UNIVERSITY OF CAMBRIDGE
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RAINBOW GRAPHICS GROUP

Advanced Graphics & Image Processing

Virtual and Augmented Reality

Part 1/4 – virtual reality

Dongyeon Kim

Dept. of Computer Science and Technology, University of Cambridge

The slides used in this lecture are the courtesy of Gordon Wetzstein.
From Virtual Reality course: http://stanford.edu/class/ee267/


Meta

simulation & training

visualization & entertainment

remote control of vehicles, e.g. drones

gaming

robotic surgery

architecture walkthroughs

education

virtual travel

a trip down the rabbit hole

Exciting Engineering Aspects of VR/AR

- cloud computing
- shared experiences

- compression, streaming

images by microsoft, facebook

- VR cameras

- CPU, GPU
- IPU, DPU?

- sensors & imaging
- computer vision
- scene understanding

- photonics / waveguides
- human perception
- displays: visual, auditory, vestibular, haptic, …

- HCI
- applications

Where We Want It To Be

image by ray ban

Where Are We?

Personal Computer
e.g. Commodore PET 1983

Laptop
e.g. Apple MacBook

Smartphone
e.g. Google Pixel

image by ray ban

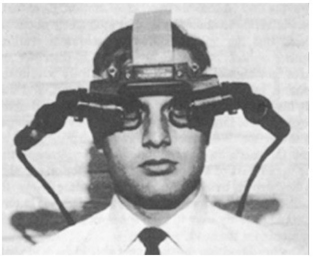
AR/VR
e.g. Microsoft Hololens

?

A Brief History of Virtual Reality

Stereoscopes
Wheatstone, Brewster, …

VR & AR
Ivan Sutherland



Nintendo
Virtual Boy

VR explosion
Oculus/Meta, Sony, HTC, …

???

1838

1968

1995

2012-

Stereoscopes

- Left / Right static images
- Occluder

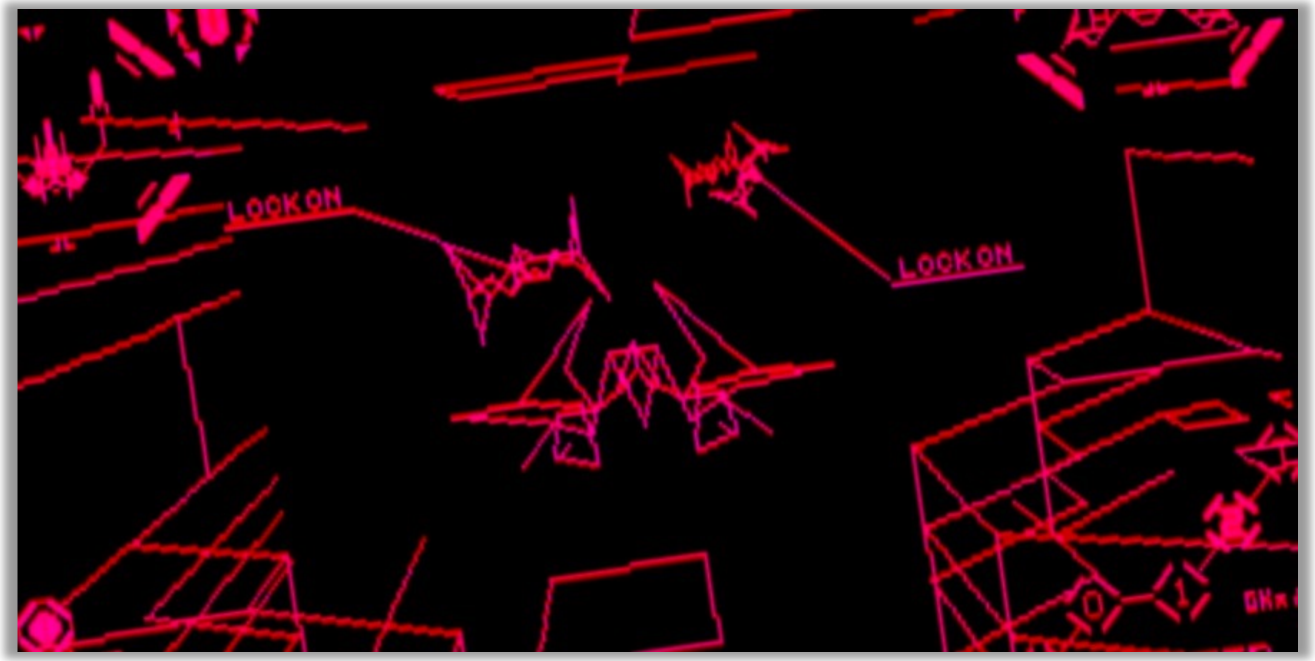
Ivan Sutherland’s HMD

- optical see-through AR, including:
  - displays (2x 1” CRTs)
  - rendering
  - head tracking
  - interaction
  - model generation
- computer graphics
- human-computer interaction

I. Sutherland “A head-mounted three-dimensional display”, Fall Joint Computer Conference 1968

Nintendo Virtual Boy

- computer graphics & GPUs were not ready yet!

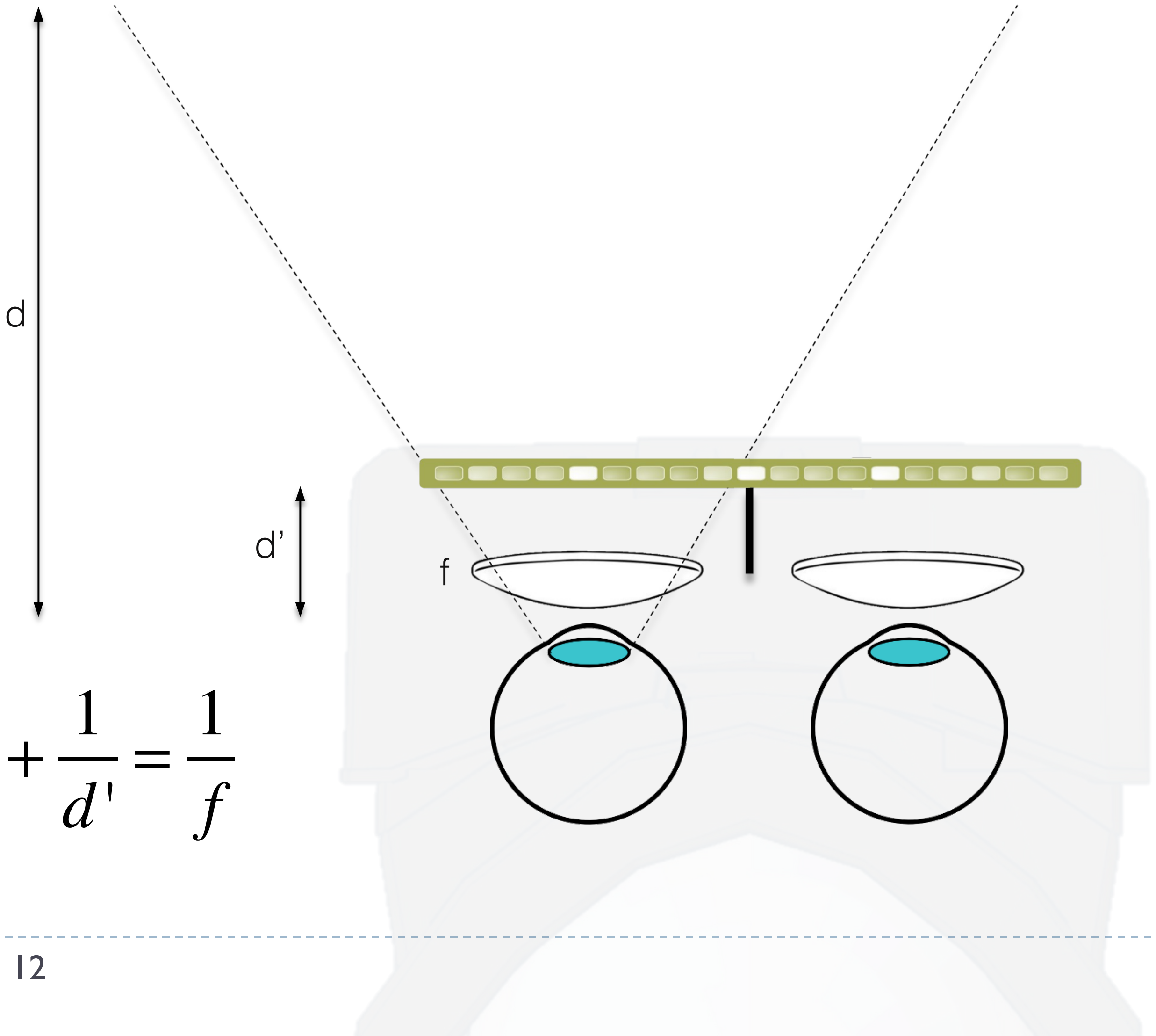


Game: Red Alarm

Where we are now

IFIXIT teardown

Virtual Image



$$\frac{1}{d} + \frac{1}{d'} = \frac{1}{f}$$

Problems:

- fixed focal plane
- no focus cues ☹
- cannot drive accommodation with rendering!
- limited resolution

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Advanced Graphics & Image Processing

Virtual and Augmented Reality

Part 2/4 – augmented reality

Dongyeon Kim

Dept. of Computer Science and Technology, University of Cambridge

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From Virtual Reality course: http://stanford.edu/class/ee267/

