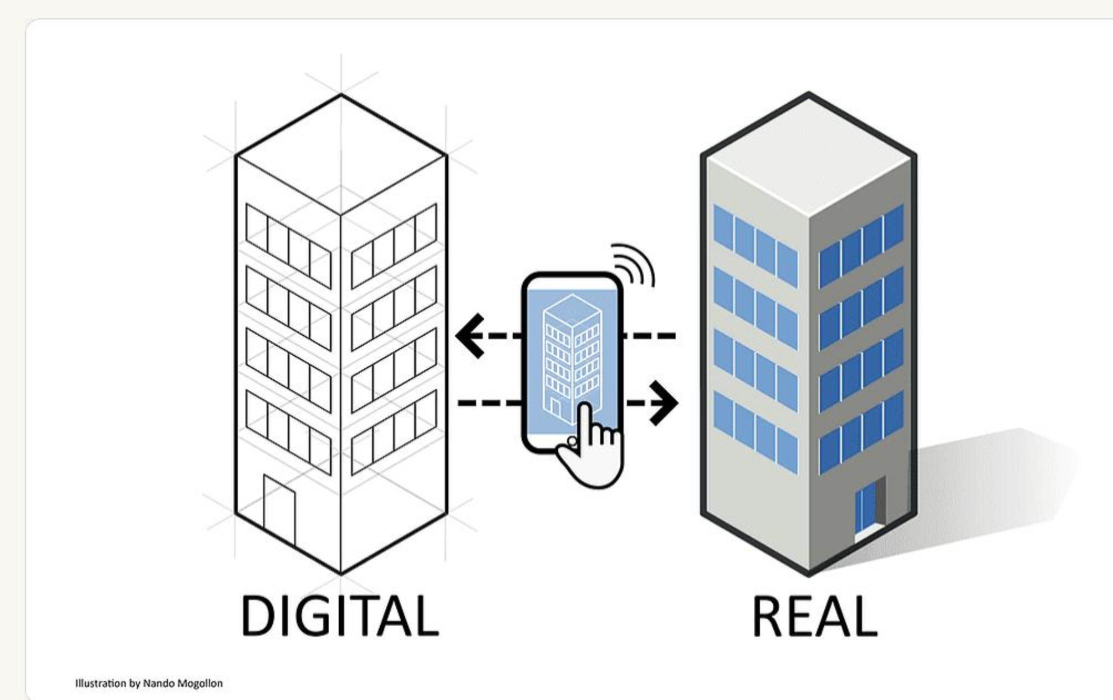
Digital Twins

Definition, VR relationship, and computer science use cases



Virtual Reality Lab 2025/2026
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Adapted and retargeted from the provided Digital Twin lecture deck.

Definition

What is a digital twin?

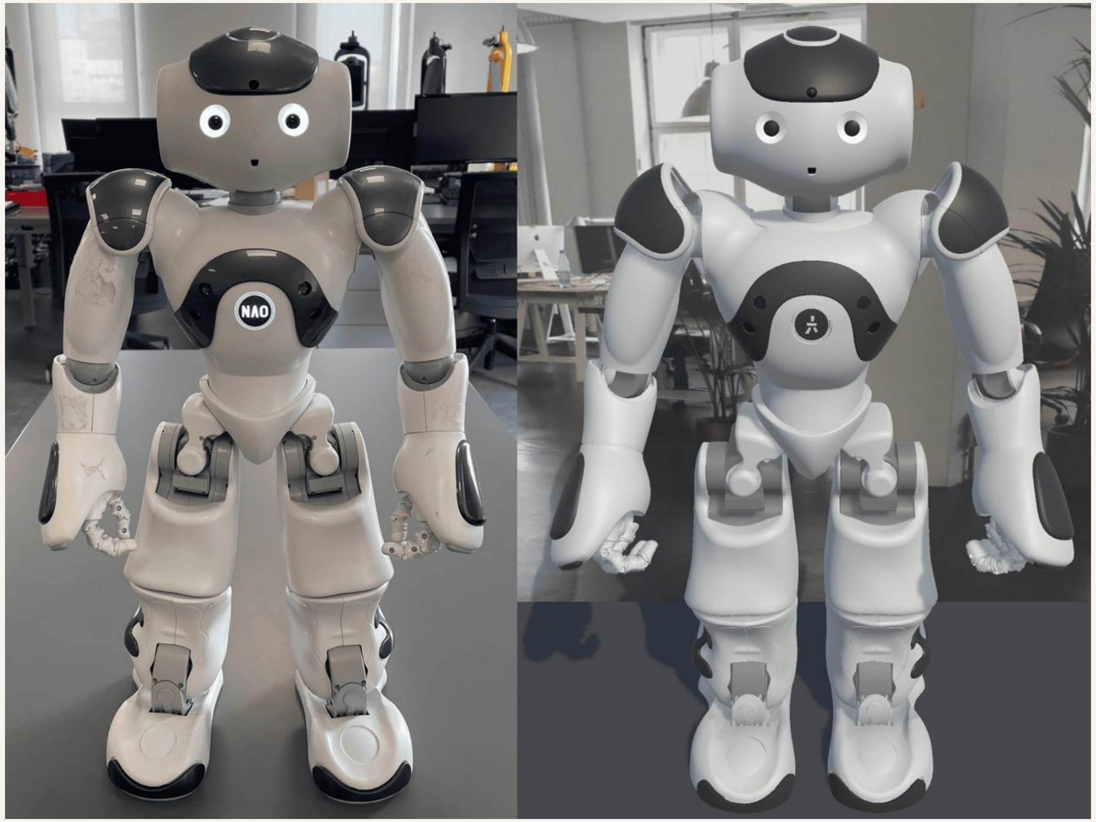
A dynamic digital representation of something in the real world.

