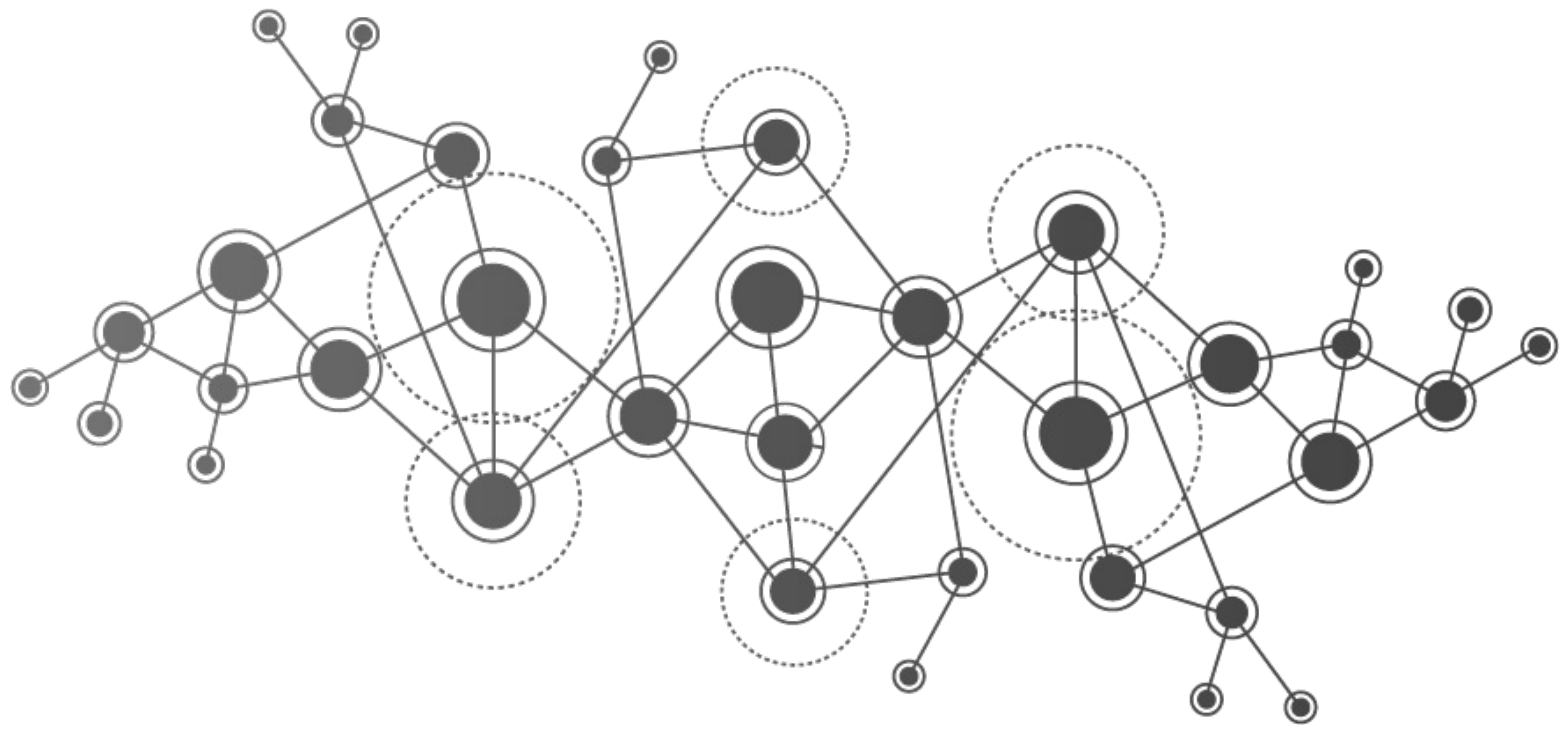


Intelligent Internet of Things

Digital Twins

Cyber-Physical Systems & IoT

Prof. Marco Picone

A.A 2023/2024

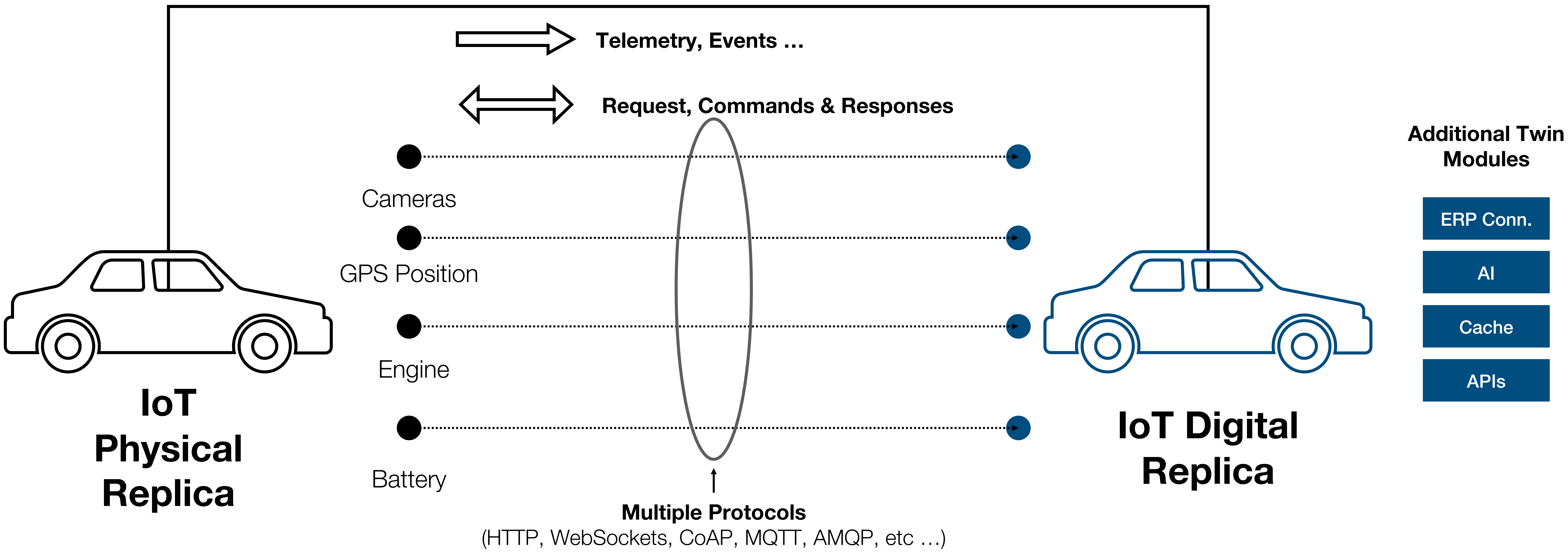
IoT & Digital Twin

Main Source & Reference:

Minerva, R, Lee, GM and Crespi, N
"Digital Twin in the IoT context: a survey on technical features, scenarios and architectural models"

- Virtual Object & Digital Twin
- Digital Twin Introduction & Attributes
- Application & Vision
- IoT Characterizing Properties
- Digital Twins Values
- Technological Challenges

Digital Twin & Virtual Object



- The concept of a digital twin has been around since 2002. The concept of the Digital Twin dates back to a University of Michigan presentation to industry in 2002 for the formation of a Product Lifecycle Management (PLM) center.
- It's only thanks to the Internet of Things (IoT) that it has become cost-effective to implement. And, it is so imperative to business today
- **A Digital Twin is a Virtual/Digital representation of a Physical Asset**

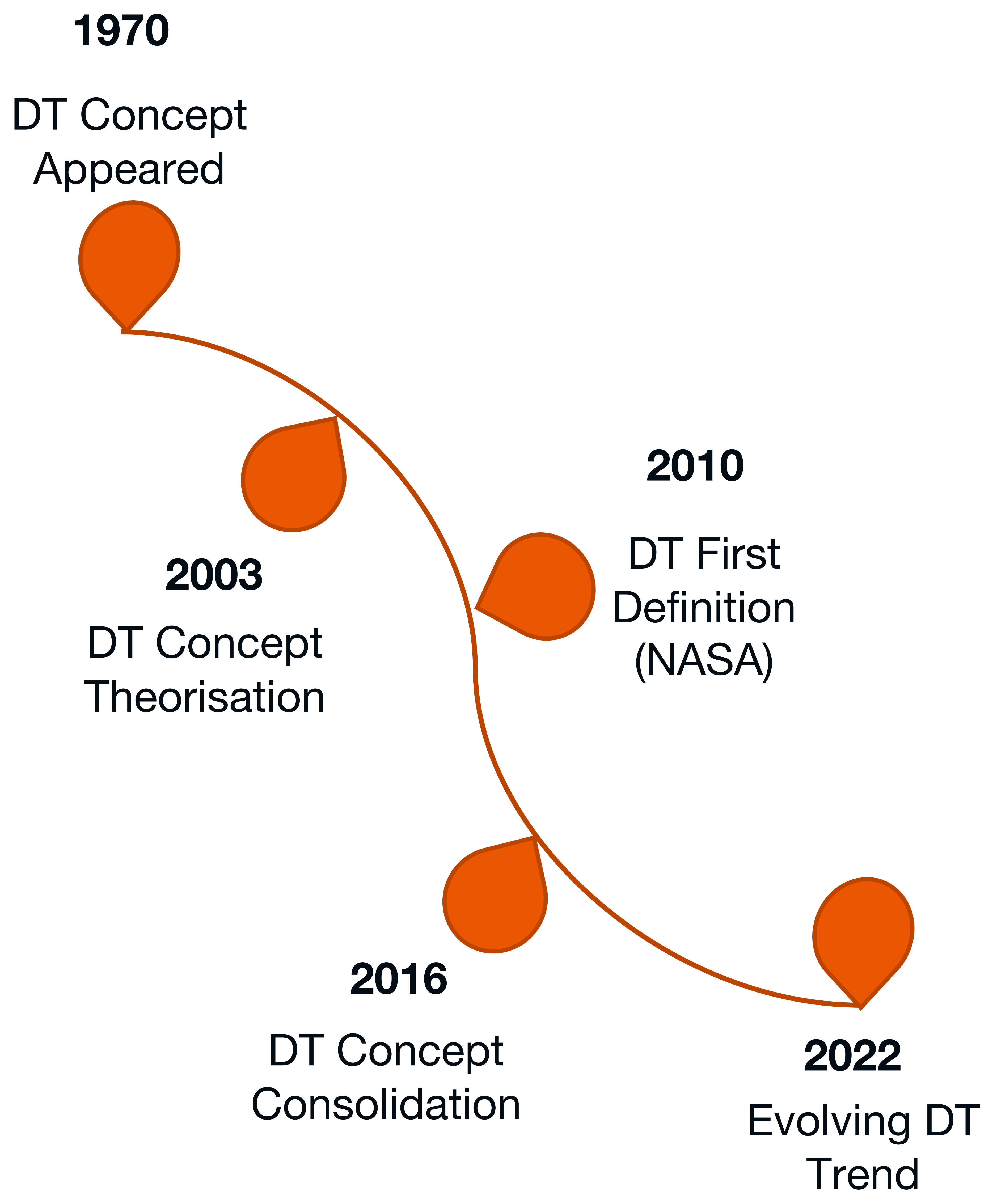
Digital Twin & Virtual Object

*"A **Digital Twin (DT)** is a **comprehensive software representation** of an individual **physical object**. It includes the **properties**, **conditions**, and **behaviour(s)** of the real-life object **through models and data**. A Digital Twin is **a set of realistic models** that can **simulate an object's behavior** in the **deployed environment**. The Digital Twin **represents** and **reflects** its physical twin and remains its virtual counterpart **across the object's entire lifecycle**"*

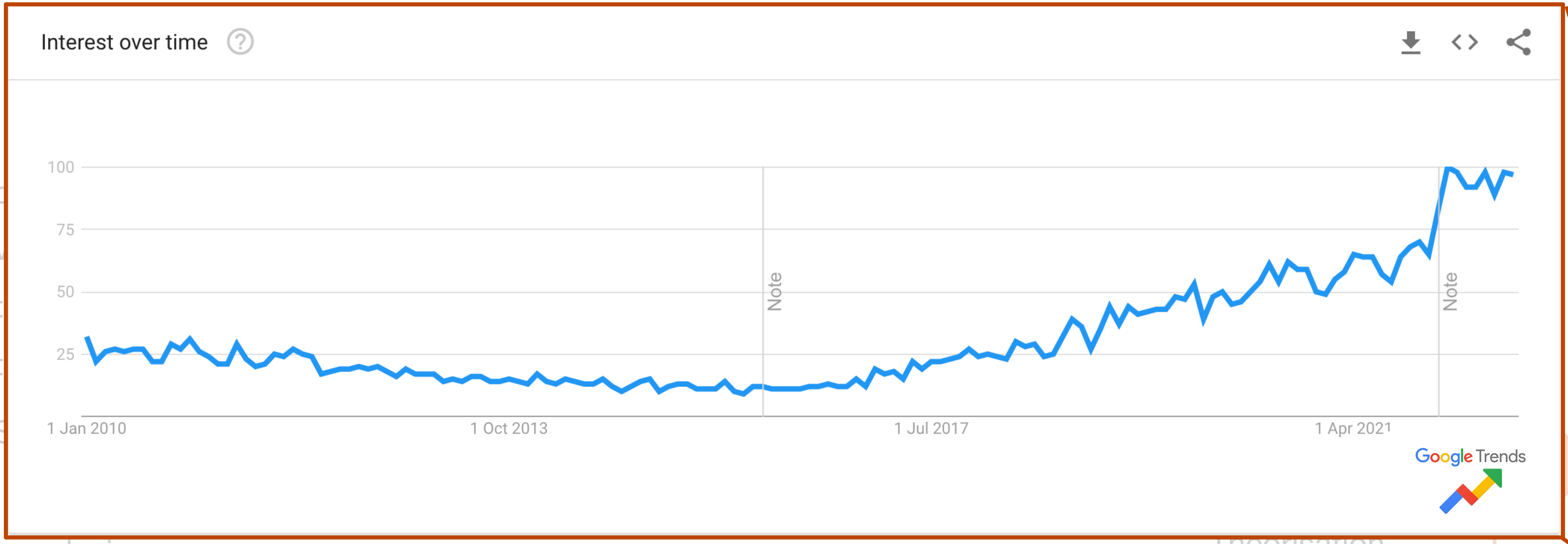
S. Haag, and R. Anderl. "Digital Twin–Proof of concept." Manufacturing Letters 15 (2018)

Digital Twins Evolution

- In the last decade, the Digital Twin paradigm has been explored in different domains as an approach to virtualise entities existing in the real world, creating **software counterparts** that provide smart services upon them
- Such services may include (but are not limited to):
  - Tracking of the actual state of the physical entity or device
  - Smarter forms of monitoring (e.g., detect and predict possible critical situations, optimise performances)
  - Augmentation of the capabilities of the physical counterpart
  - Simulate and design new or existing products



Digital Twins Evolution



device

- Smarter forms of monitoring (e.g., detect and predict possible critical situations, optimise performances)
- Augmentation of the capabilities of the physical counterpart
- Simulate and design new or existing products

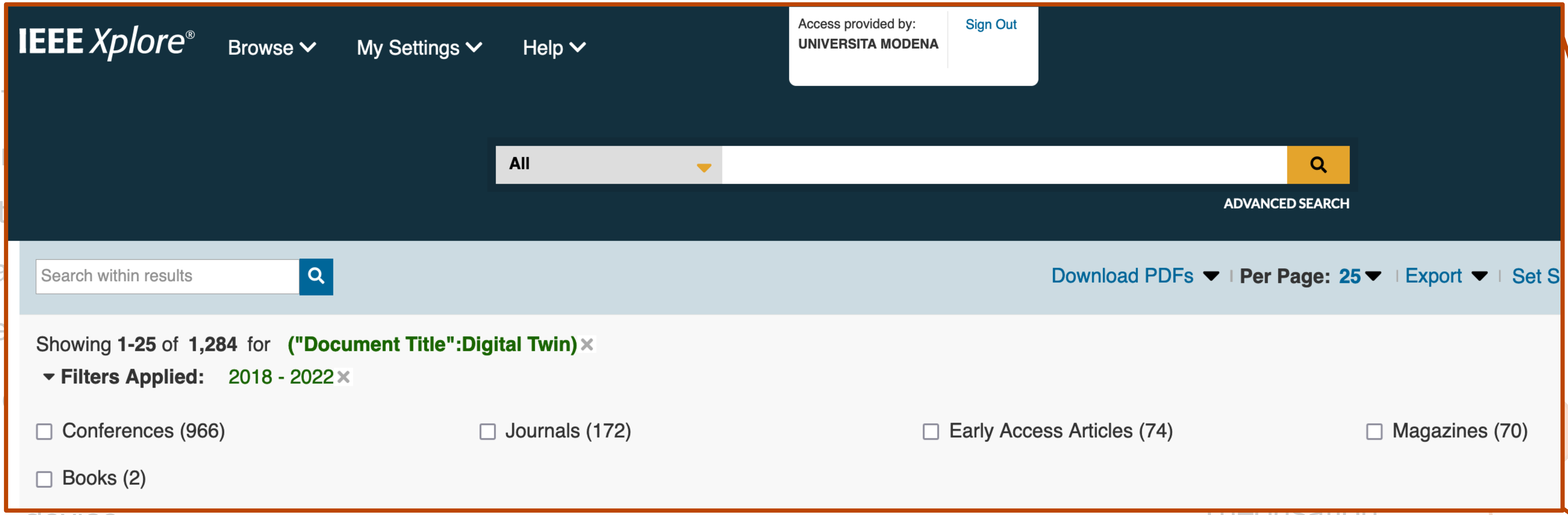
Theorisation

2010
DT First Definition (NASA)

2016
DT Concept Consolidation

2022
Evolving DT Trend

Digital Twins Evolution



- In ... do... virt... tha... the...
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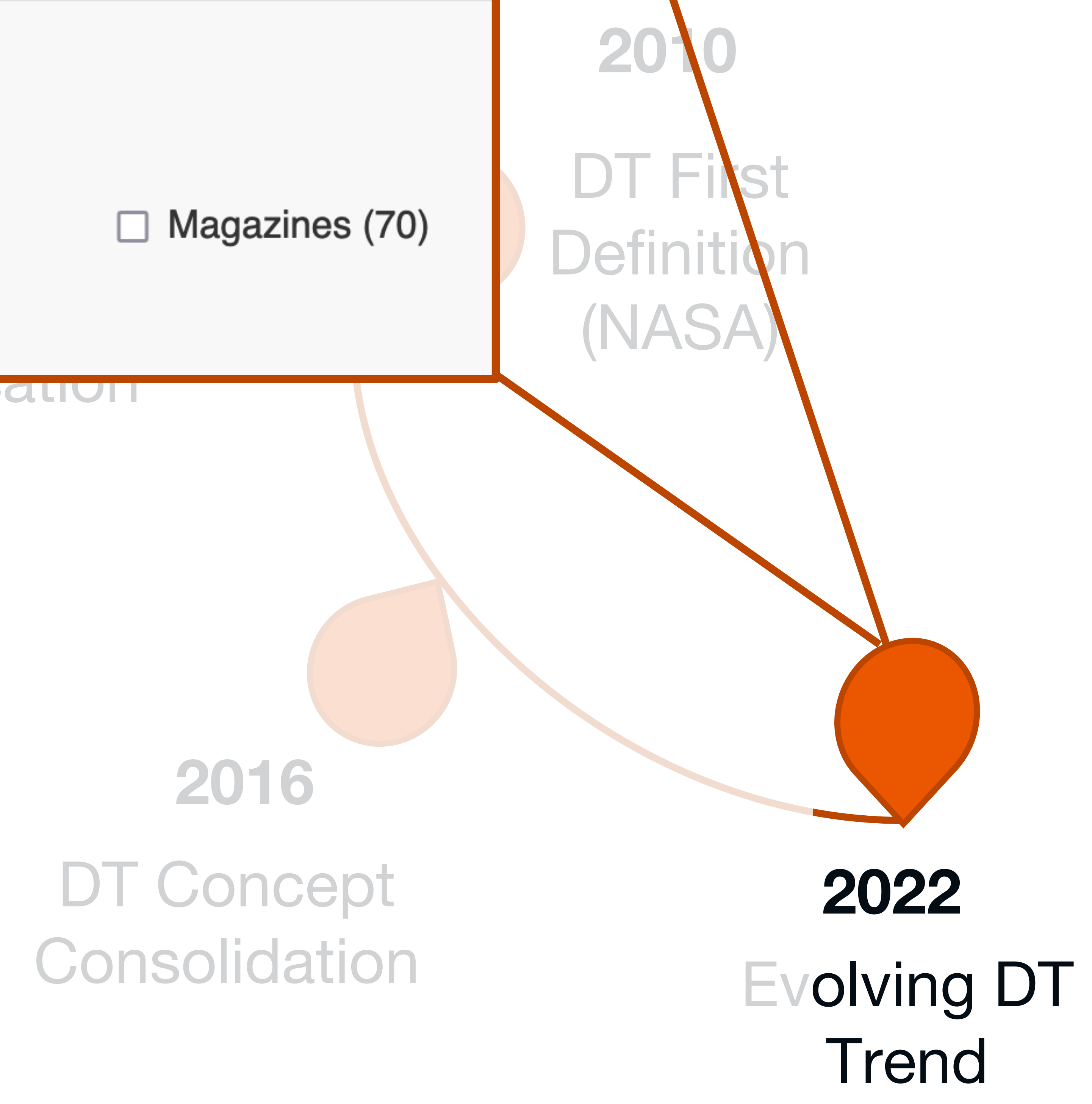

Digital Twins Evolution

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Internet Research Task Force                                     C. Zhou
Internet-Draft                                                   H. Yang
Intended status: Informational                                   X. Duan
Expires: 6 September 2022                                   China Mobile
                                                                D. Lopez
                                                               A. Pastor
                                                          Telefonica I+D
                                                                   Q. Wu
                                                                  Huawei
                                                            M. Boucadair
                                                            C. Jacquenet
                                                                  Orange
                                                            5 March 2022

       Digital Twin Network: Concepts and Reference Architecture
              draft-zhou-nmrg-digitaltwin-network-concepts-07

Abstract

   Digital Twin technology has been seen as a rapid adoption technology
   in Industry 4.0.  The application of Digital Twin technology in the
   networking field is meant to develop various rich network
   applications and realize efficient and cost effective data driven
   network management and accelerate network innovation.

   This document presents an overview of the concepts of Digital Twin
   Network, provides the basic definitions and a reference architecture,
   lists a set of application scenarios, and discusses the benefits and
   key challenges of such technology.

Status of This Memo

   This Internet-Draft is submitted in full conformance with the
   provisions of BCP 78 and BCP 79.

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   Task Force (IETF).  Note that other groups may also distribute
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   time.  It is inappropriate to use Internet-Drafts as reference
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   This Internet-Draft will expire on 6 September 2022.
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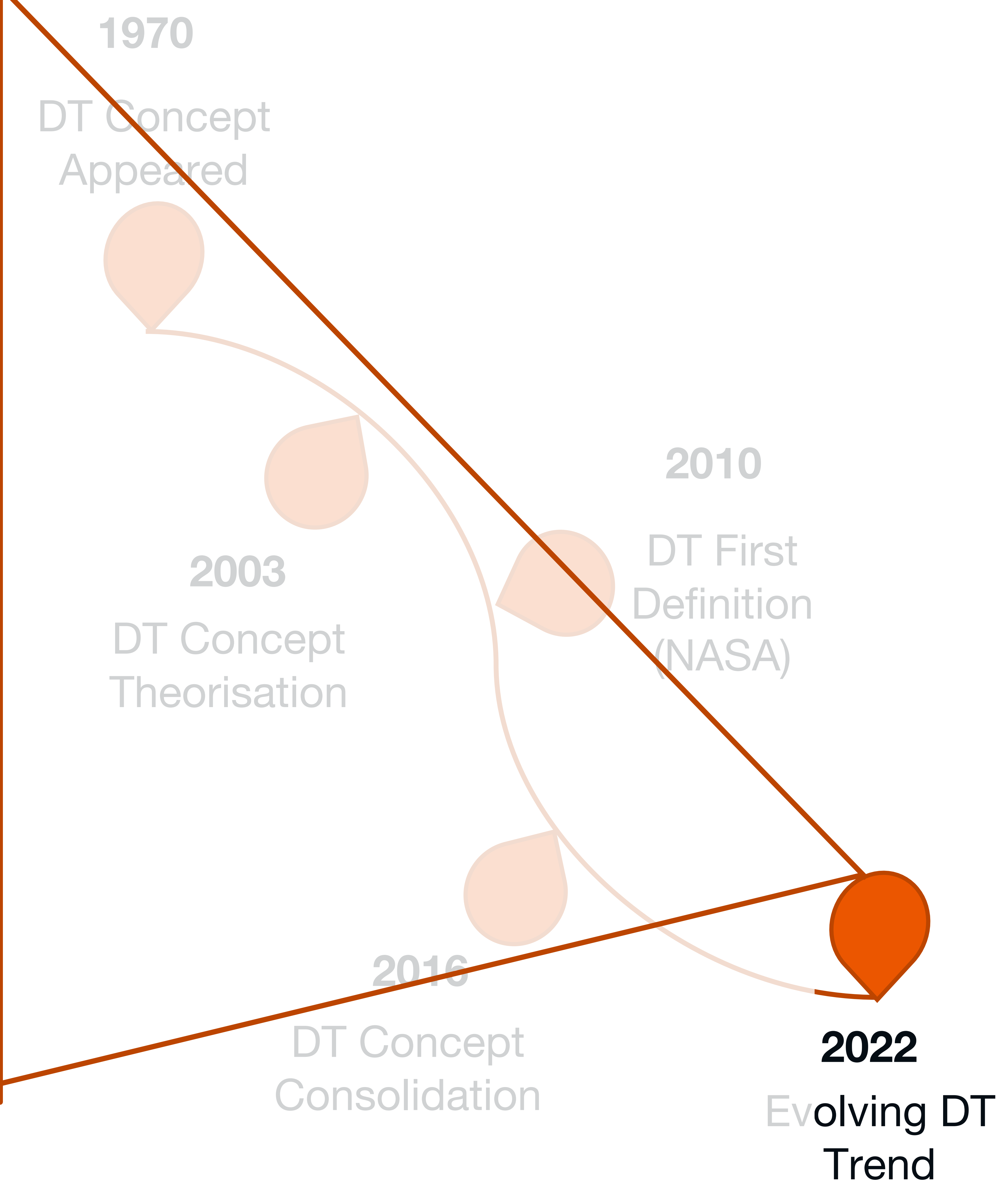
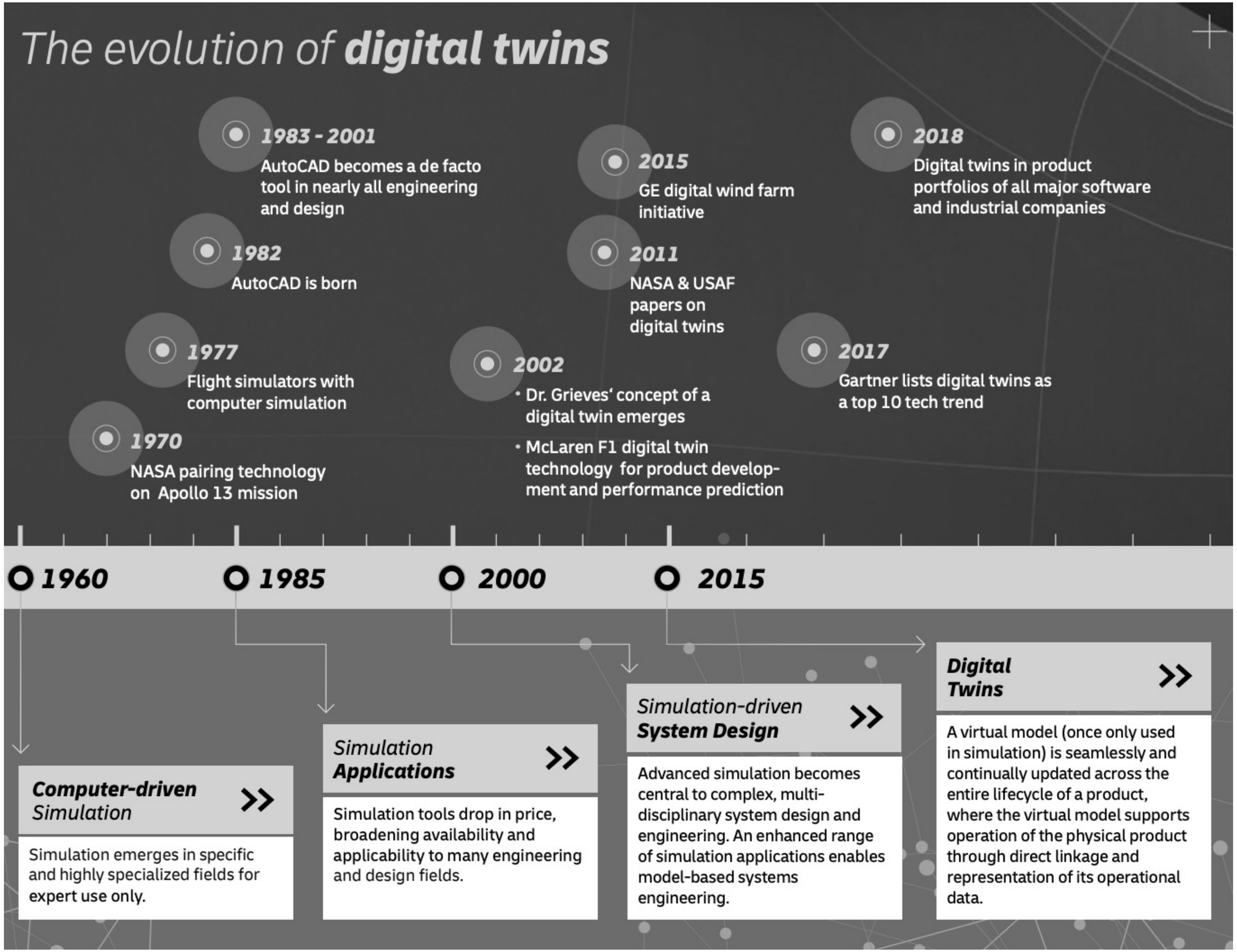
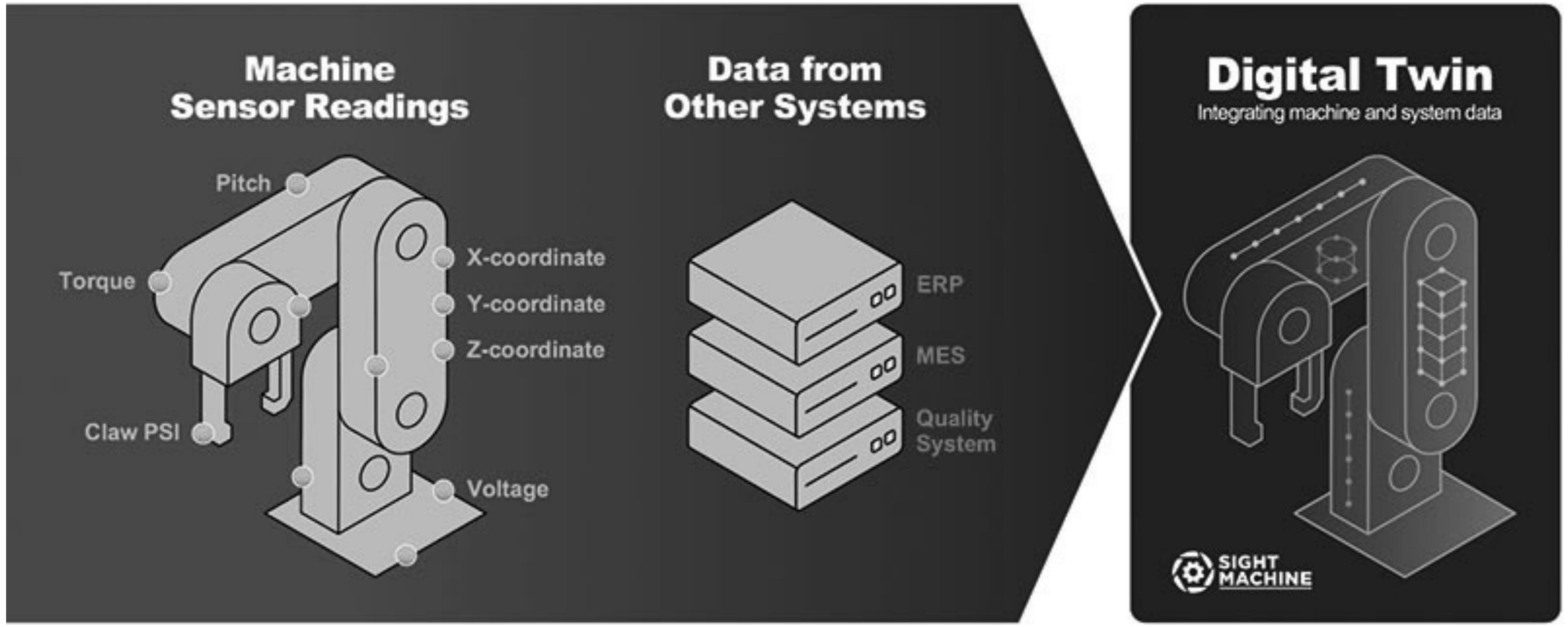


Digital Twins Evolution



Digital Twins in Logistics - https://www.logistics.dhl/content/dam/dhl/global/core/documents/pdf/glo-core-digital-twins-in-logistics.pdf

Digital Twin - Attributes



- A digital twin **simulates both the physical state and behaviour of the thing**
- A digital twin represent a unique physical asset and it is associated with a single, specific instance of the thing
- A digital twin is connected to the thing, updating itself in response to known changes to the thing's state, condition, or context
- Provides value through visualization, analysis, prediction, optimization and simplified/seamless interaction

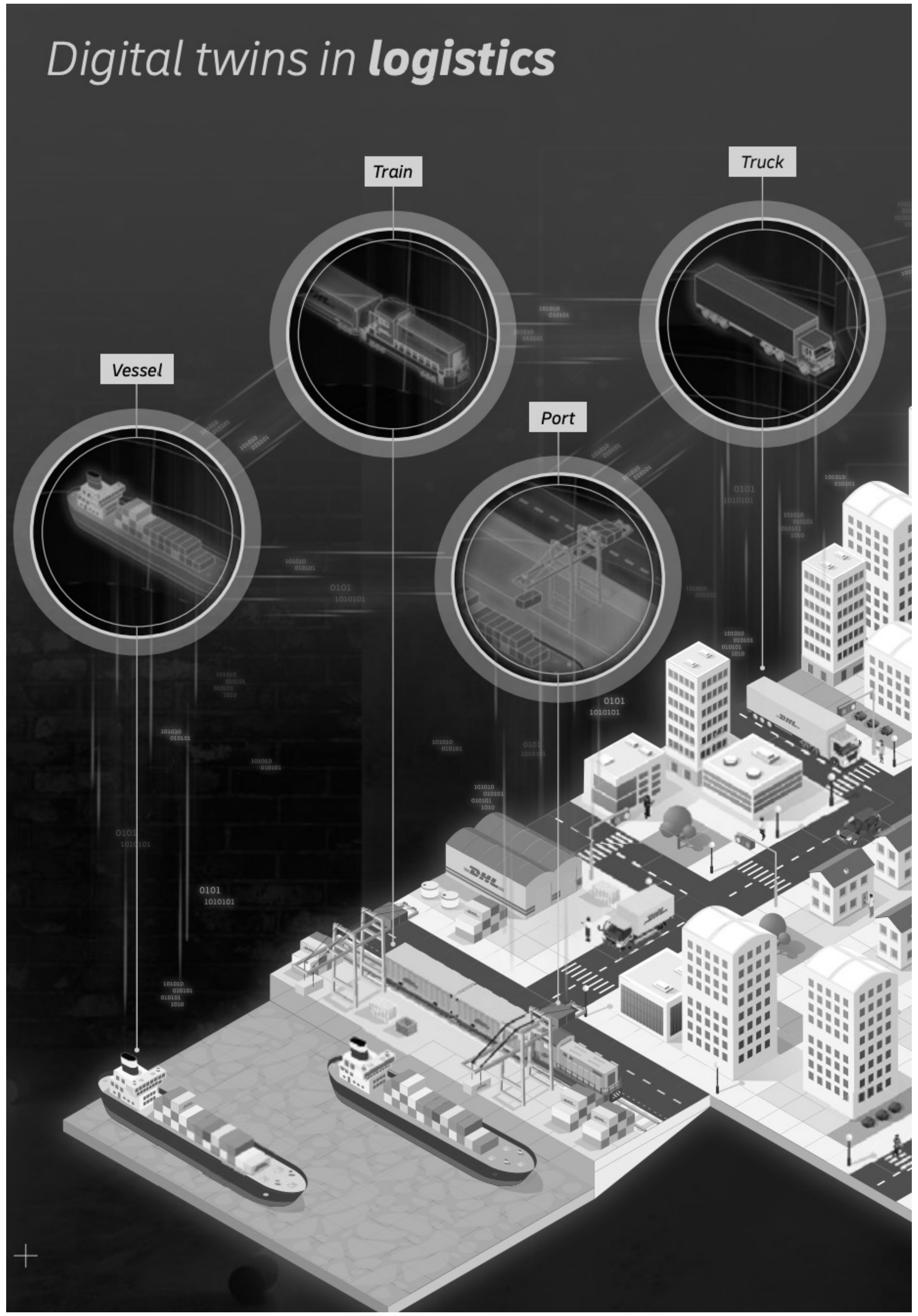
https://www.automationworld.com/products/software/article/13319468/digital-twin-makes-virtual-commissioning-a-reality

Digital Twin - Involved Technologies

- **API & Open Standards:** Provide the necessary tools to extract, share, and harmonize data from multiple systems that contribute to a single digital twin
- **Artificial Intelligence:** Leverages historical and real-time data paired with machine learning frameworks to make predictions about future scenarios or events that will occur within the context of the asset.
- **Augment, Mixed & Virtual Reality:** Renders the spatial model and visualization of the digital twin, providing the medium for collaboration and interaction with it
- **Cloud and Edge Computing:** The Cloud allows Allows storage and processing of large volumes of machine data from the asset and its digital twin. Furthermore through the Cloud it is possible to remotely accessing the twin and its data and services. The Edge approach is fundamental support real-time and low latency “local” interaction between people, device and the twin and also for security reasons.
- **Internet of Things**: High-precision sensors enable continuous collection of machine data, state, and condition from the physical asset to its digital twin in real time via heterogeneous wired/wireless networks.

