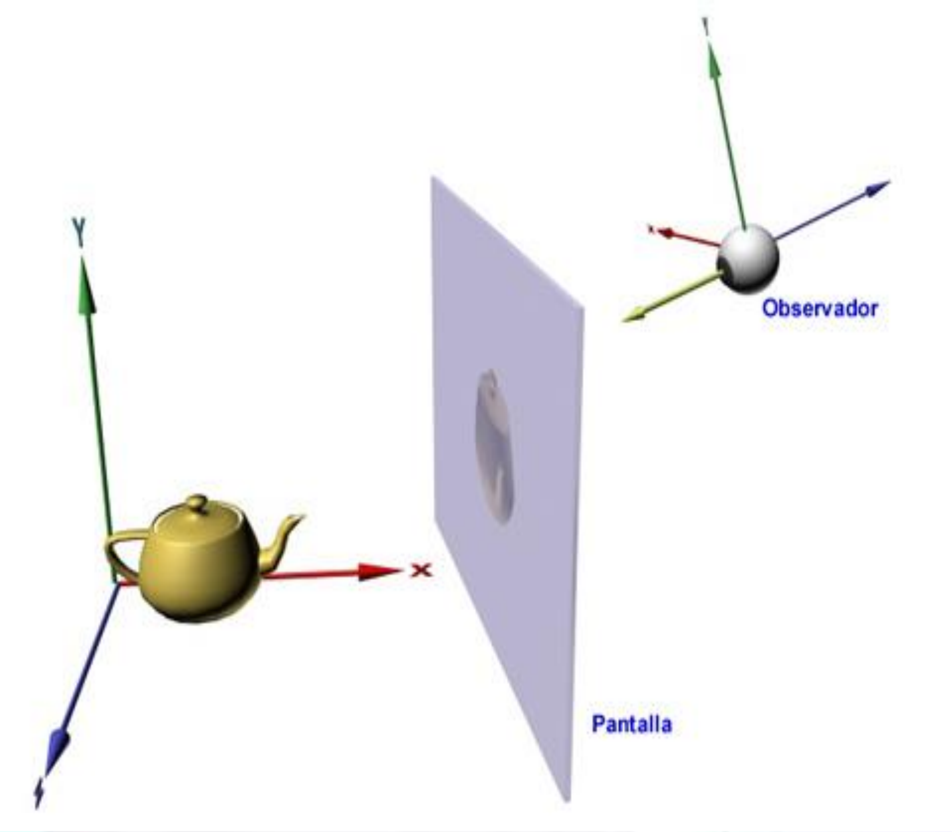
Output: Left and Right cameras:

– Extrinsic parameters: Eye (OBS), target (VRP), up (VUV) ⟶ lookAt (eye.x, eye.y, eye.z, target.x, target.y, target.z, up.x, up.y, up.z);

– Intrinsic parameters: view frustum geometry ⟶ frustum (left, right, bottom, top, near, far);

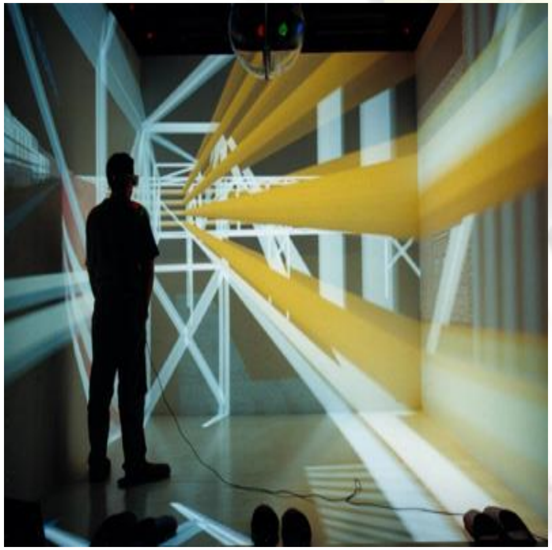
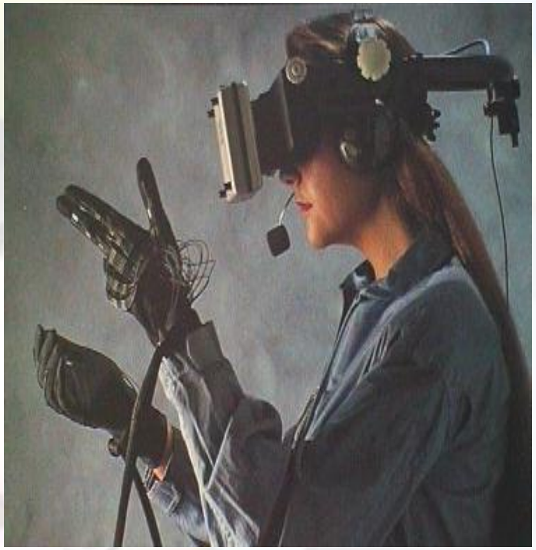
Stereo rendering

- The virtual camera must be computed taking into account:
  - Screen geometry (size, position, orientation)
  - The eye position with respect to the screen.
- This is absolutely required:
  - On tiled-displays
  - On multi-screen displays
  - On head-tracked displays



Configurations

- Static screen + head-tracking (projection-based)
- Dynamic screen + head-tracking (HMDs)
- Desktop system without tracking


Static screen

- This is the configuration of projection-based systems (CAVEs, Videowalls, workbenches…)
- Parameters:
  - Tracking data: L/R eye position
    - Two position trackers (3DOF each)
    - One 6DOF tracker (head, glasses…)
  - Display system data
    - Screen geometry

Static screen

// View Matrix

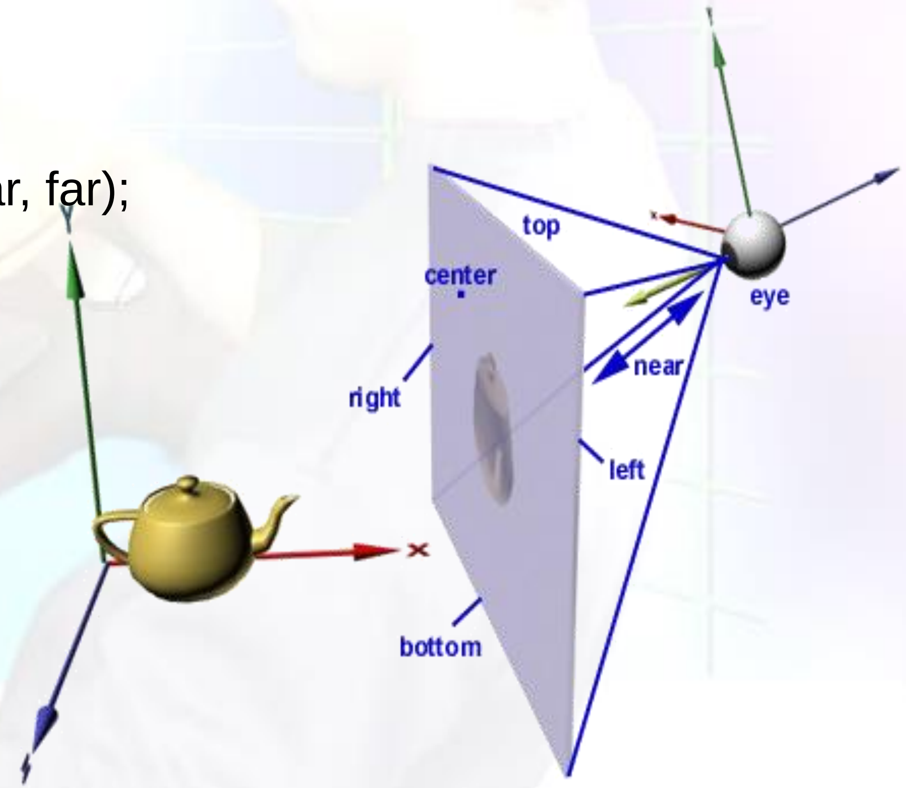
VM = lookAt(eye.x, eye.y, eye.z, center.x, center.y, center.z, up.x, up.y, up.z);

sendViewMatrix (VM);