A digital twin represents a real object, environment, process, or system across its lifecycle.

- It combines models, data, simulation, and “what-if” scenarios.
- It supports monitoring, prediction, testing, and decisions before acting on the real system.
- It is not only a 3D model: it is a data-informed replica.

Key idea

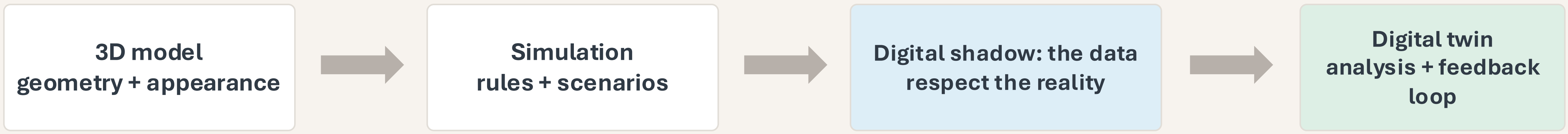
The value is not the visual copy alone, but the correspondence between the physical and virtual system.



Source material: provided lecture deck, slides 2 and 8.

Concept

Digital twin is more than a 3D model



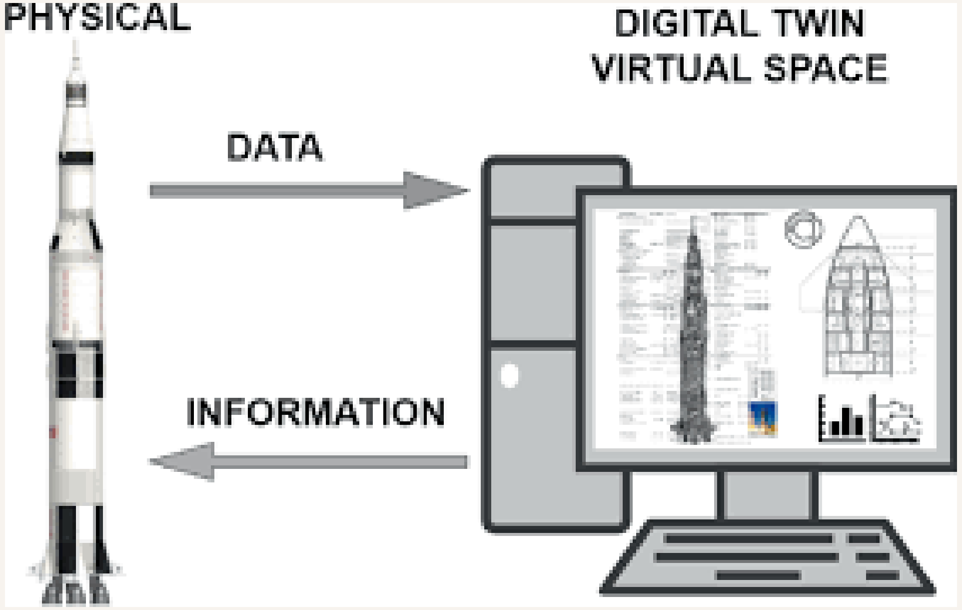
- A static model can be visually accurate, but it does not evolve by itself.
- A simulation can explore alternatives, but may be detached from live data.
- A digital twin connects representation, data, simulation, and decision-making.