Digital Twin - Application & Vision

- Digital Twin Technologies can be used to:
    - help machines to track their story across its lifecycle, using real-time data to enable understanding, learning and reasoning
    - create, test and build our equipment in a complete virtual environment
    - simplify the interaction between the object and external services and devices
    - increase security of the physical object proxing all the incoming communication through the digital clone
    - extend the physical object features and behaviour through the digital version



Digital Twin (Extended) Definition

*"A Digital Twin is a comprehensive software representation of an individual physical object. It includes the **properties, conditions, and behavior(s)** of the real-life object through models and data. A Digital Twin is a set of realistic models that can ~~**simulate**~~ bject's behavior in the deployed environment. The Digital Twin represents and reflects its physica and remains its virtual counterpart across the object's ent ecycle. [1]"*

S. Haag, and R. Anderl. "Digital Twin–Pr ncept." Manufacturing Letters 15 (2018)

*properties, conditions, **relationships** and behavior(s)*

DTs may also be responsible to model and characterize existing relationships in the physical world in order to map them also in the digital world.

Digital Twin (Extended) Definition

“A Digital Twin is a comprehensive software representation of an individual physical object. It includes the properties, conditions, and behavior(s) of the real-life object through models and data. A Digital Twin is a set of realistic models that can ***~~simulate~~*** *an object’s behavior in the deployed environment. The Digital Twin represents and reflects its physica … and remains its virtual counterpart across the object’s en… ecycle. [1]”*

S. Haag, and R. Anderl. "Digital Twin–Pr… ncept." Manufacturing Letters 15 (2018)

A Digital Twin is a set of realistic models that can ***digitalize*** *an object’s behavior in the deployed environment.*

The recent shared idea is that DTs can be used not only for simulation purposes but to support and enable any digital services or application

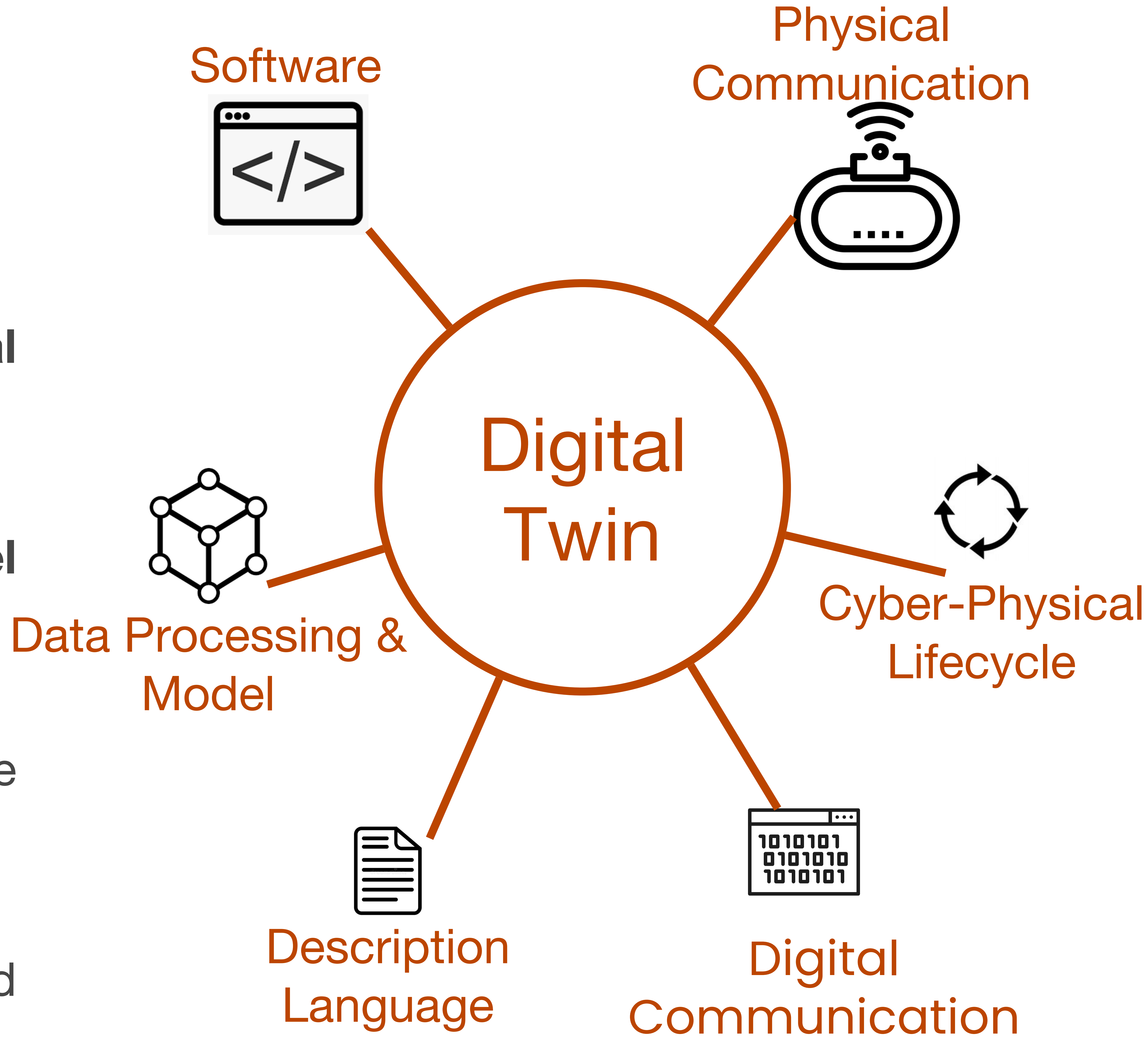
Digital Twin's Pillars

*A Digital Twin is a comprehensive **software representation** of an individual **physical object**. It includes the **properties, conditions, relationships and behavior(s)** of the real-life object through **models and data**. A Digital Twin is a set of realistic models that can **digitalize** an object's behavior in the deployed environment. The Digital Twin represents and reflects its physical twin and remains its virtual counterpart across the object's entire **lifecycle**.*

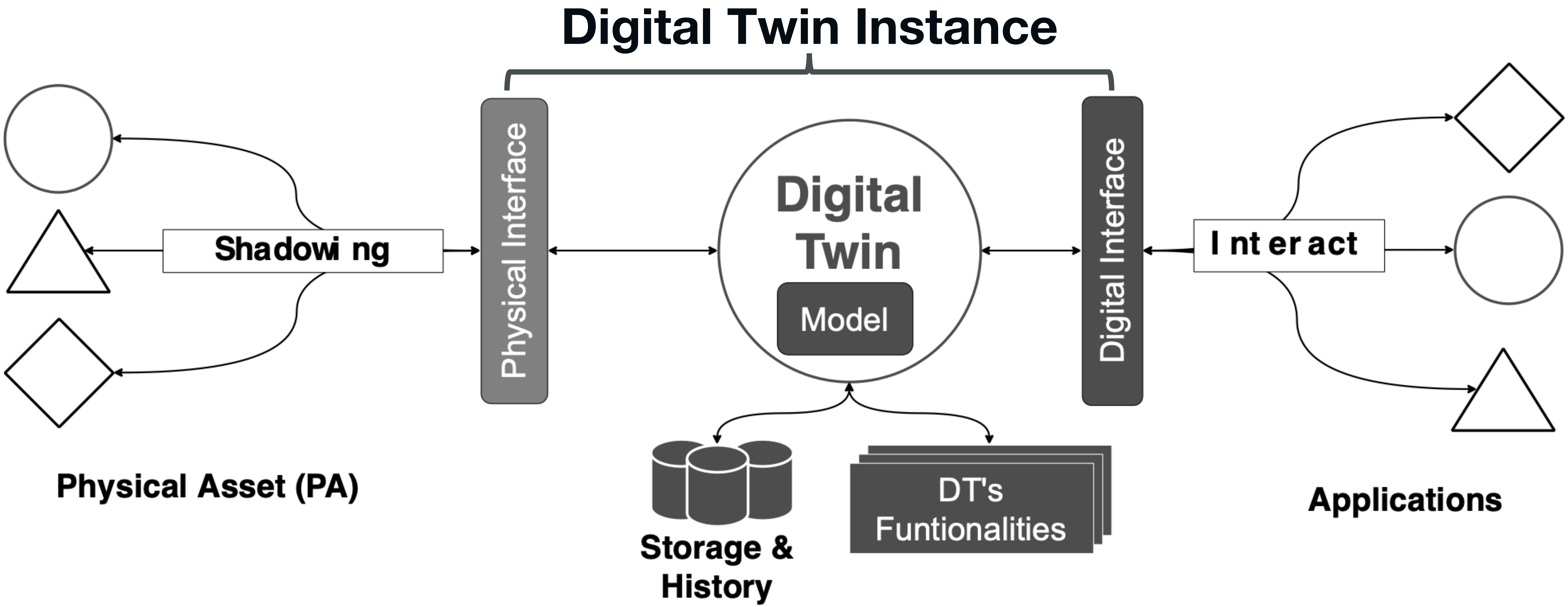
- Software
- Physical Communication
- Data Processing & Model
- Description Language
- Cyber-Physical Lifecycle
- Digital Communication

Digital Twin's Pillars (and questions)

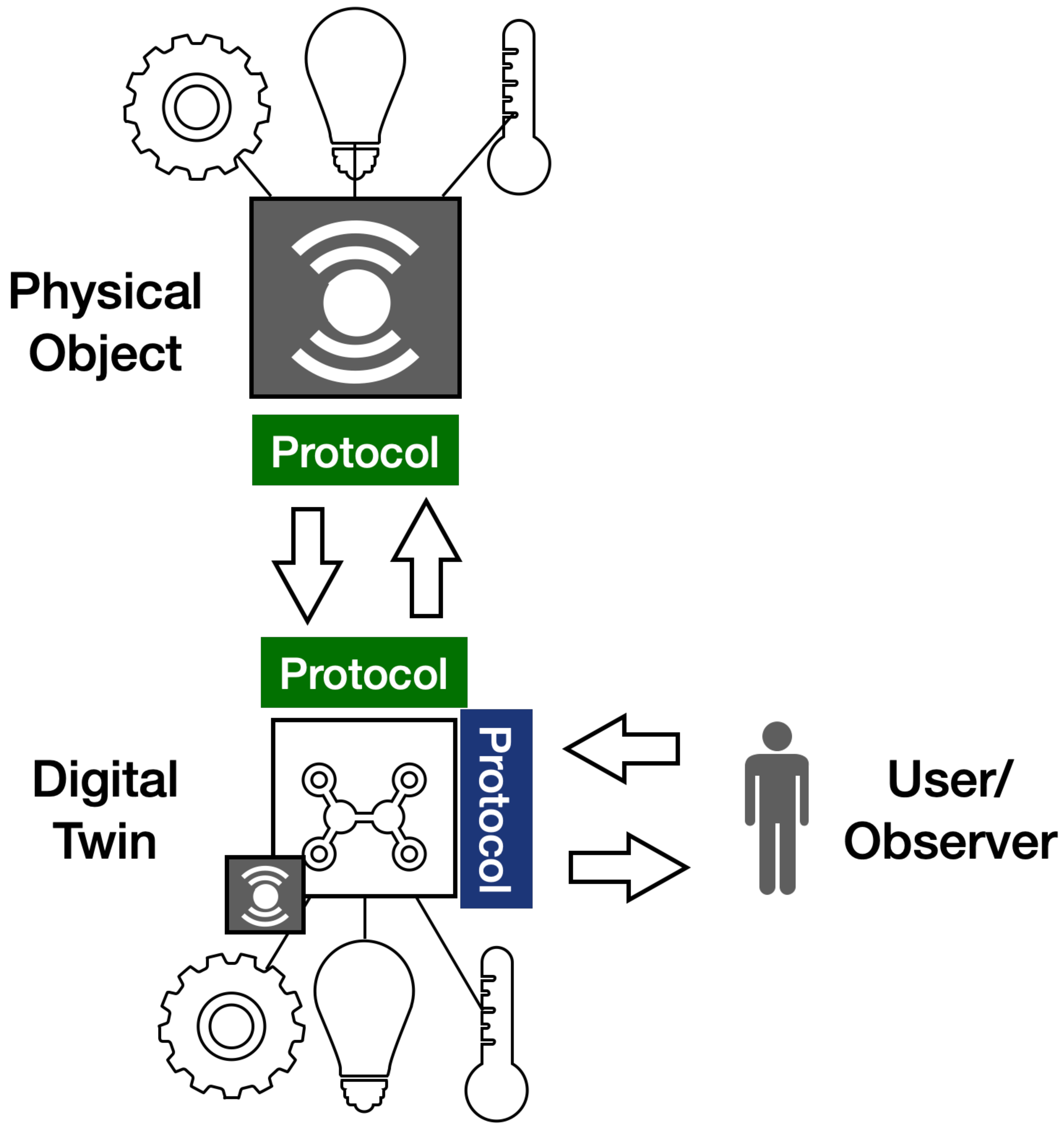
- **Software:**
  - How can we **design** and structure DT's code ?
  - How can we **deploy** DTs ?
  - How can we **monitor** DTs ?
- **Physical & Digital Communications:**
  - How a DT can **interact** with the **physical** and the **digital** layers ?
- **Data Processing & Model:**
  - How can we **define**, **update** and **execute** the DT's **model** ?
- **Cyber-Physical Life Cycle:**
  - How the DT **evolve over time** and with respect to the physical and the digital worlds ?
- **Description Language:**
  - How can we **describe** a DT through a **uniform**, and **interoperable representation** ?



Digital Twin's Pillars (and questions)

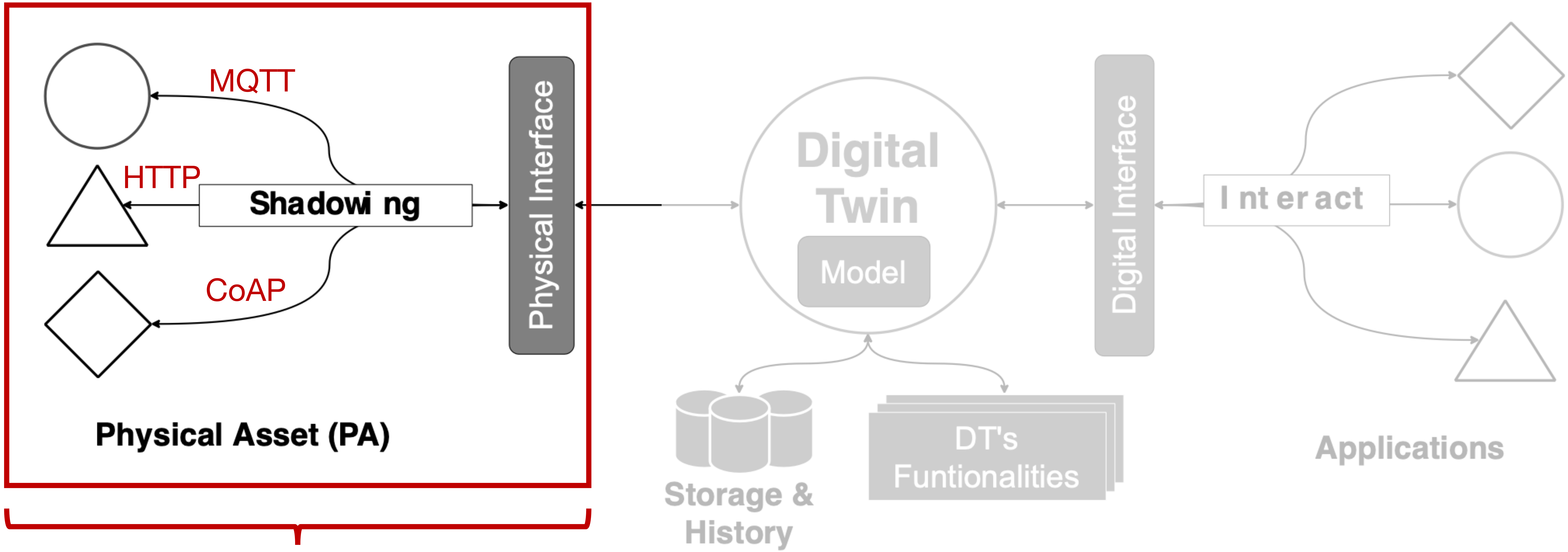


Internet of Things & Digital Twins

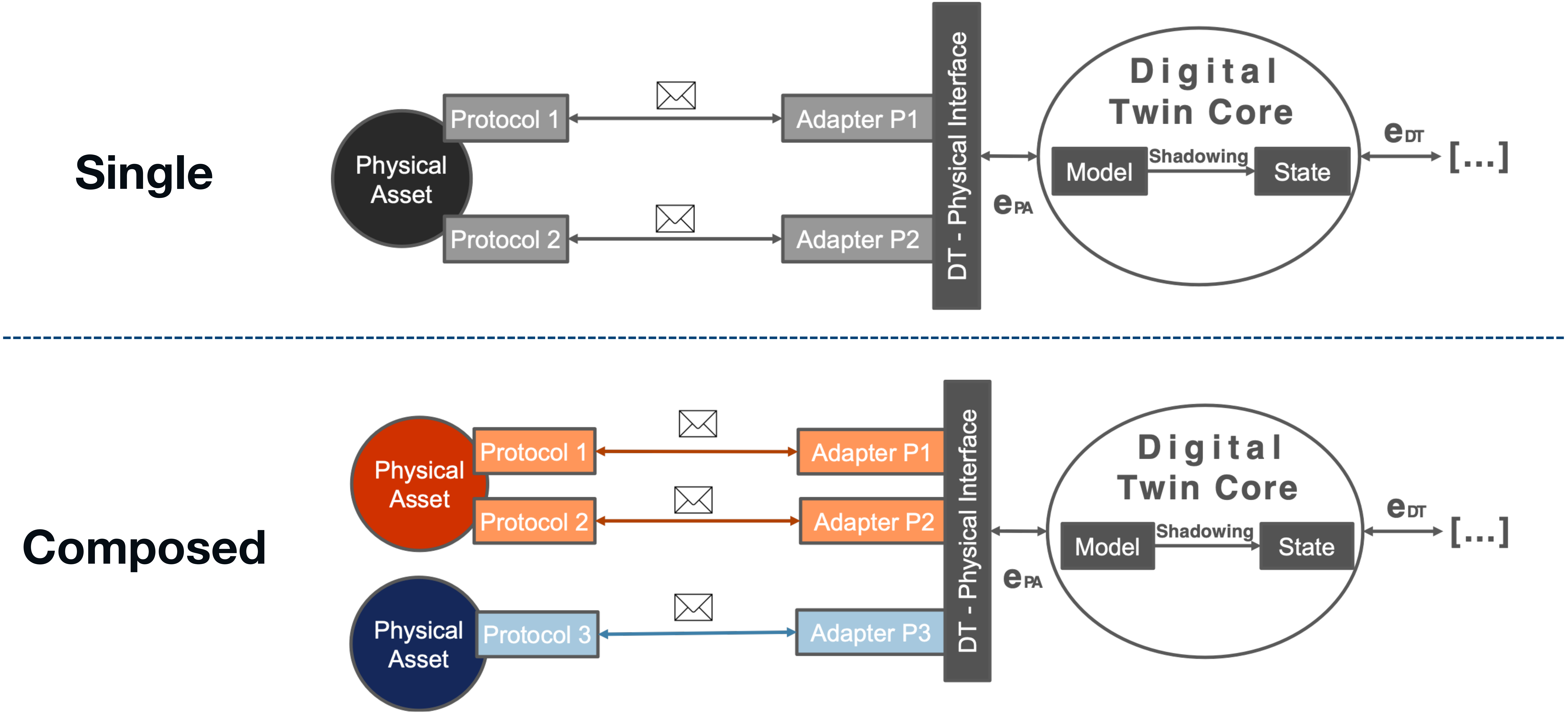


- It's only thanks to the Internet of Things that the idea of **Digital Twins has become cost-effective** to implement thanks to the possibility to "easily" communicate with a physical connected device
- **IoT** technologies represent the strategic enablers to design and **build DT's physical interfaces** allowing twins to talks through multiple languages and data formats with the aim to **read** information, **synchronize** the state, and **interact** with the environment
- At the same time, **DTs** represents an appealing opportunity to **digitalize/softwarize the physical world** (composed by a multitude of heterogeneous assets) and **simplify its complexity** to digital applications

