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Foundational Issues for an Ontology of Digital Twin

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SUMMARY

- What are we talking about when we talk of Digital Twin?
- Why do we need an ontology of Digital Twin?
- Digital Twin as an artefact
- Digital Twin as an information object
- A cyber-physical and sociotechnical perspective on Digital Twins

A BRIEF HISTORY OF DIGITAL TWINS

- The basic idea of using a **digital replica** as a means to study a physical object can be traced back to the the 1960s and NASA's exploratory space missions, when a faithful replica of each spacecraft launched into orbit was made; this was intended to remain on the ground, used for analysis and simulations

- In 1991, David Gelernter, a Computer Science Professor at Yale University, wrote the book *Mirror Worlds: or the Day Software Puts the Universe in a Shoebox...How It Will Happen and What It Will Mean*, in which he explained (partly out of speculation) a **software revolution** on the verge, which will allow to build, out of the already available technology, representations of the reality that will become **explorable** in an unprecedented detailed manner [Gelernter 1991]

A BRIEF HISTORY OF DIGITAL TWINS

- In 2002, Michael Grieves (University of Michigan) presented a model for industry, called «Conceptual idea for **Product Lifecycle Management**». The model already had all the fundamental elements of DT: real space, virtual space and a bidirectional link for data flow.
- In 2005, the conceptual model was presented in an article published by Grieves in the *International Journal of Product Development*, and was there called «**Mirrored Space Model**». The two systems composing the PLM would be connected through all phases of the lifecycle: creation, production, operation and disposal
- In 2006 Grieves, in the book *Product lifecycle management: Driving the next generation of lean thinking*, he used the name «**Information Mirroring Model**»
- In 2010, he wrote the book *Virtually Perfect*, where the expression «**Digital Twin**» was officially introduced to refer to the way in which John Vickers (NASA), with whom he was collaborating, called the Information Mirroring Model

SOME DEFINTIONS FROM THE LITERATURE

- Digital **replica** of a living or non-living physical **entity** […] to gain insight into **present** and **future** operational states of each physical twin [Wang et al. 2022]
- Comprehensive physical and **functional description** of a **component**, **product**, or **system** together with all available operational data [Rosen et al. 2019]
- Virtual **information constructs** that fully describe **potential** or **actual** physical manufactured **products** from the micro atomic level to the macro geometrical level [Grieves 2011]
- A digital twin is a virtual **representation** of a physical **system** (called the physical twin) that enables a two-way coupling between the digital and physical domains, using some form of network-based connectivity. The digital twin **evolves** over time and is **constructed** from digitised information such as recorded data and the output of computational models. [Wagg et al. 2024]

FEATURES OF DIGITAL TWIN

- They can be a representation of a wide variety of entities, both **living** and **not living**, of very different **scales**, ranging from the microscopic level (like a cell), to the mesoscopic (e.g. a human body), to the macroscopic (a galaxy). Or maybe even **events** and **processes**
- We can have (and we often have) DTs that are agglomerates, **composites** of smaller DTs
- DTs are **independent** from the **technology** they are built on (ML, symbolic AI, sensors…)
- The corresponding physical twins can be **potential** or **actual**
- DTs keep some resemblances with **models** and **simulation** technologies
- They are not static representations, but they **dynamically** update and enact a **feedback loop** of continuous calibrating mechanisms to synchronise with their physical twins and self-correct

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FUNCTIONS OF DIGITAL TWIN

Since DTs are concerned with the whole lifecycle of their physical twin, they may serve one or more of the following functions:

- **Designing**: they can describe a physical entity that does not yet exist
- **Monitoring**: they can represent as faithfully as possible the state and behaviour of an existing physical entity
- **Predicting**: they can project the future states and behaviors of an existing physical entity
- **Prescribing**: they can recommend actions (even corrective ones) to their physical twin

DIFFERENT TYPES OF DIGITAL TWINS

- **Digital Twin Prototype** (DTP): DT describing the **prototypical physical artifact**. The description is aimed at then producing the physical twin and may refer to its shape, the materials it is made of, the processes it will go through and, possibly, how it should be disposed.

- **Digital Twin Instance** (DTI): DT describing a **specific** corresponding physical twin. It remains **linked** to it throughout its life. It may contain a description of the geometry of the physical twin and its components, a list of past and current components, the list of operations performed in creating the physical twin, the results of any measurements and tests conducted on it, a description of replaced components, and all the information received from the sensors.