Reference case

Reference use case: NASA

Digital twins are used when testing directly on the physical system is expensive, risky, or impossible.

- Monitoring: understand the current state of a complex system.
- Prediction: estimate future behavior and possible failures.
- Predictive maintenance: plan interventions before breakdowns.
- Anomaly testing: try unsafe or rare scenarios in the virtual counterpart.
- Safer decisions: use the twin as a decision-support environment.



The same idea appears in aerospace, manufacturing, medicine, cultural heritage, robotics, and smart infrastructures.

- NASA “Digital Twins and Living Models at NASA” https://ntrs.nasa.gov/citations/20210023699
- NASA “Why does the world (and NASA) need digital twins?” https://science.nasa.gov/biological-physical/why-does-the-world-and-nasa-need-digital-twins/
- Leonardo “DIGITAL TWIN. TUTTO CIÒ CHE È DIGITALE È REALE” https://space.leonardo.com/it/focus-detail/-/detail/digital-twin-cavazzoni

NASA “Digital Twins and Living Models at NASA” https://ntrs.nasa.gov/citations/20210023699

Why VR is important for digital twins

Virtual Reality turns the twin into a space that students, engineers, or visitors can explore.

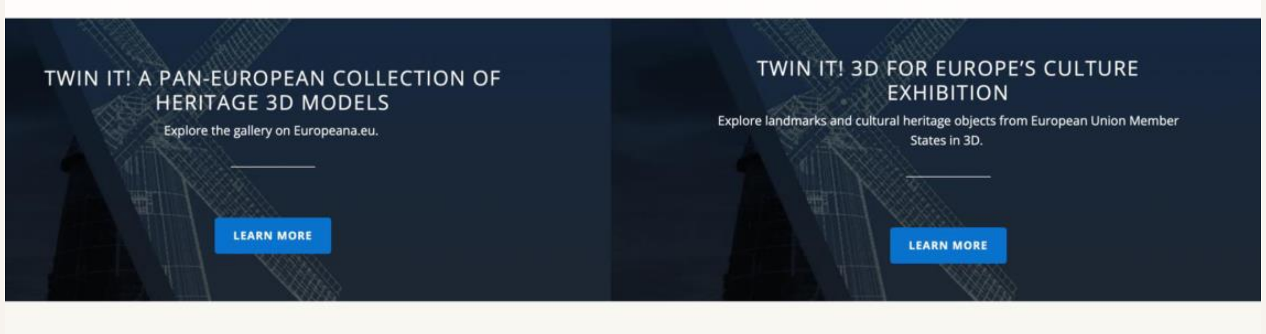
- Immersion: the user can perceive scale and spatial relationships.
- Training: repeat procedures without damaging the real system.
- Design review: inspect alternatives before construction or deployment.
- Scenario comparison: switch between normal, risky, or future states.
- Remote access: visit a twin even when the real site is not reachable.

Image/source in provided deck: UNESCO Dive into Heritage https://diveintoheritage.unesco.org/?lang=en

Cultural heritage and museums

These examples remain useful because they show how digital twins can support preservation, access, and storytelling.

- 3D documentation of fragile sites, buildings, and objects.
- Preventive conservation and simulation of risk scenarios.
- Remote and inclusive access to collections and exhibitions.
- Immersive storytelling and visitable reconstructions.
- Twin it!: a pan-European initiative for 3D digitisation of cultural heritage artefacts, monuments and sites.