Pepper's Ghost 1862

Optical See-through AR displays

Google Glass [~2013]

Microsoft
Hololens [2016]
Hololens 2 [2019]

Lumus Maximums
[CES 2017]

Meta (formerly facebook)
Project Orion
[Meta Connect 2025,
Expected launch 2027]

Meta 2 [2016]
(not the current Meta/Facebook)

Intel Vaunt [2018]

Magic Leap 2
[2022]

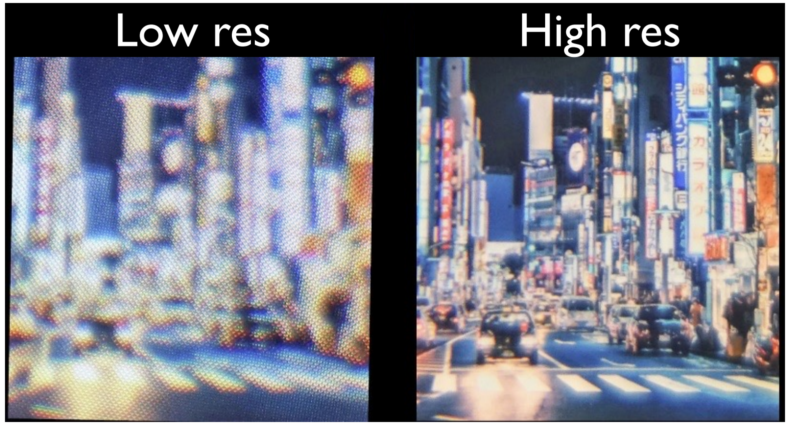
(Some) challenges of optical see-through AR

- Size, weight and weight distribution (form factor)
  - 50 grams are comfortable for long periods → Ergonomics
- Resolution and field-of-view → Immersion
- Eye-box
  - The volume in which the pupil needs to see the image
- Brightness and contrast
- Blocked vision – forward and periphery (safety)
- Power efficiency
- Transparency, lack of opacity
  - Display light is mixed with environment light
- Social issues, price, vision correction, individual variability…

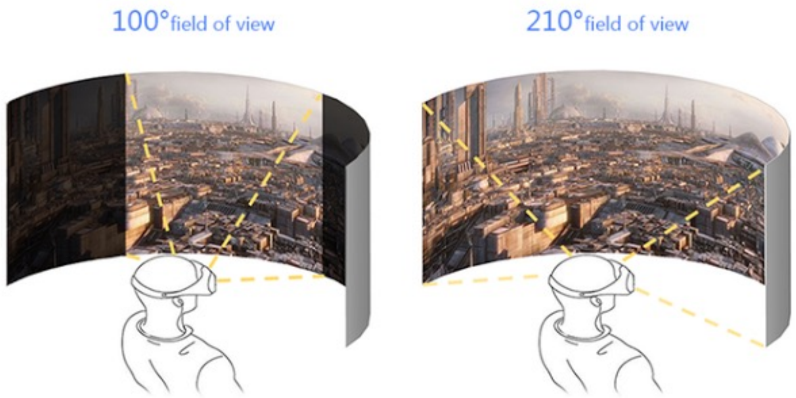
More resources: https://kguttag.com/

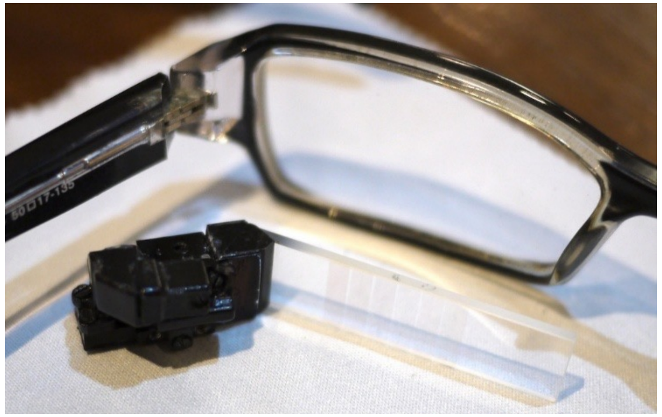
(Some) challenges of optical see-through AR - examples

Resolution

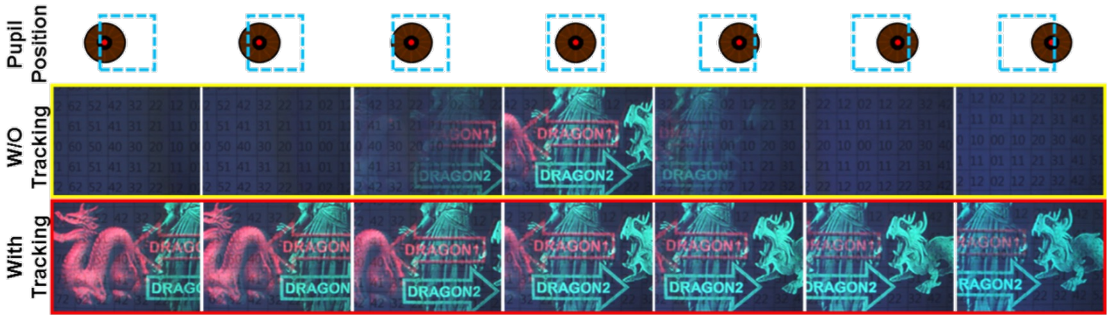


Field of view





Form factor



[Jang et al., SIGGRAPH 2017]

Eyebox

Video pass-through AR – will this bridge VR & OST-AR?

Meta Quest 3

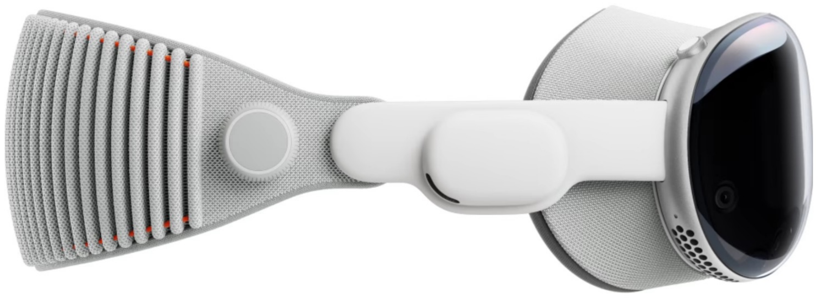
Apple Vision Pro

- Also for smartphones and tablets
- APIs
  - ARCore (by Google, Android/iOS)
  - ARKit (by Apple, iOS)
  - ARToolKit (OpenSource, Multiplatform) - http://www.artoolkitx.org/

Video pass-through AR

Pros:

- Better virtual image quality
- Occlusions are easy
- Simpler, less expensive optics
- Virtual image not affected by ambient light
- AR/VR in one device



Apple Vision Pro

Cons:

- Vergence-accommodation conflict (see the next part)
- Lower brightness, dynamic range and resolution than real-world
- Motion to photon delay
- Real-world images must be warped for the eye position (artifacts)
- Peripheral vision is occluded
  - Or display if affected by ambient light

VR/AR challenges

- Latency (next lecture)
- Tracking
- 3D Image quality and resolution
- Reproduction of depth cues (last lecture)
- Rendering & bandwidth
- Simulation/cyber sickness
- Content creation
  - Game engines
  - Image-Based-Rendering

Simulation sickness

- Conflict between vestibular and visual systems
  - When camera motion inconsistent with head motion
  - Frame of reference (e.g. cockpit) helps
  - Worse with larger FOV
  - Worse with high luminance and flicker
  - a.k.a visually induced motion sickness (VIMS)

Advanced Graphics & Image Processing

Virtual and Augmented Reality

Part 3/4 – depth perception

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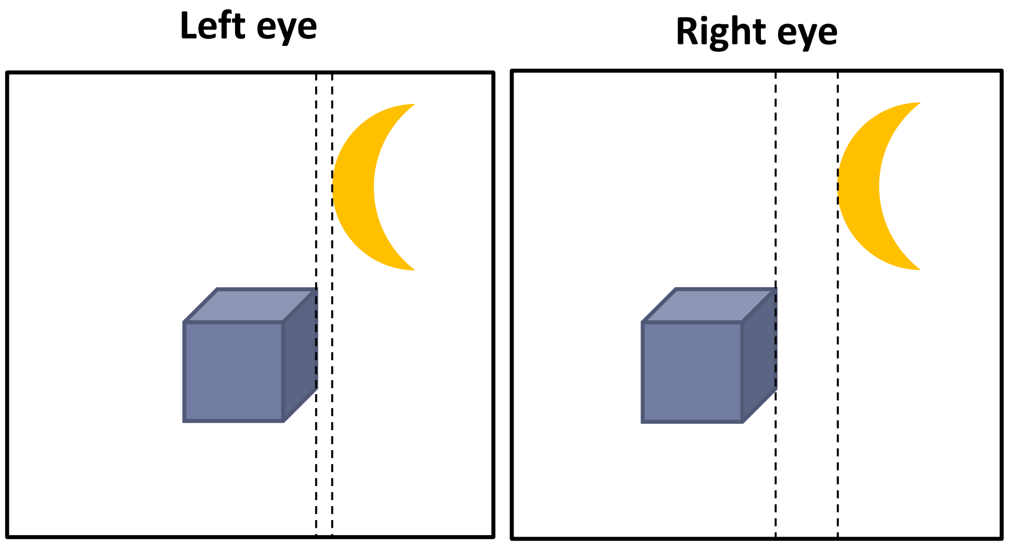
The slides in this section are the courtesy of
Piotr Didyk (http://people.mpi-inf.mpg.de/~pdidyk/)