Both types of DTs operate in a **Digital Twin Environment** (DTE): a **multi-domain** space **integrating** a physical space and a virtual one where the DT can operate

DT PROTOTYPE VS. DT INSTANCE

- Prototype DTs and Instance DTs may complement each other, the former being used at the **design phase** to test ideas before the physical twin has gone into production, the latter operating «at **run time**» with the specific twin
- Digital twin **aggregates** may help understand the behaviour of a fleet of things and they may be both aggregates of prototypes and of instances
- But **which twin should come first?** The physical or the digital? It depends from the application: in most cases with DTIs it is the physical that comes first (e.g. human patient), while for DTPs obviously the digital comes first and it can be very useful to predict and fix issues before the physical instance is built
- Whether it comes first or not, in order to have a digital twin, it seems that at a point there should be a **physical implementation**
- But we may also see them as prototype systems that can be used to explore a multitude of different ideas, which won't be then realised. Such prototypes are built using a digital twin – instead of a physical one – as input (DTs of DTs). Some call these **Digital Siblings**

OBSTACLES FOR DT'S

In [Grieves and Vickers 2017] three main obstacles to DTs full development:

- **Organisational siloing**: organisations are structured along functional units that deal with design, engineering, manufacturing, support… Each unit has information on the systems, but not much of this information is shared, thus creating the siloing phenomenon (even within the functional units). DT would require a more homogeneous perspective
- **Knowledge of the physical world**: we need to understand better physical phenomena in order to be able to simulate them
- **Number of systems' possible states**: in complex systems we deal with thousands of parameters and this calls for a huge computing capability

While the two latter obstacles seem to be related to **technical limitations**, the first one is also concerned with a **cultural issue**; this means that, likely, a technology alone would not overcome it

ONTOLOGY FOR DT: MOTIVATIONS

The digital and the physical twin are complex systems that automatically and continuously exchange data. Given their centrality, one of the most common DT's architecture nowadays includes an explicit **Data Management component**, which must address the following issues:

- Data heterogeneity
- Interoperability (also among distinct DT's)
- Integration
- Data search
- Quality and provenance

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DATA HETEROGENEITY AND INTEGRATION

- In the DT scenario, data belonging to different application domains need to be **integrated**; such data are obviously heteogeneous from a **semantic**, **terminological**, and **syntactic** point of view and are often **low quality** data
- Overcoming these issues is necessary to develop a **unified view** of the different parts composing the DT, which can enable the production of valuable knowledge
- The process of data integration presupposes **data transformation**, **semantic enrichment**, **entity resolution** (data matching) and **entity merging**
- In particular, entity resolution and merging can be attained by **structuring** the different domains referred to by the DT with ontological frameworks making explicit their relations
- At the same time, the **formal characterization** provided by ontologies allow to semantically enrich the representation of the entities inhabiting such domains, thus enhancing the quality of data

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INTEROPERABILITY

- In very complex scenarios, like e.g. that of smart cities, it is very likely that an exchange of data from **different DTs**, possibly created by **different stakeholders**, will take place

- For this reason, DTs should be **interoperable** (data and semantic interoperability)

- **Data interoperability** concerns accessibility, reusability, and understandability by all involved parties regardless of different representations, purposes and contexts (FAIR)

- **Semantic interoperability** concerns the possibility for information systems to share, understand, interpret and use the data as unambiguously as possible, based on an agreed meaning attributed to the data

- Interoperability is the main goal of ontologies. But **which kind** of ontologies?

