VIRTUAL REALITY: THEORY AND PRACTICE

LESSON 1: INTRODUCTION TO VR

GIUSEPPE TURINI - FRI 2 FEB 2024 - UNIVERSITY OF PISA

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PART 0: COURSE INTRODUCTION

This section includes:

- My **acknowledgements** to the institutions and colleagues that supported this course.
- A brief **bio** to summarize by background, including my professional **contacts**.
- Some **warnings** on the course content and information on the intended audience.
- An overview of the **syllabus**, including attendance policy and student assessment.

See: github.com/turinig/vrphd

ACKNOWLEDGEMENTS

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- The Dept. of Information Engineering (DII) of the University of Pisa, for the support and organization and dissemination of the course.
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- Kettering University for the support of my regular academic activity.

BIO AND CONTACTS

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Education: M.Sc. in Computer Science @ University of Pisa
Ph.D. in Health Technologies (Comp. Eng.) @ University of Pisa

Ex-Labs: EndoCAS Research Center @ University of Pisa
Visual Computing Lab @ CNR of Pisa

Teaching: Comp. and Algs. 1/2/3, Prog. Paradigms, CG, VR, Game Development

Research: Computer-Assisted Surgery, VR-AR, HCI-HMI

CONTENT WARNINGS

Intended Audience: This Ph.D. course has been designed considering Ph.D. students with an engineering/computing/technological background, and a basic knowledge of computer programming object-oriented.

Content Warning: All course material on *"VR app development"* is based on:
Unity (2022.3.17), Visual Studio 2022, and Windows (11 Pro).

This course will **not** include the deployment of a VR app on an actual VR HMD because of both lack of hardware and time constraints.
However, VR testing/evaluation will be discussed using the *"XR Device Simulator"* included in the *"XR Interaction Toolkit"* for Unity.

Note: All course material is available on: github.com/turinig/vrphd

Note: Some of the course material has been enhanced by using AI (Microsoft Copilot LLM).

SYLLABUS OVERVIEW

The course syllabus includes the following information:

- Instructor and course information.
- Teaching method (lesson structure).
- Course schedule (tentative).
- References and software tools used.
- Student assessment (attendance policy and final exam information).

PART 1: INTRO TO VR

Virtual Reality (VR): Technology (HW/SW) capable of providing realistic experiences artificially, by exploiting any existing multimedial technology.

VR technology can provide a total immersive experience excluding the physical world, and "transporting" the user in a realistic but not-real environment that is perceived as credible by the user's main senses.

The term *"virtual reality"* was invented by Jaron Lanier (VPL Research) in 1987.

Jaron Lanier is a founder of the field of VR.

In 1985 he founded VPL Research, and in 1989 he commercialized 2 products: the VR goggles *"EyePhones"*, and the VR gloves *"DataGloves"* della VPL Research.

See: www.hollywoodreporter.com

BASICS: AR, MR, AND XR

Augmented Reality (AR): Tecnologia capace di aumentare una visualizzazione dal vivo del mondo reale aggiungendo (aumentandola con) elementi digitali.

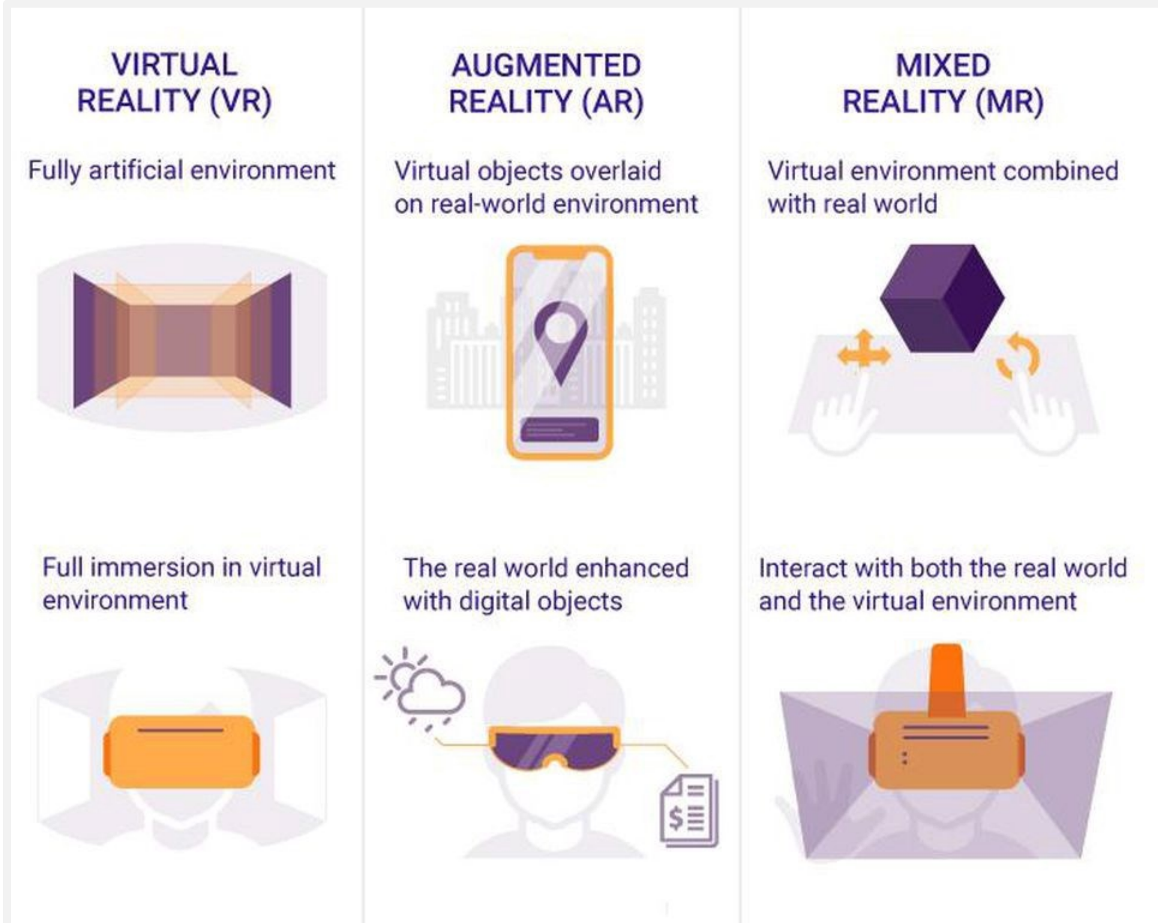
Spesso gli elementi digitali aggiunti sono configurati considerando l’ambiente reale.