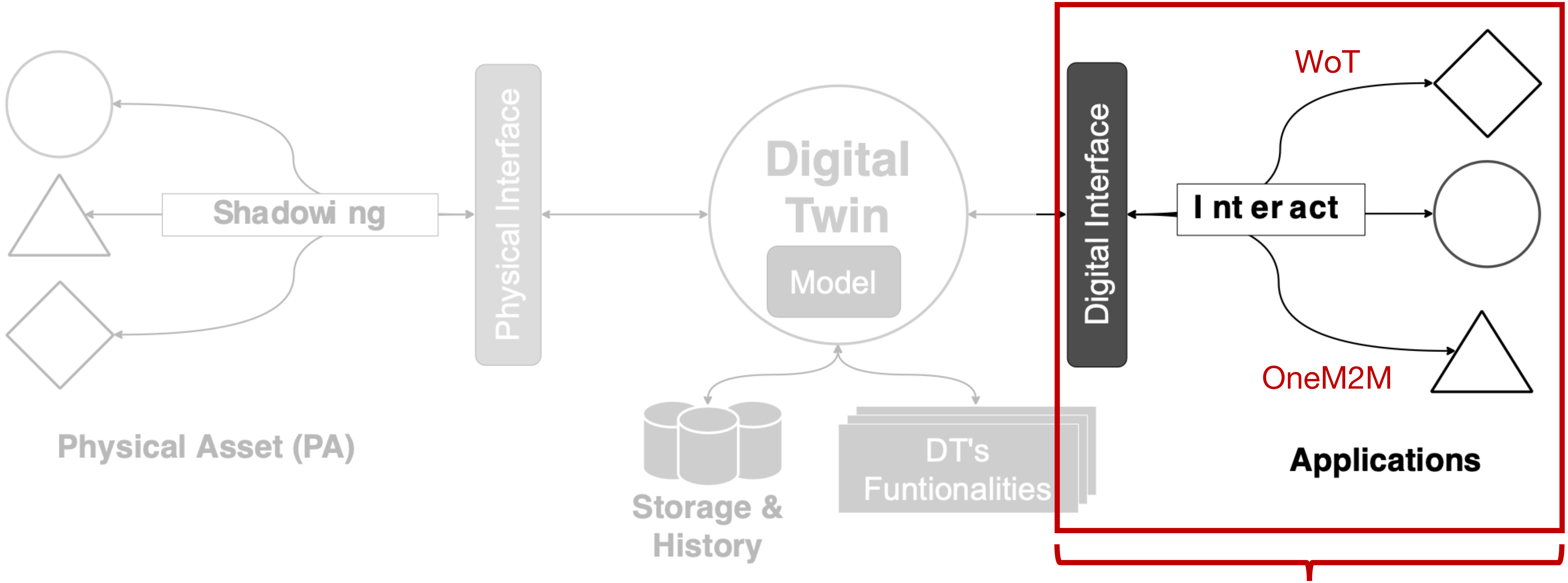
Internet of Things & Digital Twins



Internet of Things & Digital Twins



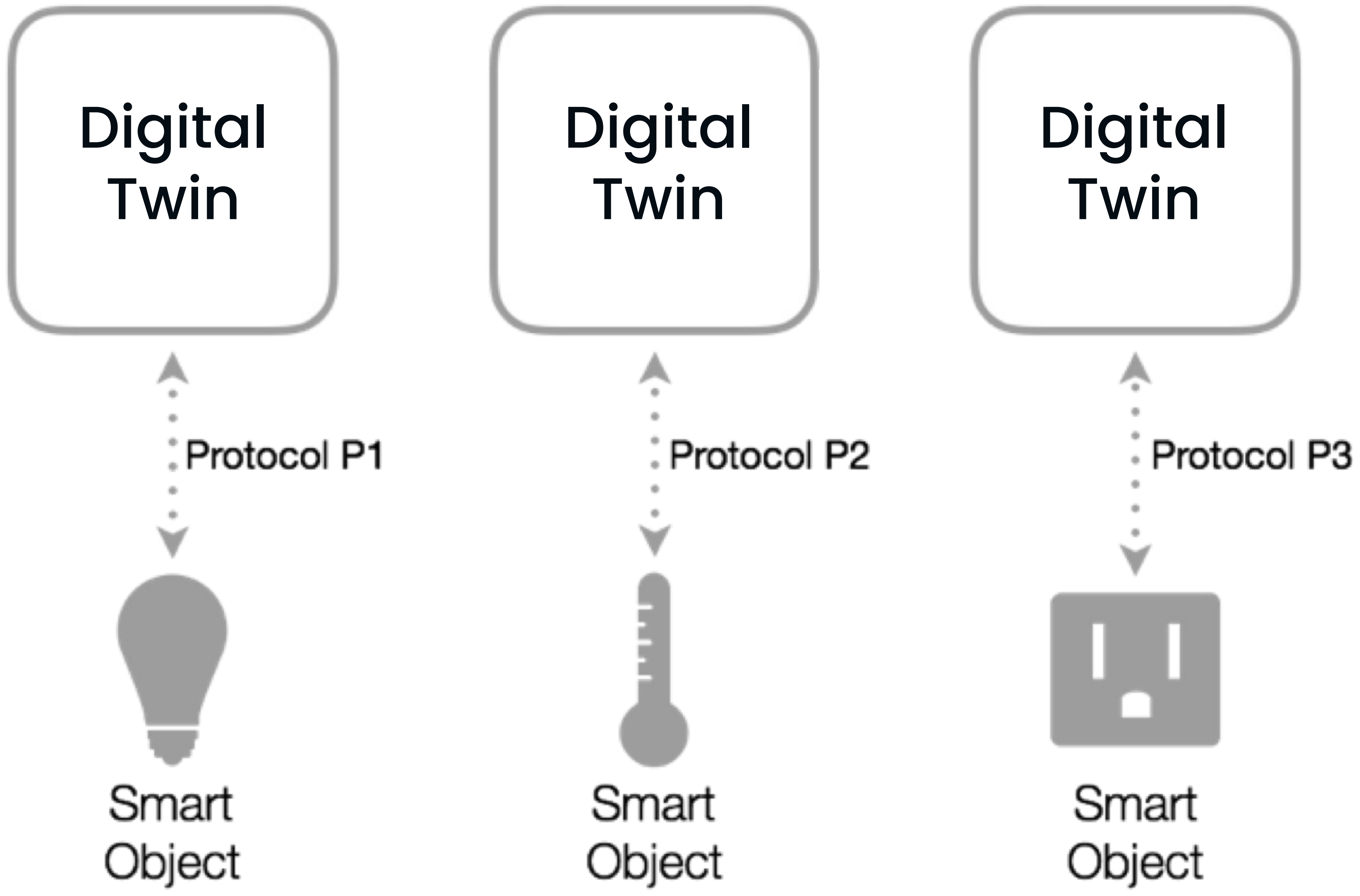
Internet of Things & Digital Twins

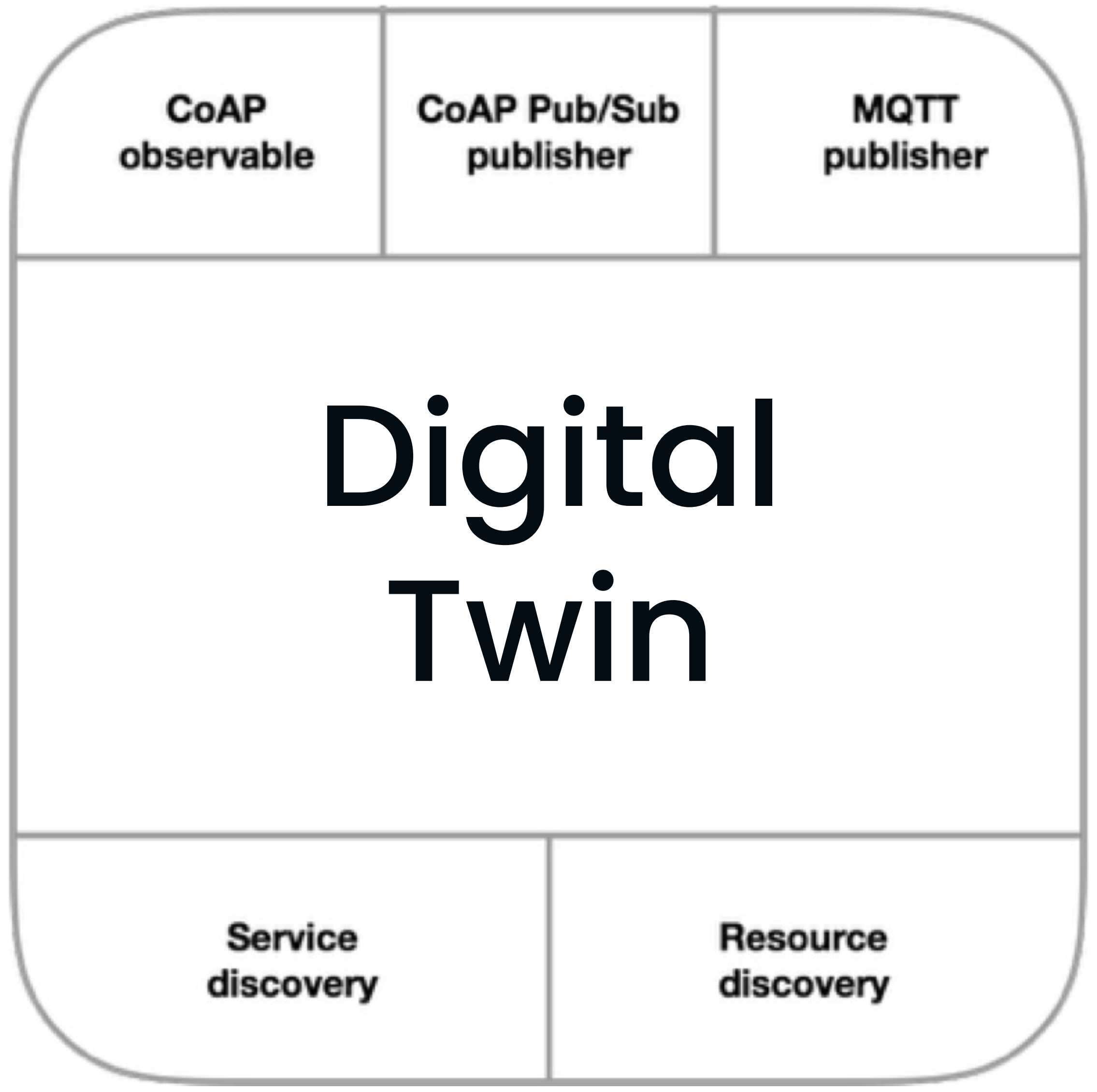


IoT as a facilitator for DT's Digital Interface

Internet of Things & Digital Twins

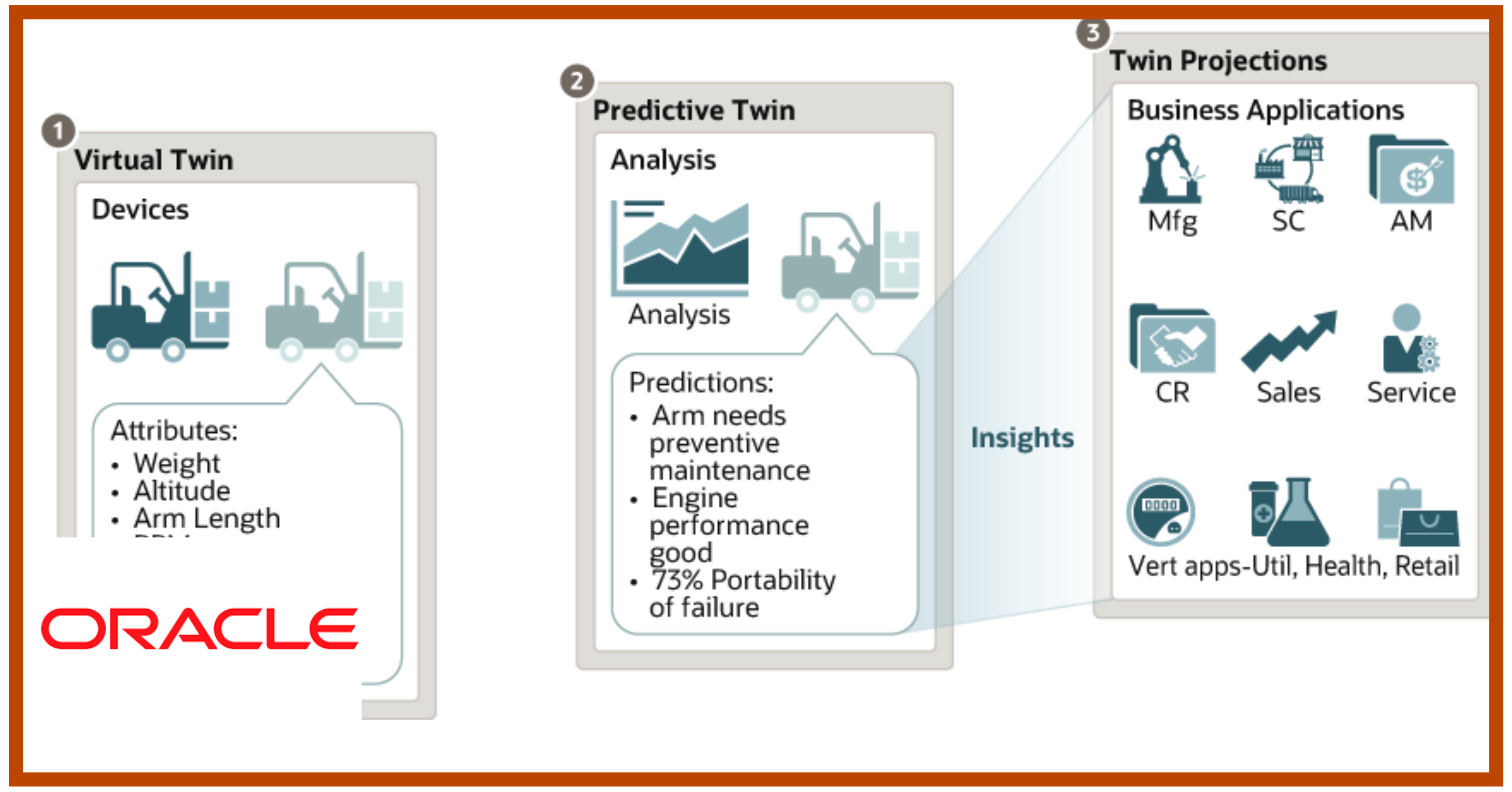
- **Physical objects come with well-defined functionalities and services that are fixed for the entire life cycle of the object**
- Even if they do not have processing capabilities, they may have limitations due to constraints and costs related to manufacturing processes and materials
- The **DT can leverage the software dematerialization in order to modify, update, improve its functions over time**
- In other words, the physical object can be functionally augmented through the implementation of update or new functions and features in the DT such as:
  - Intelligence, data Aggregation and Analytics
  - IoT Connectors and Interoperability support through multiple protocols, service and resource discovery and adoption of uniform frameworks (e.g., WoT or oneM2M)

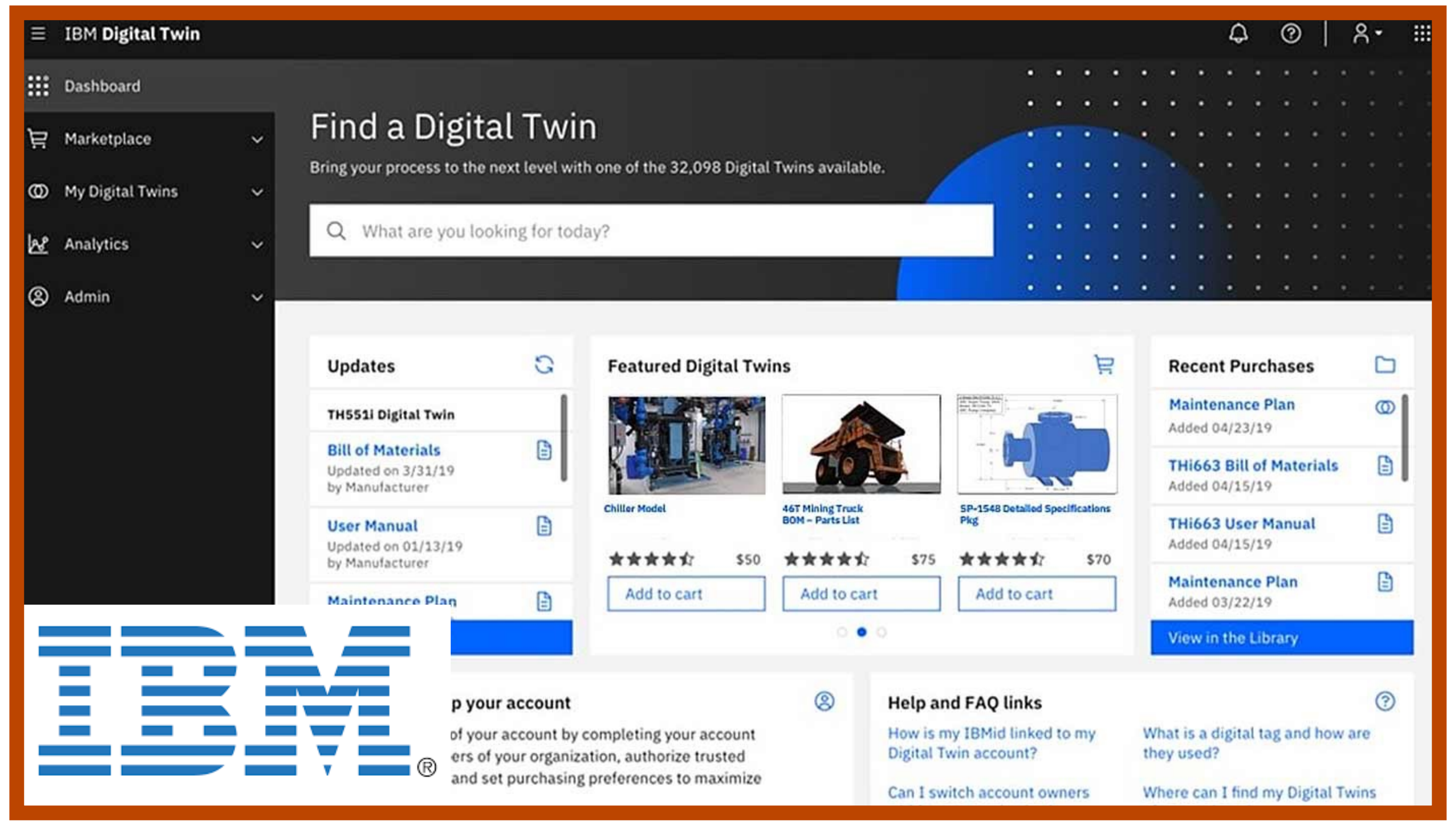




Digital Twins as a Massive Trending Topic

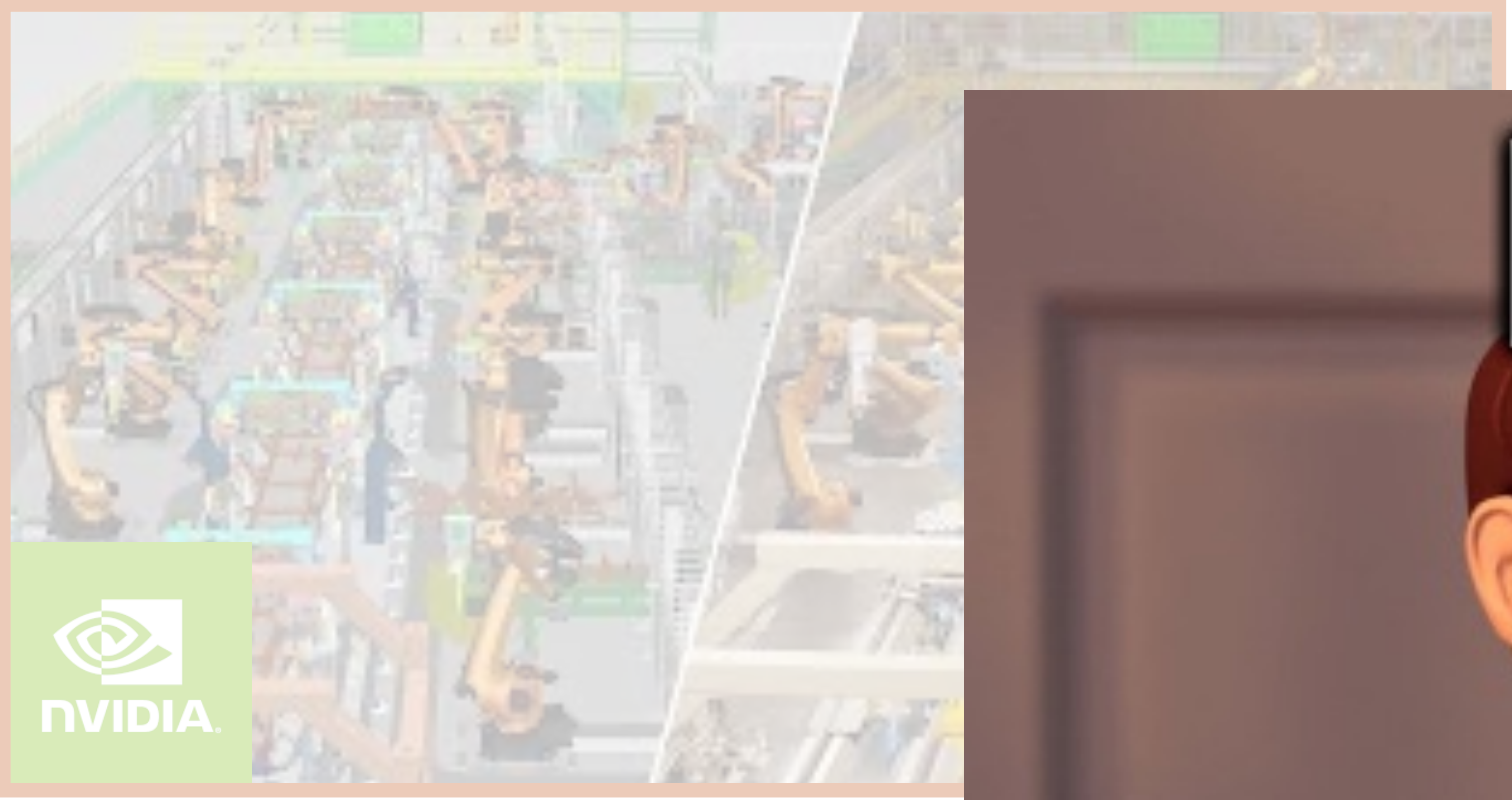
Almost "Everyone" is talking and building Digital Twin in their own way, with independent platforms and fragmented modelling …





and counting ….

Digital Twins as a Massive Trending Topic



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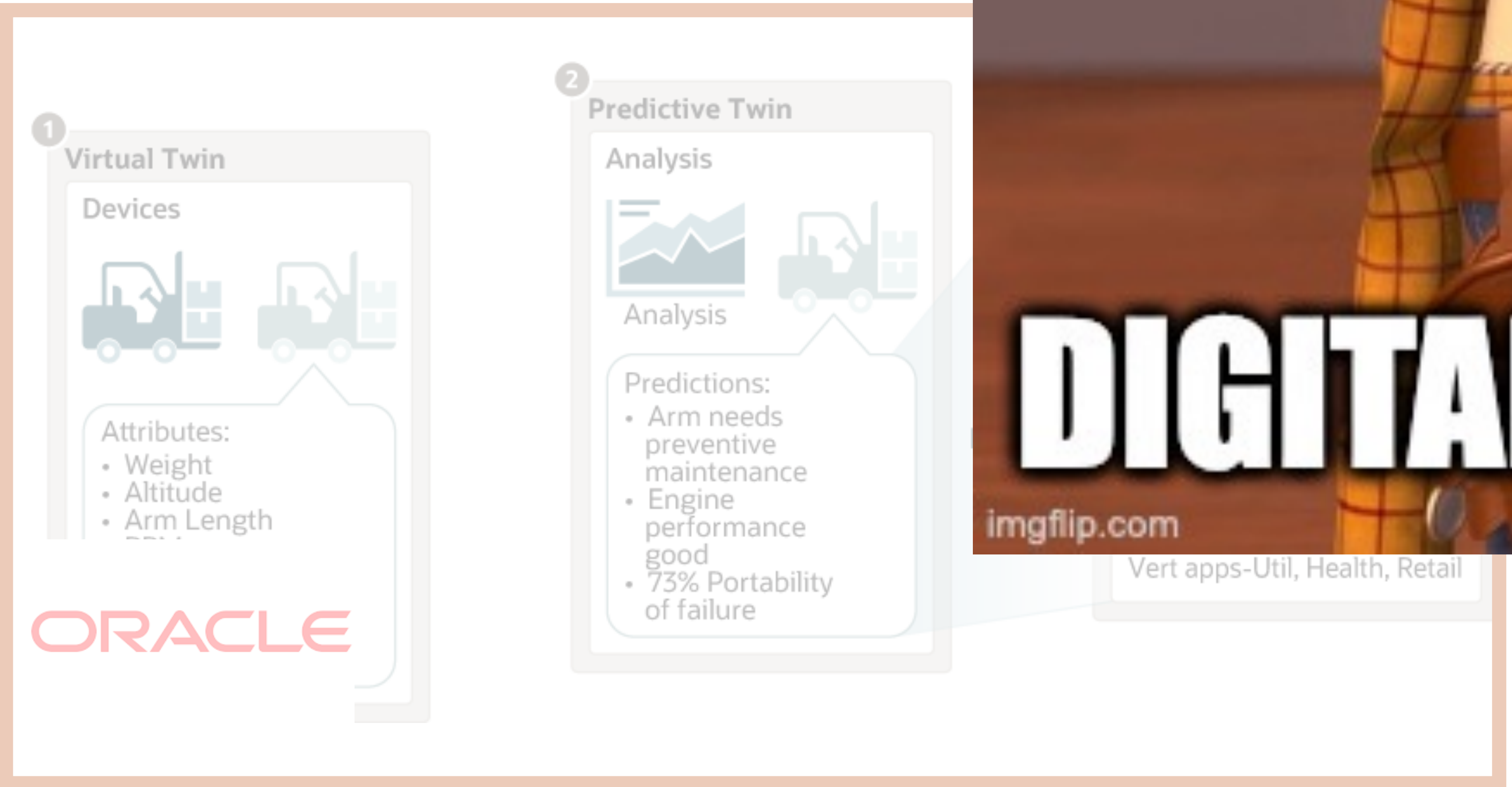
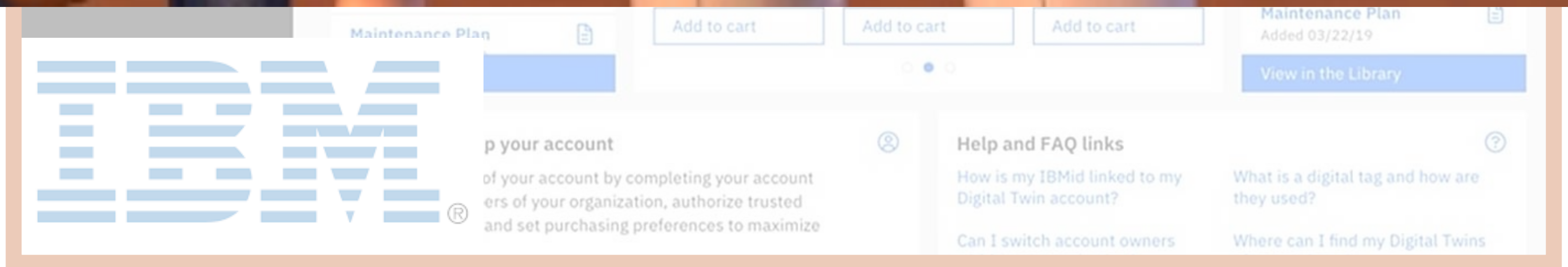




and counting ….

The Current Digital Twin Ecosystem

- **IMPORTANT:** Existing Digital Twin platforms and solutions represent amazing contributions to the domain and a tremendous effort toward a widespread experimentation and adoption **-> But they are just the starting point** ☺️
- (Some of) Existing Issues:
  - Mainly **centralised/monolithic approaches** where all DTs are aggregated and deployed in the same point (the Cloud)
  - Digital Twins are mainly **passive entities** co-located at the same architectural layer of the platform itself and **subordinated to external modules** to control their properties, data and behaviours
  - Digital Twins are often **"just" data structures** that can be used to represent an application scenario **without a model** and any active behaviour
  - **Platform Specific** Digital Twin **Description**
  - **Proprietary vertical technology** stacks which are built around a central point of control and which **don't always talk to each other** -> when they do talk to each other it requires **per-vendor integrations** to connect those systems together

Are DTs a buzzword ? -> No they represent a "new" technology that needs a lot of work to be effective without fragmentation and the definition of a unified conceptual framework

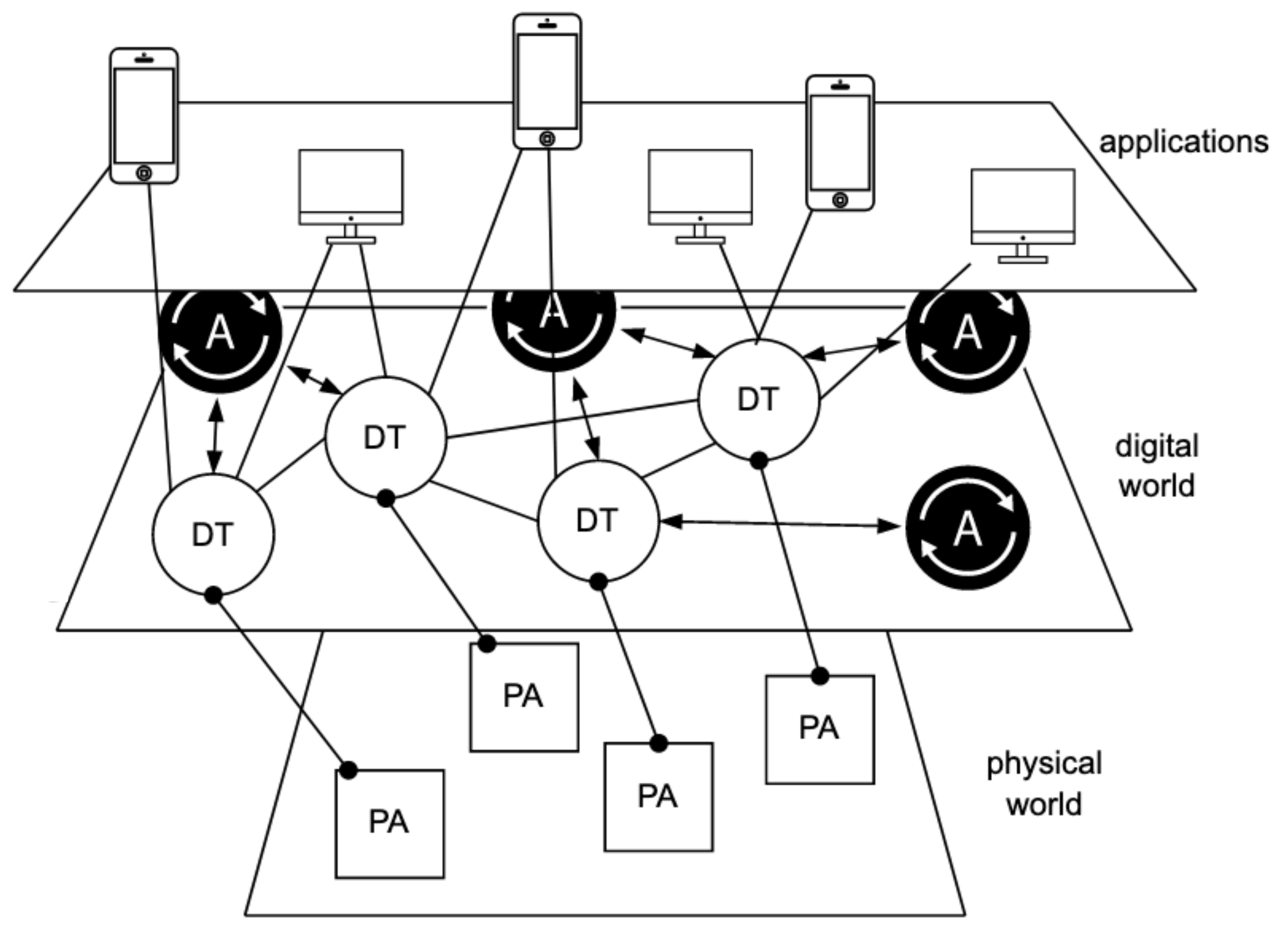
New Digital Twin Opportunities

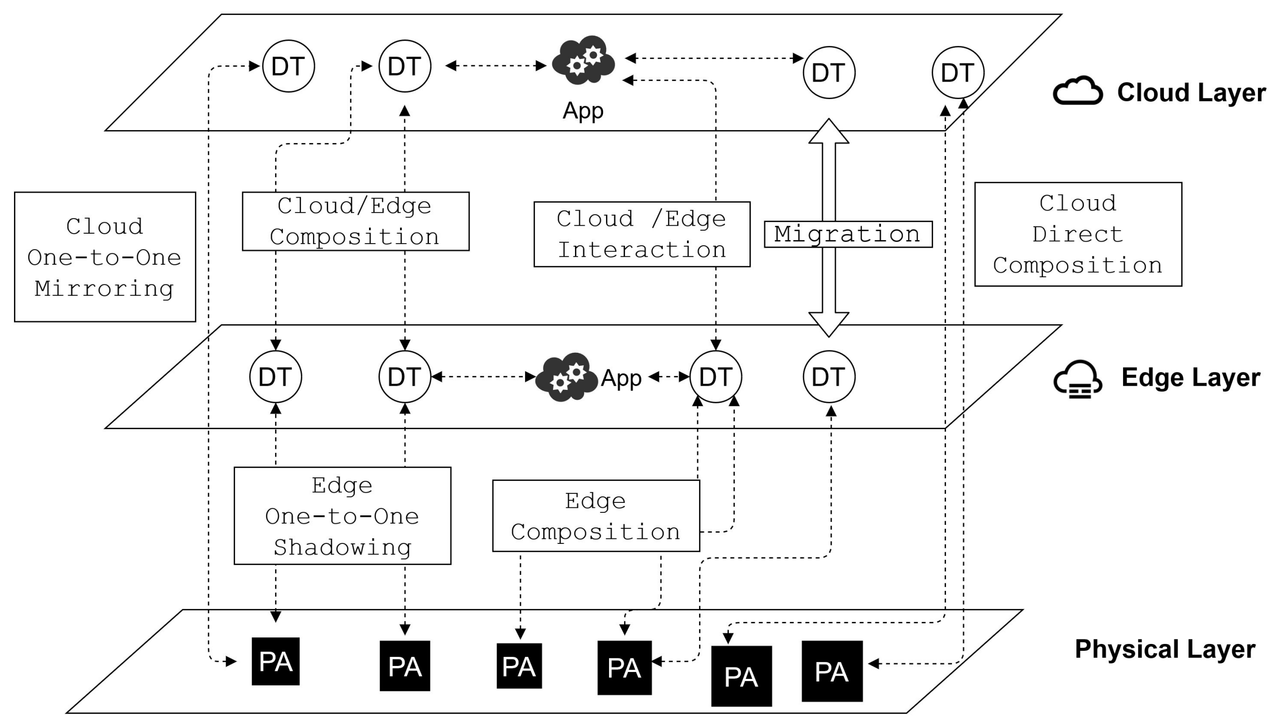
Current Digital Twin Software Evolution

Next Generation of Digital Twin Software

(Some) Open Challenges

- **Definition & Modelling**
    - DTs can be **active software entities** with an **internal model** responsible to define how to **digitalize their physical counterparts** and **implements** their own **behaviours** (there are not just data structures ☺️)
    - There is the need to **identify a basic set of foundational properties, a common set of features and a naming conventions** that can be used to fully describe and specify the characteristics of the DT in several application domains*
    - The objective is to **offer/build a unified conceptual framework** for clarifying the foundational concepts and providing a possible **consolidated definition of the DT and its features and functionalities**
- **Description Language**
    - Definition of a **shared** and **"standard" description language** to enable a through **interoperability** and **integration** among heterogeneous DTs and digital services across multiple applications domains
- **Deployment**
    - Switch from a centralized point of view to a **distributed vision** where DTs can co-exists and collaborate across multiple architectural layers (Edge, Fog and Cloud) according to their requirements and responsibilities
- **and more …**





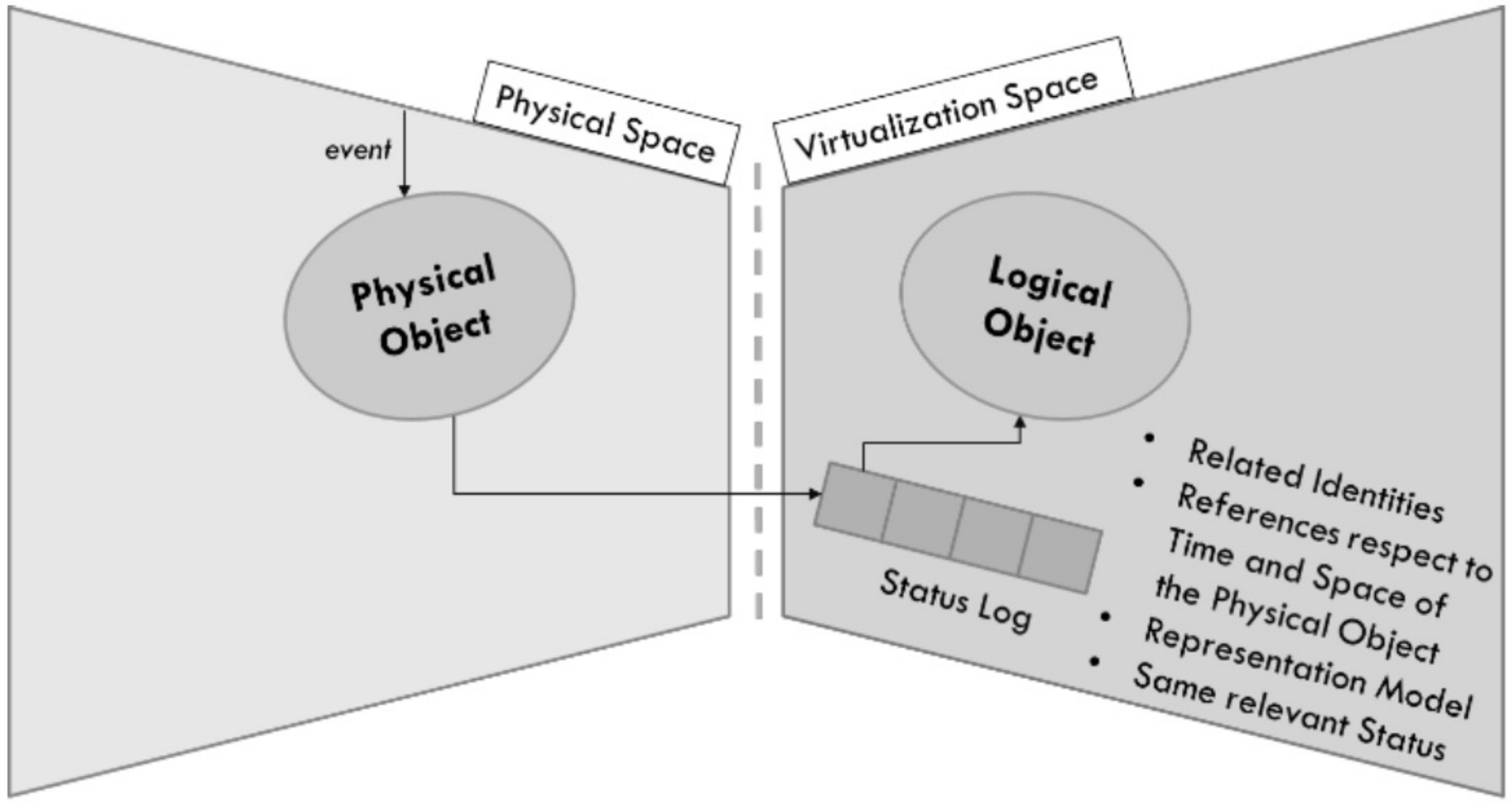
*R. Minerva, G. M. Lee and N. Crespi, "Digital Twin in the IoT Context: A Survey on Technical Features, Scenarios, and Architectural Models," in Proceedings of the IEEE, vol. 108, no. 10, pp. 1785-1824, Oct. 2020, doi: 10.1109/JPROC.2020.2998530.

Build a Digital Twin Ecosystem

Envision a **pervasive softwarisation of the physical world** in terms of highly dynamic ecosystems of **connected** and **interoperable DTs**, across **different** application **domains** and different **network levels** (from cloud to edge).