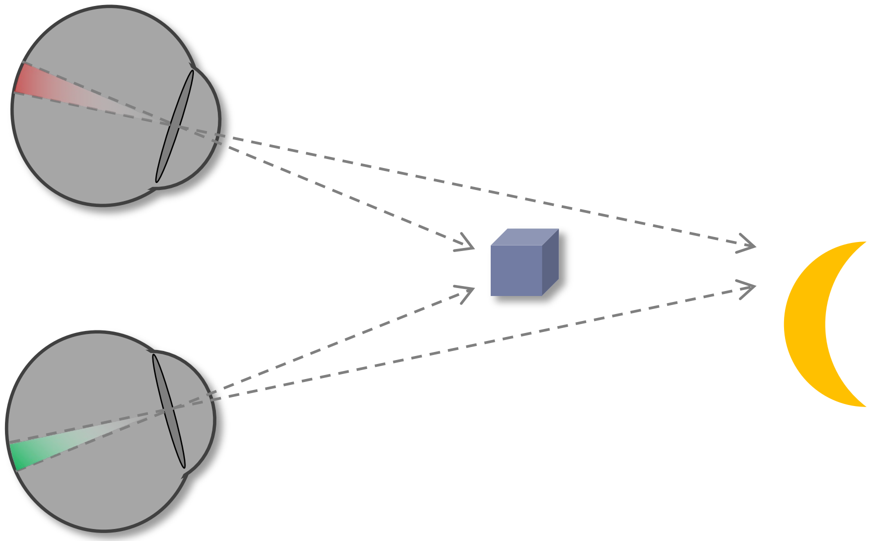
Depth perception

We see depth due to depth cues.

Stereoscopic depth cues:

binocular disparity





Depth perception

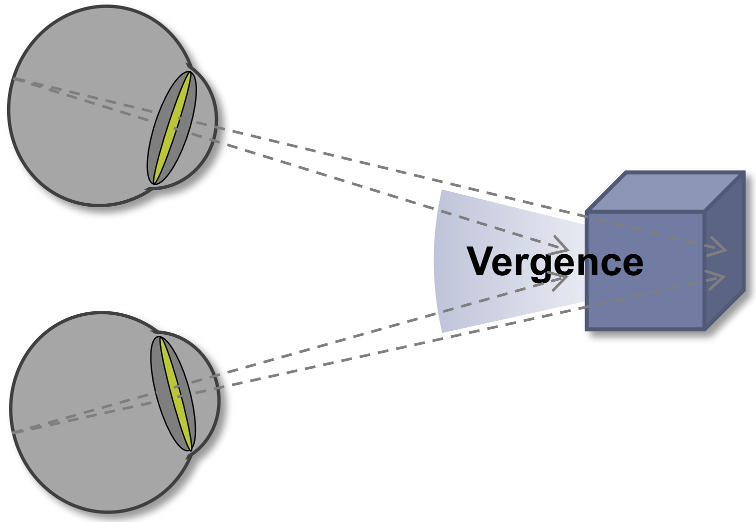
We see depth due to depth cues.

Stereoscopic depth cues:

binocular disparity

Ocular depth cues:

accommodation, vergence



Depth perception

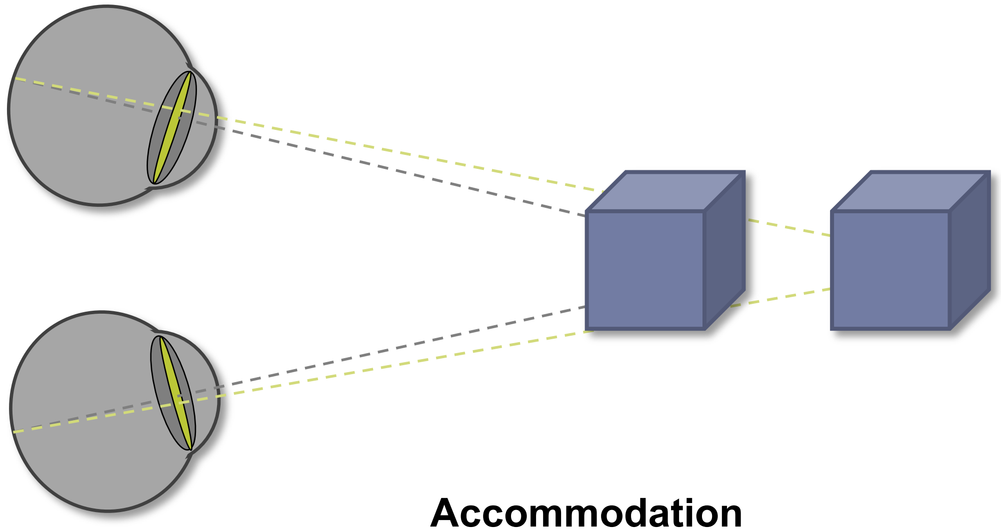
We see depth due to depth cues.

Stereoscopic depth cues:

binocular disparity

Ocular depth cues:

accommodation, vergence



Accommodation

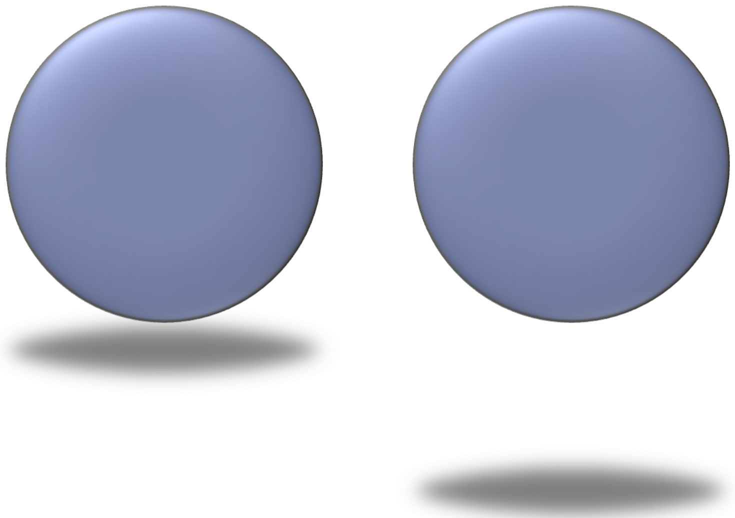
Depth perception

We see depth due to depth cues.

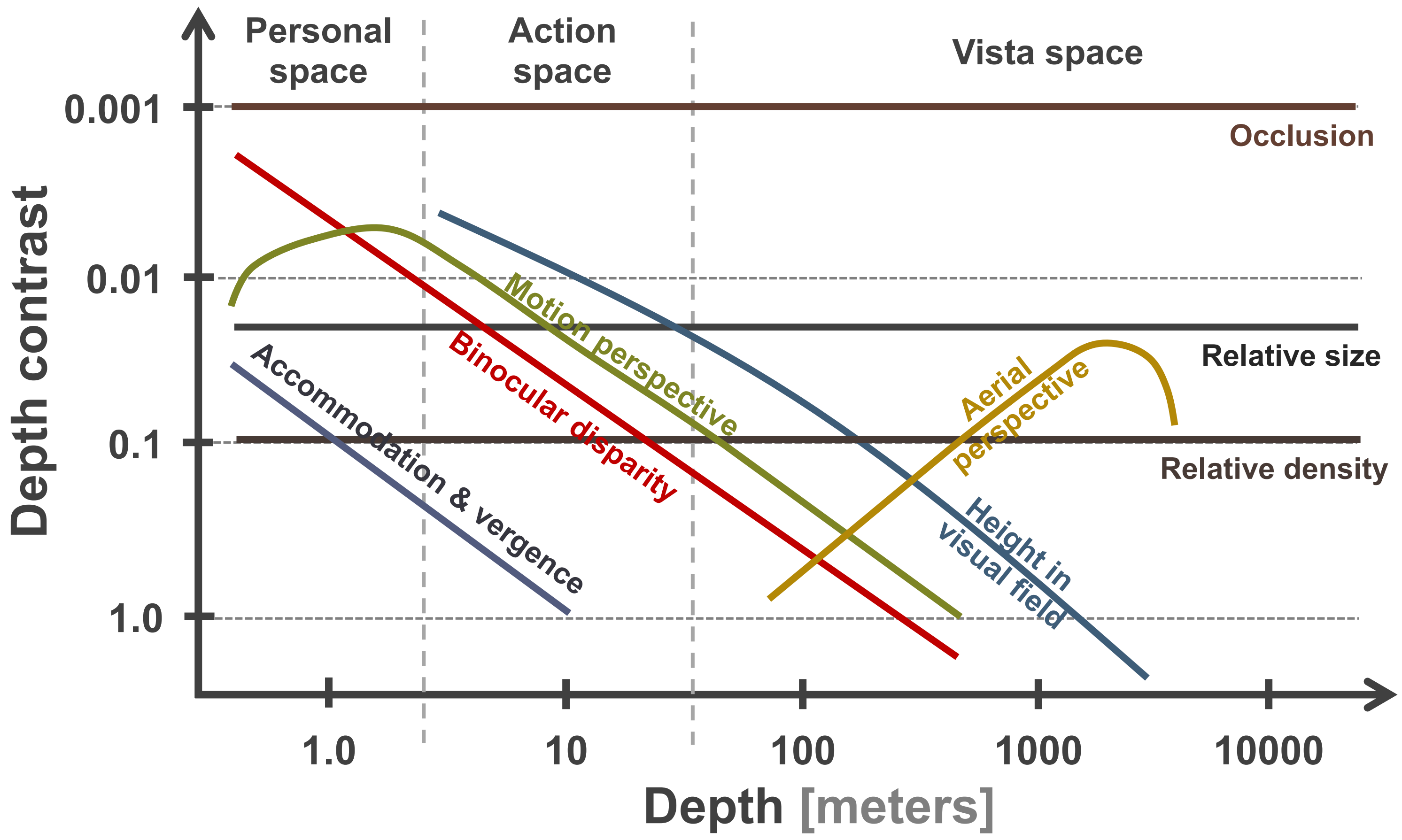
Stereoscopic depth cues:
binocular disparity