Mixed Reality (MR): Tecnologia che combina elementi sia della VR che della AR, ma focalizzata sulle interazioni reale-virtuale.

L’obiettivo e’ abilitare parte del contenuto reale ad interagire con parte del contenuto digitale, e/o viceversa.

Extended Reality (XR): Termine ombrello per VR/AR/MR e tutte le altre tecnologie che hanno come obiettivo l’estensione dei sensi dell’utente mischiando il virtuale con il reale in una esperienza unificata.

BASICS: VR VS AR VS MR



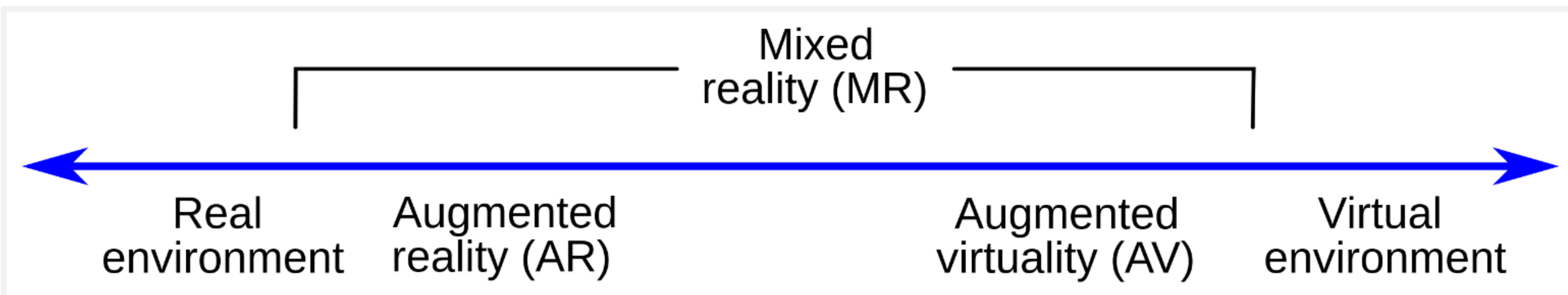
See: rubygarage.org/blog/difference-between-ar-vr-mr

BASICS: REALITY-VIRTUALITY CONTINUUM

Reality-Virtuality Continuum

A continuous scale between an environment/experience completely virtual (VR) and an environment/experience completely real (physical world).

It includes all possible variations and compositions of real content mixed with virtual content, including: VR, AR, *"Augmented Virtuality"*, etc.



See: en.wikipedia.org/wiki/Reality-virtuality_continuum

BASICS: REALITY-VIRTUALITY-MEDIALITY CONTINUUM

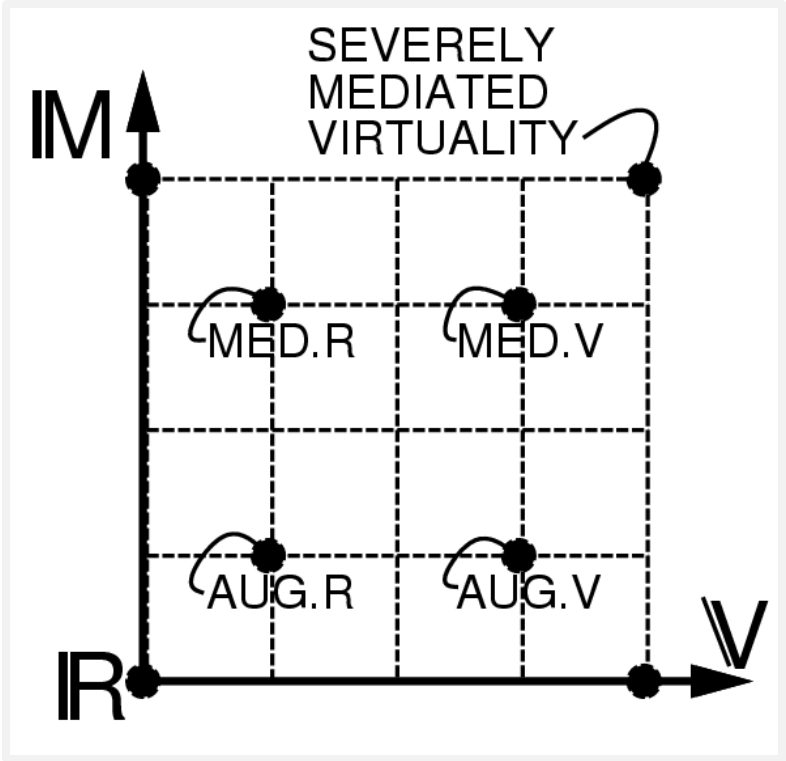
Mediated Reality/Virtuality: Reality/virtuality including artificial modifications of human perception by using devices that alter sensory input.