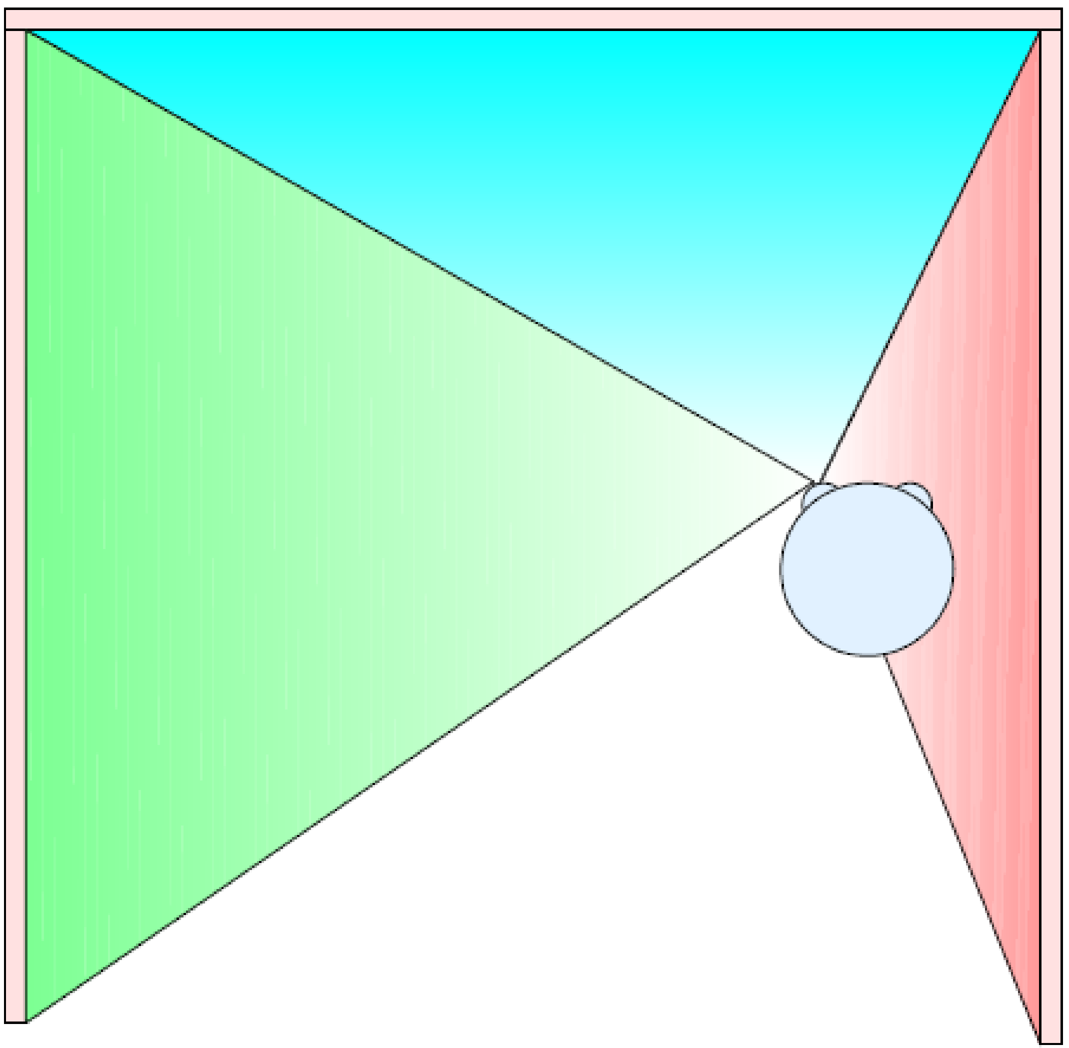
// Projection Matrix

PM = frustum (left, right, bottom, top, near, far);

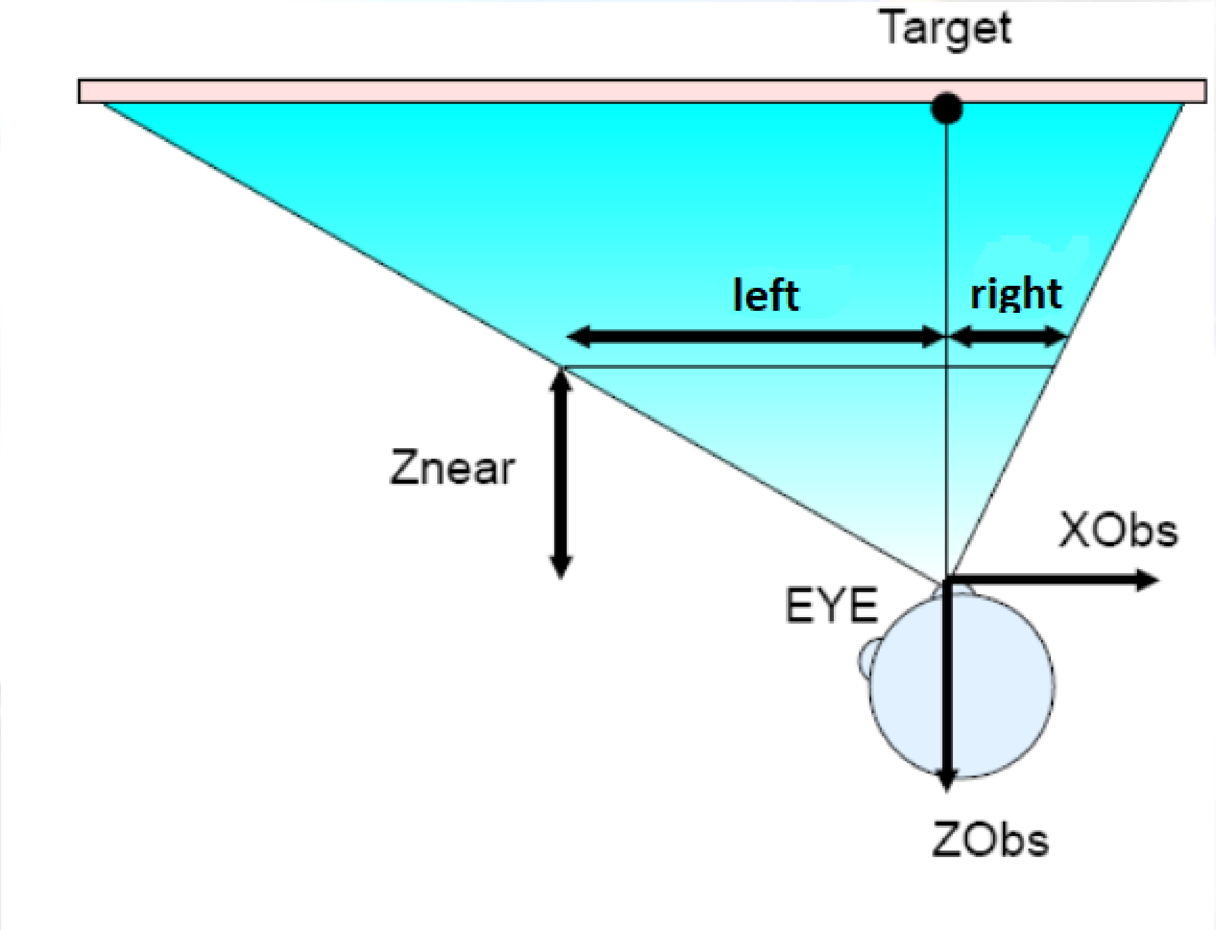
sendProjectionMatrix (PM);



