Virtual and Augmented Reality:
A Technology Tutorial

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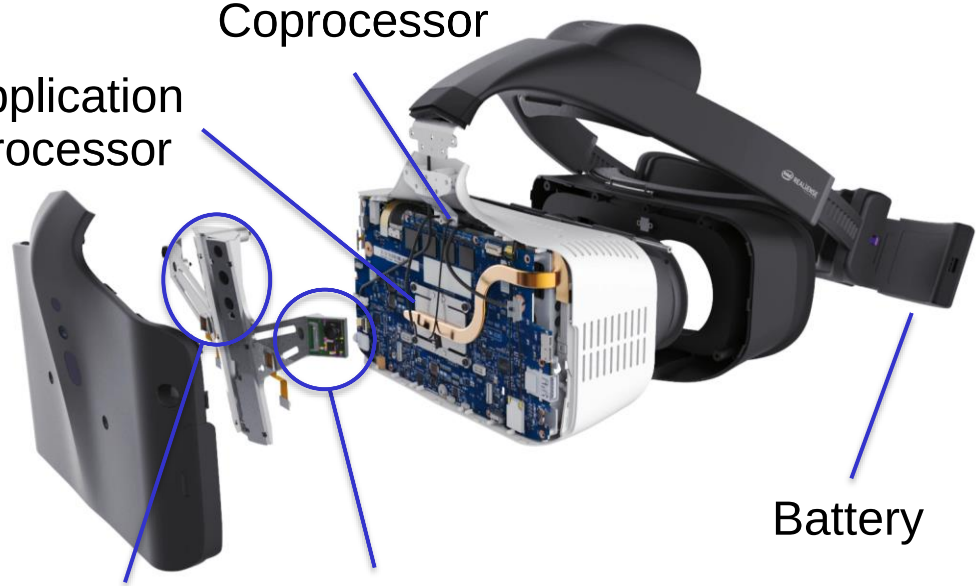
Adjunct Professor, Stanford University School of Medicine

From My Oct ‘16 BA-SID Presentation



Untethered, all-in-one design

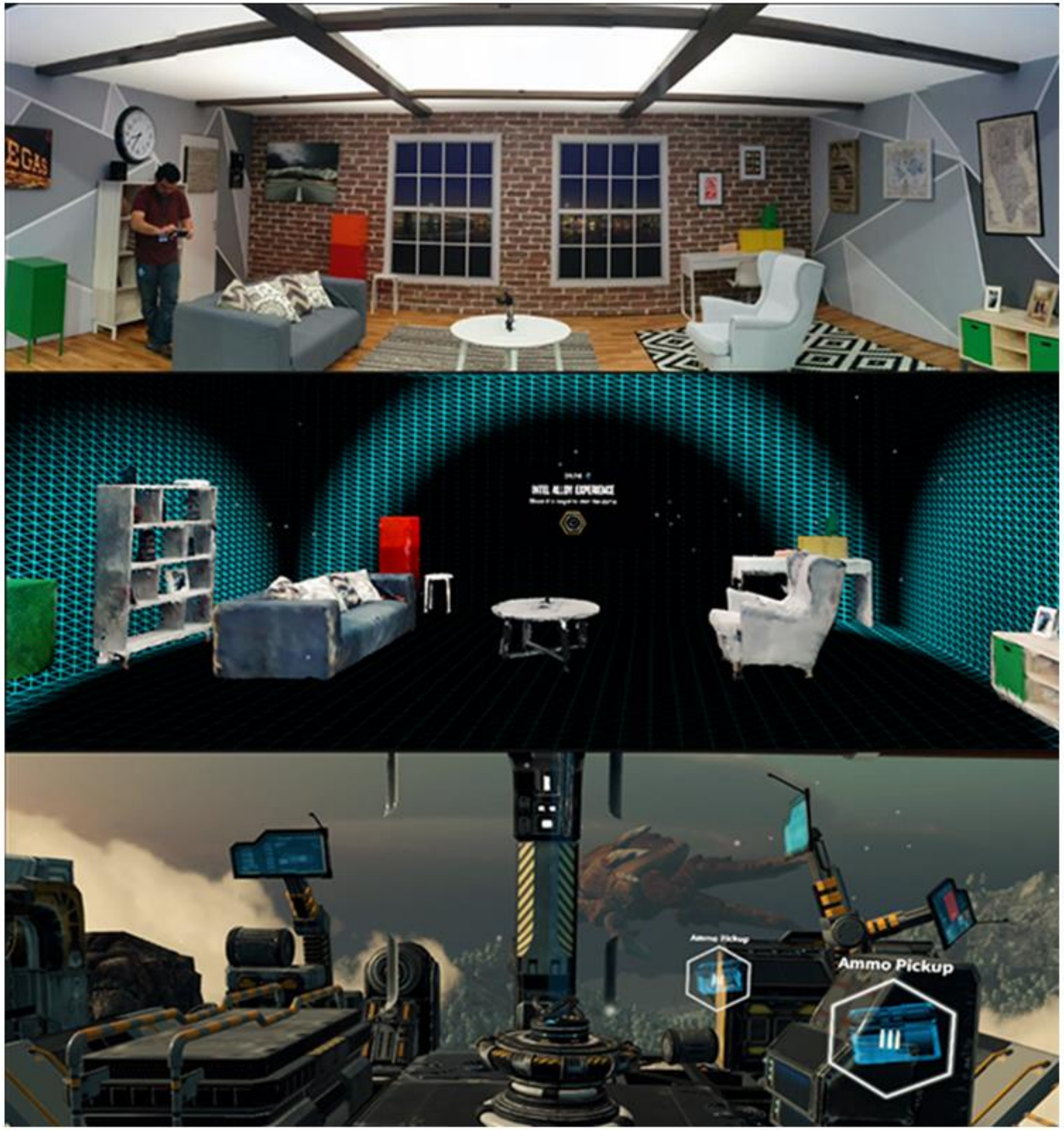
- Multi-room scale mobility, no setup

Intel® RealSense™ Technology

- Inside-out 6DOF tracking
- Hand tracking & natural interactions
- Merged reality experiences

High-performance computing

- PC-class processor, graphics, computer vision & artificial intelligence accelerators


INTEL ALLOY EXPERIENCE
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Inspector

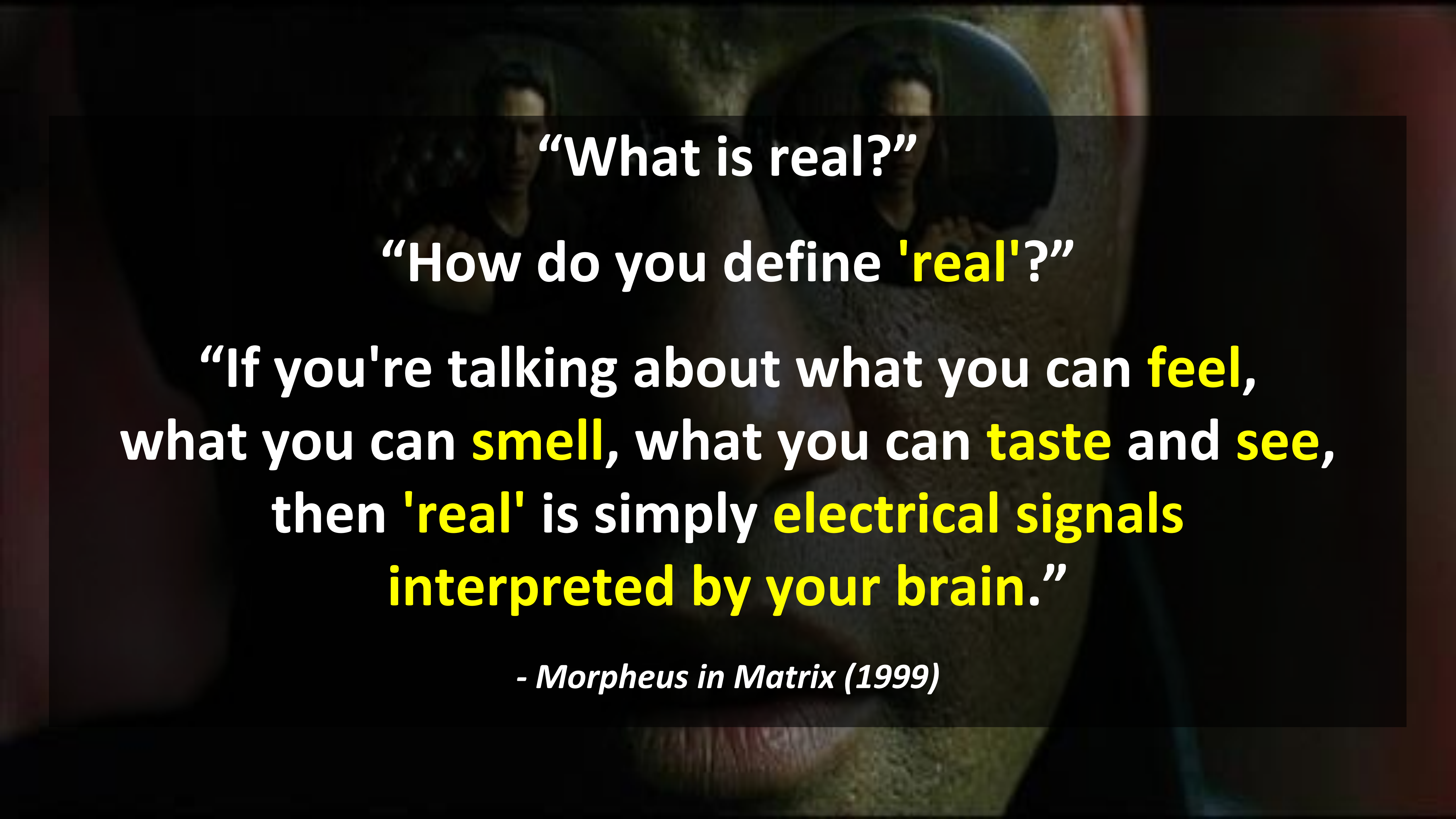
Virtual & Augmented Reality: Objectives

- Place users in simulated virtual environments, and virtual objects in the real-world.
- Generate sensory stimuli (visual, auditory, vestibular, haptic, …) that create the illusion of “presence” and “immersion”.
- Ensure consistency of perceptual cues between the physical and digital elements, and enable natural interactions.

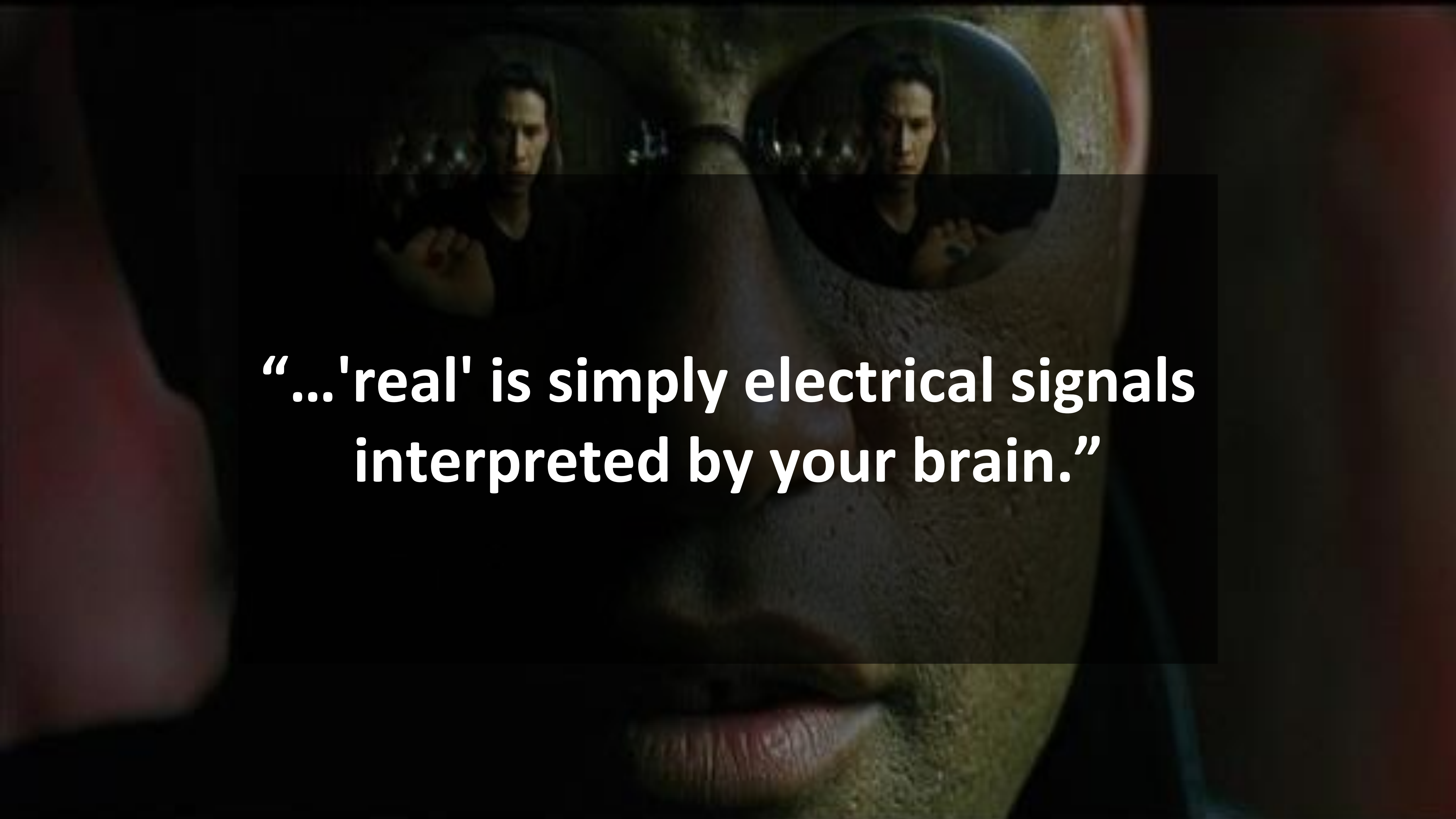
Ultimate Goal:
Merge the “Real” and the “Virtual” worlds,
so they are indistinguishable from one another!

Johnny English Strikes Again

Thanks For Watching....!! Movie Fa


"What is real?"
"How do you define 'real'?"
"If you're talking about what you can feel,
what you can smell, what you can taste and see,
then 'real' is simply electrical signals
interpreted by your brain."
- Morpheus in Matrix (1999)

project-ican.com
project-ican.com


“…'real' is simply electrical signals
interpreted by your brain.”

Human Factors Considerations:
Sensory & Perception System

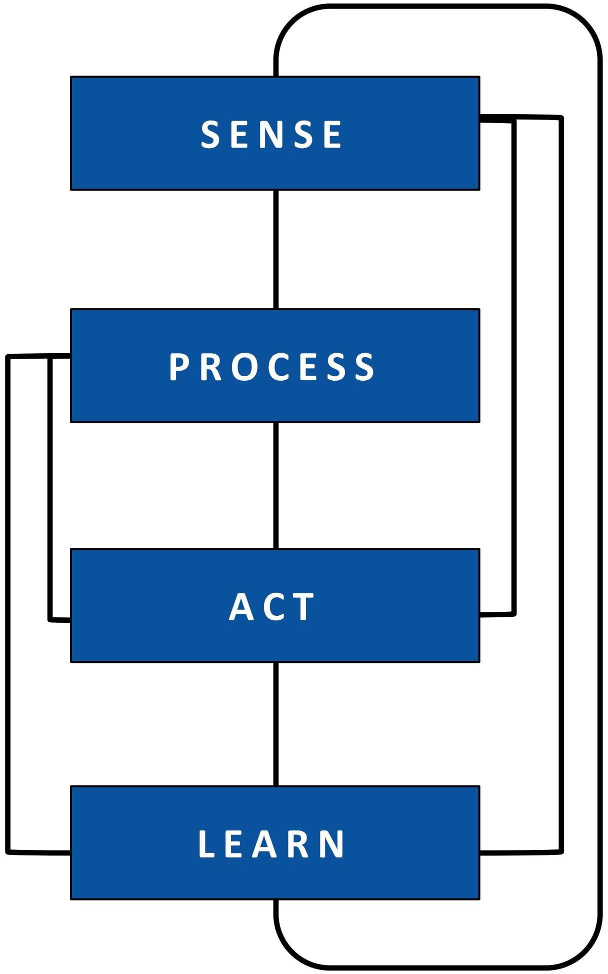
(In)famous "User Experience" Issues in VR & AR

- Inconsistent perceptual cues from the visual and vestibular sensory systems
  - Motion that is "felt" but not "seen", or "seen" but not "felt"
  - Both systems detect and estimate motion, but they do not correspond
- Visual experiences
  - "Screen-door" effects due to "low" display resolutions
  - Field-of-view (FOV) limitations
- Inconsistent oculomotor cues
  - Eye accommodation and convergence mismatch
  - Incorrect focus and blur cues

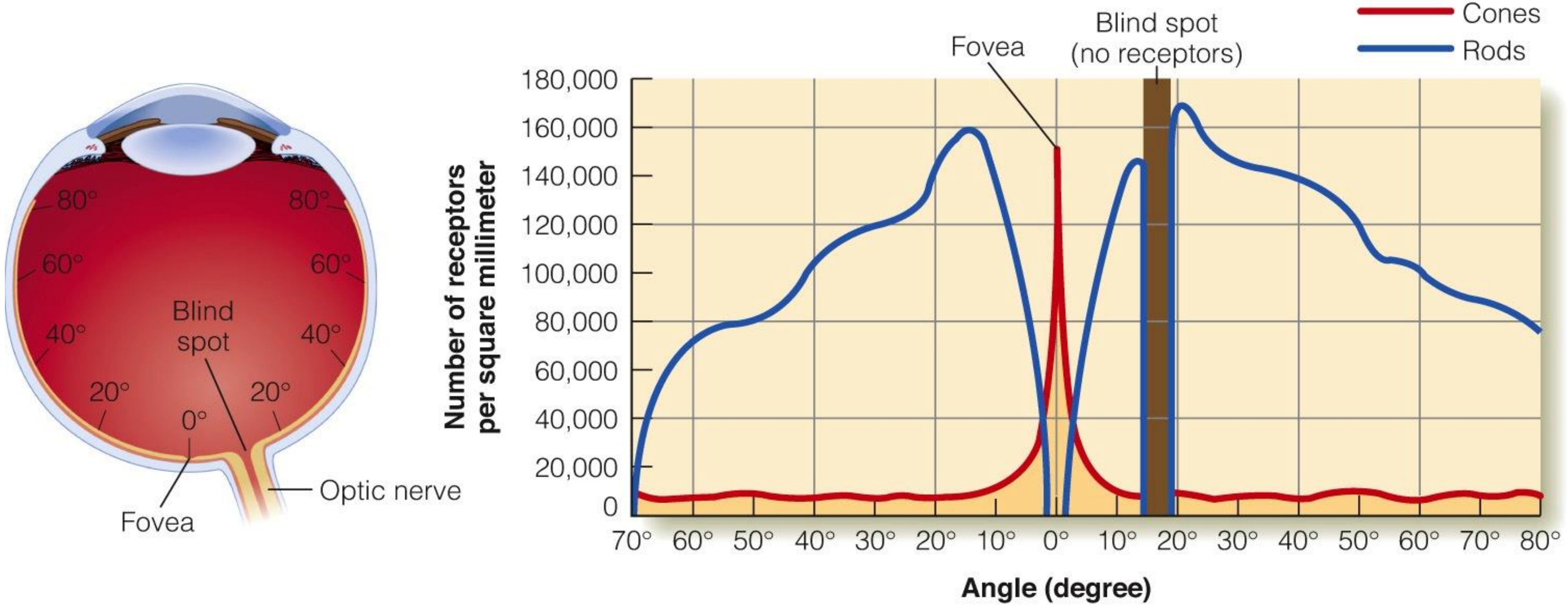
(In)famous “User Experience” Issues in VR & AR

- Systems and ergonomic issues
  - Latencies, weight, comfort, tether, eye relief, power dissipation, battery life, …
  - Tracking setup vs. “inside-out” tracking, 3-DOF vs. 6-DOF
- Missing or inconsistent proprioception cues
- Other perceptual issues we will inevitably discover in the future…

Perceptual Computing

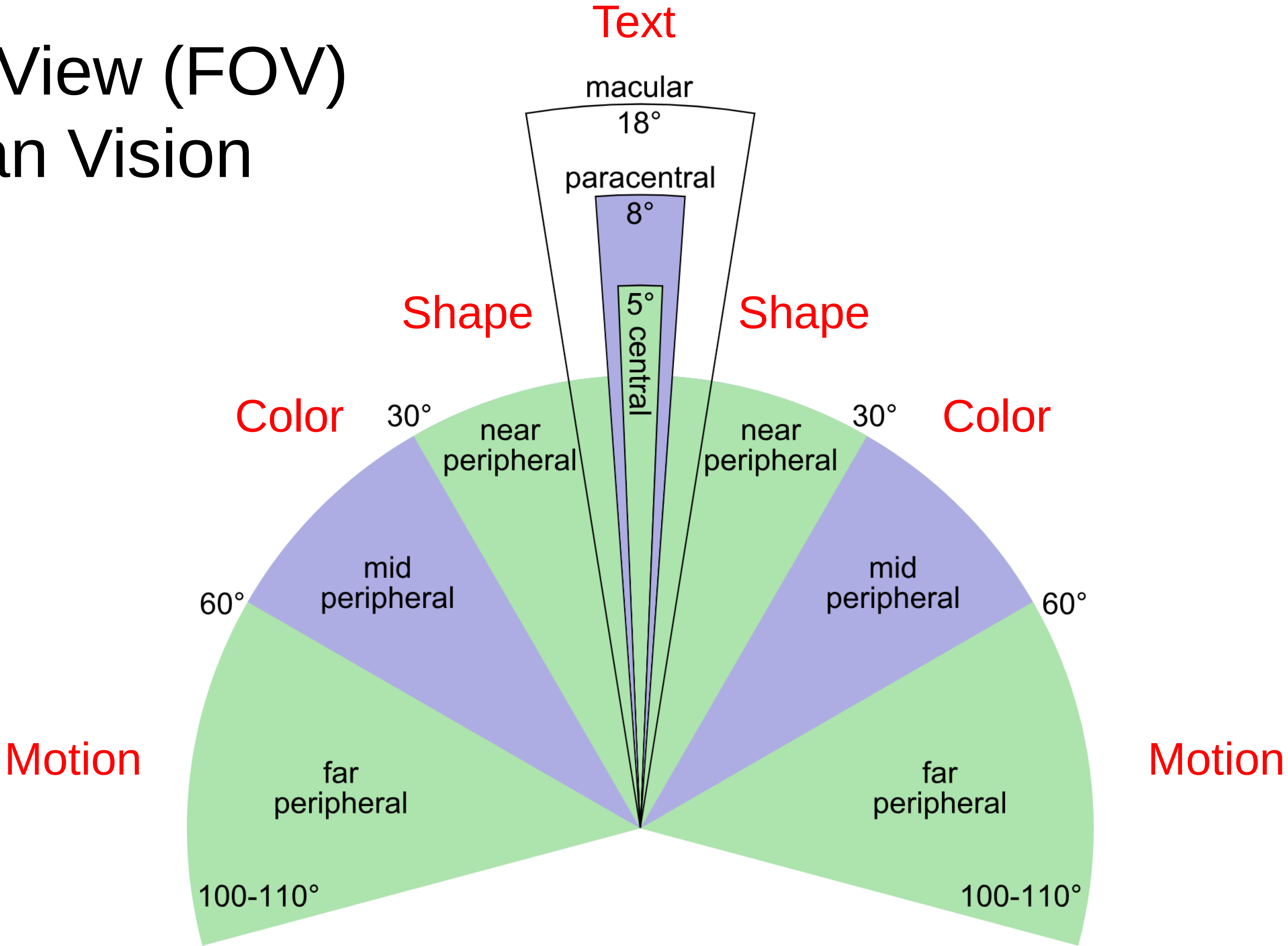


Construction & “Resolution” of the Human Eye



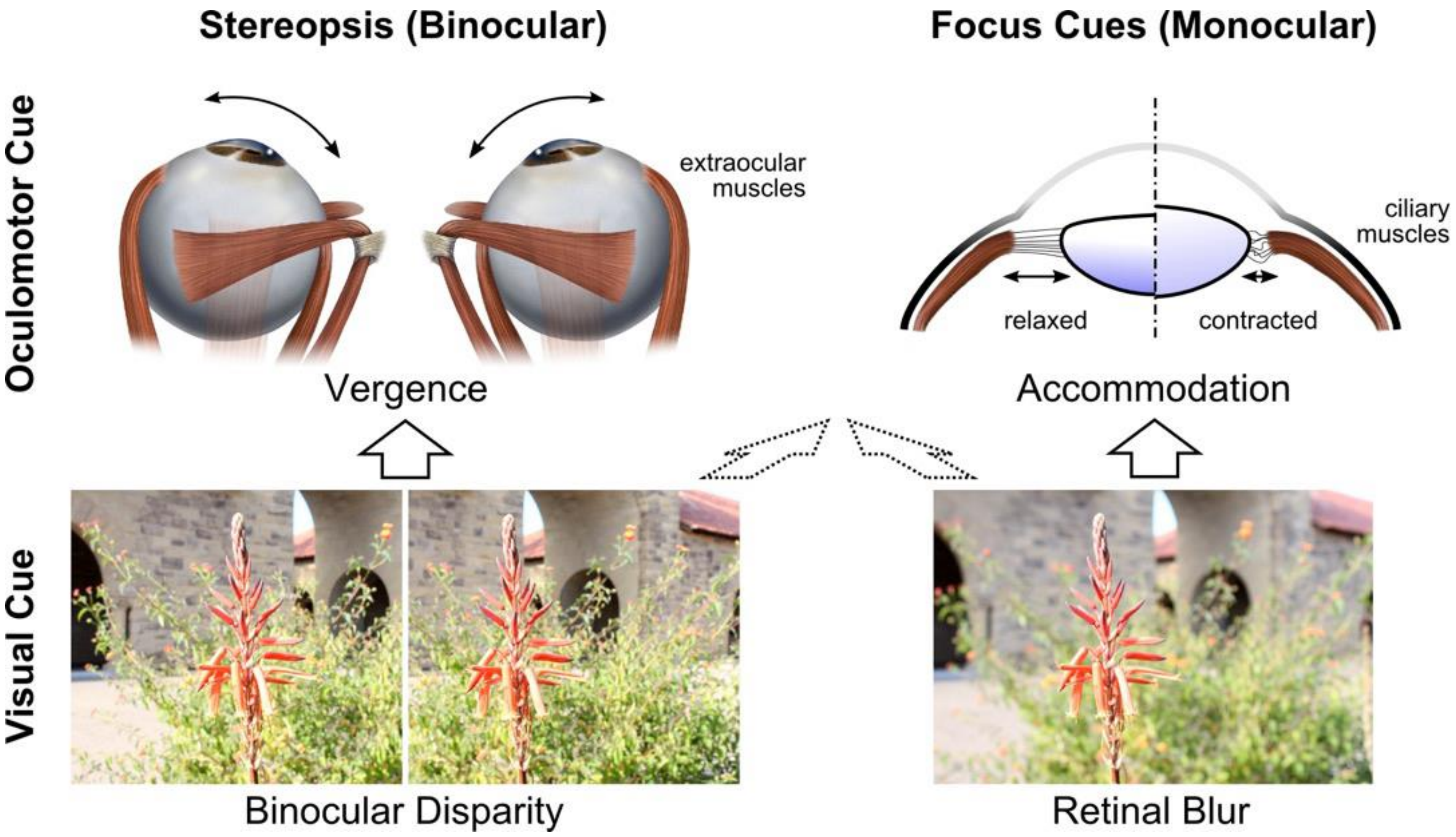
Visual Acuity for Foveal Vision: ~1/60th of a Degree