Reality-Virtuality-Mediality Continuum

The origin R denotes unmodified reality.

The Virtuality axis V represents the amount of virtual content in the environment, and includes: AR as well as Augmented Virtuality.

The Mediality axis M represents environments including modifications of sensory input, including: mediated reality, mediated virtuality, etc.



See: en.wikipedia.org/wiki/Reality-virtuality_continuum

BASICS: IMMERSION

Immersion: The objective level of sensory fidelity provided by a VR system.

Immersion is achieved by surrounding the user with accurate artificial sensory inputs (audio, visual, etc.) making the VR experience realistic and believable.

Immersion mainly depends on ***"sensory immersion"***: the degree to which the range of sensory channels is engaged by the VR simulation.

Sensory Immersion: Sensory immersion includes all sensory inputs: olfactory, visual, auditory, and haptics; relying on advanced technology (e.g., computer graphics, high-resolution displays, multi-channel sound systems, seat movements and force feedback controllers, etc.).

See: en.wikipedia.org/wiki/Immersion_(virtual_reality)

BASICS: PRESENCE

Presence: The subjective psychological response of a user experiencing a VR environment. In other words: the user sense of being in the virtual world.

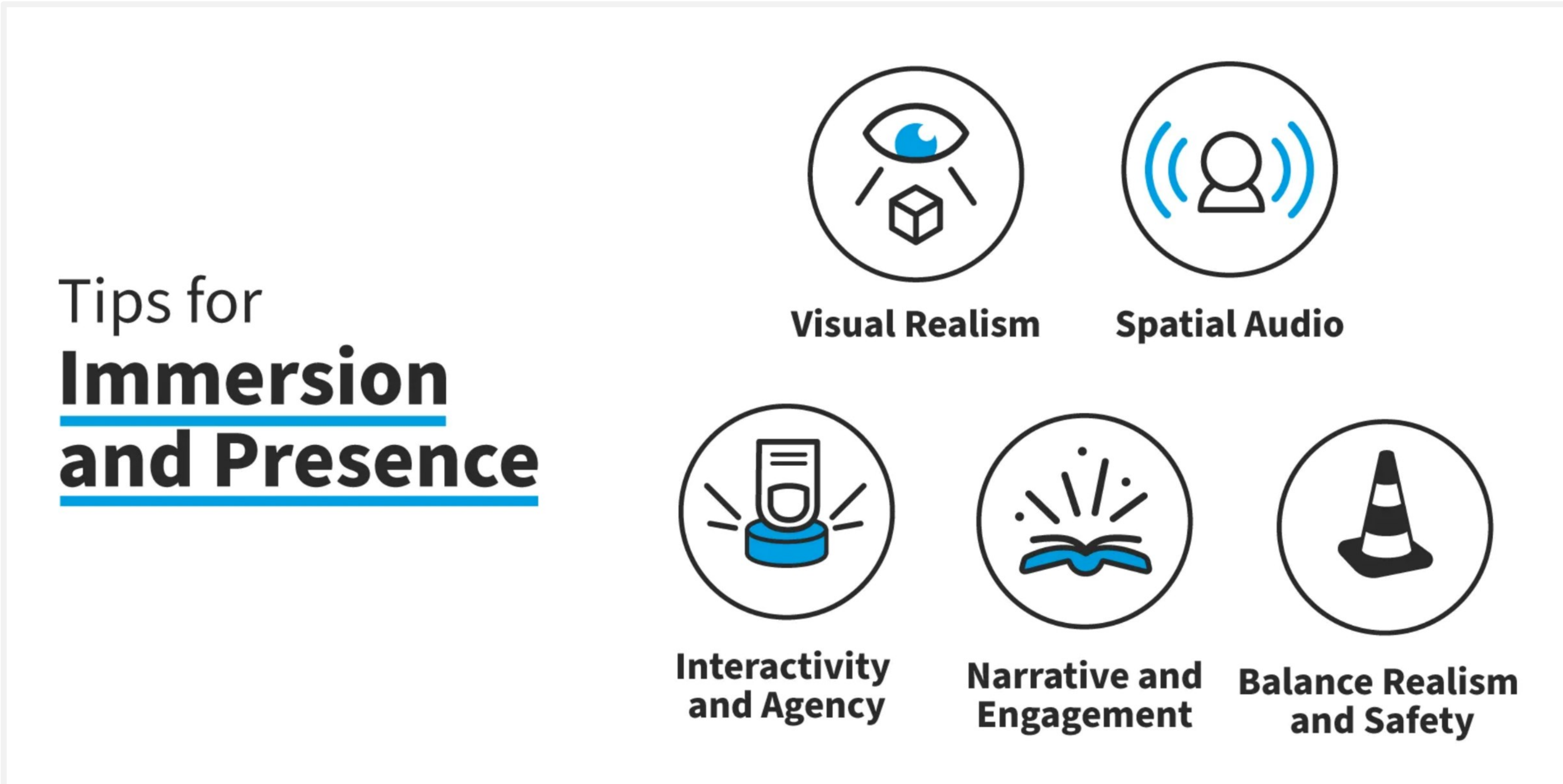
Presence is a perceptual illusion, not a cognitive one: the perceptual system identifies the events and objects and the brain-body system automatically reacts to the changes in the environment, while the cognitive system slowly responds with a conclusion of what the person experiences is an illusion.

Presence is achieved exploiting: technology, psichology, ergonomics, etc.

See: en.wikipedia.org/wiki/Immersion_(virtual_reality)

Note: Sometimes, the terms *"presence"* and *"immersion"* are used interchangeably, but remember that they refer to different aspects of the VR experience!