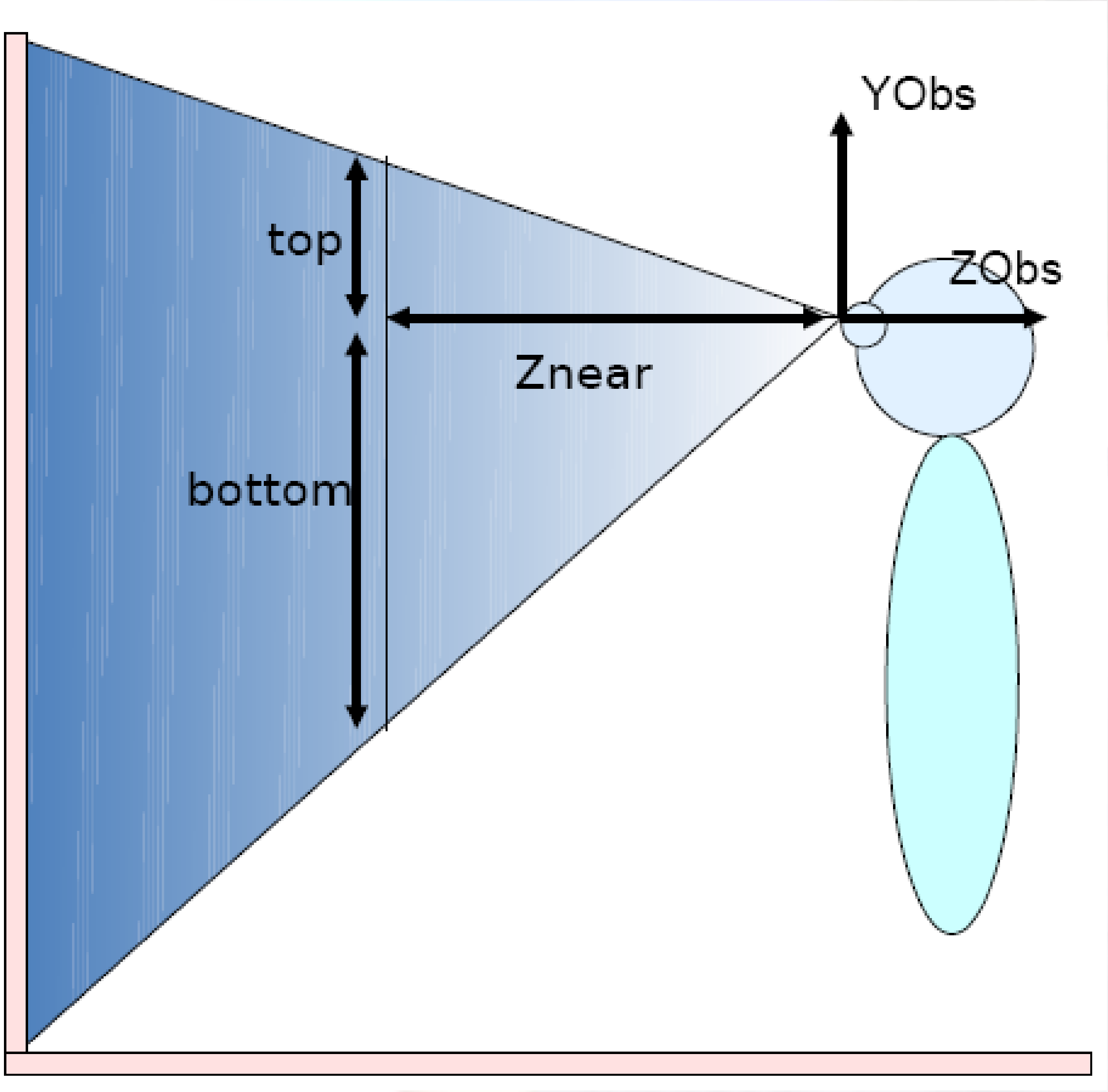
Static screen



Static screen

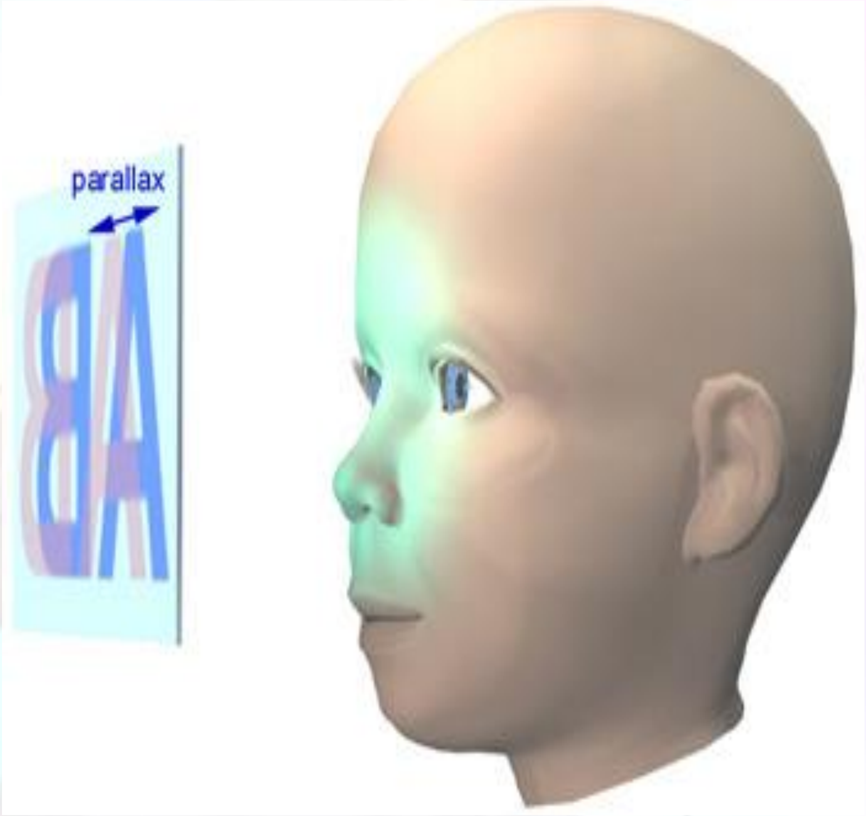


Static screen



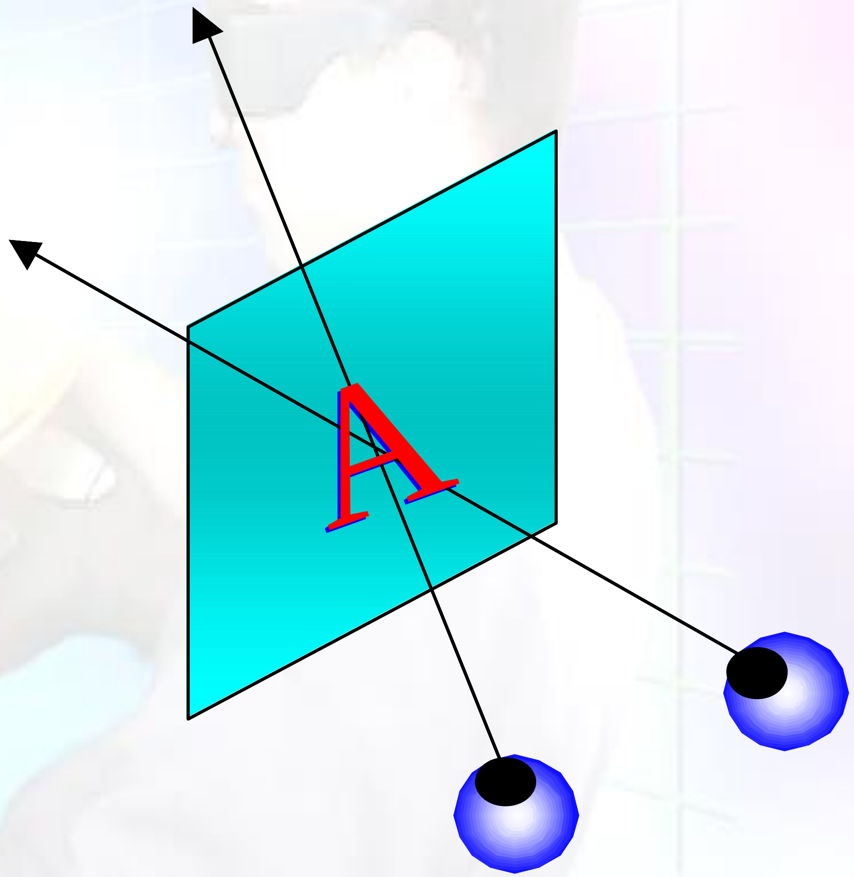
Parallax

- **Parallax** is a 3D stereo concept.
- Related to (but distinct from!) **retinal disparity**.
- **Parallax**: distance between L/R points **measured on the screen**.
- Unlike retinal disparity, **parallax does not depend on eye convergence**.



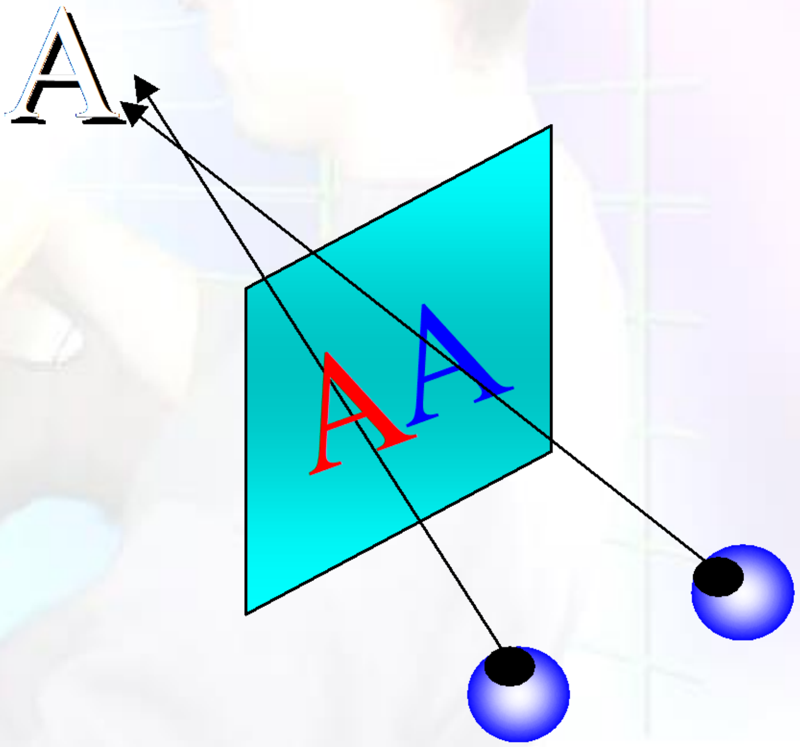
Zero parallax

- An object has zero parallax when the corresponding L/R points overlap.