Europeana "Twin it!" https://pro.europeana.eu/page/twin-it-3d-for-europe-s-culture

Computer science use cases

Smart campus / IoT

rooms, sensors, energy, occupancy

Robotics

test control logic before moving a physical robot

Networks / cyber ranges

test attacks and defenses safely

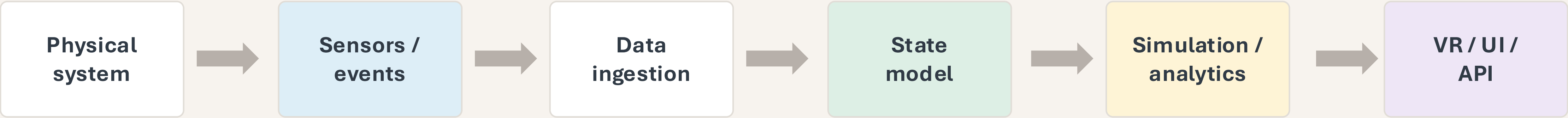
Software systems

mirror runtime behavior for debugging and monitoring

Serious Games and VR training

rehearse procedures in realistic worlds

A typical digital twin architecture



The twin can (1) **inform human decisions** or (2) **trigger actions on the real system**.

- Implementation choices: Unity/Unreal/WebXR for visualization; databases and streams for live data; ML or physics models for prediction.
- **The architecture should preserve synchronization**: time, identity, coordinate systems, and units must match.

A digital twin is a combination of representations data and real time interaction

Data

- What data is measured?
- How often is it updated?
- How reliable is it?
- Who can access it?

Model

- Geometry and coordinate system
- Behavioral rules
- Assumptions and limits of the real item

Interaction

- VR inspection and navigation
- What-if controls
- Collaborative views
- Logs and explanations

Case study

Case study: NAO physical robot and digital twin

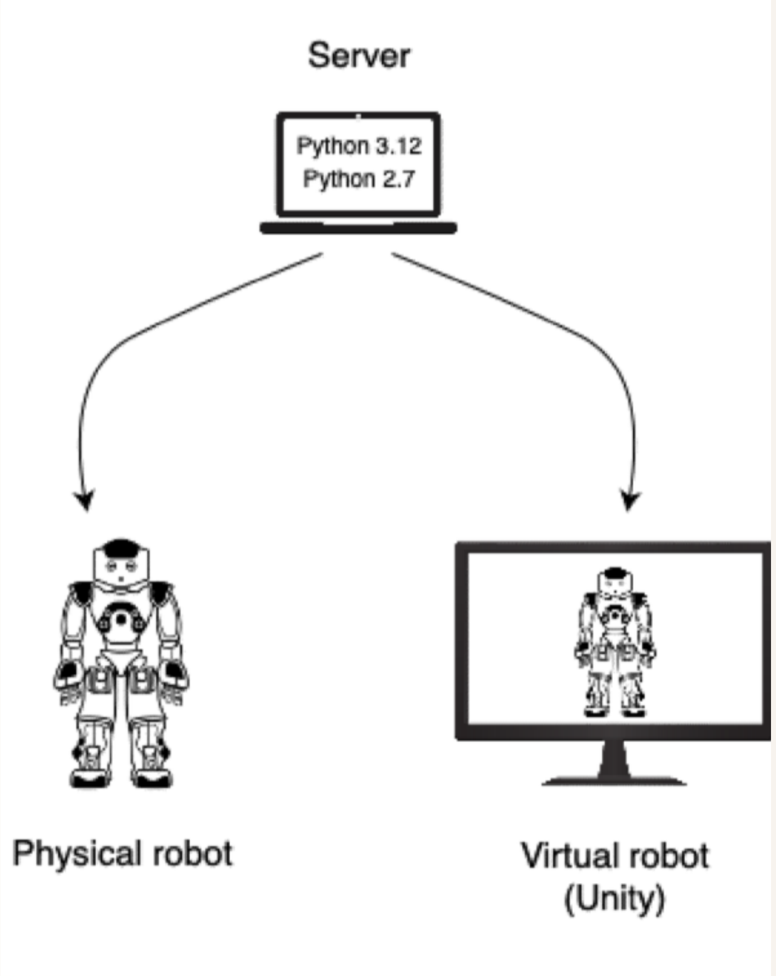
Research question: does the physical body of the robot influence how users read its emotions?

- Comparison between the physical NAO and a high-fidelity virtual twin.
- Same commands and same movements: only embodiment changes.
- The virtual twin keeps correspondence with the joints of the real robot.
- Secondary goal: use the twin for empathic dialogue guided by an LLM.

How the NAO twin was built

A twin can be visual, but for robotics it also needs behavioral correspondence.