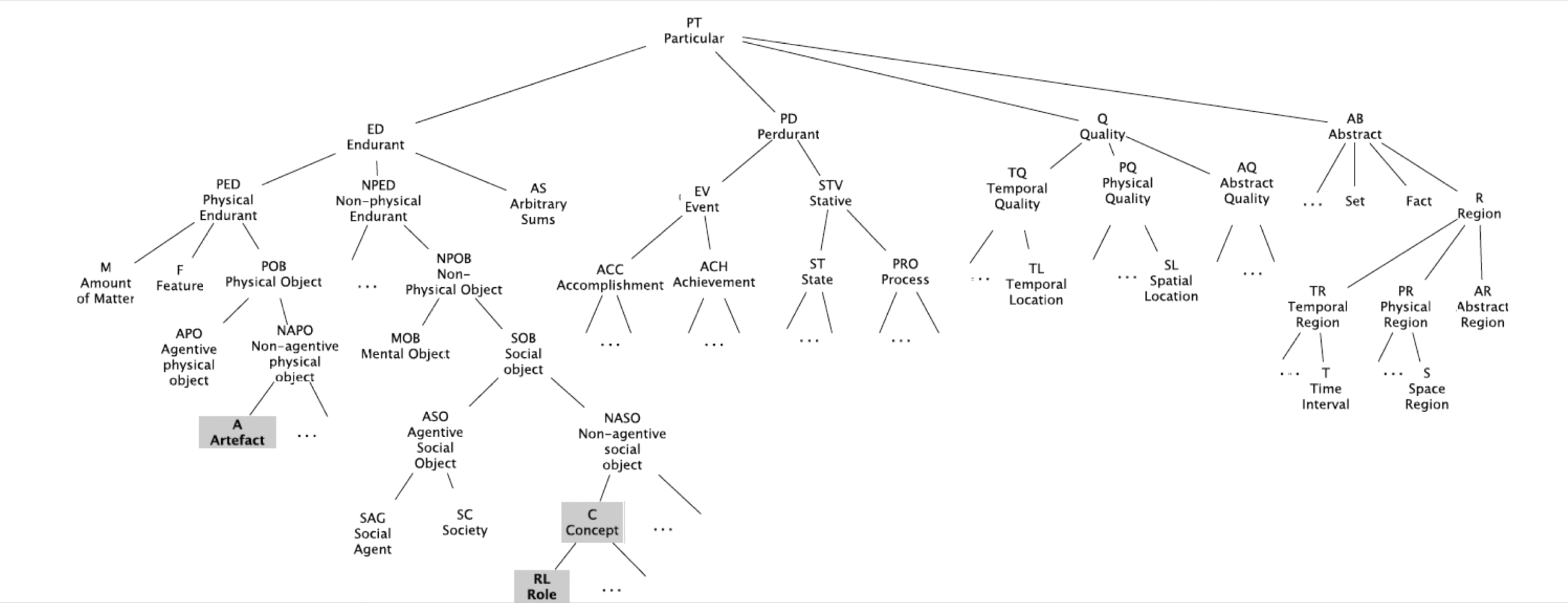
WHICH KINDS OF ONTOLOGIES? (TENTATIVE)

- **Ontologies of data**: to model the **flow of data** between the physical and the digital twin, making explicit their format, provenance, transformations etc.
- **Domain ontologies**: to model **DT instances**, based on the structure and domain properties ascribed to the corresponding physical twin
- **Foundational ontologies**: to model **DT prototypes**, based on the properties that distinguish the physical and the digital layer within a single ontological framework
- As usual, the process should start **from foundational to domain to data** (and from prototype to instance to data exchange)
- This should allow designers of DTs, belonging to different organisations, to **make explicit** the assumptions behind the design within a single framework and thus allow their systems to **interoperate** with other systems based on a different framework