- When looking at the object, the eyes converge in the screen plane.
- The object appears to be **on the screen plane**.



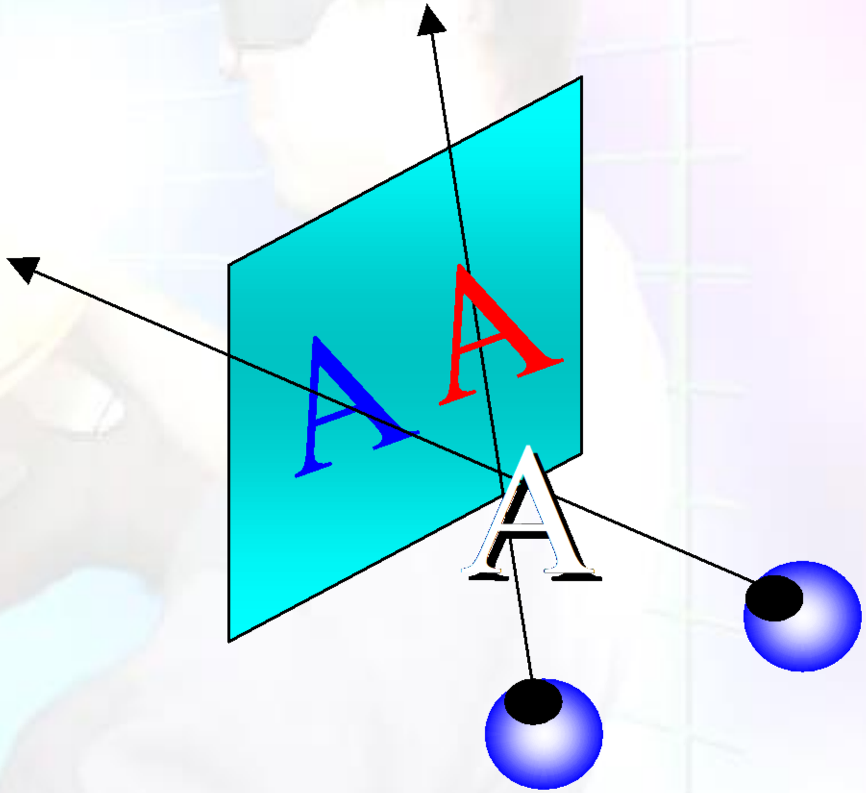
Positive parallax

- An object has **positive parallax** when the corresponding L/R points have positive distance (**L point is to the left** of the R point).
- When looking at the object, the eyes converge at a point **behind the screen plane**.
- The object appears to be behind the screen.
- It should be in [0, 6.3cm]
- If stereo cameras are computed correctly using actual eye positions, it will never be greater than the IOD.



