Introduction to Augmented Reality

Fivos DOGANIS

Course contents

- **Theory**
  - Definitions
  - History, 3 Types of AR
  - Technologies, Calibration, Registration, Tracking
  - Rendering, Interactions
- **Practice**
  - Overview of existing apps and tools
  - AR Web **Programming**
    - **WebXR**, **AR.js** and more!

whoami

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cover photo: www.instagram.com/steveroe_

isep
École d'ingénieurs du numérique

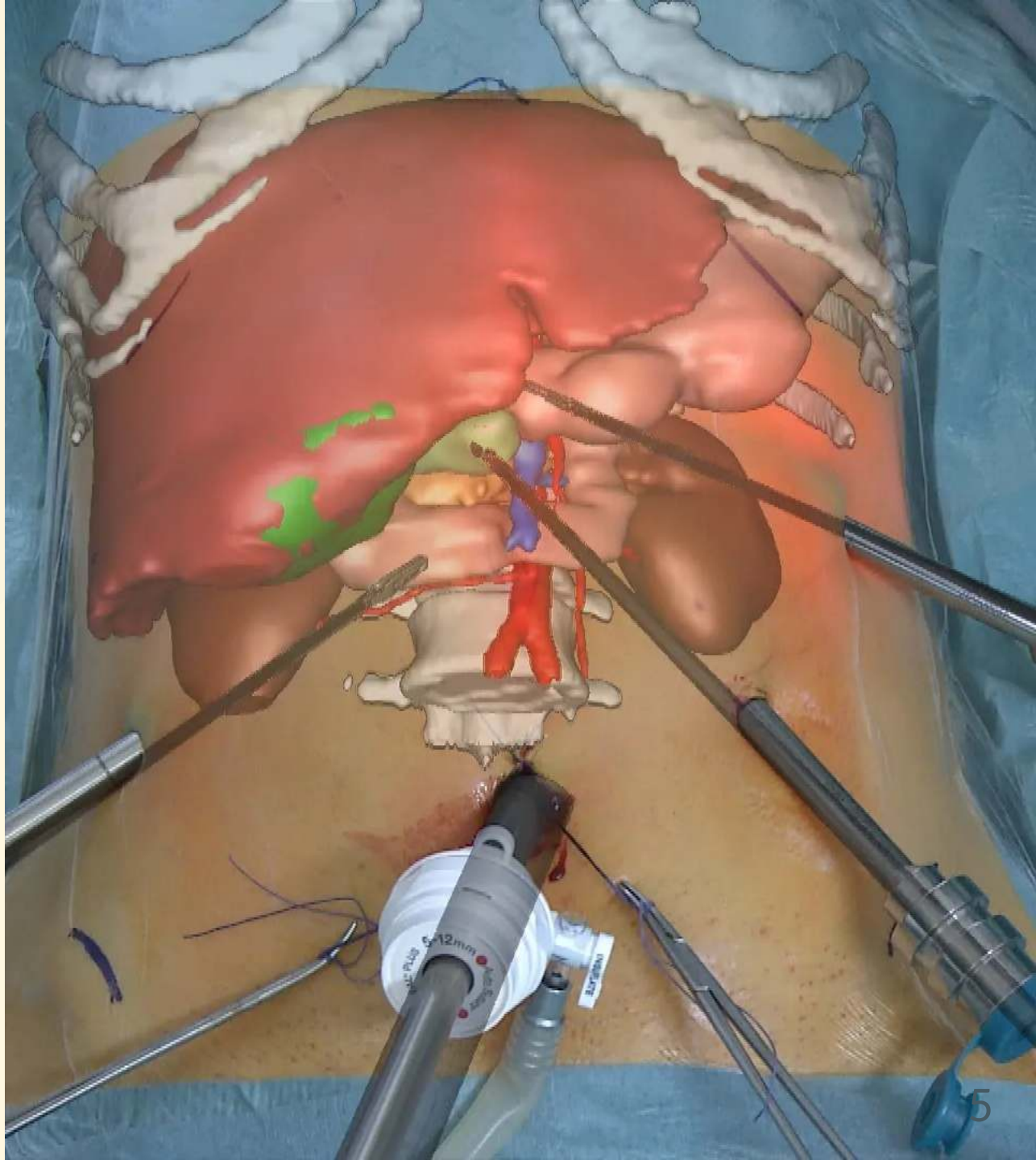
UNIVERSITY OF HULL

University of Hull

- Master of Science by Research (2001)
  Augmented Reality in Archaeology: Registration Issues

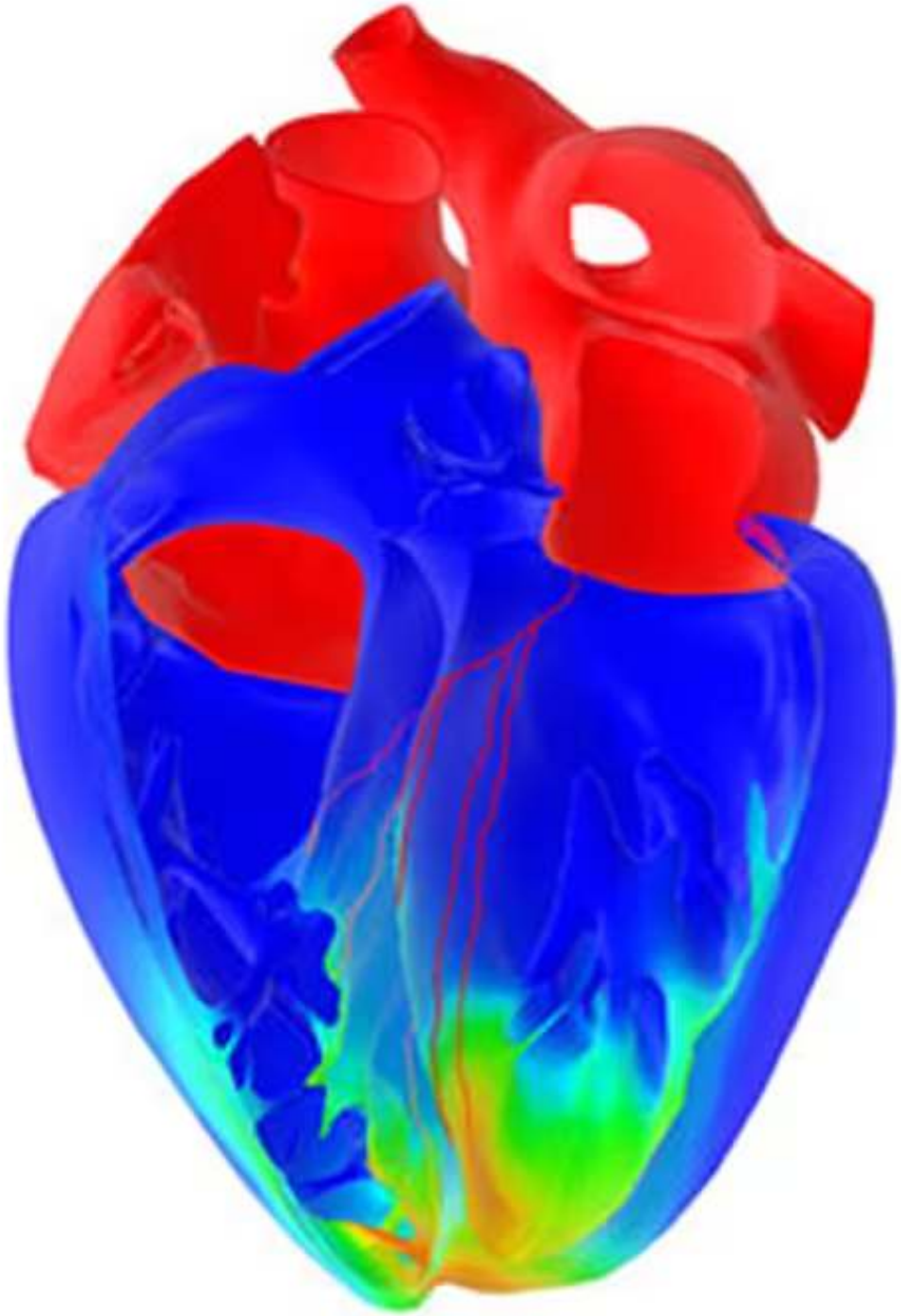
IRCAD (2002 - 2003)

- Institut de Recherche contre les Cancers de l'Appareil Digestif
- Startup
  - Virtual-Surg team
- Augmented Reality Research Engineer



Dassault Systèmes (2003+)

- 3D Visualization Engineer
  - Scenegraph, Materials
  - Geometry, Tessellation
- Virtual and Augmented Reality (XR) Engineer
- XR Research Engineer
- XR Research Manager



Dassault Systèmes

From Shape to Life

1981
3D Design

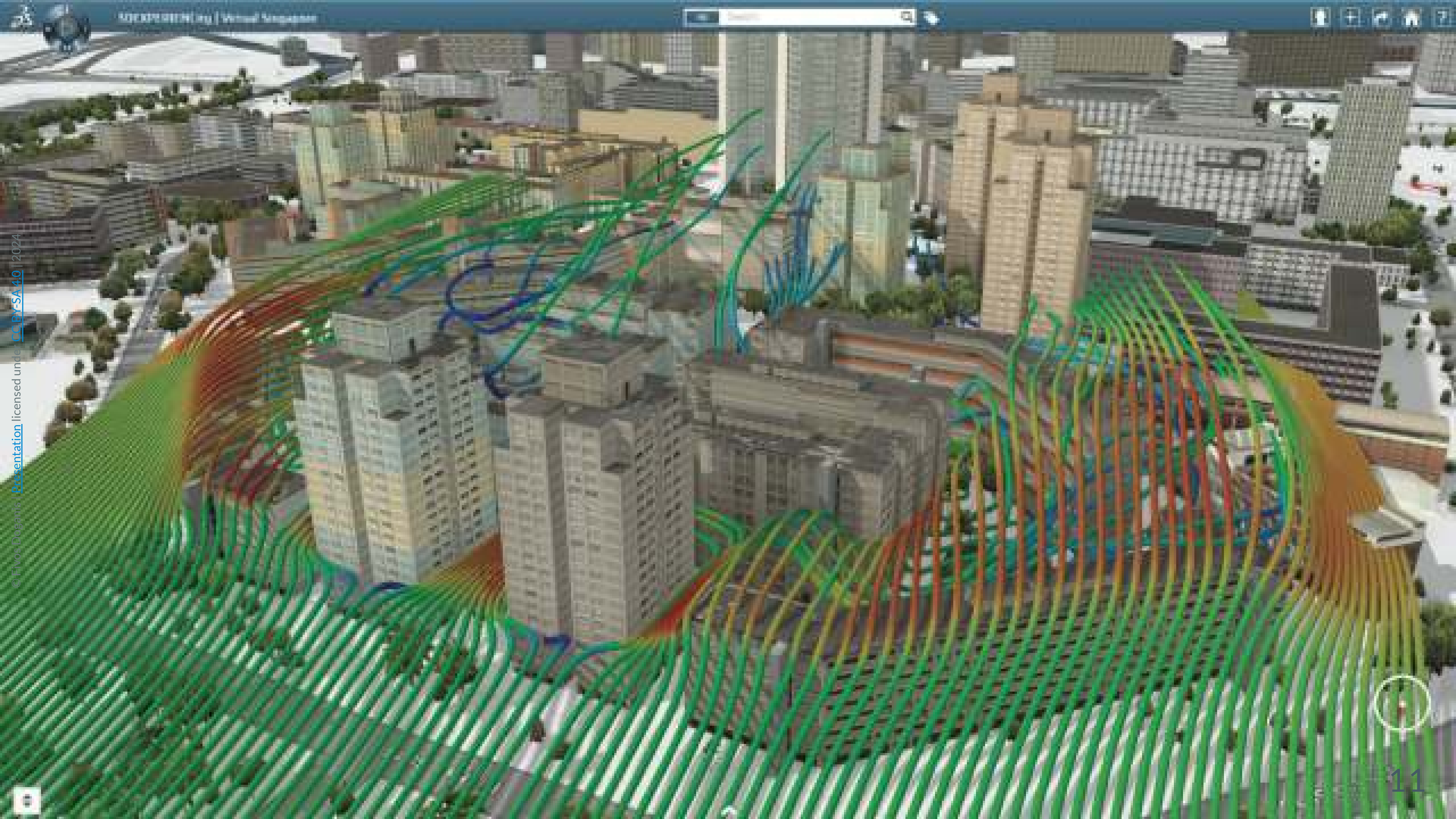
1989
3D DMU
Digital Mock-up

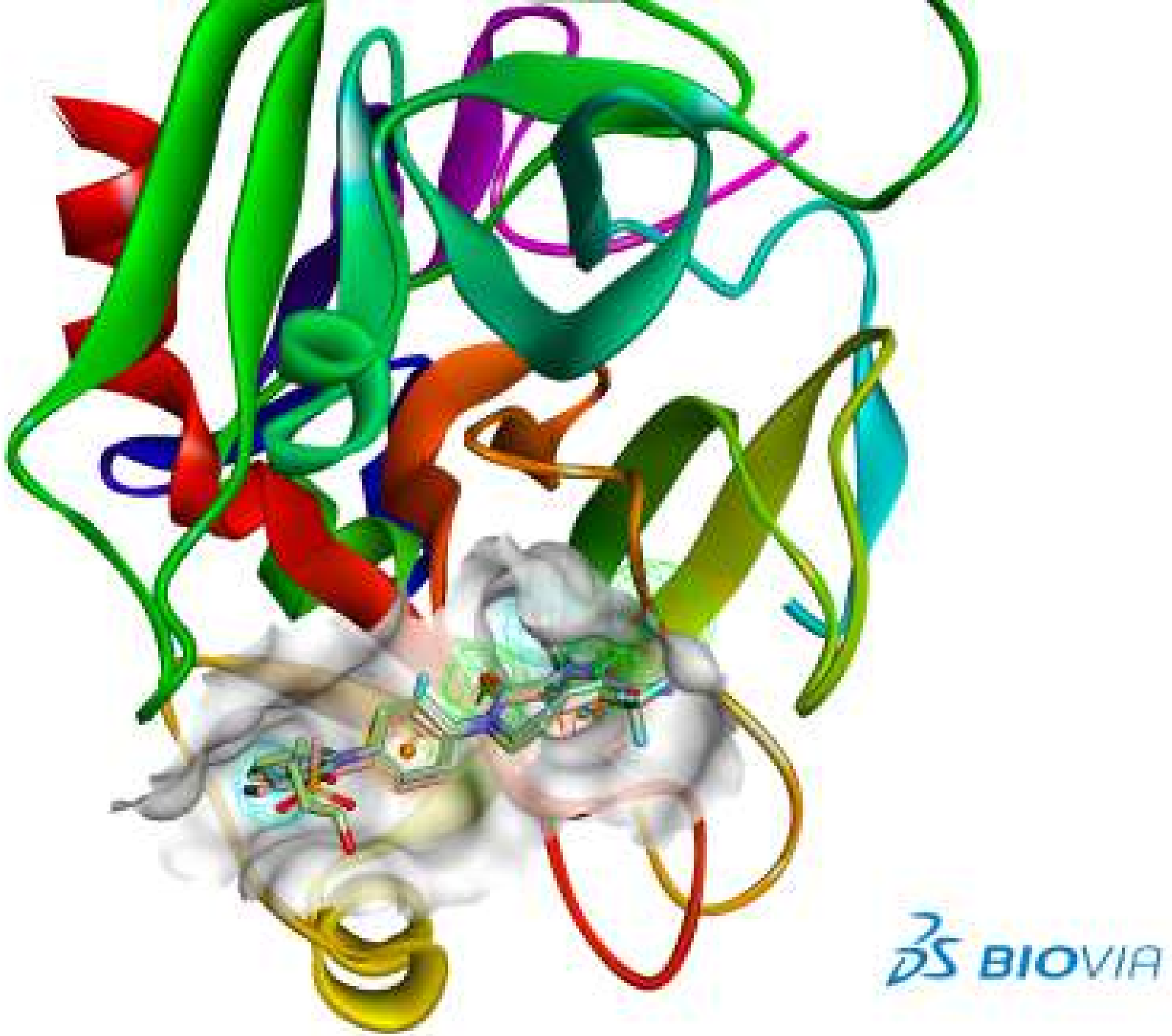
1999
3D PLM
Product Lifecycle Management

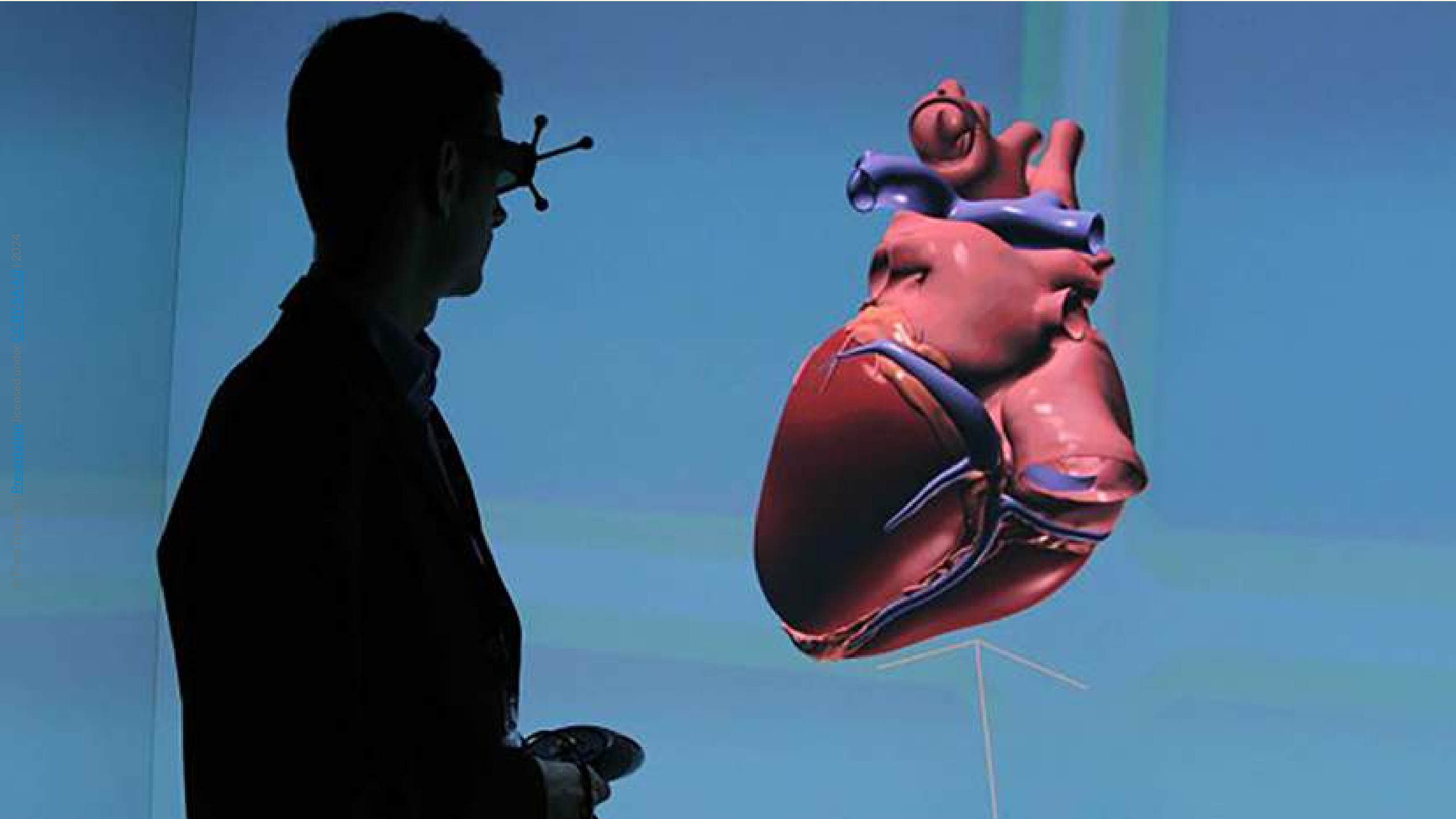
3DEXPERIENCE®

2012
3DEXPERIENCE® platform

2020
Virtual Twin Experience of **Humans**







Course audience

- Anyone looking for a simple introduction to Augmented Reality
- Computer Science students and engineers looking for a way to create cross-platform XR prototypes or even full-fledged apps

➡️ Feel free to skim through technical sections and use this course as future reference