BASICS: ACHIEVE IMMERSION AND PRESENCE



See: www.interaction-design.org/literature/topics/presence

BASICS: ACHIEVE IMMERSION AND PRESENCE (2)

In 2014 Michael Abrash stated that **all of the following are needed to establish presence:**

- Wide field of view (FOV) of 80 degrees or more.
- Adequate display resolution of 1080p (1920x1080) or better.
- Low pixel persistence (3 ms or less).
- High refresh rate (60 Hz or more).
- Global display with all pixels on simultaneously (rolling display only with eye tracking).
- VR optics with max 2 lenses per eye with trade-offs (ideal optics not practical).
- Optical calibration considering inter-pupillary distance (IPD) etc.
- Solid tracking (accuracy of 1 mm on trans and 0.25 deg on rot, volume 1.5x1.5x1.5 m^3).
- Low latency (25 ms motion to last photon or less).

See: en.wikipedia.org/wiki/Immersion_(virtual_reality)

THEORY: BINOCULAR VISION

FOV: The field of view (FOV) is the extent (described as a solid angle) of the observable world that is seen by the user or a sensor.

Binocular Vision: A type of vision system of a human/animal that includes 2 eyes capable of facing the same direction (share the FOV) to perceive a single 3D image of the virtual/real world.

Monocular Vision: A type of vision system of a human/animal that includes only 1 eye or multiple eyes not facing the same direction (do not share the FOV).

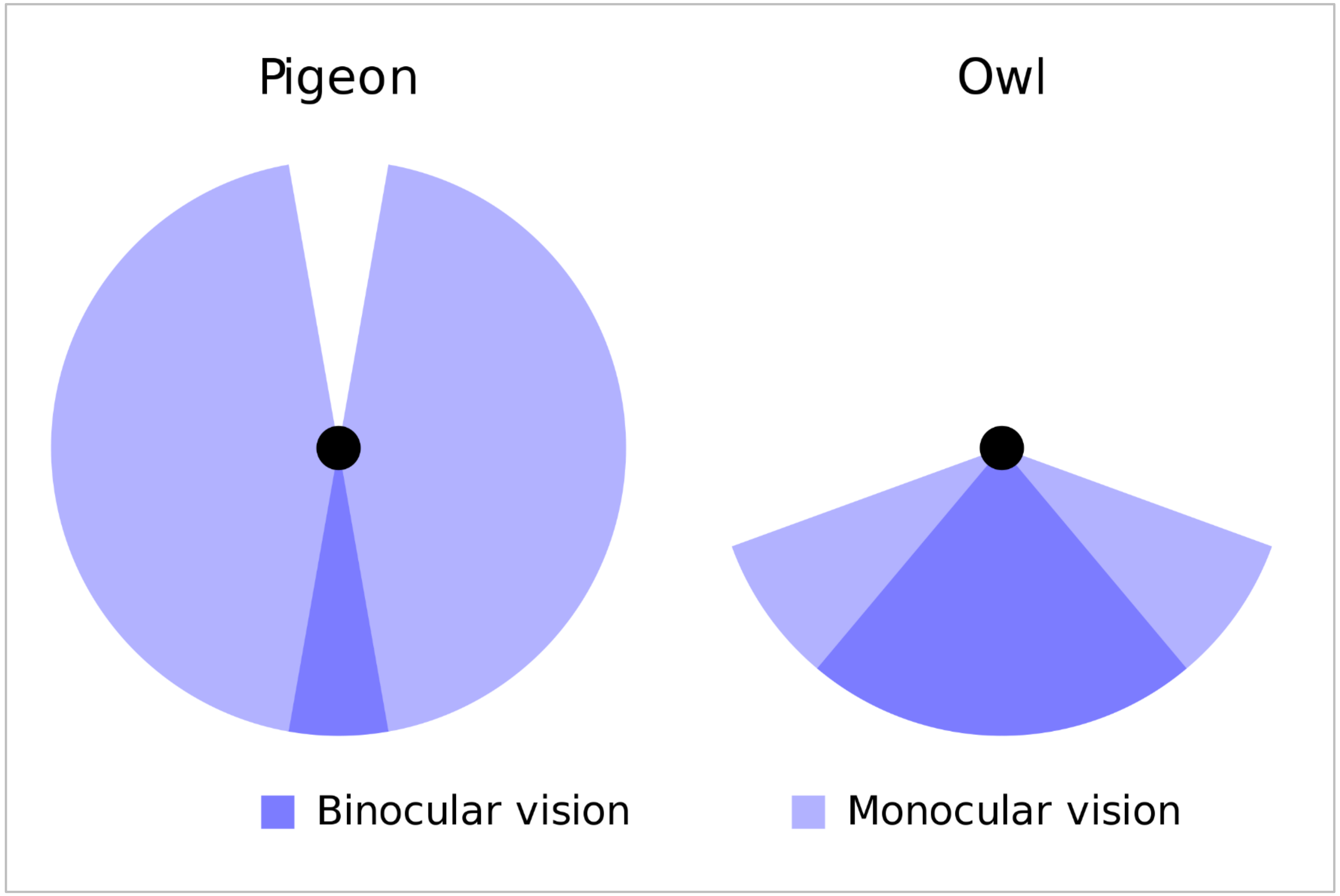
Example: The vision system of a horse is mainly monocular, its eyes are positioned laterally on its head, this arrangement provides the horse with increased field of view, but poor depth perception.

THEORY: BINOCULAR VISION (2)

The FOV of a pigeon (left) and of an owl (right).

Pigeons have 2 eyes arranged laterally on their head, whereas owls have 2 eyes positioned frontally on their head.

Different colors show FOV areas where binocular vision is enabled and where only monocular vision is available.



THEORY: DEPTH PERCEPTION

Depth Perception: The human ability to perceive distance (depth) to objects in the real/virtual world using a visual system. It is a major factor in perceiving the real/virtual world in 3D.