Negative parallax

- An object has **negative parallax** when the corresponding L/R points have negative distance (**L point is to the right** of the R point).
- When looking at the object, the eyes converge at a point **in front of the screen plane**.
- The object appears to be **in front of the screen**.
- Some studies recommend not to exceed 1.5 degrees (object is too close).



Desktop system

- Used in low-cost systems (fish-tank VR)
- As in projection-based systems but guessing user’s location.

Dynamic screen

- Used in HMDs
- The screens follow the head movements, so they are fixed with respect to the eyes.
- Parameters:
  - Head orientation
  - Head position (optional)
  - HMD frustum + distortion

Dynamic screen

If we could neglect lens distortion:

// View Matrix

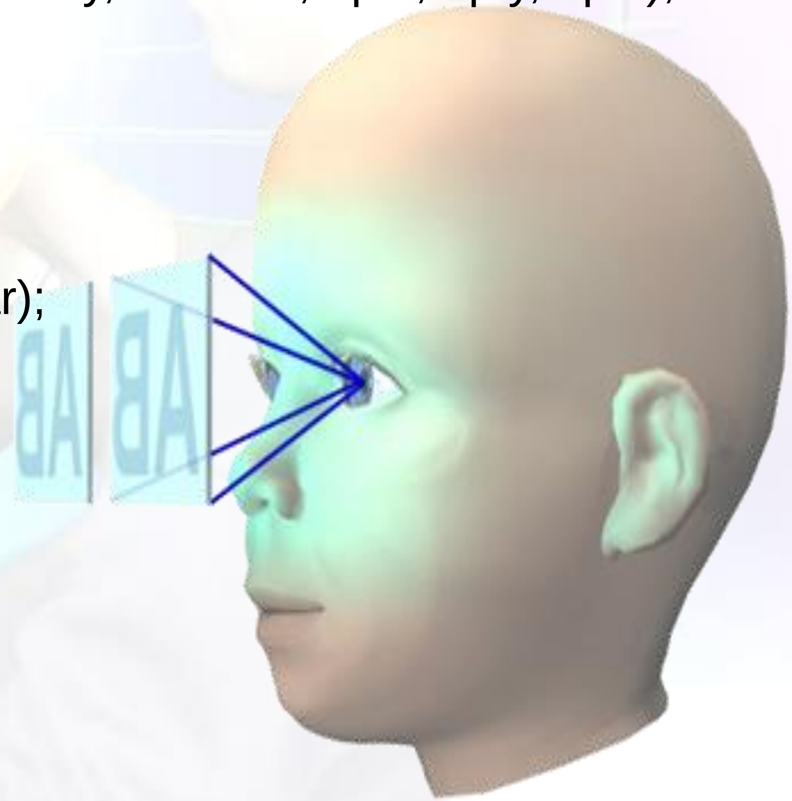
VM = lookAt(eye.x, eye.y, eye.z, center.x, center.y, center.z, up.x, up.y, up.z);

sendViewMatrix (VM);

// Projection Matrix

PM = frustum (left, right, bottom, top, near, far);

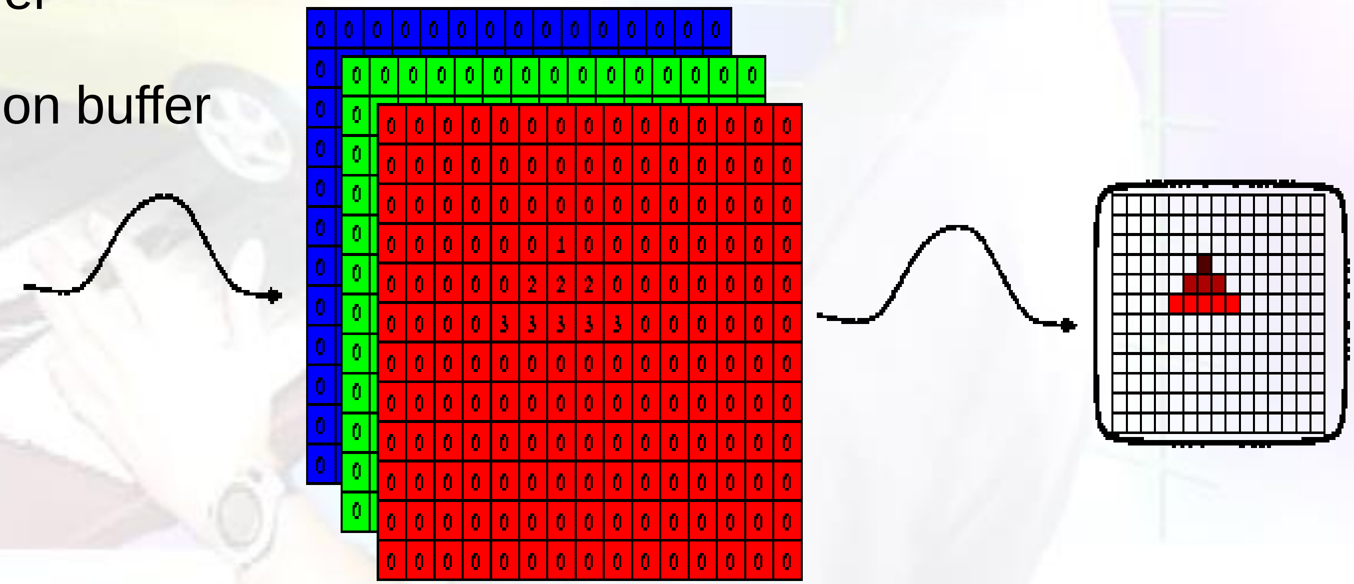
sendProjectionMatrix (PM);



Dynamic screen

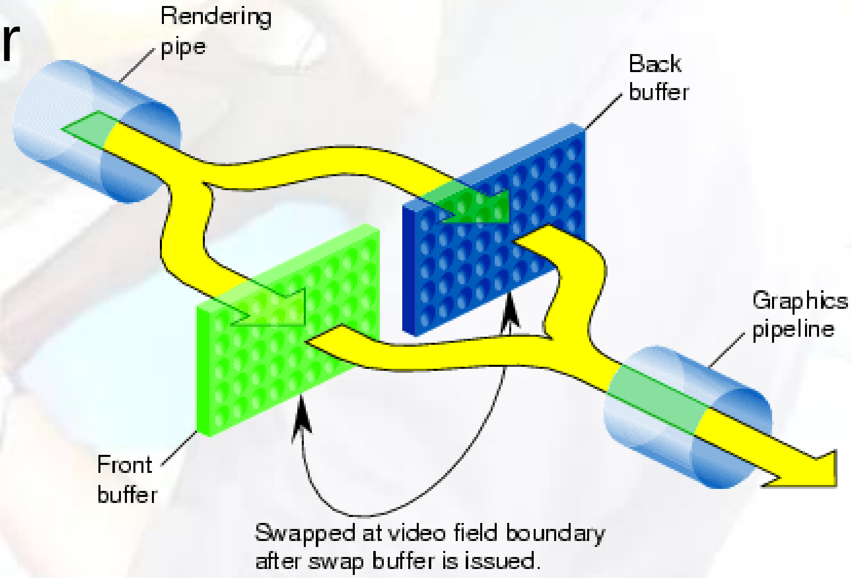
Frame buffer: review

- Frame buffer
  - Color buffer(s)
  - Depth buffer
  - Stencil buffer
  - Accumulation buffer