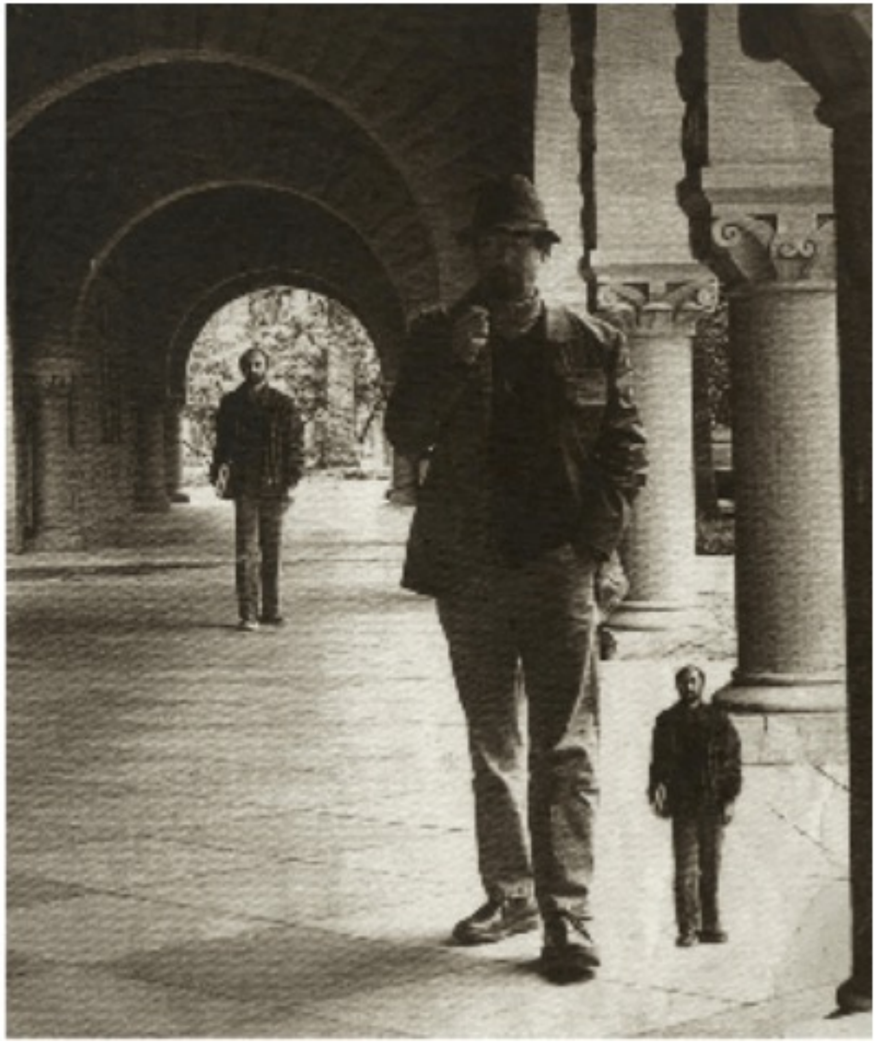
Ocular depth cues:
accommodation, vergence

Pictorial depth cues:
occlusion, size, shadows…



Cues sensitivity





"Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth"
by Cutting and Vishton [1995]

Depth perception

We see depth due to depth cues.

Stereoscopic depth cues:
binocular disparity

Ocular depth cues:
accommodation, vergence

Pictorial depth cues:
occlusion, size, shadows…

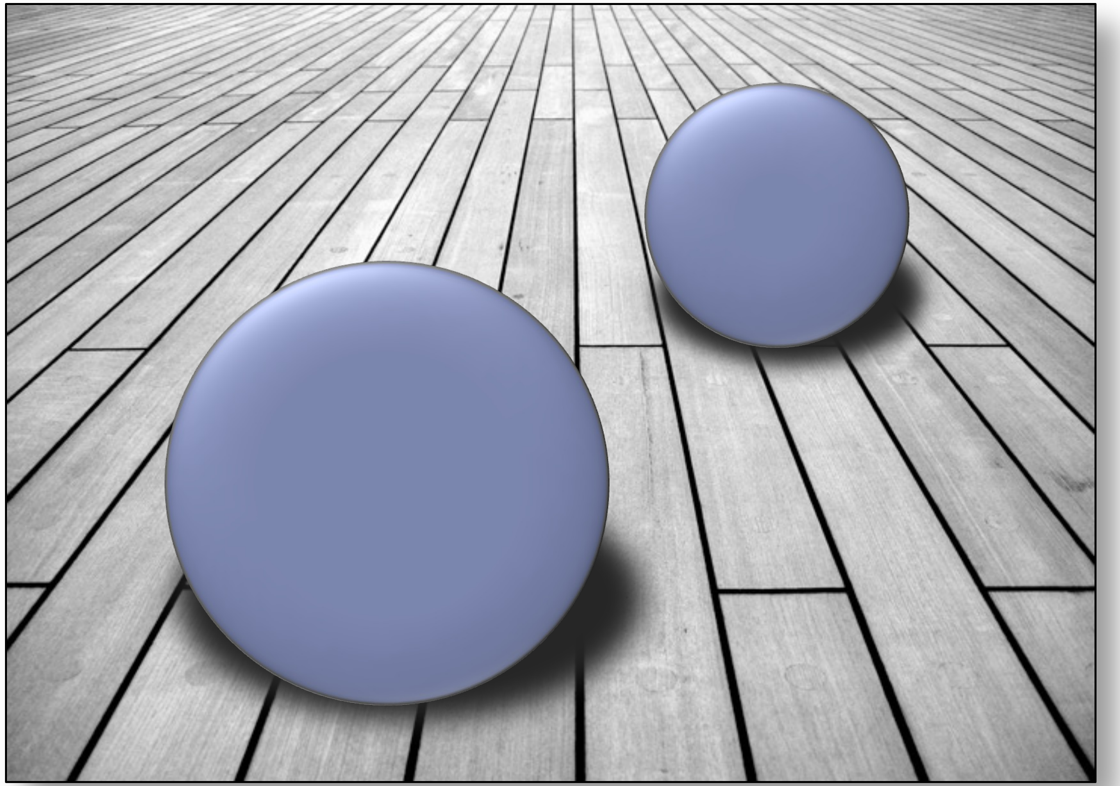
Challenge:
Consistency is required!

Simple conflict example

Present cues:

- Size
- Shadows
- Perspective

- **Occlusion**



Disparity & occlusion conflict

Objects in front

Disparity & occlusion conflict

Disparity & occlusion conflict

Depth perception

We see depth due to depth cues.