Course prerequisites

- **Math** 🔢
  - 3D vectors and matrices
- **Programming** 💻
  - **JavaScript** notions, or any similar language (HTML kept minimal)
- 3D Web API 🧊
  - **THREE.js notions strongly recommended** (see Web 3D course)
  - alternatives: Babylon.js, WebGL, WebGPU
- Desktop + Smartphone (or, even better, a XR HMD!) 📱 🥽
  - VSCode

📅 Planning

- **Session 1** (2 hours)
  - 📖 **Theory** (45 min)
  - 💻 WebXR Theory + **Exercises** (1h)
  - 🪑 Explore examples (15 min)
- **Session 2** (4 hours)
  - ⭐ **Project kick-off** (must be finished at home 🏠)
    - upgrade your existing THREE.js 🧊 project to AR 📱 🥽
    - 👥 2 people per project: clear responsibilities (who does what)
    - send git repo link: source + live testing

Project evaluation criteria

- originality 👀
- interactions 👋
- physics 💥 / animations 🧎 / sounds 🎶 / eye-candy 🎇
- healthcare 👨‍⚕️
- code quality ✨, tricks 😏, performance ⏱️
- fun 🎉
- **clever use of AR** 📱 🥽
  - tangible interactions, body tracking 🧍
  - real world interactions, spatial design 🌍

Grading system

- **20** points maximum
- choose features from previous slide
- for each implemented **feature**:
  - not done: **0 pt** 🥱 💤
  - nice try / buggy: **1 pt** 🤨 🐛
  - basic / good enough: **2 pts** 😐
  - great / polished: **3 pts** 🙂
  - impressive: **4 pts** 🤠 ⭐

AR Applications

Consumer applications

- Entertainment
  - Games: Pokemon GO AR+, Minecraft Earth (RIP 💀)
  - Social Networks: SnapChat (City Painter), Facebook
- Interior Design
  - IKEA Place
  - HomeByMe AR
- IGN: Time Machine

Pokemon GO AR+

Minecraft Earth

CHRISTIAN MARCLAY X SNAPCHAT

PLAYING POMPIDOU

SnapChat

IKEA Place

HomeByMe

IGN Time Machine

Professional applications

- Industry
- Healthcare
- Marketing

Renault Trucks

Zeal AR

Alain Afflelou

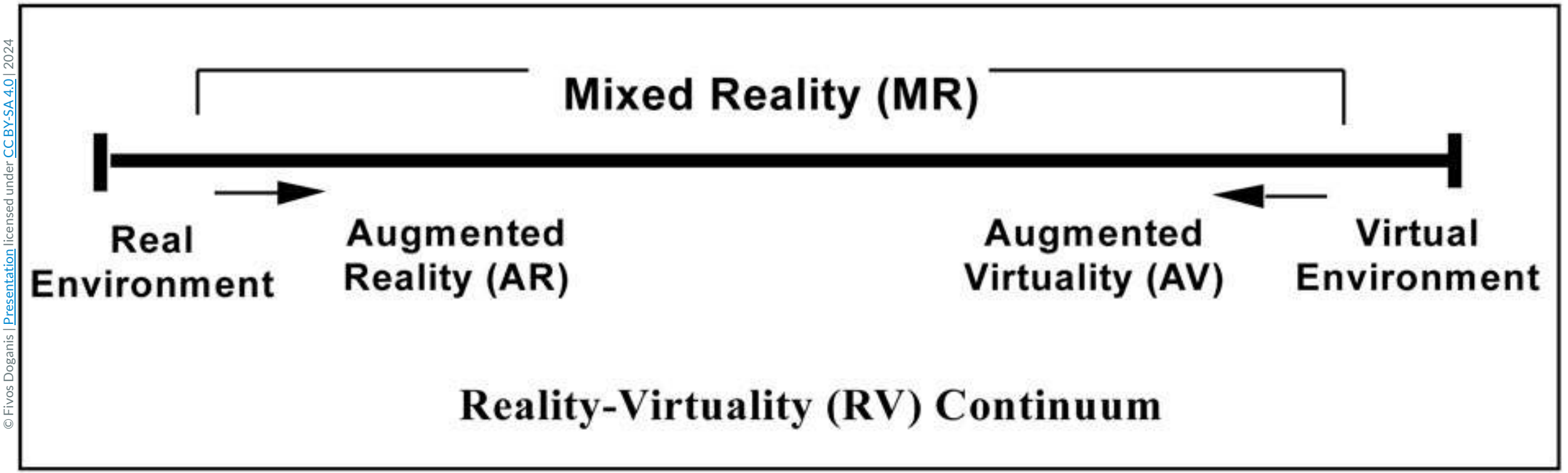
Definitions

Reality
Virtual Reality
Augmented Reality
Mixed Reality
Extended Reality
Metaverse
Spatial Computing
...

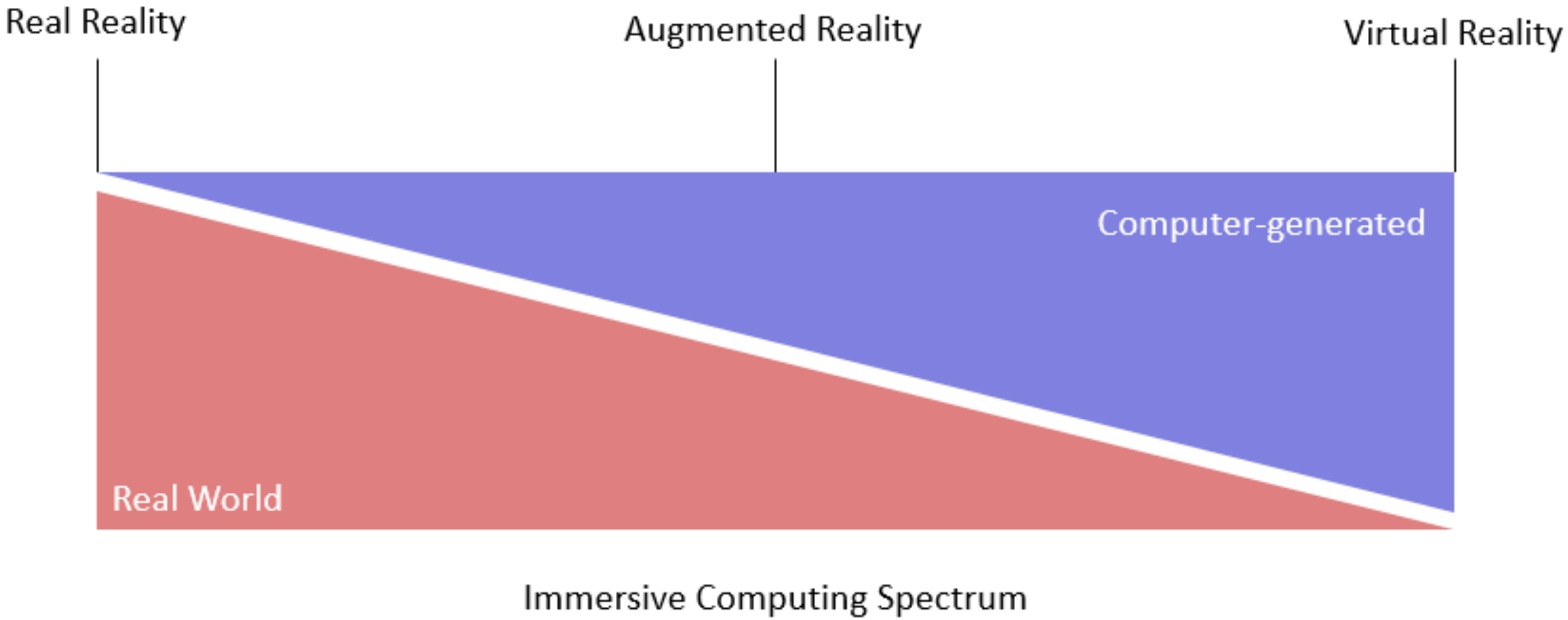
Definitions

- Milgram's **Reality-Virtuality Continuum**

Milgram, Paul; H. Takemura; A. Utsumi; F. Kishino (1994). *"Augmented Reality: A class of displays on the reality-virtuality continuum".*



Google's version



Properties of an AR system ★

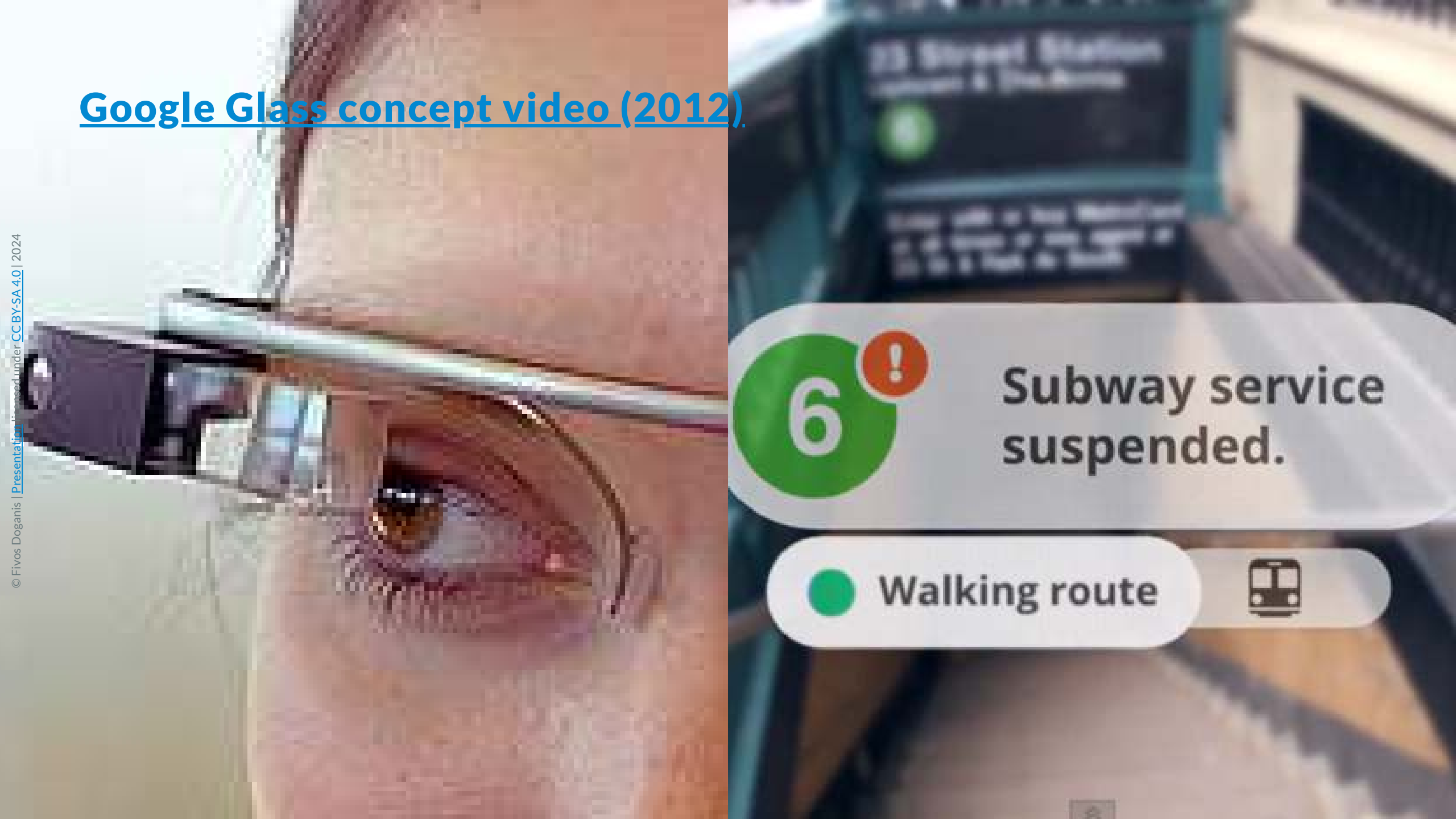
(according to Azuma, 2001)

- **combines real and virtual objects** in a **real environment**
- runs **interactively**, and in **real time**
- **registers** (aligns) real and virtual objects with each other.

Not AR:

- special effects in movies
  - technology close to AR
  - **not real time** ❌
  - not in a real environment ❌
- Google Glass
  - combines real and virtual objects in a real environment ✅
  - **no registration** ❌
  - it's a **HUD** (**H**ead-**U**p **D**isplay)
    - can still be useful! (maintenance, sports etc.)

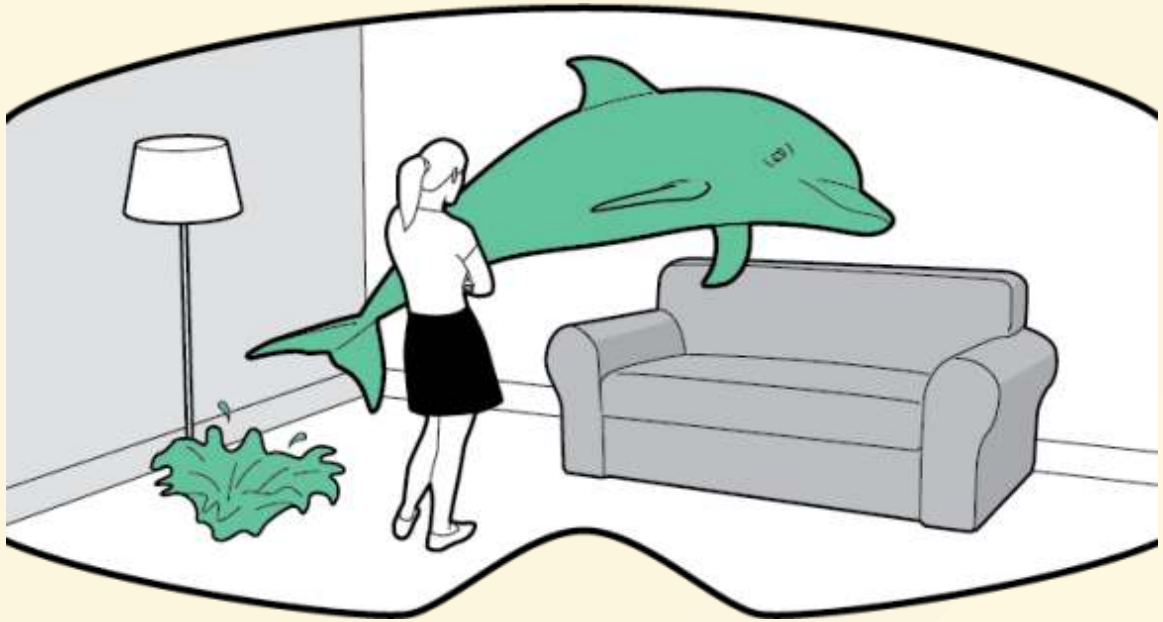
Google Glass concept video (2012)

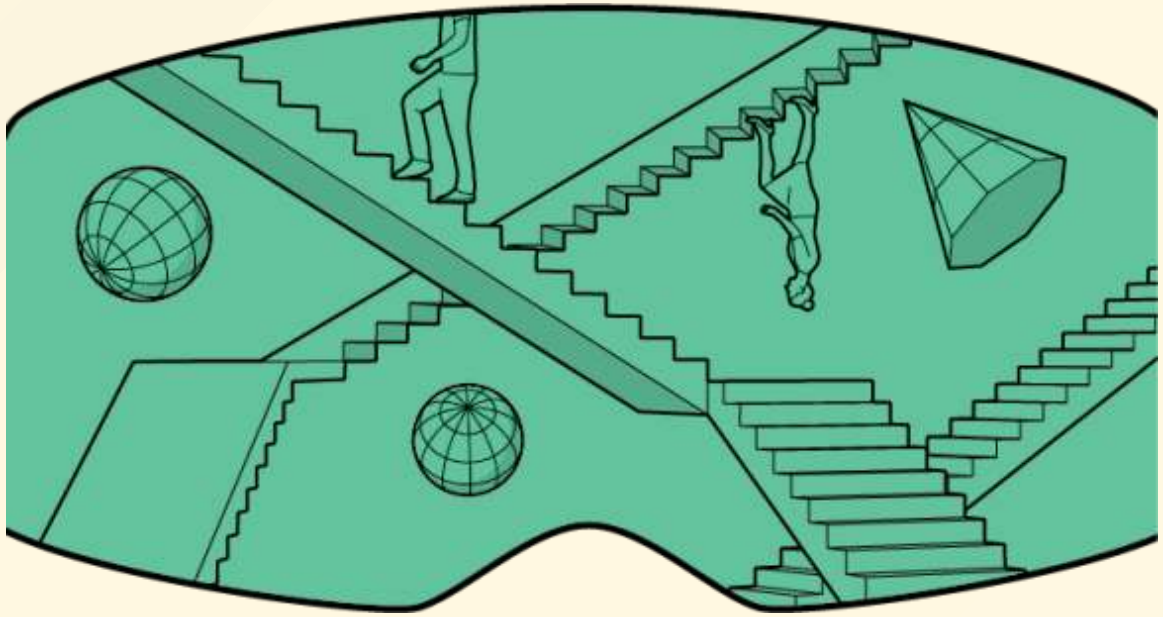


Definitions ⭐

- **VR** : Virtual Reality Jaron Lanier, 1987
- **AR** : Augmented Reality Thomas P. Caudell, 1990
- **MR** : Mixed Reality
  - marketing term used by Microsoft
  - ⚠️ **no clear definition**! ➡️ Term must be defined before use!
    - cf. What is Mixed Reality?
- **XR** : X = { e**X**tended / Cross (**+**) / Any (*) / A+V } Reality
  - **recent** generic term which **encompasses AR and VR**

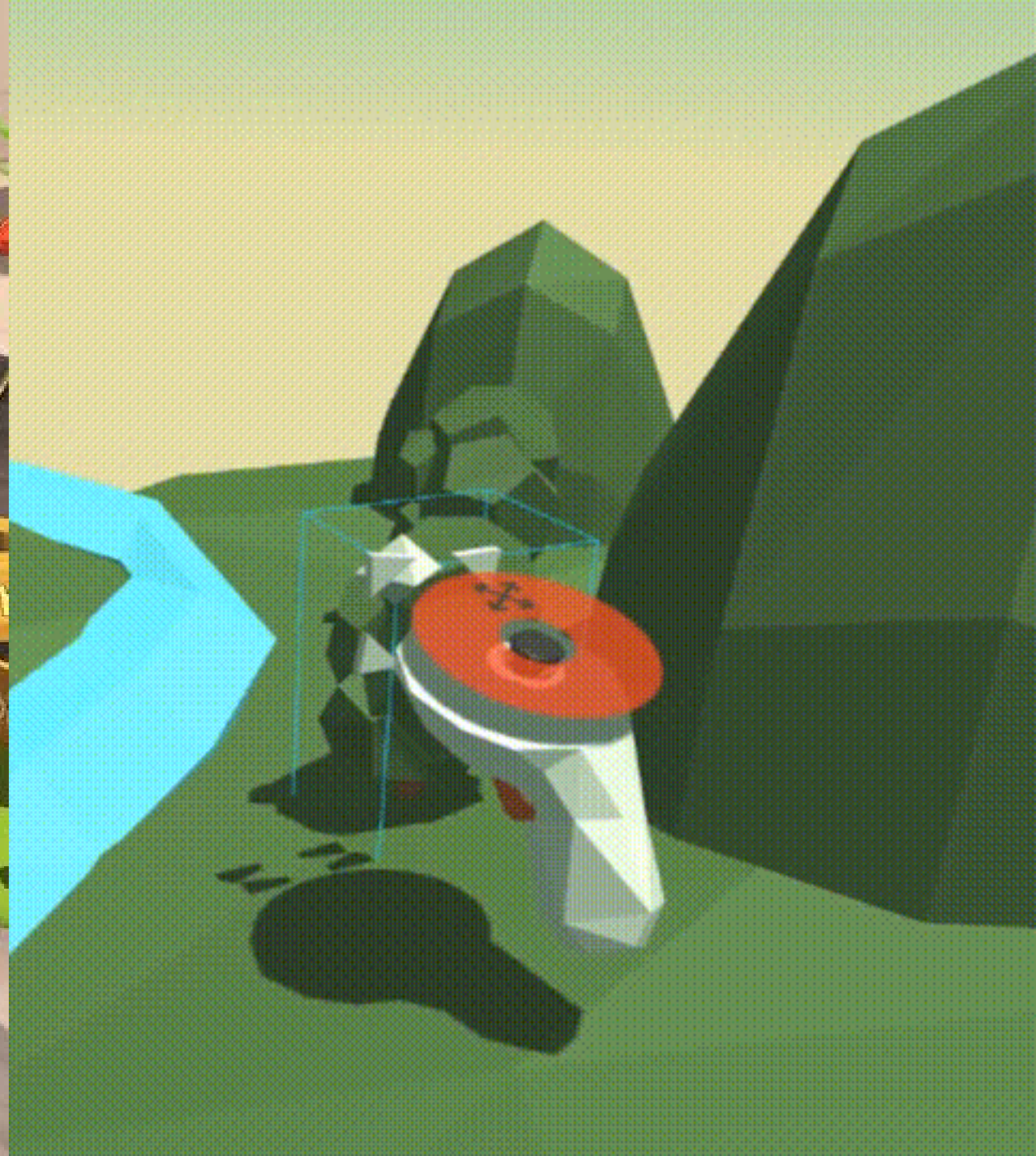
AR | VR





images:https://www.wired.com/2016/04/magic-leap-vr/

AR | VR



AR or VR?