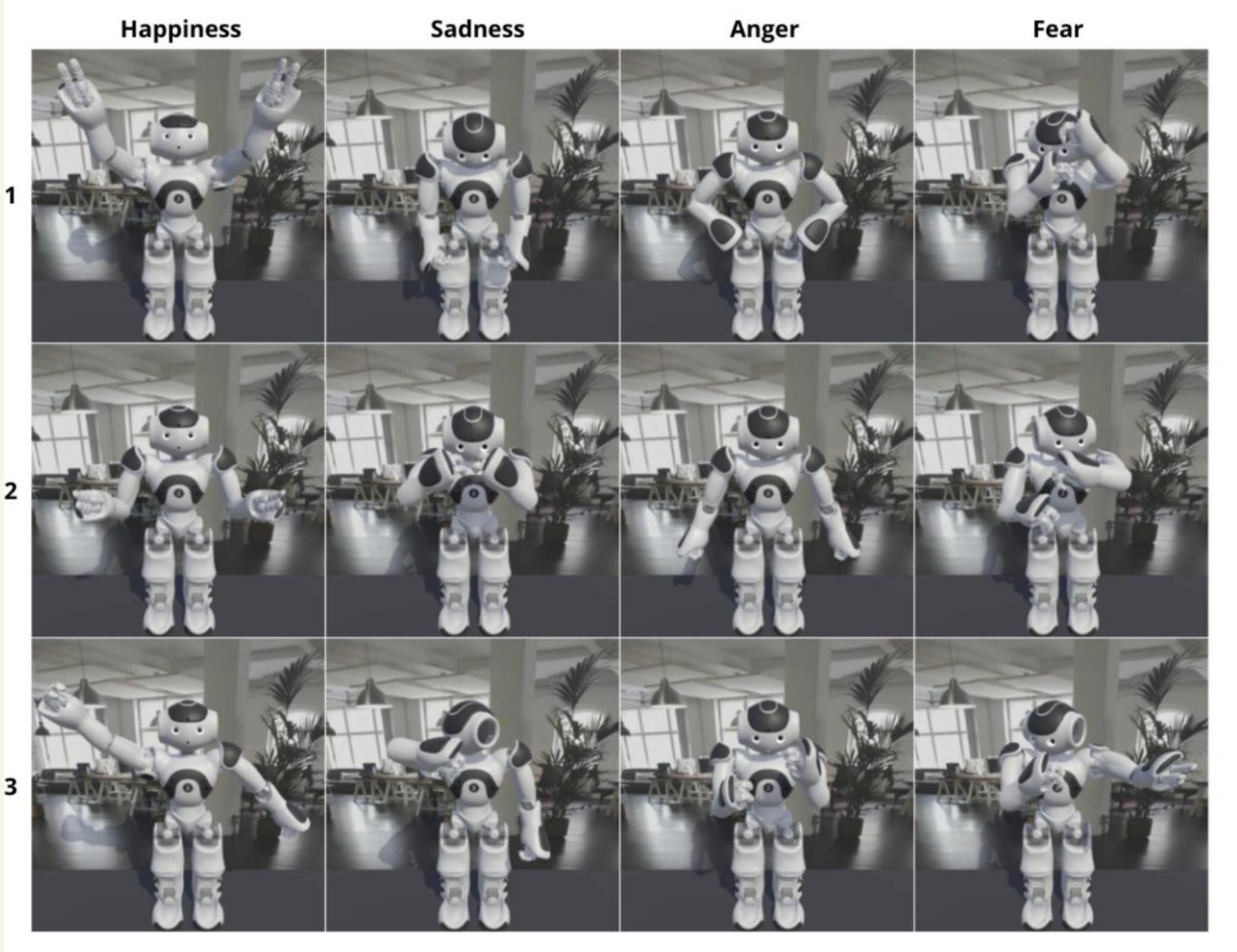
- 3D replica of the robot with 25 degrees of freedom and visual/environmental parity.
- The same animations work on both the real robot and the virtual robot.
- Timing, trajectories, and poses remain equivalent between physical and virtual execution.



Emotions and multimodal interaction

- Four basic emotions: happiness, sadness, anger, and fear.
- Twelve gestures: three variants per emotion.
- User recognition was similar for physical and virtual conditions.
- An LLM can add emotion tags such as [happy] or [sad] to select voice and gesture.

The same emotional gestures can be tested on a physical robot and on its virtual twin.




NAO