To make DTs a real opportunity we need a structured **cross-field fertilization and collaboration** (e.g., Software Engineering, Networking, Standardization Bodies, Companies, Universities …)

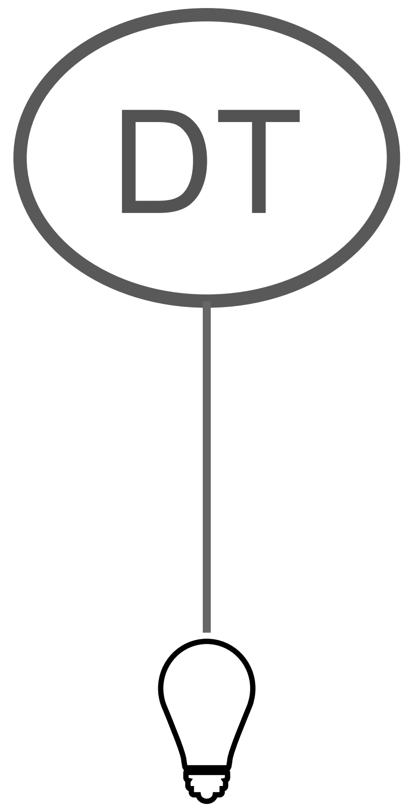
Digital Twin - IoT Characterizing Properties

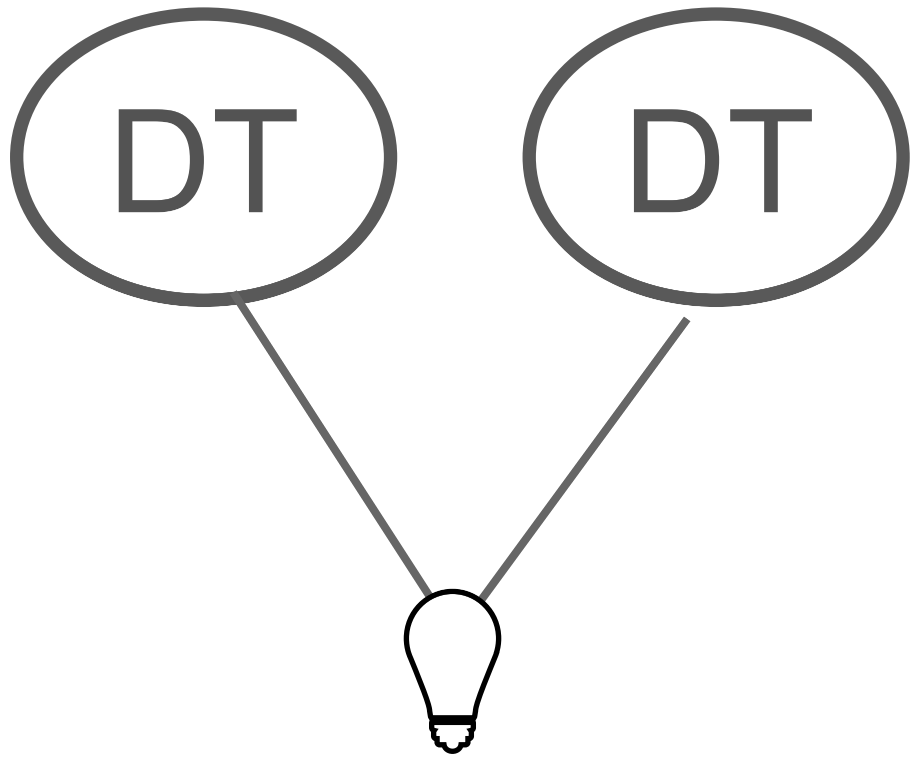


- There is the need to **identify a basic set of foundational properties** of the Digital Twin that can effectively fit for different contexts and situation and still maintain generality
- This effort is instrumental **to identify a common set of features and naming conventions** that can be used to fully describe and specify the characteristics of the DT in several application domains
- The objective is to **offer/build a unified conceptual framework** for clarifying the foundational concepts and providing a possible consolidated definition of the DT and its features and functionalities

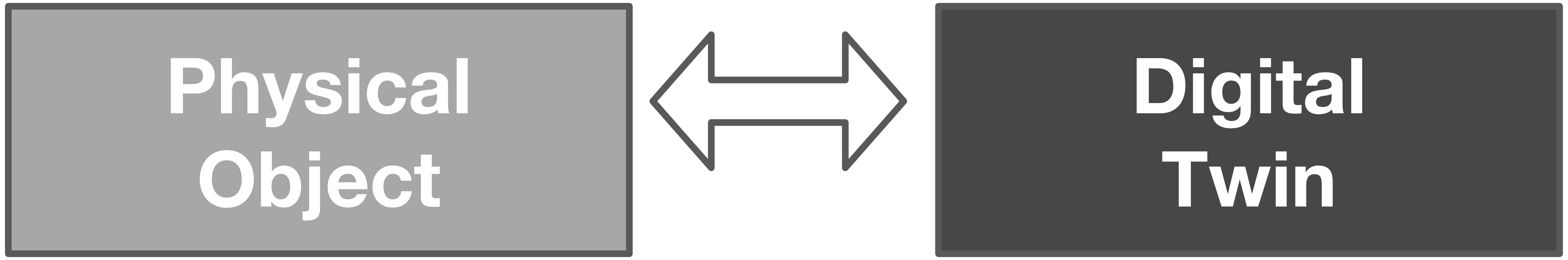
Digital Twin - Relationship with the Physical World

- **Identity**
  - The physical object must have a univocal identity (e.g., by a product code, version or other mechanisms)
  - The digital clone needs to have a unique identifier too in order to make it addressable into a software space
- DT may have both a ***1-to-1*** or a ***1-to-N*** cardinality/relation between the assets and the digital instance. In that second case **different replicas may exists with respect to the same physical asset**
- If more than a replica refers to the physical object, each of them must have a unique identifier and a pointer to the physical object identifier





Digital Twin - Definition of Physical & Logical



- The idea is that any physical object can be represented and virtualized. The creation of a Digital Twin is based on:
  - the physical object (PO)
  - the Digital Twin(s) (DT)
  - the relation between the physical and logical entities
- The physical entity associated to the DT can be referred to by a few synonyms such as object, artifact, product or physical asset
- The DT refers to the virtualization of the features of the physical object and it is usually implemented by software. It is usually termed *logical object*, *digital object*, *digital counterpart*, *clone*, *counterpart*, *reciprocal form*, *companion* or *mate* etc … :)

Digital Twin - Qualifying Properties

- An initial set of the qualifying properties of a Digital Twin, derived from the research state of the art can be summarized as follow:

- Representativeness & Contextualization
- Reflection
- Replication
- Entanglement
- Persistency
- Memorization
- Composability
- Accountability/Manageability
- Augmentation
- Ownership
- Servitization
- Predictability

Digital Twin - Representativeness & Contextualization

- Generally speaking, the DT has to be as much as possible “similar” to the original; However, representing a physical object in all its aspects and implications is difficult and sometimes worthless
- A DT **should be supported by a model** designed and implemented with a set of **goals** and **purposes**, and refer to a target **context** in which to operate
- One of the basic concepts of the Digital Twin is related to **how much the replica represents the original object**
- A physical object can be described by its:
  - **Properties:** data fields that represent the state of an entity (e.g., a temperature sensor or a switch)
  - **Behaviours:** actions that can be performed by the device or on the physical device to change its status (e.g., a toggle to turn on and off the light)
  - **Relationships:** represent how a DT can be involved with other digital twins (composability). They can represent different semantic meanings, such as contains ("floor contains room"), cools ("hvac cools room"), isBilledTo ("compressor is billed to user"), and so on …
- The DT should at least represent those properties, behaviors and relationships that are necessary and sufficient to qualify it in the target operational context (e.g., optimize energy consumption in a building)

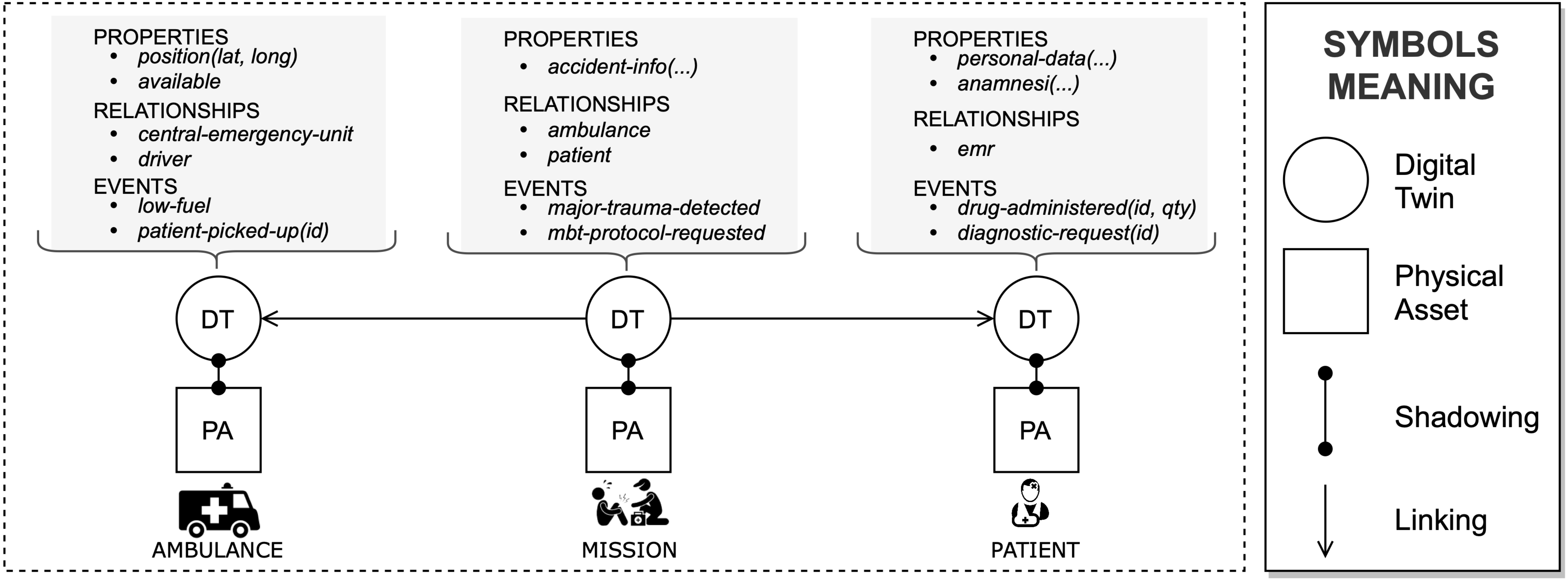
Digital Twin - Representativeness & Contextualization

- Representativeness should be considered under three major parameters:
  - **Similarity ->** how much and how well the DT reproduces the original object and its characteristics (properties, behaviours and relationships);
  - **Randomness ->** the probability that the DT has a different status or is providing diverging features from the original one;
  - **Contextualization ->** the two previous features must be considered in the context of the operation of the correlated objects. If the usage context of the DT is a specific environment, most likely only a subset of all the features, properties and information of the physical object are relevant.

Digital Twin - Representativeness & Contextualization

- In many application scenarios, some of the attributes of the physical object are not relevant, i.e., they do not characterize or influence the behavior over time, or the states of the object for the intended purpose of the DT.
- In this case, they are not considered in the description of the DT
- **Contextualization** means that all the relevant features and data available are needed and sufficient to represent the physical object in the specific virtual space under consideration

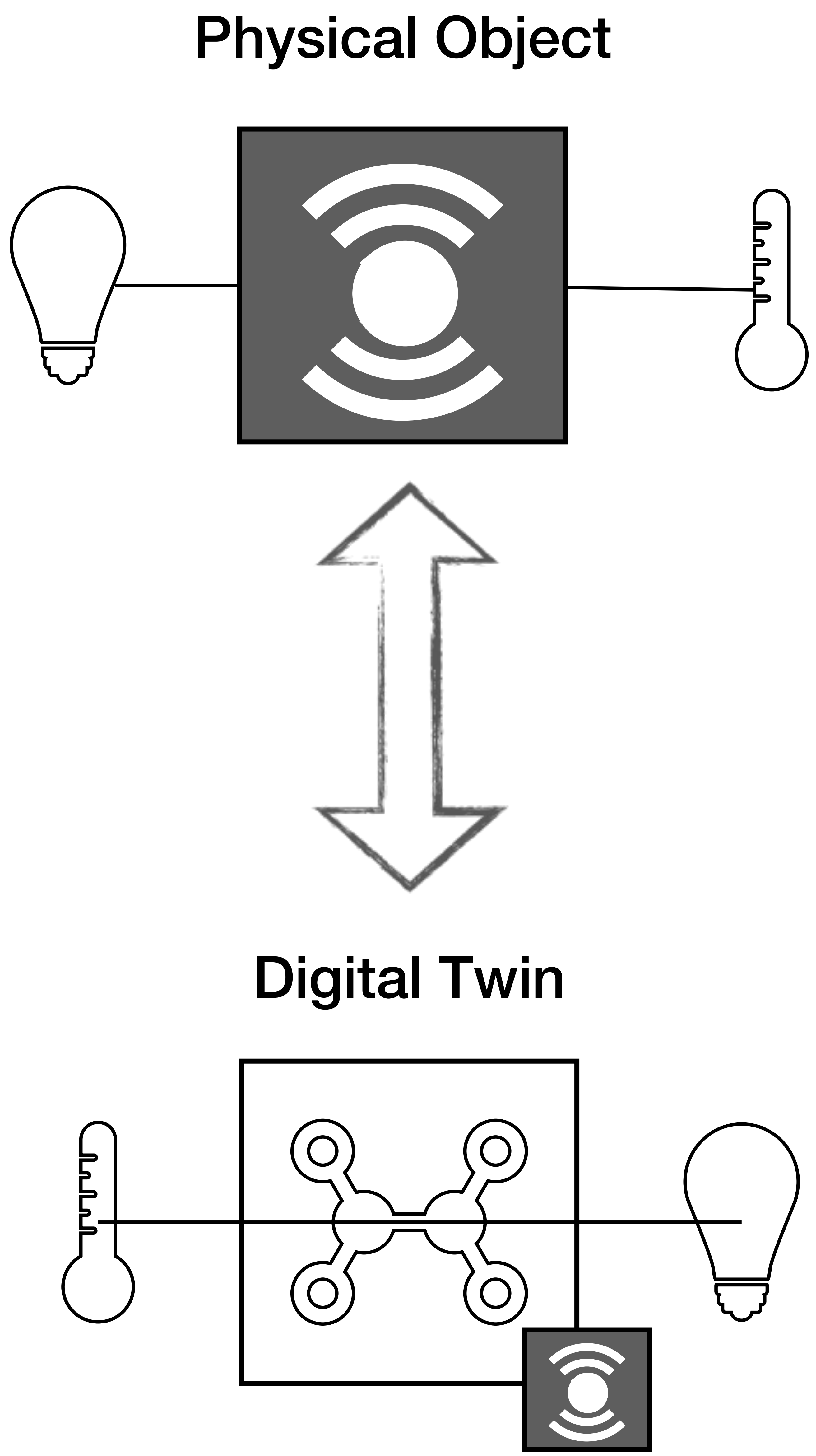
Digital Twin - Representativeness Example



Web of Digital Twins
A. Ricci, A. Croatti, S. Mariani, S. Montagna, M. Picone
ACM Transactions on Internet Technology 2022, ISSSN: 1533-5399, DOI: 10.1145/3507909
https://dl.acm.org/doi/abs/10.1145/3507909

Digital Twin - Reflection

- **Reflection property refers to a physical object that can be accurately measured and represented with respect to the application goals**
- Under this perspective, a physical object is described by a logical object as a set of **values, related to status, resources attributes** and **behaviours**
- The reflection capability of the DT suggests **that each relevant value and resource of the physical object is univocally represented in the DT**
- This information may change over time. The physical object is fully described if all these values are timely mapped on a mirrored set of the same values describing the logical object (**Synchronization**)



Digital Twin - Reflection

- There may be several transformation functions that relate the values of the physical object to the values of the digital reflection
- We can assume that a physical object is fully described and characterized by a set of variables *X* and their values in a multi-dimensional space *S where* (the sign ≡ indicates that it is equivalent or congruent)*:*

$$X = \{x_1, x_2, \dots, x_n\}$$

$$\exists\, f(X) = X' \; where \quad X' = \{x'_1, x'_2, \dots, x'_n\},$$

$$X' \in S, and \quad \forall\, i \;\; x_i \equiv x'_1$$

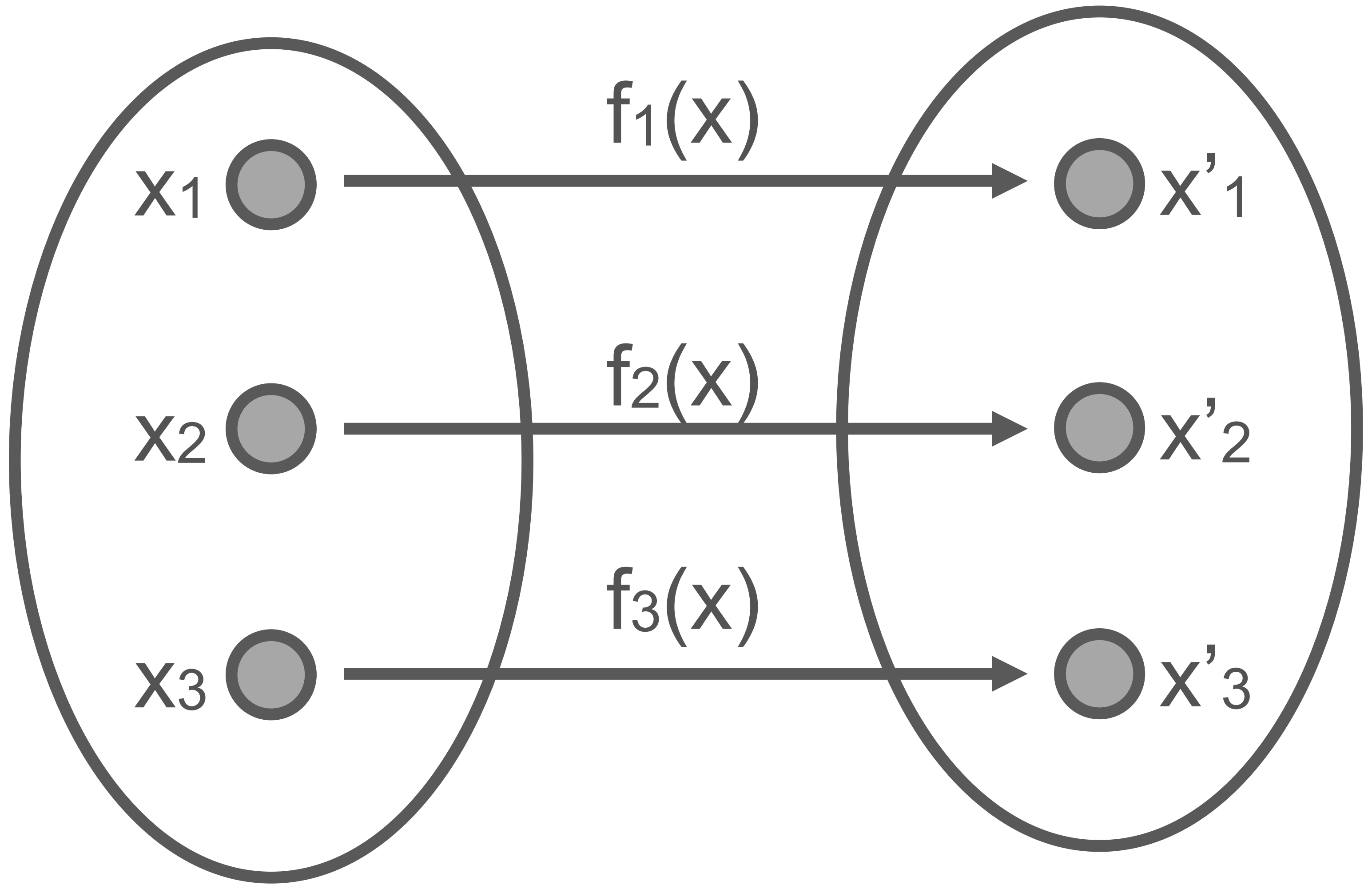
- The function *f(X)* can be generically an equality function, or in some cases, **it could transform** the **values of X into a different X'** (passing from a raw IoT data to structured SenML content format) that is congruent to the original set. In other cases, more than just a transformation function could be needed. In these cases, the combined function set from X to X' is *injective*

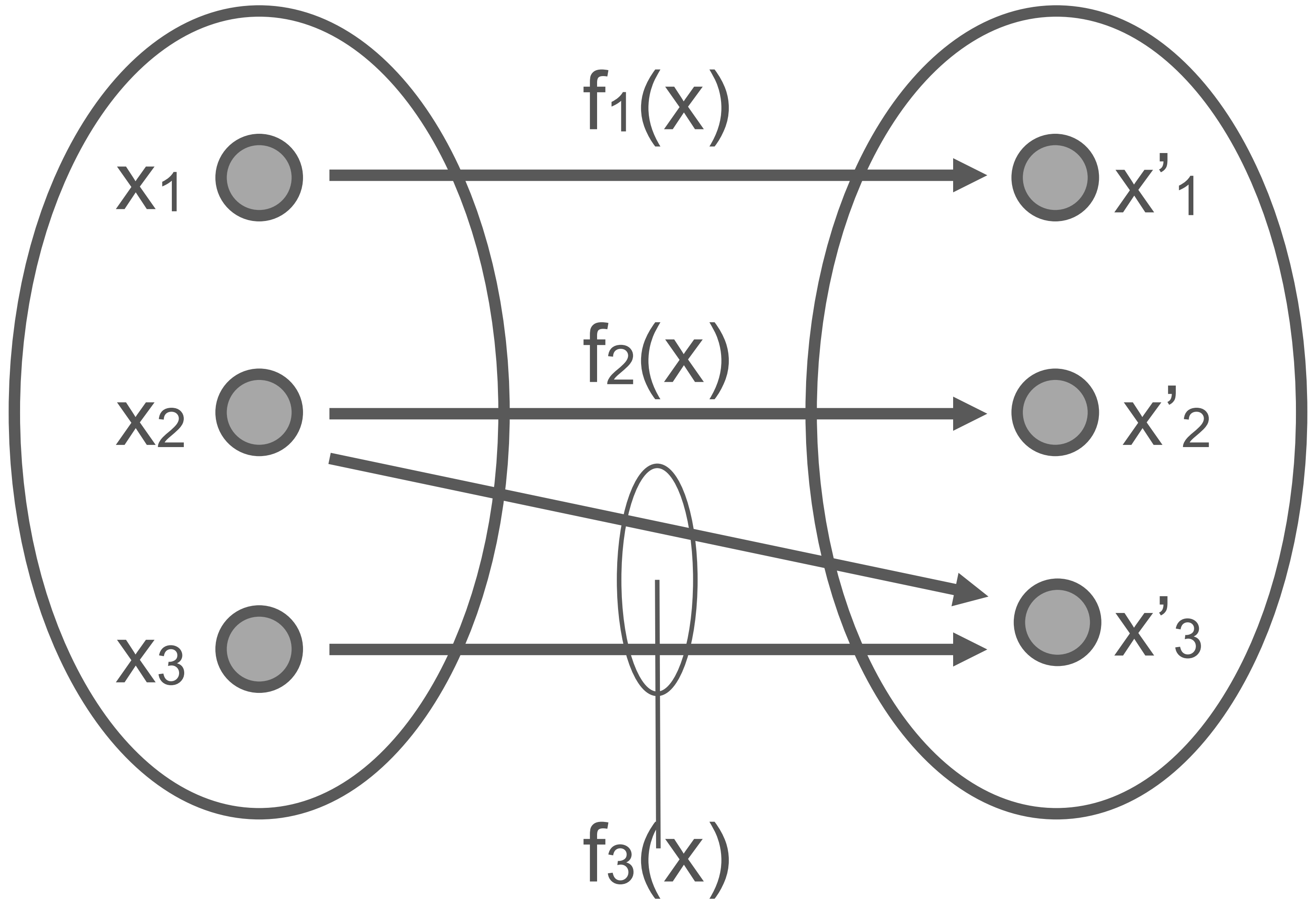
$$\forall\, i \;\in S, \exists!\; x'_i \; such\ that \;\; f_i(x_i) \equiv x'_i$$

Digital Twin - Reflection

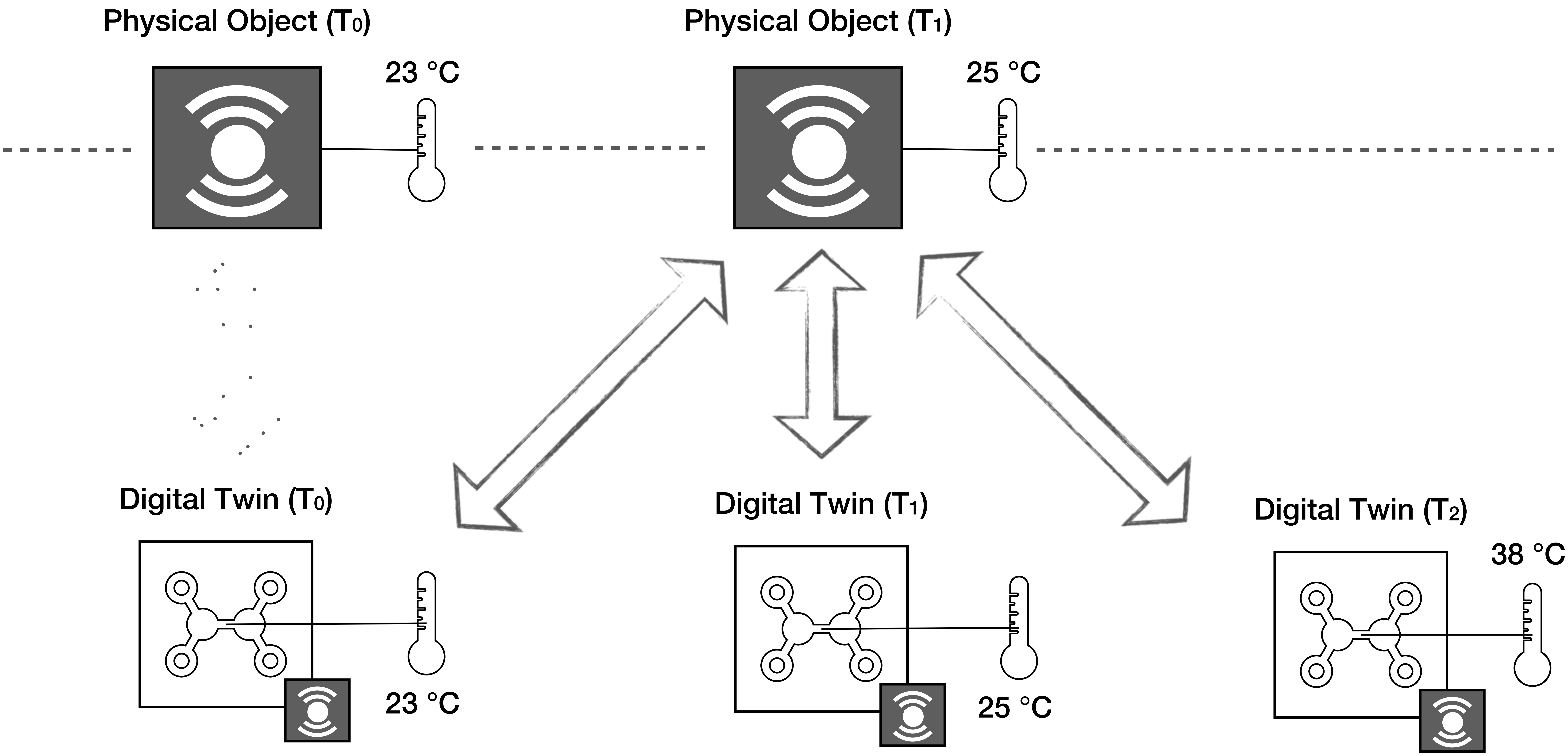
- Figure shows a case where different transformations can be applied to the logical object. In this case the relationship between X and X' is injective
- Injection is not mandatory, in the sense that more complex relationships can be established between the sets. (e.g., When applying AI techniques, different values and features may contribute to determine a single value of the logical object)
- **The reflection property is also associated to the fact that the physical object is placed in time and space.** A typical structure for representing a physical object can have the following format:

$$Attribute_i =< timestamp, location, value >$$





Digital Twin - Reflection



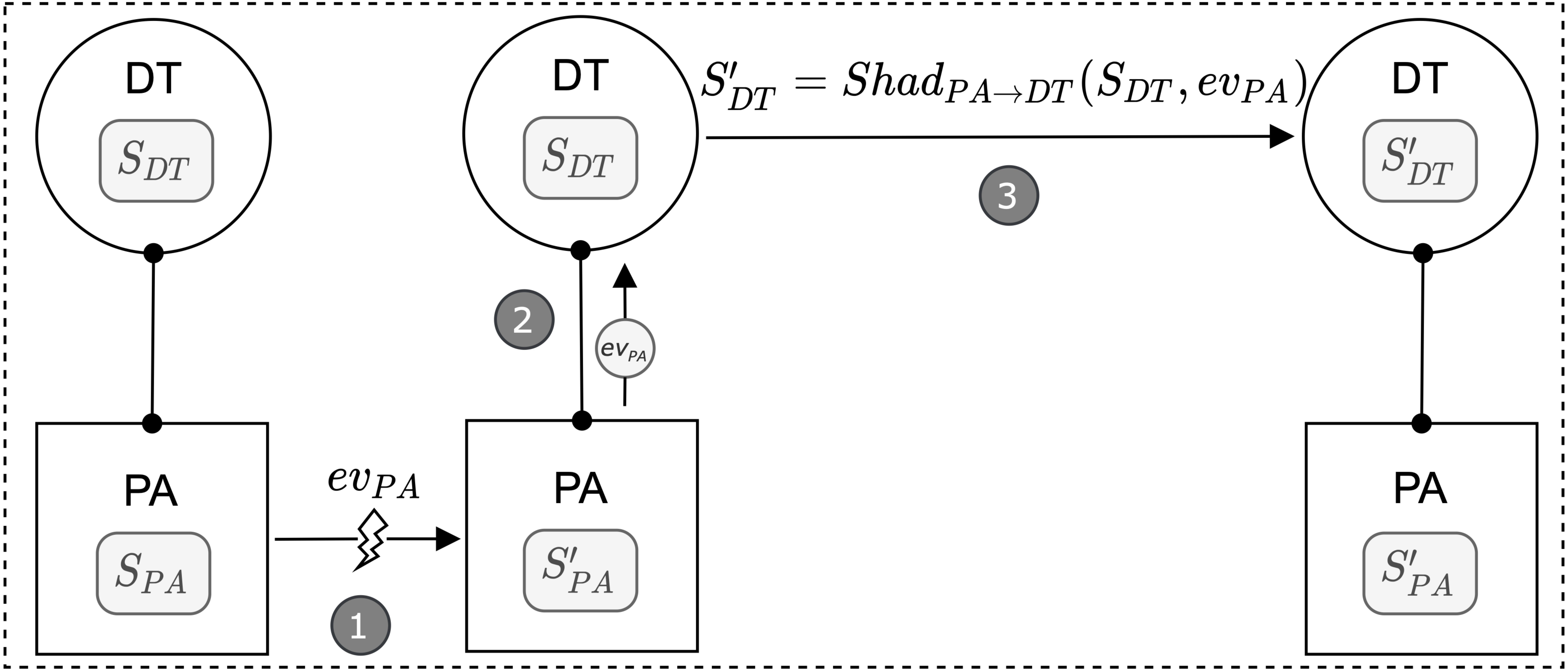
Digital Twin - Reflection (or Shadowing) & DT State

- The result of the shadowing/reflection process should be the State of the Digital Twin representing the status of the digital replica at a specific timestamp (**t**) in terms of:
  - Properties (**P**): the current set of properties (including data values)
  - Relationships (**R**): the current set of relationships
  - Events (**E**): the sequence of events generated so far
- Shadowing is the process to keep the DT state S_{DT} synchronised to the state of the Physical Asset (PA) denoted as S_{PA} according to the Digital Twin Model ($\mathbb{M}$)

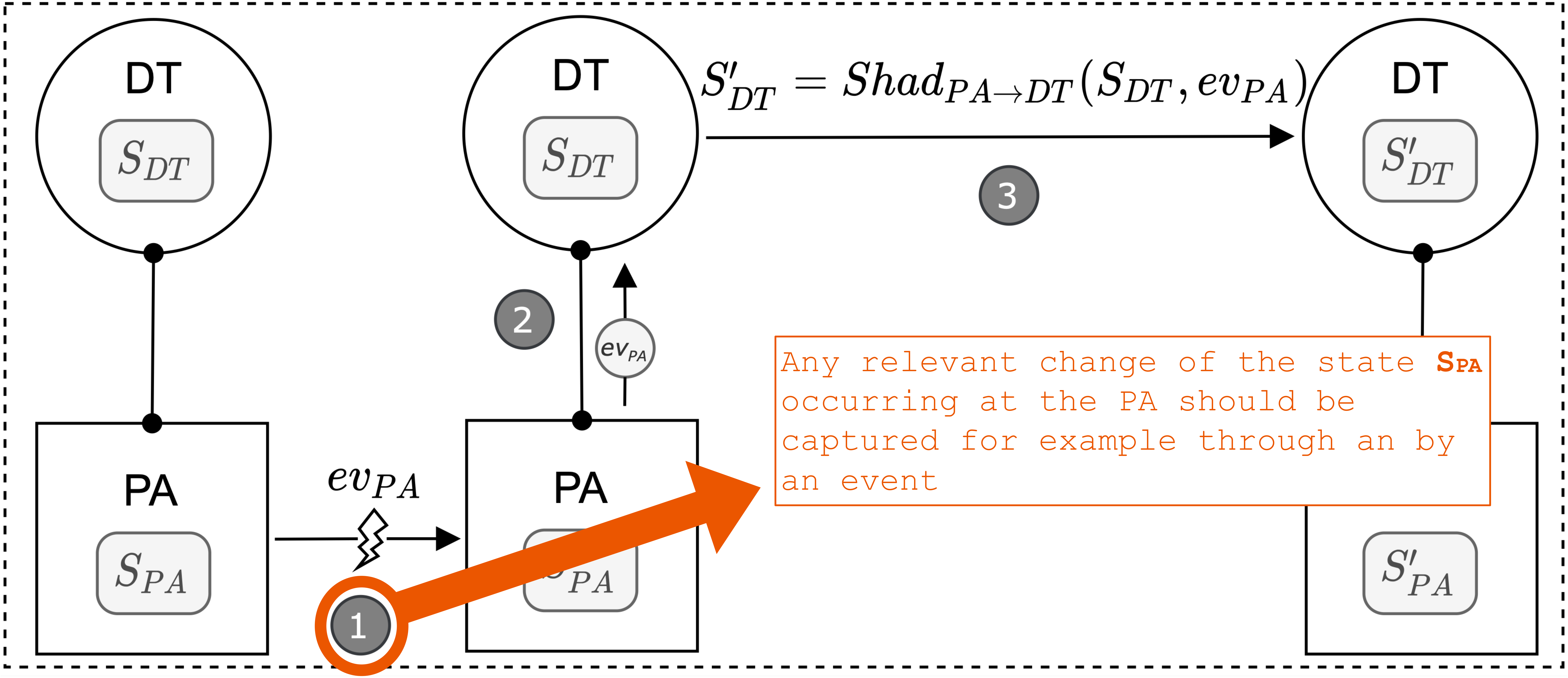
$$S_{DT} = \langle P, R, E, t \rangle$$

Web of Digital Twins
A. Ricci, A. Croatti, S. Mariani, S. Montagna, M. Picone
ACM Transactions on Internet Technology 2022, ISSSN: 1533-5399, DOI: 10.1145/3507909
https://dl.acm.org/doi/abs/10.1145/3507909