- Similar technologies
  - 3D rendering
  - Tracking
  - Immersive interactions
- **Different effects** on the user

Effects of VR

- **Isolates** the user from the real world
- **Teleports the user** to another world, which is entirely virtual

Tiltbrush

The limits of VR

- Reminder: **continuum**!
  - No clear boundaries
- When the whole world is modeled and registered in 3D, is it still VR?
- Photogrammetry / Lightfields / NeRF / Gaussian Splats
  - VR but immersion in a world entirely rebuilt in 3D

Greg Madison @ Unity

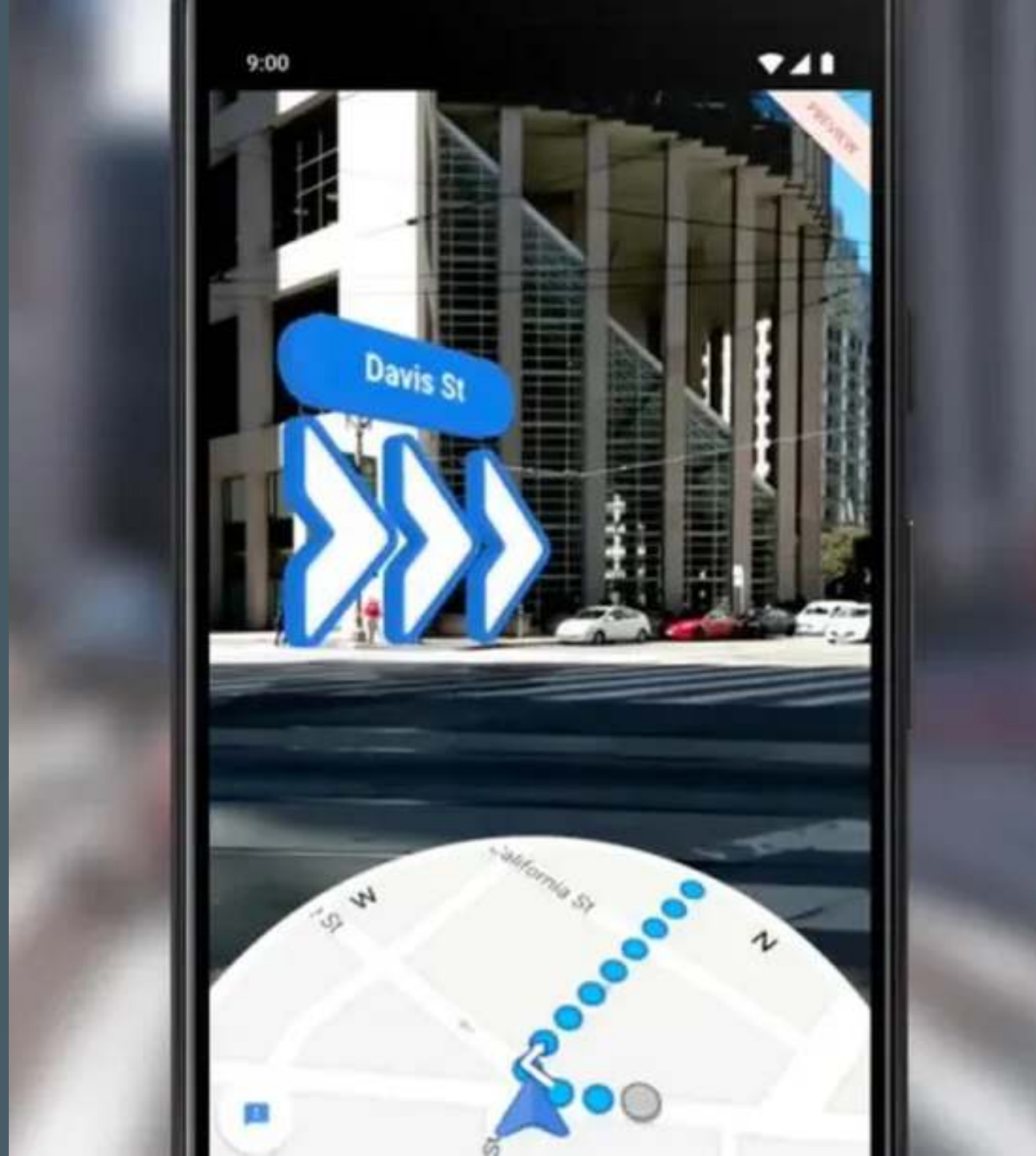
VersaillesVR

Effects of AR

- The user **stays in the real world**
- AR **enhances** the real world with contextual information
- Augmented user: acquires **new senses**!
- Information becomes visible
  - spatialized **information overlaid on top of the real world**

Google Maps AR

The browser of the future? 🧐



Audi AR manual (Metaio, 2012)

The limits of AR

- Reminder: **continuum**!
  - No clear boundaries
- When more virtual elements than real ones: **Augmented Virtuality**
  - Window to the real world
  - Real users visible

Augmented Virtuality

Varjo Teleport

video

Dangers of AR ★

- **Information overload**: Hyper-reality
  - Diminished Reality desirable?
- **Excessive assistance, altered behaviors, surveillance**
  - Black Mirror: Nosedive
- **Digital divide**
  - Some people will feel **handicaped**, missing a sense, **daltonians**
- **Privacy**: Cloud Wars
  - MAMAA* vs Open AR Cloud

MAMAA = Meta Alphabet Microsoft Apple Amazon

Hyper-reality (concept)

Black Mirror (fiction)

Scene Responsiveness (Meta 2023)

paper video

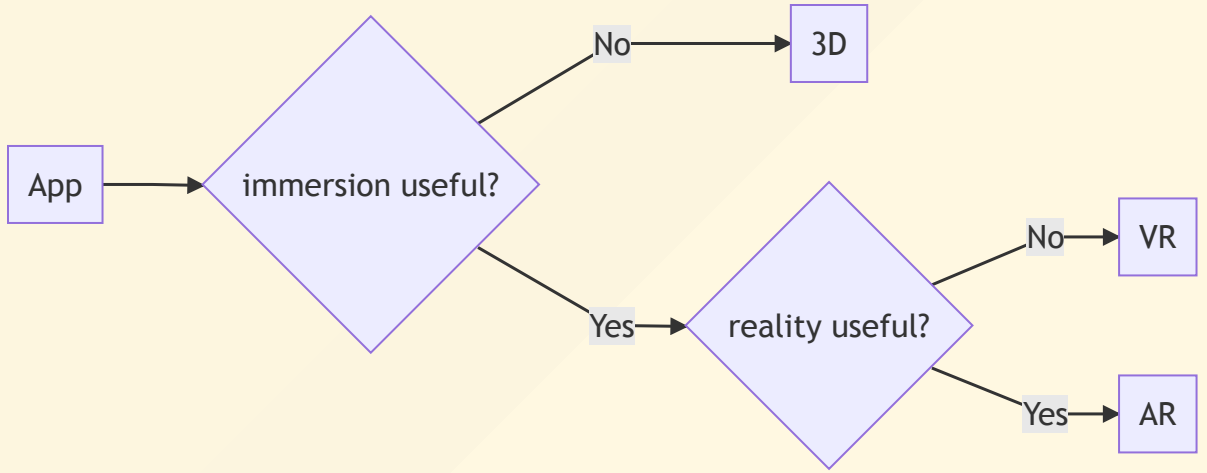
Takeaways ⭐

- VR **immerses** the user in a **virtual wolrd**
- AR **brings virtual objects** into **the real world**

Choosing the right paradigm

- Immersion useful ?
  - Yes ➡️ VR
  - No ➡️ 3D
- Immersion and real environment useful ?
  - Yes ➡️ AR
  - No ➡️ VR
- Keep in mind continuum to pick the right paradigm to create the best possible experience

Choosing the right paradigm



History

Understand technological evolutions to anticipate the future

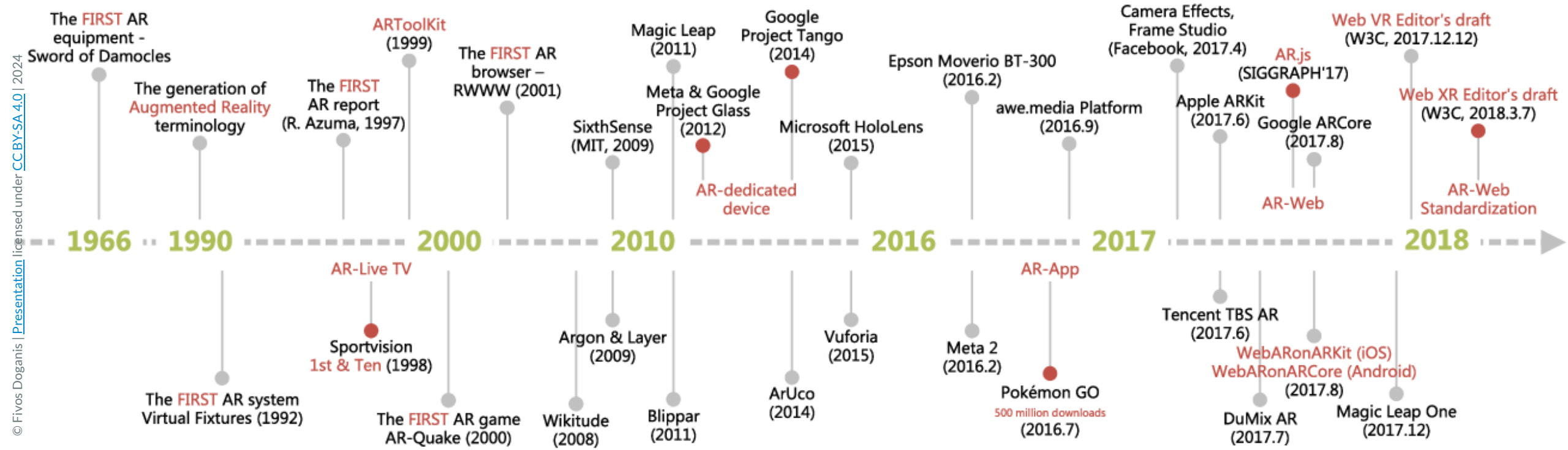


Fig. 1. ***Historical evolution of AR.***

History

Key milestones

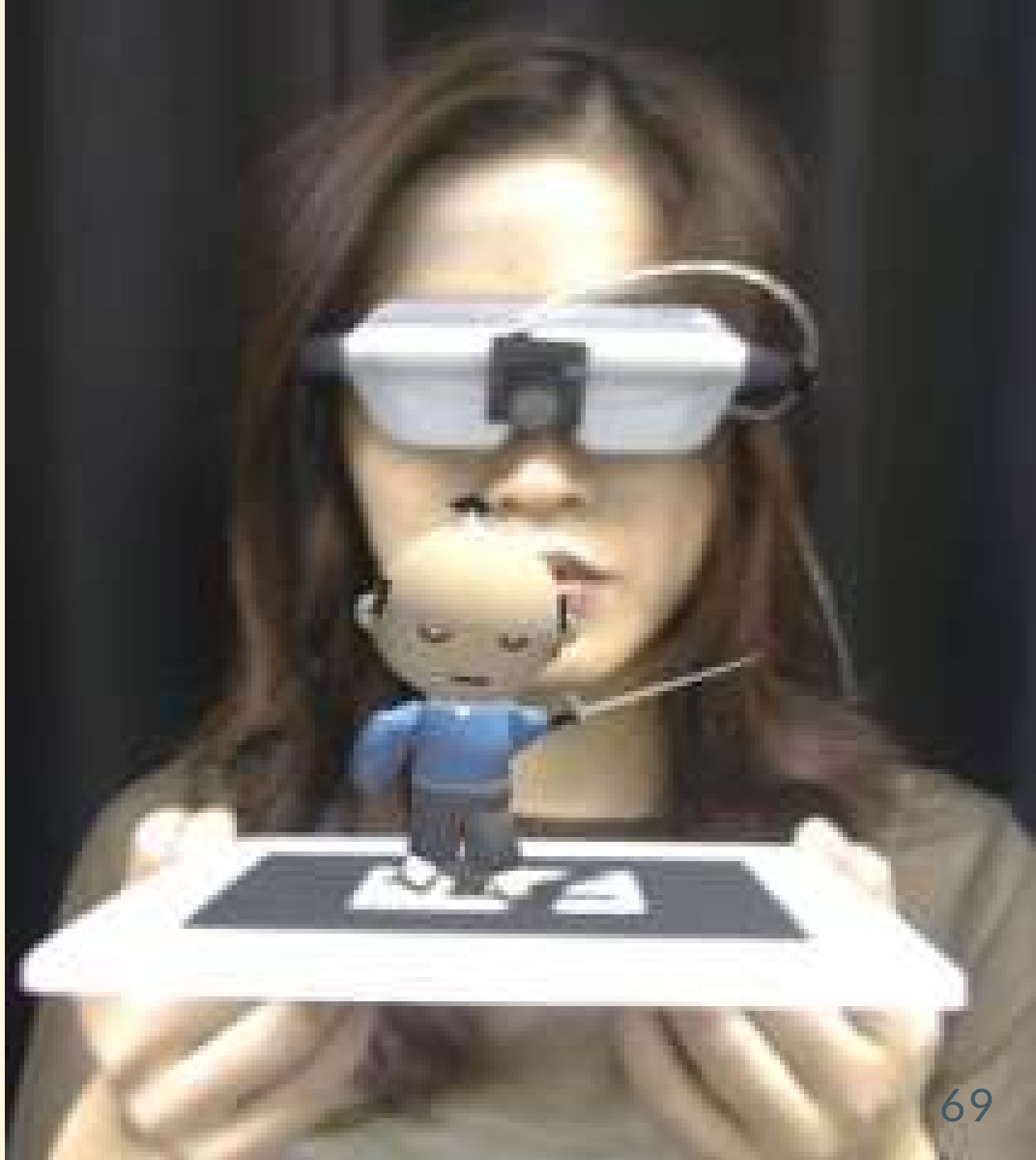
Prehistory (1966) ⭐

- Ivan Sutherland invents the first AR headset
- Can display a cube
- Follows the movements of the head (**6 DOF**)
- Nickname : The Sword of Damocles
- paper: *The Ultimate Display*

Markers (1999)

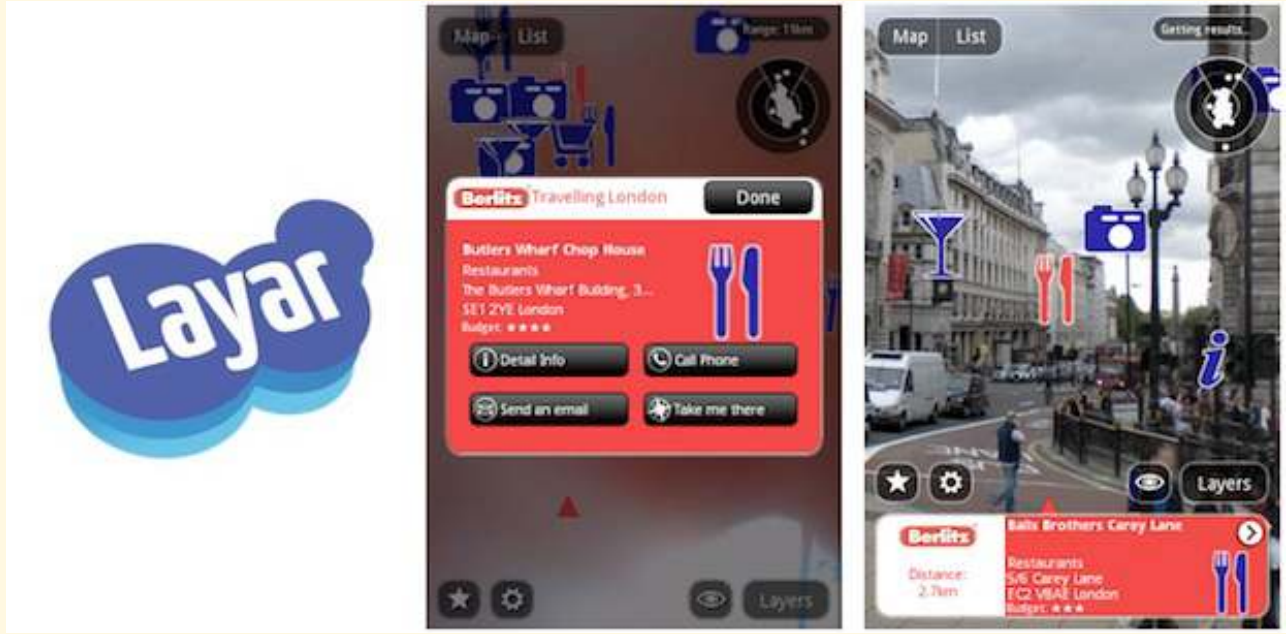
- Monochrome markers
- **ARToolkit** created by Hirokazu Kato

- Alternatives: ARTag, ArUco
- PC + Webcam



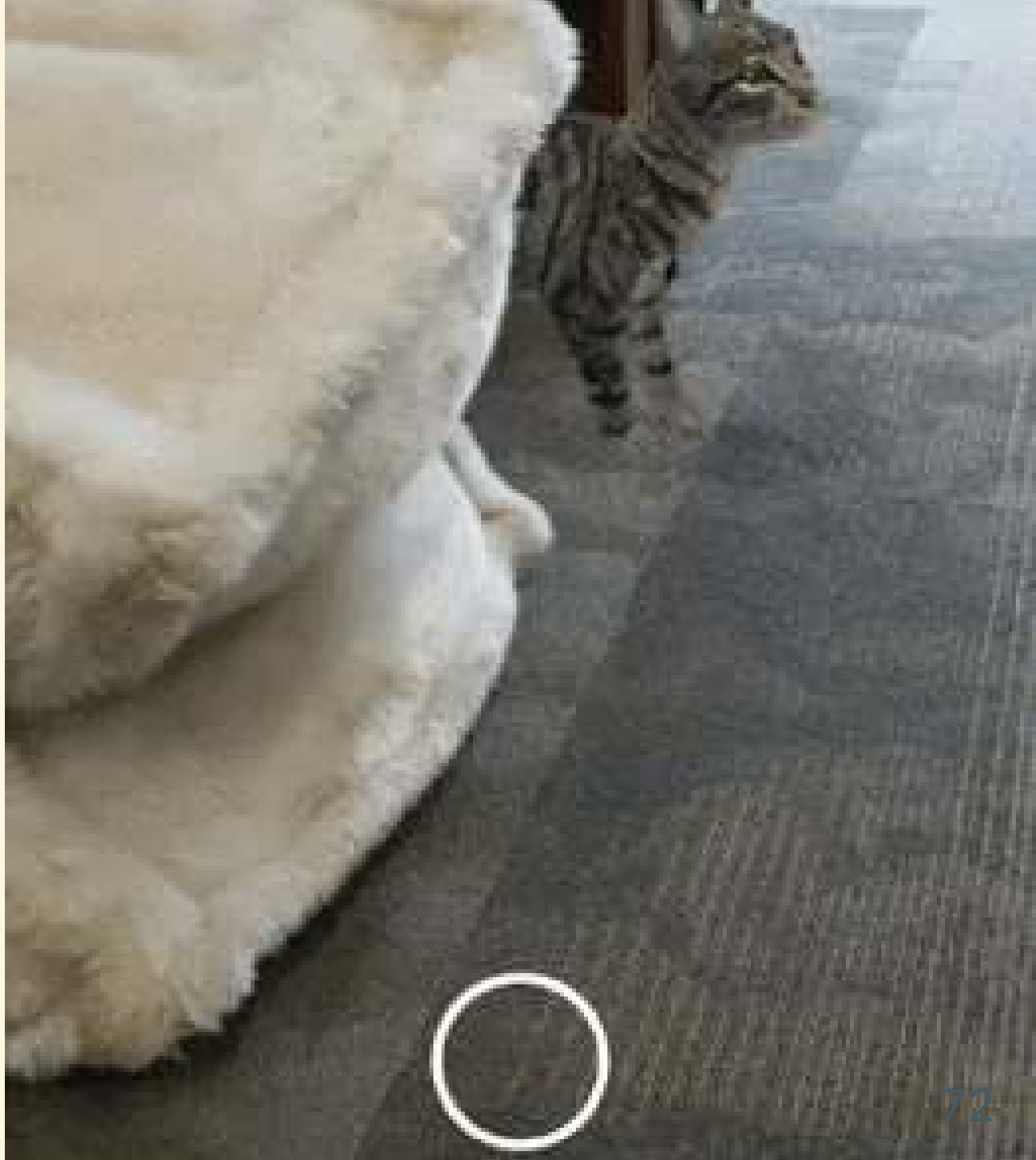
NFT, GPS (2005)