Field of View (FOV) of Human Vision

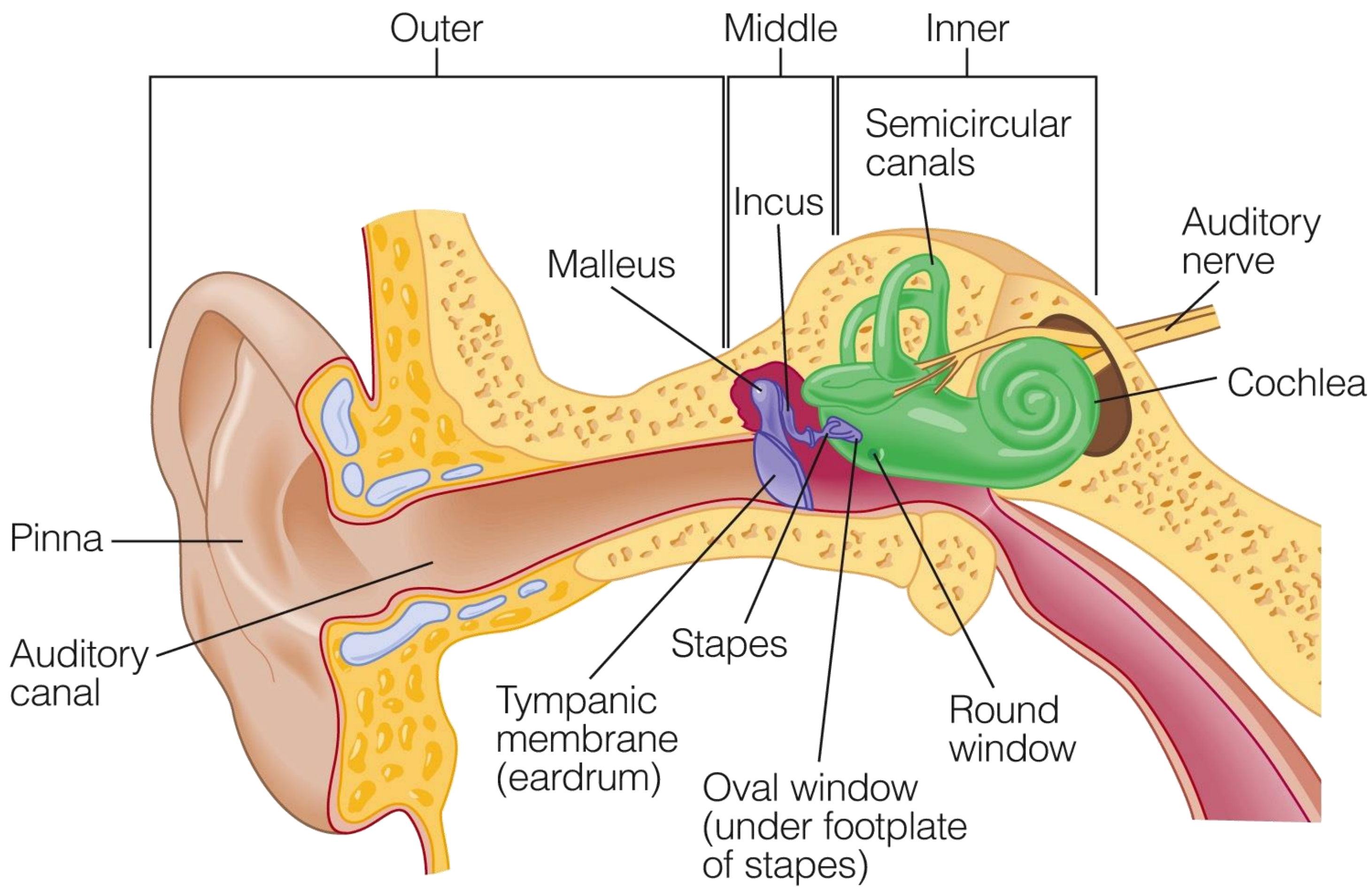


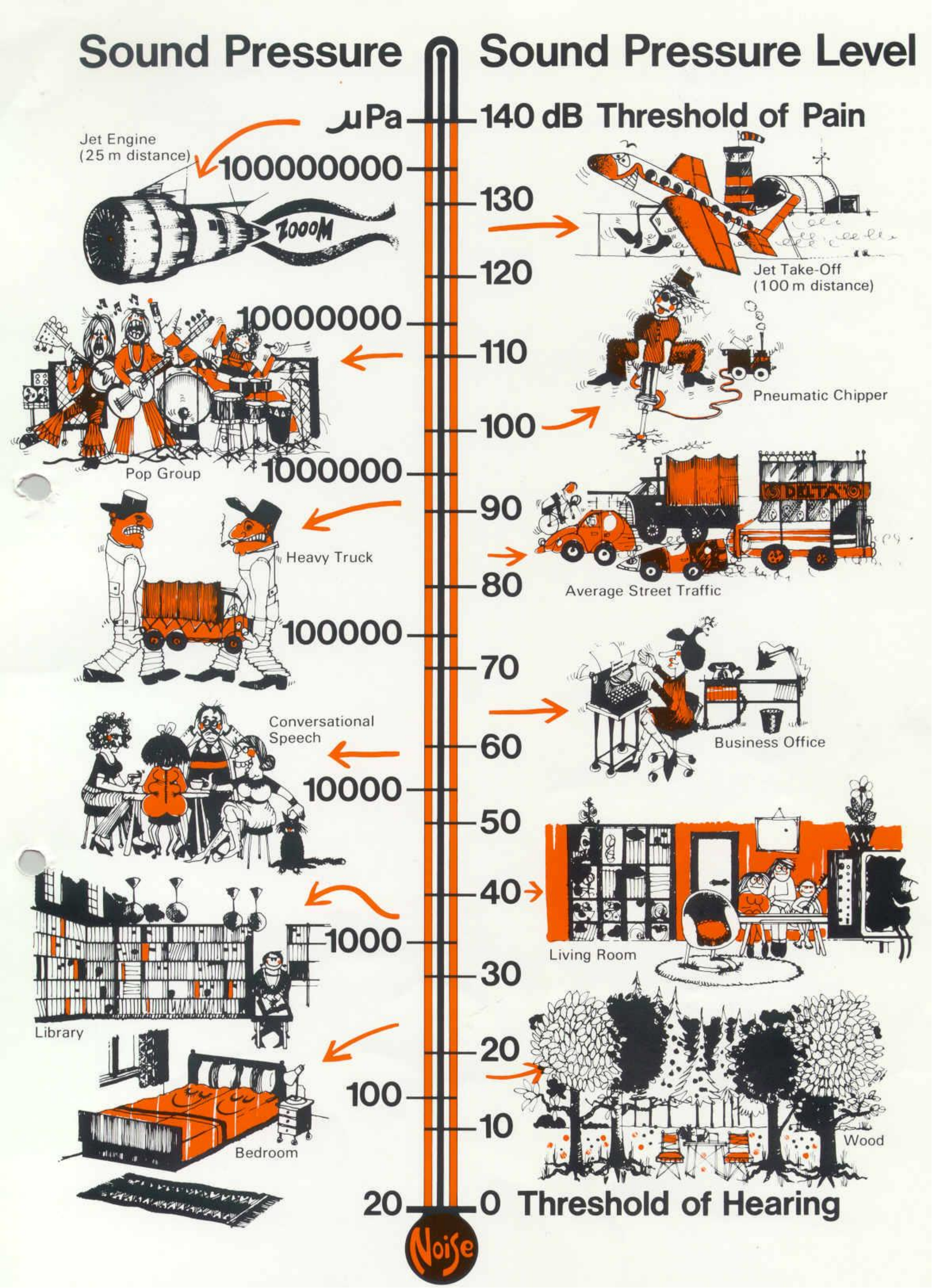
Wikipedia

http://blog.gingkoapp.com/essays/seeing-an-idea


Stereopsis (Binocular)
Focus Cues (Monocular)
Oculomotor Cue
extraocular muscles
ciliary muscles
relaxed
contracted
Vergence
Accommodation
Visual Cue
Binocular Disparity
Retinal Blur

The Ear & Sound Transduction



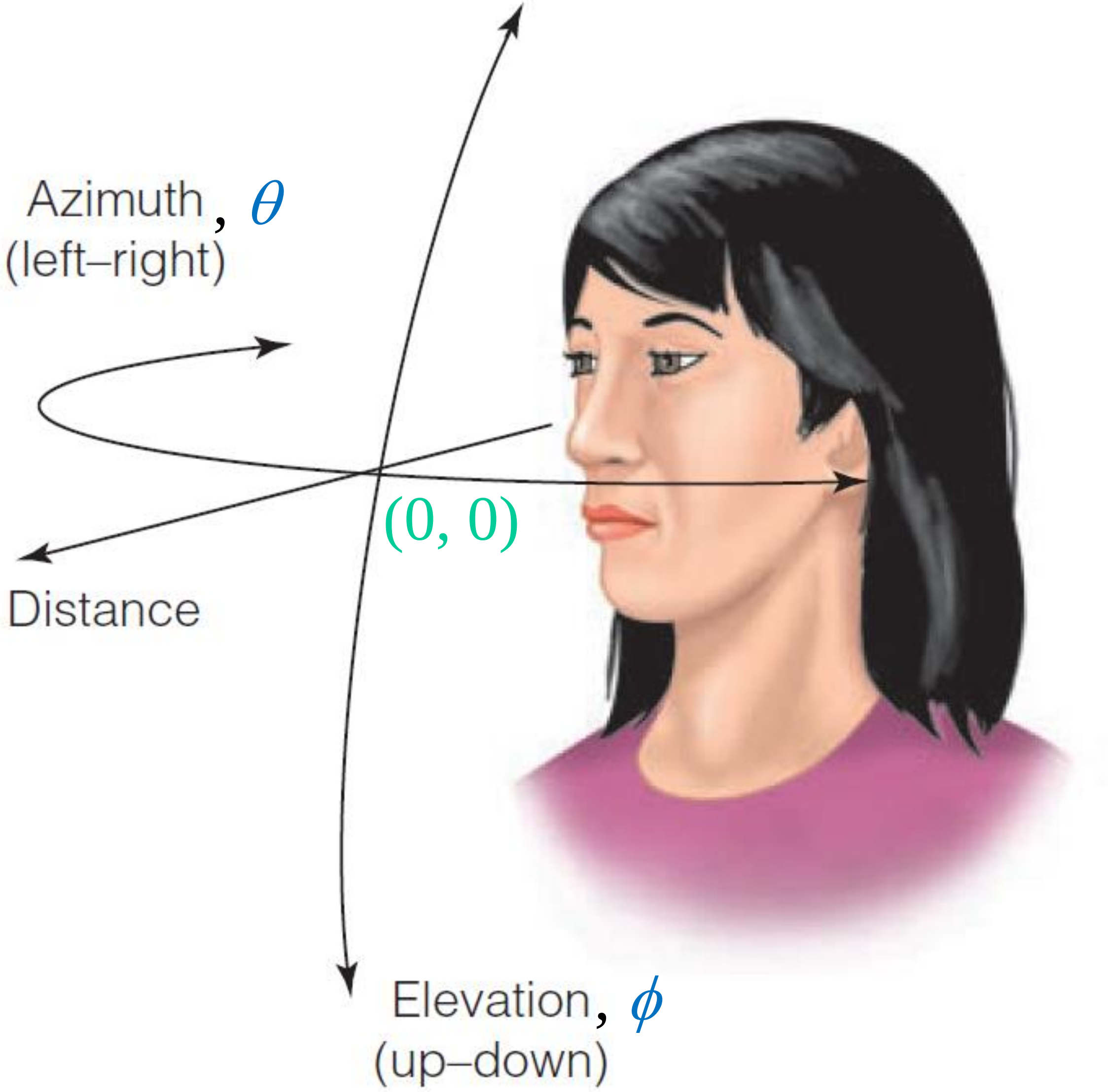


Sensation and Perception, E. Bruce Goldstein

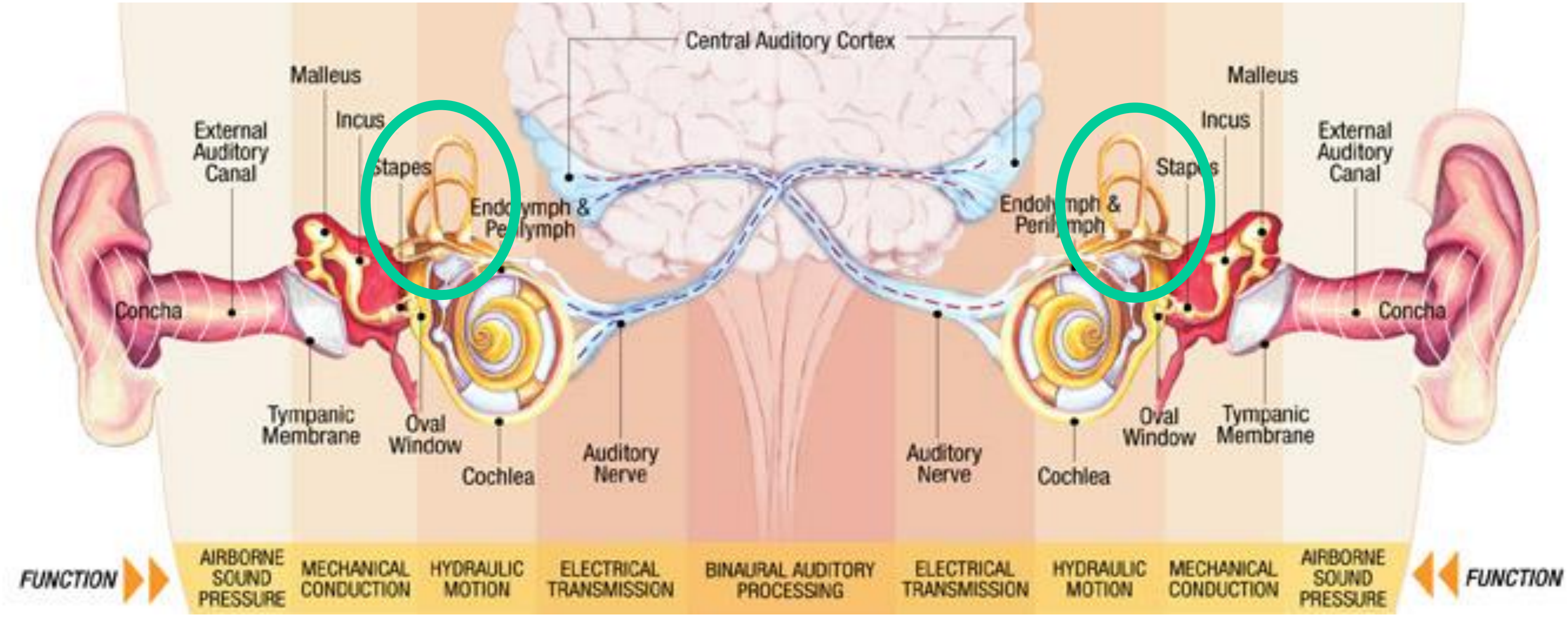
Auditory Localization

Binaural Cues:
- Interaural Time Difference (ITD)
- Interaural Intensity Difference (IID)

Monoaural Cues
- Spatial-dependence of the sound frequency spectra (filtering by the outer ear and head)