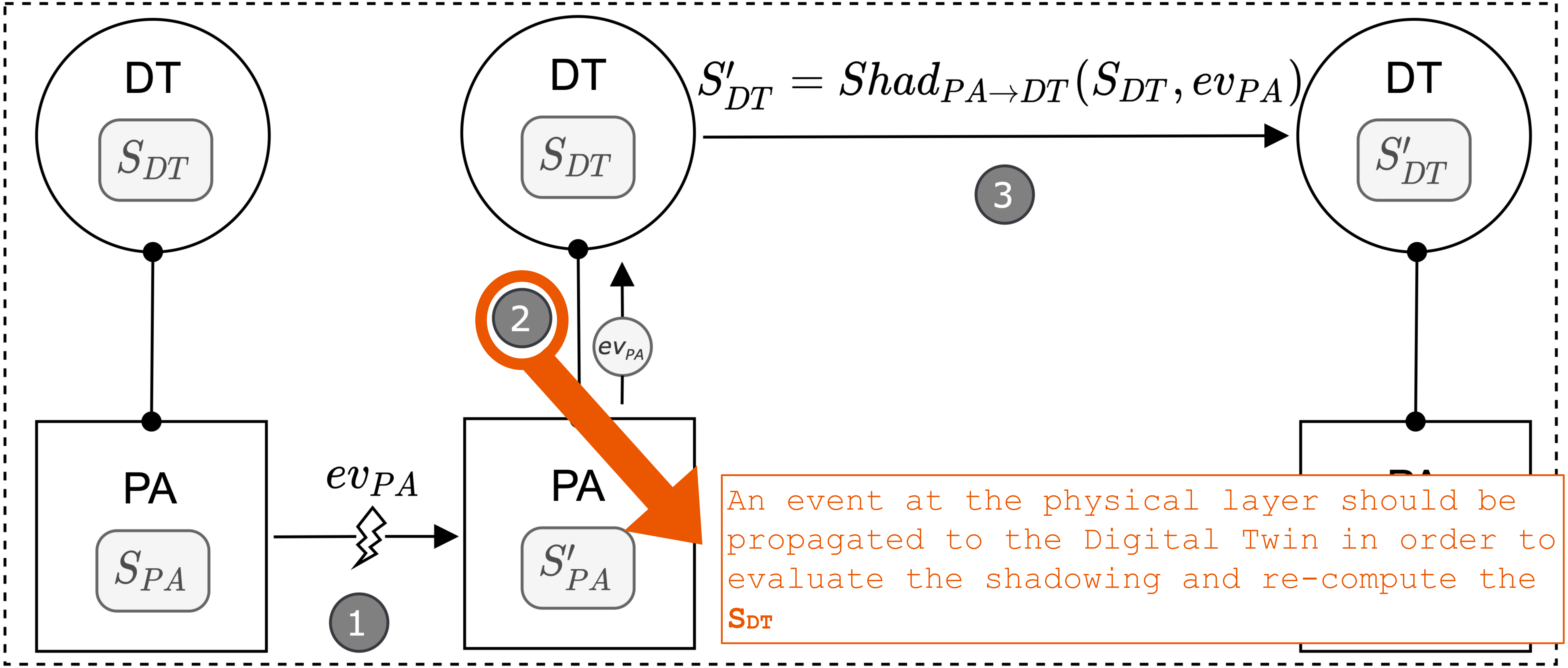
Digital Twin - Shadowing from PA to DT



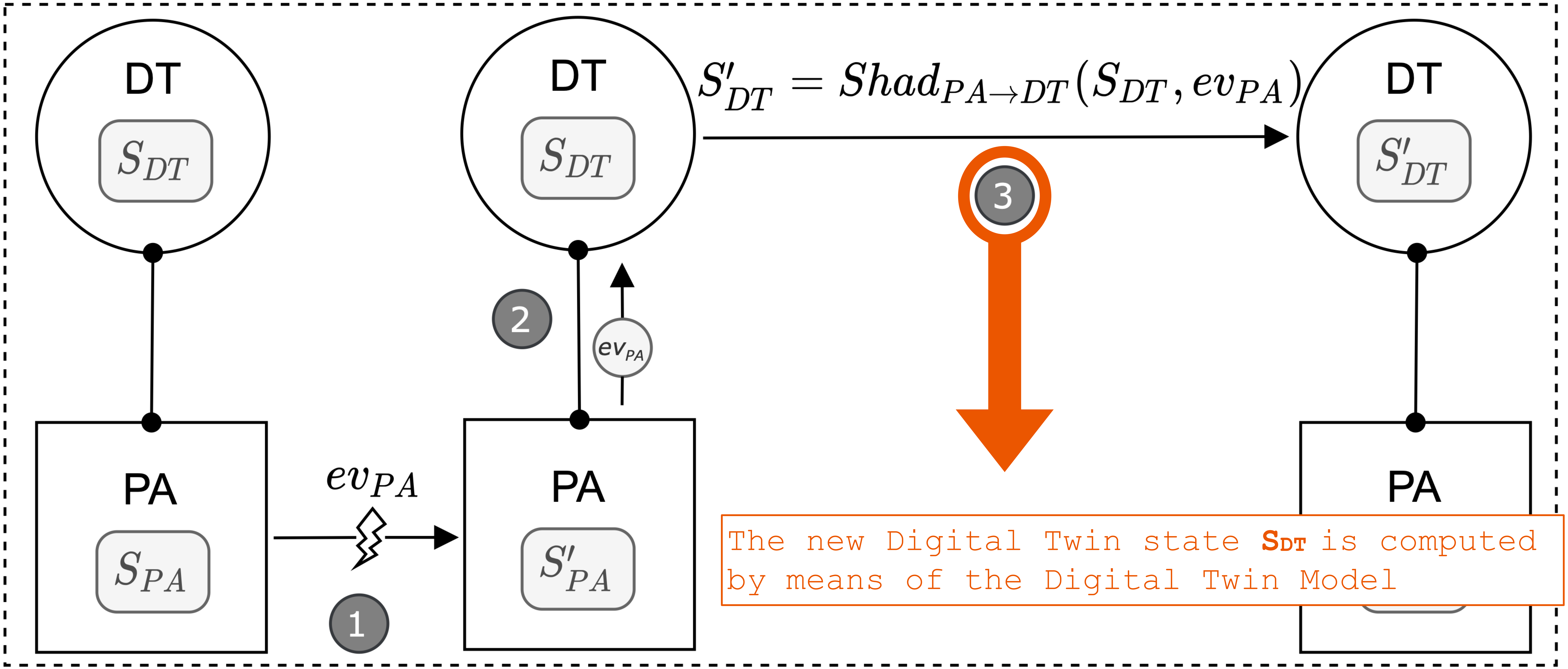
Digital Twin - Shadowing from PA to DT



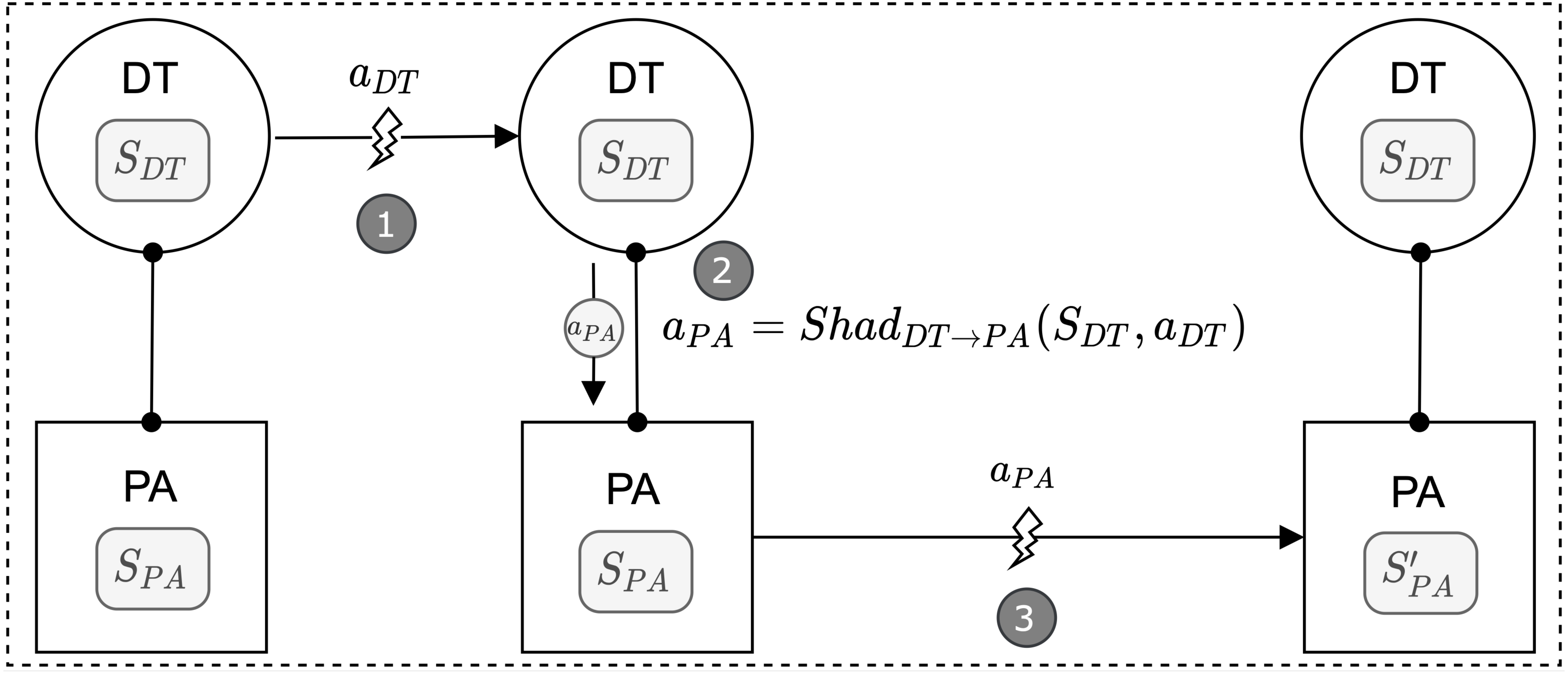
Digital Twin - Shadowing from PA to DT



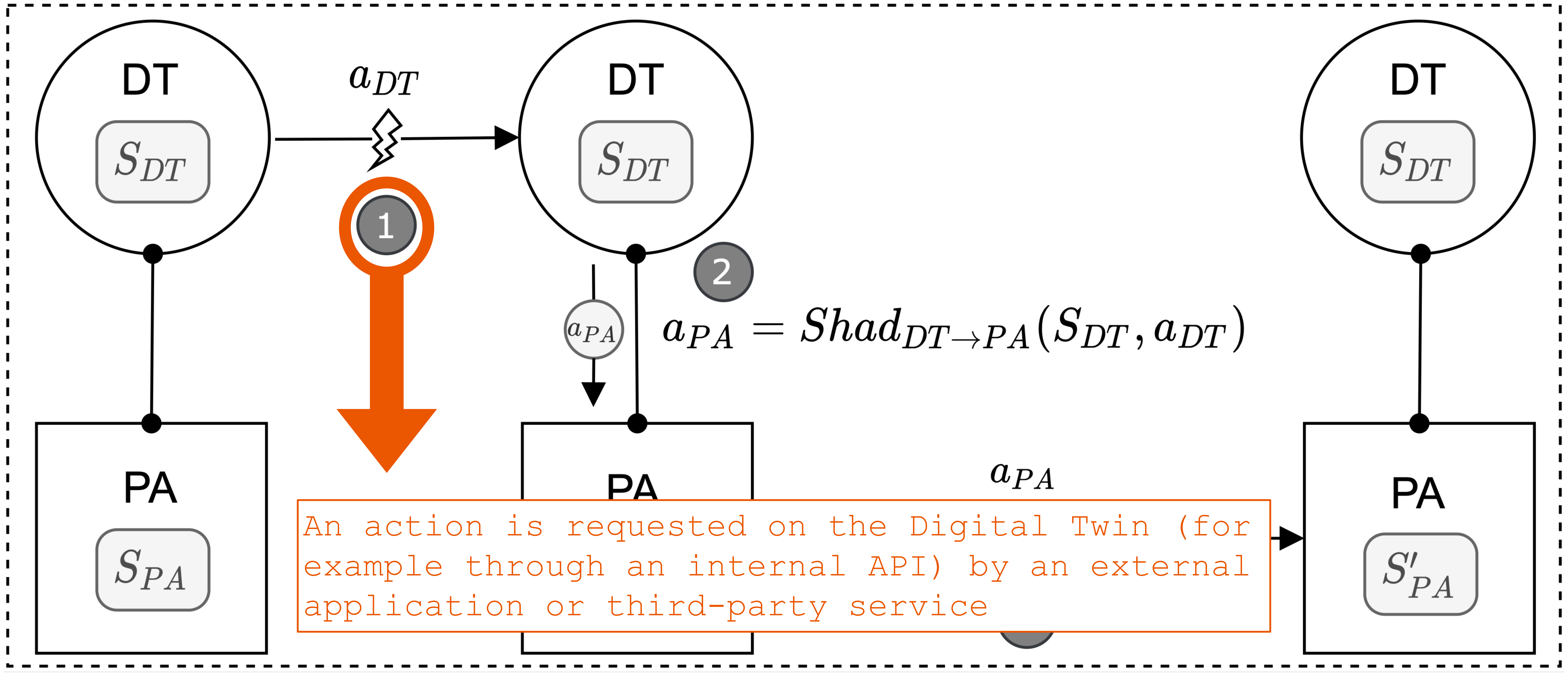
Digital Twin - Shadowing from PA to DT



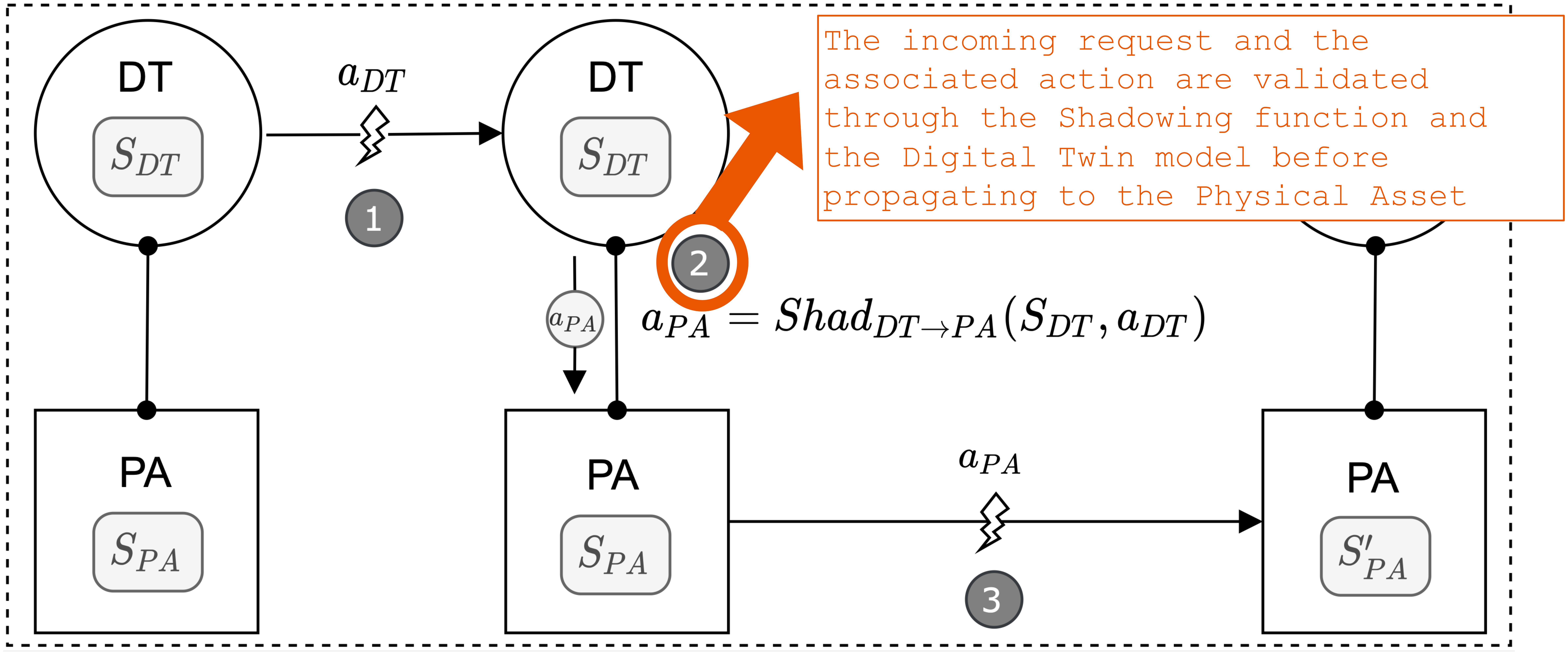
Digital Twin - Shadowing from DT to PA



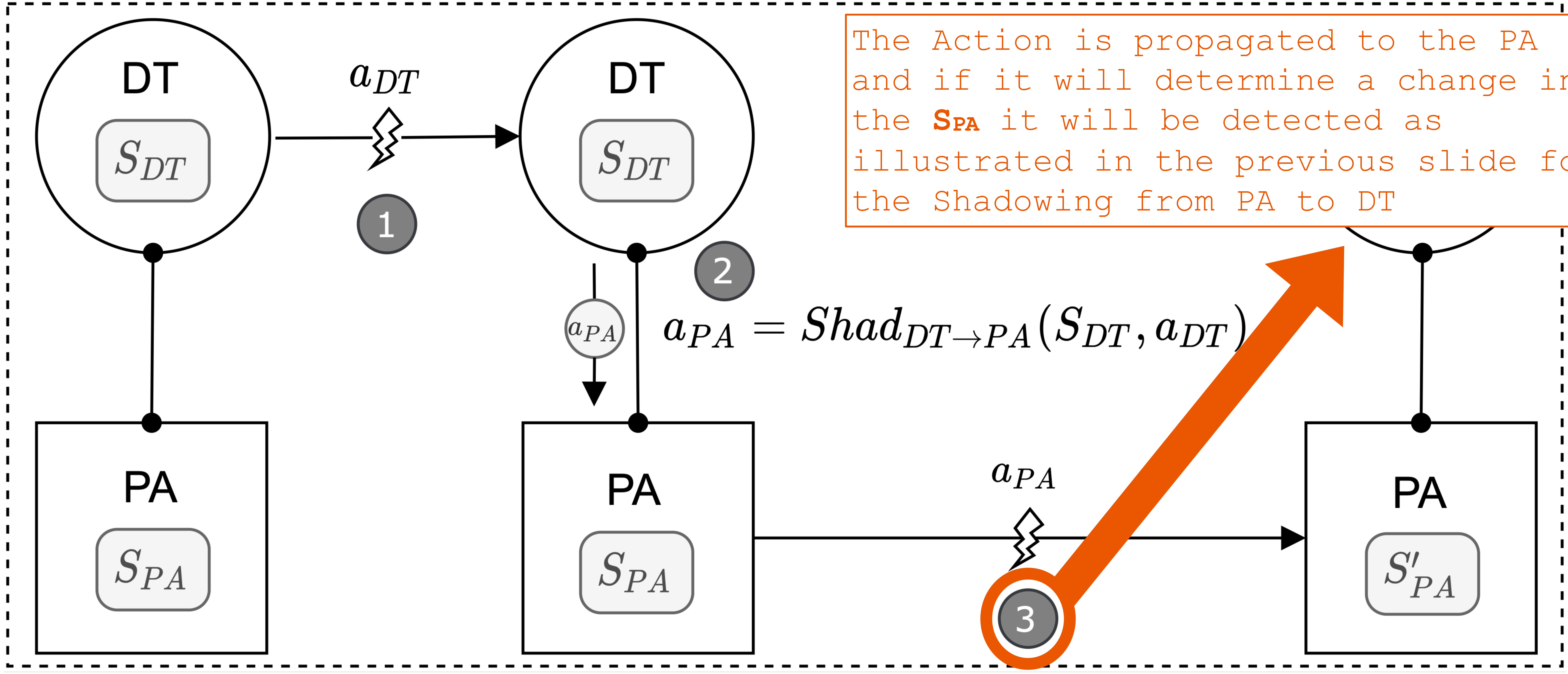
Digital Twin - Shadowing from DT to PA



Digital Twin - Shadowing from DT to PA

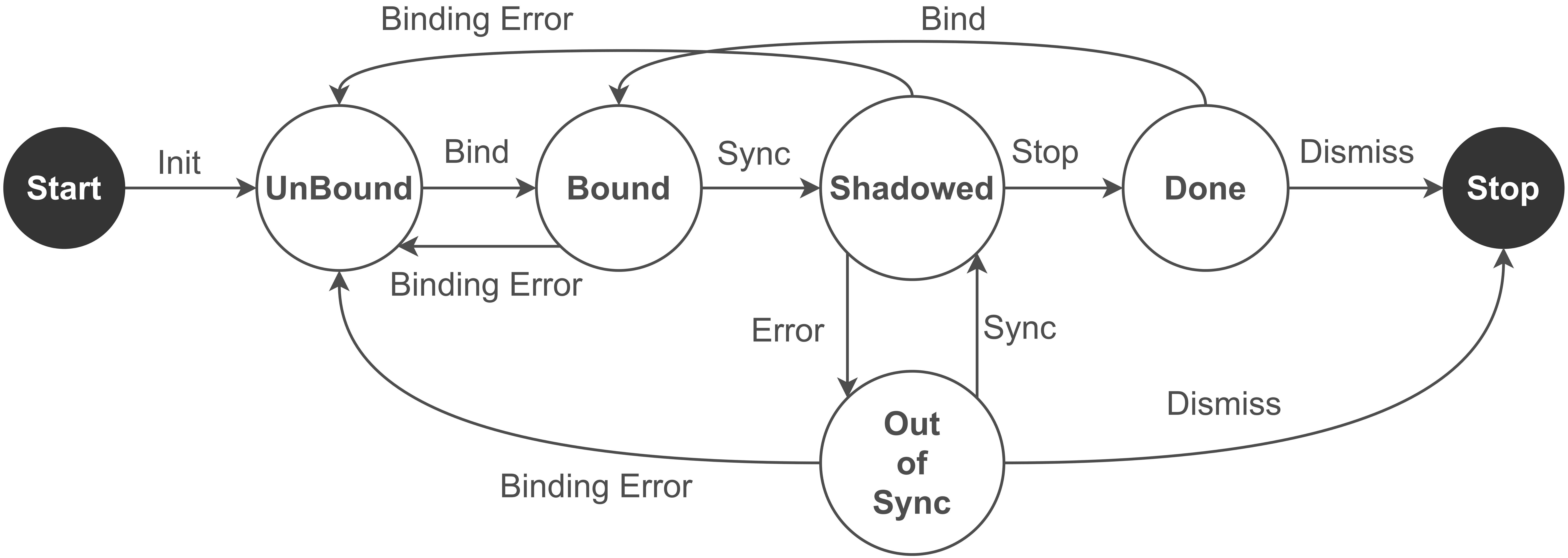


Digital Twin - Shadowing from DT to PA



The Action is propagated to the PA and if it will determine a change in the **S_{PA}** it will be detected as illustrated in the previous slide for the Shadowing from PA to DT

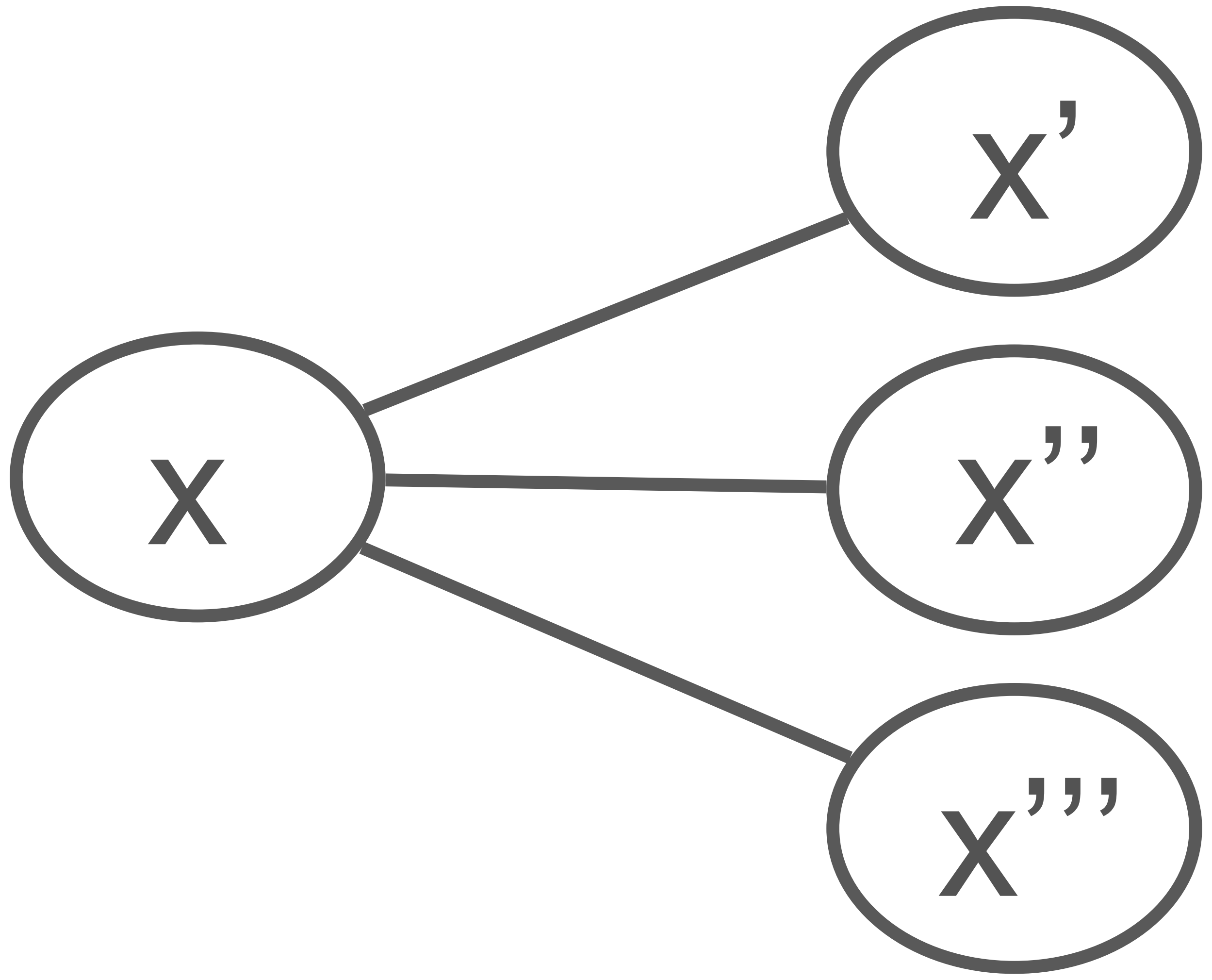
Digital Twin – Reflection – Life Cycle

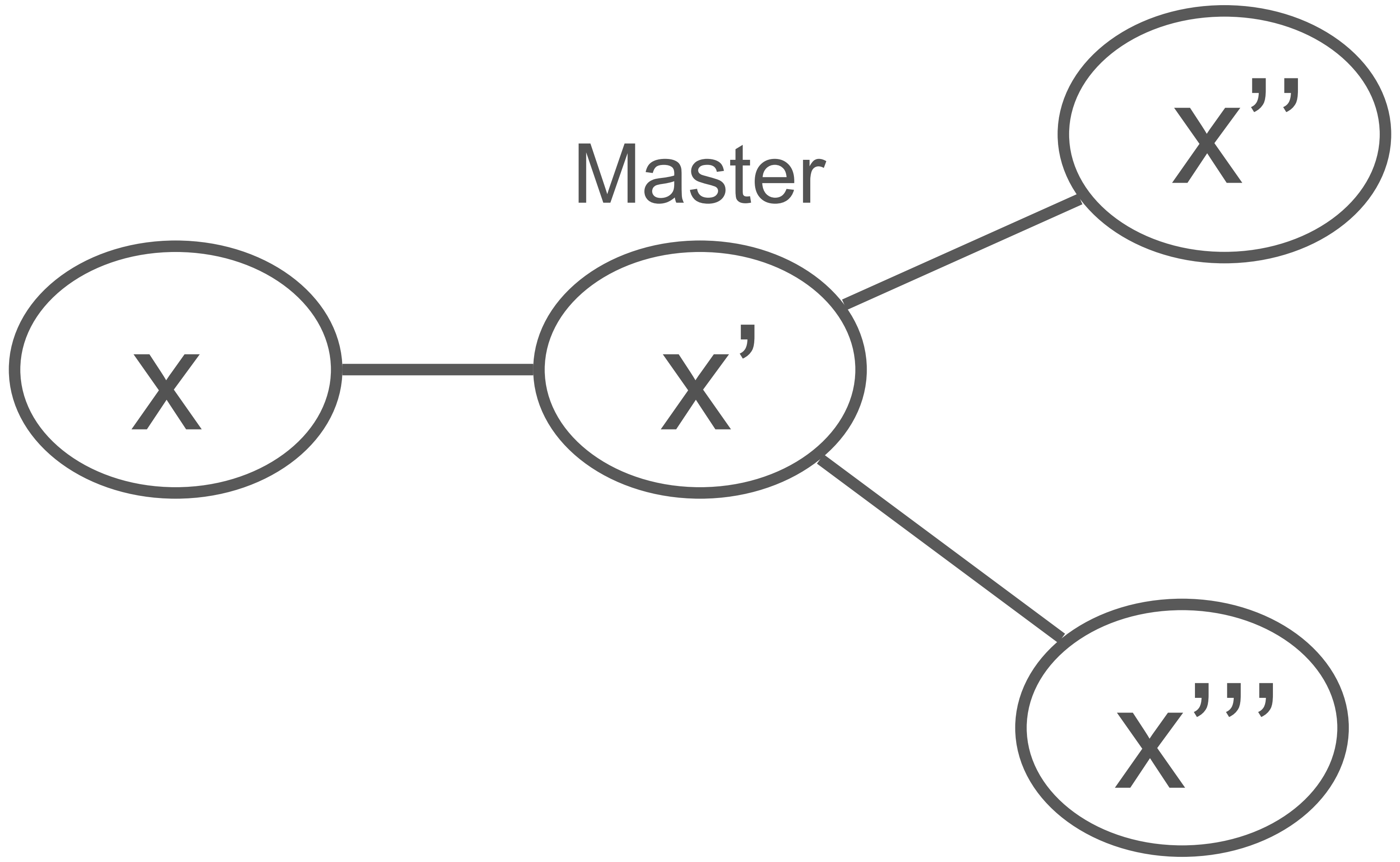


Alessandro Ricci, Angelo Croatti, Stefano Mariani, Sara Montagna, and Marco Picone. 2021. **Web of Digital Twins**. ACM Trans. Internet Technol. Just Accepted (December 2021). https://doi.org/10.1145/3507909

Digital Twin - Replication

- This is the general ability to replicate an object into a different environment
- **A physical object can be virtualized and replicated several times in a virtualization space**
- Essentially, **physical objects can be softwarized, i.e., cloned**, several times, and each logical object can itself be replicated as well
- We may have different replication techniques for example associated to:
  - **One-to-One Synchronization:** each digital object is directly in synch with the original physical entity
  - **Master-Slave Synchronization:** a logical object acts as a master replica by keeping the synch with the physical counterpart and maintaining at the same time synchronized the group of connected replicas (slaves)