- **NFT**: **N**atural **F**eature **T**racking
  - Color photo tracking
- Wikitude, Layar (**GPS**)
  - no image processing needed with GPS!
- Vuforia
- Marketing use-cases
- PC, mobile phones, tablets



SLAM, 3D (2015)

- **3D environment tracking**
- **SLAM**: ★ **S**imultaneous **L**ocalization **A**nd **M**apping
- **3D object tracking**
- Deep Learning
- Occlusion 3D
- ARKit, ARCore
- Smartphones, HoloLens, Azure Kinect



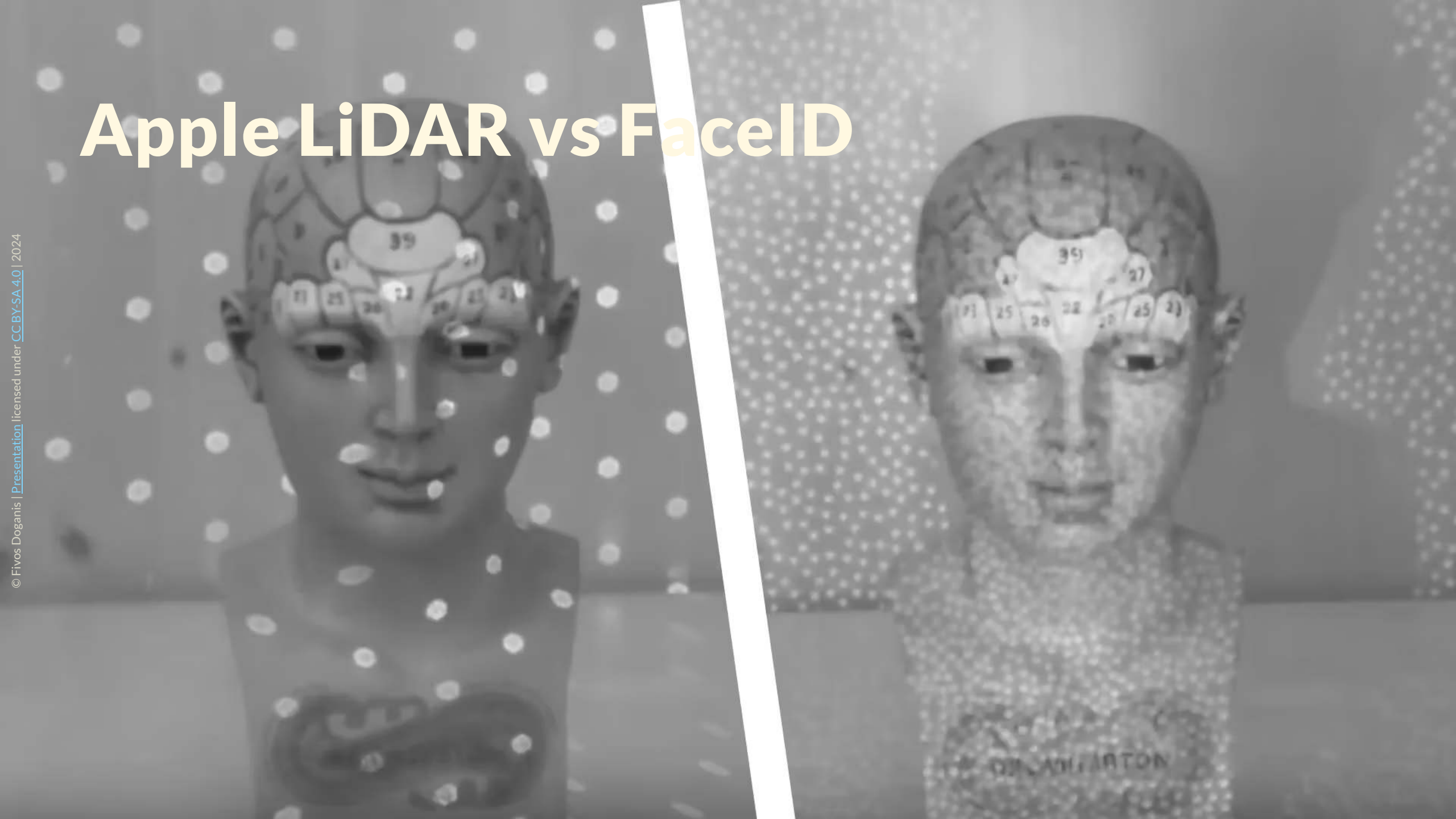
Azure Kinect + HoloLens 2

HoloLens 2

Apple LiDAR

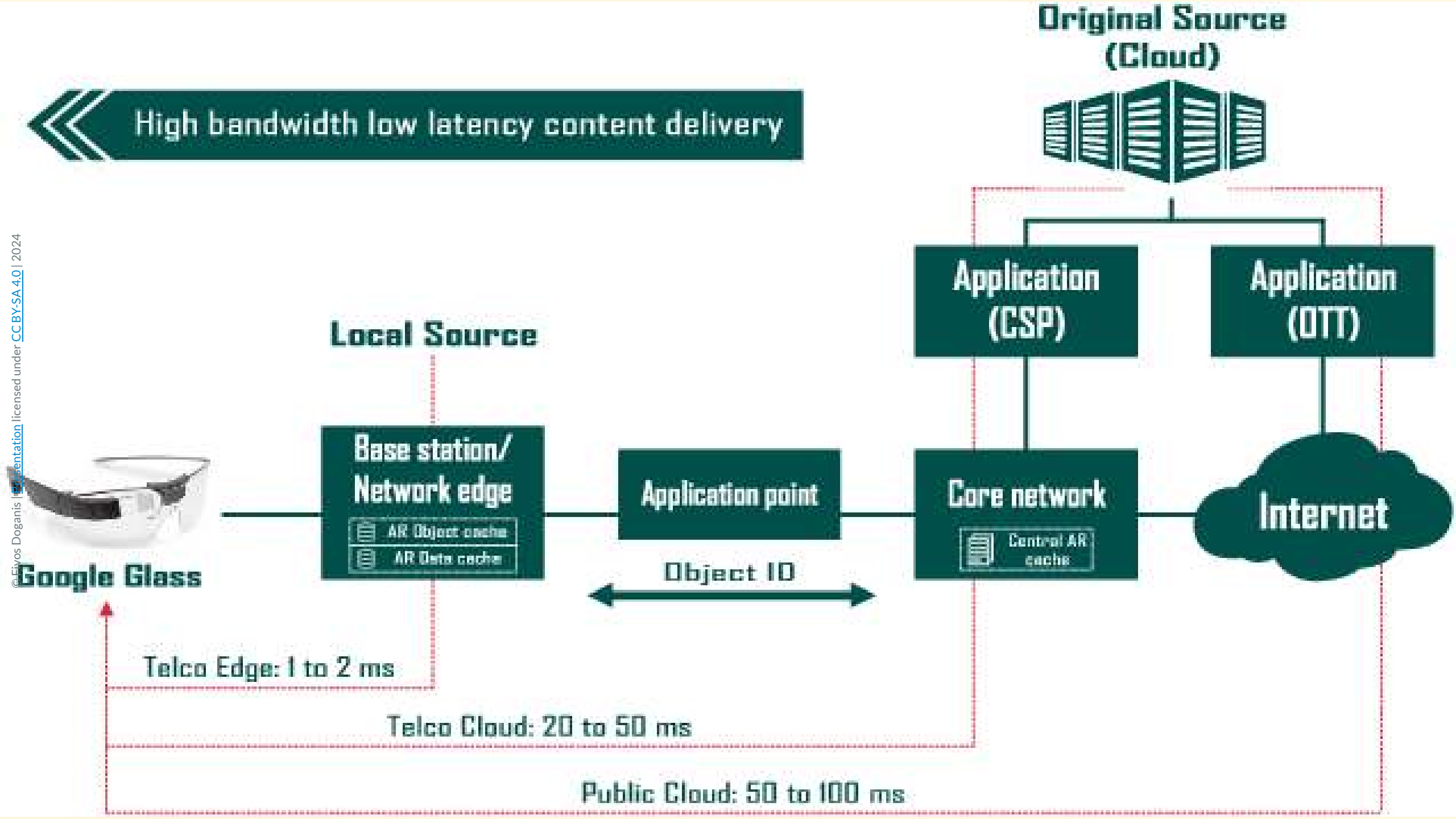
iPad Pro 2020, iPhone 12 Pro

Apple LiDAR vs FaceID



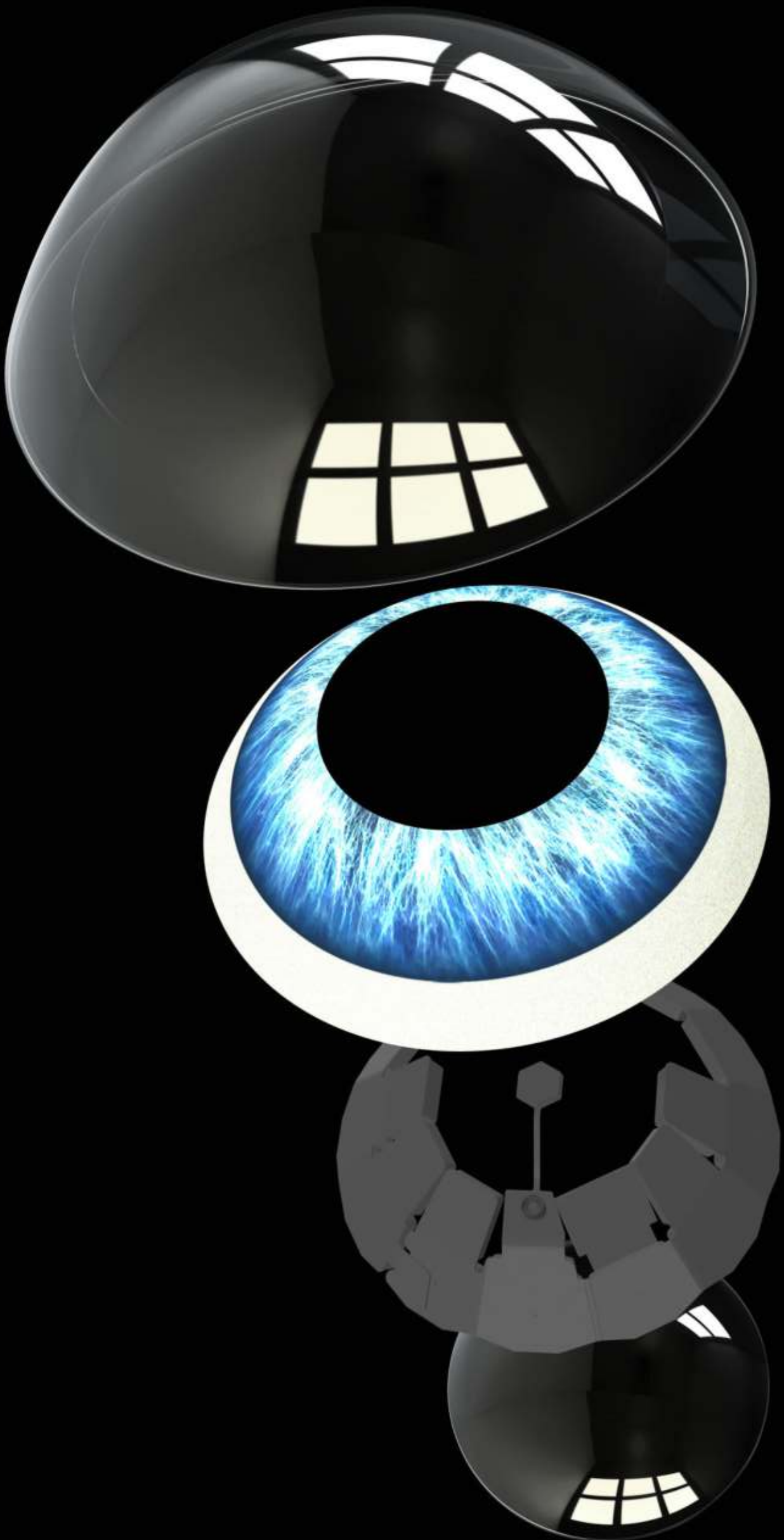
Near future

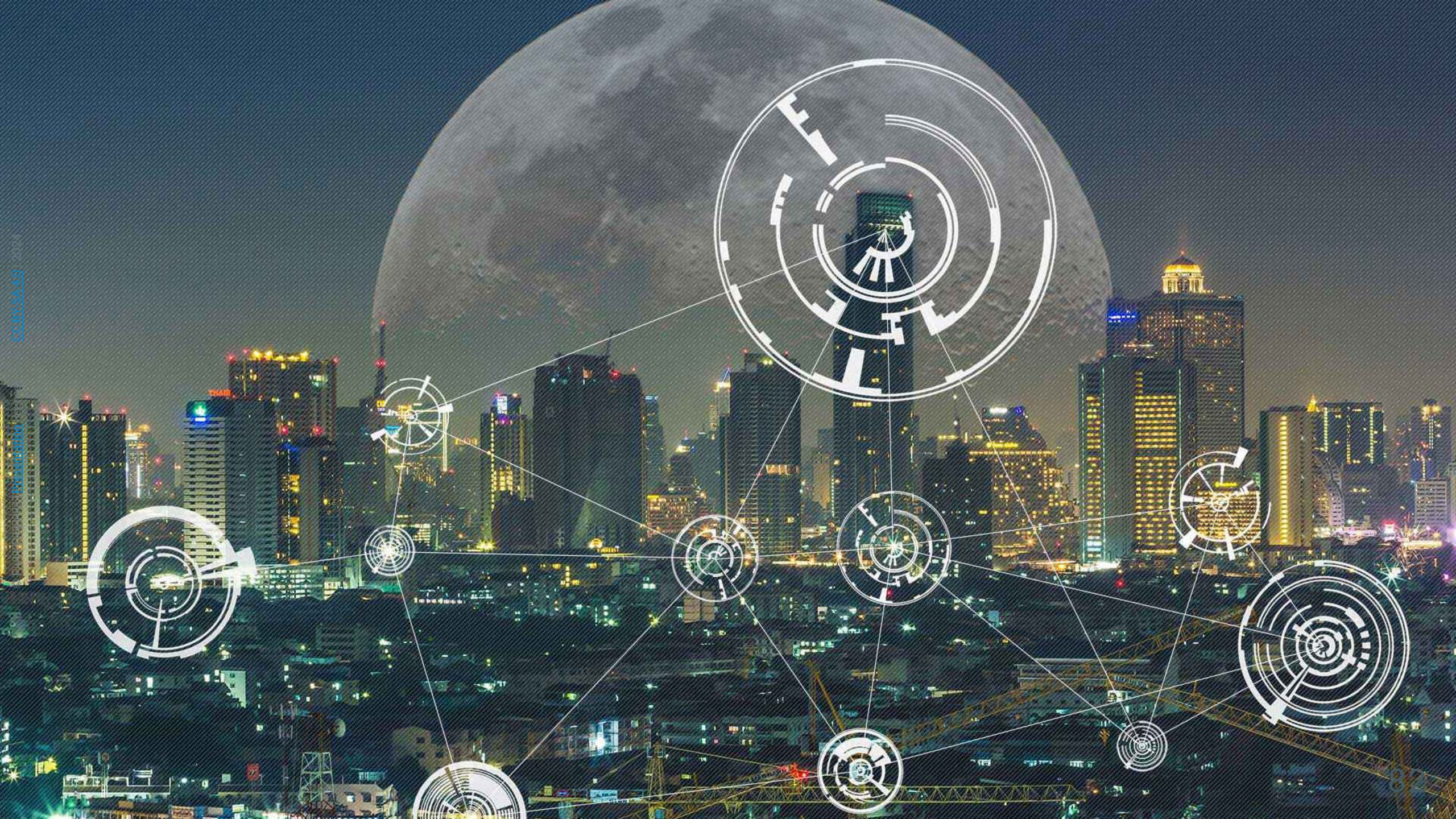
- Form-factor: glasses 😎
- **AI**
  - contextual assistance
  - understands both environment and user
- **5G**
  - application and information streaming (**Edge Computing**)
- Spatialized Web: **AR Cloud**



Far future

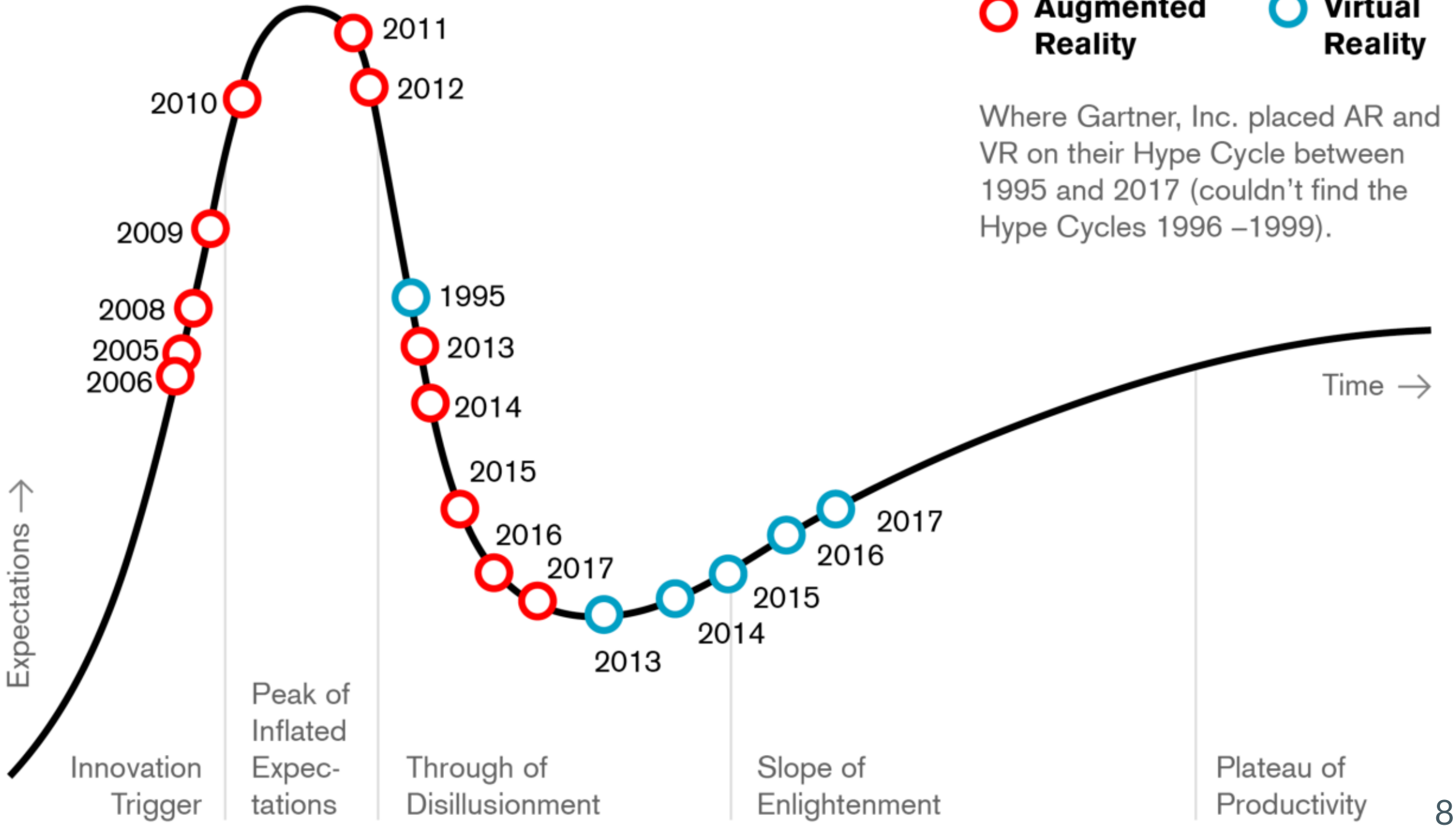
- AR will **replace or complement smartphones**
  - users will raise their heads again
    - but will they see better?
- Contact Lens (Mojo Vision)
  - RIP (2023) 💀
- **Ambient Computing**
- Ubiquitous Computing
- **Smart Cities**





Gartner Hype Cycle

- Technology trends evolution
- Gartner
  - 2005 - 2017 period



Where do we stand now?