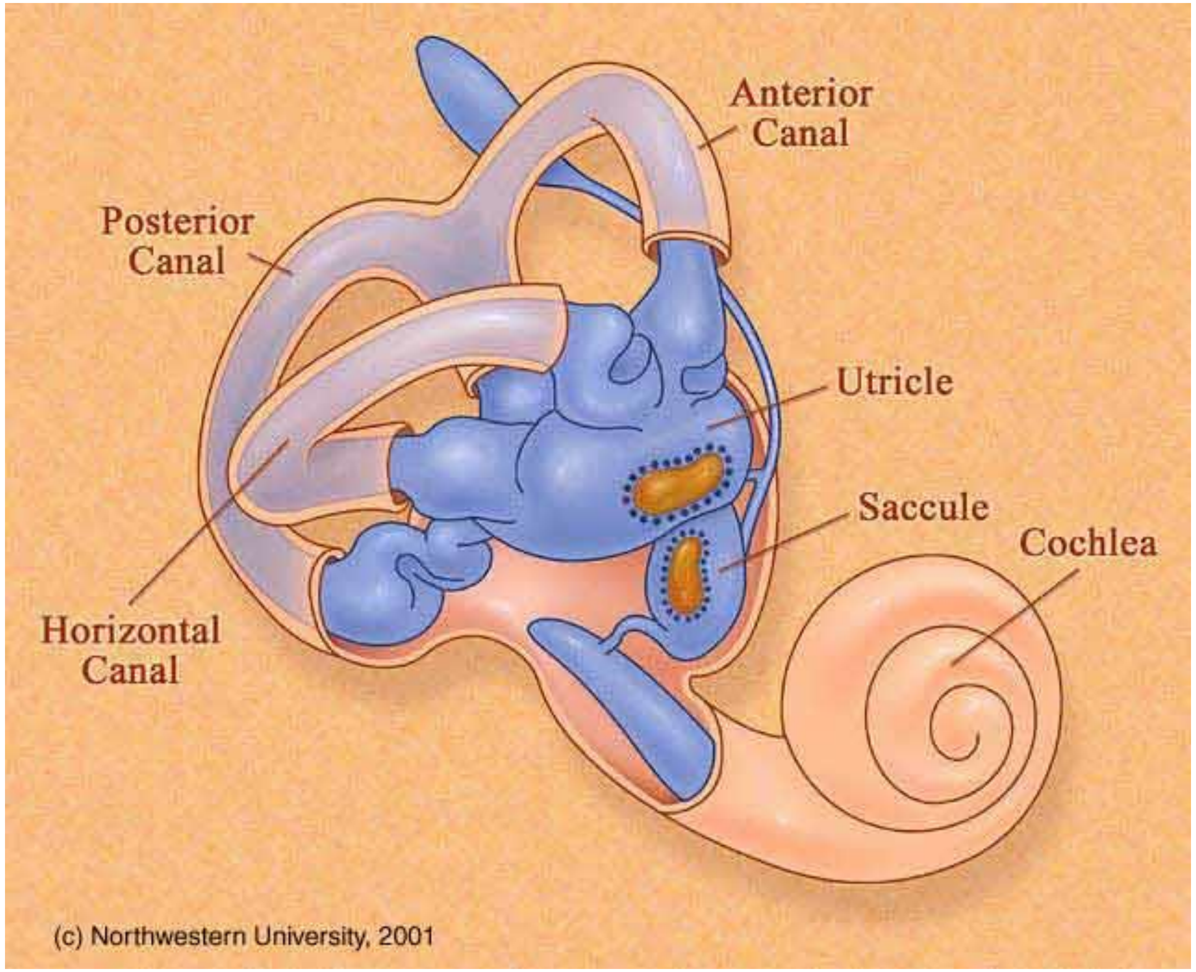


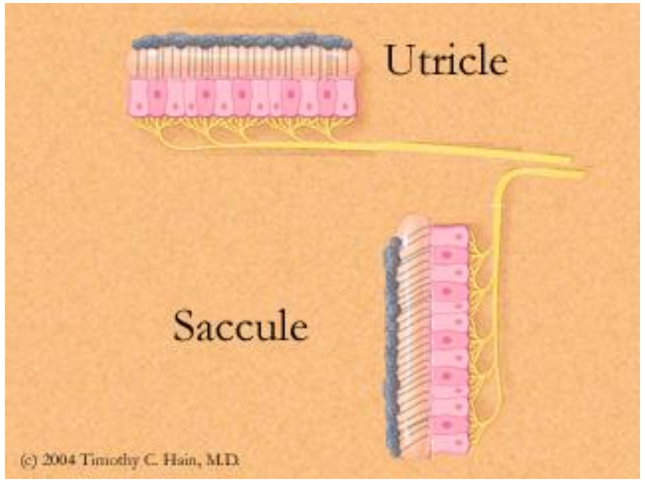
Human Vestibular System



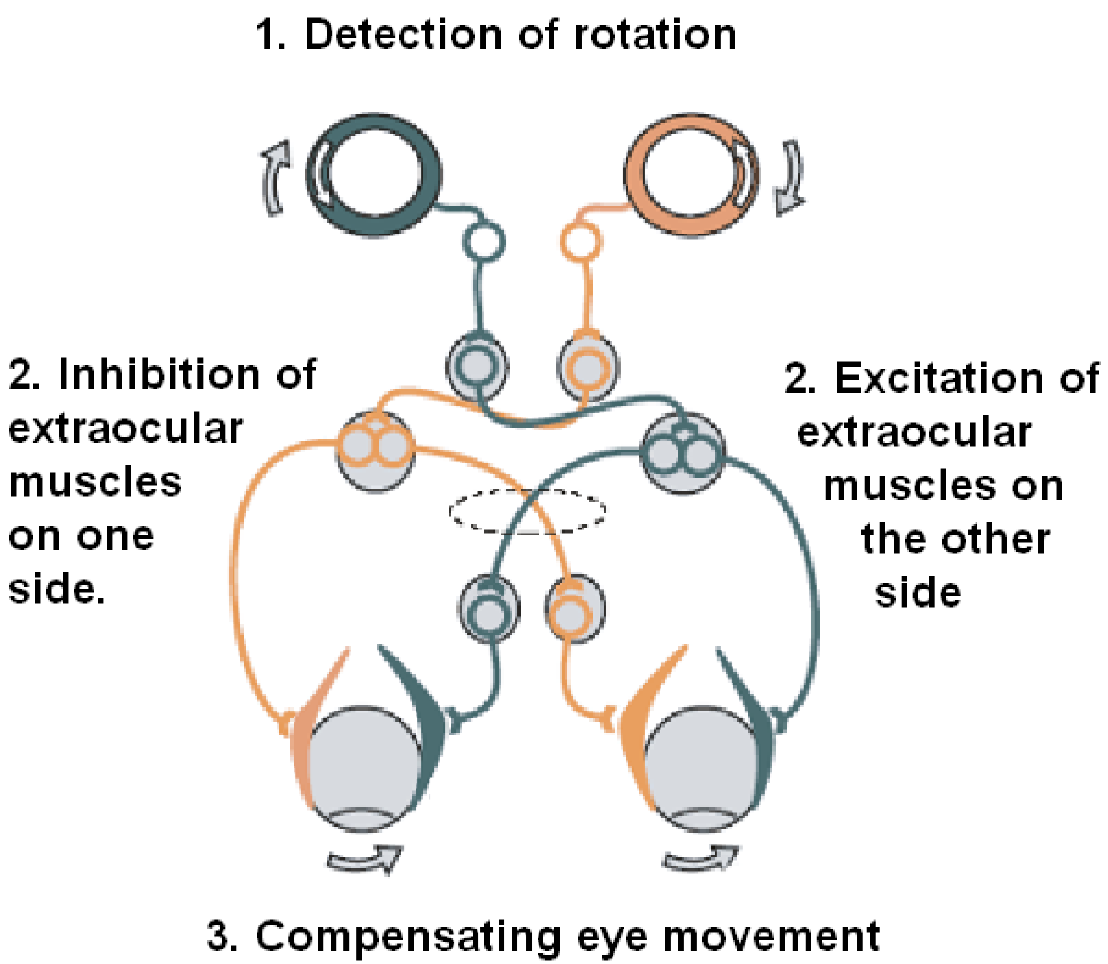
www.hearingloss.com/hearing-two-ears

Human Vestibular System



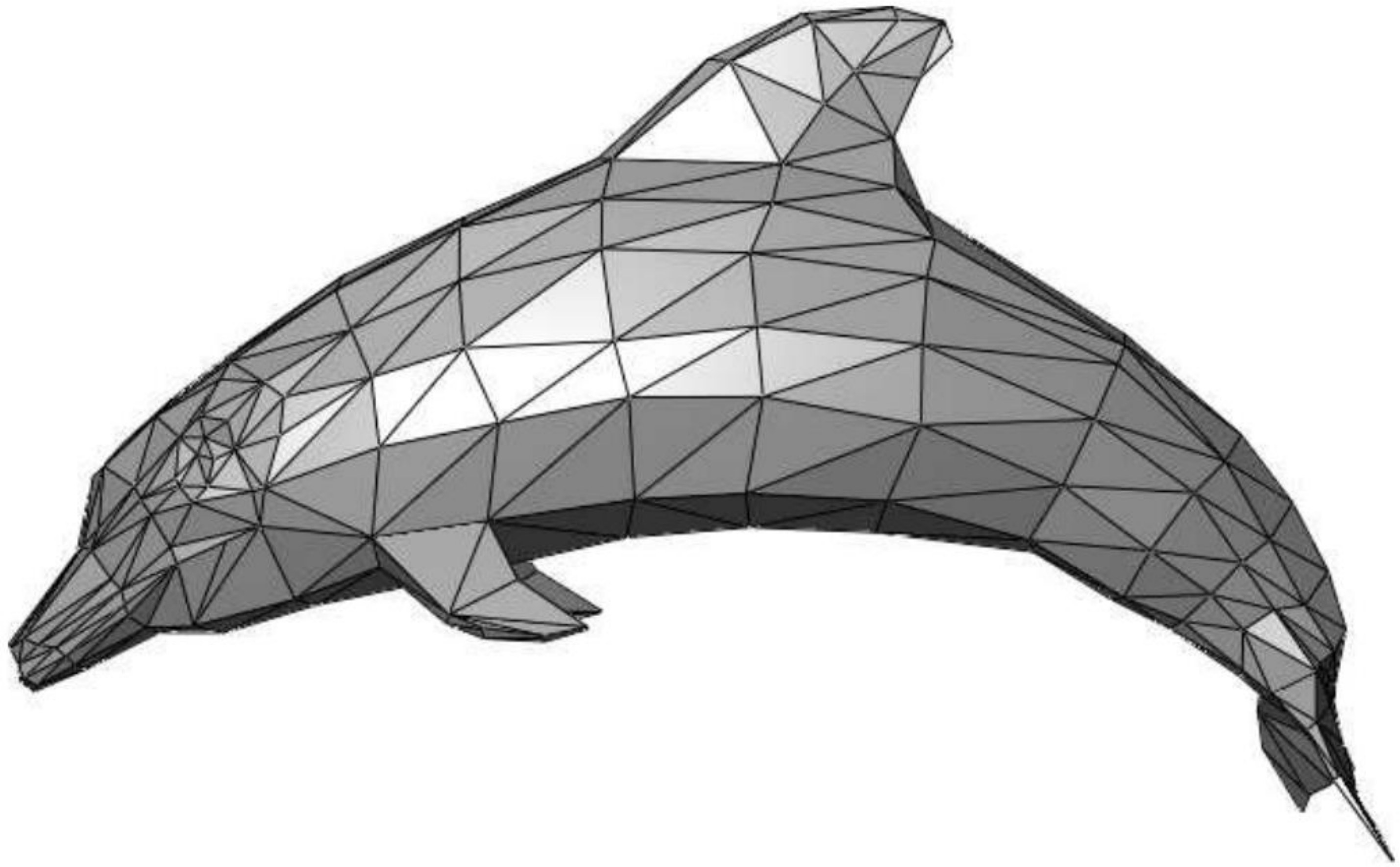


Vestibulo-Ocular Reflex



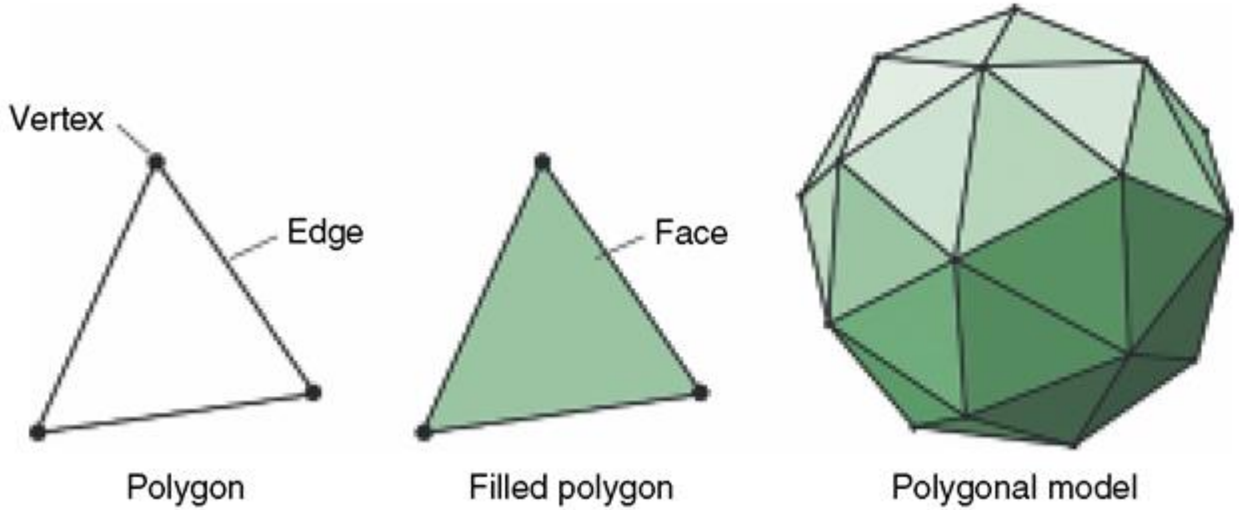
Virtual World Creation:
3D Graphics/Computation for VR/AR

Geometric Models in VR/AR/MR: Mesh of 3D Primitives



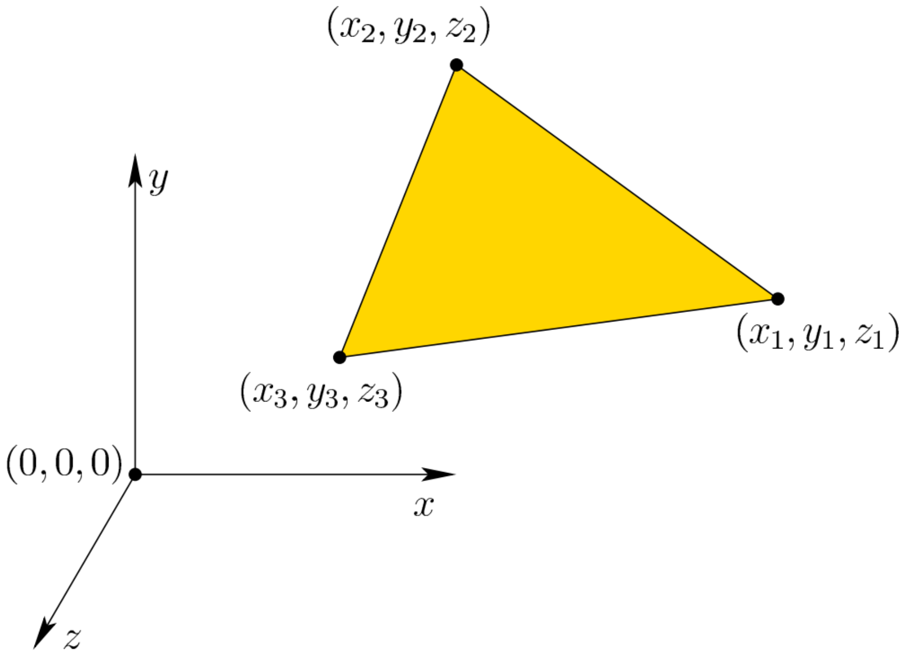
Wikipedia: Chrschn

Geometric Models in VR/AR/MR: Mesh of 3D Primitives

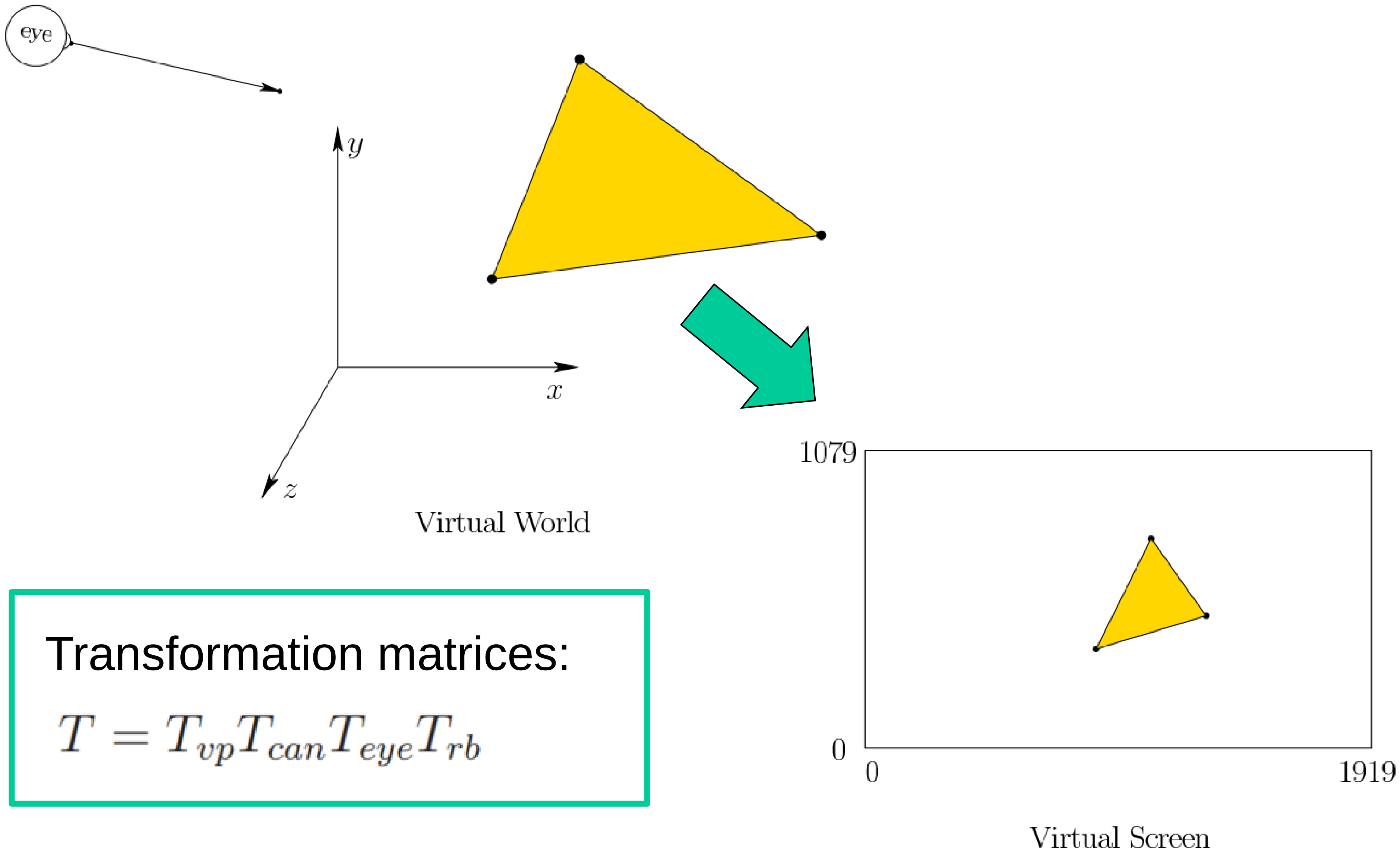


http://what-when-how.com/wp-content/uploads/2012/06/tmp49c617_thumb.png

3D Primitive



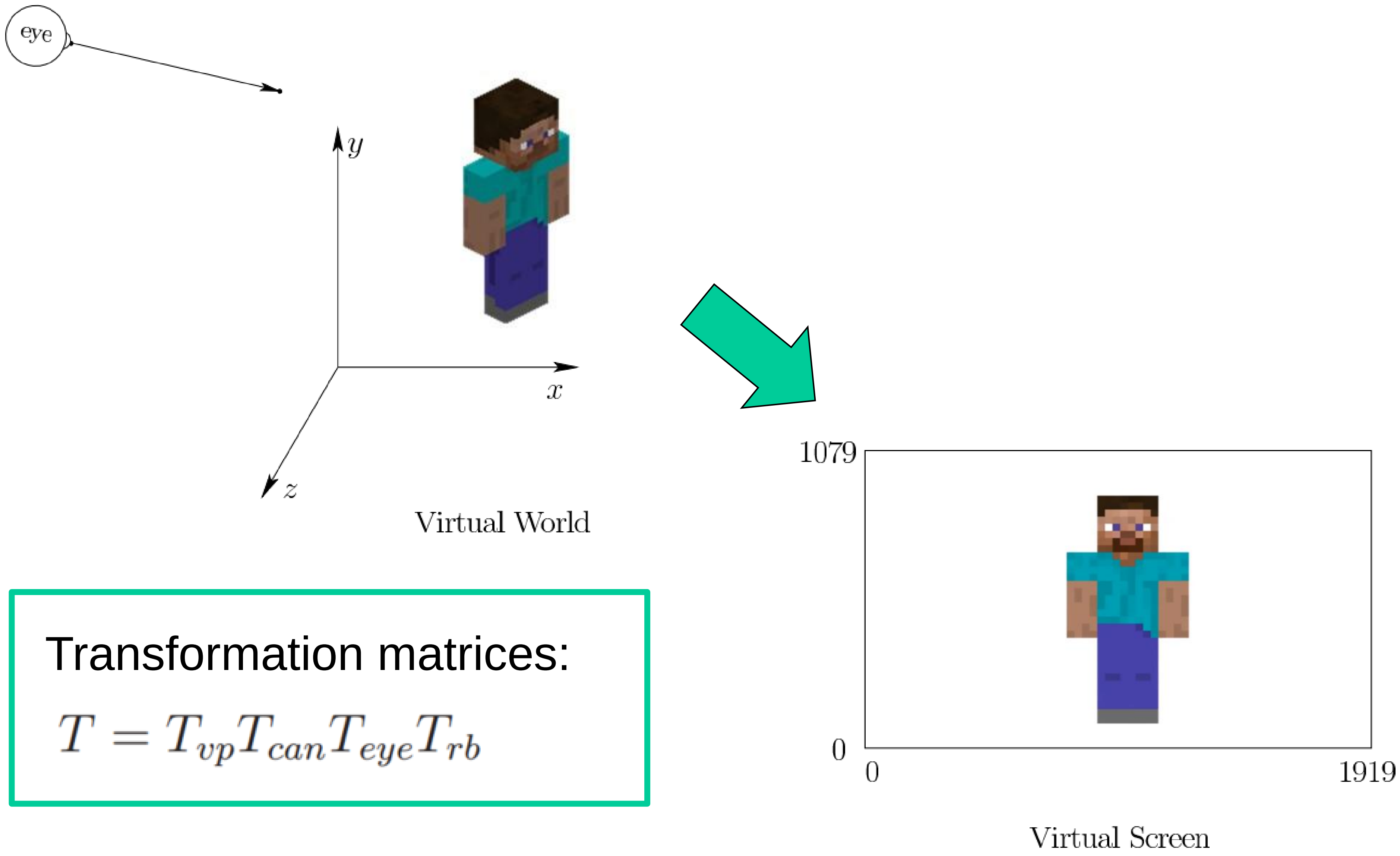
Viewing Transformations



Transformation matrices:

$$T = T_{vp} T_{can} T_{eye} T_{rb}$$

Viewing Transformations



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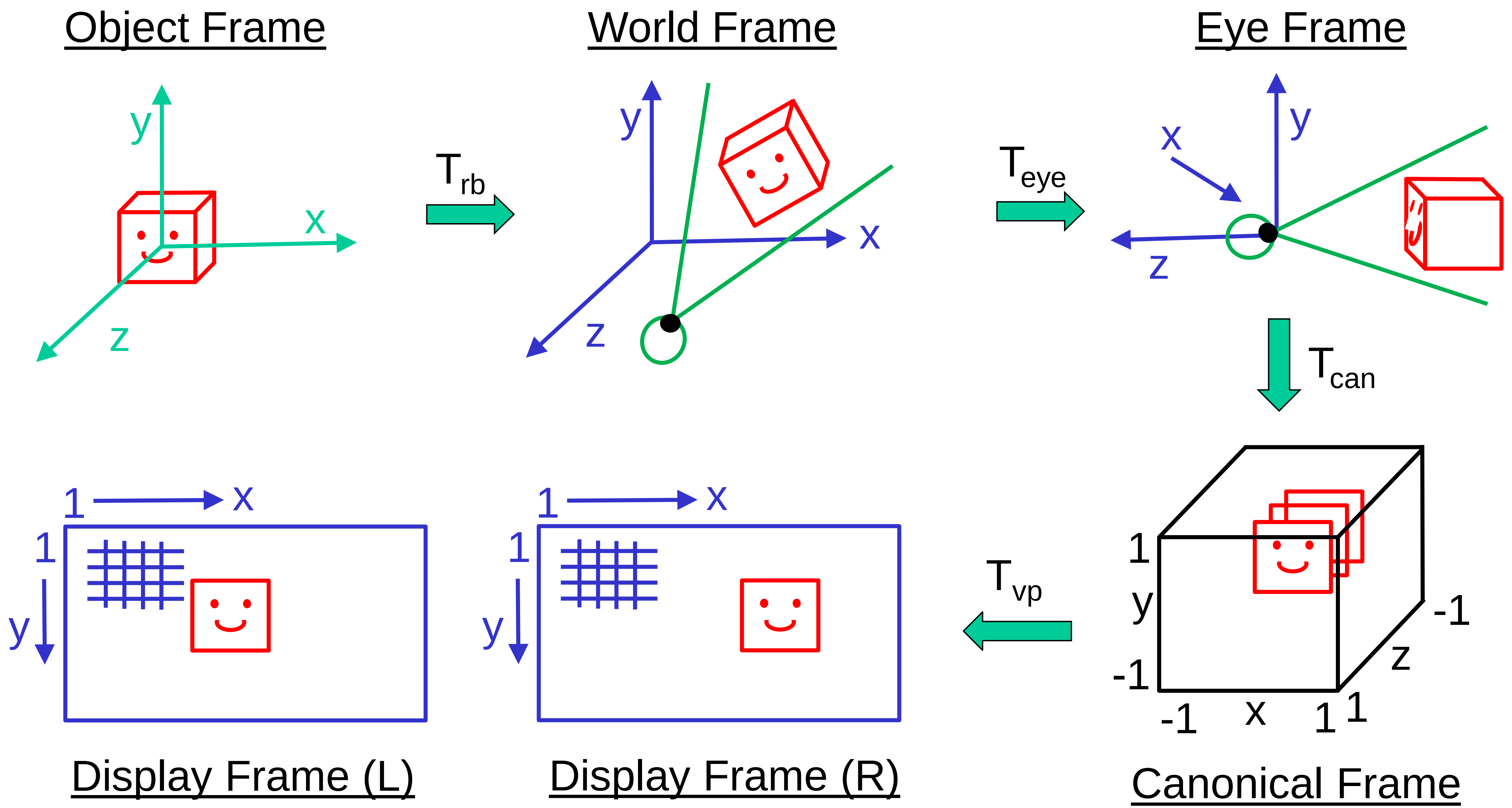
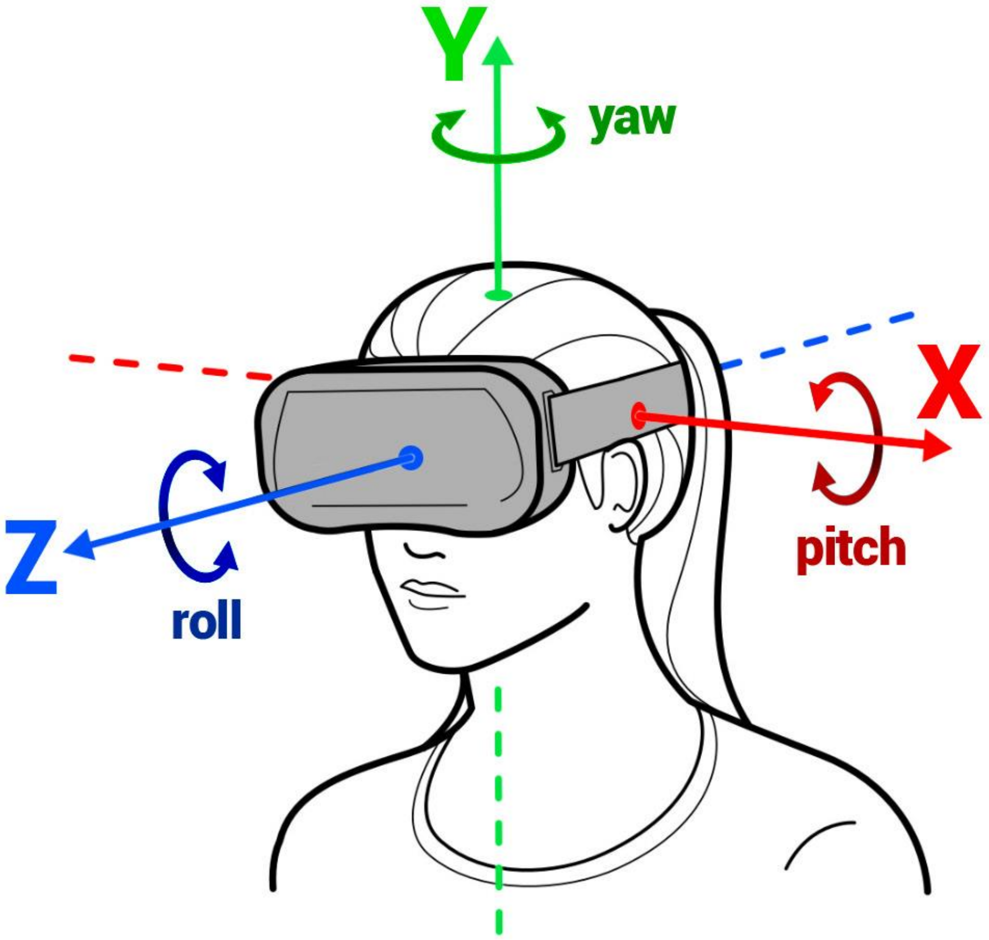
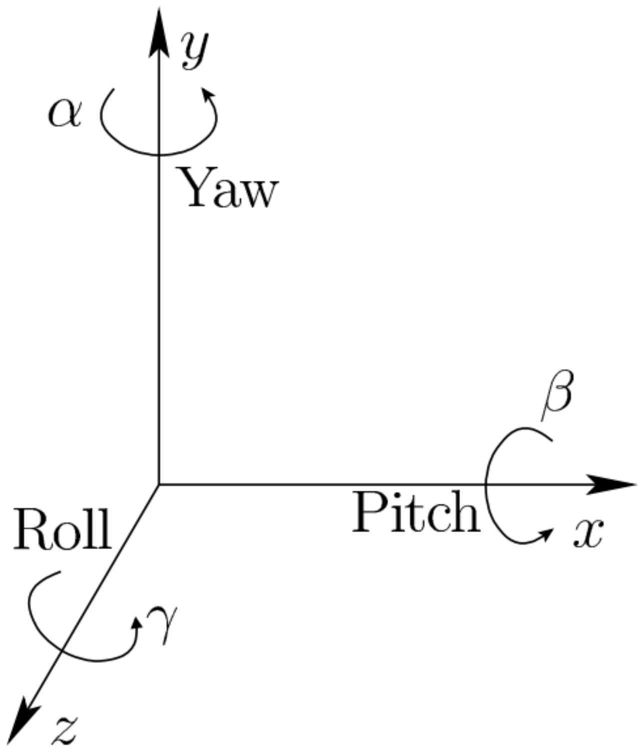

Object Frame
World Frame
Eye Frame
y
x
z
T_rb
T_eye
T_can
T_vp
Display Frame (L)
Display Frame (R)
Canonical Frame
1
-1

3D Rotation and 3D Translation: Six Degrees of Freedom



3D Rotation: Yaw, Pitch and Roll



$$R_y(\alpha) = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{bmatrix}$$ Yaw

$$R_x(\beta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{bmatrix}$$ Pitch

$$R_z(\gamma) = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}$$ Roll

Combining rotations: $R(\alpha, \beta, \gamma) = R_y(\alpha) R_x(\beta) R_z(\gamma)$

3D Rotation and 3D Translation

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = R \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} x_t \\ y_t \\ z_t \end{bmatrix}$$

Can the rotation and translation be combined into a single matrix?