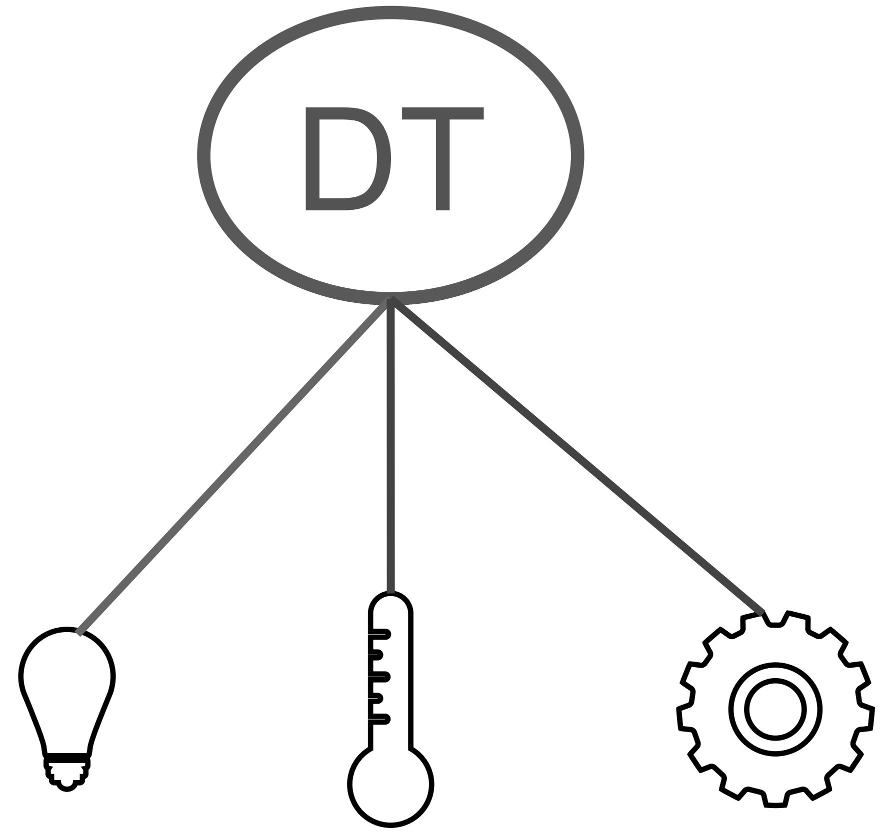


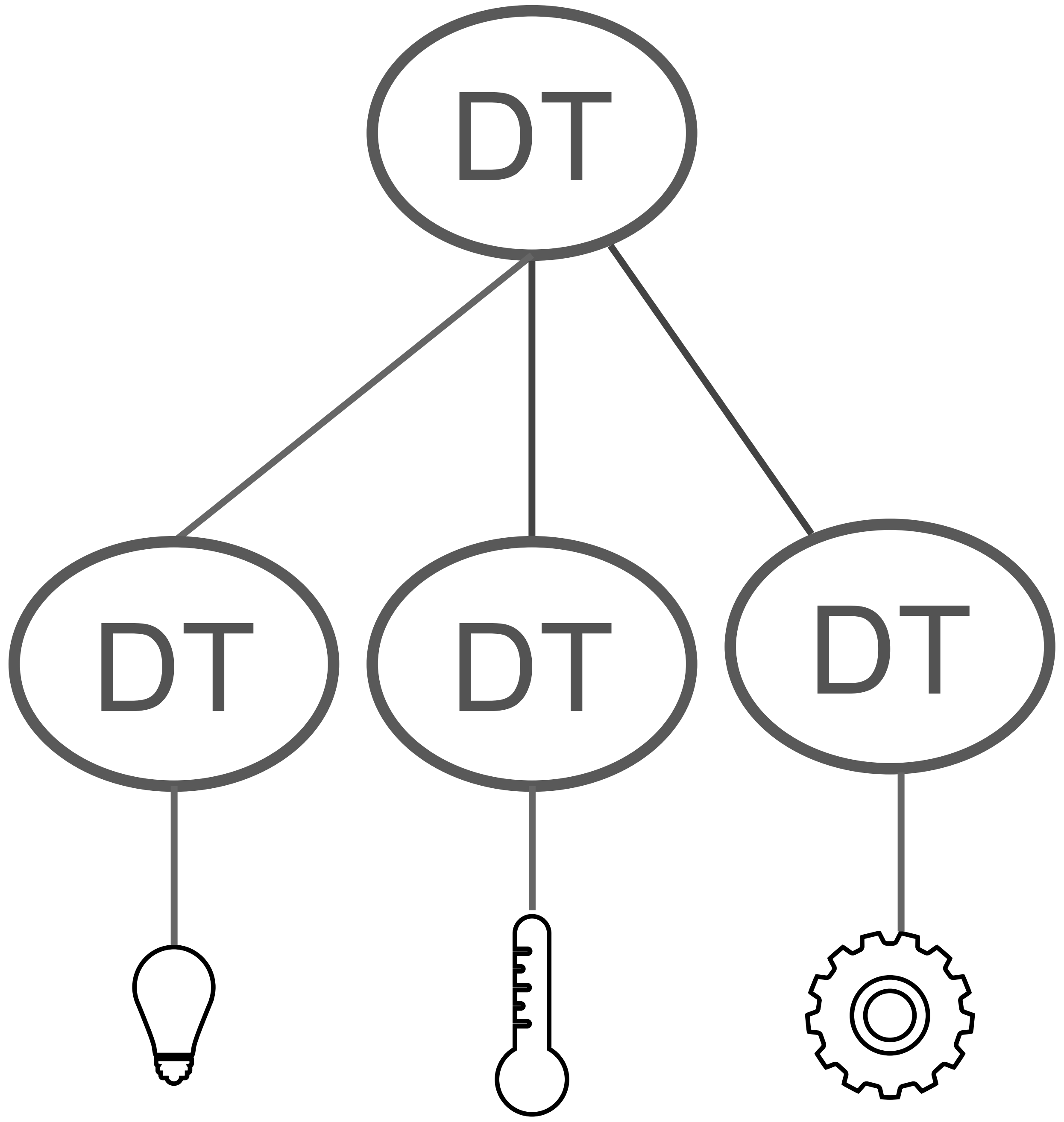


$X \equiv X' \equiv X'' \equiv X'''$

Digital Twin - Composability

- In general, objects can be seen as groupings of sub-parts (sub- objects) or as the combination of several individual objects
- For example a car could be considered as a single object, but it can also be seen as the aggregate result of a combination of different objects such as: i) the brake system; ii) the transmission; iii) the power production
- **Composability also represents the ability to abstract the complexity of a large system and to focus on a few relevant, for specific applications, status and behaviours of the entire system without having to consider the functioning of all the aggregates' sub-systems**
- Through DTs we can obtain composability both if the **DT is directly connected to multiple physical devices** or if a **DT is "linked" with other DTs to represent complex relationships** such as the IoT device *inside* a Room *within* a Building



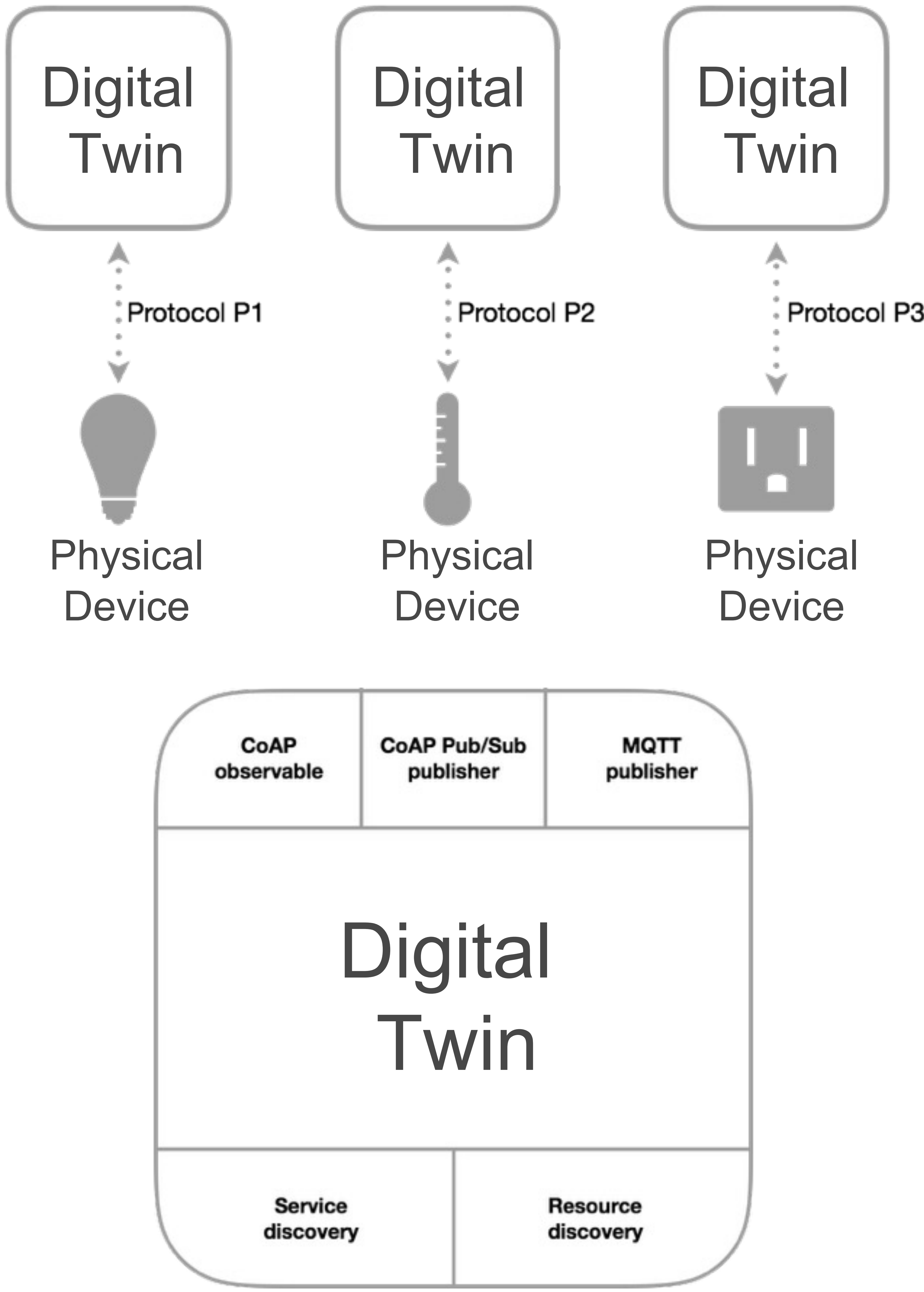


Digital Twin - Composability, Linking & Orchestration

- **Orchestration** is an essential function in order to **govern** the aggregations and composition of Digital Twins
- **Simulation theory** and **agent-based simulation and modelling** technologies for large systems can play a key role in representing the behaviour of a large system composed of different interacting Digital Twins
- In this challenging context multiple technologies and representations can (must) be used at the same time to characterize, identify, manage, and improve both internal DT processes and how it is able to communicate and interact with other twins and external applications and services
- **A large composition of Digital Twins could become the definition of a large system of systems, and hence reliable approaches to complexity are needed [OPEN CHALLENGE]**

Digital Twin - Augmentation

- **Physical objects come with well-defined functionalities and services that are fixed for the entire life cycle of the object**
- Even if they do not have processing capabilities, they may have limitations due to constraints and costs related to manufacturing processes and materials
- The DT can leverage the **software dematerialization** in order to **modify**, **update**, **improve its functions over time**
- In other words, **the physical object can be functionally augmented through the implementation of update or new functions and features in the DT** (e.g., in Big Data, IoT Connectors, Multiple Protocols Management, Augmented and Virtual Reality, etc …)



Digital Twin - Augmentation

- New DT's features will be **software-based** and take the form of innovative and more intelligent functions enabled by **APIs** or by the analysis of datasets related to the physical object
- By means of new APIs, a set of physical objects, through their logical object counterparts, can be made **interoperable within a complex environment** in order to cooperate and achieve specific business results
- Augmentation can be achieved by using the Digital Twin's data and by the **exposure of APIs for controlling, governing, orchestrating or simple-querying the Digital Twin**

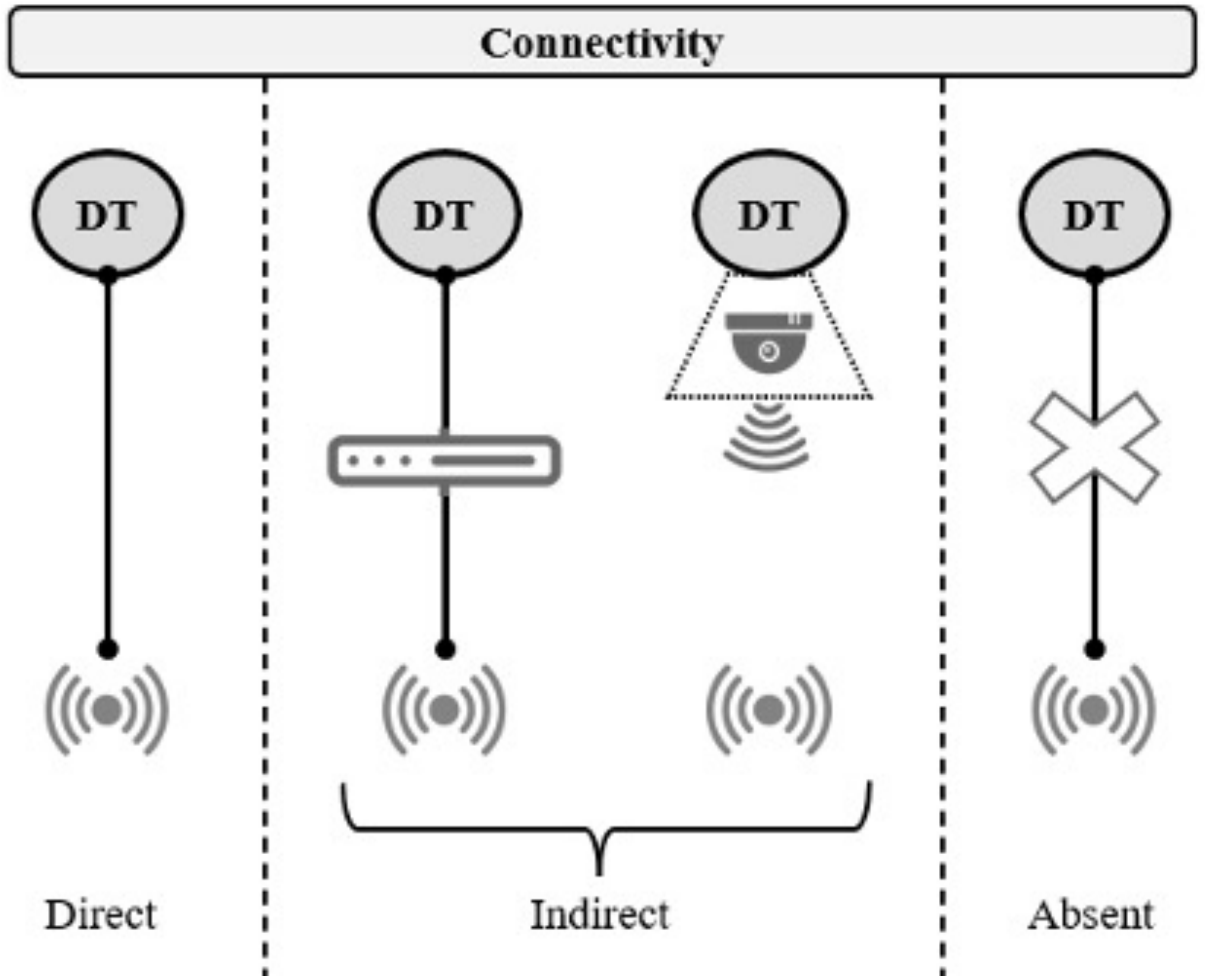
Digital Twin - Entanglement

- The Digital Twin concept represents the linkage between a physical object and its logical one. This means that **all the information that fully describes the object must be passed to the logical replica**, and in real (or very close to) time. The logical replica makes this information available to the applications and services
- This communication relationship is termed here entanglement because it refers to the **instantaneous exchange of information between two closely related entities**. This entanglement characterizes the physical and the logical objects and so at least three properties must be considered:

- **Connectivity**
- **Promptness**
- **Association**

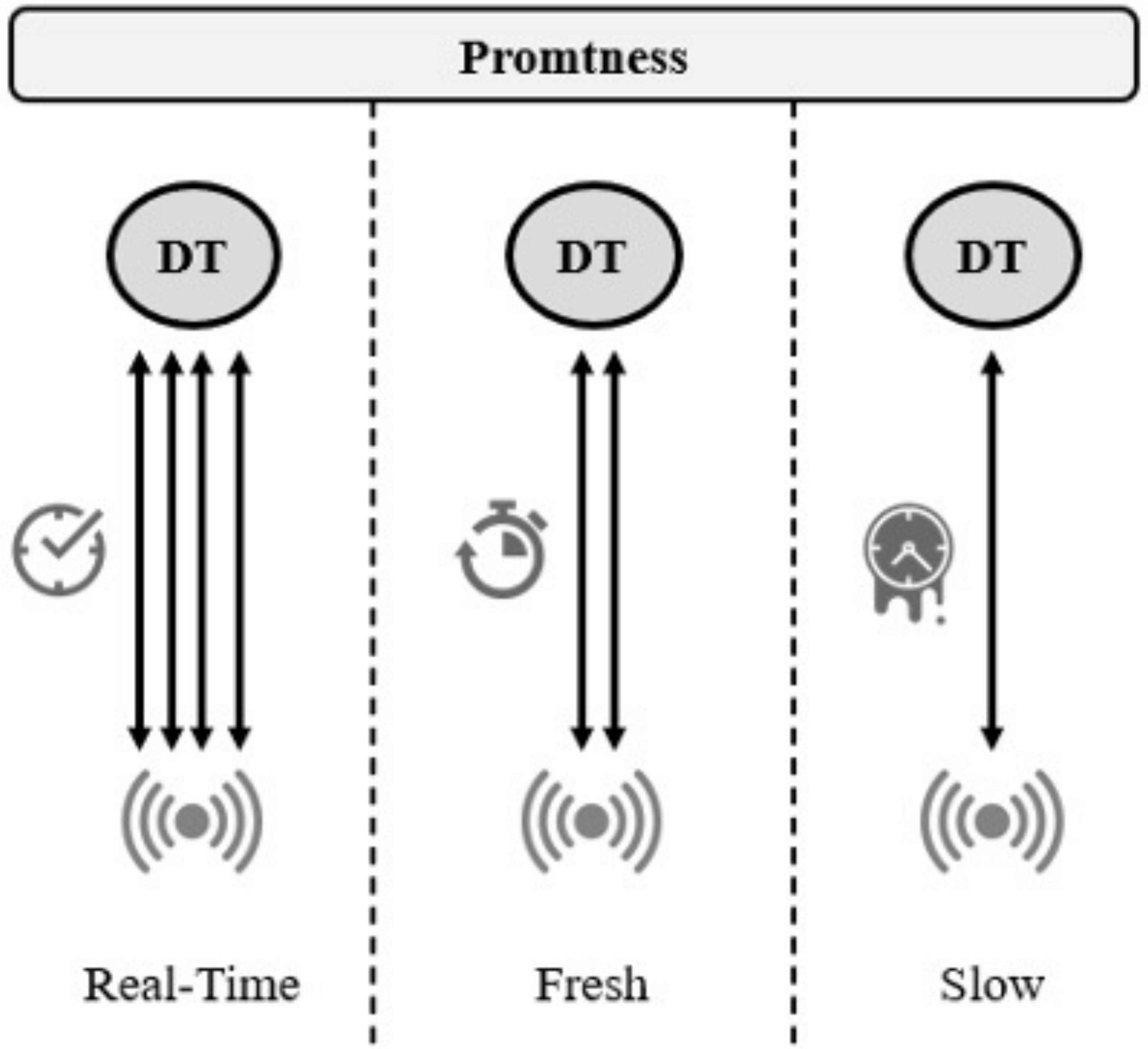
Digital Twin - Entanglement - Connectivity

- There should be a direct or indirect way to communicate the changes of status and related data between the physical and the softwarized logical objects
- **Transmission** can be **direct**, i.e., the physical and the logical objects are capable of direct communication; or **indirect**, i.e., the two communicating objects relay on a third party for sending and receiving information.
- Not all of the physical objects are capable of communication or processing. In this case, communication can occur by means of other objects that are capable of directly observing and determining the status of a physical object and then feed that information to the logical object of the observed physical entity.
- *For instance, the status of an object can be monitored by means of a camera and/or sensor, with any relevant information extracted from the multimedia flow and passed to the logical object.*



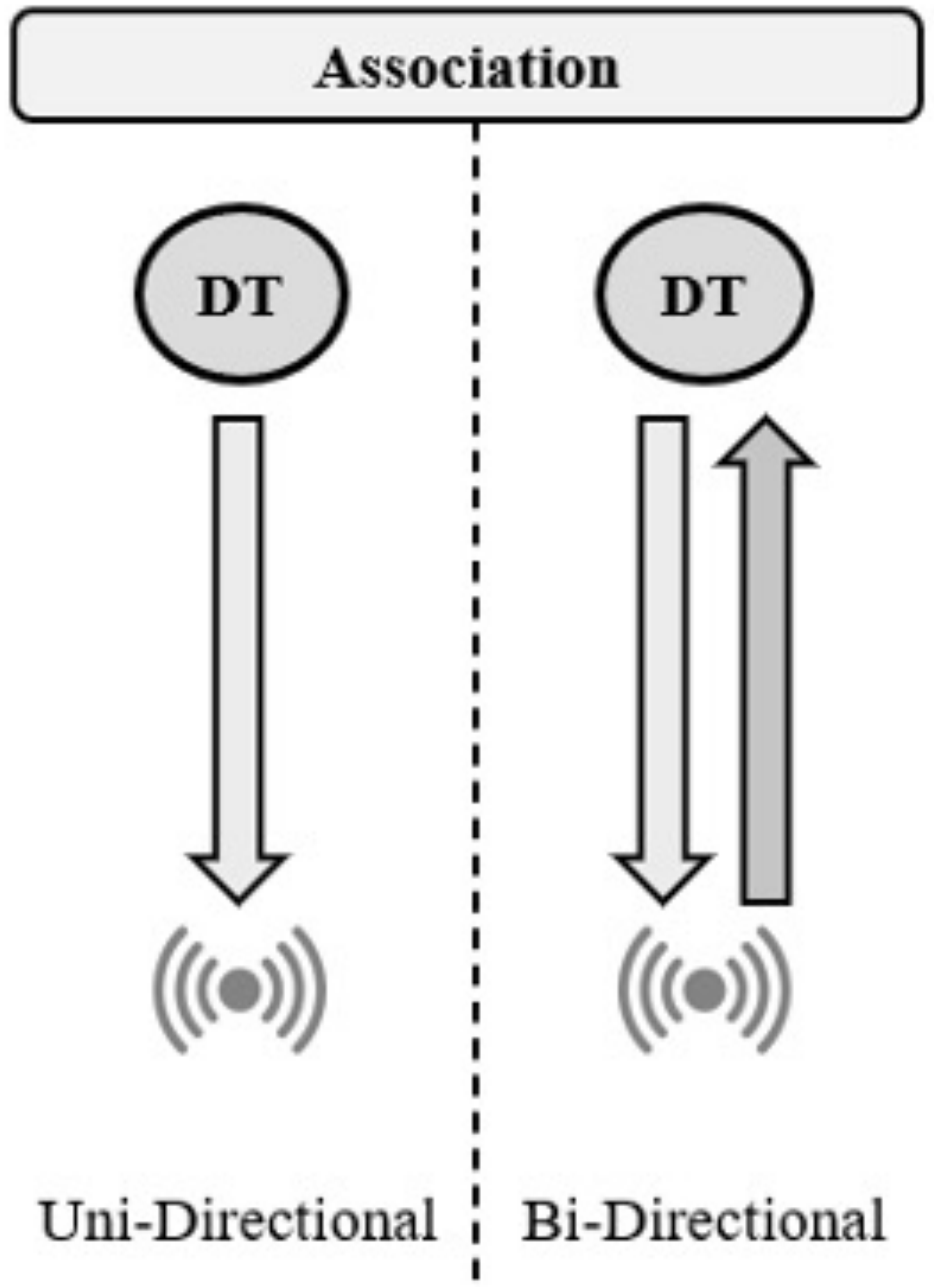
Digital Twin - Entanglement - Promptness

- The **exchange of information** between physical and the logical objects **should be timely** -> in a way that the time between the changes of states of the physical object is negligible with respect to the needs and intended usage of the logical object by applications or users
- For instance, if the entanglement is between a physical parking lot and its logical object, the information about the parking lot occupancy should be exchanged in less time that the time needed for a car to enter or leave the parking
- For some physical objects, **real-time processing**, communication and storage capabilities could be required in order to properly keep track of the events and changes in status, while for other objects updates within seconds or **even longer (daily) periods may be acceptable**
- As a reference rule -> the average time elapsed between two changes of status should be intended as the upper limit interval for sending updates to the other object. For some objects, a very short interval for synchronization may be a stringent requirement for the use of the Digital Twin approach, e.g., medical applications, robotics, Industrial Internet applications and the like



Digital Twin - Entanglement - Association

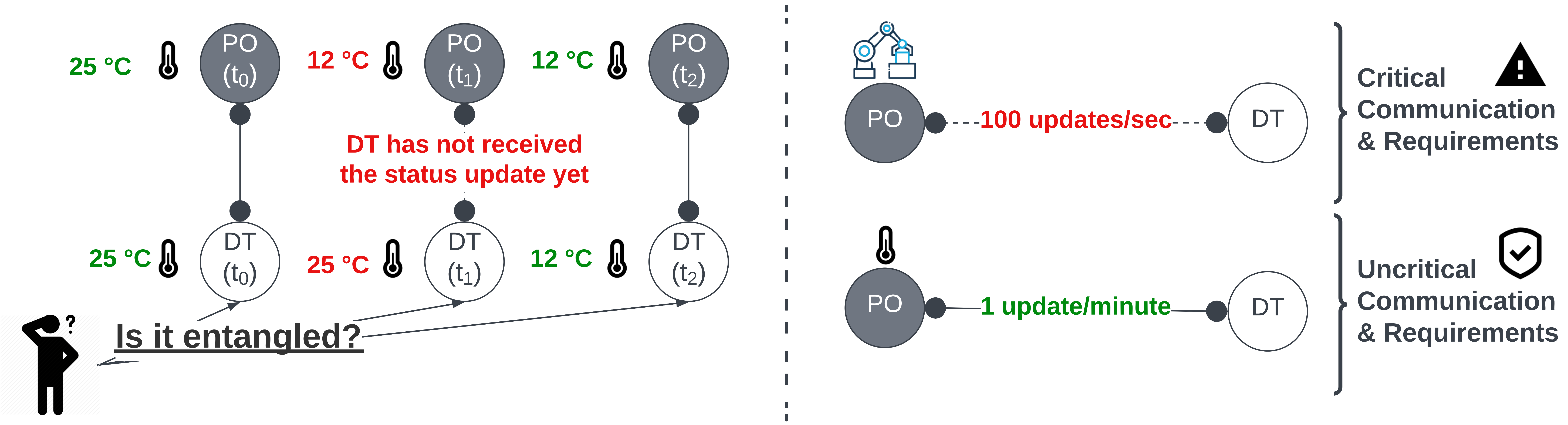
- The relationship between physical and logical objects can be:
  - **unidirectional ->** from the physical to the logical object (e.g., a sensor sending data), or from the digital to the physical object (e.g., the LO of an actuator is sending commands to its PO);
  - **bi-directional ->** a continuous exchange of status information between the objects. Typically, the intended direction of communication is from physical to logical
  - However, for physical objects that are instrumented, there could be a great value in supporting bidirectional communication. The physical object could provide relevant status information, and the logical object could provide relevant updates and adjustments to the physical one to improve its functioning.



Digital Twin - Entanglement

- Entanglement is a fundamental property that strongly characterized the concept of Digital Twin and that can be divided in three main options:
  - **strong ->** when the physical object is **constantly linked to the logical one.** The link is **bidirectional** and the logical object has the ability to modify or update the status of the physical object
  - **simple ->** the communication is **unidirectional or it is not real time**, or the linkage **may be interrupted for a certain time**
  - **weak ->** this form of association between a physical object and its logical object can be established when **data and information about a physical object are inferred** and derived by the analysis of data stemming from the environment **around and external to the specific physical object**

Digital Twin – Entanglement – Can we trust DT ?



Can we rely on traditional network metrics ?
Do we need something more related to the cyber-physical relationship between the DT and the PO ?

Example

Context: Network Delay = 1 Sec

Question: Is it a problem for an application observing and interacting with the DT ?

P. Bellavista, M. Fogli, C. Giannelli, M. Mamei, M. Picone, **Measuring Digital Twin Entanglement in Industrial Internet of Things**, IEEE International Conference on Communications (ICC), 28 May – 01 June 2023, Rome, Italy

Digital Twin – Entanglement – Can we trust DT ?

Timeliness
How fresh the collected data are

$$T(100\ ms, now - 5\ m, O) = 0.99$$

Reliability
The ratio of the received status updates to the expected ones

$$R(now - 5\ m, O) = 0.8$$

Availability
The expected up-time of the PO from the perspective of the DT

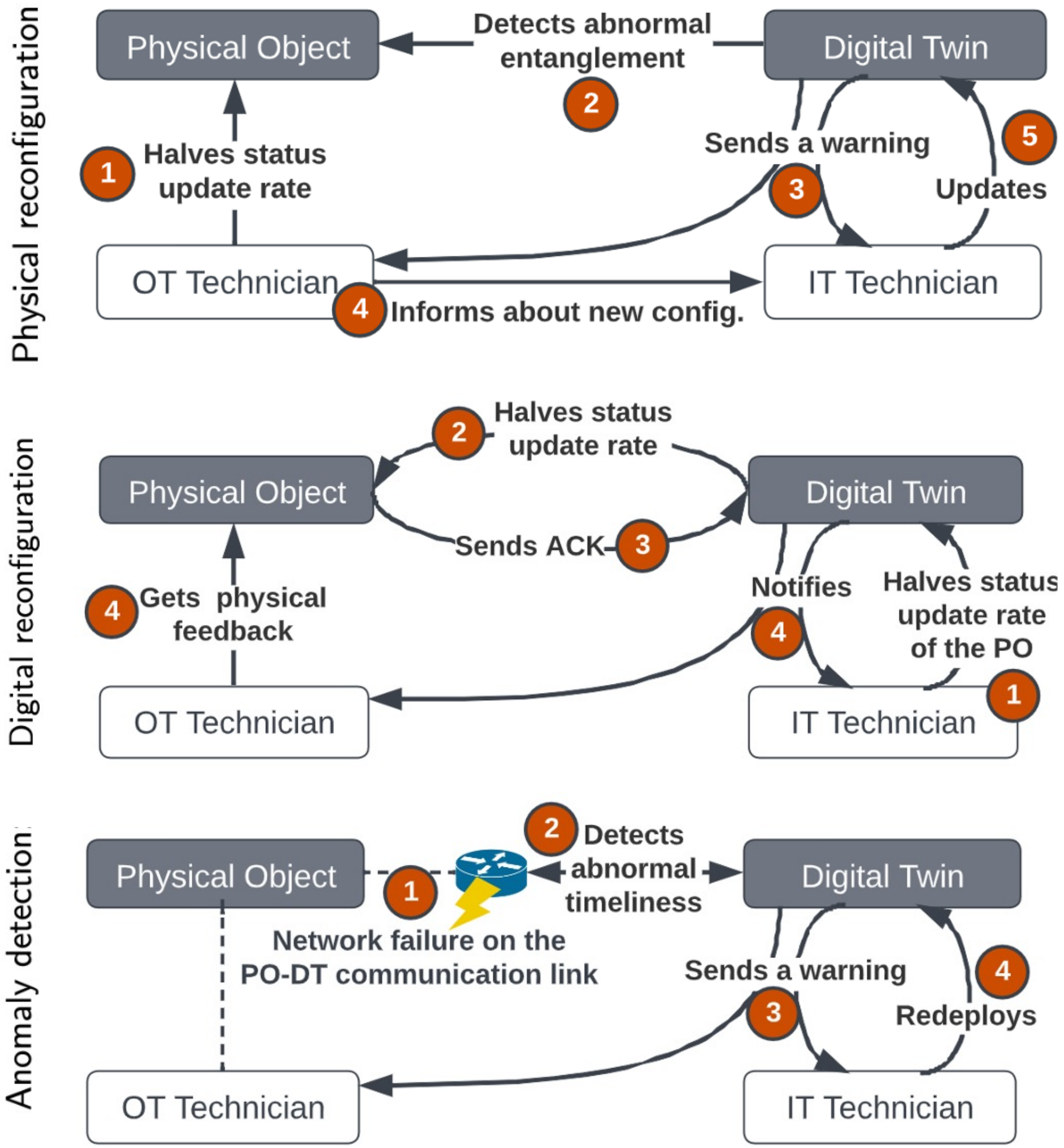
$$A(now - 5\ m) = 0.5$$

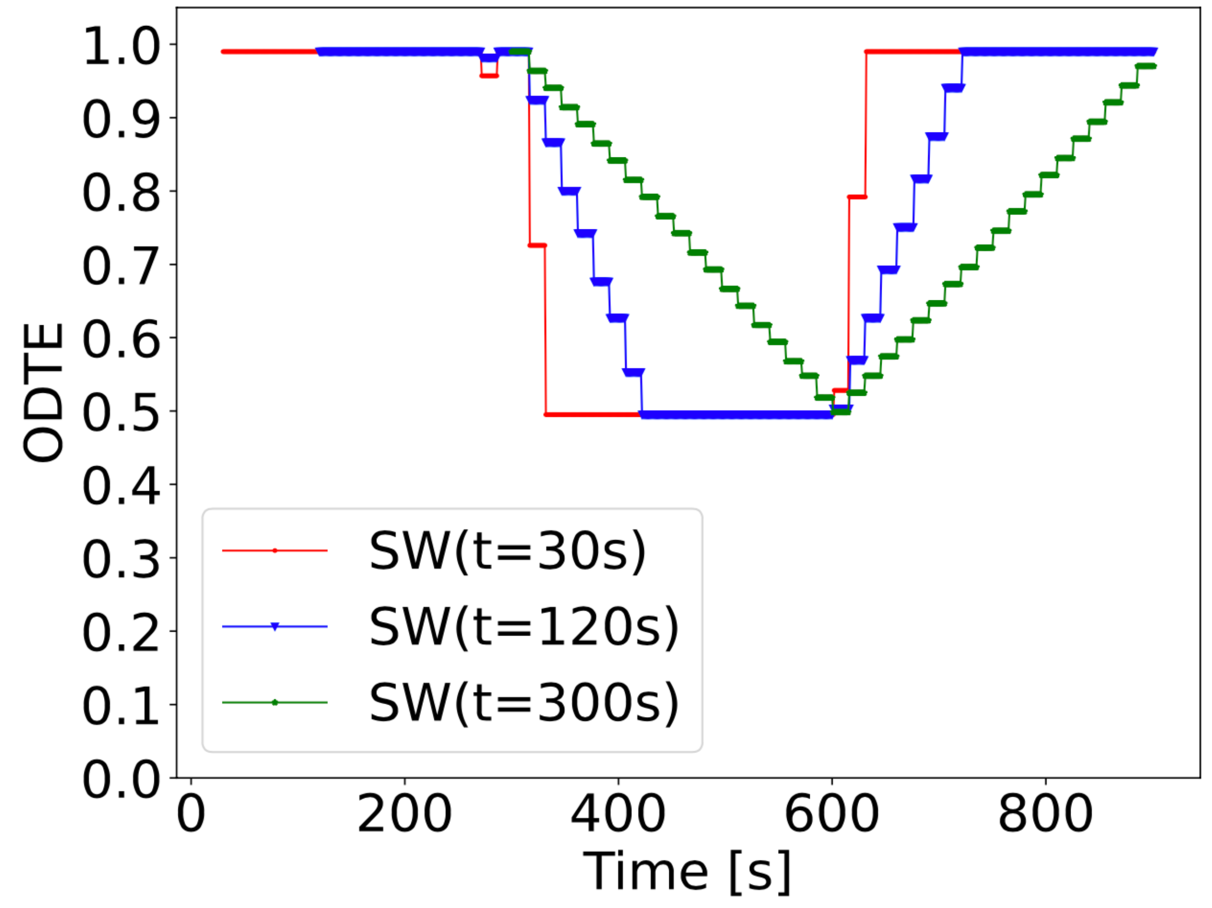
Putting it all together: **Overall Digital Twin Entanglement** (ODTE)

$$ODTE = Timeliness \times Reliability \times Availability$$

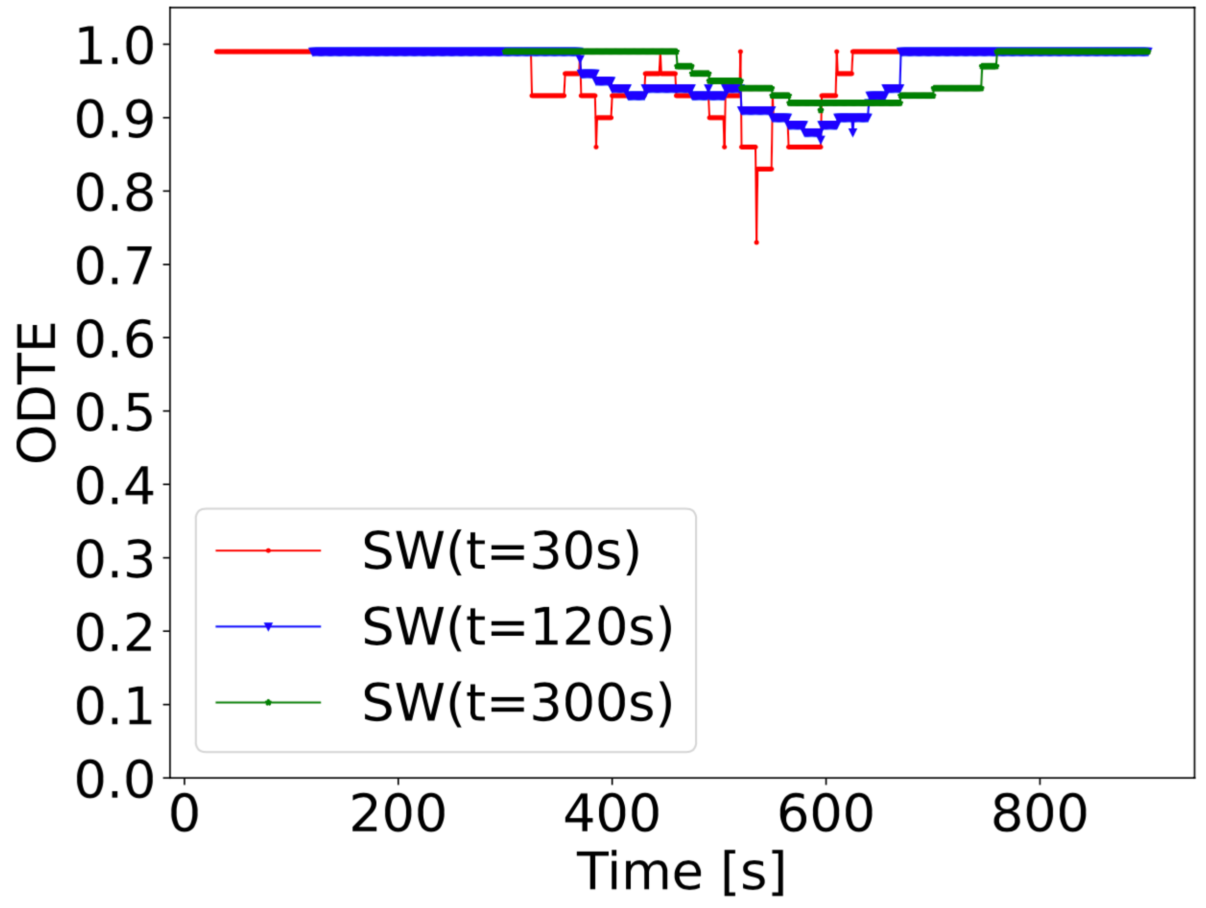
P. Bellavista, M. Fogli, C. Giannelli, M. Mamei, M. Picone, **Measuring Digital Twin Entanglement in Industrial Internet of Things**, IEEE International Conference on Communications (ICC), 28 May – 01 June 2023, Rome, Italy

Digital Twin – Entanglement – Can we trust DT ?