Frame buffer: review

- Doble buffering
  - Two color buffers: GL_FRONT, GL_BACK
  - Depth buffer
  - Stencil buffer
  - Accumulation buffer



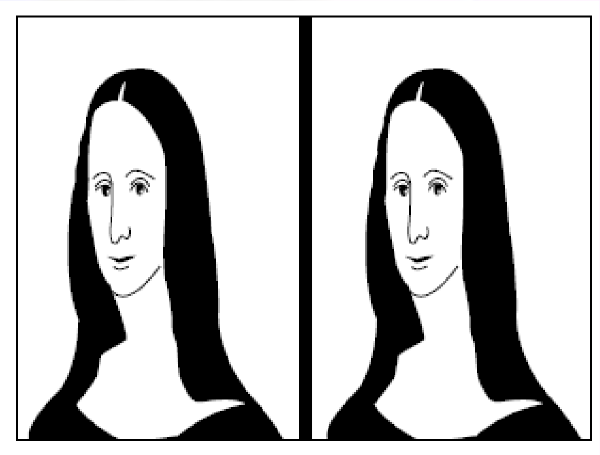
Frame buffer formats

- How to encode a stereo pair in the color buffer.
- Required when a single frame buffer has to hold both L/R images
- Not required when each image is generated by a different PC.
- Must work together with *image separation*
- Classification:
  - Color based
    - Anaglyph stereo
  - Frame-based:
    - Above-and-below, or Side-by-side
    - Quad buffering
  - Line-based and column-based
    - Line-interlived (line sequential), column-interlived

Anaglyph stereo

- One color channel (eg Red)→ left image
- The other two color channels (eg Green, Blue) → right image

Side-by-side



- Left half → left image
- Right half → right image
- Typical configuration:
  - The graphics card has two outputs → two projectors

Quad buffering

- Frame buffer
  - Four color buffers: GL_FRONT_LEFT, GL_FRONT_RIGHT
    GL_BACK_LEFT, GL_BACK_RIGHT
  - Depth buffer
  - Stencil buffer

- Quad buffering is used in *active stereo*
  - *Why two front buffers?* We need to provide both images during the time the application takes to draw the next frame.
  - *Why two back buffers?* Both L/R buffers are swapped simultaneously!
  - Supported by *stereo-ready* graphics cards (eg Nvidia Quadro)
  - Preferred format when using a single monitor/projector.

Quad buffering: sample code

Setup a stereo format (Qt sample code):

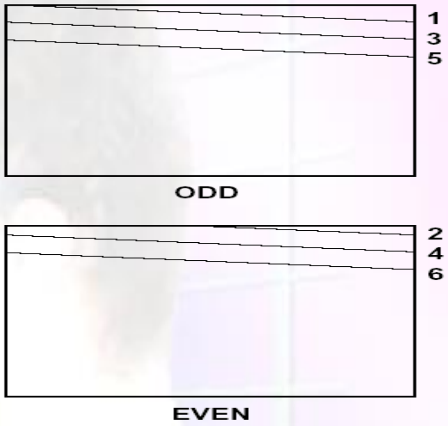
```
QGLFormat f;
f.setStereo(true);  // more flags…
QGLFormat::setDefaultFormat(f);
```

Draw left/right images (OpenGL sample code):

```
Glboolean isStereo;
glGetBooleanv (GL_STEREO, &isStereo);

void paintGL() {
    glDrawBuffer(GL_BACK_LEFT);
    setupCamera(left);
    drawScene();
    glDrawBuffer(GL_BACK_RIGHT);
    setupCamera(right);
    drawScene();
}
```

Line/column-interlived



- Line interlived:
  - Odd lines encode the left image
  - Even lines encode the right image
- Column-interlived
  - Odd columns encode the left image
  - Even columns encode the right image
- Limitation: each eye sees half the number of lines (or columns).

Display generator

- Converts the contents of the (FRONT) color buffer(s) into a video signal.
- Multiple configurations:
  - **Stereo-ready cards**: **one video signal**, encoding sequentially left and right images.
  - **Dual-head PCs** (most current graphics cards): two independent video signals (often DVI+VGA or DVI+DVI connectors)
  - **Quad-head PCs** (high-end graphics cards, eg Matrox QID)

Display generator

Dual-head PCs

- Most current graphics cards support two monitors.
- Simplest solution:
  - Configure a virtual desktop two times wide (eg 2x1024x768 = 2048x768 desktop)
  - Graphics card will automatically output one half to each video signal.
  - Solution adopted in many display devices.

Display generator

Dual-head PCs

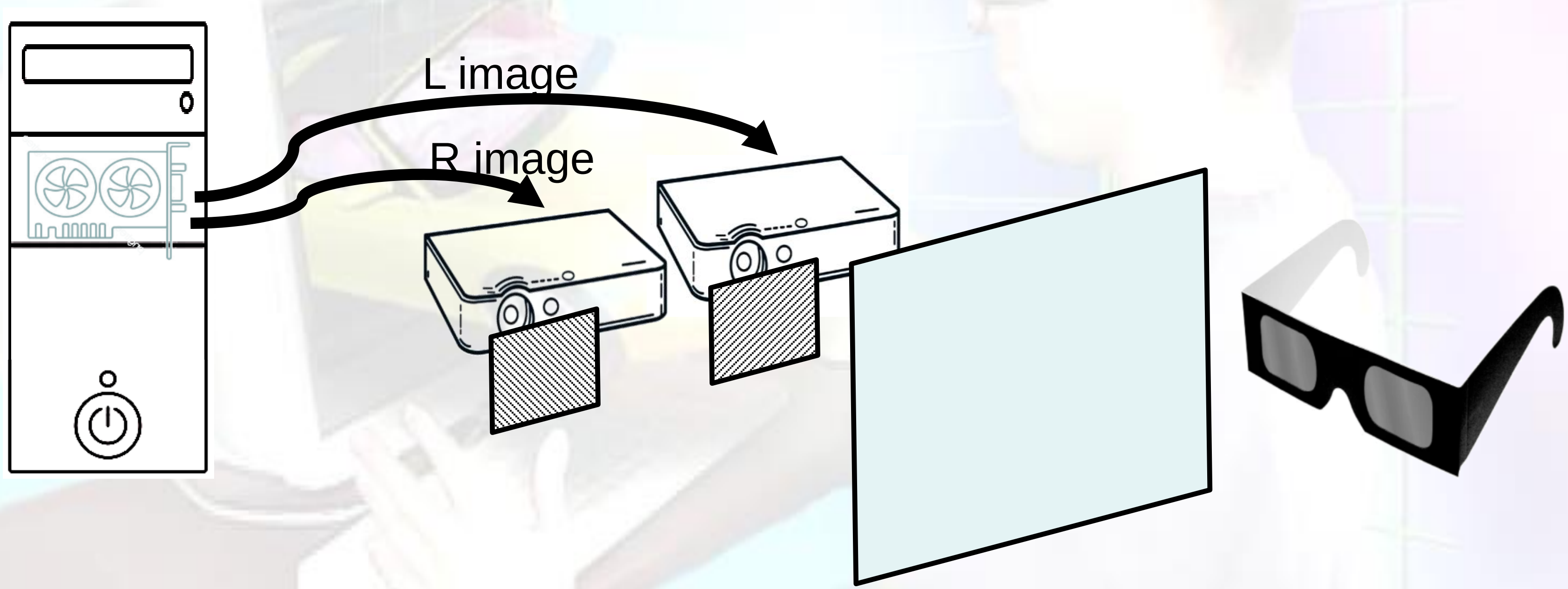
- OpenGL sample code (assuming a 2048x768 desktop)

```
void paintGL() {
  glViewport(0,0,1024,768);
  setupCamera(left);
  drawScene();
  glViewport(1024,0,1024,768);
  setupCamera(right);
  drawScene();
}
```