Not with a single 3X3 matrix…

Combining 3D Rotation & 3D Translation: Homogeneous Transformation Matrix

$$T_{rb} = \begin{bmatrix} & R & & x_t \\ & & & y_t \\ & & & z_t \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

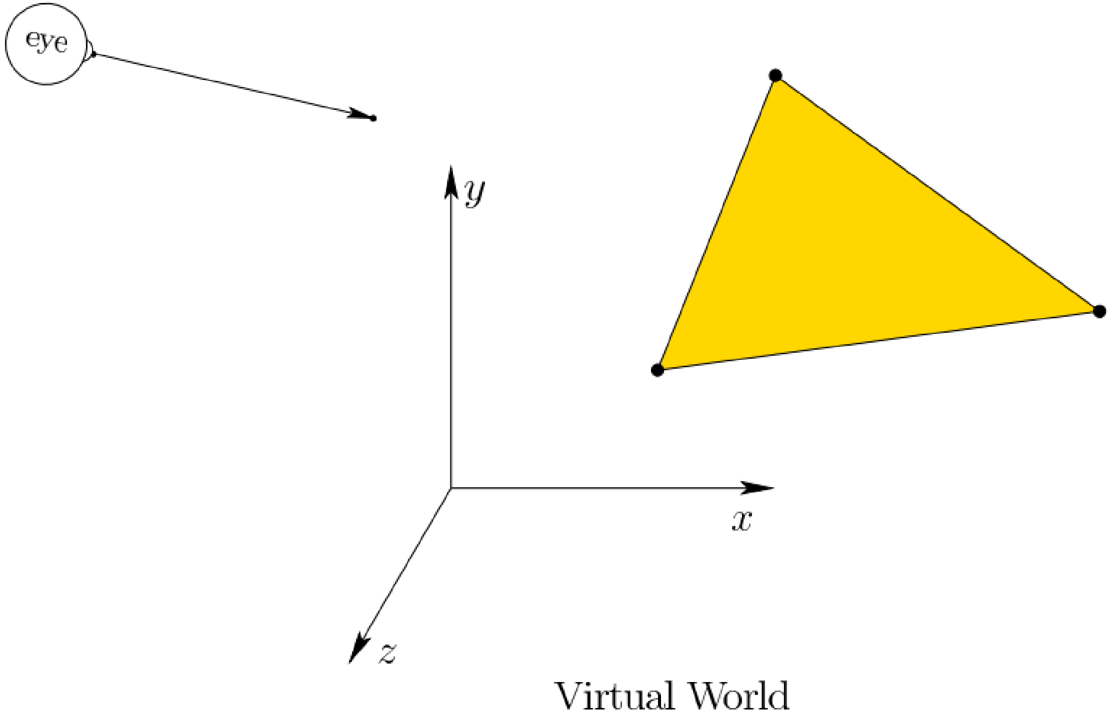
$$\begin{bmatrix} & R & & x_t \\ & & & y_t \\ & & & z_t \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix}$$

Note:

T_{rb} = Rigid body transform

The sequence in this matrix is rotation followed by translation

Eye Transform (T_{eye})



Eye position & orientation:

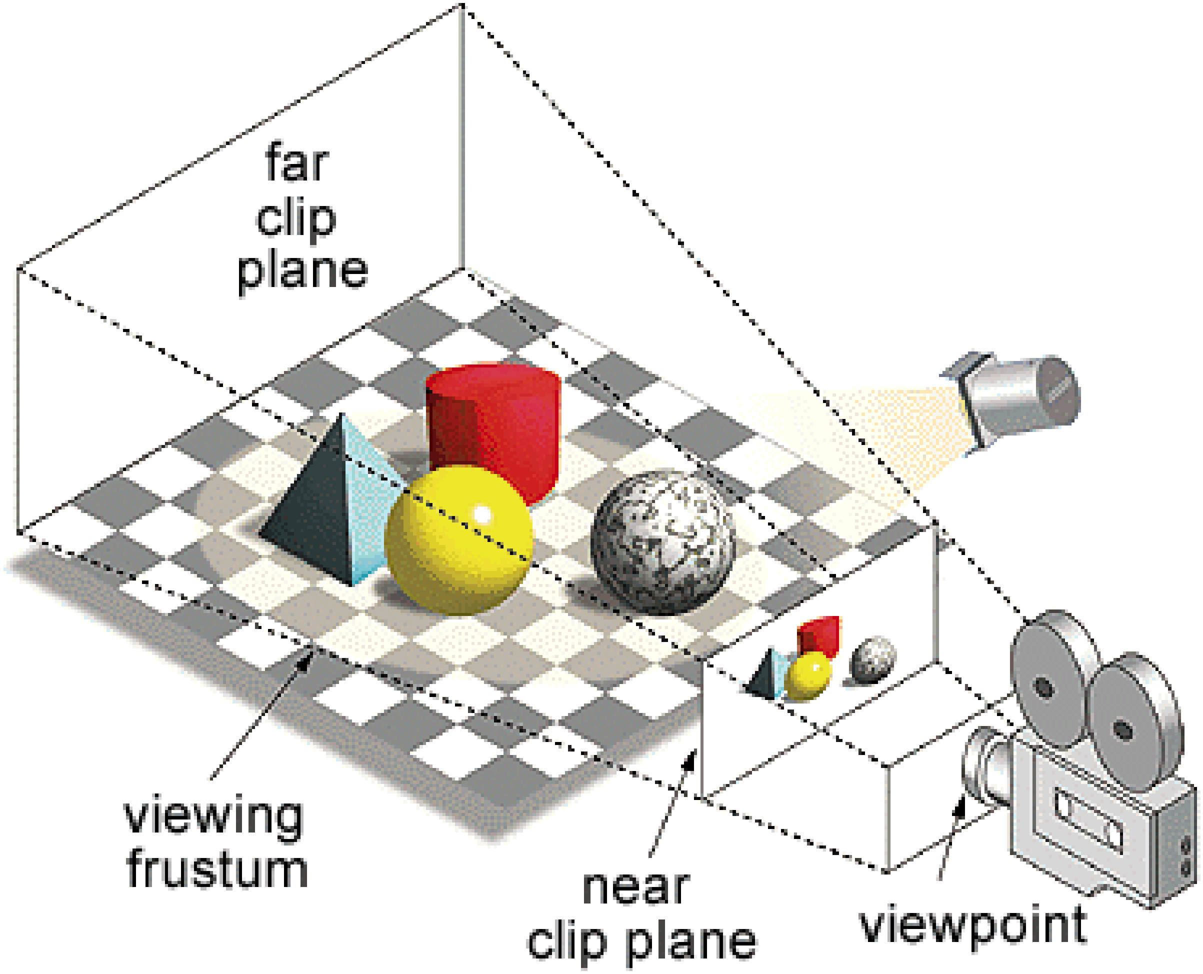
$$e = (e_1, e_2, e_3)$$

$$R_{eye} = \begin{bmatrix} \hat{x}_1 & \hat{y}_1 & \hat{z}_1 \\ \hat{x}_2 & \hat{y}_2 & \hat{z}_2 \\ \hat{x}_3 & \hat{y}_3 & \hat{z}_3 \end{bmatrix}$$

$$T_{eye} = \begin{bmatrix} \hat{x}_1 & \hat{x}_2 & \hat{x}_3 & 0 \\ \hat{y}_1 & \hat{y}_2 & \hat{y}_3 & 0 \\ \hat{z}_1 & \hat{z}_2 & \hat{z}_3 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & -e_1 \\ 0 & 1 & 0 & -e_2 \\ 0 & 0 & 1 & -e_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Canonical View Transform (T_{can})

Perspective Projection, Scaling & Translation



$$T_{can} = T_{st} T_p$$

$$T_p = \begin{bmatrix} n & 0 & 0 & 0 \\ 0 & n & 0 & 0 \\ 0 & 0 & n+f & -fn \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$T_{st} = \begin{bmatrix} \frac{2}{r-\ell} & 0 & 0 & 0 \\ 0 & \frac{2}{t-b} & 0 & 0 \\ 0 & 0 & \frac{2}{n-f} & -\frac{n+f}{n-f} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Finally: Viewport Transform (T_{vp})

Bring the projected points to the coordinates used to index pixels on the physical display screen:

$$T_{vp} = \begin{bmatrix} \frac{m}{2} & 0 & 0 & \frac{m-1}{2} \\ 0 & \frac{n}{2} & 0 & \frac{n-1}{2} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

m: number of horizontal pixels
n: number of vertical pixels

For example, n = 1080 and m = 1920 for a 1080p display.

One More Thing: "Cyclopean" to Stereo Views

Assuming interpupillary Distance (IPD) = *t*

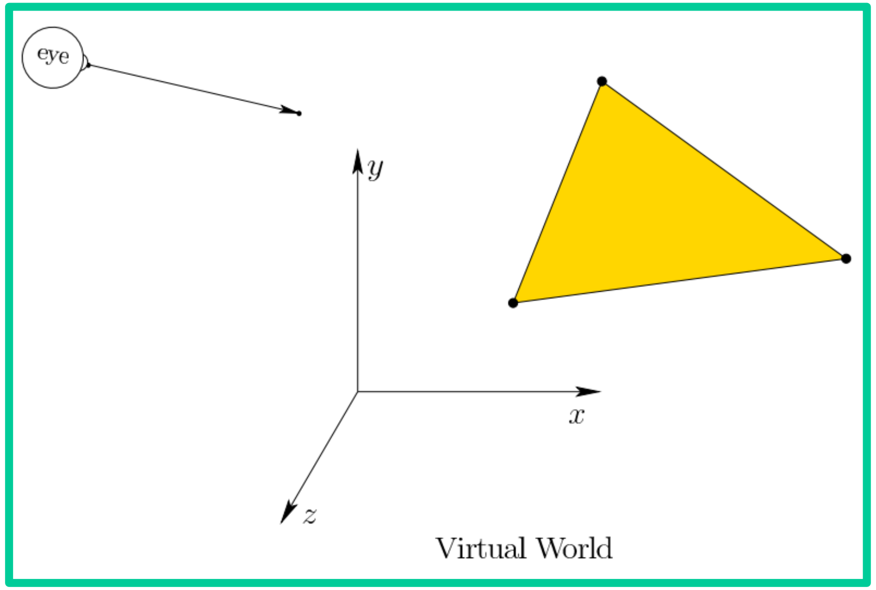
$$T_{left} = \begin{bmatrix} 1 & 0 & 0 & \frac{t}{2} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

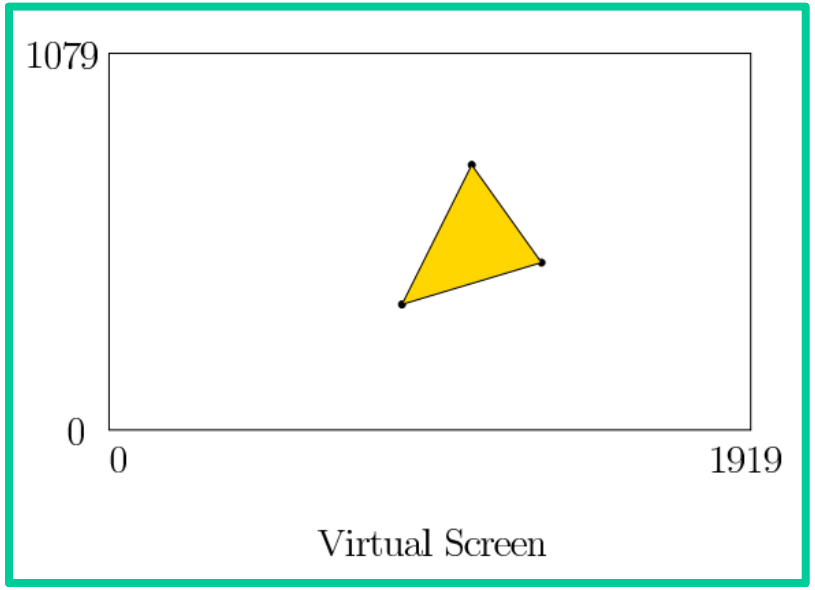
$$T = T_{vp} T_{can} T_{eye} T_{rb}$$

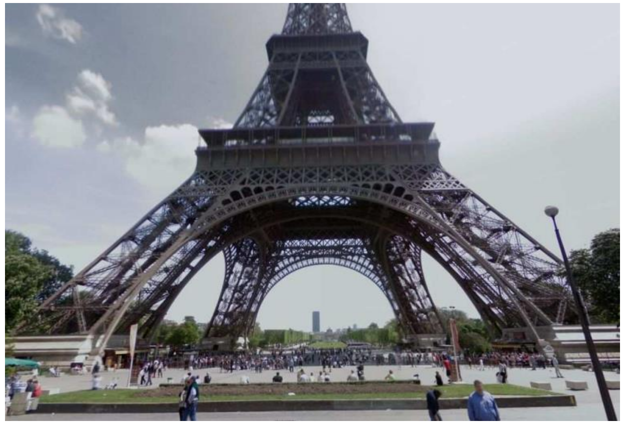
$$T = T_{vp} T_{can} T_{left} T_{eye} T_{rb}$$

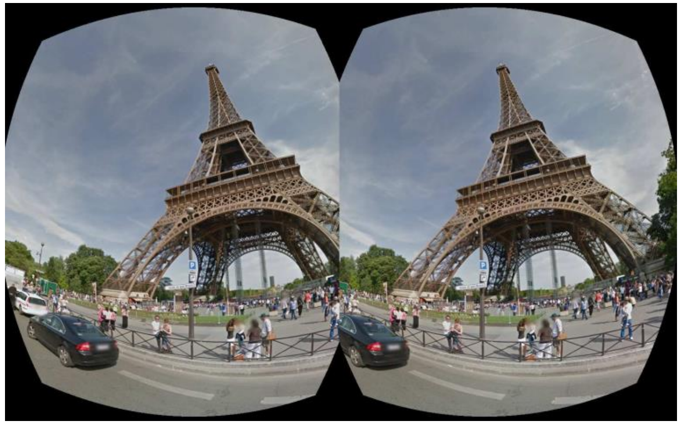
Similarly, $T_{right} = \begin{bmatrix} 1 & 0 & 0 & -\frac{t}{2} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

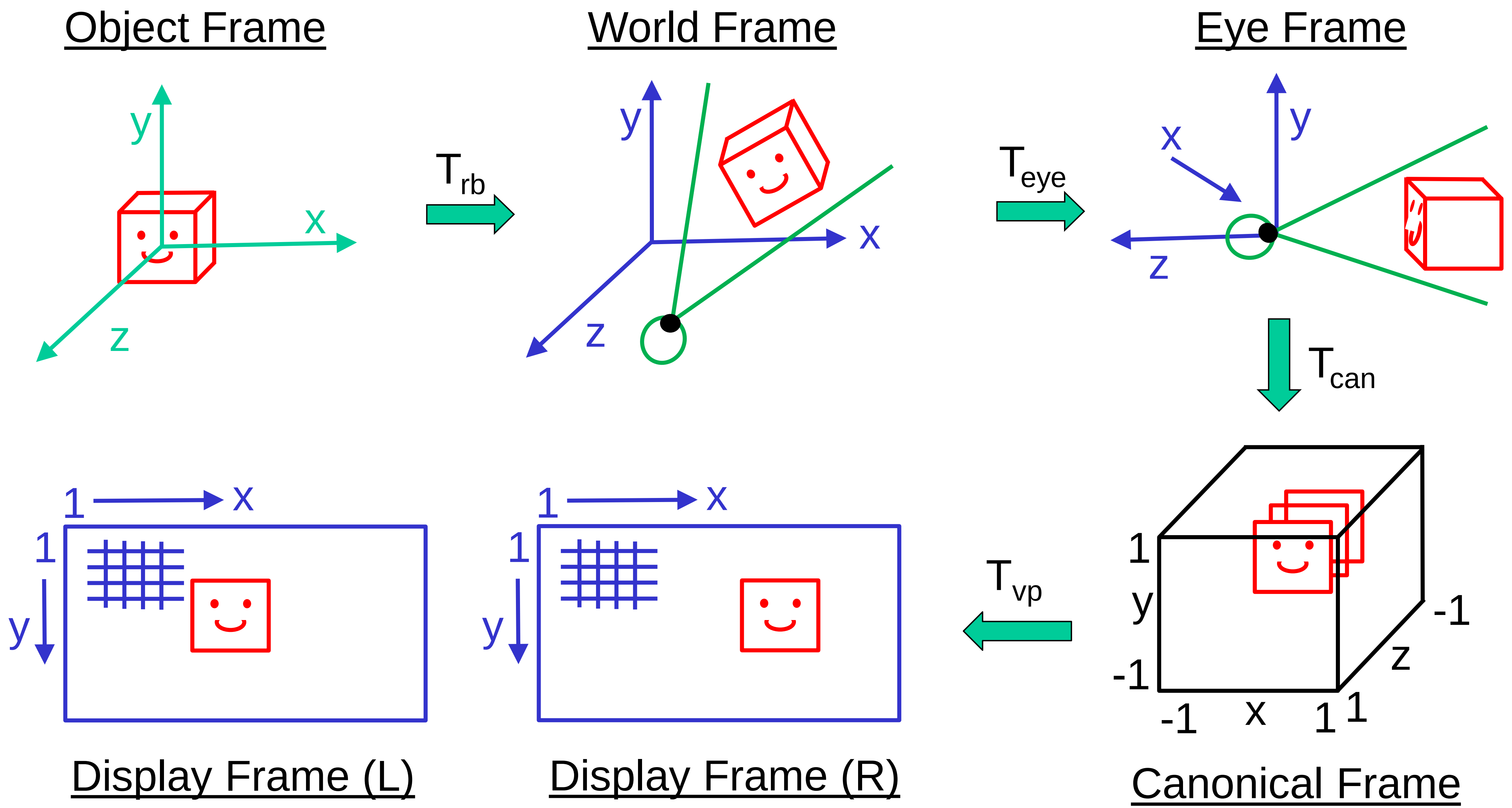
So, after applying all the viewing transformations…





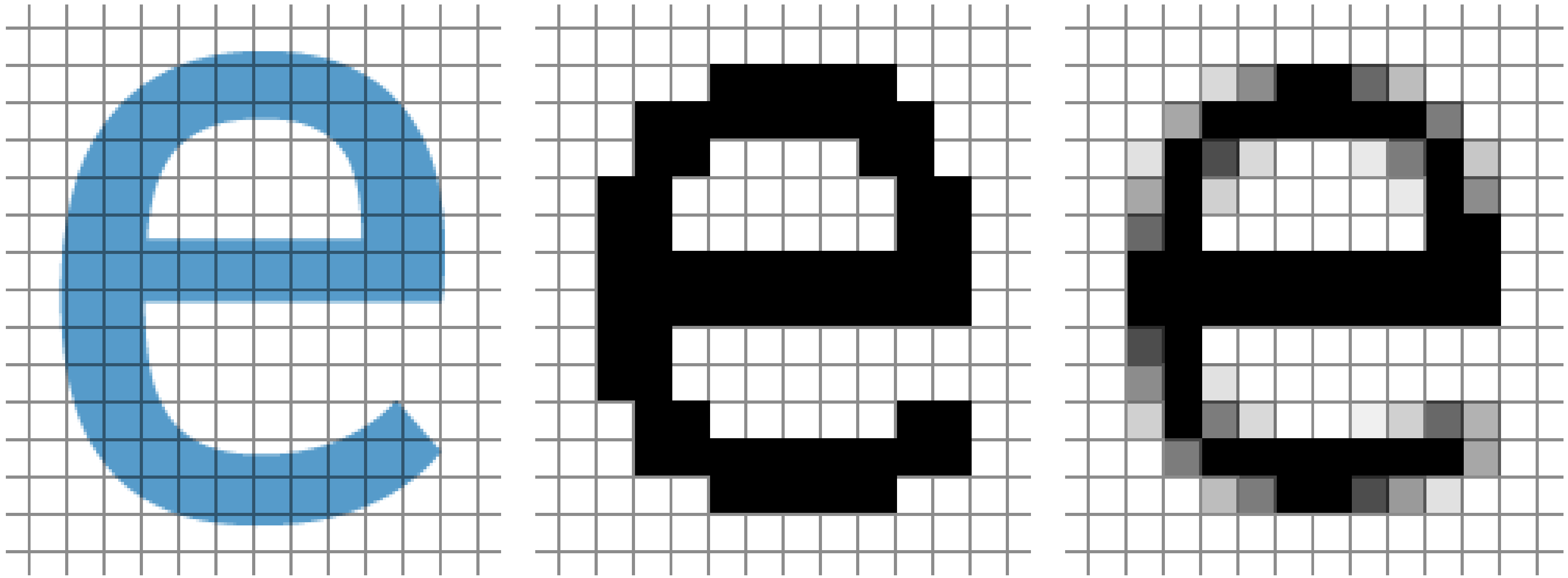






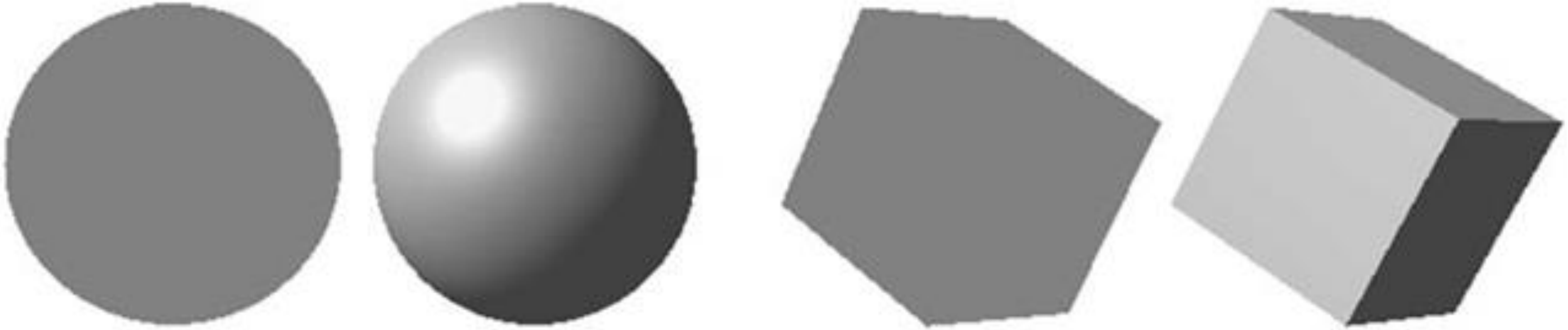
Object Frame
World Frame
Eye Frame
y
x
z
T_{rb}
y
x
z
T_{eye}
x
y
z
T_{can}
1
x
1
y
Display Frame (L)
1
x
1
y
Display Frame (R)
T_{vp}
1
y
-1
-1
x
1
1
z
-1
Canonical Frame

Rasterization + Antialiasing

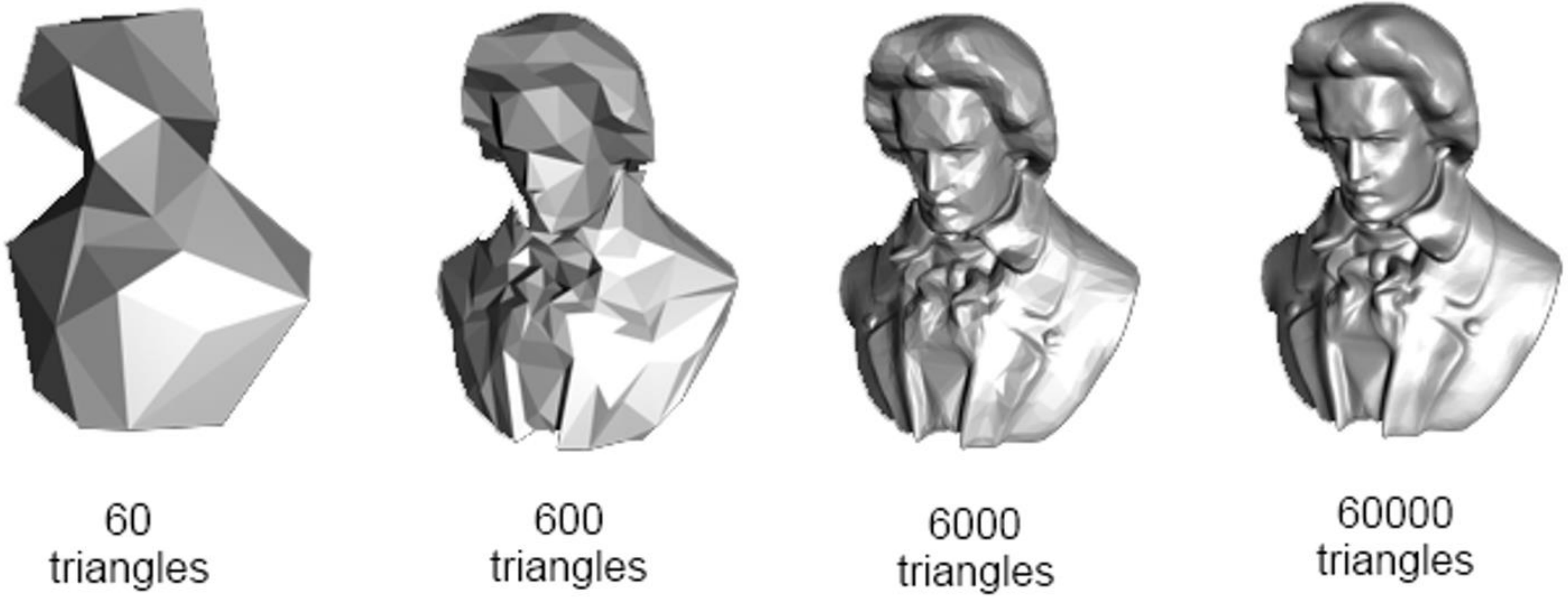


Illumination + Shading

Illumination + Shading



Geometric Models in VR/AR/MR:
How many polygons are needed?



Sensing & Tracking Technologies

“When it comes to VR, a system is only as good as your tracking setup.”

“A chief complaint for many current high-end VR systems is that they’re just too damn complicated.”