Depth Sensation: The animal (non-human) ability to perceive distance (depth) to objects in the real/virtual world using a visual system.

Note: It is known that non-human animals can perceive depth, but it is not known if it it the same perception as humans (vision systems could be different, etc.).

Stereopsis: The process performed by the human brain (visual cortex) allowing the depth perception when a scene is viewed with both eyes (binocular vision).

THEORY: DEPTH CUES

Depth perception is essential in VR systems,
and it is based on the correct generation of stereo pairs!

To understand how depth perception works we must consider that there are several *"depth cues"* utilized by our brain. These are the **(monocular) depth cues available in 2D graphics:**

- **Perspective:** objects (projections) become smaller if the distance from the point of view increases.
- **Relative Dimensions:** we expect certain dimensions of familiar objects.
- **Detail:** we can see more details of closer objects in respect to distant targets.
- **Occlusion:** occluding objects appear on the foreground in respect to occluded objects.
- **Illumination:** near objects are brighter than distant objects.
- **Relative Movement:** distant objects move slower than near objects.

THEORY: DEPTH CUES (2)

These are the **(binocular) depth cues only available in 3D graphics:**

- **Binocular Disparity:** difference between the left and right images of a stereo pair.
- **Accomodation:** muscular tension needed by our eyes to focus on a target.
- **Convergence:** muscular tension needed to rotate our eyes toward the focal point.

Binocular disparity is considered the dominant depth cue dominante!

All other depth cues, if incorrect, can have a severe detrimental effect!

THEORY: DEPTH CUES (3)

To achieve a correct depth perception, the stereo pair must be properly visualized so that the visual cortex can *"fuse"* it.

If a stereo pair is generated with conflicting depth cues:

- Any depth cue could become dominant (accidentally).
- Depth perception could be exaggerated or diminish (in respect to the correct one).
- The 3D content could be uncomfortable to view.
- The visual cortex could fail *"fusing"* the stereo pair (resulting in double vision).

If a stereo pair is generated correctly:

- Both binocular disparity and convergence are correct!
- Accomodation will always be inconsistent, but usually this issue is tolerated...

THEORY: STEREOSCOPY

Stereopsis: Depth perception produced by the reception in the brain (visual cortex) of visual stimuli (stereo images) from both eyes in combination (binocular vision).

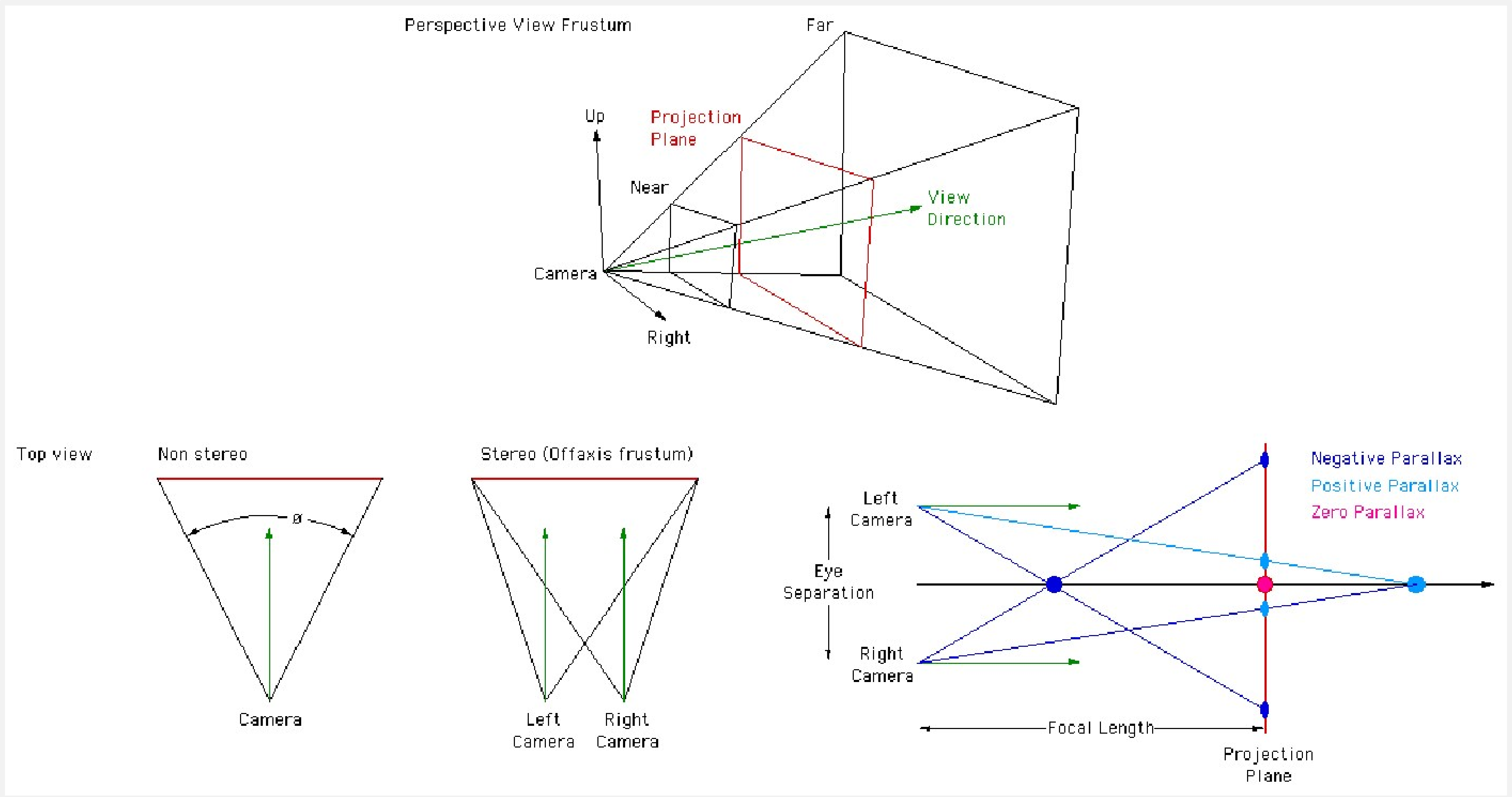
Stereo Pair: A pair of views of a 3D object designed to be viewed independently by the left and right eyes of the viewer. Any type of stereoscopic system involves visualizing a stereo pair to the viewer in some way.