- We are getting close to productivity for AR and VR
- Or AR is nows considered as "productive" since 2020?
- Future trends:
  - AR Cloud
  - "Metaverse" and "Digital Humans"

2023

Magicverse Layers

The Layers of Spatial Computing

A nearly infinite number of application layers make up the city-scale Magicverse.

User choices and contextual AI power this system of systems, navigated through a spatial computing interface.

Spatial Application Layers

Entertainment

Communications

Health & Wellness

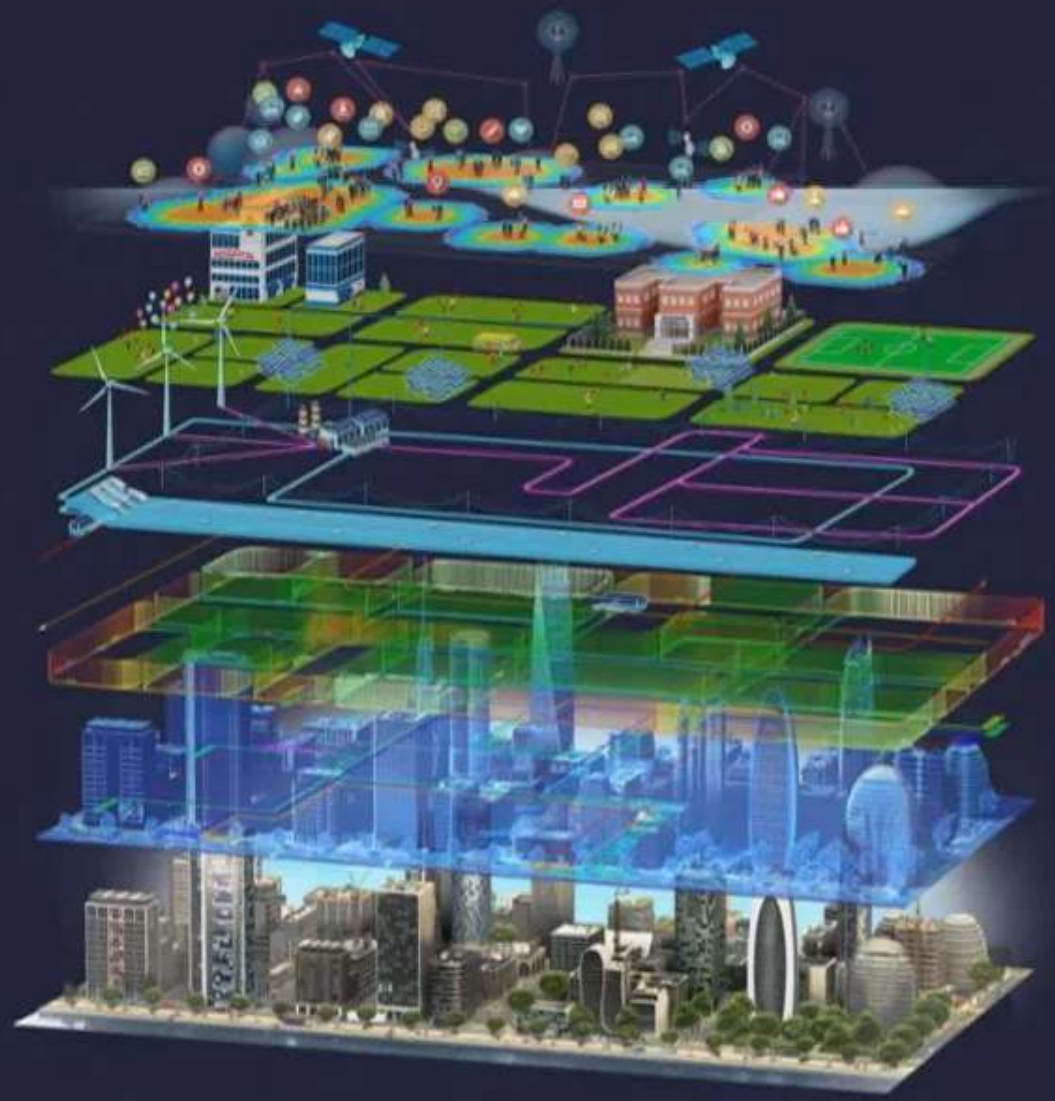
Energy & Water

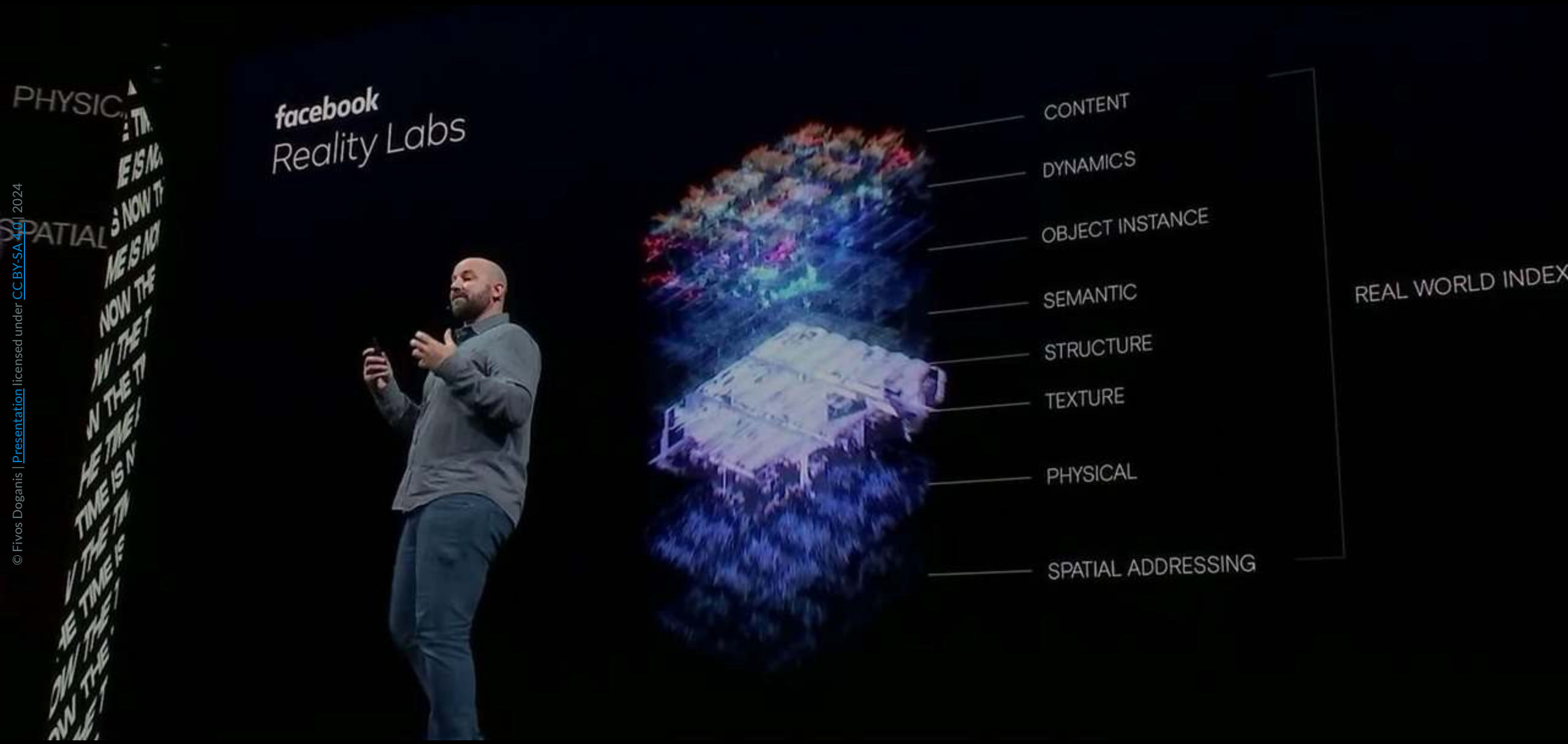
Mobility

Base Layers

Digital World

Physical World





OPEN AR CLOUD

BUILDING A BETTER REALITY, TOGETHER

MAMAA Strategies

Meta, **A**lphabet, **M**icrosoft, **A**pple, **A**mazon
and others!

Google

> **AR *[is for]* adding shared meaning in the interaction between people**.
> *Johnny Lee*, Google I/O 2017

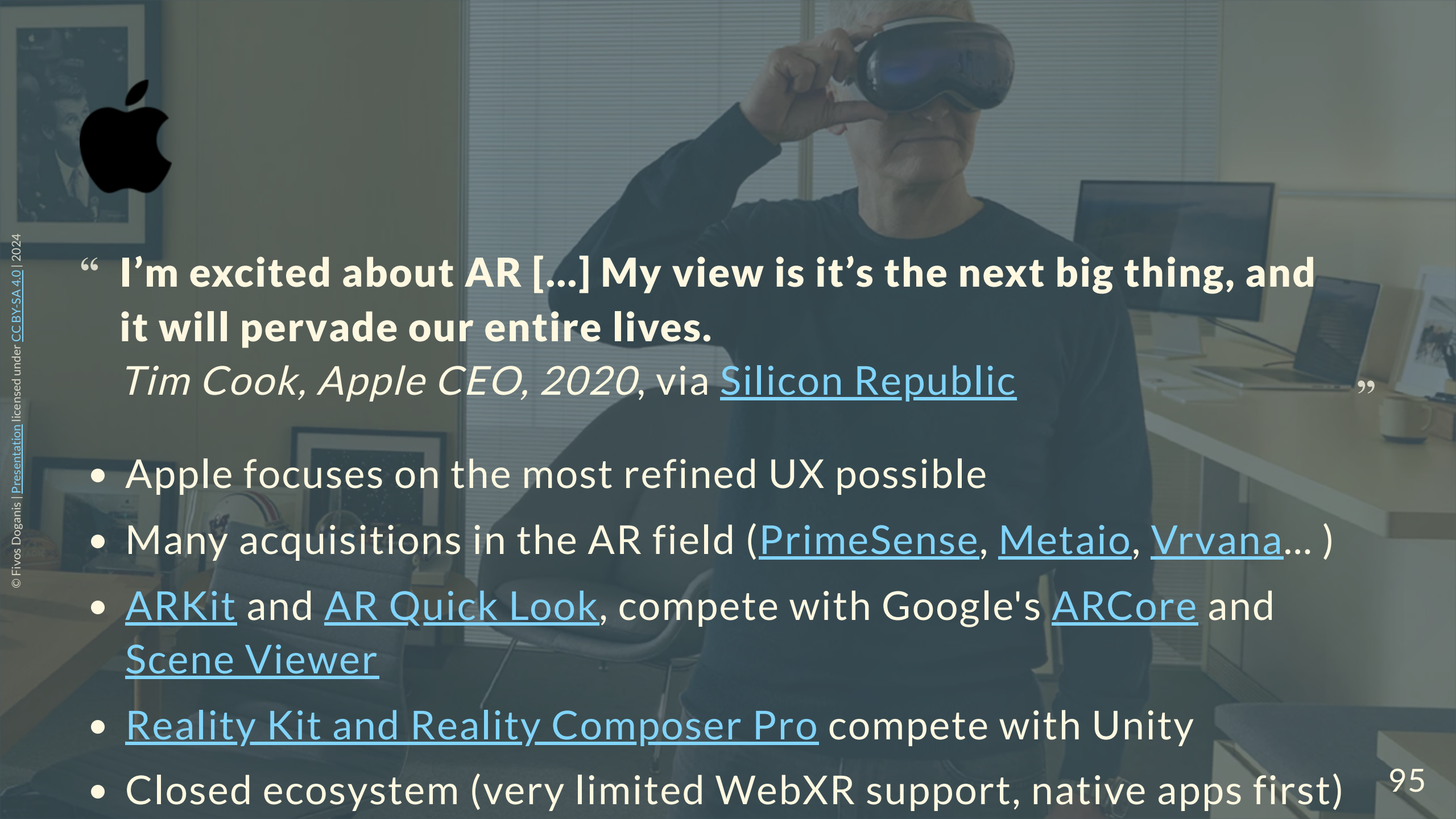
- Dropped mobile VR (Cardboard 💀, Daydream 💀)
- Dropped Tango 💀, to reach more devices: rely on **RGB camera + AI**
- API ARCore, competes with Apple's ARKit
- Google wants to provide **cross-platform AR services**
- Google + Qualcomm + Samsung XR Headset coming in 2025

> **The Web connects the world's information, and AR connects information with the physical world. So together they can be applied to solve real life problems.**
>
> *Andrey Doronichev*, Google I/O 2017

Google Glass Enterprise Edition 2

Google Glass killed, for the second time, in 2023 💀

Gorillaz mobile AR app



> **I'm excited about AR [...] My view is it's the next big thing, and it will pervade our entire lives.**
> *Tim Cook, Apple CEO, 2020*, via Silicon Republic

- Apple focuses on the most refined UX possible
- Many acquisitions in the AR field (PrimeSense, Metaio, Vrvana...)
- ARKit and AR Quick Look, compete with Google's ARCore and Scene Viewer
- Reality Kit and Reality Composer Pro compete with Unity
- Closed ecosystem (very limited WebXR support, native apps first)

Hardware

- Adds **LiDAR** for a robust **SLAM** (e.g. white walls scenario)
- Extends its 'wearables' category
  - AirPods
  - Apple Watch
  - **Apple Vision Pro**
    - unveiled in June 2023
    - released in February 2024

People Occlusion + Scene Understanding (iOS)

Eye tracking (visionOS)

"Spatial Computing", "EyeSight", Real Virtual Continuum

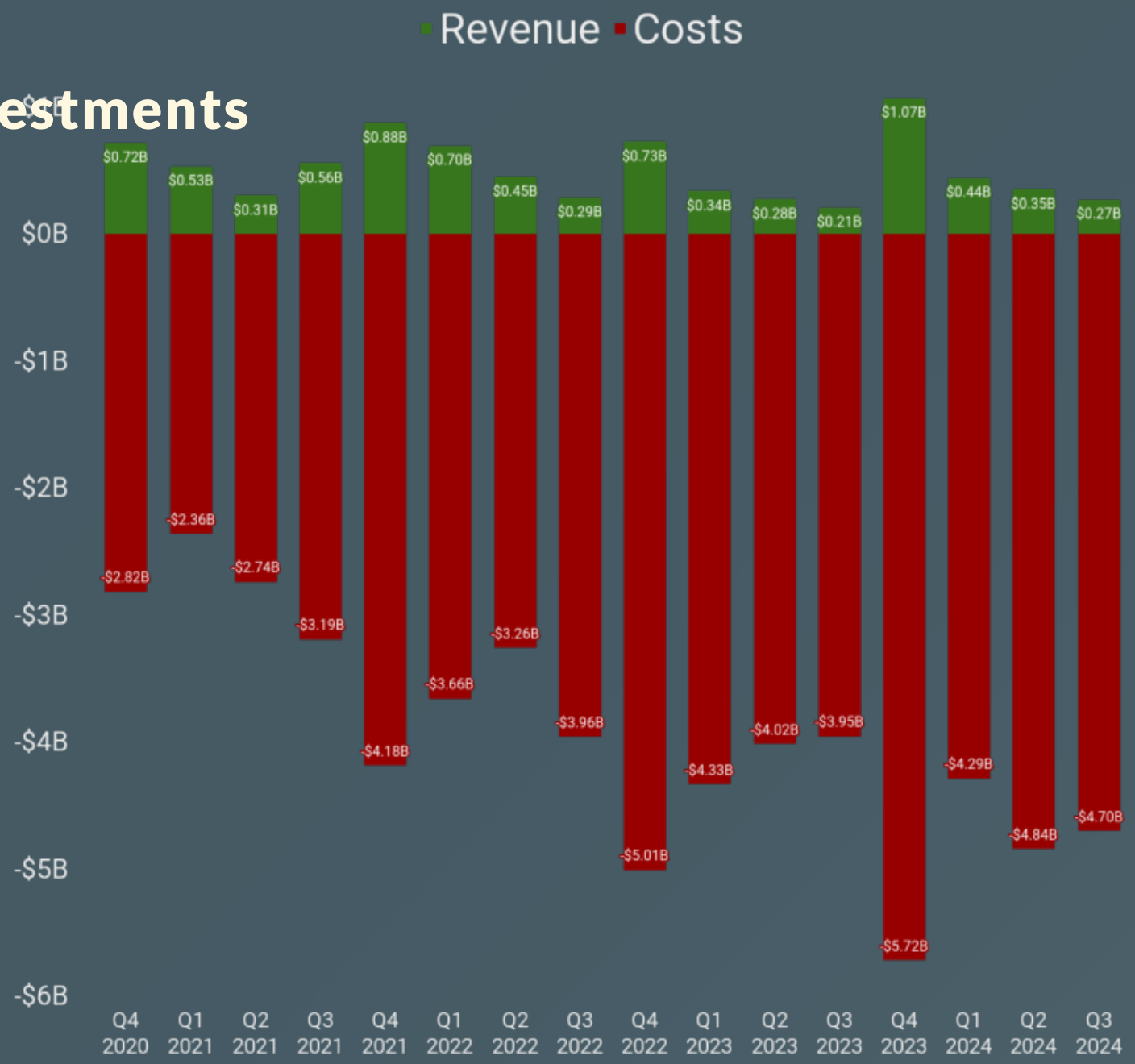
Avatars

Collaboration

Meta

- Created **Horizon Worlds social network** for virtual encounters, and **Horizon Workrooms for remote collaboration**
- Believes that **AR will replace smartphones** and every screen in 10 years, does not want to miss this revolution: Project Aria / Orion
- Interested in **personal data**, centers of interest of their users (eye-tracking, scanned environment), although they claim the opposite
- VR with Oculus, but they now focus on AR, cf. Infinite Office
- ~~AR filters Facebook and Instagram via Spark AR~~ RIP 💀
- Great WebXR supporter

Meta XR Investments

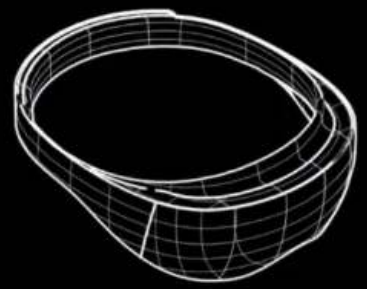
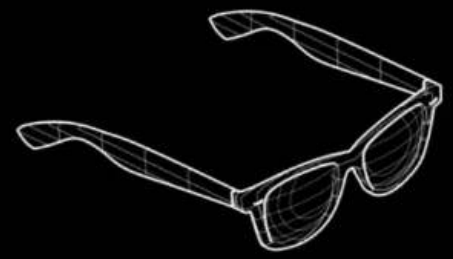


Oculus Infinite Office

Meta Quest 3: focus on AR

Reverse Passthrough prototype (CAD render) video

Michael Abrash in 2019

VR	AR
	
FULL CONTROL OF PIXELS	SOCIALLY ACCEPTABLE
FEWER CONSTRAINTS	WEIGH 70 GRAMS
BEST MIXED REALITY	DISSIPATE 500 MILLIWATTS

Project Aria

Next?