Stereoscopic depth cues:
binocular disparity

Ocular depth cues:
accommodation, vergence

Physiological cues

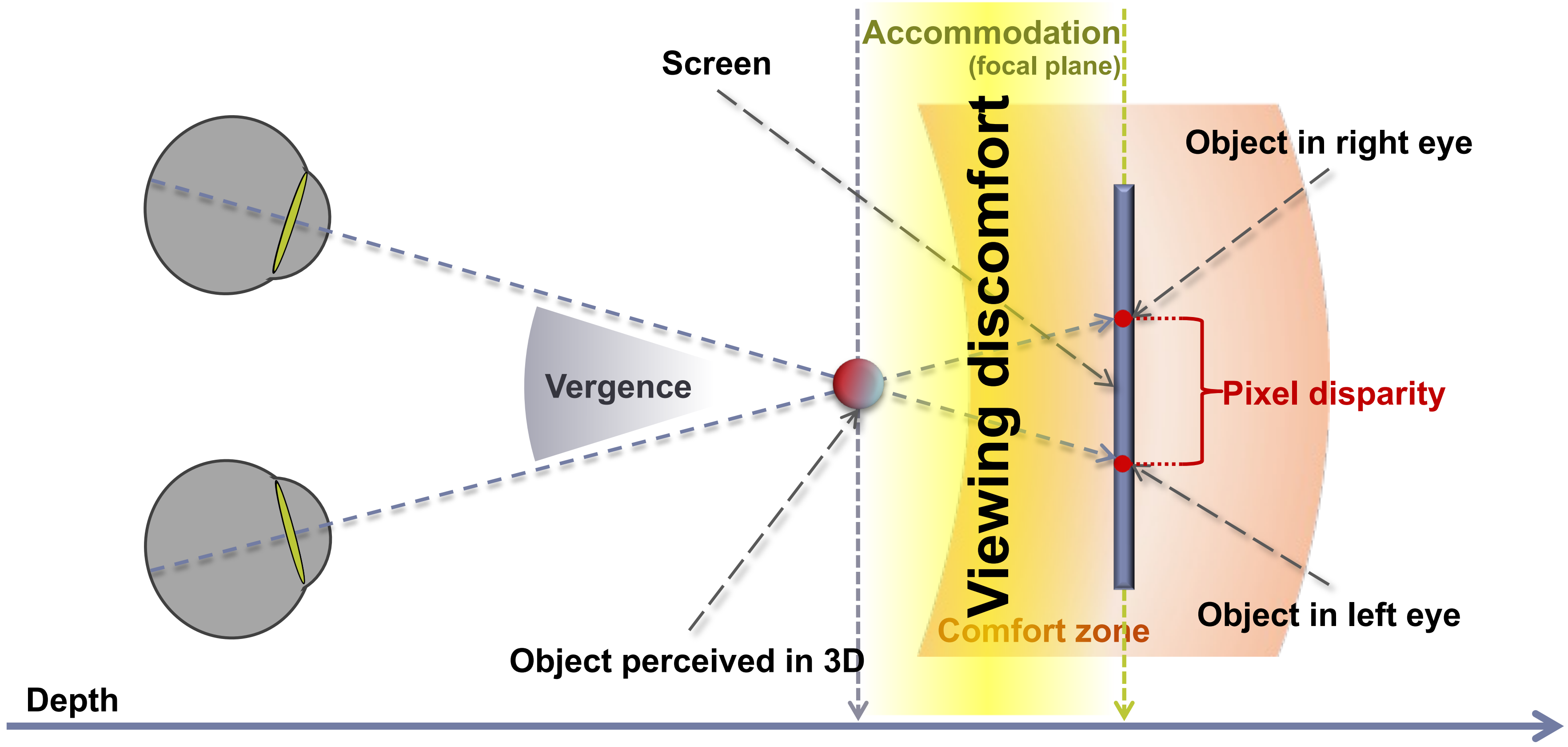
→ **Require 3D space**

We cheat our Visual System!

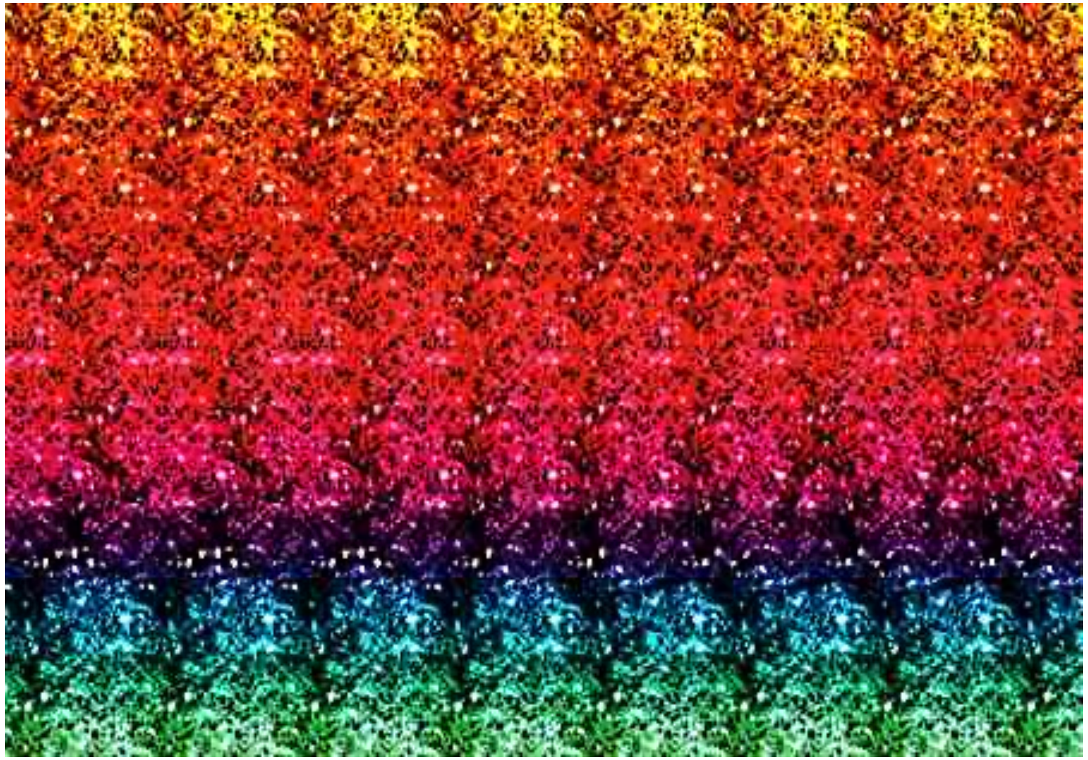
Pictorial depth cues:
occlusion, size, shadows…

→ **Reproducible on a flat displays**

Cheating our HVS

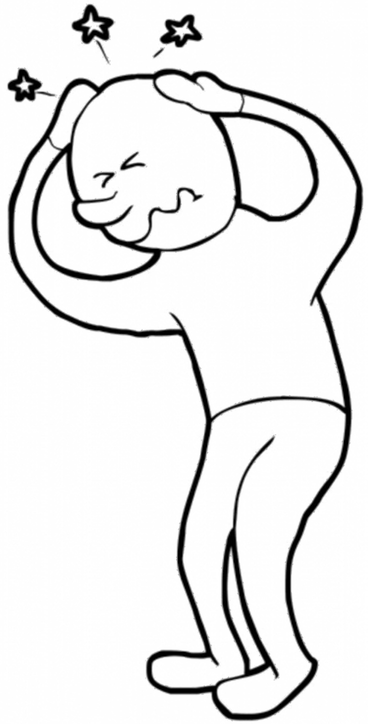


Single Image Random Dot Stereograms



- Fight the vergence vs. accommodation conflict to see the hidden image

Viewing discomfort

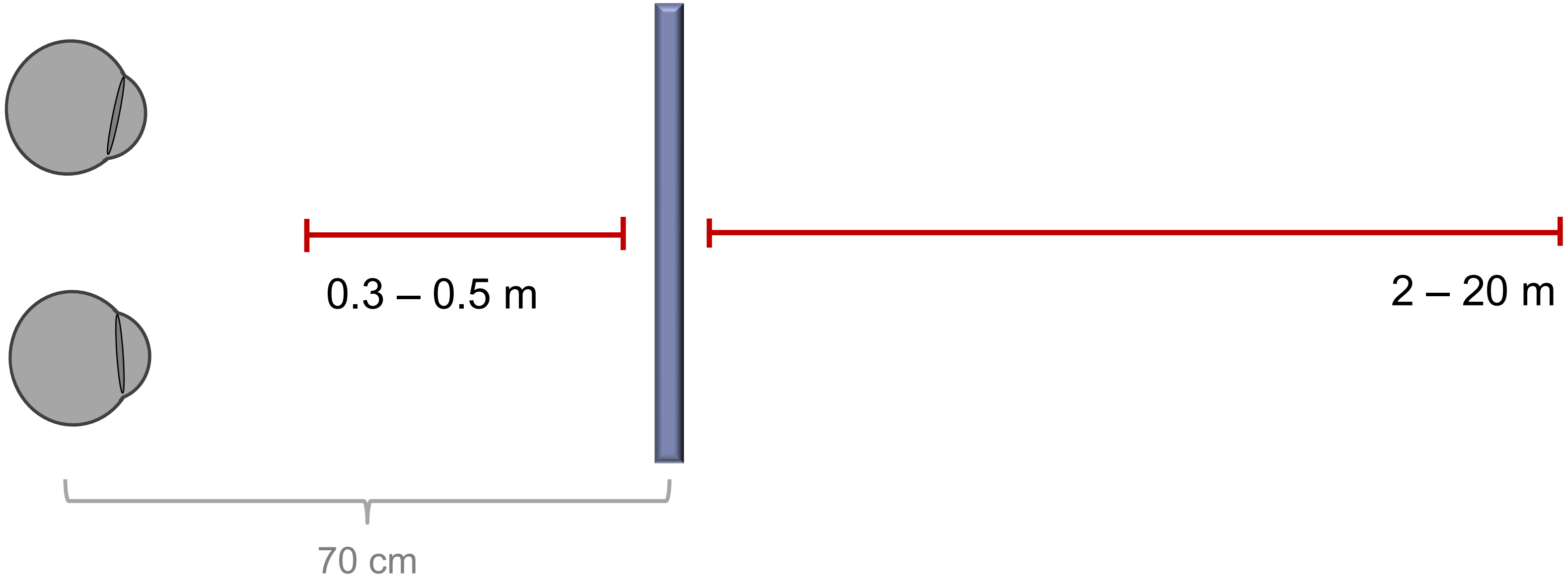


Comfort zones

Comfort zone size depends on:

- Presented content
- Viewing condition

Simple scene



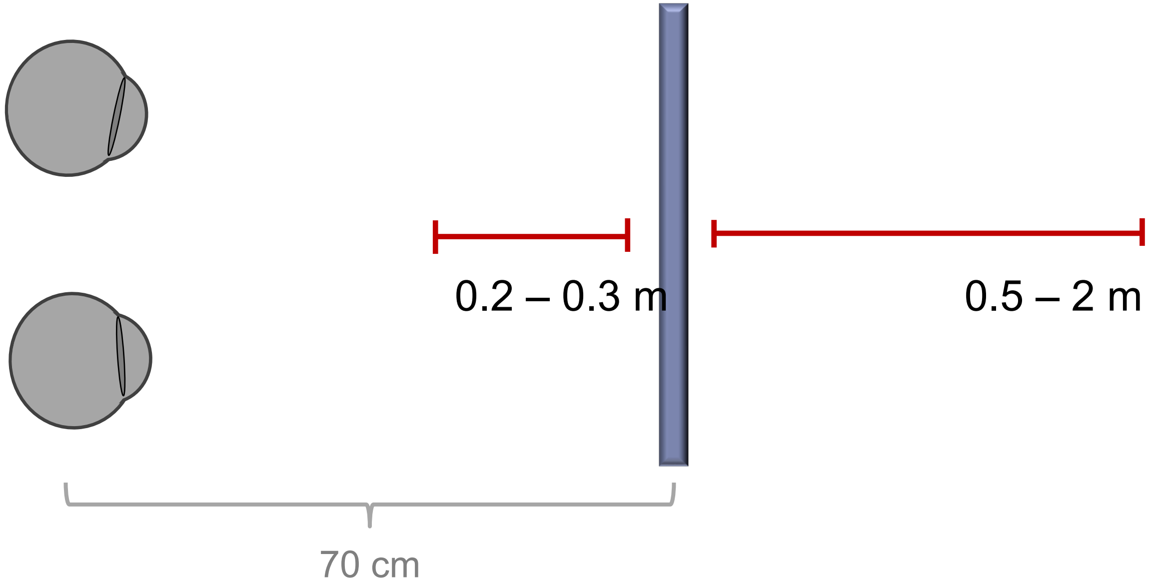
"Controlling Perceived Depth in Stereoscopic Images" by Jones et al. 2001

Comfort zones

Comfort zone size depends on:

- Presented content
- Viewing condition

Simple scene, user allowed to look away from screen



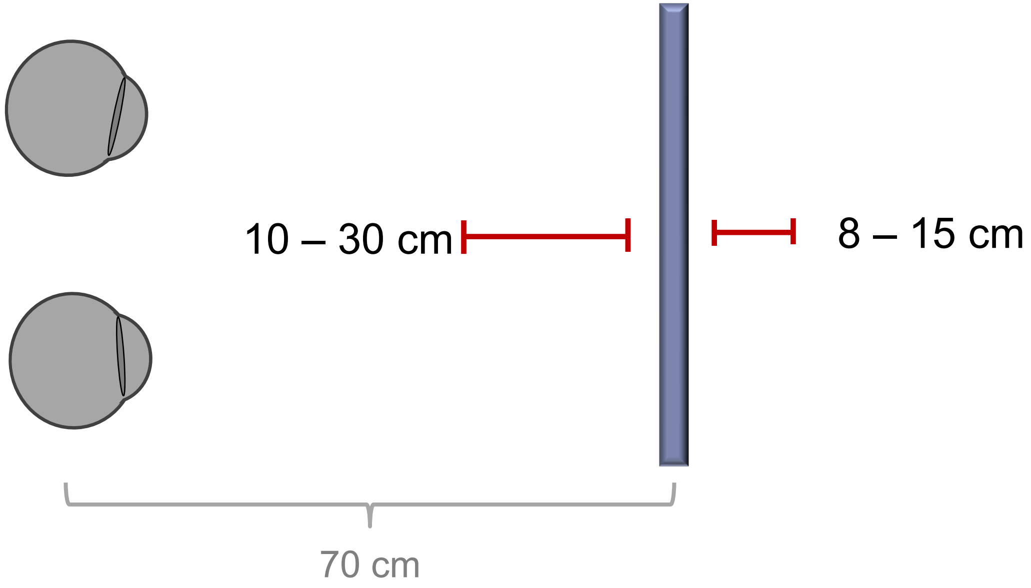
"Controlling Perceived Depth in Stereoscopic Images" by Jones et al. 2001

Comfort zones

Comfort zone size depends on:

- Presented content
- Viewing condition

Difficult scene



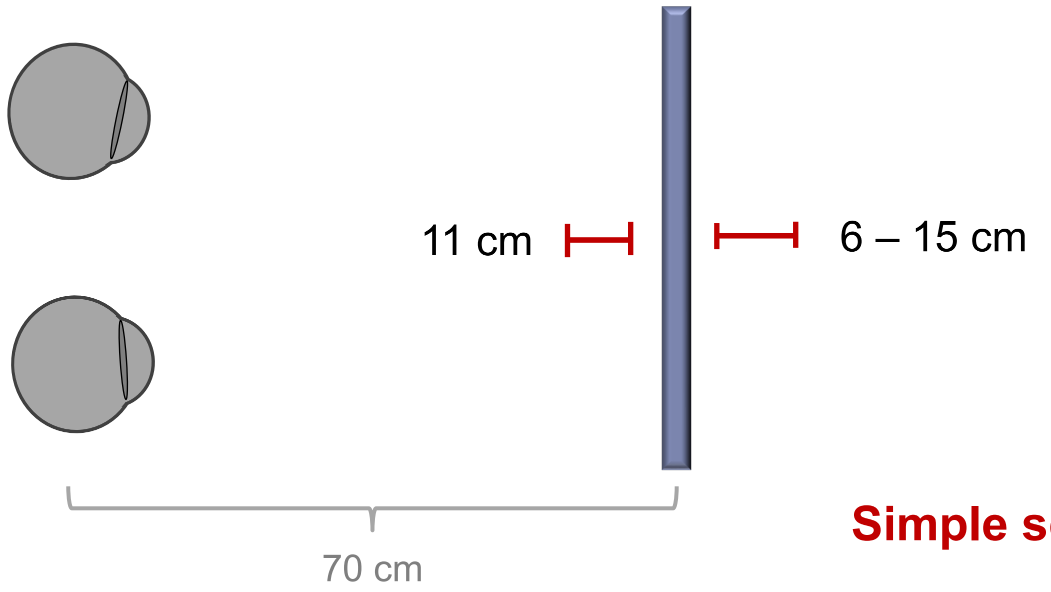
"Controlling Perceived Depth in Stereoscopic Images" by Jones et al. 2001

Comfort zones

Comfort zone size depends on:

- Presented content
- Viewing condition

Difficult scene, user allowed to look away from screen



Simple scene vs. Difficult scene ?

"Controlling Perceived Depth in Stereoscopic Images" by Jones et al. 2001

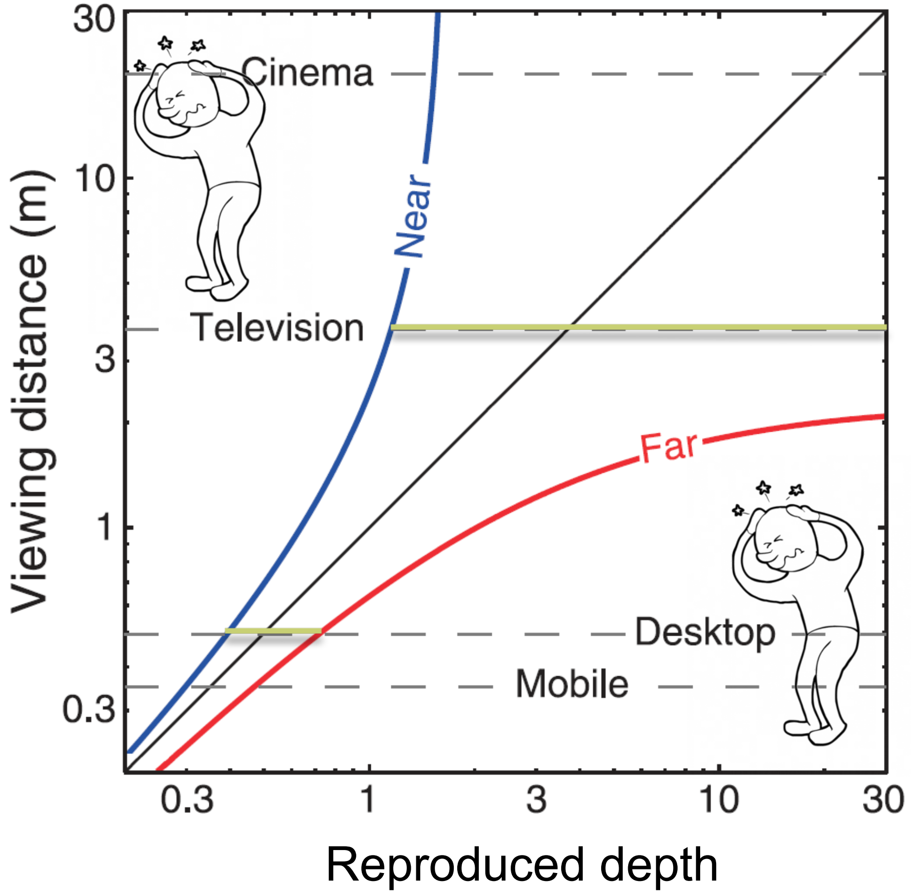
Comfort zones

Comfort zone size depends on:

- Presented content
- Viewing condition
- Screen distance

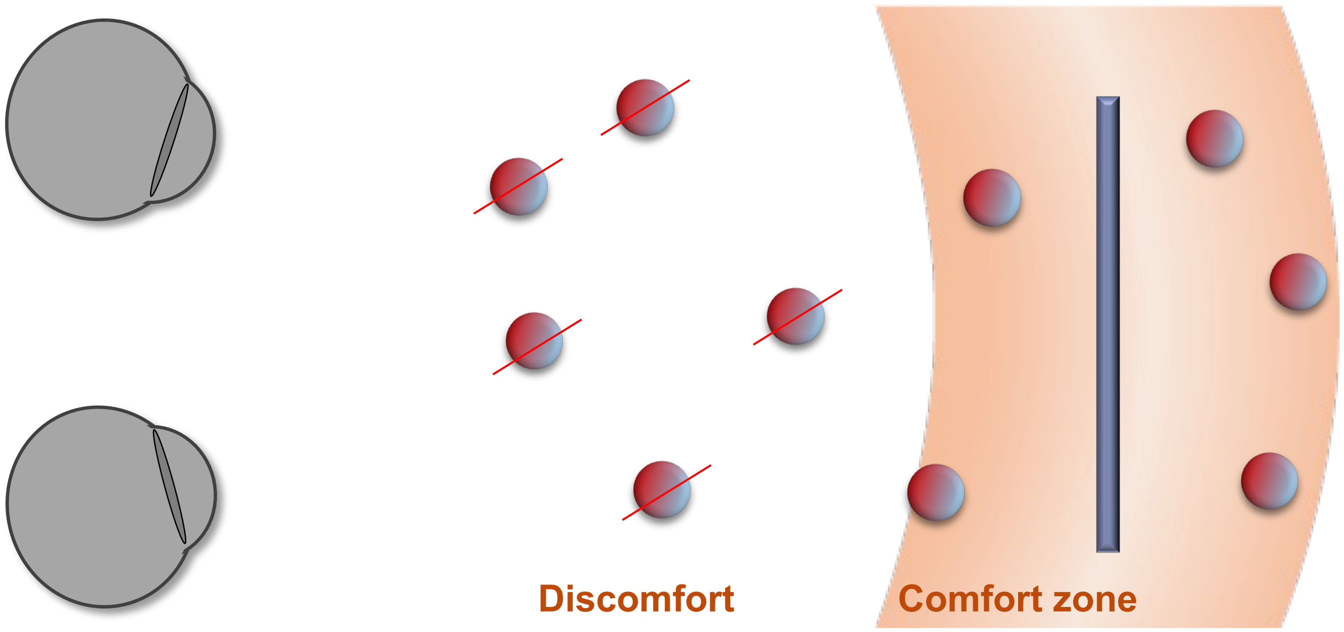
Other factors:

- Distance between eyes
- Depth of field
- Temporal coherence



"The zone of comfort: Predicting visual discomfort with stereo displays" by Shibata et al. 2011

Depth manipulation



Viewing discomfort $\xrightarrow{\text{Scene manipulation}}$ **Viewing comfort**

Advanced Graphics & Image Processing

Virtual and Augmented Reality

Part 4/4 – stereo rendering

Dongyeon Kim

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The slides used in this section are the courtesy of Gordon Wetzstein.
From Virtual Reality course: http://stanford.edu/class/ee267/

Put on Your 3D Glasses Now!

pintrest.com

Anaglyph Stereo - Monochrome

- render L & R images, convert to grayscale
- merge into red-cyan anaglyph by assigning I(r)=L, I(g,b)=R (I is anaglyph)

from movie “Bick Buck Bunny”

Anaglyph Stereo – Full Color

- render L & R images, convert to grayscale
- merge into red-cyan anaglyph by assigning I(r)=L, I(g,b)=R (I is anaglyph)

from movie "Bick Buck Bunny"

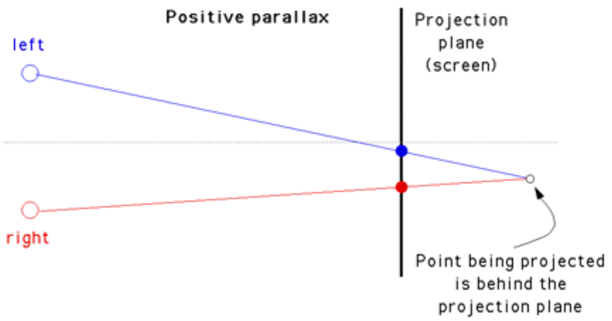
Open Source Movie: Big Buck Bunny

Rendered with Blender (Open Source 3D Modeling Program)

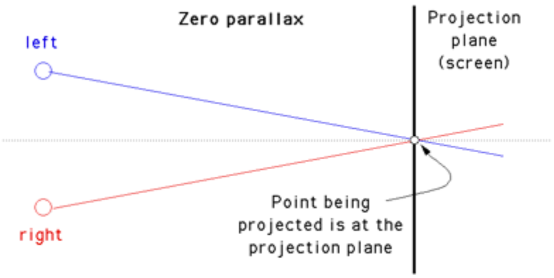
http://bbb3d.renderfarming.net/download.html

Parallax

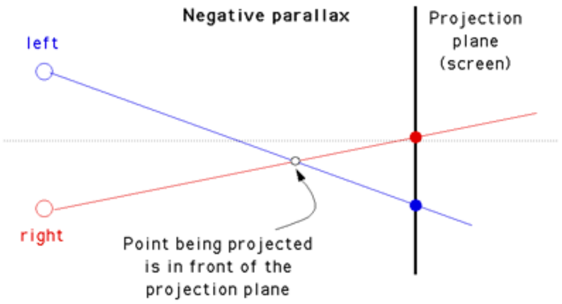
- Parallax is the relative distance of a 3D point projected into the 2 stereo images



case 1



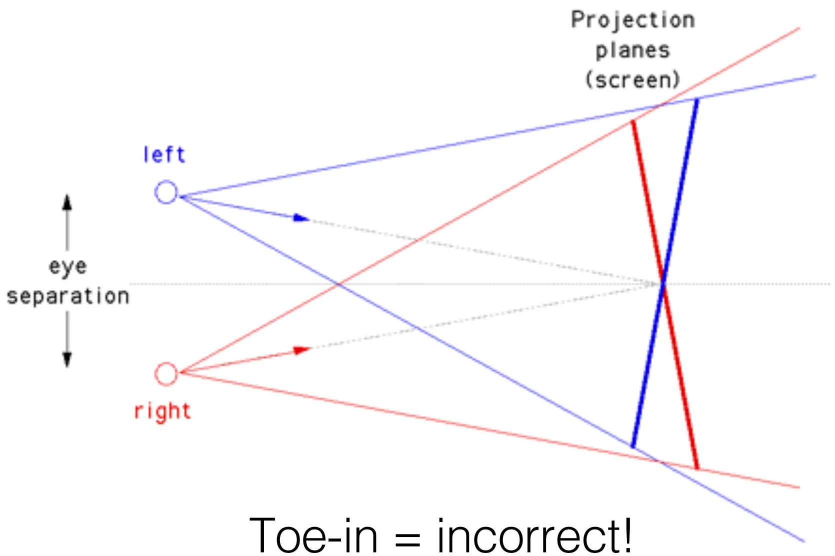
case 2



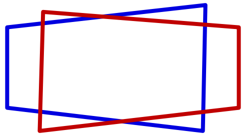
case 3

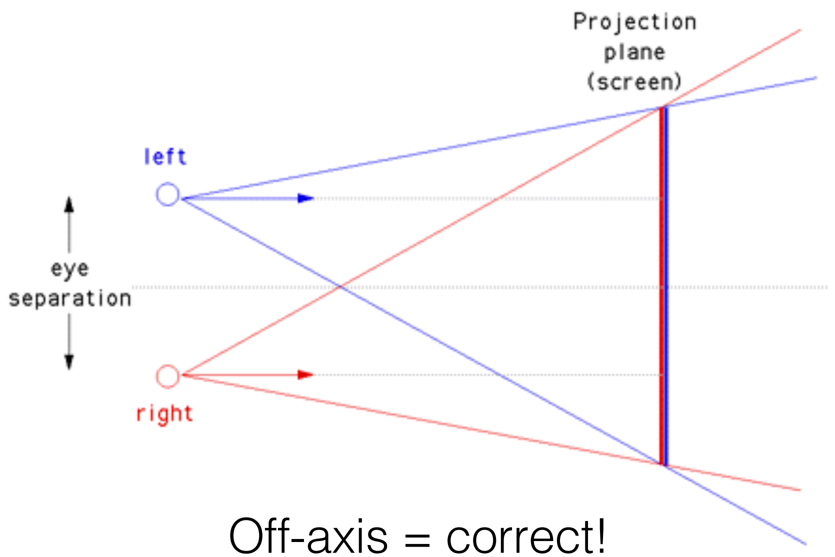
Parallax

- Visual system only uses horizontal parallax, no vertical parallax!
- Naïve toe-in method creates vertical parallax and visual discomfort



Toe-in = incorrect!