IPD: The inter-pupillary distance (sometimes referred as pupillary distance, or PD) is the distance in millimeters between the centers of each pupil.

Stereo Rendering: The computer graphics process to visualize 3D content by rendering a stereo image pair in order to induce the viewer to achieve stereopsis.

Stereoscopic System: A system (hardware and software) that presents the viewer with an image of a 3D object such that it appears to have *"real"* depth (enabling the viewer to have depth perception of virtual content).

THEORY: VR STEREO CAMERA



THEORY: VR LOCOMOTION

Locomotion: The ability to move from place to another in the real world.

VR Locomotion: The ability to move from place to place in VR. It relies on technology that tracks user movements and converts them into VR avatar movements.

Physical VR Locomotion: The avatar movement in VR is controlled by the user movement in the physical world. For example: the user head movement always corresponds to the VR camera movement.

Artificial VR Locomotion: The avatar movement in VR **does not** directly correspond to user movement in the physical world. For example: a VR avatar body movement controlled by using the VR controller thumbsticks.

Unobtrusive and natural locomotion is critical to achieve immersion and presence!

See: developer.oculus.com/resources/bp-core-types-of-locomotion

THEORY: MOTION PERCEPTION

Vection: The sensation of movement in space produced purely by visual stimulation.

For example: the illusion of self-motion experienced when watching a moving train through the windows of a stationary train.

Vestibular System: Apparatus in the human inner ear that detects the position and movement of our head in space, allowing for the coordination of eye movements, posture, and equilibrium.

Visual-Vestibular Mismatch (VVM): Sensory conflict between visual and vestibular signals.

BASICS: COMFORT

Physiological Comfort: Body senses do not feel conflict in sensory stimulation.

Lack of physiological comfort results in fatigue, nausea, etc.

Environmental Comfort: Discomfort depending on the environment.

Lack of environmental comfort results in claustrophobia, vertigo, etc.

BASICS: VR SICKNESS

Motion Sickness: Discomfort that occurs due to a difference between actual/real and expected/perceived motion.

Common symptoms are: nausea, cold sweat, headache, sleepiness, etc.

VR Sickness: (aka Simulator Sickness) It is the discomfort caused by sensory conflicts experienced by a VR user, and generated by a VR experience.

Common symptoms are: nausea, cold sweat, headache, sleepiness, etc.

Ergonomics: The application of psychological and physiological principles to the engineering and design of products, processes, and systems. The goals are to reduce human error, increase productivity, enhance safety and comfort, with a specific focus on human-X interactions.

BASICS: VR SICKNESS (2)

These factors can cause VR sickness:

- **Acceleration** (minimize any acceleration).
- **Control** (ensure that the user has a good degree of control in VR).
- **Session Duration** (allow breaks during VR sessions or design short sessions).
- **Visual Flow** (avoid strong visual flows).
- **Binocular Disparity** (remember that not everyone is capable of fusing stereo pairs).
- **FOV** (decreasing the FOV could reduce comfort).
- **Latency** (minimize it because *"lags"* cause discomfort in VR).

Remember that VR developers/users become resilient to VR sickness!

BASICS: VR AVATAR

VR Avatar: A VR avatar is a virtual representation of the user in the VR environment, and it facilitates both locomotion and interactions.

A VR avatar can range from a basic 3D shape (e.g., a capsule-like body) to an animated 3D model (e.g., a player character).

See: en.wikipedia.org/wiki/Avatar_(computing)

Codec Avatar: Invented at Facebook Reality Labs (FRL), Pixel Codec Avatars (PiCA) are AI-models of 3D human faces optimized for reconstruction/computation.

See: research.facebook.com/publications/pixel-codec-avatars/

See: www.youtube.com/watch?v=TKIxw0vh9X0

BASICS: HMD AND CAVE

HMD: A head-mounted display (HMD) is a display device designed to be worn on the head. Usually, it includes a small display optic in front of one eye (monocular HMD) or each eye (binocular HMD). VR HMDs usually integrate IMUs (inertia measurement units).

OST-HMD: An optical see-through HMD (OST-HMD) is an HMD with a semi-transparend display that allows the user to see the content visualized as well as the reality (because of the transparency of the display).

VST-HMD: A video see-through HMD (VST-HMD) is an HMD integrating cameras aligned with the HMD optics so that the display can visualize in real-time the video streaming from the cameras.

CAVE: A Cave Automatic Virtual Environment (CAVE) is a VR system including a room-sized cube in which 3-6 walls are back-projected in order to create an immersive virtual environment, designed specifically for a multi-user experience.

BASICS: HAPTICS

Force Feedback: Also called kinesthetic feedback, it refers to the feelings provided by sensors in your muscles, joints, etc. Humans use this feedback to estimate properties (sizes, weights, etc.) of objects we touch.

Tactile Feedback: It refers to the feelings provided by the sensors in your skin tissue. Humans use this feedback to estimate vibration, texture, etc.