> I might get myself in trouble for saying this; I think it might be the **most advanced piece of technology on the planet in its domain**. In the domain of consumer electronics, it might be **the most advanced thing that we've ever produced as a species**.
>
> *Andrew 'Boz' Bosworth, Meta CTO*, January 2024

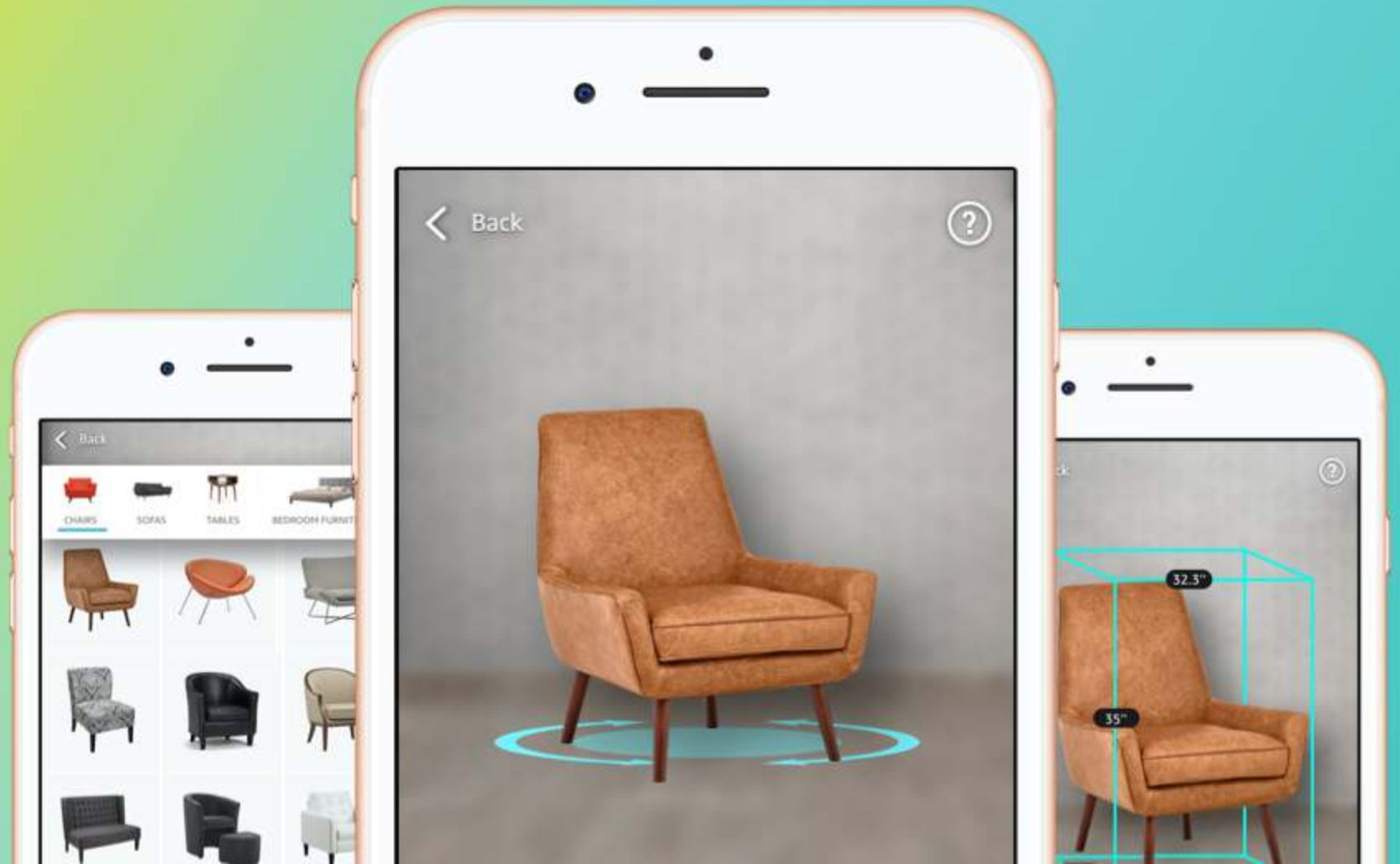
Project Orion (2024)

$10 000 prototype

- Amazon focuses on e-commerce and its Web Services
- AR View to see a product at home before buying it
- Offers Sumerian as a paid tool via AWS (Amazon Web Services) to create XR experiences
- Pushes machine learning, smart assistants (Alexa)
- Bets on AR on demand via 5G with its Wavelength Project
  - **5G + Edge computing**
  - AWS

View in Your Room

Design and Decorate Your Home with Augmented Reality



Microsoft

- Consumer: Minecraft
- Focuses on AR and industry, to maximize added-value
  - assistance and training
- ~~HoloLens 1 et 2, Kinect~~ RIP 2024 💀
- VR: OEM Partners
- ~~Windows Mixed Reality~~: RIP 2023 💀
  - now provides popular software to competitors!

Other players

- Hardware
  - Magic Leap, Lynx, XReal, Qualcomm, Snap
- SDK
  - Wikitude, Kudan
  - PTC Vuforia: IoT
- Web
  - ~~Firefox Reality~~ Wolvic
  - Chrome

Takeaways

- Big tech companies invest massively in AR, which they see as **a promising technology** evolving fast
  - hardware
  - algorithms
  - services, **data**
- Many players try to bring their users into their **closed ecosystem** (hardware, app store, cloud)
- Others focus ont the openness of the **Web** to **create and share open AR experiences**
  - ➡️ **ultimate goal of this course!** 🎉

Further reading

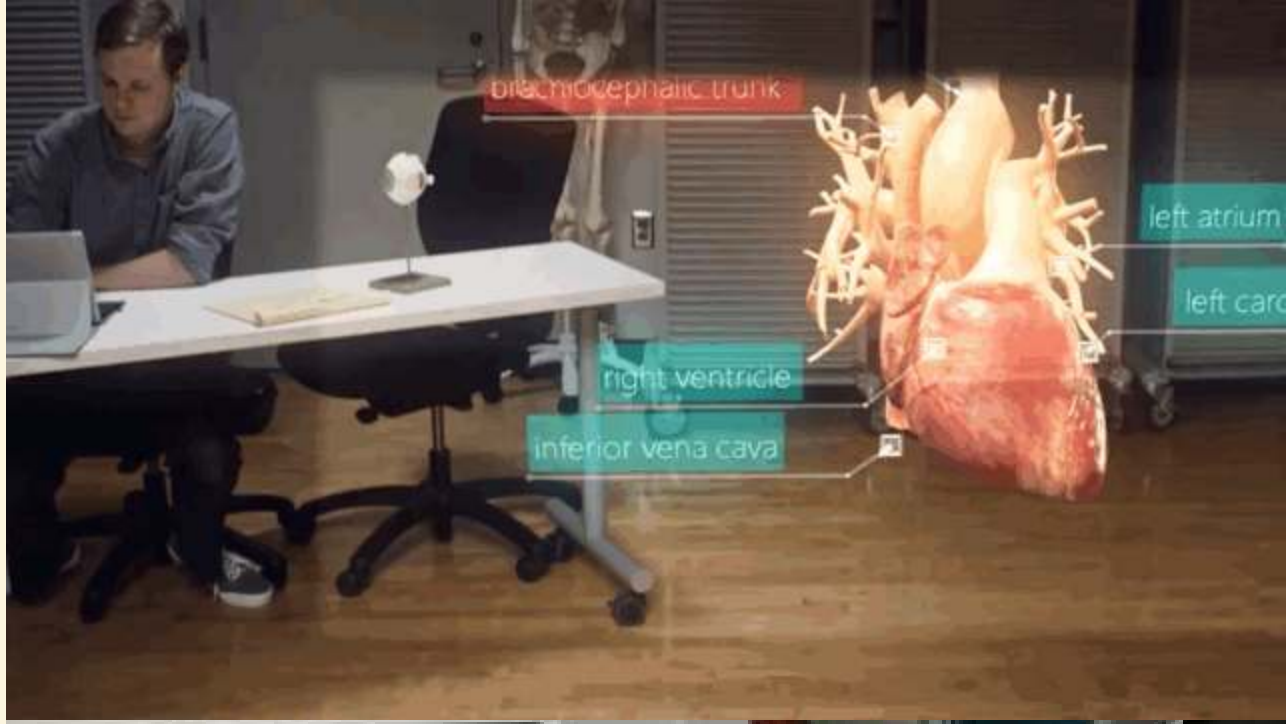
- **History and future of Web AR**
  - **Web AR: A Promising Future for Mobile Augmented Reality -** State of the Art, Challenges, and Insights.

  Qiao, Xiuquan & Pei, Ren & Dustdar, Schahram & Liu, Ling & Ma, Huadong & Junliang, Chen. (**2019**).

  Proceedings of the IEEE. 107. 1-16. 10.1109/JPROC.2019.2895105.

3 Types of AR ⭐

- **Video**
  - e.g.: smartphone, Meta Quest 3, Apple Vision Pro, Lynx-R1*
- **Optical**
  - e.g.: HoloLens
- **Projective**
  - e.g.: DIOTA ➡️



Lynx-R1: see next page ⬇️

Lynx-R1 (video)

Technologies Required for AR

Calibration
Tracking
Interactions
Rendering

Calibration

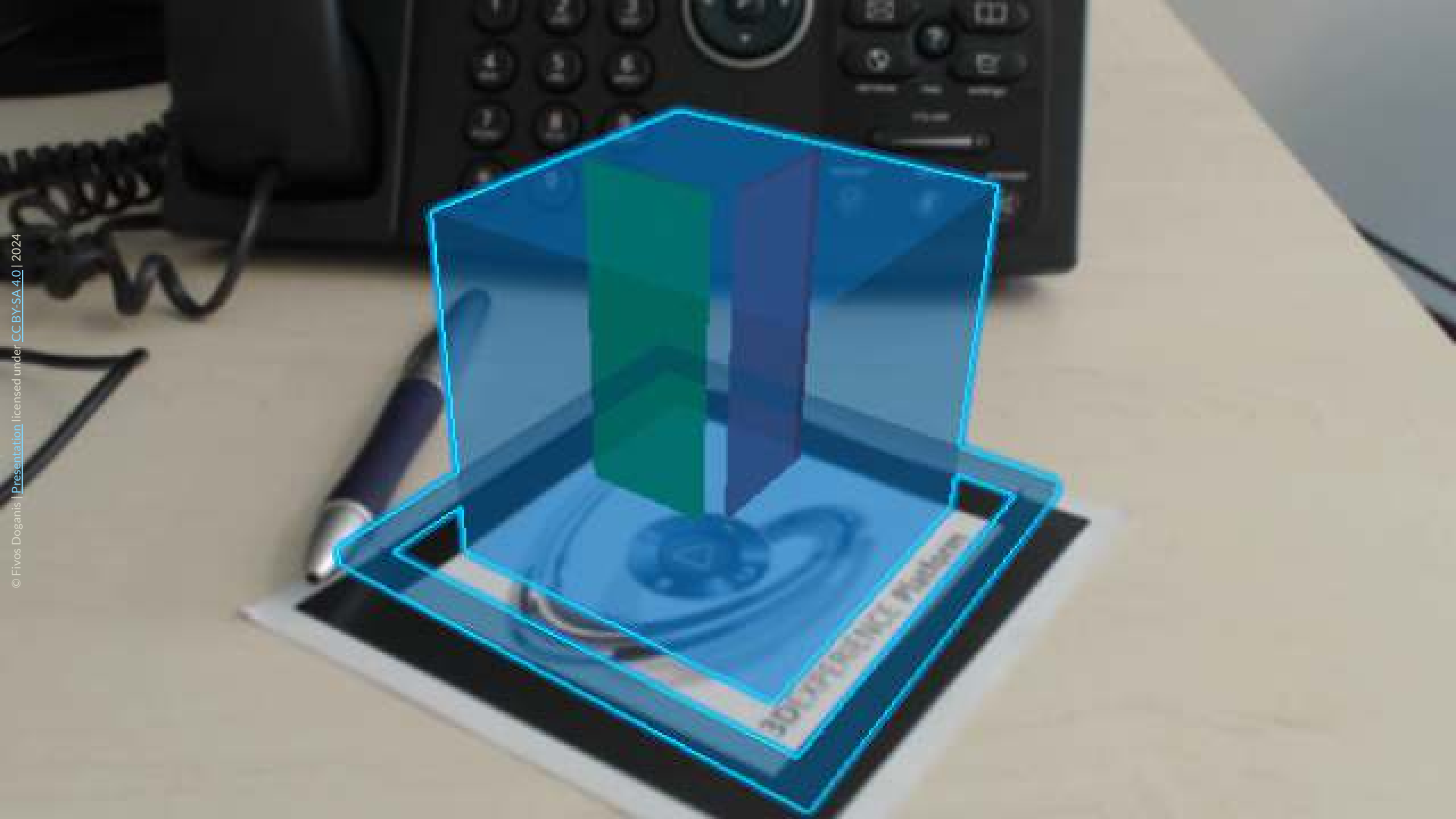
Goal: overlay accurately **the virtual rendering and the real image**

Optical AR calibration

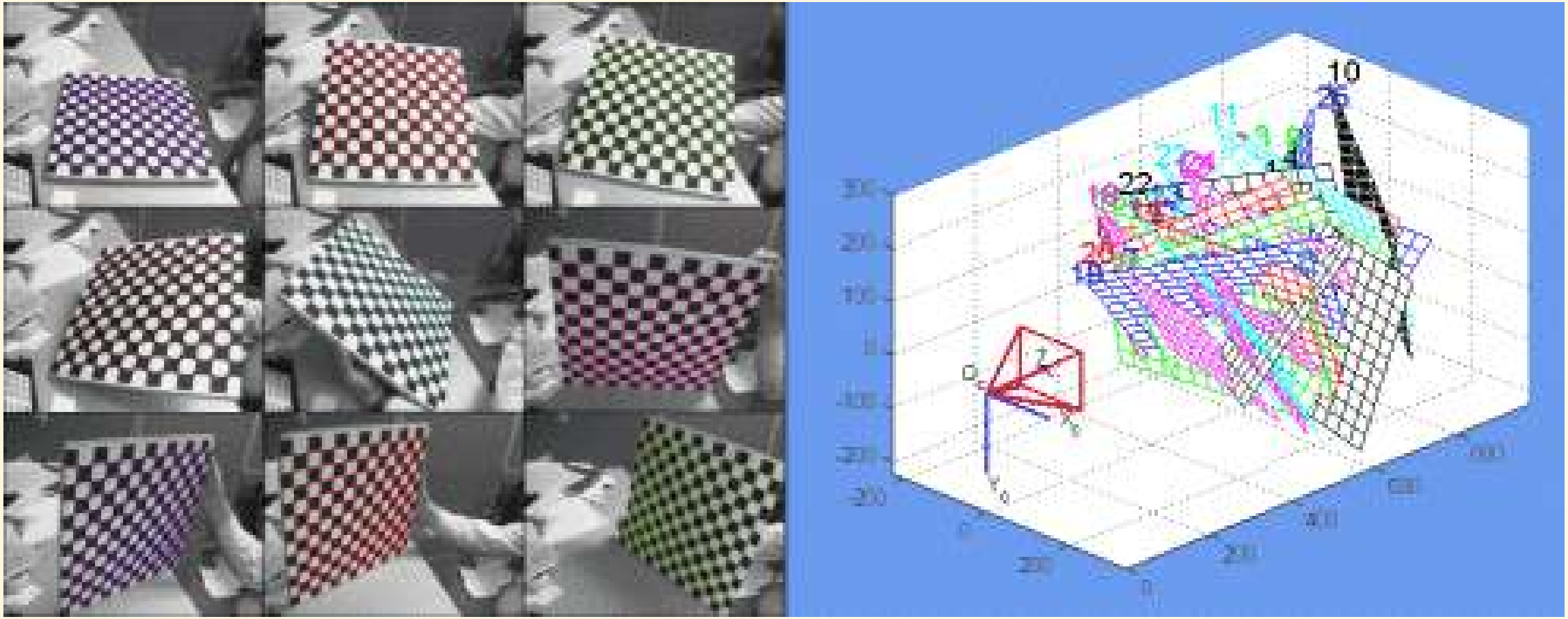
- very complex
- hardware dependent
  - projection and image formation systems
- depends on the body metrics of the user
- **made and provided by the AR hardware manufacturer**
  - possible adjustments for each user, cf. eye calibration in HoloLens

Video camera calibration

- Goal: compute the **optical parameters of the real camera**
  - **focal length**
  - radial distortion, lens imperfections
- Method:
  - capture images of known patterns (grids, **calibration patterns**) with a real camera
- ⚠️ **the focal length may be variable** (autofocus)
  - update calibration data for each frame
  - calibration data is provided by the API (ARKit, ARCore, WebXR)



Video camera calibration method



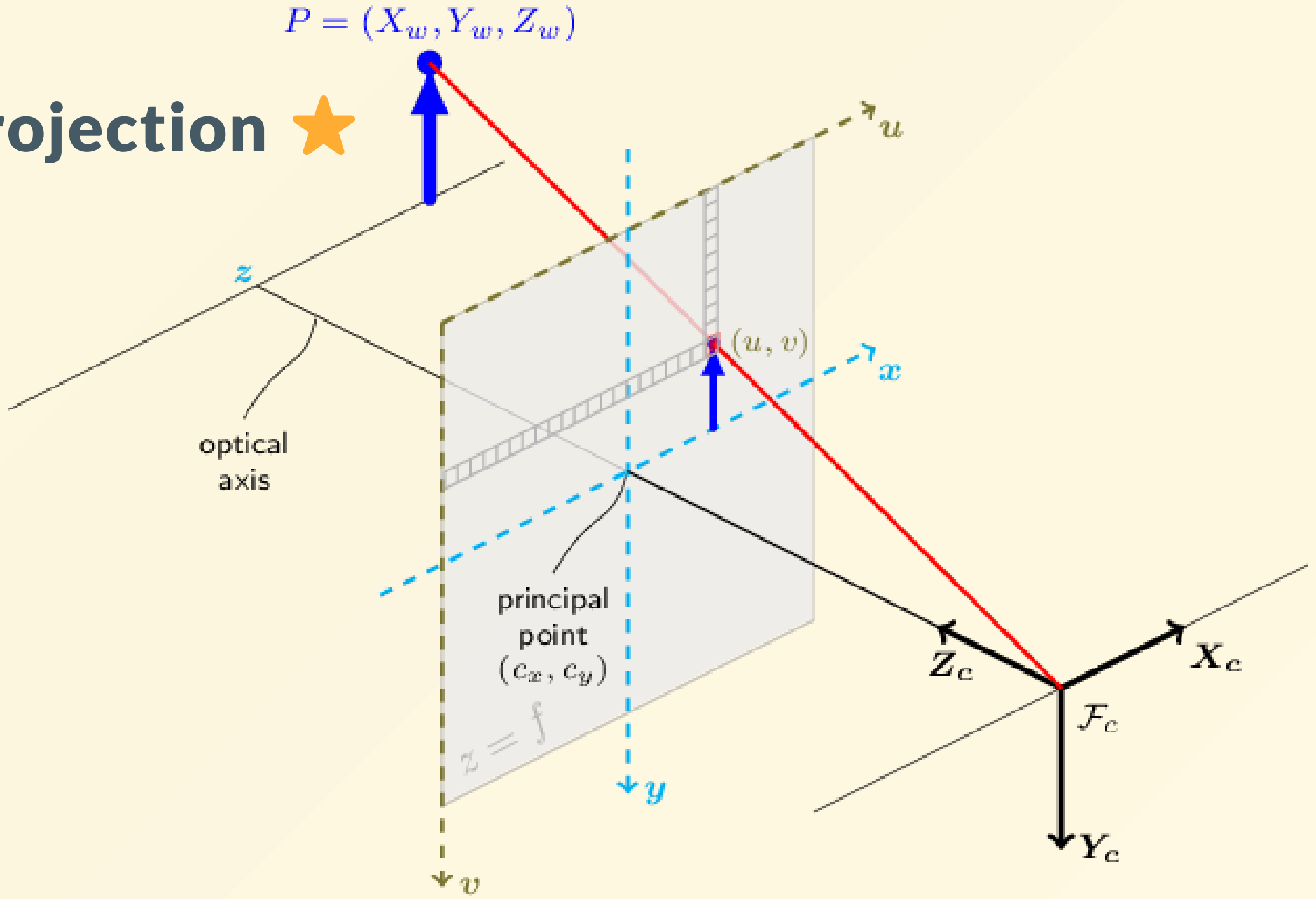
Pinhole camera model

source: https://www.mathworks.com/help/vision/ug/camera-calibration.html#buvr2qb-1

Extrinsic and intrinsic parameters

3D coordinates ➡️ Camera 3D coordinates ➡️ Image coordinates

Projection ★



$$s\ p = A[R|t]P$$

$$s \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix}$$

(X_w, Y_w, Z_w) 3D world coordinates O_w

(u, v) projected coordinates (pixels)