Sample configurations

- Passive stereo – 1 PC
- Passive stereo – 2 synced PCs
- Active stereo – 1 PC
- Active stereo – 4 PCs

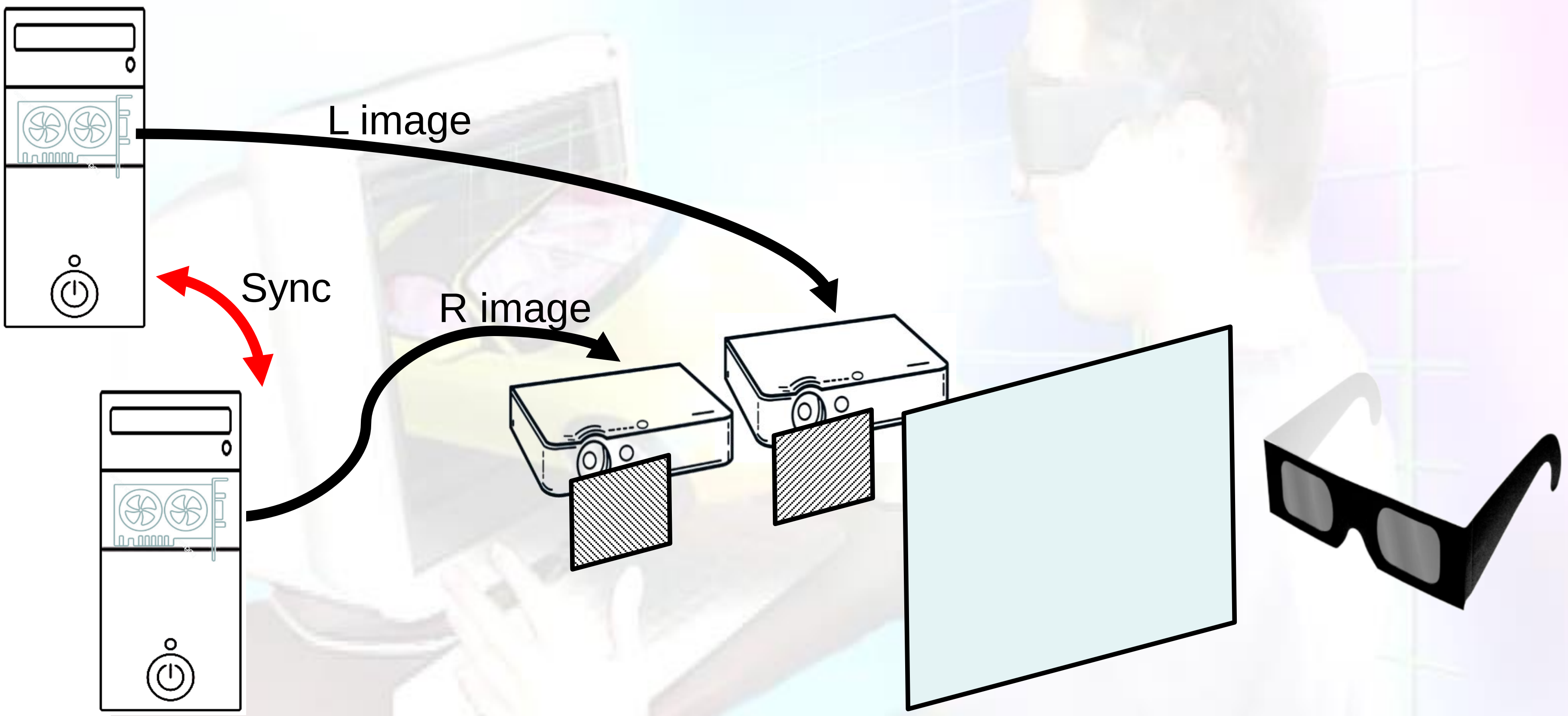
Passive stereo, 1 PC



Sample configurations

# PC	# Gfx cards	FB format	# Projectors	Filter	# Screens	Glasses	Comment
1	**1 (dual-head)**	**Side-by-side**	**2 (passive, 60 Hz)**	**Polarizing filter**	**1**	**Polarizing glasses**	**Passive stereo**
2	2	Normal	2 (passive, 60 Hz)	Polarizing filter	1	Polarizing glasses	Passive stereo; Needs PC sync
1	1	Quad buffering	1 (active, 120Hz)	-	1	Shutter glasses	Active stereo
4	4	Quad buffering	4 (active, 120 Hz)	-	4	Shutter glasses	Active CAVE Needs gfx sync!