- TechCrunch, Jan 25, ‘17

3D Position Tracking:
Artificial Features Tracked by External Cameras

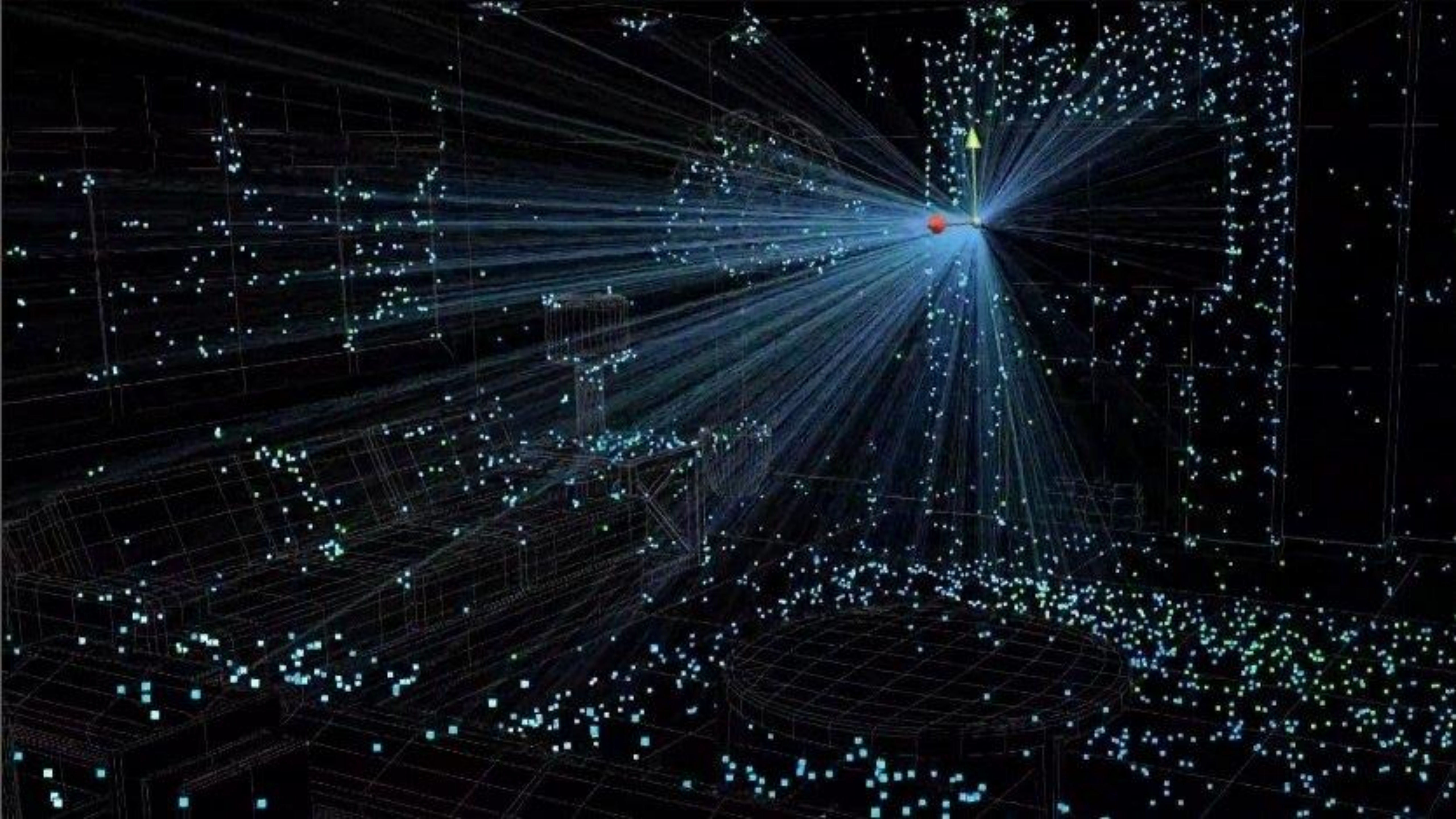
Photo: iFixit

“Constellation” tracking system
used in Oculus Rift

“Lighthouse” tracking system
used in HTC Vive

“Inside Out” Tracking:

Natural Visual Features Extracted and Tracked with Computer Vision along with Inertial Motion

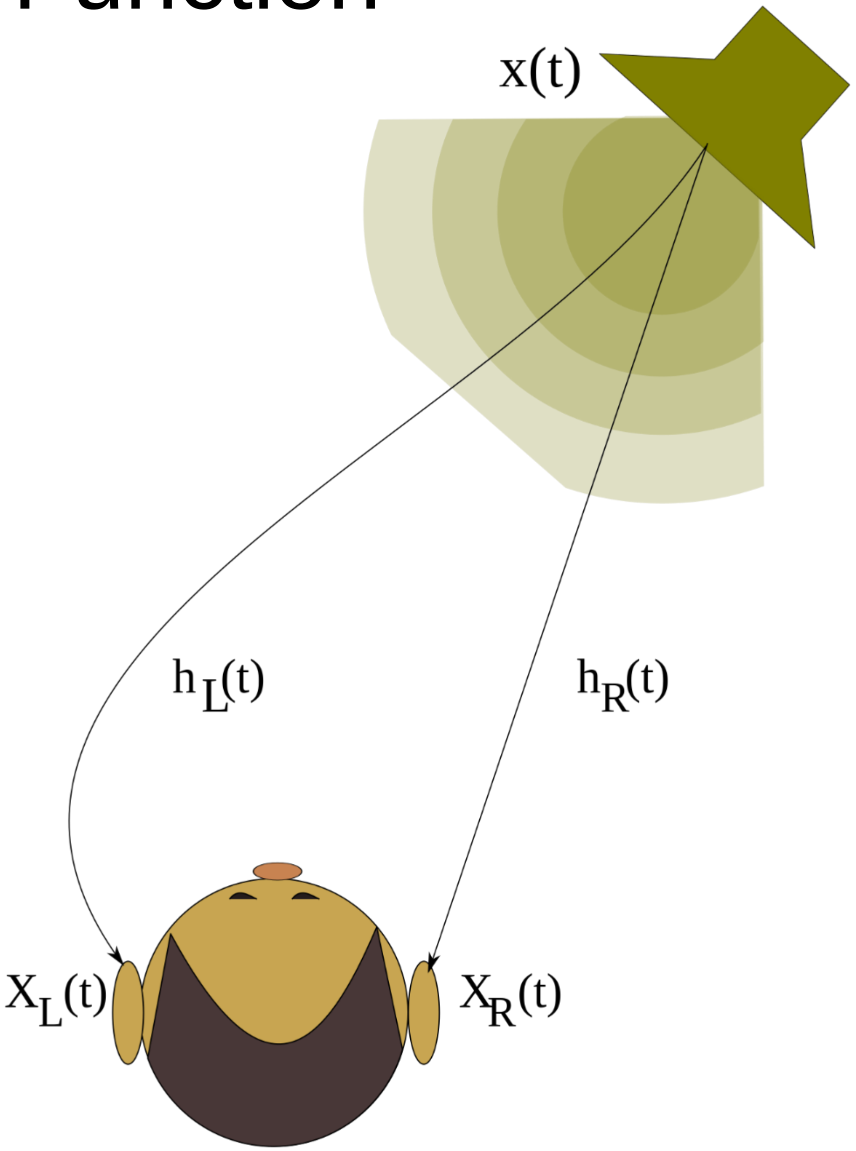


3D Sound Localization

Head-Related Transfer Function (HRTF)

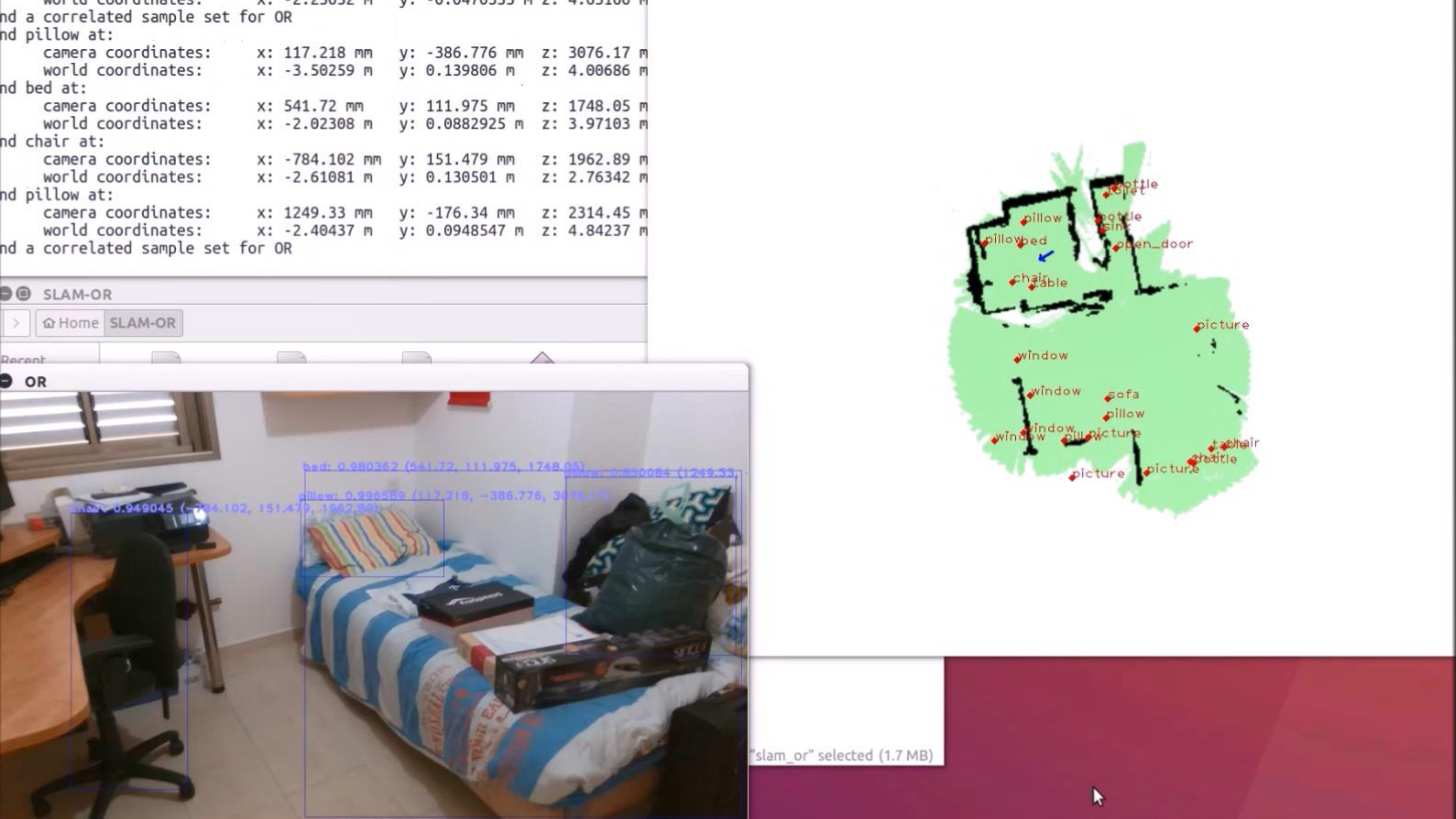
HRTF characterizes how an ear receives a sound from a point in space.

The size and shape of the head, ears, ear canal, density of the head, size and shape of nasal and oral cavities, all transform the sound and affect how it is perceived, boosting some frequencies and attenuating others.



Wikipedia

Some Key Trends…

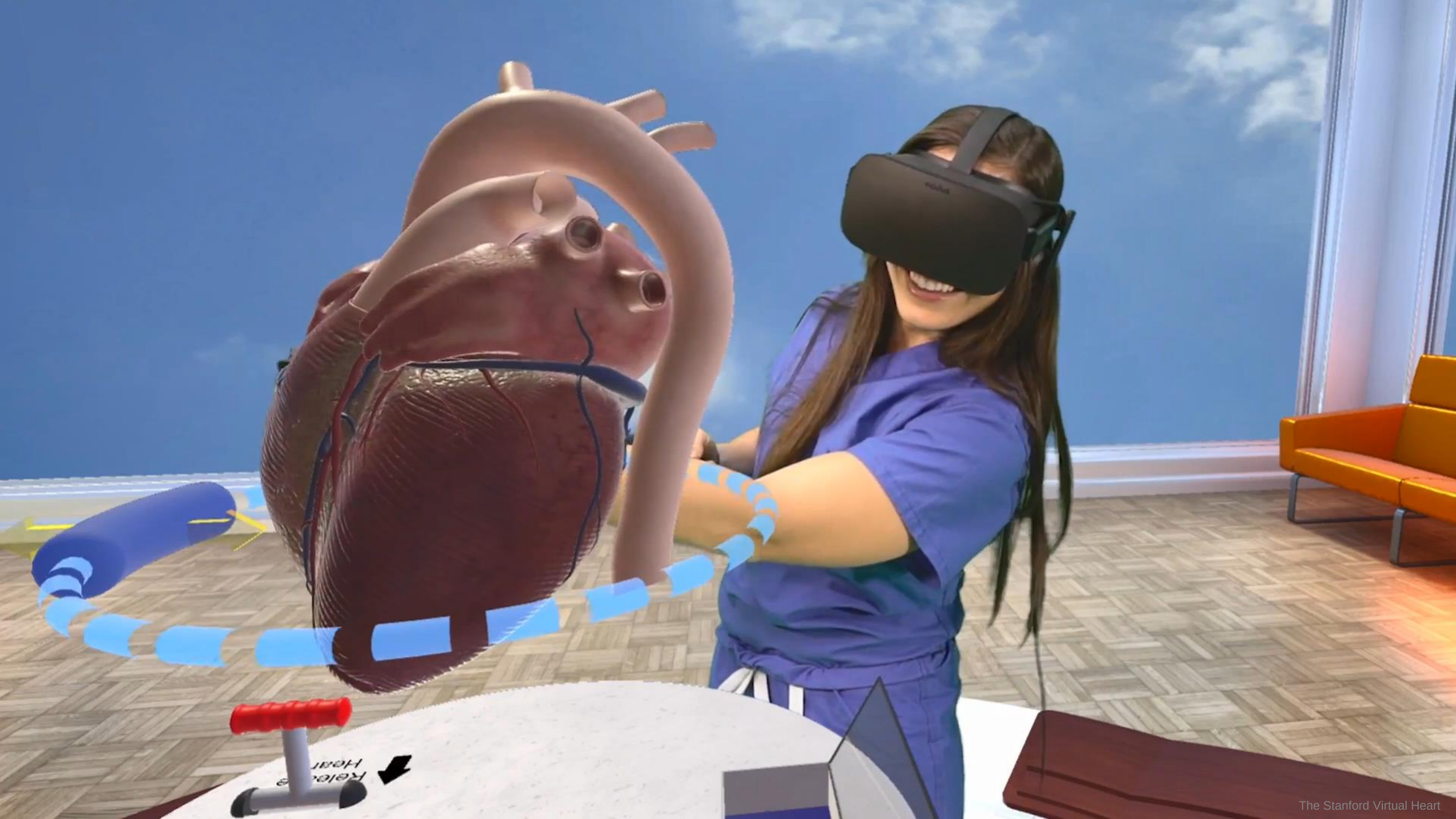

nd a correlated sample set for OR
nd pillow at:
camera coordinates: x: 117.218 mm y: -386.776 mm z: 3076.17 m
world coordinates: x: -3.50259 m y: 0.139806 m z: 4.00686 m
nd bed at:
camera coordinates: x: 541.72 mm y: 111.975 mm z: 1748.05 m
world coordinates: x: -2.02308 m y: 0.0882925 m z: 3.97103 m
nd chair at:
camera coordinates: x: -784.102 mm y: 151.479 mm z: 1962.89 m
world coordinates: x: -2.61081 m y: 0.130501 m z: 2.76342 m
nd pillow at:
camera coordinates: x: 1249.33 mm y: -176.34 mm z: 2314.45 m
world coordinates: x: -2.40437 m y: 0.0948547 m z: 4.84237 m
nd a correlated sample set for OR
SLAM-OR
Home
SLAM-OR
OR
pillow
bed
chair
table
bottle
sink
open_door
picture
window
sofa
"slam_or" selected (1.7 MB)


struct StaticMesh
struct StartLocation
struct StaticMesh
struct StaticMesh
struct StaticMesh
struct GoldLatheObject
Inspector

VentureBeat

AR and VR need to move from what developers like to what consumers want


Yukon St.
PETSMART
Home
6.55 mi
Take exit right on Cambie St towards
City Center
6.55 mi
Home
arrival in 13:24
11 mph
25
4:35
74°
aug 6
Mr. Blue Sky
Electric Light Orchestra
Phiar



The Stanford Virtual Heart

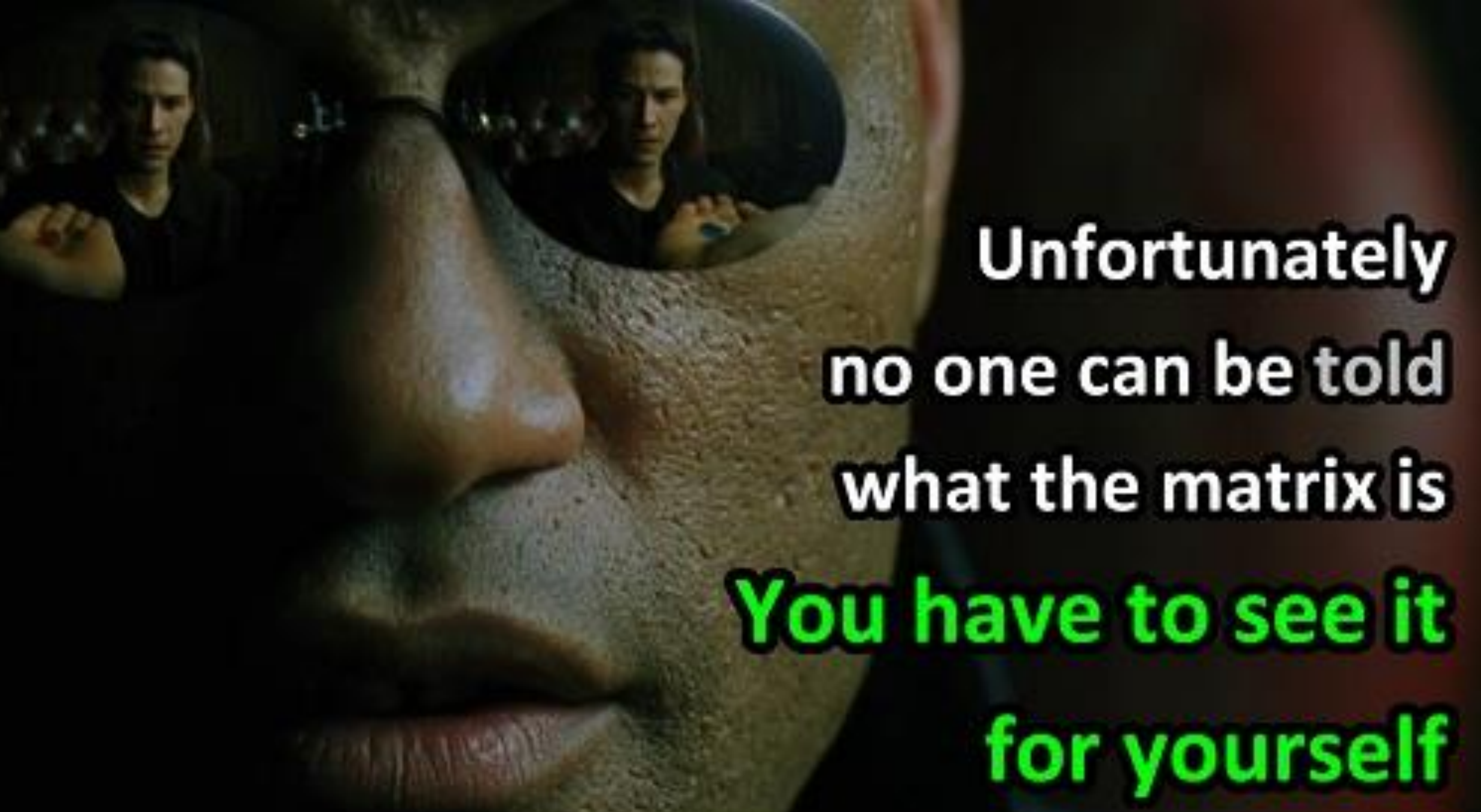
Parting Thoughts…

- Key requirements for virtual and augmented reality devices and applications are now relatively well-understood.

- Lots of progress recently in the development of technologies and components, but some major challenges remain to be solved for mass adoption.

- Ingredients are important, but end-to-end integration (hardware, software, system, interfaces) is critical.

- Commercial success will hinge on delivering compelling applications with natural user experiences.


Unfortunately
no one can be told
what the matrix is
You have to see it
for yourself

The Matrix

Thank You!

achintya.k.bhowmik@gmail.com


너를만났다
어딨어?

References & Acknowledgements

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- clinicalarchitecture.com
- Phiar, www.youtube.com/watch?v=CQqPWEp0Zew
- www.marketplace.org, Tim P. Whitby / Getty Images
- Johnny English Strikes Again (2018 action comedy film), wikipedia.org/wiki/Johnny_English_Strikes_Again
- iFixit
- Wikipedia

A (Brief) Historical Perspective…
and Why Now?

The Sensorama

Morton Heilig described his vision of a multi-sensory theater in 1955.

Built a prototype in 1962, along with five short films. Halted due to lack of financial support.

Capabilities:
- Stereoscopic 3-D images
- Body tilting
- Stereo sound
- Wind and aromas

References:

- Heilig M. (1962). US Patent #3,050,870
- Rheingold, H. (1992). Virtual Reality, Simon & Schuster, New York, N.Y.
- wikipedia.org/wiki/Sensorama

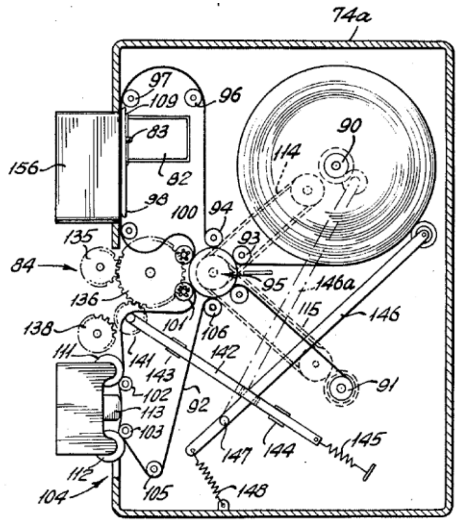
Wikipedia

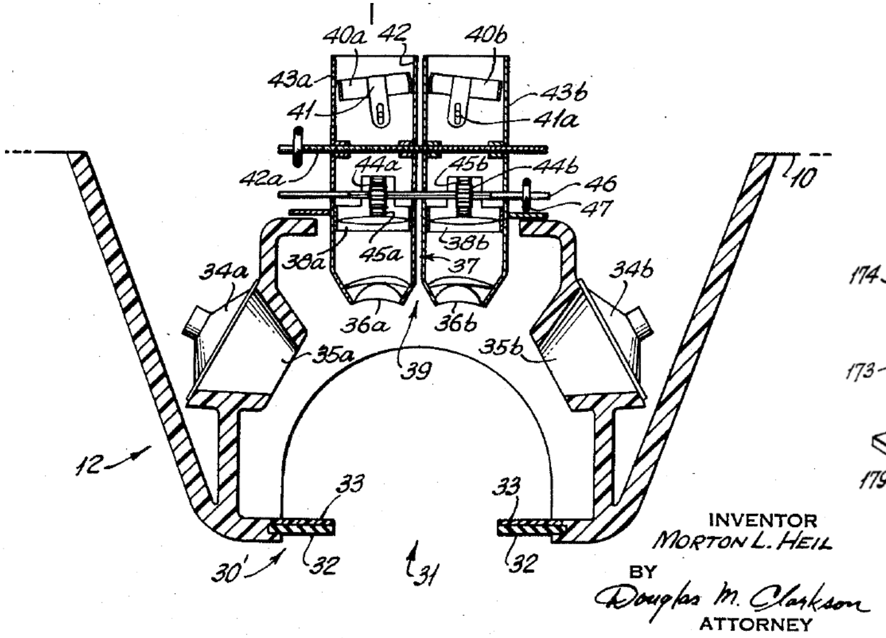
3,050,870
SENSORAMA SIMULATOR

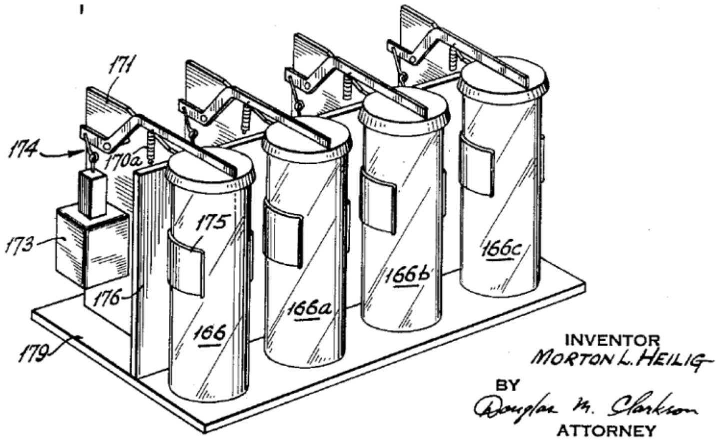
Morton L. Heilig, Long Beach, N.Y.
(10 Sheridan Square, New York 14, N.Y.)