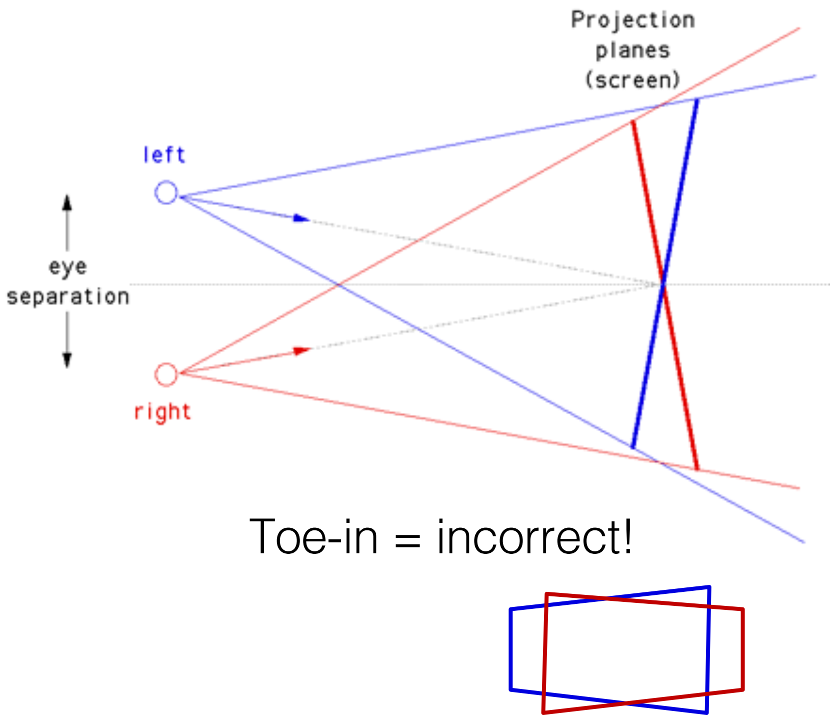




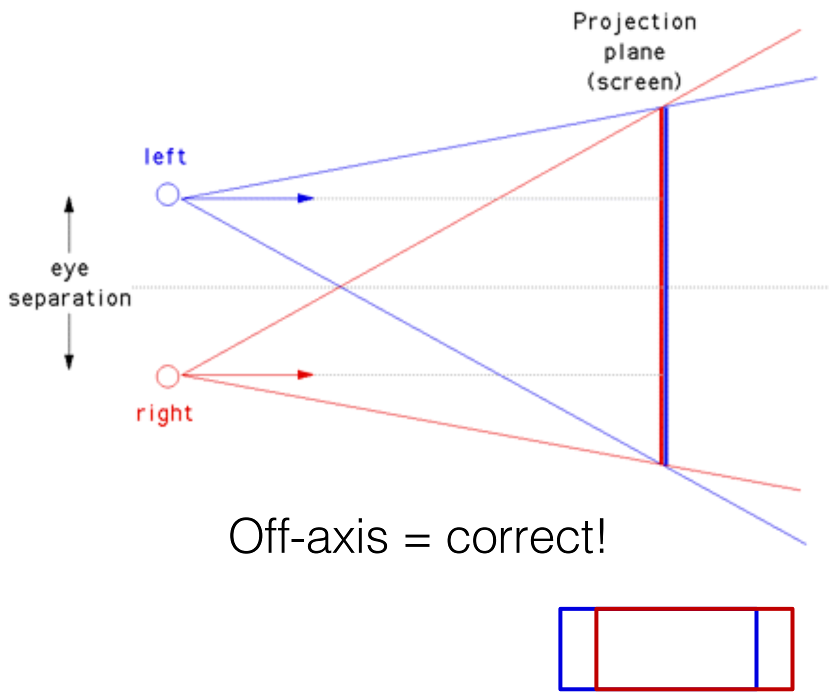
Off-axis = correct!

Parallax – well done

- Visual system only uses horizontal parallax, no vertical parallax!
- Naïve toe-in method creates vertical parallax and visual discomfort



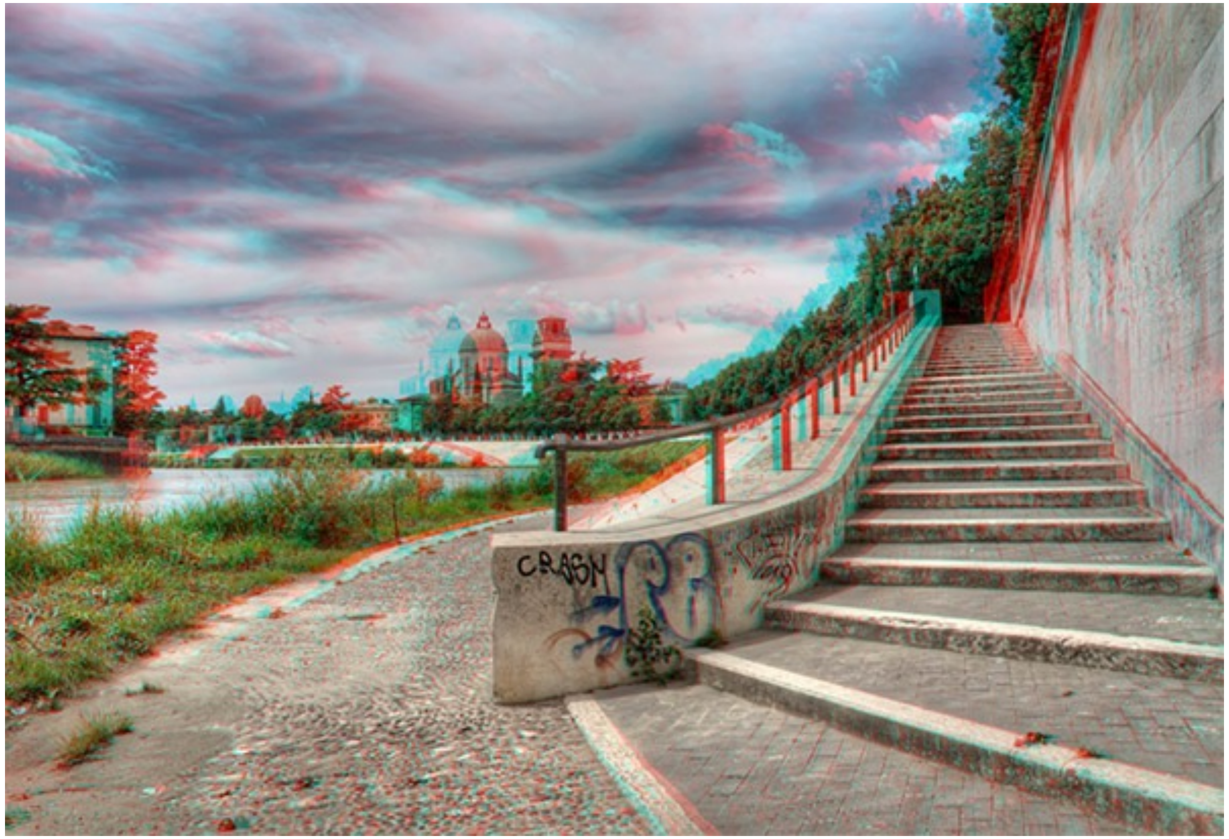
Toe-in = incorrect!



Off-axis = correct!

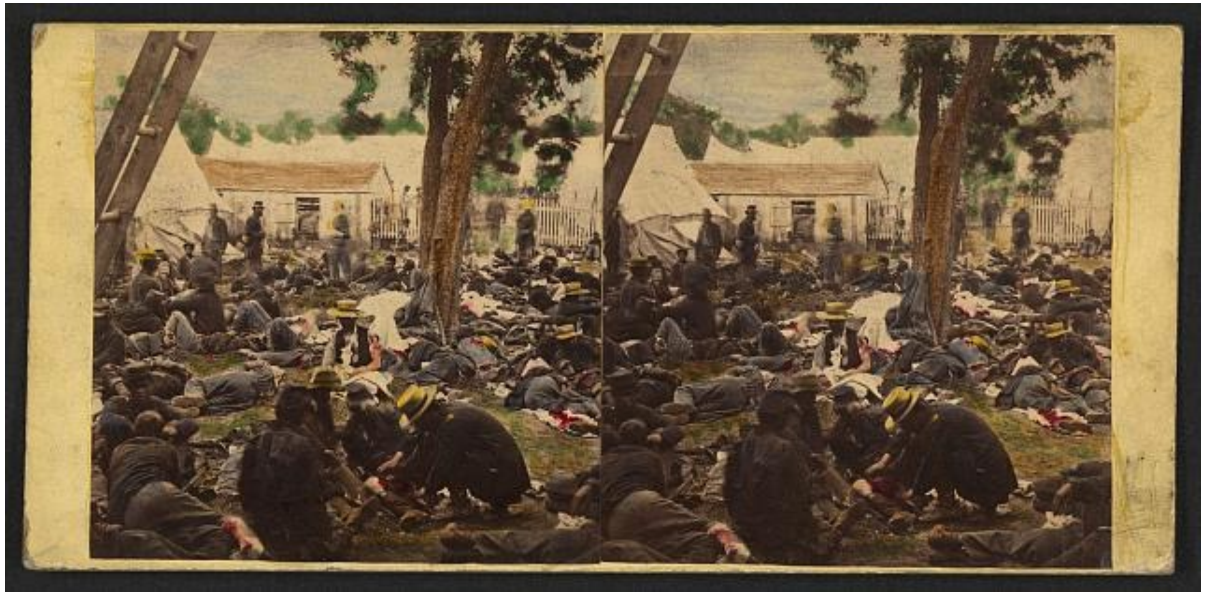
http://paulbourke.net/stereographics/stereorender/

Parallax – well done



http://paulbourke.net/stereographics/stereorender/

Parallax – well done



1862
“Tending wounded Union soldiers at Savage's Station, Virginia, during the Peninsular Campaign”,
Library of Congress Prints and Photographs Division

http://paulbourke.net/stereographics/stereorender/

Parallax – not well done (vertical parallax = unnatural)

References

- LaValle "Virtual Reality", Cambridge University Press, 2016
  - http://vr.cs.uiuc.edu/
- Virtual Reality course from the Stanford Computational Imaging group
  - http://stanford.edu/class/ee267/
- KGOnTech blog
  - https://kguttag.com/

- The selected slides used in this lecture are the courtesy of Gordon Wetzstein (Virtual Reality course: http://stanford.edu/class/ee267/)