Haptics: Any technology that can create an experience of touch by applying forces, vibrations, or motions to the user. Simple haptic device examples are: game controllers integrating vibrations, steering wheels with torque feedback, etc. Haptic feedback includes both force/kinesthetic feedback and tactile feedback.

APPLICATION: VR APPLICATION FIELDS

There are numerous application fields in which VR can provide enormous benefits:

- Healthcare (medicine, rehabilitation, psychology, surgery, etc.).
- Security and safety (military, police, fire fighters, first responders, etc.).
- Architecture, engineering, and construction (AEC).
- Art and entertainment (virtual museums, immersive exhibitions, etc).
- Education and training (geography, history, etc.).
- Business and scientific simulation (virtual maintenance, VR simulators, etc.).
- News and media (VR-enabled sport events, etc.).
- Sport and fitness (reinforce tactics, engaging rehab, perfomance eval, etc.).

This list is just a summary, and the actual list of application fields is endless.

APPLICATION: VR IN HEALTHCARE

VR systems in healthcare can be designed targeting different user groups with different objectives, for example: (1) training systems for doctors, (2) motivational tools and treatment elements for patients, (3) supporting educational platforms for medical students.

These are some specific examples:

- VR training for caregivers (experience patient perspective in VR).
- VR systems to support different patient groups and their families.
- Virtual surgical training and planning.
- VR systems for pain management (stress, palliative care).
- Virtual physical therapy and rehabilitation (engagement, motivation, neuro-rehab).
- VR supporting tools for mental health treatments (phobia treatment, etc.).
- VR systems for medical education and training.

APPLICATION: VR IN HEALTHCARE (2)

A VR surgical interactive training simulator designed as a training tool for medical staff.

See: *A VR Training Simulator* developed by Visualise.

APPLICATION: VR IN SECURITY AND SAFETY

VR systems are frequently used in security (disaster control teams, defense, fire brigades, police forces, crisis centres) to simulate and train in critical scenarios (natural disasters, acts of terrorism, danger prevention, emergency care). These are some specific examples:

- VR training for emergency situations and critical scenarios.
- Learning safety procedures and hazard identification.
- Disaster response and search-and-rescue.
- VR training in crisis negotiation and de-escalation.
- Equipment familiarization and maintenance in VR.
- VR supporting tools for stress inoculation and resilience building.
- Crime scene investigation (CSI) and forensics in VR.
- VR training in tactical decision-making and team coordination.
- Language and cultural training in VR.

APPLICATION: VR IN SECURITY AND SAFETY (2)

VR systems are frequently in security and safety to simulate and train in critical scenarios.

See: *Korea Tech Today - "ETRI Develops VR-Based Firefighting Training Simulator"*