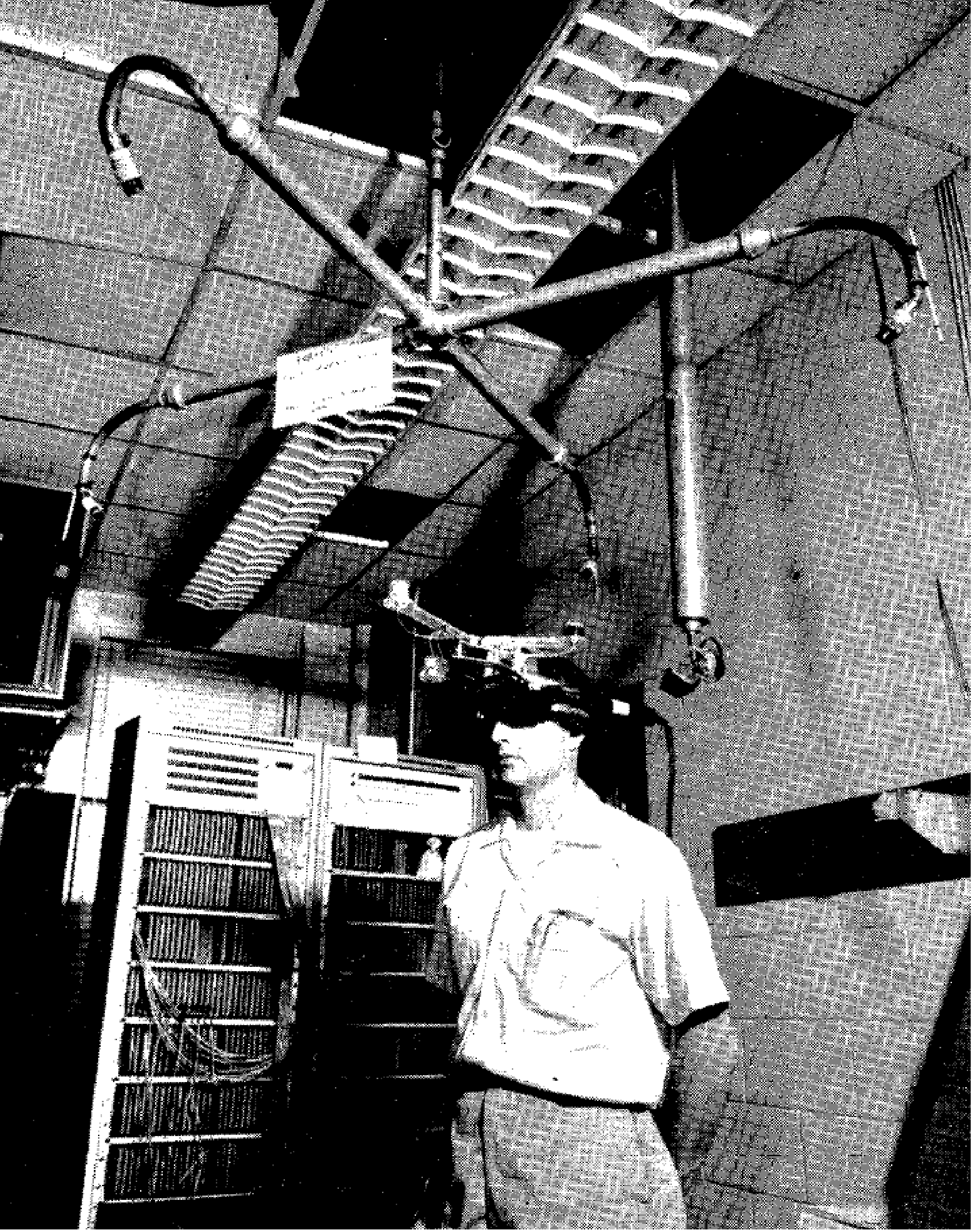
Filed Jan. 10, 1961, Ser. No. 81,864
13 Claims. (Cl. 35—1)

The present invention, generally, relates to simulator apparatus and, more particularly, to apparatus to stimulate the senses of an individual to simulate an actual experience realistically.









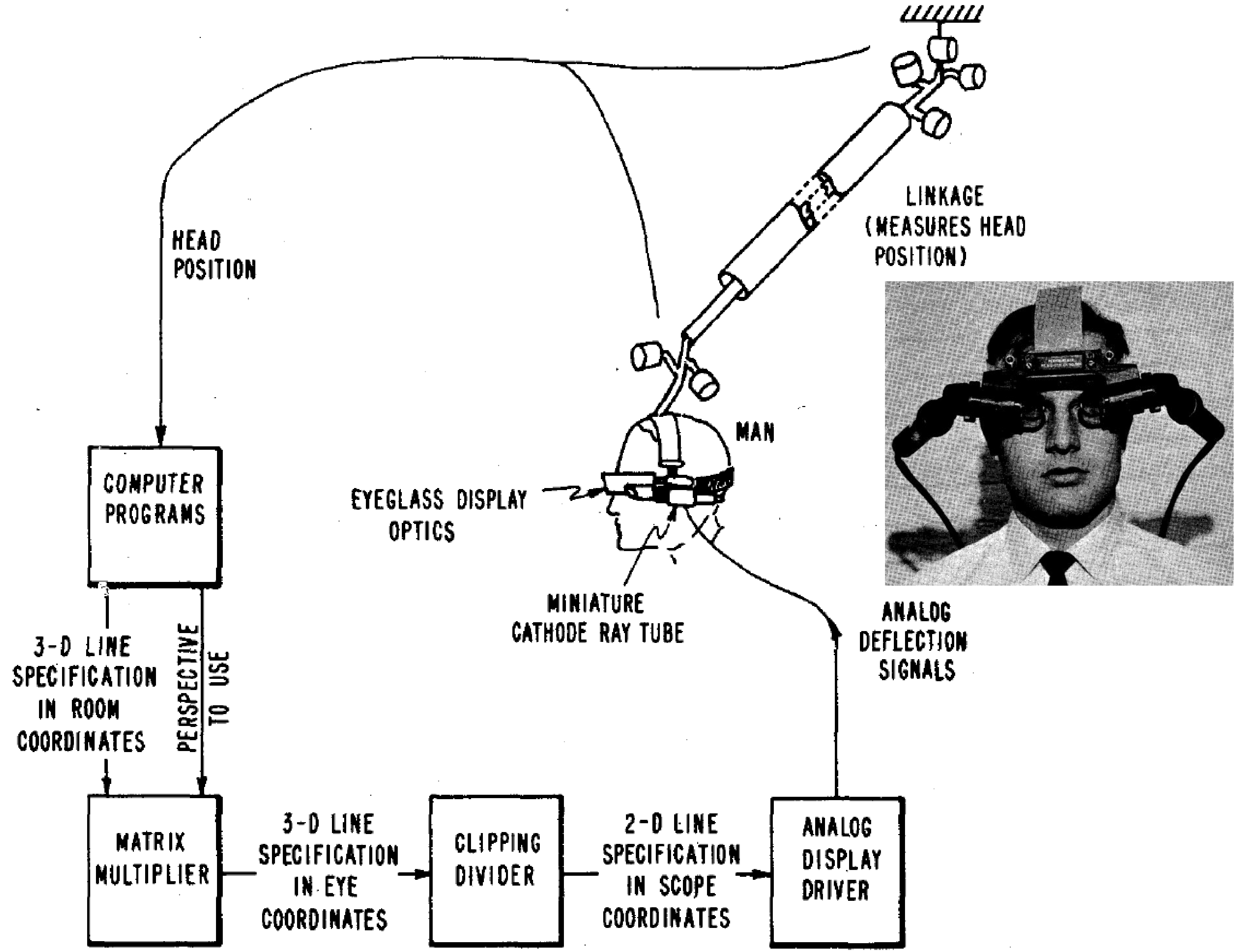
The Sword of Damocles

Ivan Sutherland and his student **Bob Sproull** created the first VR/AR system with head-mounted displays in 1968.

Displayed output from a computer program in a binocular display (2 CRTs). The perspective changed with user's head tracking.

References:

- Sutherland, I. E. (1968). "A head-mounted three dimensional display". Proceedings of AFIPS 68, pp. 757-764
- wikipedia.org/wiki/The_Sword_of_Damocles_(virtual_reality)


HEAD POSITION
LINKAGE (MEASURES HEAD POSITION)
MAN
EYEGLASS DISPLAY OPTICS
MINIATURE CATHODE RAY TUBE
COMPUTER PROGRAMS
3-D LINE SPECIFICATION IN ROOM COORDINATES
PERSPECTIVE TO USE
ANALOG DEFLECTION SIGNALS
MATRIX MULTIPLIER
3-D LINE SPECIFICATION IN EYE COORDINATES
CLIPPING DIVIDER
2-D LINE SPECIFICATION IN SCOPE COORDINATES
ANALOG DISPLAY DRIVER

VPL EyePhone & DataGlove

Jaron Lanier founded **VPL Research** in 1984, and was among the first to build and sell virtual reality products.

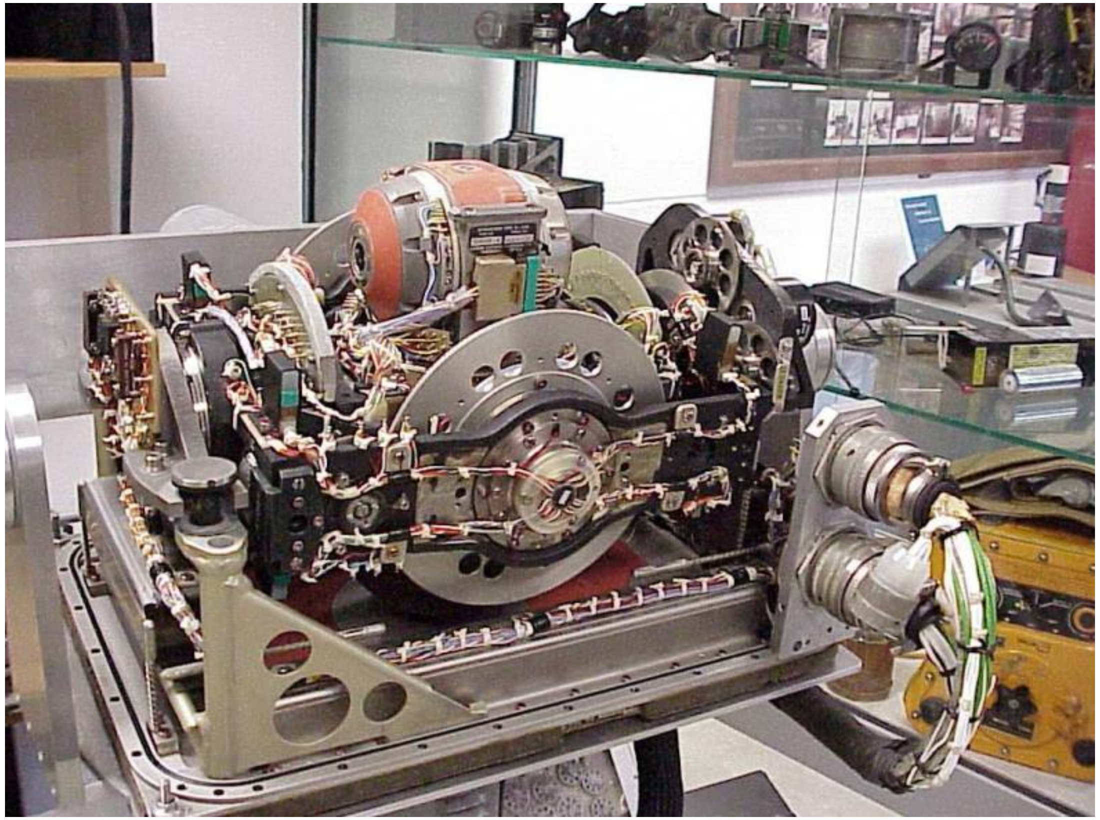
The EyePhone was an HMD intended to immerse users into a computer simulation. It could track head movements. The headset used Fresnel lenses.

Model 1: 2.4Kg
Model 2: 2.5lbs
Both >$9K

References:

- wikipedia.org/wiki/VPL_Research
- vrwiki.wikispaces.com/VPL+EyePhone

So… Why Now? An Example…



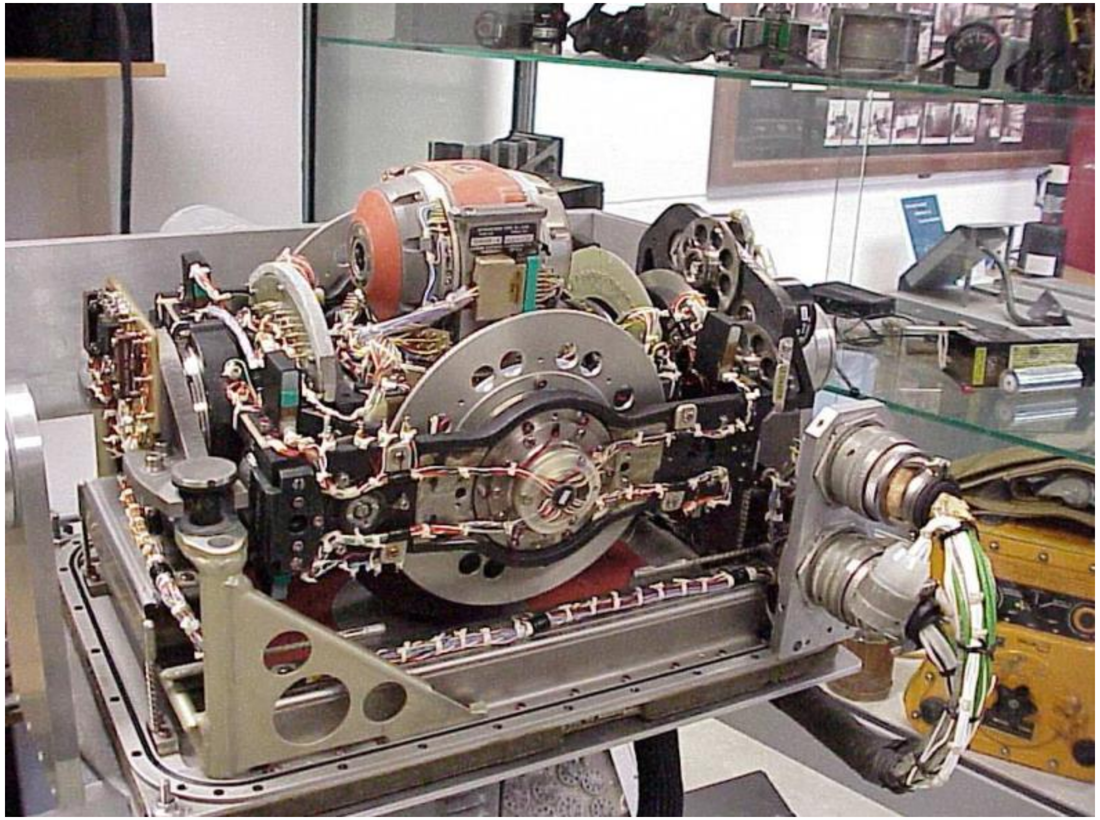
The LN-3 Inertial Navigation System, developed in the 1960s by Litton Industries

"They tell me about electric motors that are the size of the nail on your small finger… But that's nothing; that's the most primitive, halting step in the direction I intend to discuss.

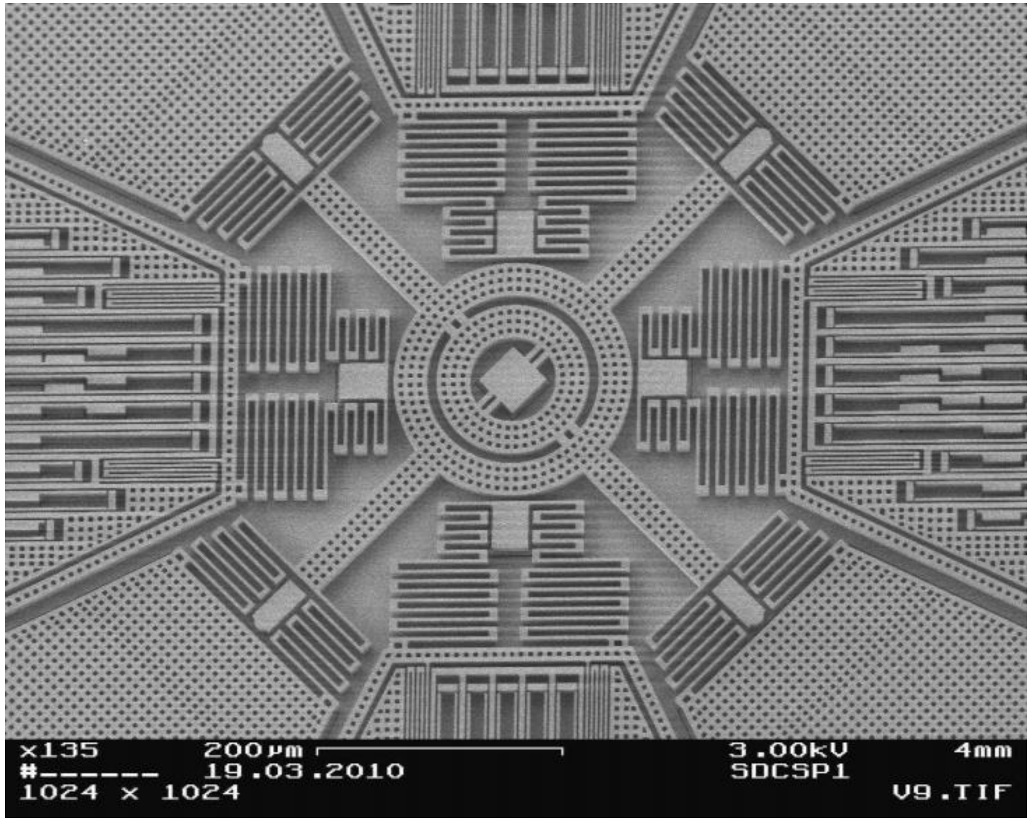
It is a staggeringly small world that is below. *In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction."*

– **Richard Feynman,** "There's Plenty of Room at the Bottom", at the1959 annual meeting of American Physical Society

So… Why Now? An Example…



The LN-3 Inertial Navigation System, developed in the 1960s by Litton Industries



The internal structures of a modern MEMS gyroscope; the total width is less than 1mm

So… Why Now? Another Example…

CRT Display, Circa 2000

55” OLED TV, LG, 2012

Examples of Modern-Day VR Devices

(PC and Console Based)

HTC Vive
with Valve

Facebook
Oculus Rift

Sony
PlayStation VR


IFIXIT

Examples of Modern-Day VR Devices
(Smartphone Based)

Samsung
Gear VR

Google
Daydream

Examples of Modern-Day AR/MR Devices
(Standalone and Tethered)

Microsoft
Hololens 2

Magic Leap
One

Examples of Phone/Tablet-Based AR

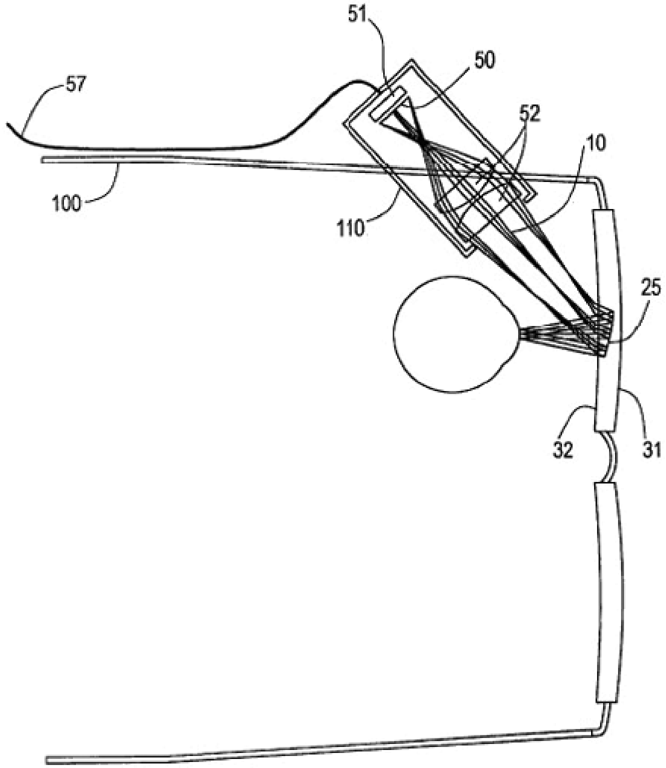
Apple ARKit

Google ARCore

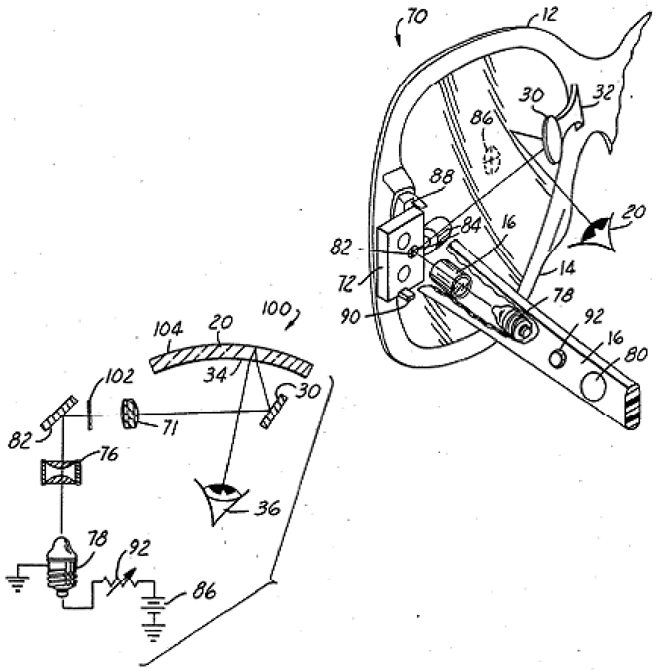
Examples of Optics for See-Through Head-Worn Displays (HWD) in Augmented/Mixed Reality Systems

HWD Examples (Slide 1 of 18)

Spitzer. Eyeglass Display Lens System Employing Off-Axis Optical Design.
US 6,353,503
Mar. 5, 2002



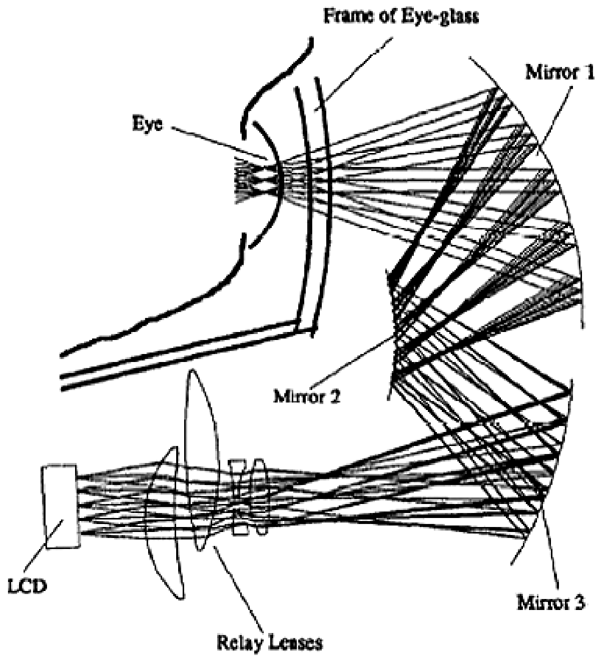
Bettinger. Spectacle-mounted ocular display apparatus.
US 4,806,011
Feb. 21, 1989



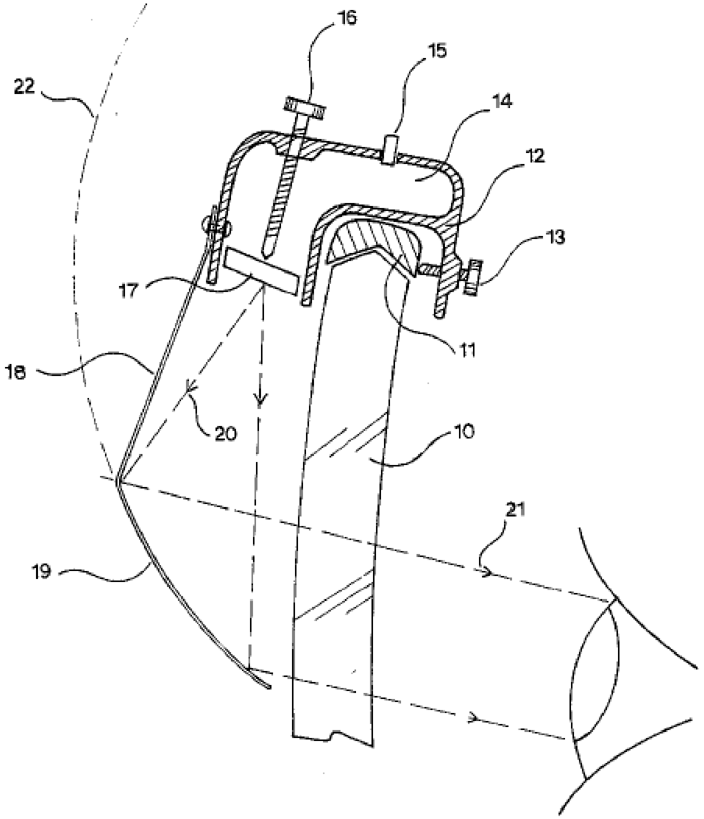
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 2 of 18)

Hoshi *et al.* Off-axial HMD optical system consisting of aspherical surfaces without rotational symmetry. In Proc. of SPIE Vol. 2653



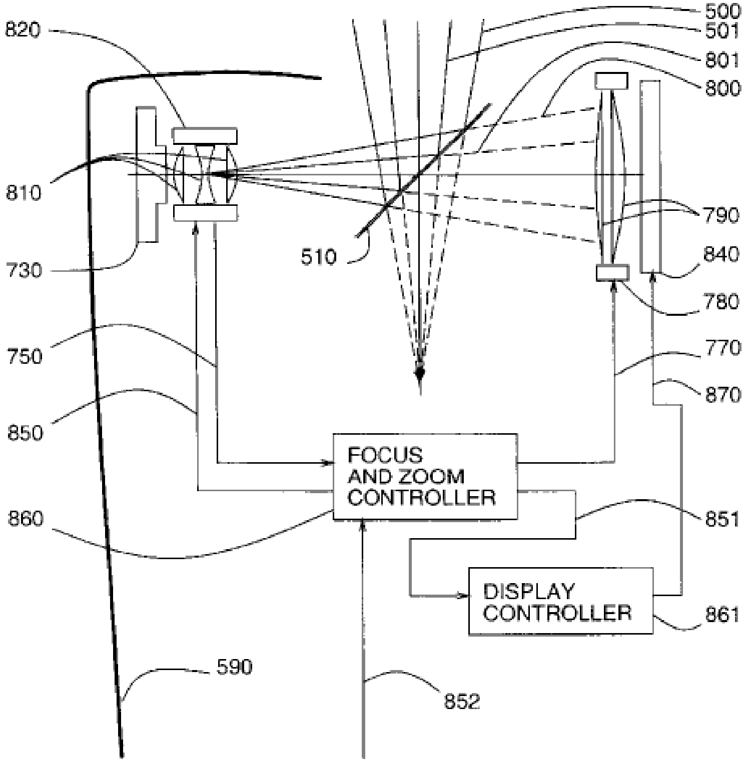
Perera. Display Projection Optical System for Spectacles or Sunglasses.
US 4,867,551
Sep. 19, 1989