$[R|t]$ **extrinsic** matrix, A **intrinsic** matrix

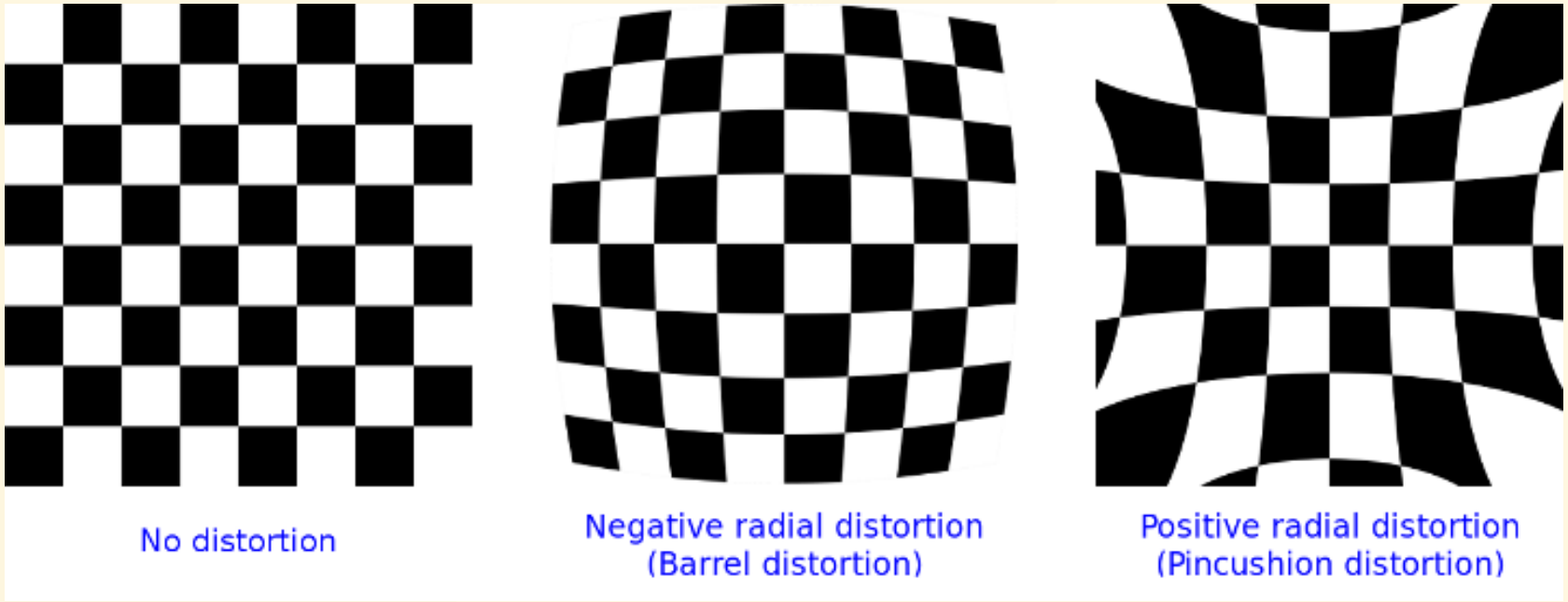
(cx, cy) principal point (pixels), **center of the image** in the ideal case

f_x et f_y focals along x and y (pixels), **equal** in the ideal case

Non linear radial distortion

- due to the lens,approximated by a polynomial expression

$$x_{distorted} = x(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)$$
$$y_{distorted} = y(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)$$



Registration

Goal: find the **rigid transformation** $[R|t]$ between a 3D point in the world and the center of the camera

Pose estimation

- Computed from 2D/3D pairs of points
- Optimization: projection error minmization between transformed 3D points V_i et image 2D points v_i

$$\arg\min_{R,t} \sum_i ||P(RV_i + t) - v_i||$$

P: projection function

R: rotation matrix

t: translation vector

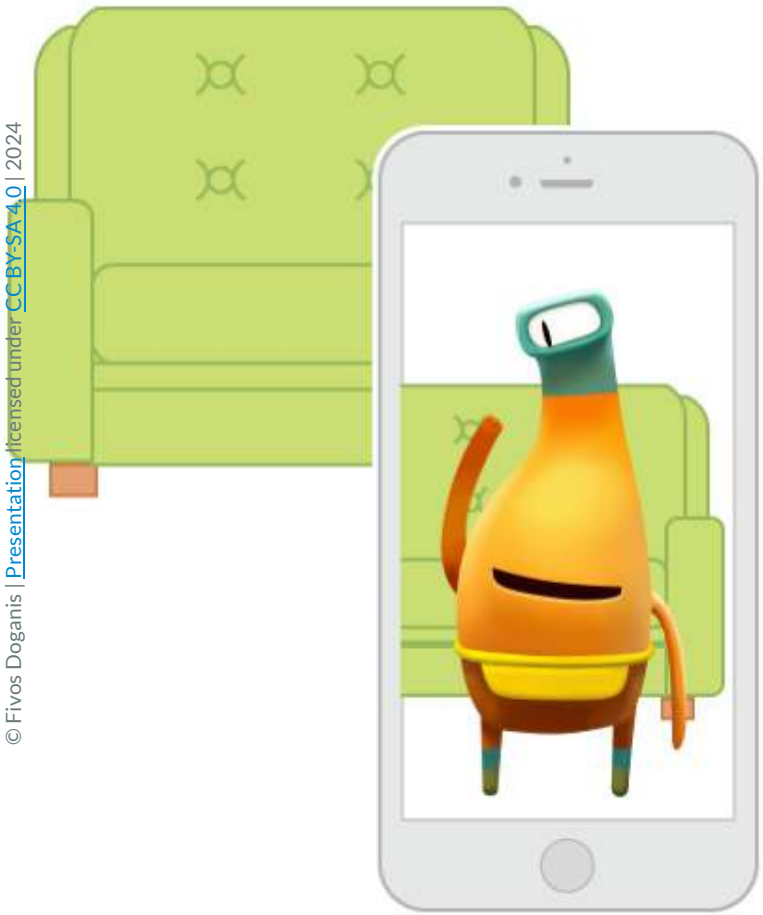
Tracking

after initial registration

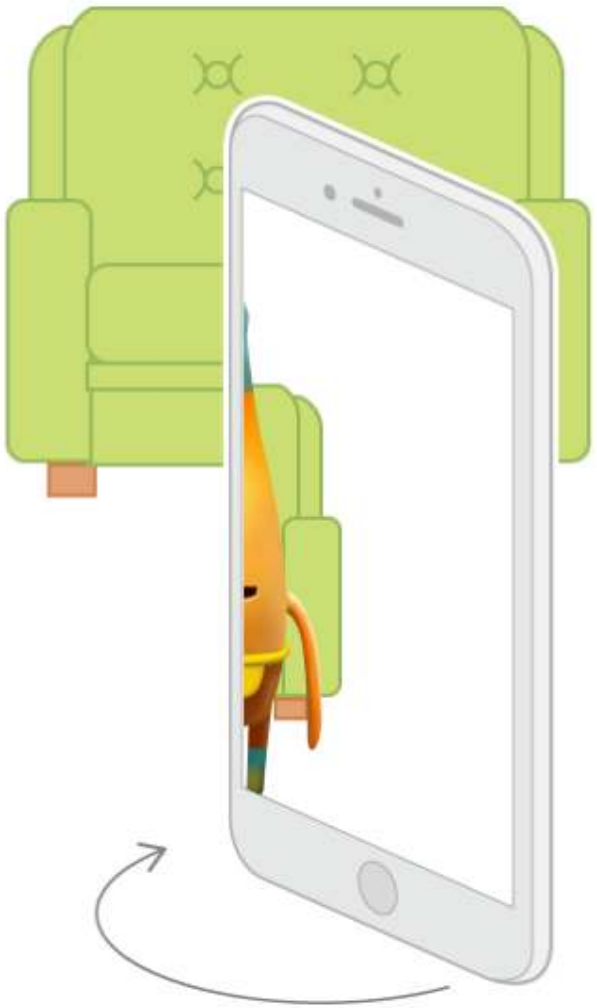
Tracking

- **D**egrees **O**f **F**reedom (**DOF**):
  - **0 DOF**
    - no tracking!
    - simple information overlay, cf. HUD
  - **3 DOF**
    - **rotation** only (gyroscope, accelerometer, compass)
      - limited experience (can be good enough, cf. planetarium)
  - **6 DOF**
    - **rotation + position**

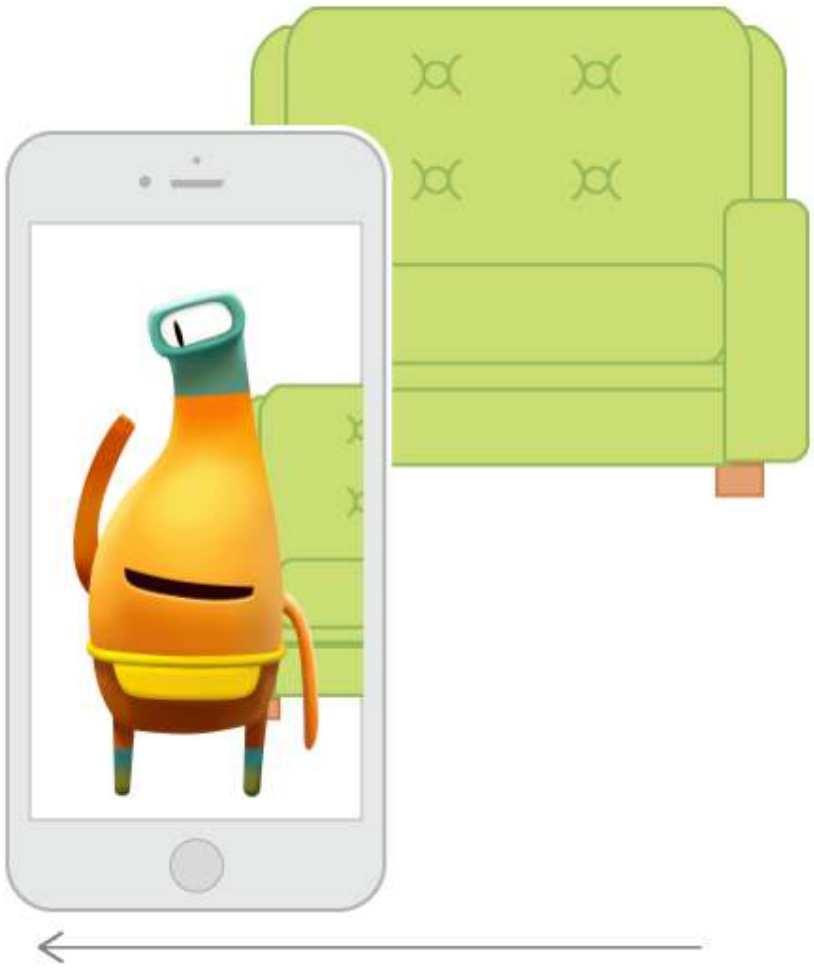
3 DOF



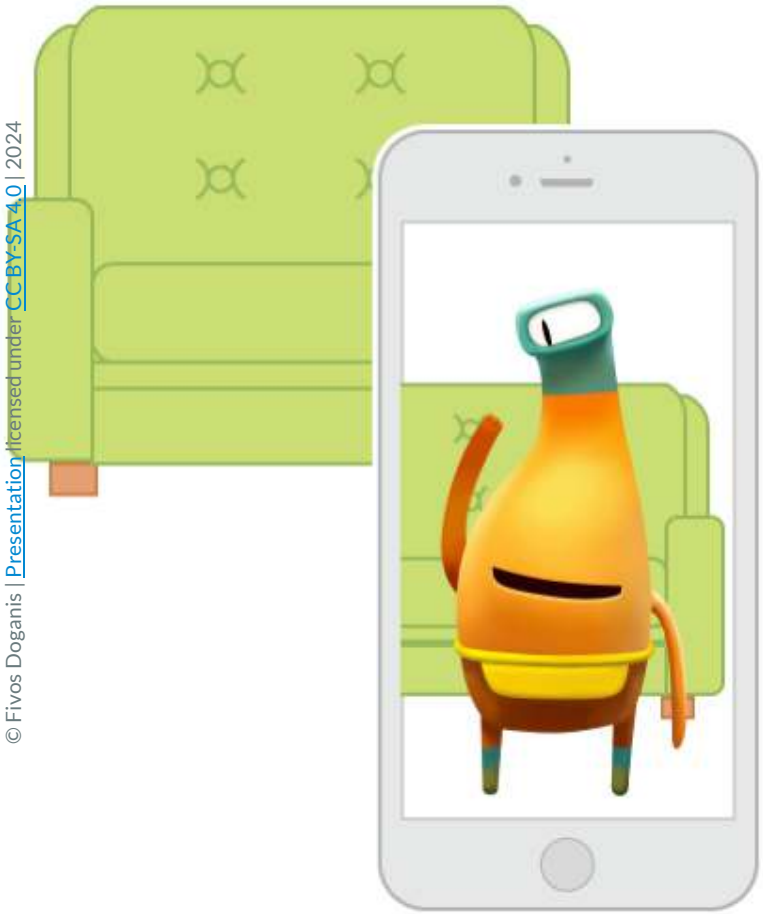
Device rotation



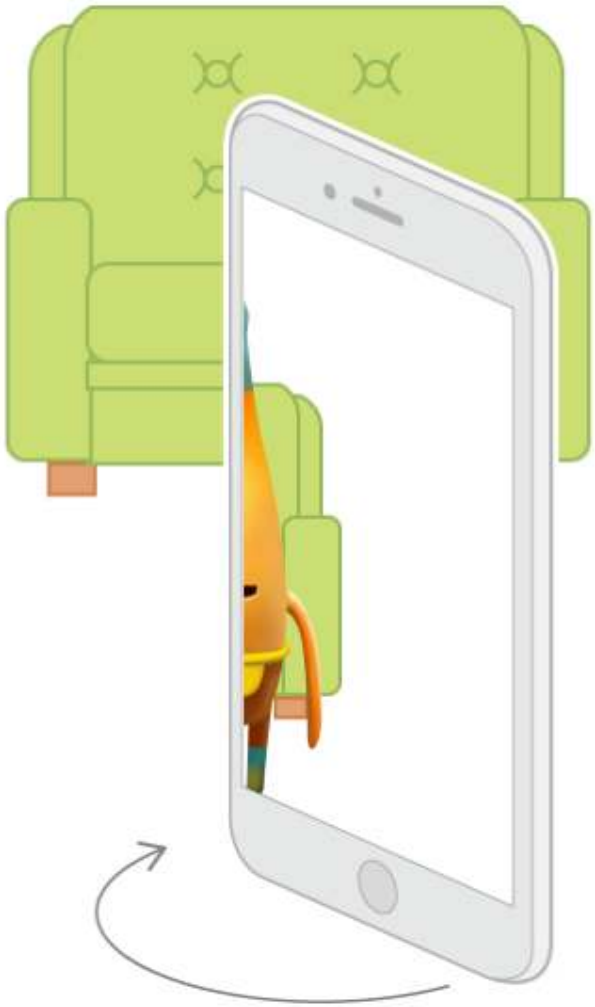
Device position



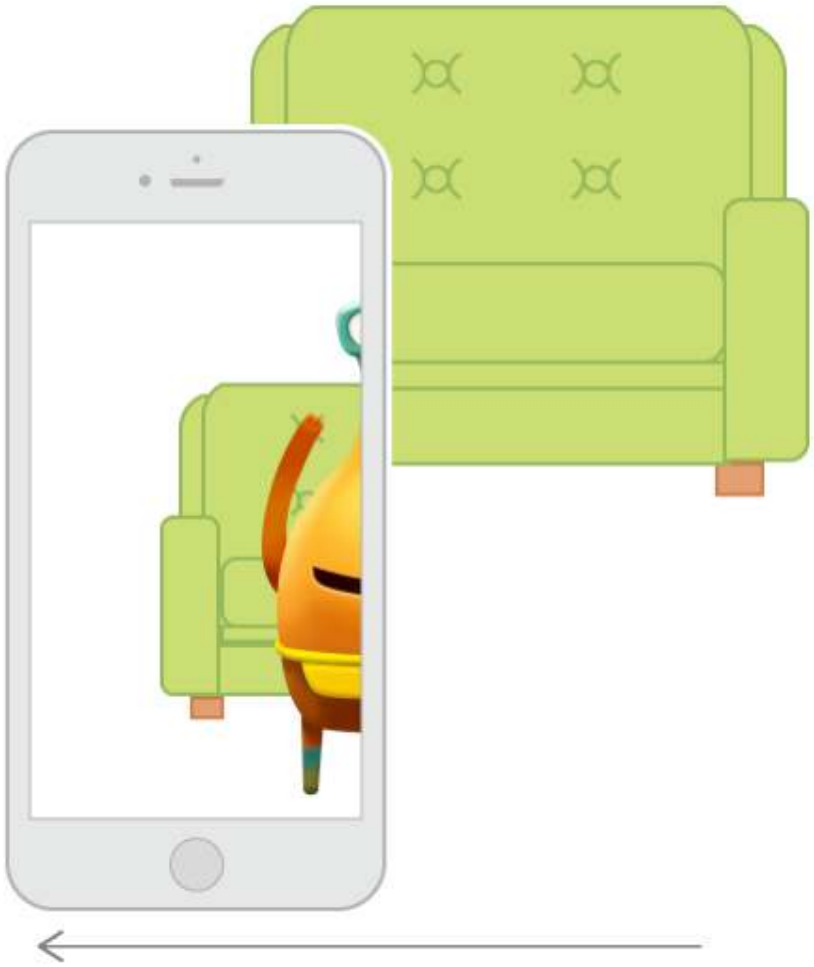
6 DOF



Device rotation



Device position



Tracking techniques ⭐

GPS
Marker
NFT
SLAM
3D

GPS

- global, satellite based, **no network connectivity required** ✅
- **no image processing** ✅
- **outdoors** only ❌
- **slow** ❌
- **not very accurate** ❌

Marker

- accurate, **fast** ✅
- **tangible**, printable ✅
- need to display a marker to enable AR ❌
- **non-aesthetic** ❌
- **can be hard to detect** (low lighting, motion blur, occlusions) ❌

Valve VR HMD early prototype

Natural Feature Tracking

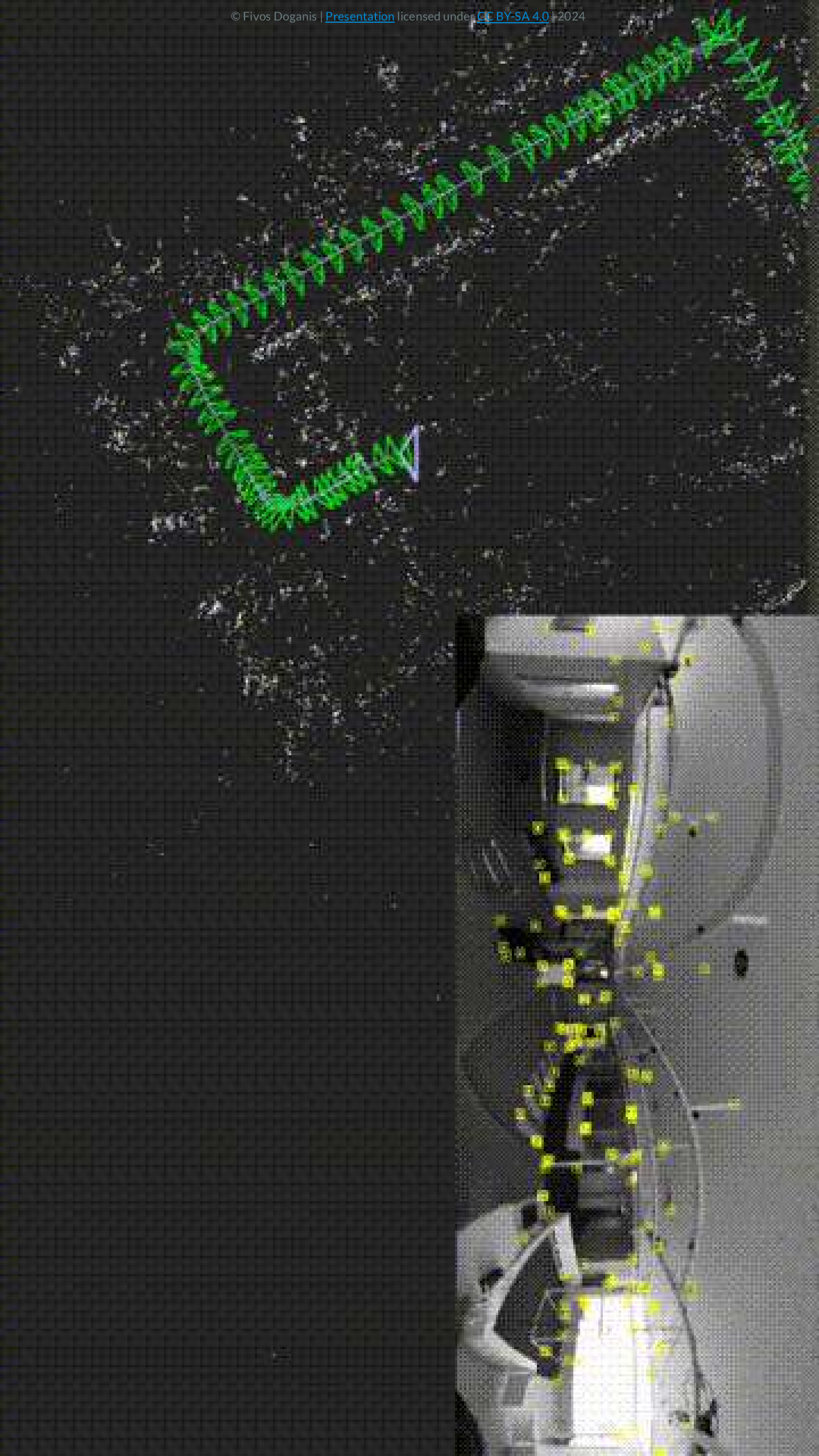
Same as marker but

- more **aesthetic**, easier to embed in the real world (ads) ✅
- **more robust to occlusions** ✅