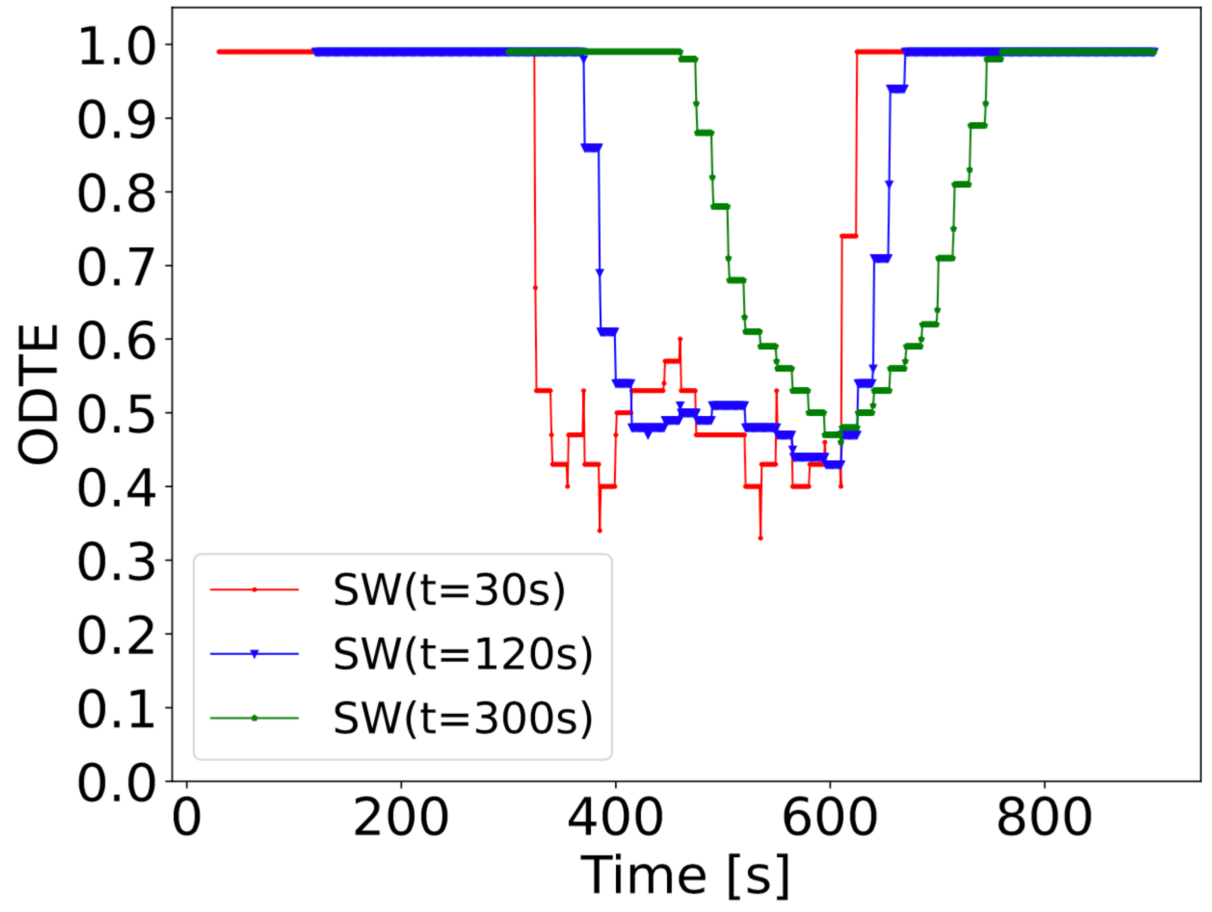




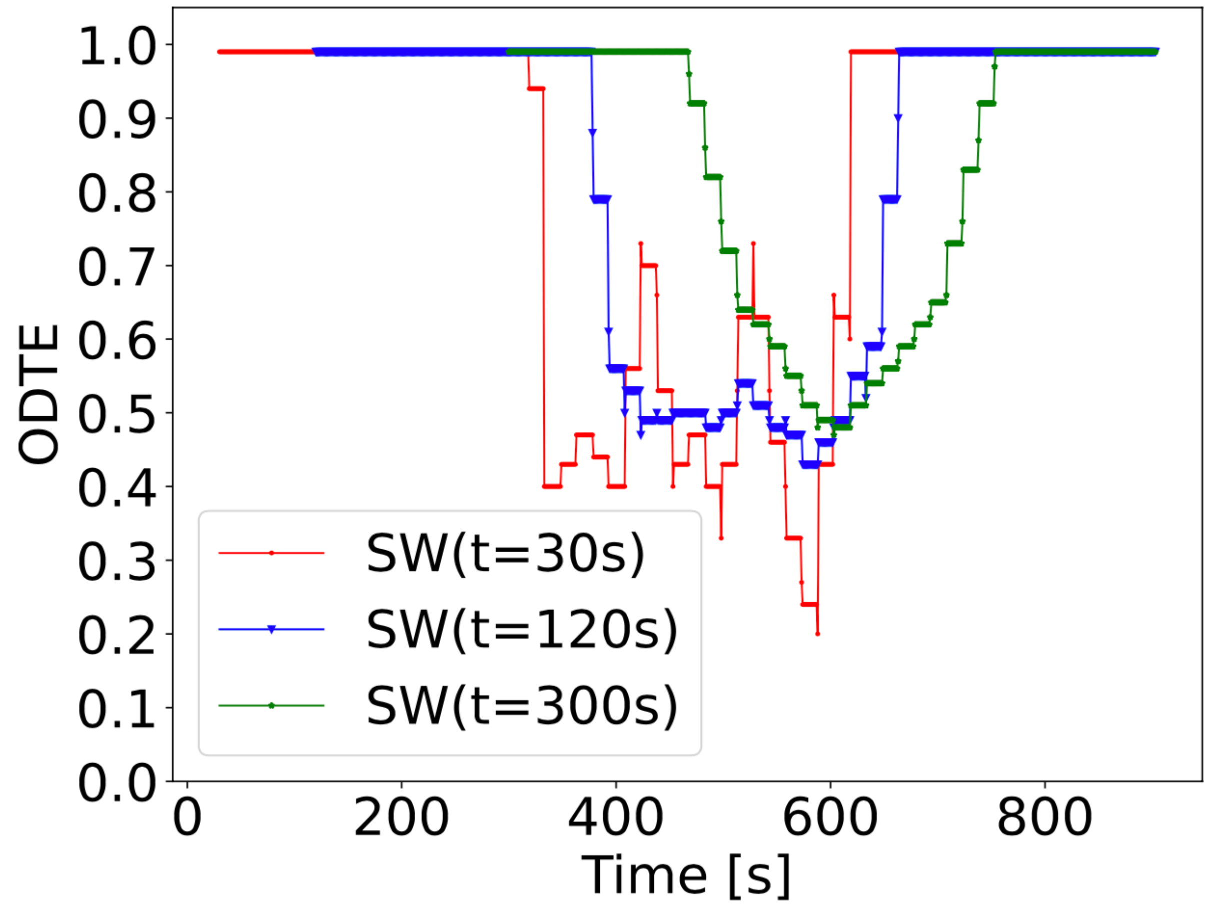
Physical reconfiguration



Digital reconfiguration



Anomaly detection: Latency



Anomaly detection: Latency & loss

P. Bellavista, M. Fogli, C. Giannelli, M. Mamei, M. Picone, **Measuring Digital Twin Entanglement in Industrial Internet of Things**, IEEE International Conference on Communications (ICC), 28 May – 01 June 2023, Rome, Italy

Digital Twin - Persistency

- This property refers to the fact that the **Digital Twin should be persistent over time**
- The physical object can have real world limitations that limit its functioning while the logical object should be able to **compensate and mitigate these limitations and to support a constant availability (and serviceability) of the DT**
- The **logical object** within the DT is the main enabling factor for this property, it has to be persistent and resilient in order to be **always available.** It is the main instance within the DT, and **its states and values should be the reference values for the applications**
- **In case of malfunctioning** or other problems with the physical object, **the logical object** should be the **source of information** for re-establishing and **synchronizing** the physical object to an **acceptable and meaningful state**

Digital Twin - Memorization

- The properties of **contextualization** and **representativeness** introduce another important feature of the Digital Twin, i.e., **the ability to store and represent all the present and past data relevant for the DT**
- These data characterize and describe both the current state and the past behavior of the DT
- This concept brings with it some important issues:
  - *how much of the complex context in which the physical object is immersed should be considered by the digital copy ?*
  - *What are the relevant data to be stored ?*
  - *how much should it be contextualized with respect to the envisaged application of the Digital Twin ?*
  - *Should the entire context of a physical object be recreated and represented ?*

Digital Twin - Memorization

- In principle, the Digital Twin should keep a set of all the meaningful data together with their location and time indication
- If an object changes, the meaningful features of this change will be stored and the object can be analyzed in a specific period of time while considering its several locations
- However, **the relations of the objects with their environment could become very important and meaningful in the future**
- *It is important to collect and store (or be able to calculate and infer) as much as possible data*. This abundance approach is mandated because Digital Twins should capture all the facets and all the features and relationships of their physical objects with respect to the contexts and environments in which they operate.

Digital Twin - Memorization

- For instance, if an application is using a Digital Twin to monitor a home radiator, most likely its only valuable information is related to its temperature and internal pressure
- Additional and secondary properties like color, size, etc. may have little or no relevance for the context of the Smart Home applications
- <u>It is essentially up to the applications to select the aspects and facets of data that are meaningful for the goal at hand among all that are available and stored</u>
- However, the DT should be programmed for abundance and completeness of its associated data set. It is important to store and preserve a large amount of raw data that could be better used with future techniques and tools.
- **The DT datasets are to be used in two ways:**
  - **to understand the behavior of the object within its operational space**
  - **to predict its possible behavior in the same space or in other environments**

Digital Twin - Memorization

- **Contextualization** in this case means to **organize data** in such a way to be able to **represent**, **discover** and **manage new dimensions or relationships of the logical objects with its environment**.
- Considering that physical objects can last for several years, there needs to be a way to properly store and manage this amount of data in an open fashion respectful of privacy and of the ownership of people's data
- The quantity of historical information, for certain objects, increases over time and there are also new findings and new contextualization of them. **This can lead to new discoveries and identification of new relationships between**
- **Objects with memory** is a technology that tackles the issue to save the history of the 'old things' in the context of IoT.

Digital Twin - Accountability/Manageability

- This property refers to the ability to accurately and fully manage Digital Twins
- While physical objects can fail or break, logical (digital) objects should not ‘break’, instead, they should enter into a recovery state in which they are still capable of responding to queries about the physical counterpart and to show all the latest important functional values
- Logical objects should also apply policies and measures to limit the impacts and the damages to physical objects
- The logical object can be seen as a ‘flying recorder’, i.e., it is a trustworthy recording of all the states of the physical object. This feature could also be used to understand and recover the latest states of a physical object and to resume its operation.

Digital Twin - Accountability/Manageability

- A **physical object** may be subject to **management** and **accountability** processes that should be **fully replicated by the logical one**
- The **logical object** should also **guarantee** its existence beyond the lifetime of the real object and it should be possible **to manage and execute it as a virtual entity** within a highly distributed software environment.
- These requirements point to the **manageability** of the physical object as well as the manageability of a logical object, a software entity, within a virtualization space
- **Furthermore**, due to the composability property, the logical object should be part of **a larger and complex system** that can be mirrored and **monitored/managed as a whole**
- Management techniques for **large virtualized infrastructure** could be usefully adopted in these cases for example to create **specialized environments** that are **segregated** and devoted to **specific tenants**, applications and use cases (improving also security)

Digital Twin - Ownership

- Ownership is another important property of a Digital Twin and it is declined in two different ways:
  - **Data Ownership ->** The DT, as many IoT systems, produce a large quantity of data. It is important to determine and regulate the ownership and usage rights of these data
  - **DT Ownership ->** The second way refers to the ownership of the DT and in particular of the logical object. The physical objects have, typically, an owner. Their replication can create a set of logical objects that refer to the physical one, but they not necessarily share the same ownership. In addition, some logical objects can **offer different capabilities** of **interaction** or better ways to exploit the features of the physical object and, consequently, they can have **different constraints in ownership**

Digital Twin - Servitization

- Servitization refers here to the ability to **offer in the market** the association of a product with services, functionalities, processes and access to data of a physical object by means of software capabilities, tools and interfaces
- DT's servitization range from **personalization** and **customization** to the definition of a compelling set of **software functionalities** that will **complement** and **augment** the **product** and will be the major added value of a physical product
- <u>From a business perspective, the ability to create a large number of new services and functionalities on the entire Digital Twin is a great possibility for transforming existing and future products into services appealing to customers.</u>

Digital Twin - Predictability

- A Digital Twin represents large data sets of events and properties. It is intended to operate in known, well understood and embodied contexts
- It is capable of interacting with other objects
- The predictability property refers to the possibility of **embedding a logical object** of a DT in a specific environment and **to simulate its behavior and interactions with other objects in the future or during the specific period of time**
- Thanks to Artificial Intelligence IoT systems and Digital Twins can even lead to the control and simulation of the behavior of large complex systems like cities, factories, logistics networks etc …

Digital Twin - The Overall Value

- There are a few typical scenarios for the usage of the Digital Twin that can be inferred from the state of the art:
  - **Design and consolidation of products ->** Digital Twins are used to help in the design and the production phases of complex products and then used as a means to collect and check the operation of the product in order to identify variations or unexpected behavior;
  - **Prediction and simulation ->** Analyze, simulate and predict the behavior of an aggregated set of Digital Twins in order to understand, control, govern, and orchestrate the behavior of a complex system. This is supported by the collection of historical data that show the past behavior of the physical object;
  - **Physical Device's Servitization and Augmentation->** Digital clones can augment physical assets in terms of new functions and interaction with the customers, services in multiple application scenarios
- Large IoT systems, such as manufacturing or smart cities, could especially benefit from the unique properties of the DT concept

Digital Twin - The Interoperability Value & Challenge

- **The DT approach is sometimes based on a ‘closed-loop’ approach**. The focus is on representing a context and its performing entities for a specific purpose. This creates **silos of interoperability**, i.e., specialized systems that offer some level of internal programmability. They are efficient and effective for the immediate goal and tasks, but they pose issues in interoperating with other systems
- The IoT ecosystem is moving forward to support the **interoperability** of different systems and a strong push towards interoperability, often by means of **standardization**
- IoT Interoperability is possible at different levels:
  - Sensors & Actuators
  - Semantic
  - Data Structure and Representation
  - APIs
  - Protocols -> For instance CoAP and MQTT are largely used depending on applications needs and they can also be reused in DT supporting systems.

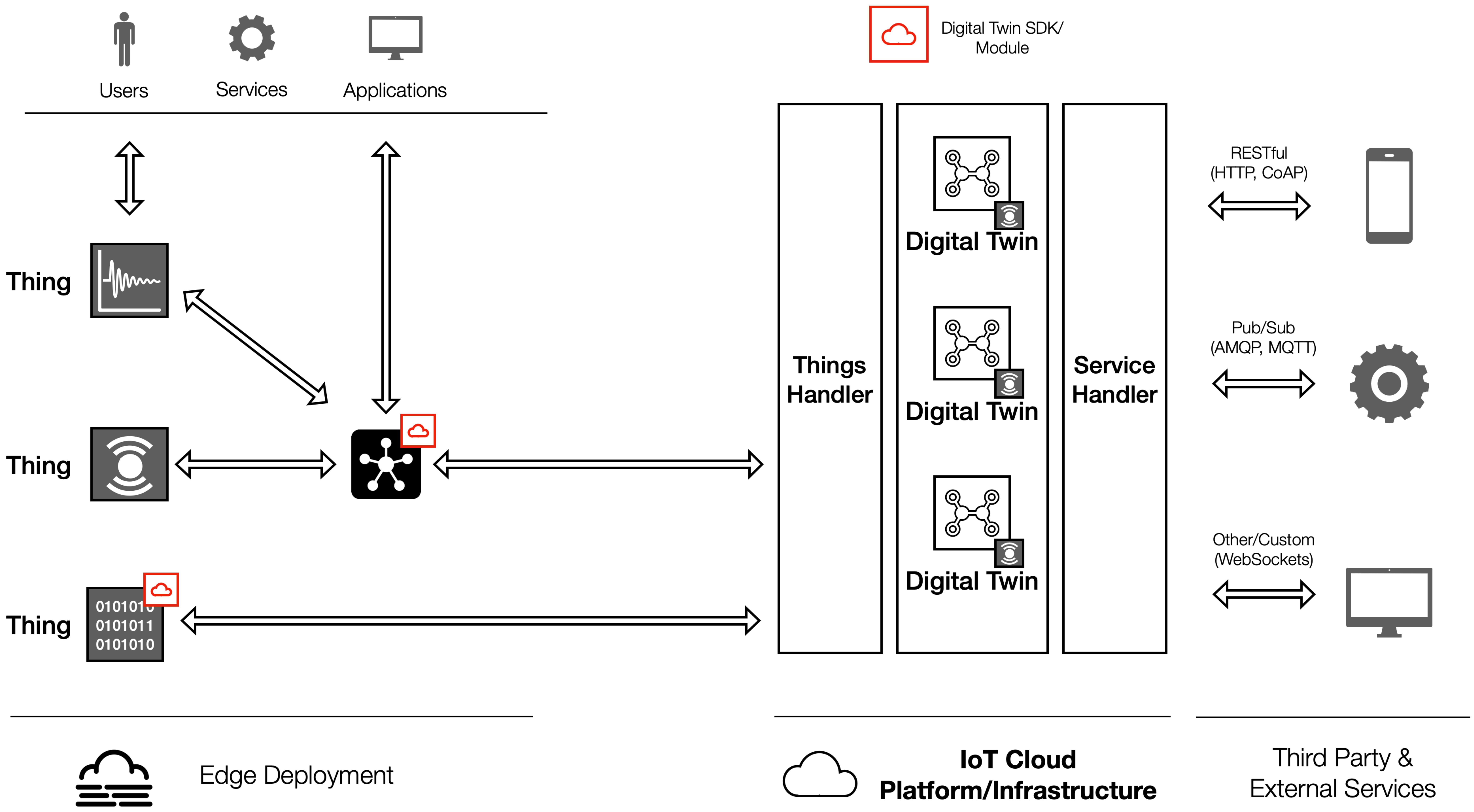
Digital Twin - Open Challenges

- Considering the analyzed features of Digital Twins some relevant issues may arise in their application in complex and larger open systems:
  - **Knowledge of the Physical World:** it is a daunting task to determine and to describe the models, laws and effects of the real world in a logical object. A deeper comprehension of the physical environments in which the physical object will operate can be difficult to realize and to represent in a virtual environment
  - **Massive Amount of Components:** large systems and products may need to represent a considerable number of parts and their dynamic behavior. Their descriptions and status changes could introduce a higher level of complexity;
  - **Siloing/Programming:** if proprietary and closed interfaces are used, it will be extremely difficult to create ecosystems of Digital Twins capable of working together and being interoperable.

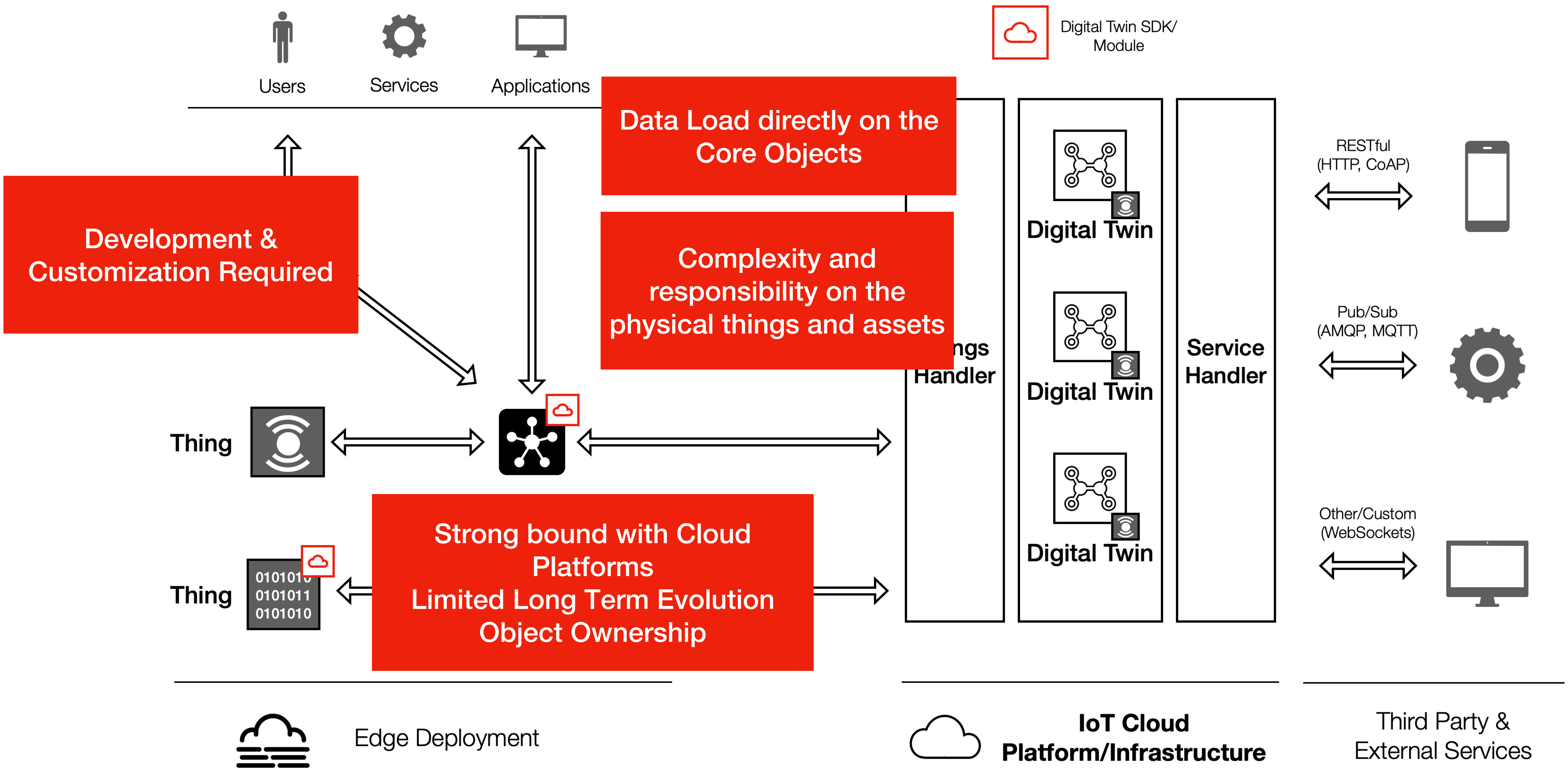
Digital Twin & Edge Computing

- The linkage between physical and digital entities is a fundamental feature of a Digital Twin
- From a practical perspective, the linkage is subject to the issue of distributed applications, always-on devices and the dependency of Internet Connectivity
- **Latency, delay and reliability issues can introduce disruption in the Digital Twin implementation and in the synchronization between the two counterparts**
- The recent advancements of **Edge Computing** represent a strategic architectural evolution promising to reduce latency and delay in such a way to enable high demanding applications (such as DT adoption and diffusion)
- Some of these applications are Industry Automation, Autonomous Driving, Healthcare, and others. These applications show requirements very similar to those of the DT. Actually, some of these applications could be well implemented by means of DT
- **From a practical perspective, the linkage between the physical and the logical object is effective if the refresh time of the status of logical object is lower than the average access time of applications using the logical object -> We should start thinking to interoperable Cloud & Edge Digital Twins**

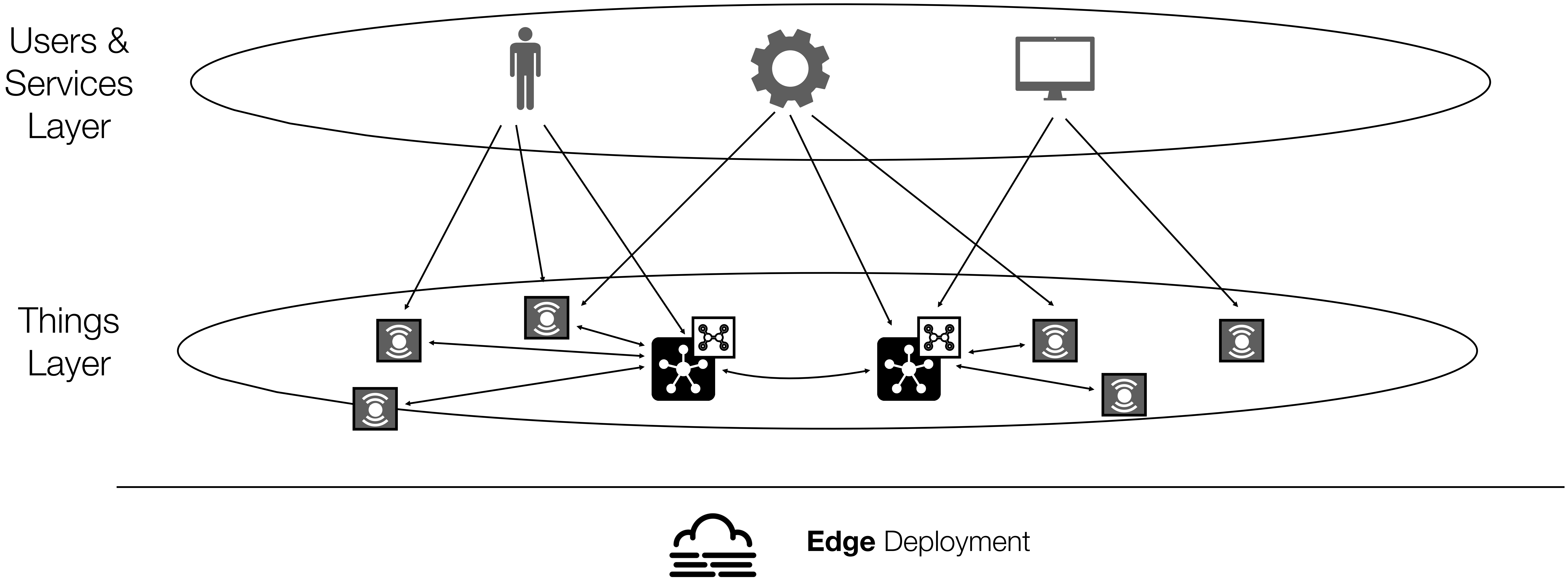
Cloud Digital Twins -> Improved Device Complexity



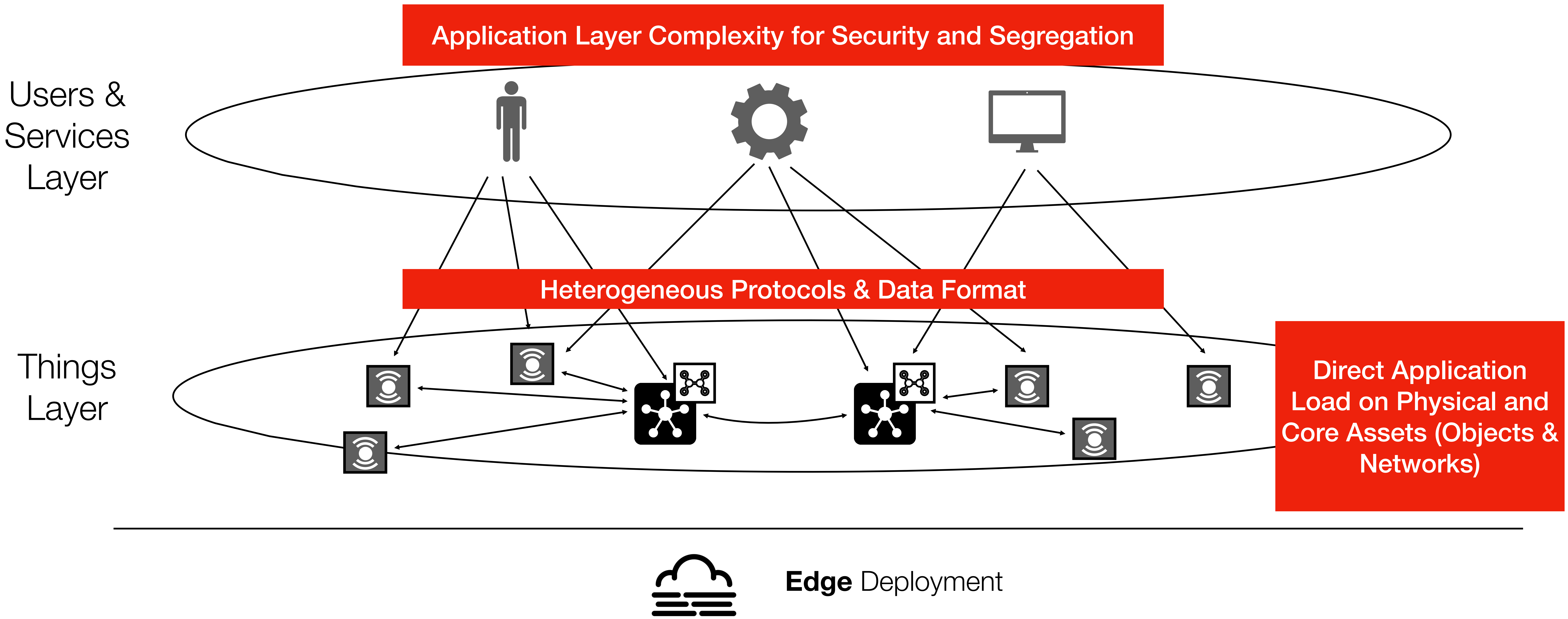
Cloud Digital Twins -> Improved Device Complexity