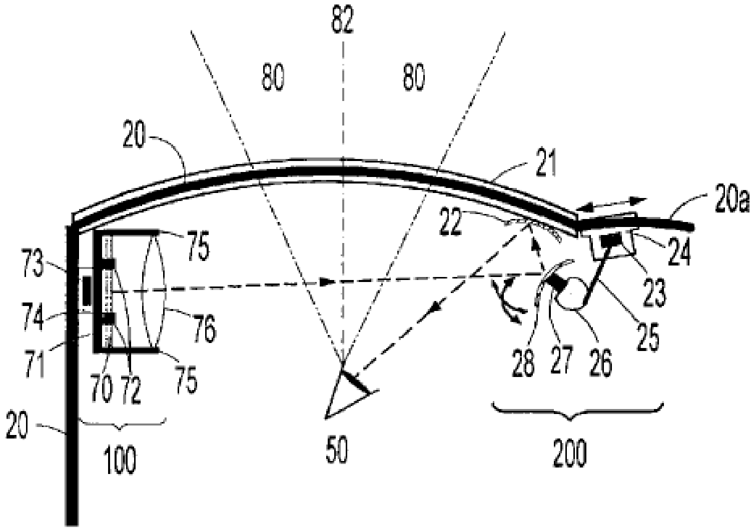
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 3 of 18)

Mann. Wearable Camera
System With Viewfinder Means.
US 6,307,526
Oct. 23, 2001



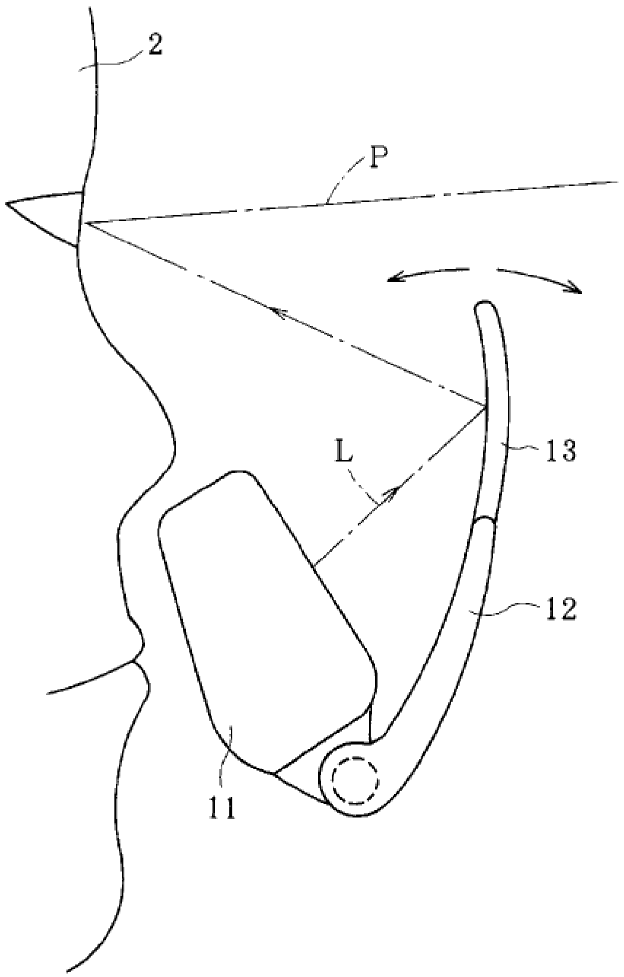
Geist. Head-mounted virtual display
apparatus with near-eye deflecting element
in the peripheral field-of-view.
US 6, 771,423
Aug. 3, 2004



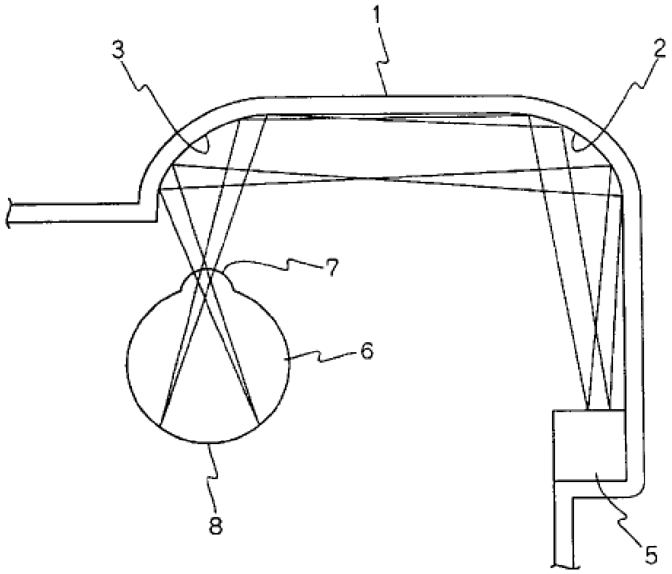
O. Cakmakci, et al., "Head-Worn Displays: A Review," J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 4 of 18)

Amafuji. Head Mounted Display Device.
US 6,359,602
Sep. 19, 2002



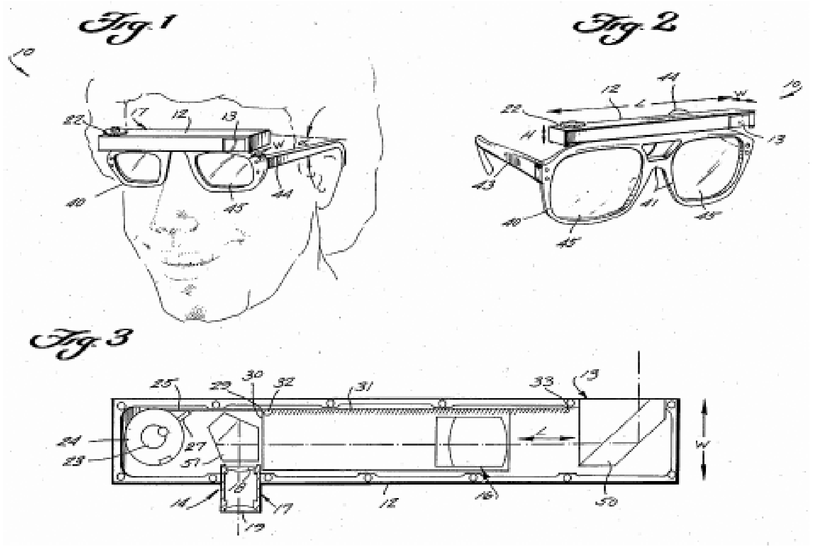
Kuriyama. Image Display Apparatus
US 6,081,304
Jun. 27, 2000



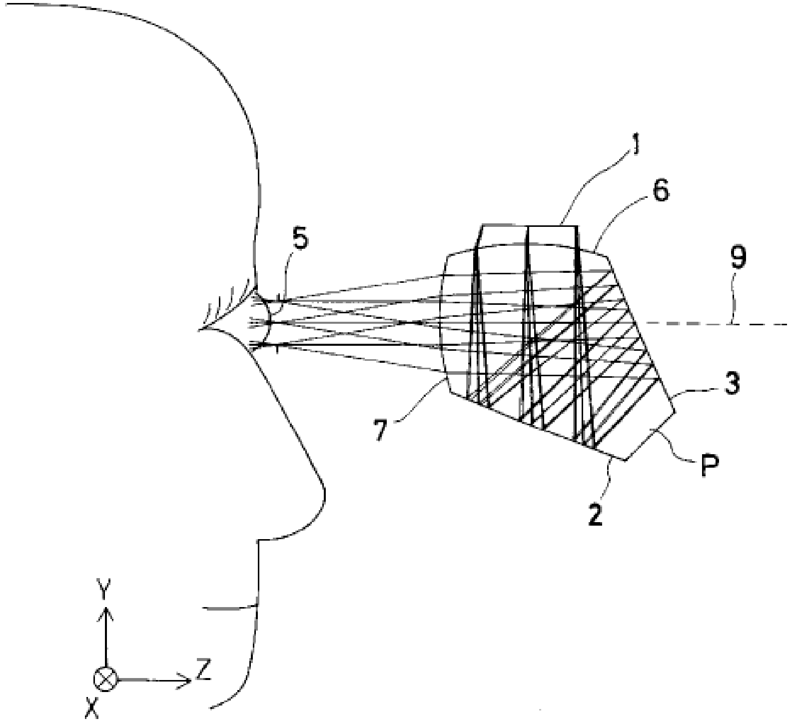
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 5 of 18)

Pekar. Vision enhancing system.
US 4,704,000
Nov. 3, 1987



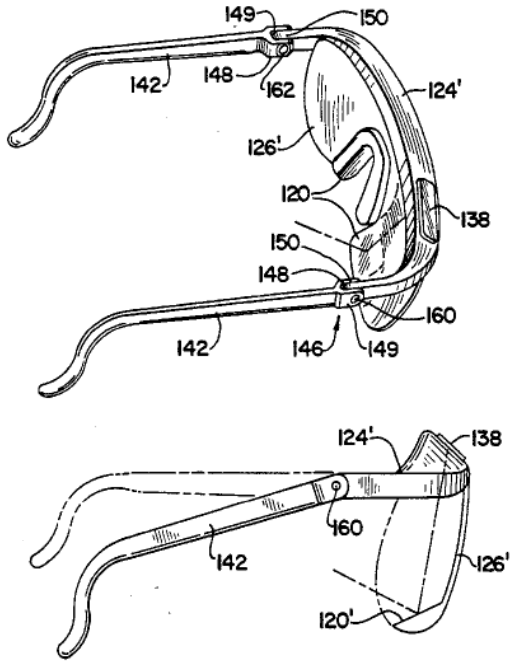
Togino. Prosm Optical System.
US 5,991,103
Nov. 23, 1999



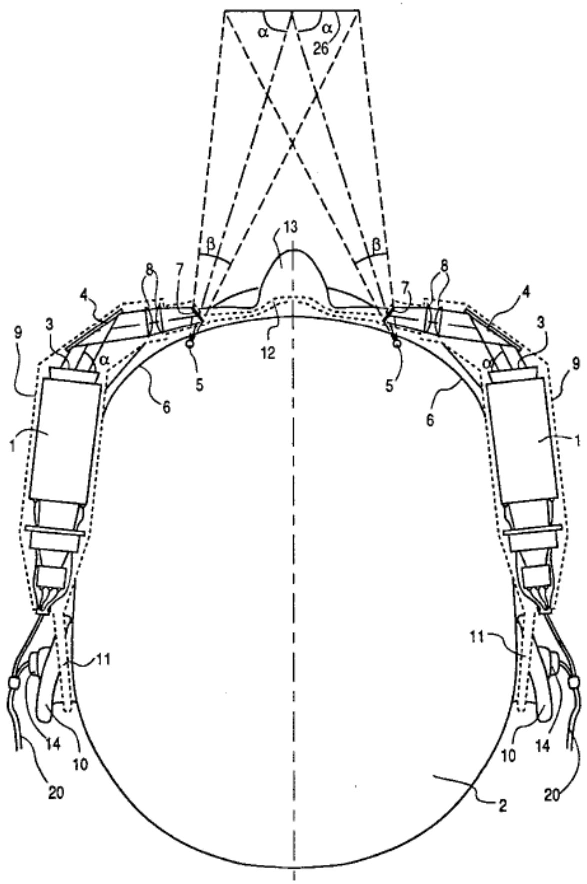
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 6 of 18)

Furness. Display System for a Head Mounted Viewing Transparency.
US 5,162,828
Nov. 10, 1982



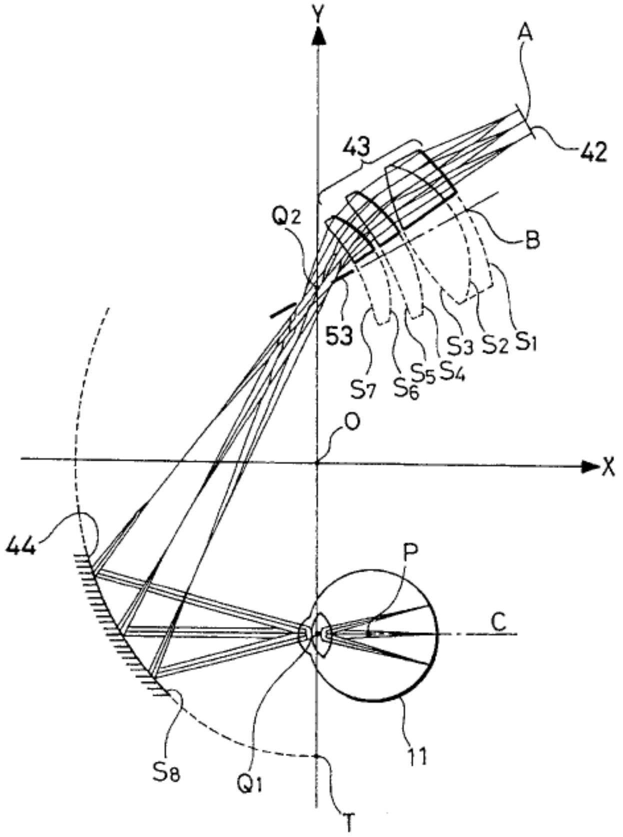
Holakovszky. Stereoscopic video image display appliance wear-able on head like spectacles.
US 5,129,716
Jul. 14, 1992



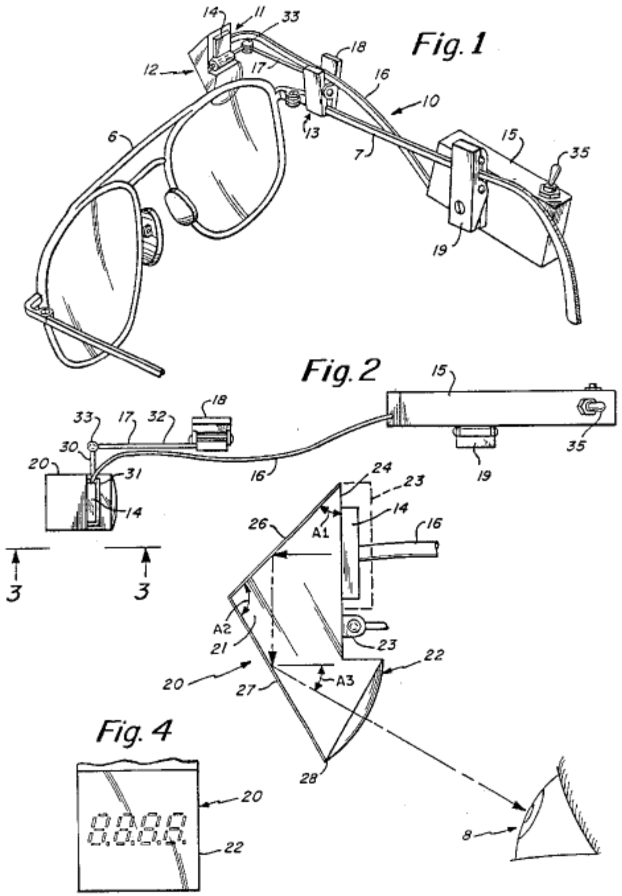
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 7 of 18)

Iba. Image Observation Device.
US 5,384,654
Jan. 24, 1995



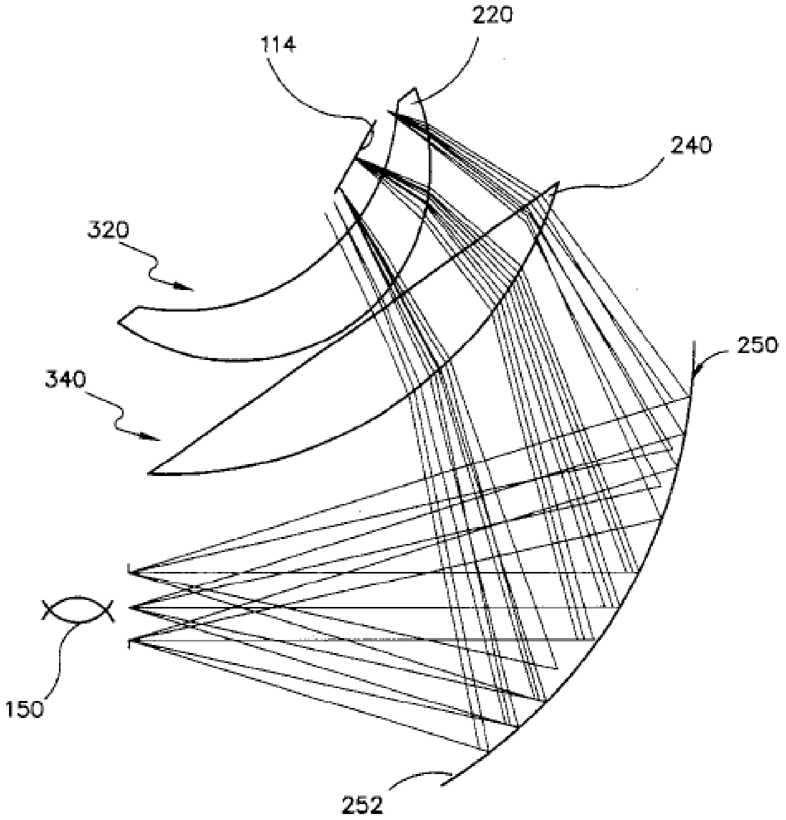
Kubik. Headwear-mounted
Periscopis Display Device.
US 4,753,514
Jun. 28, 1993



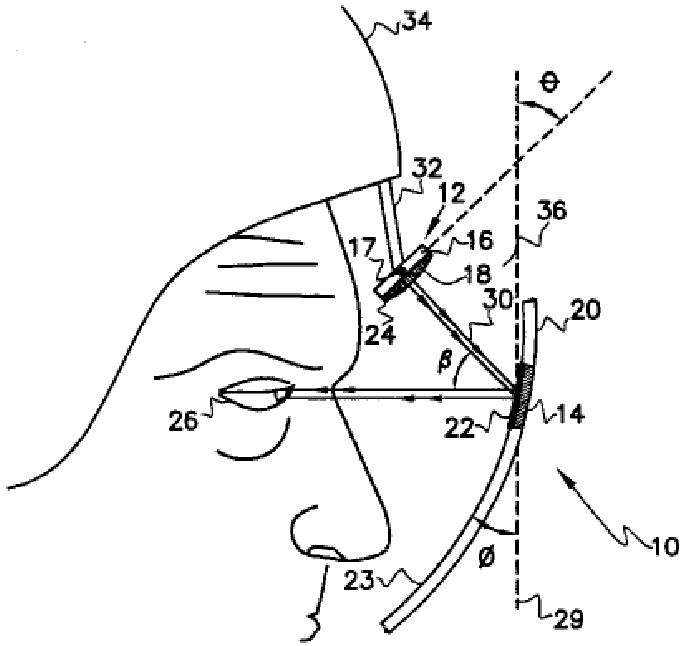
O. Cakmakci, et al., "Head-Worn Displays: A Review," J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 8 of 18)

Ferrin. Headgear Display System
Using Off-axis Image Sources.
US 5,576,887
Nov. 19, 1996



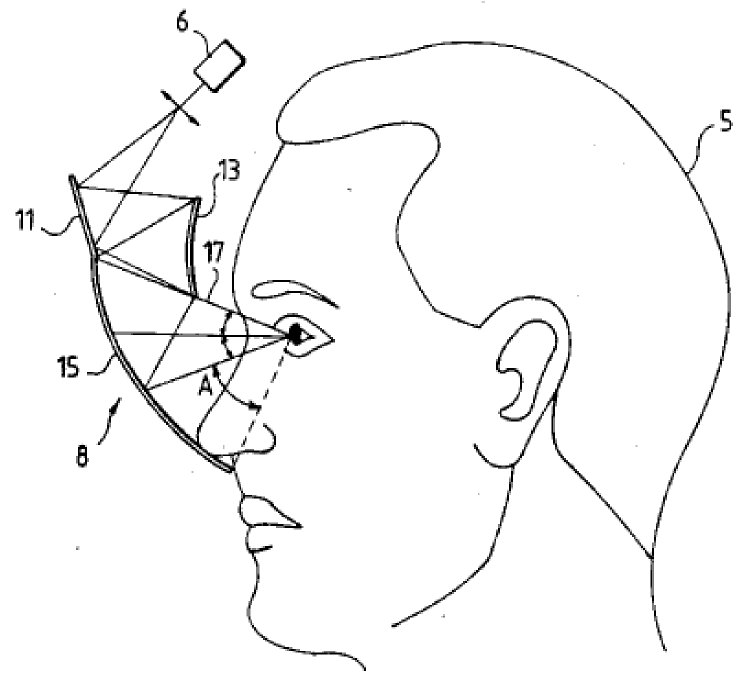
Lippert. Visor Display with
Fiber Optic Faceplate Correction.
US 5,309,169
May 3, 1994



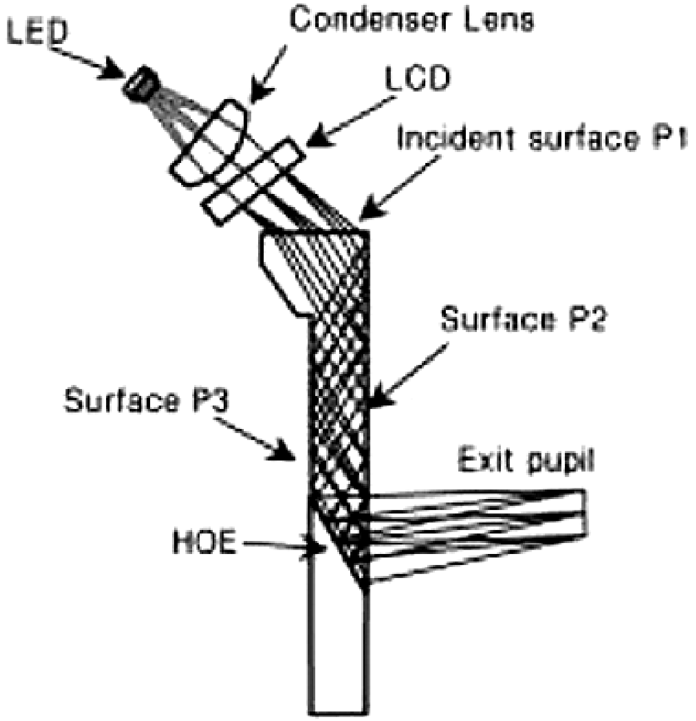
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 9 of 18)

Lacroix. Device for the Display
of Simulated Images for Helmets.
US 5,184,250
Feb. 2, 1993



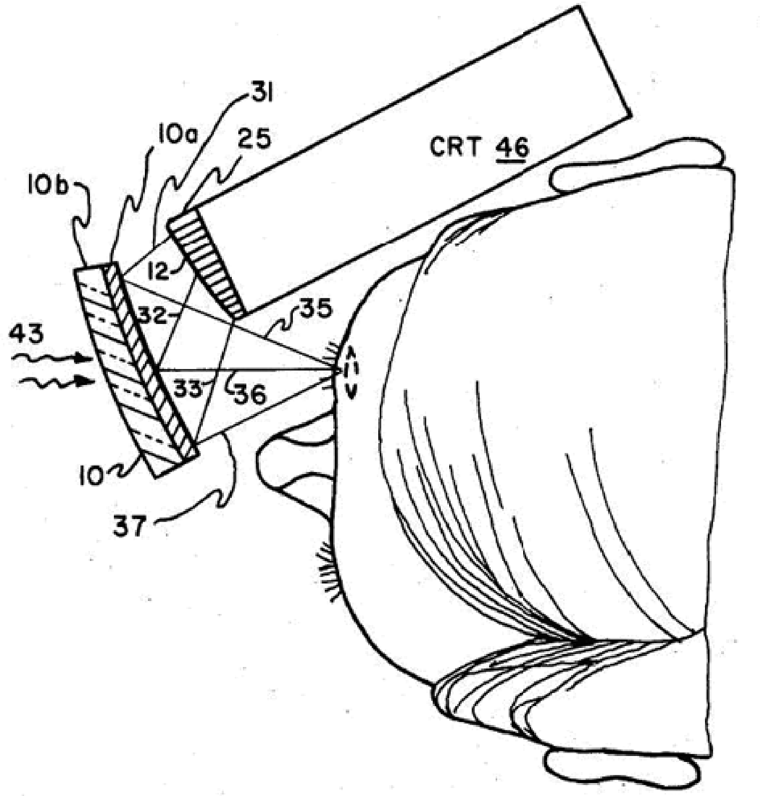
Kasai. A Forgettable Near-Eye Display.
ISWC 2000



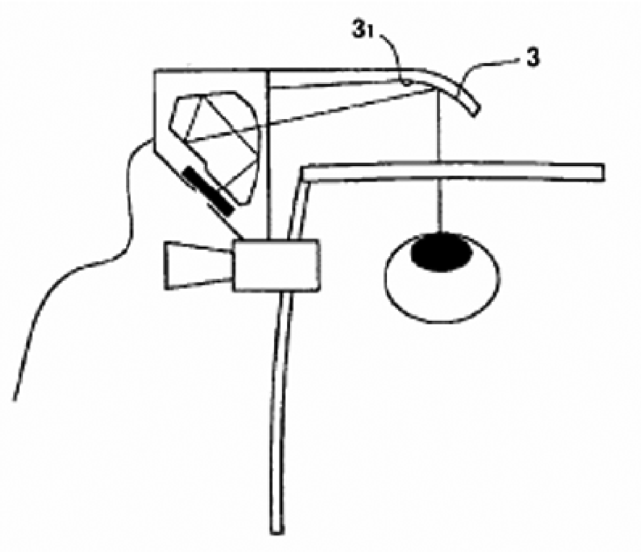
O. Cakmakci, et al., "Head-Worn Displays: A Review," J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 10 of 18)