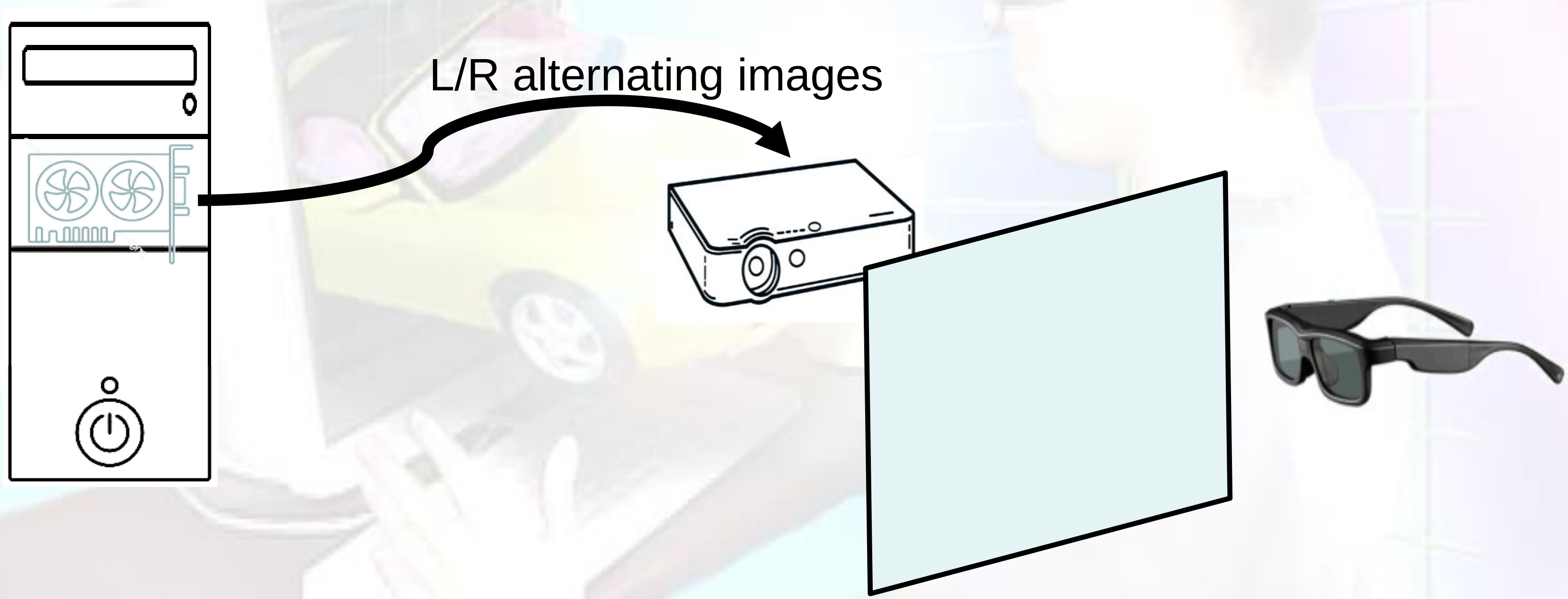
Passive stereo, 2 synced PCs



Sample configurations

# PC	# Gfx cards	FB format	# Projectors	Filter	# Screens	Glasses	Comment
1	1 (dual-head)	Side-by-side	2 (passive, 60 Hz)	Polarizing filter	1	Polarizing glasses	Passive stereo
2	**2**	**Normal**	**2 (passive, 60 Hz)**	**Polarizing filter**	**1**	**Polarizing glasses**	**Passive stereo; Needs PC sync**
1	1	Quad buffering	1 (active, 120Hz)	-	1	Shutter glasses	Active stereo
4	4	Quad buffering	4 (active, 120 Hz)	-	4	Shutter glasses	Active CAVE Needs gfx sync!

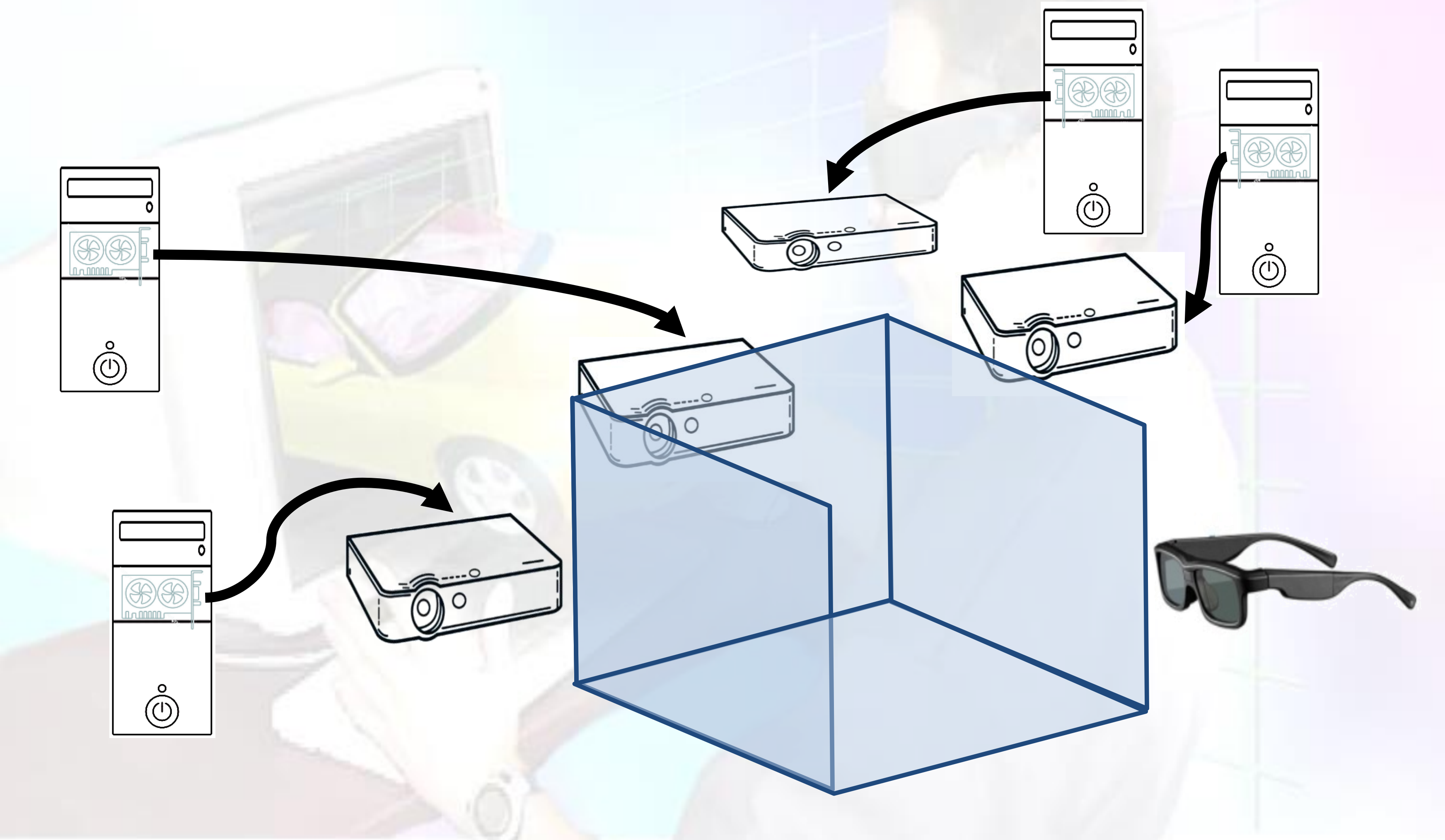
Active stereo, 1 PC



Sample configurations

# PC	# Gfx cards	FB format	# Projectors	Filter	# Screens	Glasses	Comment
1	1 (dual-head)	Side-by-side	2 (passive, 60 Hz)	Polarizing filter	1	Polarizing glasses	Passive stereo
2	2	Normal	2 (passive, 60 Hz)	Polarizing filter	1	Polarizing glasses	Passive stereo; Needs PC sync
1	**1**	**Quad buffering**	**1 (active, 120Hz)**	**-**	**1**	**Shutter glasses**	**Active stereo**
4	4	Quad buffering	4 (active, 120 Hz)	-	4	Shutter glasses	Active CAVE Needs gfx sync!

Active stereo, 4 PCs



Sample configurations

# PC	# Gfx cards	FB format	# Projectors	Filter	# Screens	Glasses	Comment
1	1 (dual-head)	Side-by-side	2 (passive, 60 Hz)	Polarizing filter	1	Polarizing glasses	Passive stereo
2	2	Normal	2 (passive, 60 Hz)	Polarizing filter	1	Polarizing glasses	Passive stereo; Needs PC sync
1	1	Quad buffering	1 (active, 120Hz)	-	1	Shutter glasses	Active stereo
4	**4**	**Quad buffering**	**4 (active, 120 Hz)**	**-**	**4**	**Shutter glasses**	**Active CAVE Needs gfx sync!**

STEREOSCOPY

Course 2024/2025