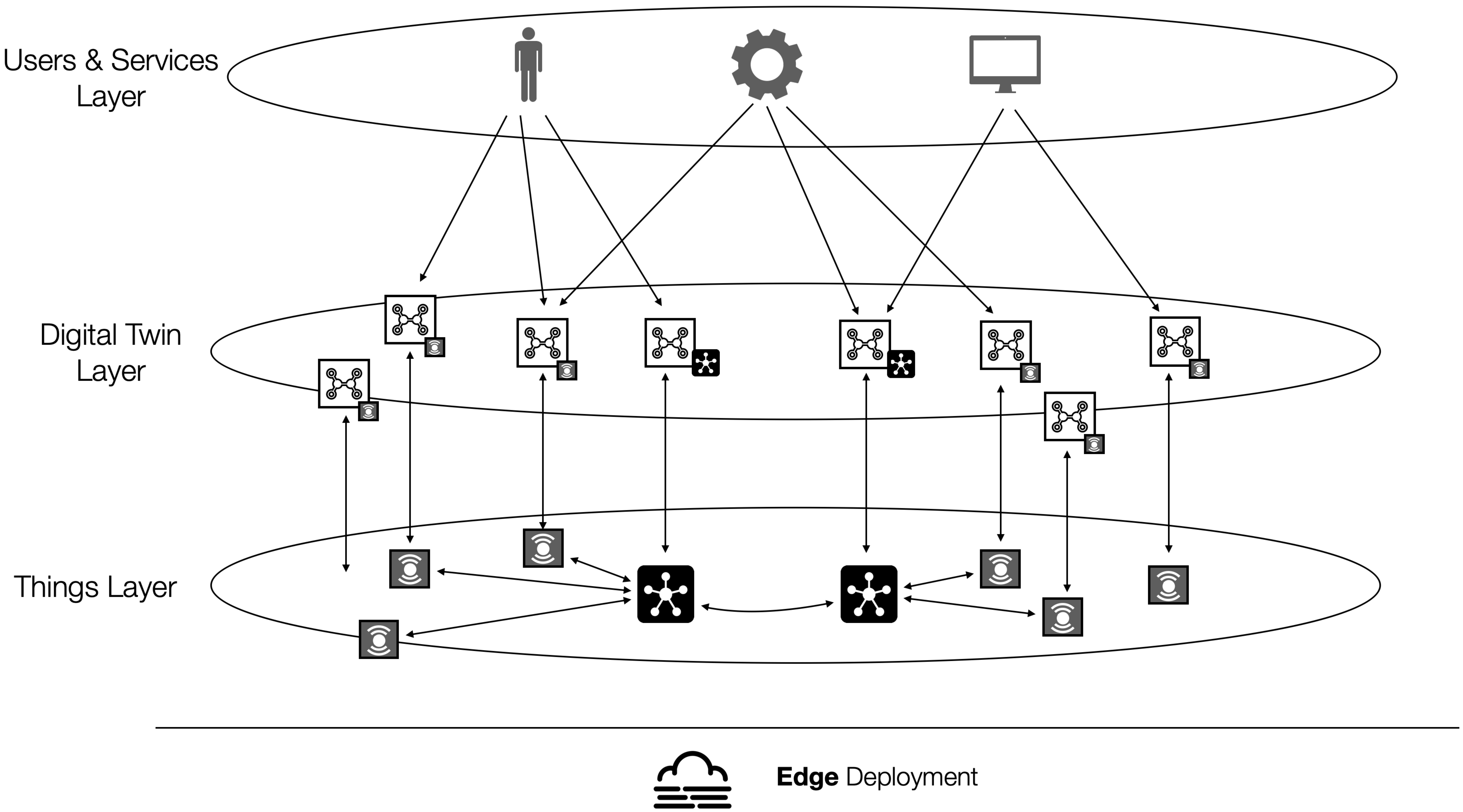
Cloud Only Digital Twins -> Edge Heterogeneity



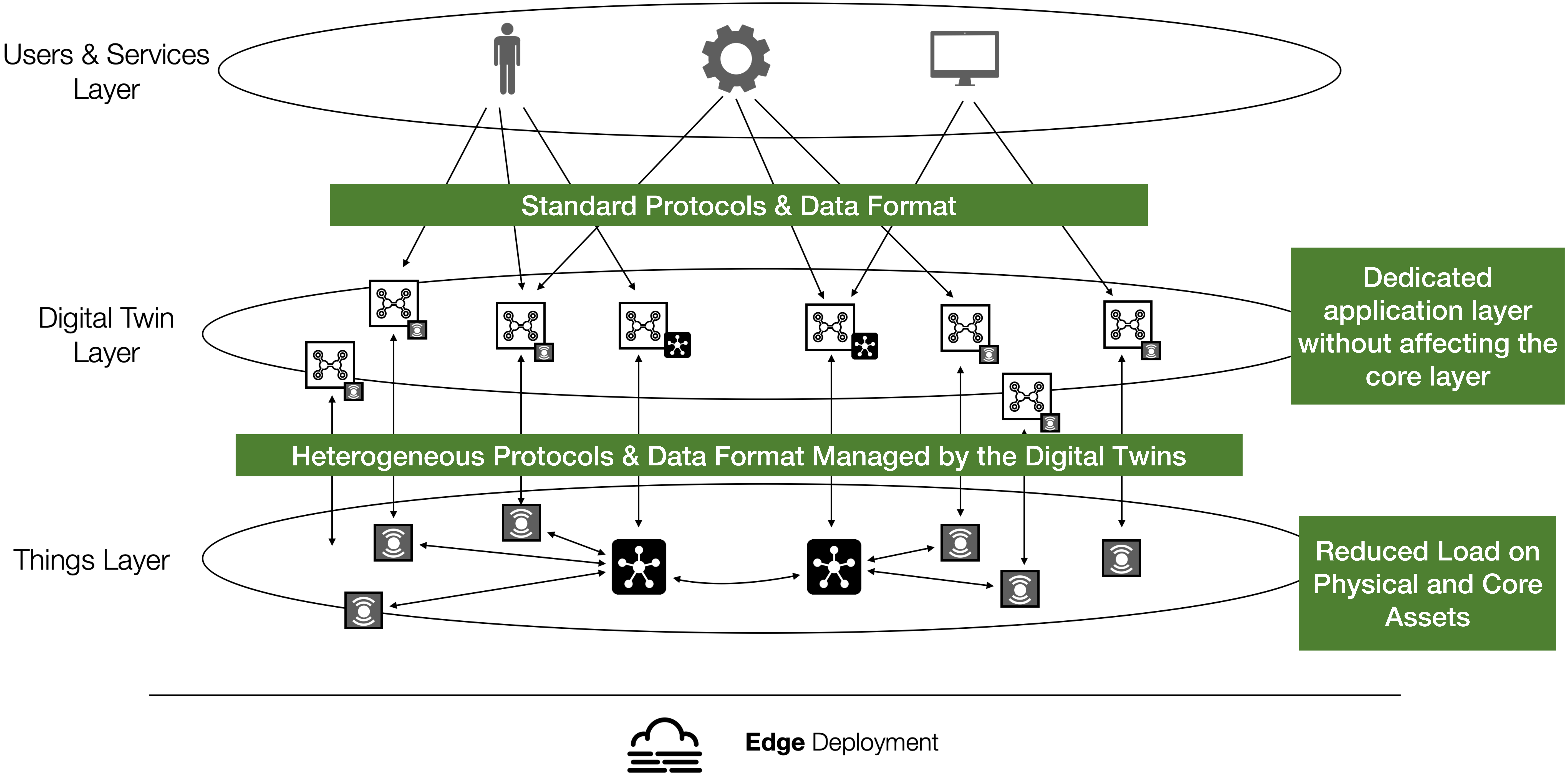
Cloud Only Digital Twins -> Edge Heterogeneity



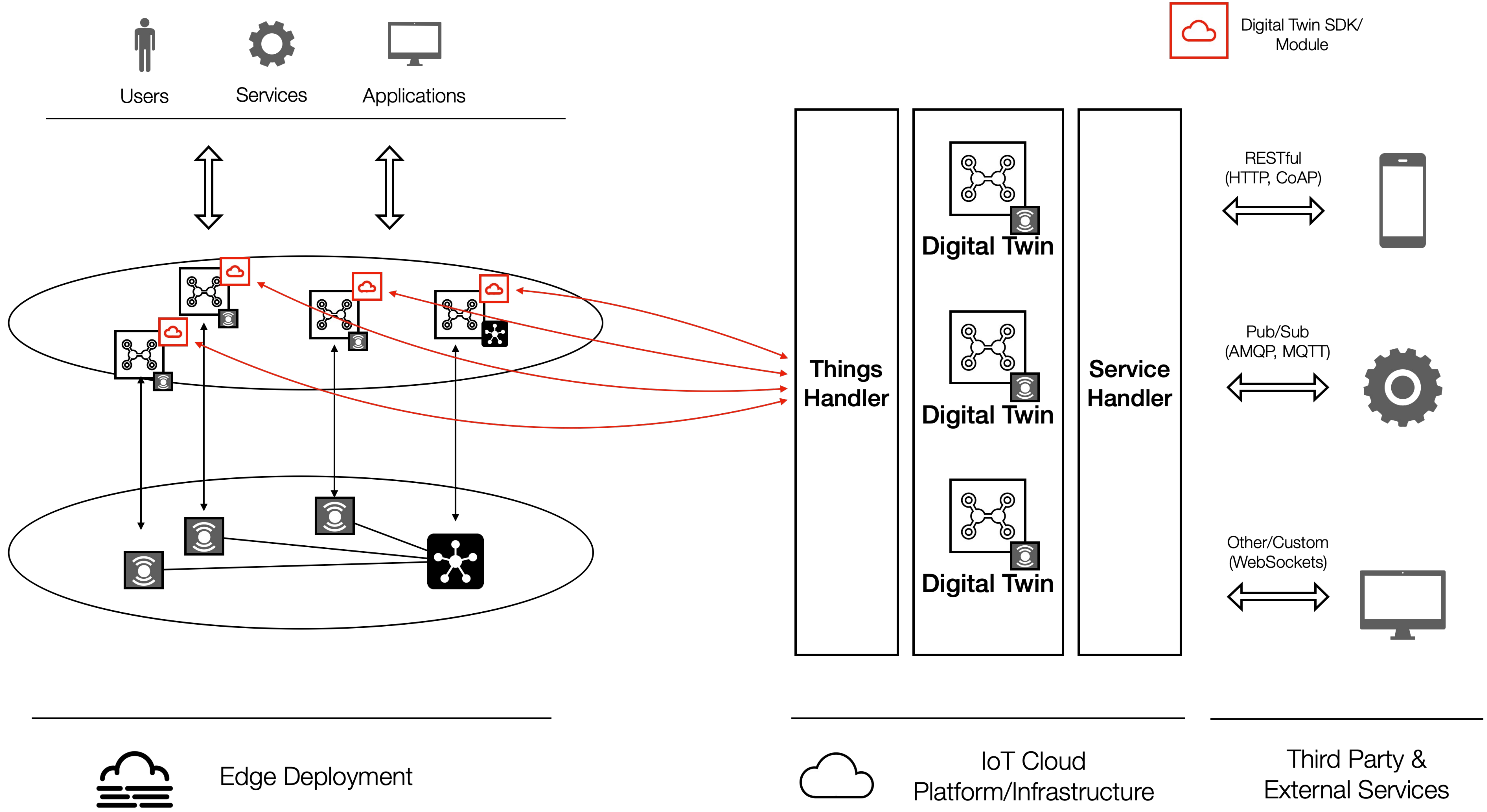
Edge Digital Twins



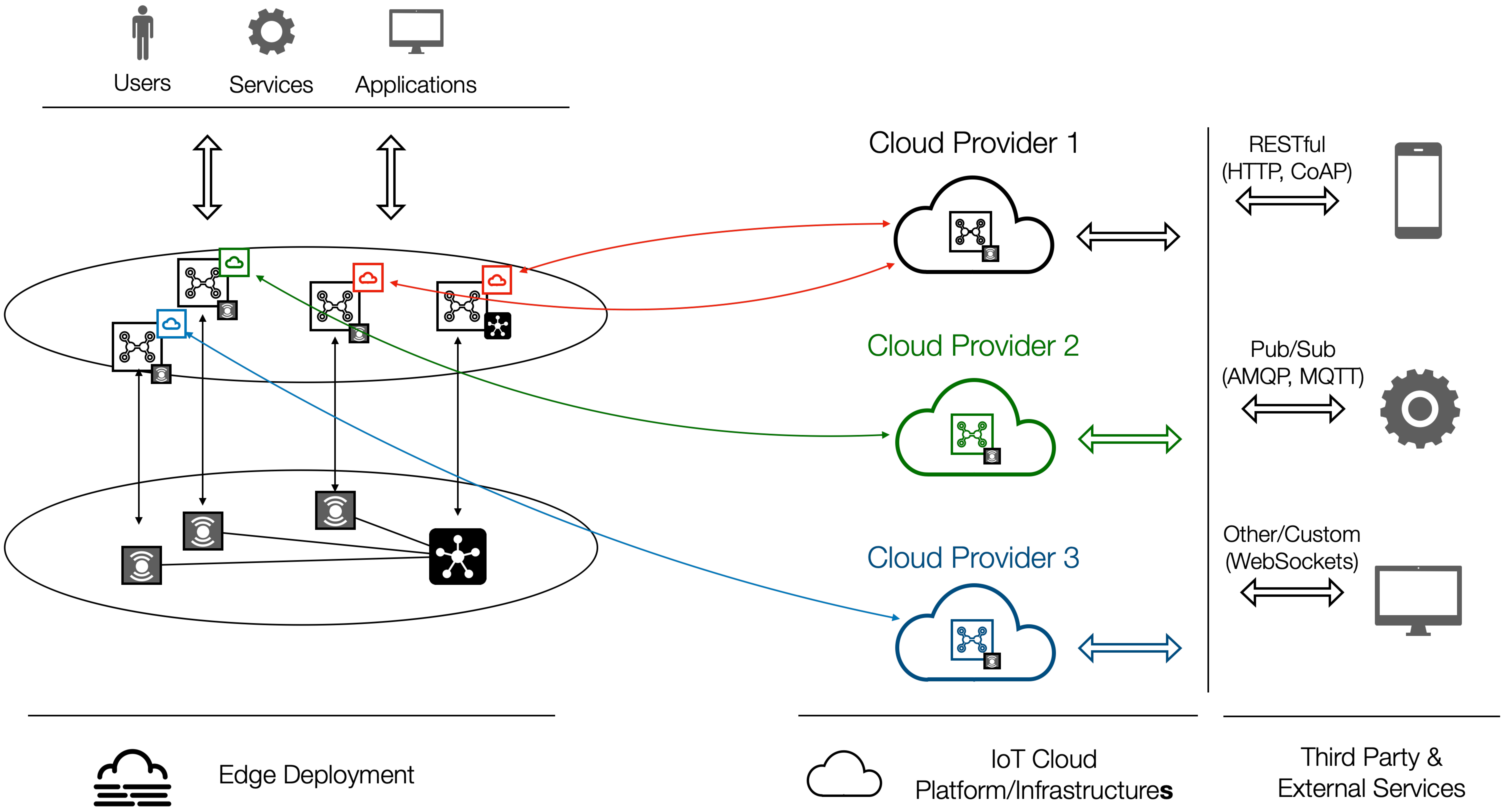
Edge Digital Twins



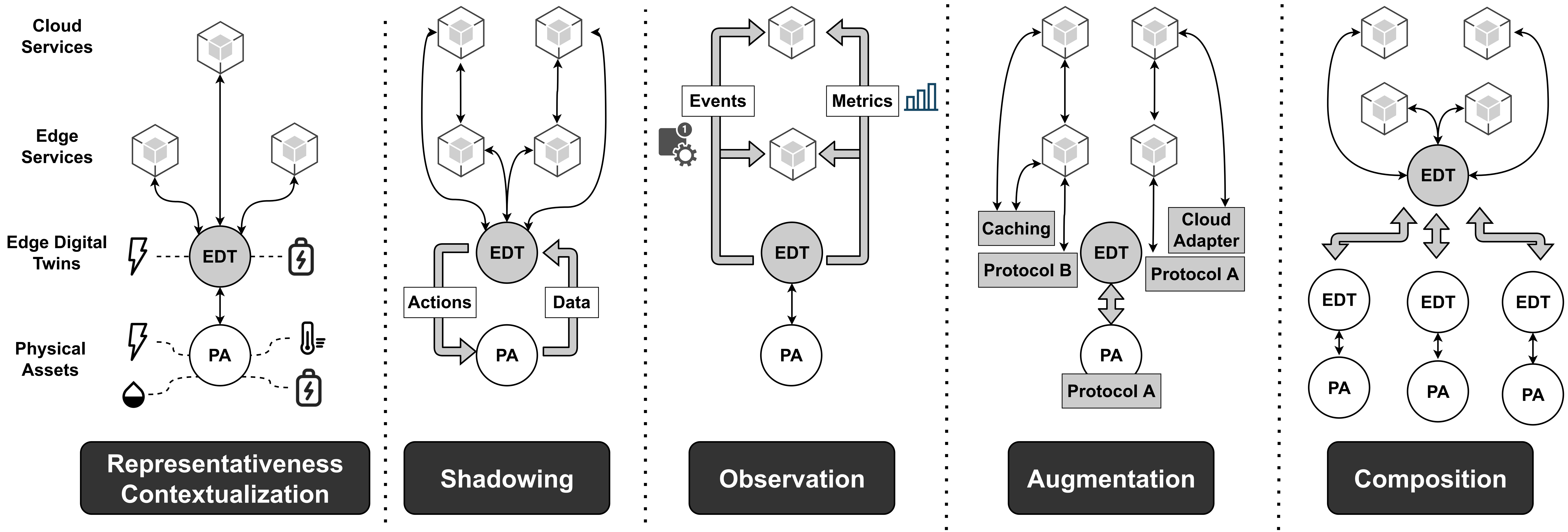
Edge & Cloud Digital Twins



Edge & Cloud Digital Twins

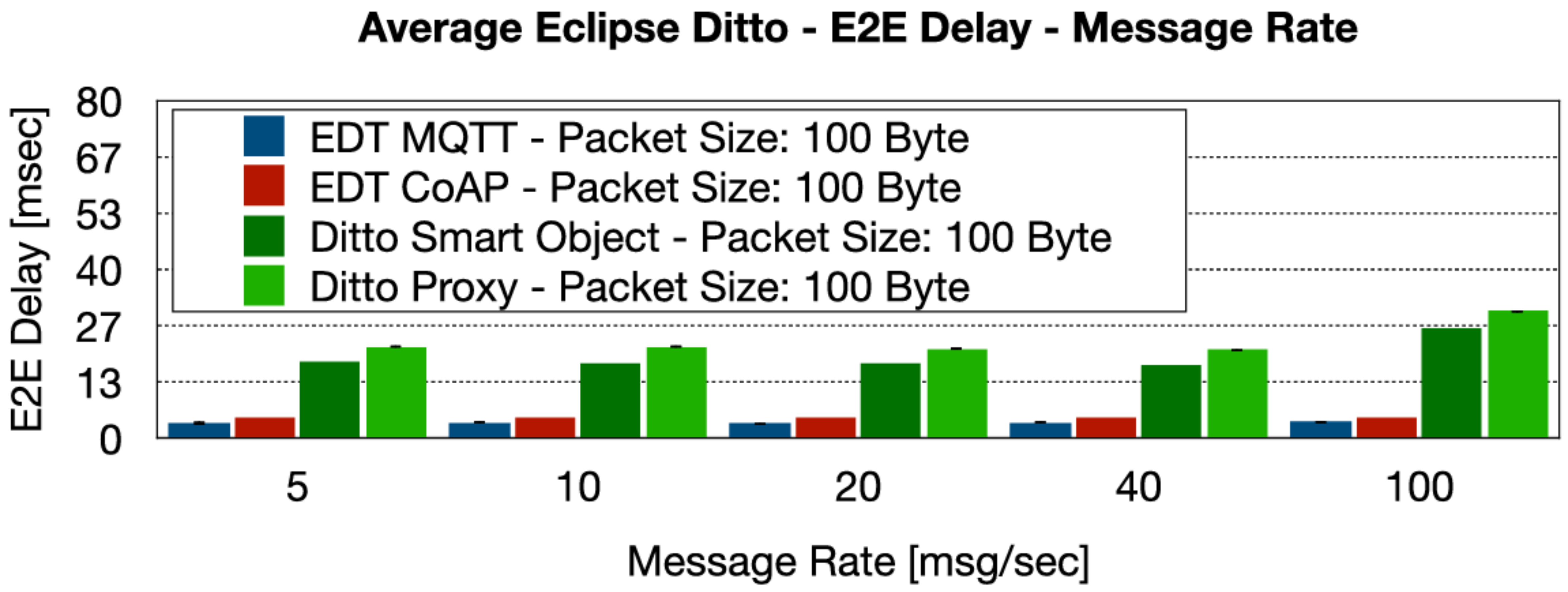


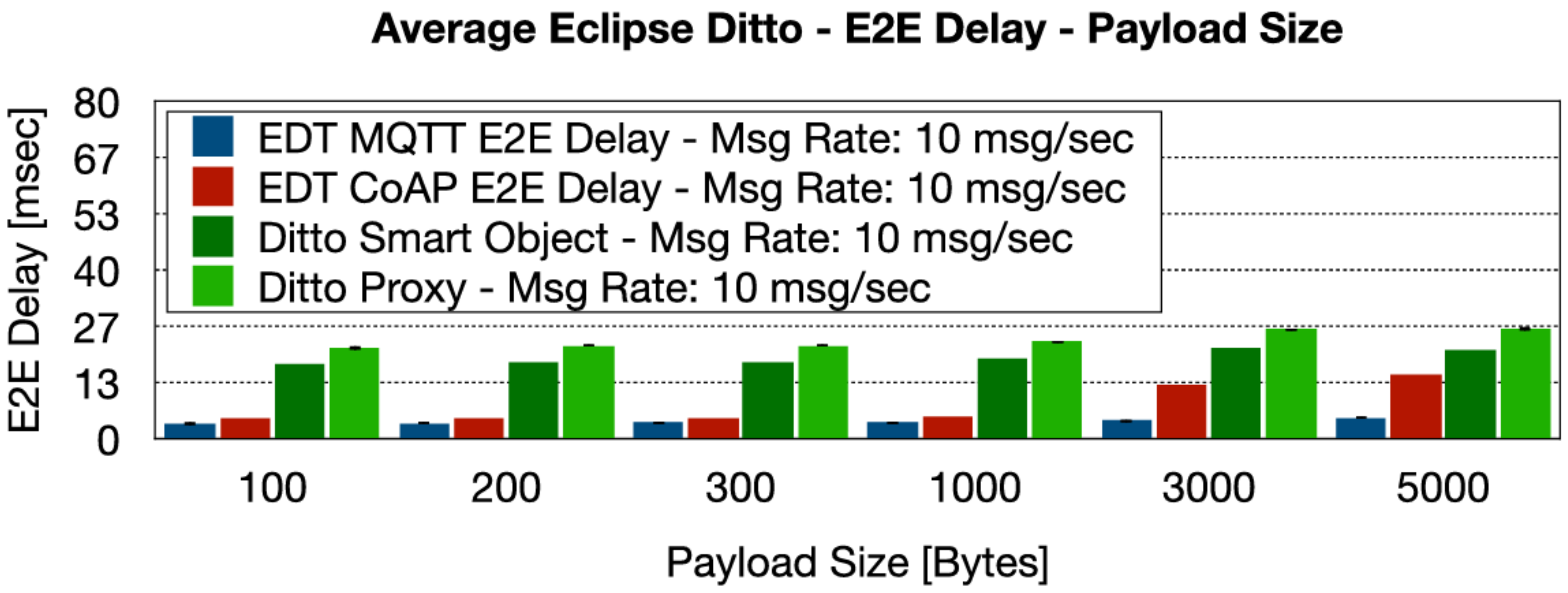
Edge & Cloud Digital Twins

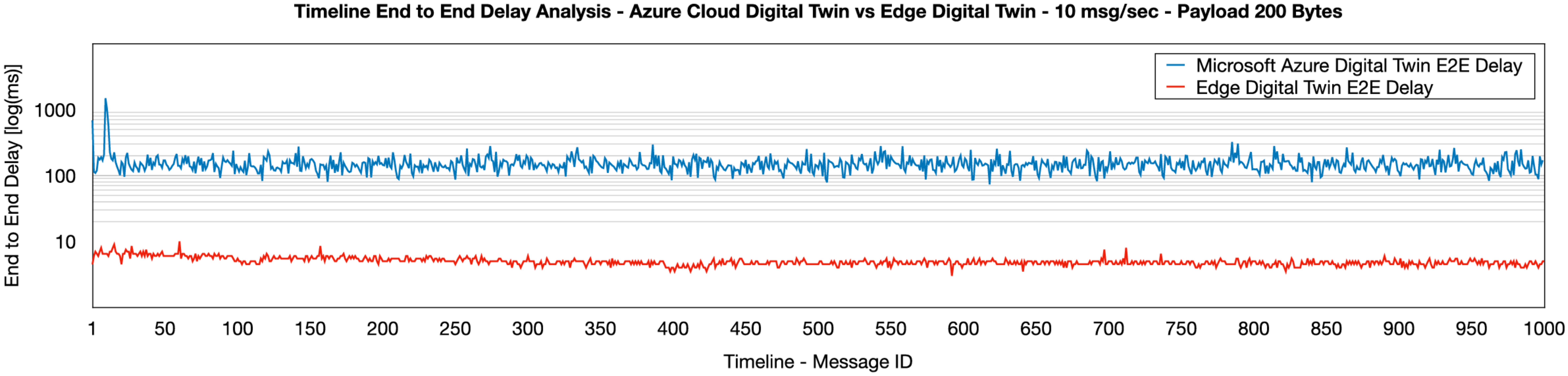


Marco Picone, Marco Mamei, and Franco Zambonelli. 2023. **A Flexible and Modular Architecture for Edge Digital Twin: Implementation and Evaluation.** ACM Transaction of Internet of Things 4, 1, Article 8 (February 2023), 32 pages. https://doi.org/10.1145/3573206

Edge & Cloud Digital Twins







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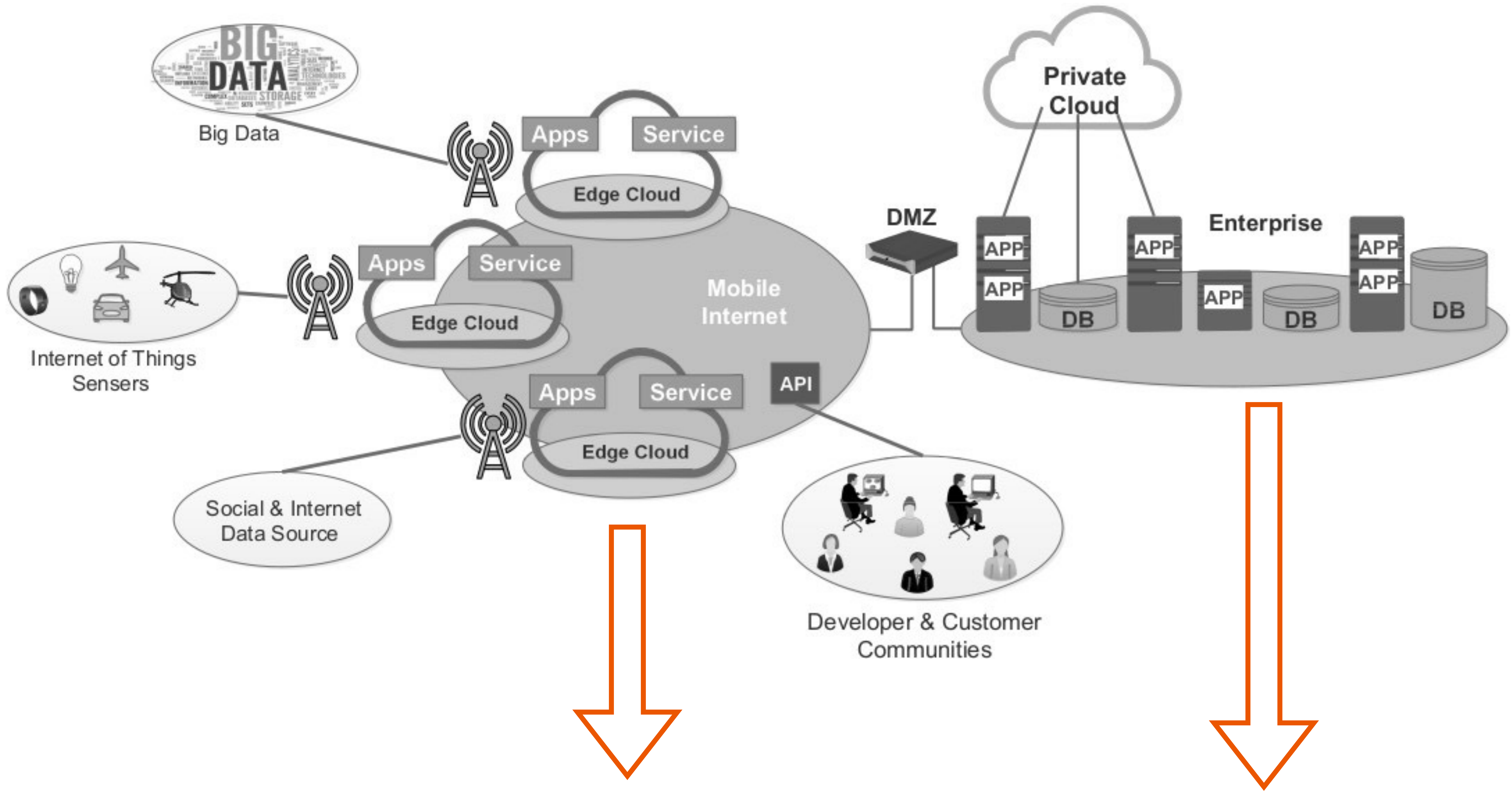
5G MEC & Digital Twins



Digital Twins will join (with different responsibilities) both on the Edge and in the Cloud. 5G Digital Twins will represent a fundamental asset to support interoperability and real-time applications.

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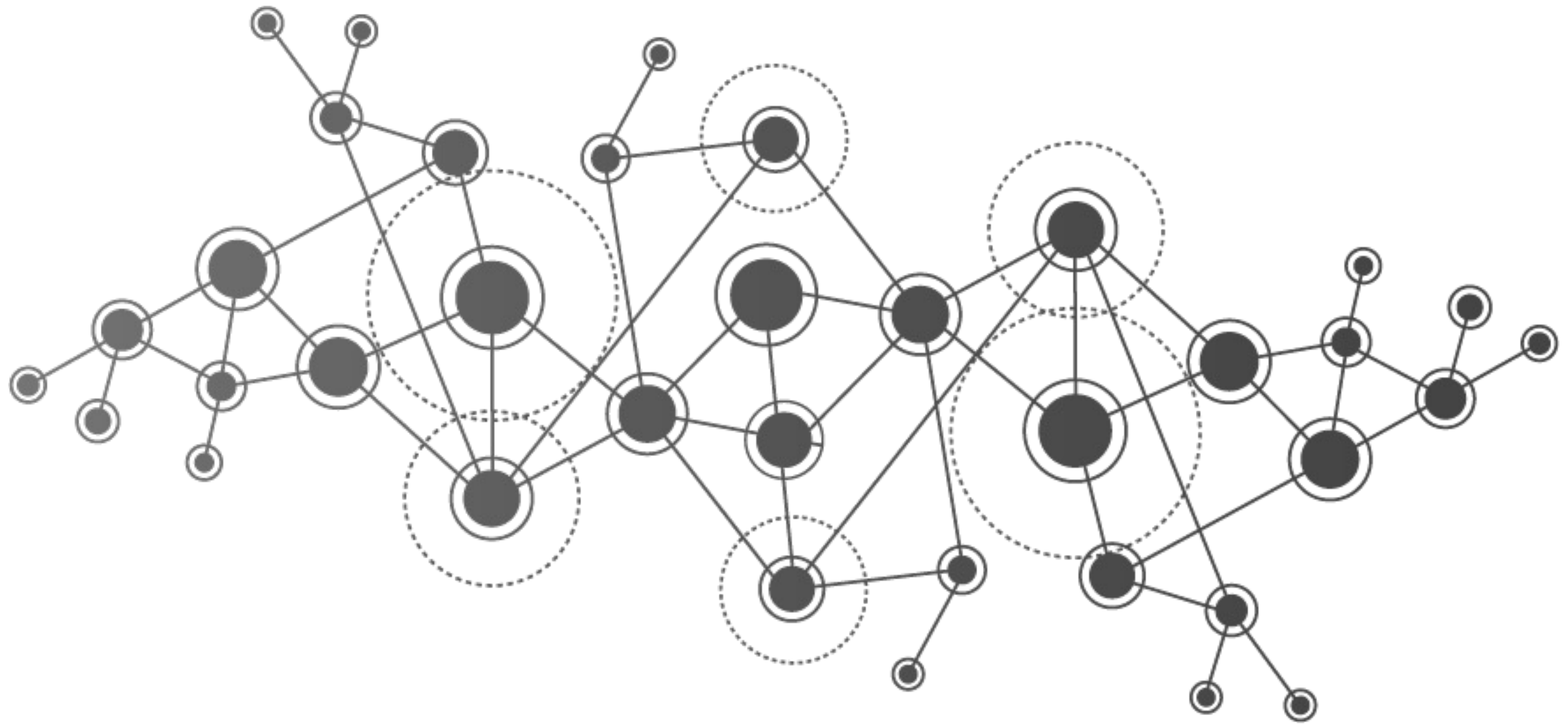

Intelligent Internet of Things

Digital Twins

Cyber-Physical Systems & IoT

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A.A 2023/2024