Bosserman. Toric reflector display.
US 4,026,641
May 31, 1977



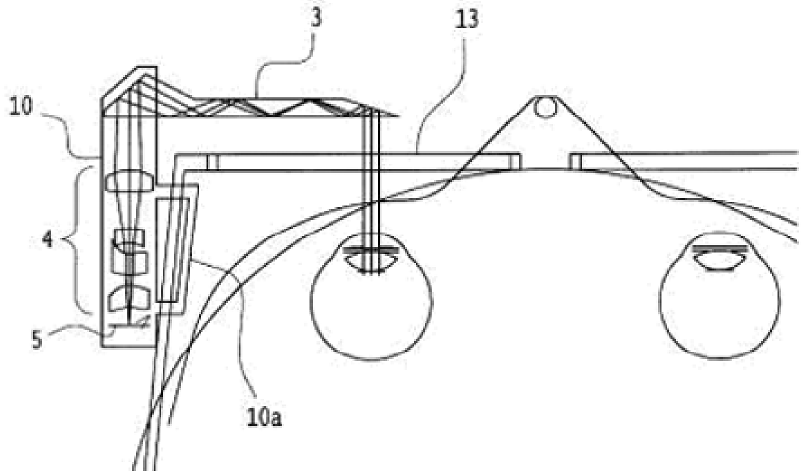
Nagaoka. Light weight head mounted image display device.
US 6,697,200
Feb. 24, 2004



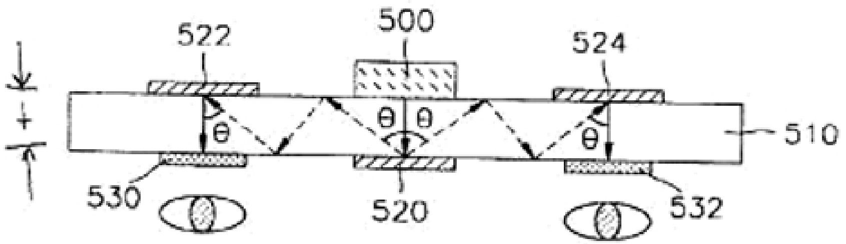
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 11 of 18)

Takeyama. Observation optical system.
US 6,710,902
Mar. 23, 2004



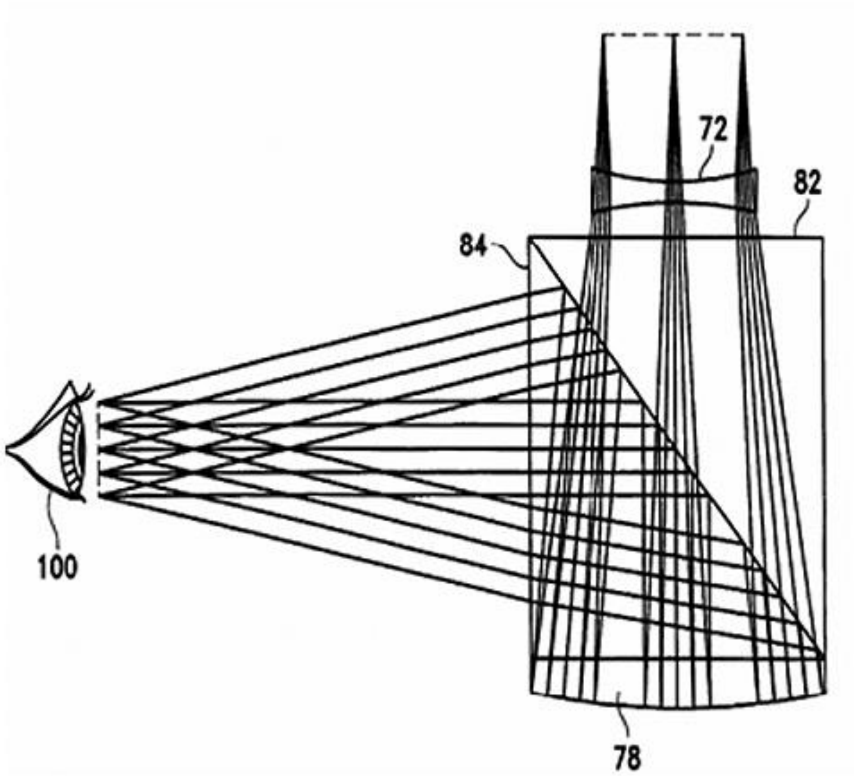
Song. Wearable display system.
US 6,882,479
Apr. 19, 2005



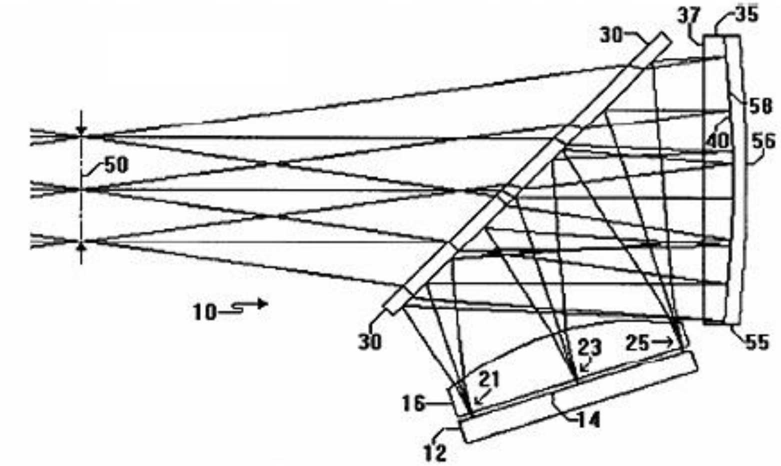
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 12 of 18)

Robinson. Video headset.
US 5,696,521
Dec. 9, 1997



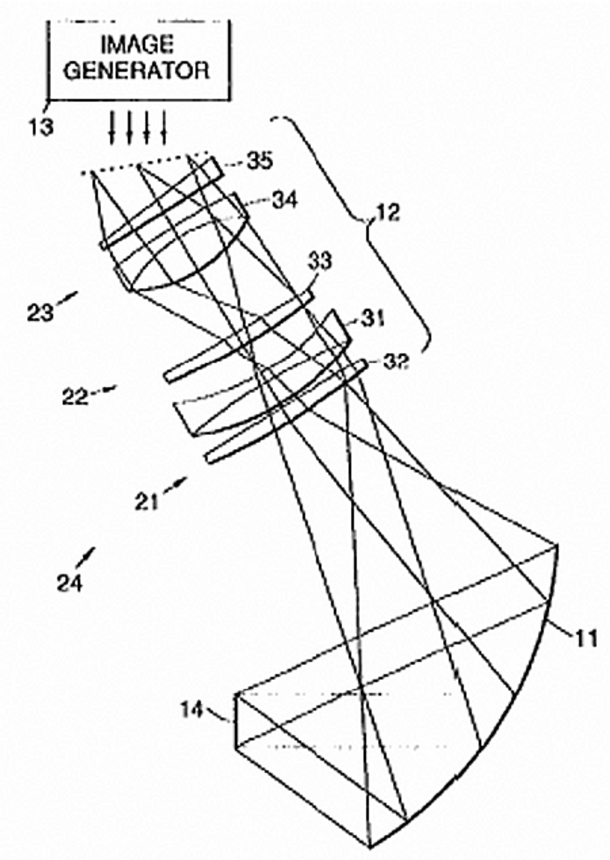
Fritz. Head mounted display
using mangin mirror combiner.
US 5,838,490



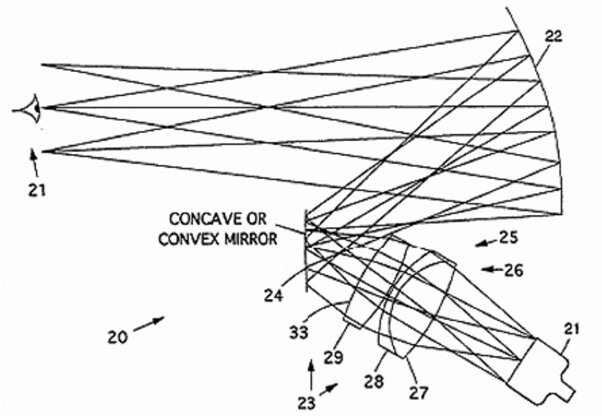
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 13 of 18)

Chen. Helmet visor display employing reflective, refractive and diffractive optical components
US 5,526,183
Jun. 11, 1996



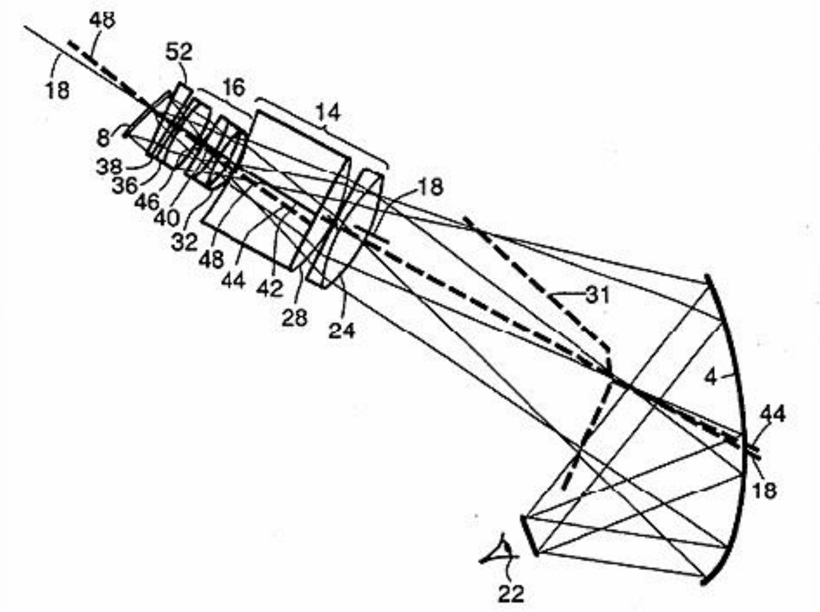
Chen. Wide spectral bandwidth virtual image display system.
US 5,436,763
Jul. 25, 1995



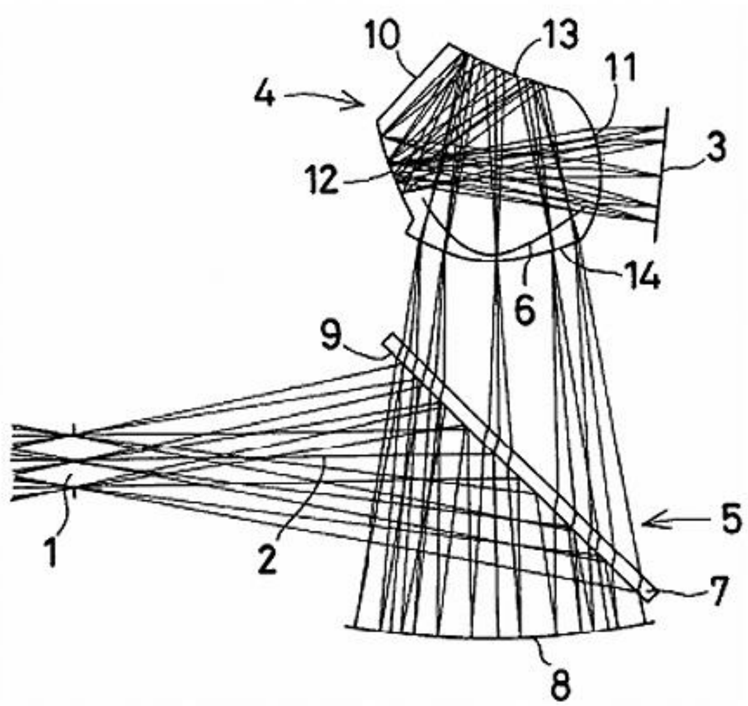
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 14 of 18)

Chen. Ultra-wide field of view, broad spectral band visor display optical system.
US 5,499,139
Mar. 12, 1996

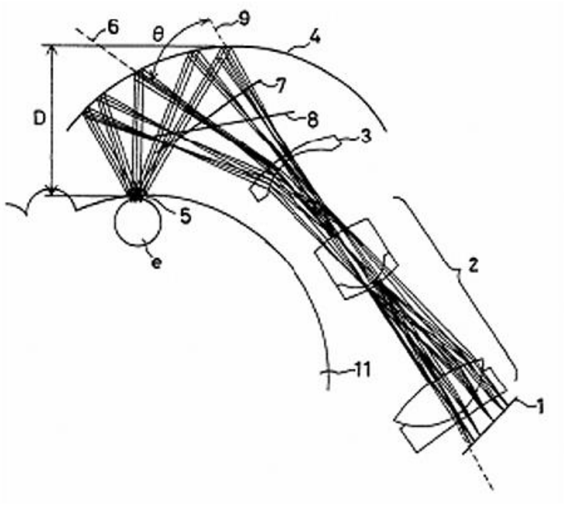


Takeyama. Image display apparatus.
US 6,342,871
Jan. 29, 2002

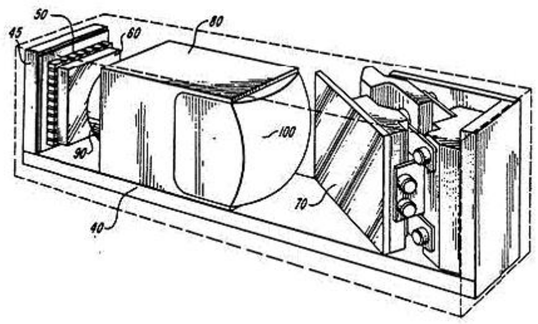


HWD Examples (Slide 15 of 18)

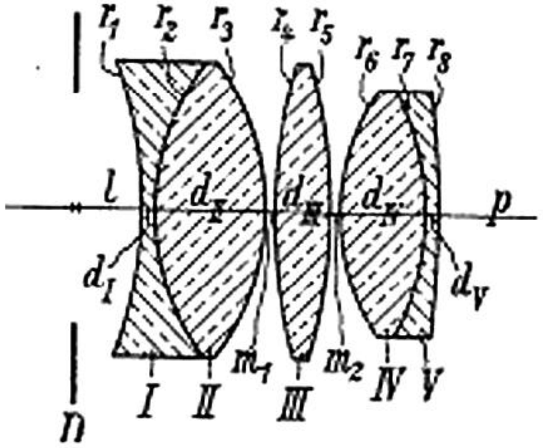
Togino. Visual display apparatus
US 5,436,765
Jul. 25, 1995



Becker. Head Mounted Display for
Minian Video Display System.
US 5,003,300
Mar. 26, 1991



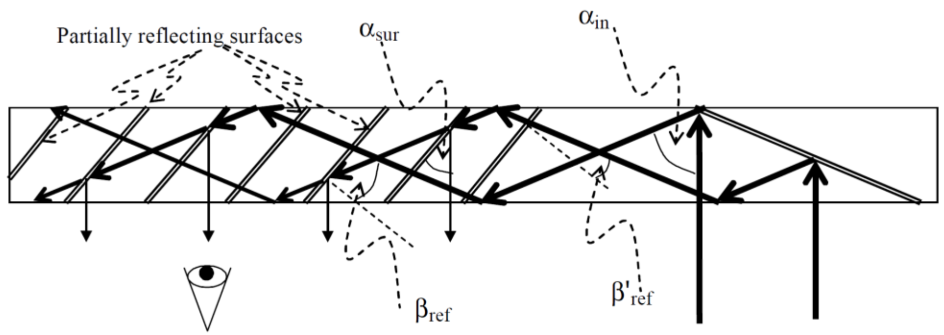
Erfle. Ocular.
US 1,478,704
Dec. 25, 1923

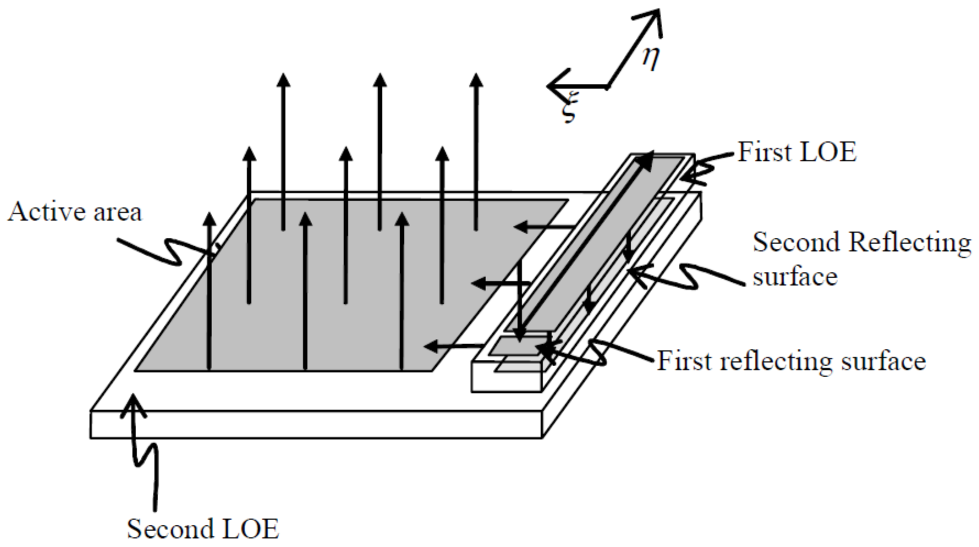


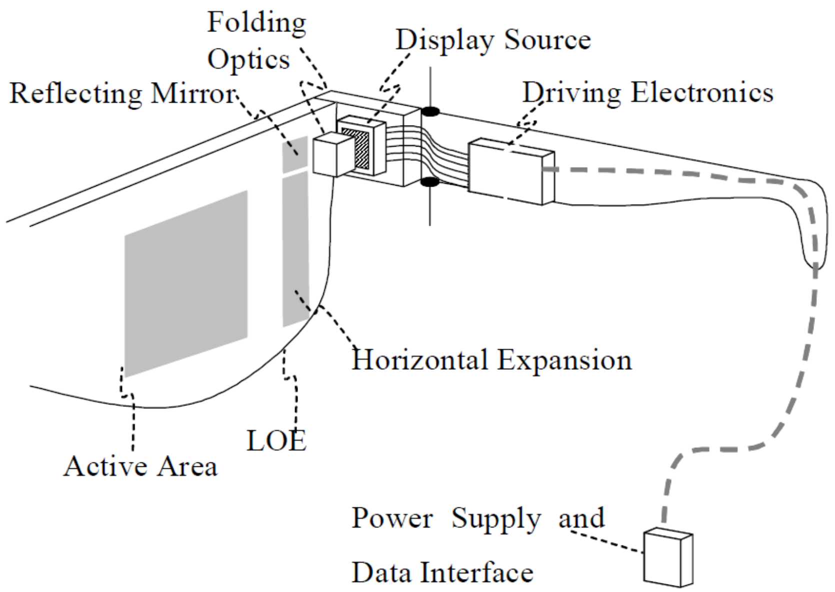
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 16 of 18)

Waveguide with Cascaded Mirror-Array (Lumus)



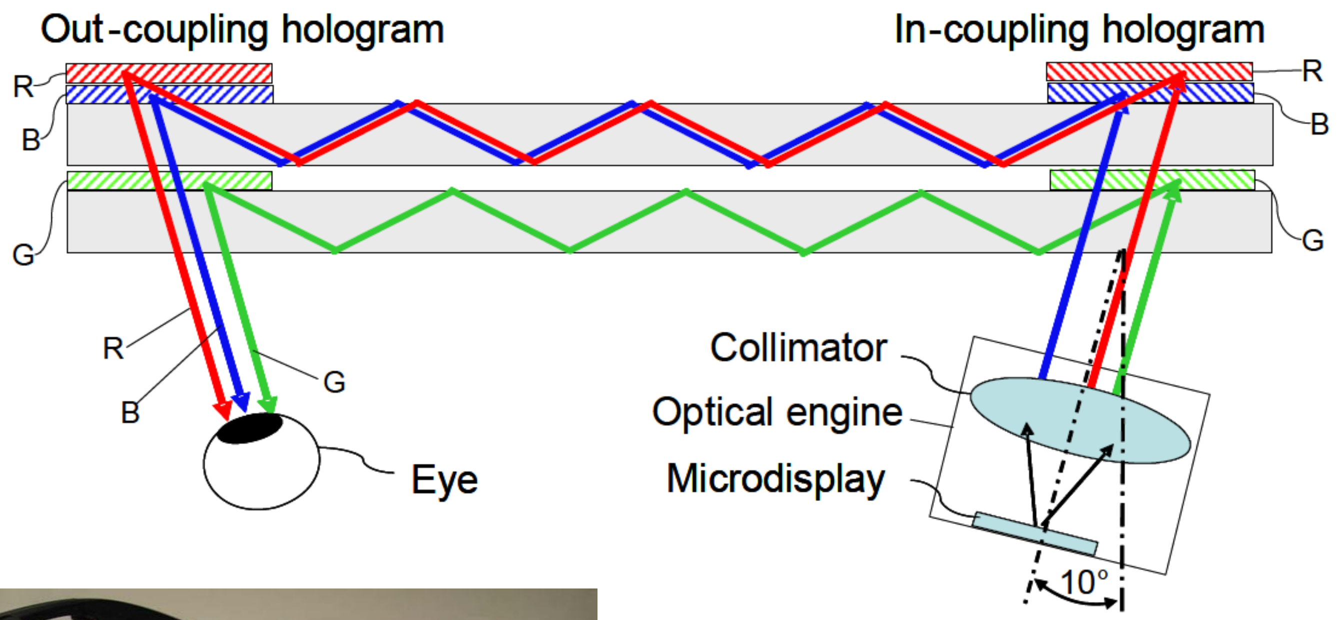




Y. Amitai, SID Symposium Digest of Technical Papers, 2005

HWD Examples (Slide 17 of 18)

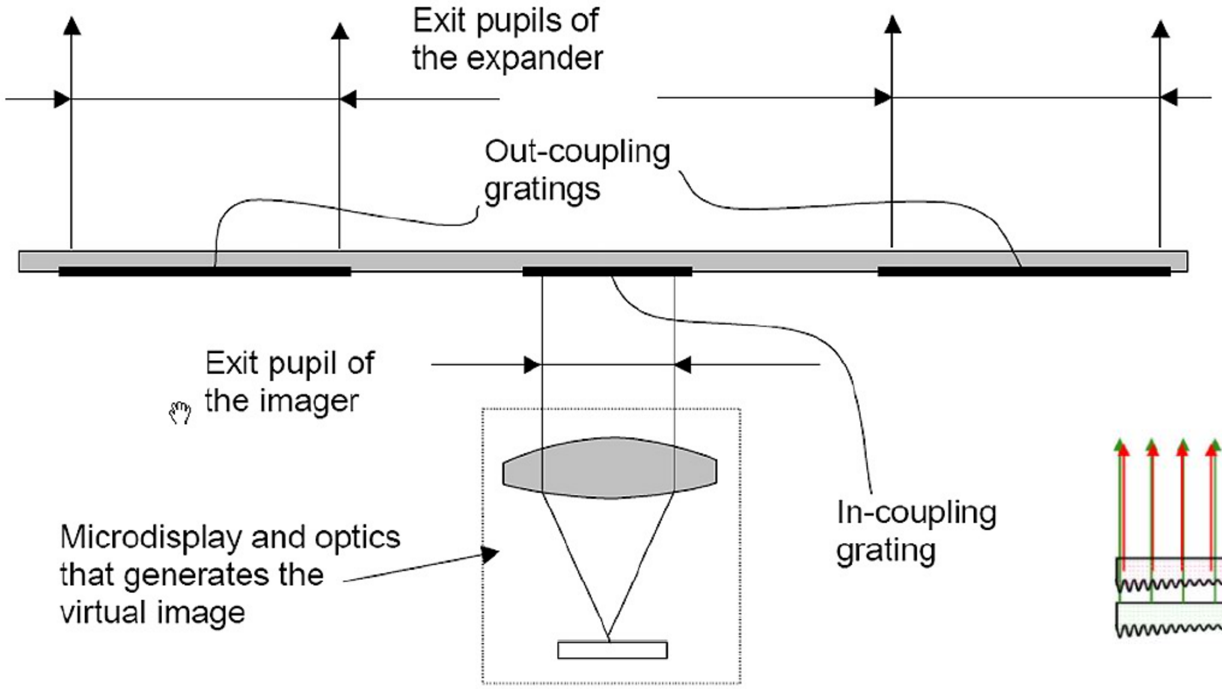
Holographic Planar Waveguide (Sony)

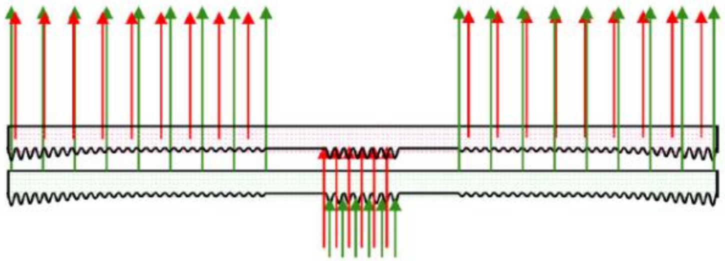


H. Mukawa, et al., SID Symposium Digest of Technical Papers, 2008

HWD Examples (Slide 18 of 18)

Diffractive Waveguide (Nokia, Vuzix)





T. Levola, Journal of the SID 14/5, 2006