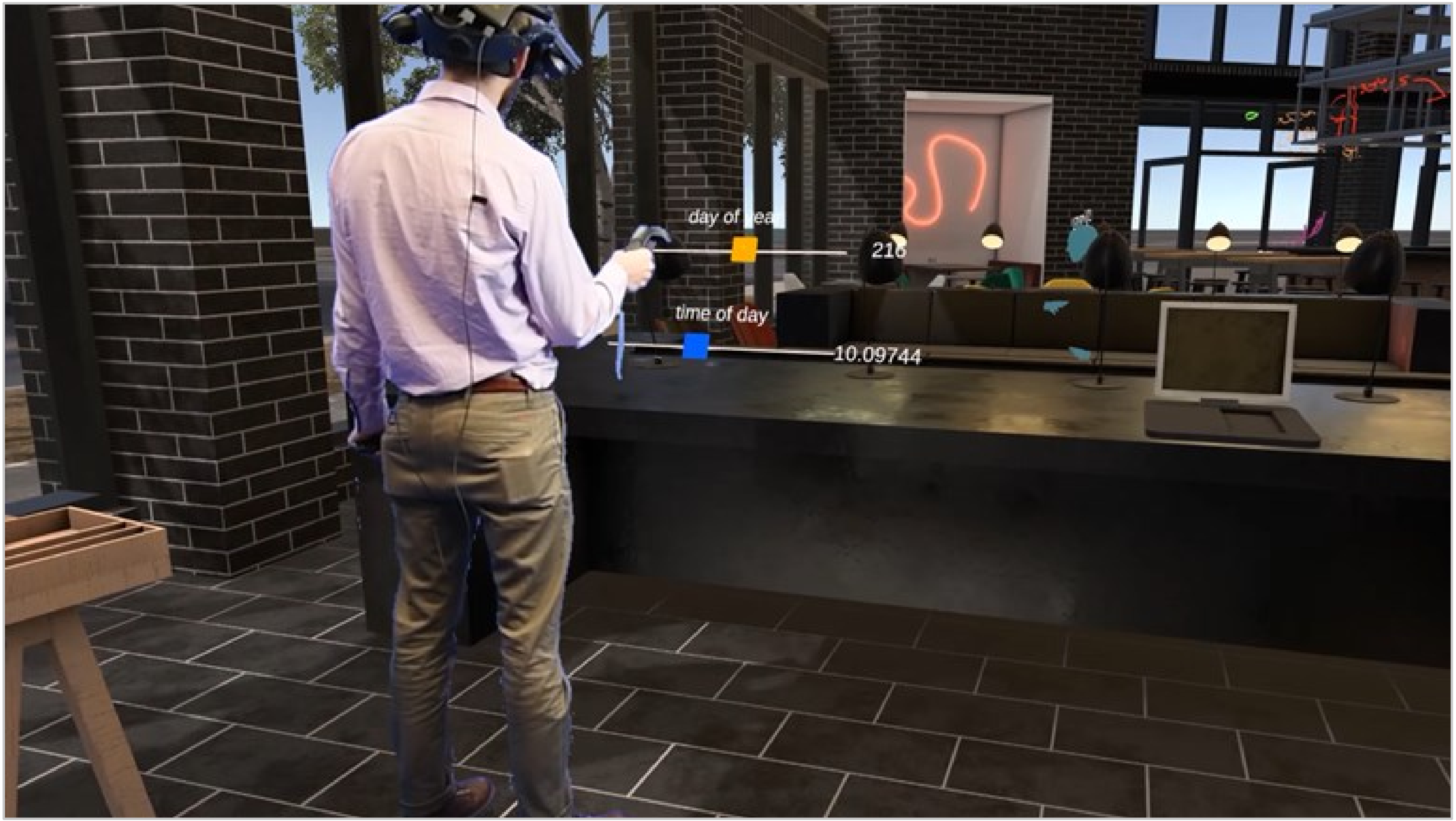
APPLICATION: VR IN ARCHITECTURE

VR has several transformative applications in the fields of architecture, civil engineering, and construction (AEC). These are some of the most impactful use cases:

- Iterative design and visualization in VR.
- VR supporting tools for client presentations and stakeholder engagement.
- VR systems for safety training and risk assessment.
- VR training in crisis negotiation and de-escalation.
- Construction site planning and logistics in VR.
- VR systems for collaborative design and coordination.
- VR supporting tools for historical preservation and restoration.
- Facility management and maintenance in VR (see also *"digital twins"*).
- Material selection and aesthetics design in VR.

APPLICATION: VR IN ARCHITECTURE (2)

An example of application of VR to architecture, engineering, and construction (AEC).



See: *"Better building designs and lower costs with Unity"* a case study for AEC.

APPLICATION: VR IN ART AND ENTERTAINMENT

VR has already transformed the way we create art, and experience art and media:

- Immersive art installations.
- Democratization of art access.
- Virtual museums, art galleries, and exhibitions.
- Collaborations with technology companies.
- Art education and creation tools.

VR has also significantly impacted the entertainment industry:

- VR videogames.
- 360-degree films (VR180 and VR360) and experiences.
- VR-enabled live concerts, and sport events.
- Virtual travel, and attractions.
- VR social network/platforms.

APPLICATION: VR IN ART AND ENTERTAINMENT (2)

An example of application of VR to art.

See: *"Mona Lisa: Beyond the Glass"* the Louvre’s first VR project.

APPLICATION: VR IN BUSINESS AND SCIENTIFIC SIMULATION

VR has several applications in business:

- VR systems to train personnel.
- Product design, prototyping, data visualization, and data analytics in VR.
- VR supporting tools for remote work and collaboration.
- VR systems for marketing, customer engagement, maintenance, and repair.

VR has also significantly impacted academic research with scientific VR simulators:

- VR interactive simulation of complex scenarios.
- Advanced VR-enabled visualization of scientific data.
- Shared remote VR systems for collaborative scientific experiments.
- VR as supporting tool for dissemination of scientific findings.
- VR trainers for scientific education
- VR systems for psychological and behavioral studies.

APPLICATION: VR IN BUSINESS AND SCIENTIFIC SIMULATION (2)

A VR system for the personnel training in the water servicing of an airplane.

APPLICATION: VR IN BUSINESS AND SCIENTIFIC SIMULATION (3)

A real-time interactive scientific simulator as supporting tools for scientific research.

See: *["Foldit"]* an Online Video Game About Protein Folding by the University of Washington.

APPLICATION: VR IN SPORT AND FITNESS

VR has already impacted sports, fitness, and overall well-being:

- VR enhanced sport training.
- VR-enabled injury prevention, rehabilitation, and physical therapy.
- Virtual fitness training, exercise programs, and group meditation.
- VR competitive gaming and e-sports.

APPLICATION: VR IN SPORT AND FITNESS (2)

VR systems can also be used as training tools for athletes.

See: [*"QB Sim Academy"*] a VR simulation-based training system for NFL quarterbacks.

PART 2: INTRO TO UNITY

"Unity is so much more than the world's best real-time development platform – it's also a robust ecosystem designed to enable your success. Join our dynamic community of creators so you can tap into what you need to achieve your vision."

UNITY TECHNOLOGIES

Applicazion Fields: videogames, architecture, automotive, movies, XR, etc.

"Create once, deploy across 25+ leading platforms and technologies to reach the largest possible audience."

UNITY TECHNOLOGIES

See: unity.com

INTRODUCTION TO GAME ENGINES

Today, most VR applications are developed by using game engines.

A game engine is a software framework mainly designed for the development of video games. When VR technology became popular, these engines started including functionalities to support the design and development of VR software applications as well as the integration of VR interfaces (headsets and controllers).

These are some of the functionalities/modules typically included in a modern game engine:

- A 2D/3D **editor** to configure the game content.
- **Code libraries** to support game programming/scripting.
- A **rendering engine** (renderer) to visualize 2D/3D graphics.
- A **physics engine** responsible for rea-time interactive physics simulation.
- A **collision detection** module to manage collision events and collision responses.
- Then other modules for: sounds, animation, VR-AR, AI, networking, etc.

INTRODUCTION TO GAME ENGINES (2)

The main game engines on the market today (2024) are: **Unreal**, **Unity**, Godot, etc.

See: The *"Unity Editor"* software app part of the Unity game engine.

REFERENCES

- Unity website: unity.com
- Unity online manual: docs.unity3d.com/manual
- Unity scripting reference: docs.unity3d.com/scriptreference
- Unity Asset Store: assetstore.unity.com

- *"Virtual Reality"* by Steven M. LaValle: lavalle.pl/vr

- *"Best Practices for Immersive VR"*: developer.oculus.com/resources/bp-overview