SLAM ⭐

NFT evolution + reconstruction

- more **natural** markerless experience ✅
- partial **scene reconstruction** ✅
  - allows advanced functionalities (occlusions, collisions etc.)
- not very accurate ❌ (not ideal for medical uses)
  - **drift**, loop closure
  - scene reconstructed and refined in real-time
  - difficult to define the origin of the scene
    - stable **anchor** points required



3D object detection in a real scene

- using **computer vision** (lighting, edges, silhouette)
  - generic algorithm ✅
  - but **slow**, especially during initial registration ❌
- using **Deep Learning**
  - faster initial detection ✅
  - more robust regarding occlusions and lighting changes ✅
  - **not generic**: requires per model training ❌

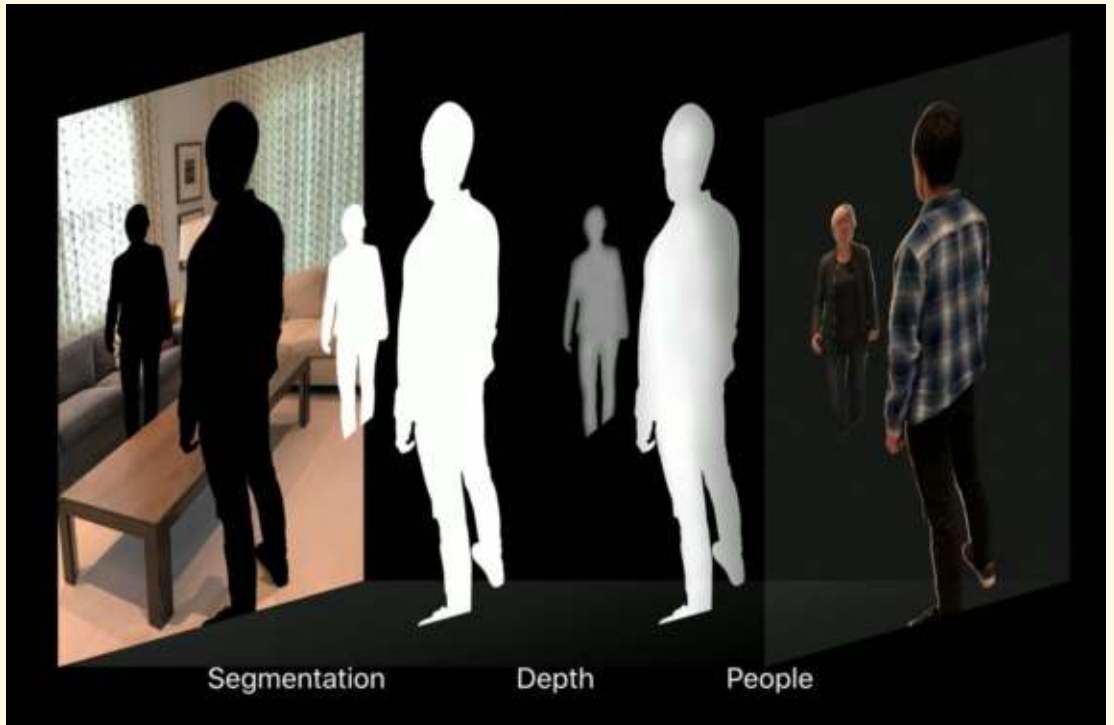
Tracking techniques : Conclusion

- No tracking technique is ideal
- Keep them all in mind and choose the right one according to:
  - the **scenario** of the AR experience
    - industrial context, consumer, generic or specific
  - **constraints**
    - indoor, outdoor, mobile

Rendering

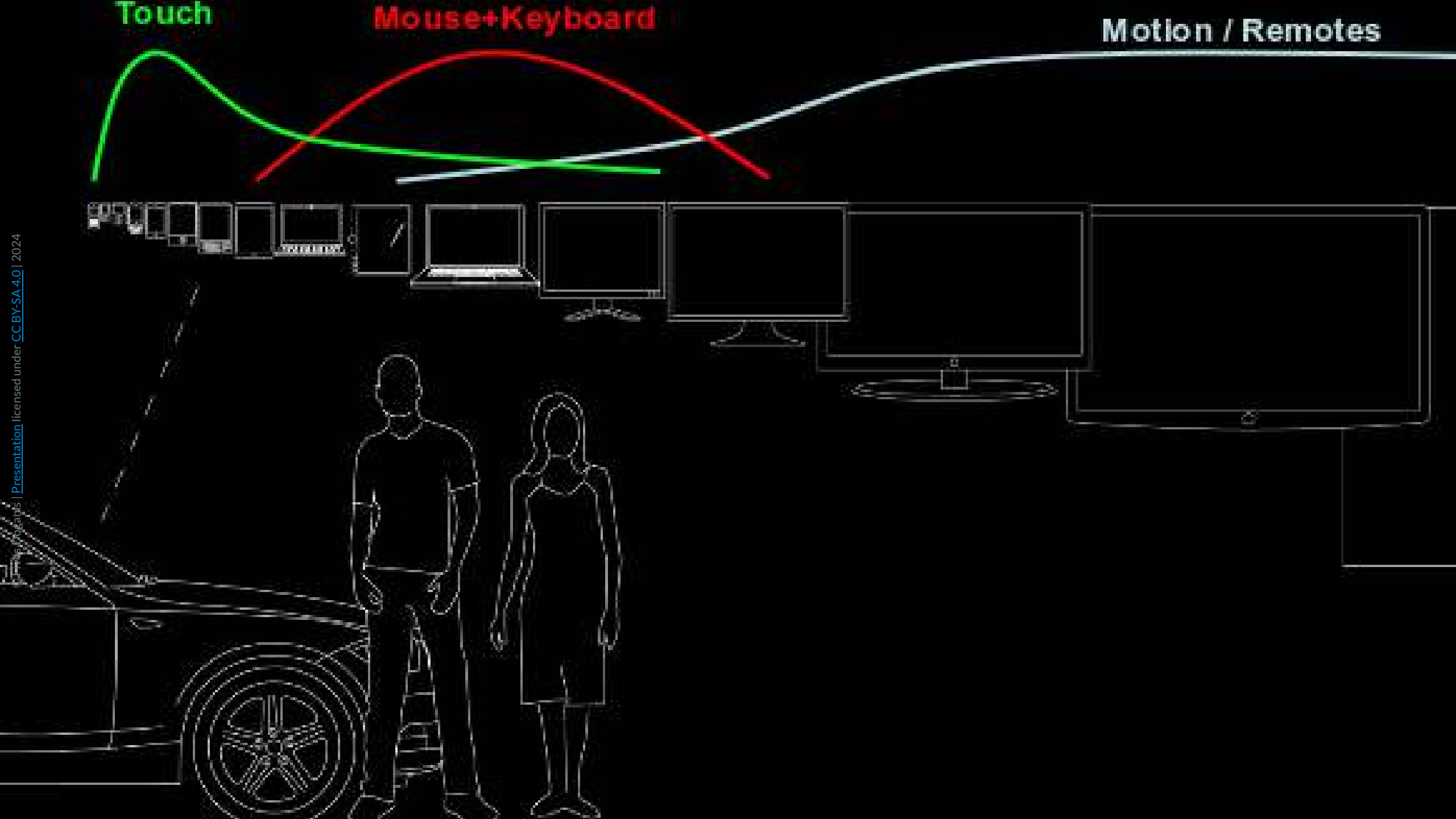
Rendering

- Realistic or not
- Lighting
  - detect the direction and intensity of real lights
  - fast environment reconstruction to simulate reflections (SLAM + AI)
- Occlusions
  - people, objects



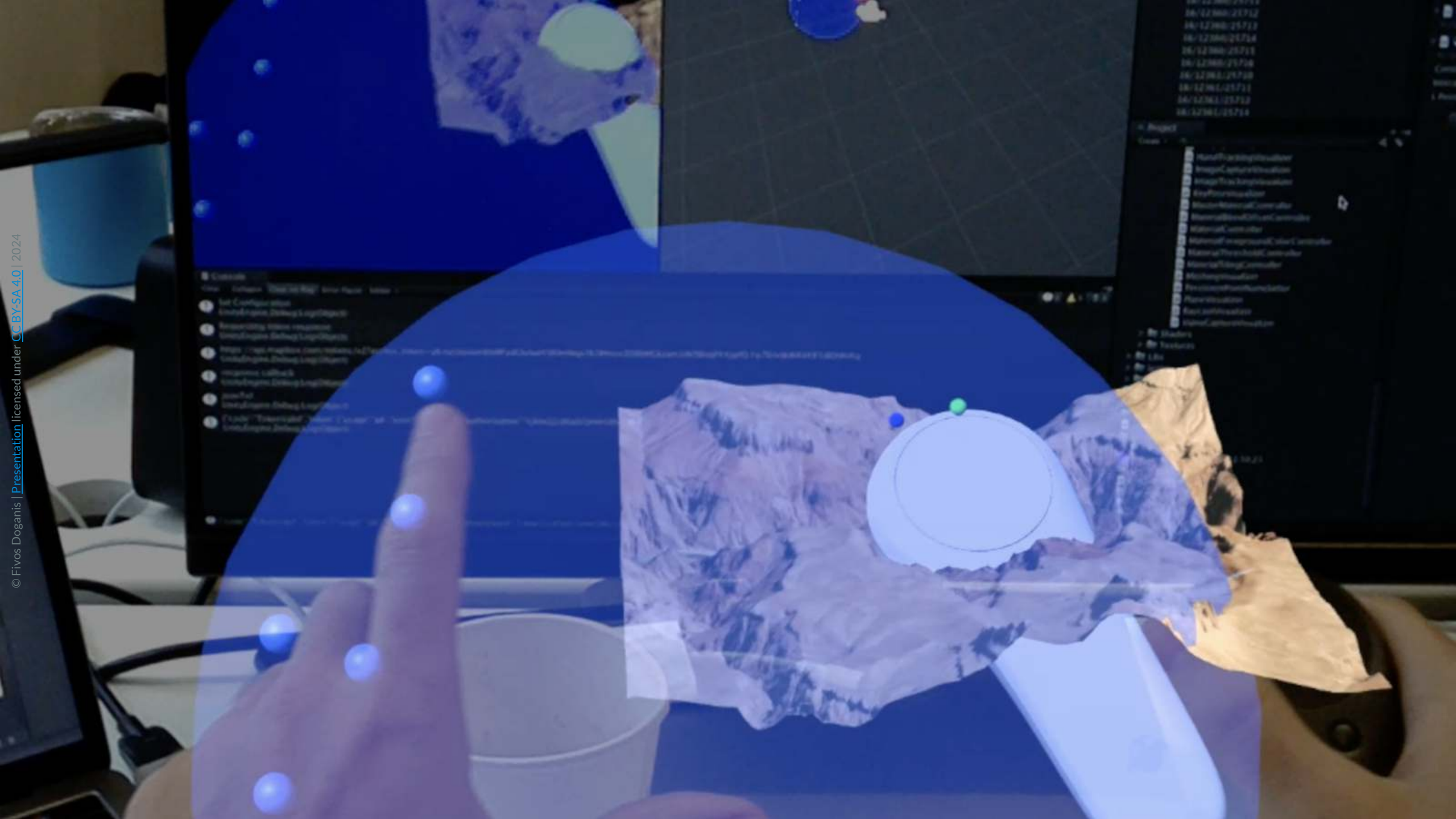
Interactions

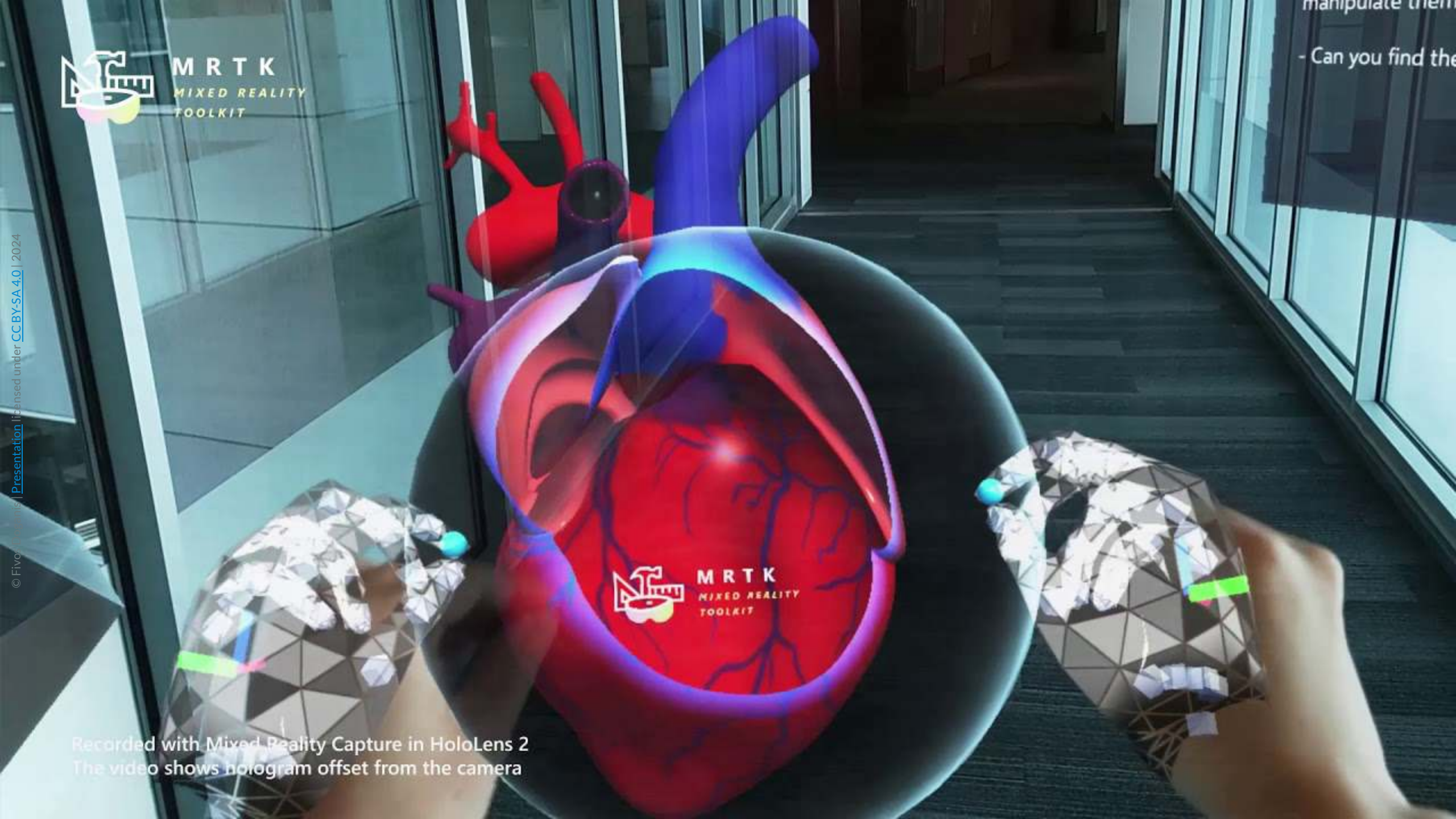
- The missing part of the equation
- Often neglected (cf. NReal)
- Myth of the dying mouse (p. 17)
  - each form factor has an optimal interaction technique
  - most headsets handle hand tracking, but also offer controller, keyboard and mouse support!
- **The XR equivalent of the mouse has not been invented yet!**

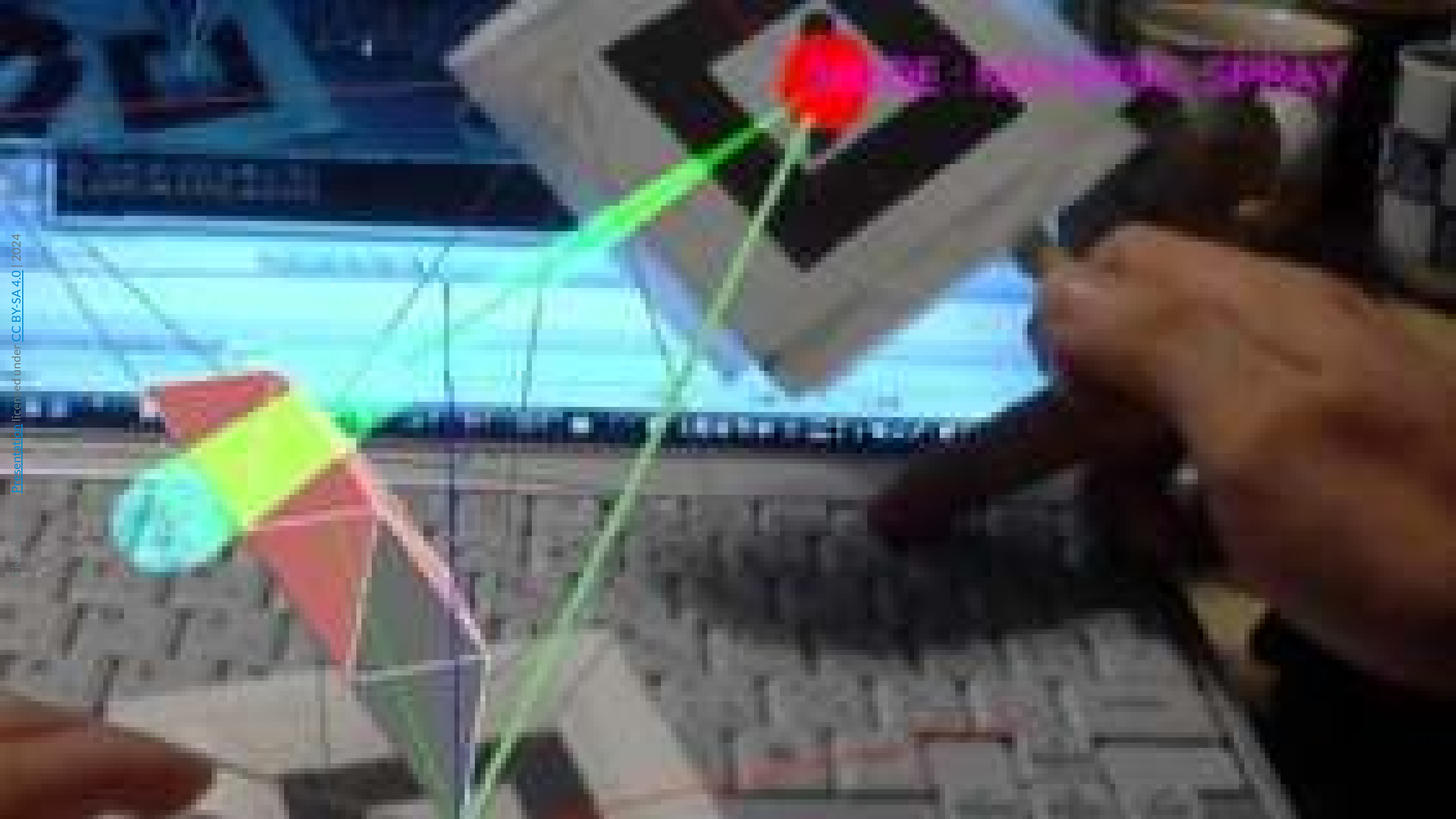


Interaction techniques

- **Screen**, when using a smartphone 📱
  - not very immersive but accurate, and provides tactile feedback
- **Controllers with buttons** 🎮
  - great haptic feedback but not immersive
- HoloLens **GGV** : **G**aze, **G**esture, **V**oice 👀 ✋ 👄
  - natural interactions, with no external hardware
  - great but tiring, lacks privacy ("hey Cortana!"), and accuracy
- **Tangible interactions** ✏️ 🔲
  - markers or accessories to add some tactile feedback ⬇️







Interactions

Conclusion

- Immersive AR interactions **have yet to be invented**!
- No interaction paradigm has become a standard yet
- We must **guide the users** and try to **understand their intent**

End

of part 1!

Questions?

Extra :)

Reconstruction 3D

- Colmap
- AliceVision
- Capturing Reality
  - RealityScan for iOS (link)
- MicMac
- **Scaniverse** ★

Links

http://www.ign.fr/institut/innovation/minecraft-a-carte

http://lsc.univ-evry.fr/~didier/home/lib/exe/fetch.php?media=cours:ra:ra.pdf

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