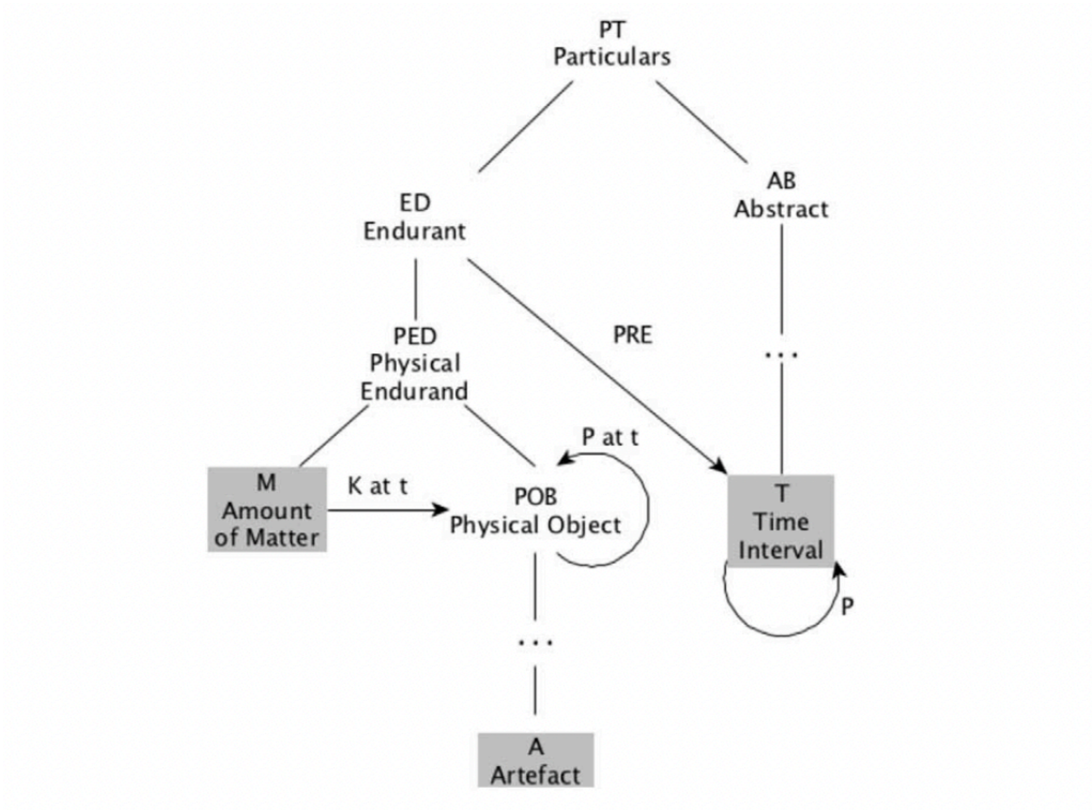
DIGITAL TWIN AS AN ARTEFACT

- Not much work on **foundational** ontologies for DT (I only found a 2021 workshop paper on UFO, [Barros et al. 2021]), but some questions emerging from it caught my attention
- The DT is seen as a particular kind of **artefact**, namely a **model** (of a type or of an instance)
- More precisely, a DT instance can be seen as a **composition of multiple models** of (different) individuals.
- Which is the relation between such models of individuals and the DT instance? Is it **parthood**?
- Which parts or properties of the physical twin are represented in the DT depends on the purpose for which the latter has been built so, which relation should hold between the **whole DT** and the **DTs of the components** of the physical twin?
- If a digital twin is expected to actively intervene in a physical entity, is it really only a **representation**?

ARTEFACT IN DOLCE



ARTEFACT IN DOLCE



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INHERITING FROM THE ANALYSIS OF ARTEFACT IN DOLCE

- DOLCE has focused so far on **material artefacts** [Borgo and Vieu 2009; Masolo and Sanfilippo 2020] (subclass of physical object), but are DT physical, or should we consider to categorise them as **non physical artefacts**?
- If material artefacts are **constituted** by physical objects or amount of matter, what are DT's constituted by?
- Remember that **consitution involves dependence** : the constituted entity cannot be present unless the constituting one it is made of is also present
- Material artefact introduces a third level of constitution in DOLCE (amount of clay – specifically shaped physical object – statue)
- Each artefact has a **capacity**, a single individual quality that characterizes all the capacities the physical artefact has. This quality maps into a quale that is a region in the capacity space, which can be seen as some sort of functional conceptual space [Gärdenfors, 2000]. Some of these capacties are **attributed** (by the designer)

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INHERITING FROM THE ANALYSIS OF ARTEFACT IN DOLCE

- **Identity criteria** for artefacts are different from those of the consituting entity: they can be repaired and have some parts substituted without loosing their identity

- For material artefacts, some identity criteria could be size, shape, weight and composition and, more prominenty, **attributed capacity**. Which are those of DTs?

- In DOLCE **artefact types** are modelled as **concepts of artefacts** [Borgo and Vieu 2009]. The concept discriminates between the attributed capacities of the artefacts to collect artefacts of the same type. Can thus **DTPs** be modelled as **types of non physical artefacts**?

DT'S AS COMPOSITES

- If we follow the idea that a DTI is a **composition of multiple models**, what is it really constituted by?
- In [Masolo et al. 2020] a notion of **composite** was introduced
- A composite differs from the **plurality** of its components: different pluralities may form a composite at different times, since some of them can change across time
- A composite can be dismantled. The plurality of its components survives, while the composite does not
- So, as collectives, composites are **constituted** by the plurality of their components
- Composites differ from **collectives** because membership is not **transitive**, while componenthood is
- In [Masolo et al. 2020] a **specific temporalised relation of constitution** that links the composites to the pluralities of their components is introduced. As for collectives and pluralities, our characterisation of composites does not rely on the existence of a **(material) substrate**

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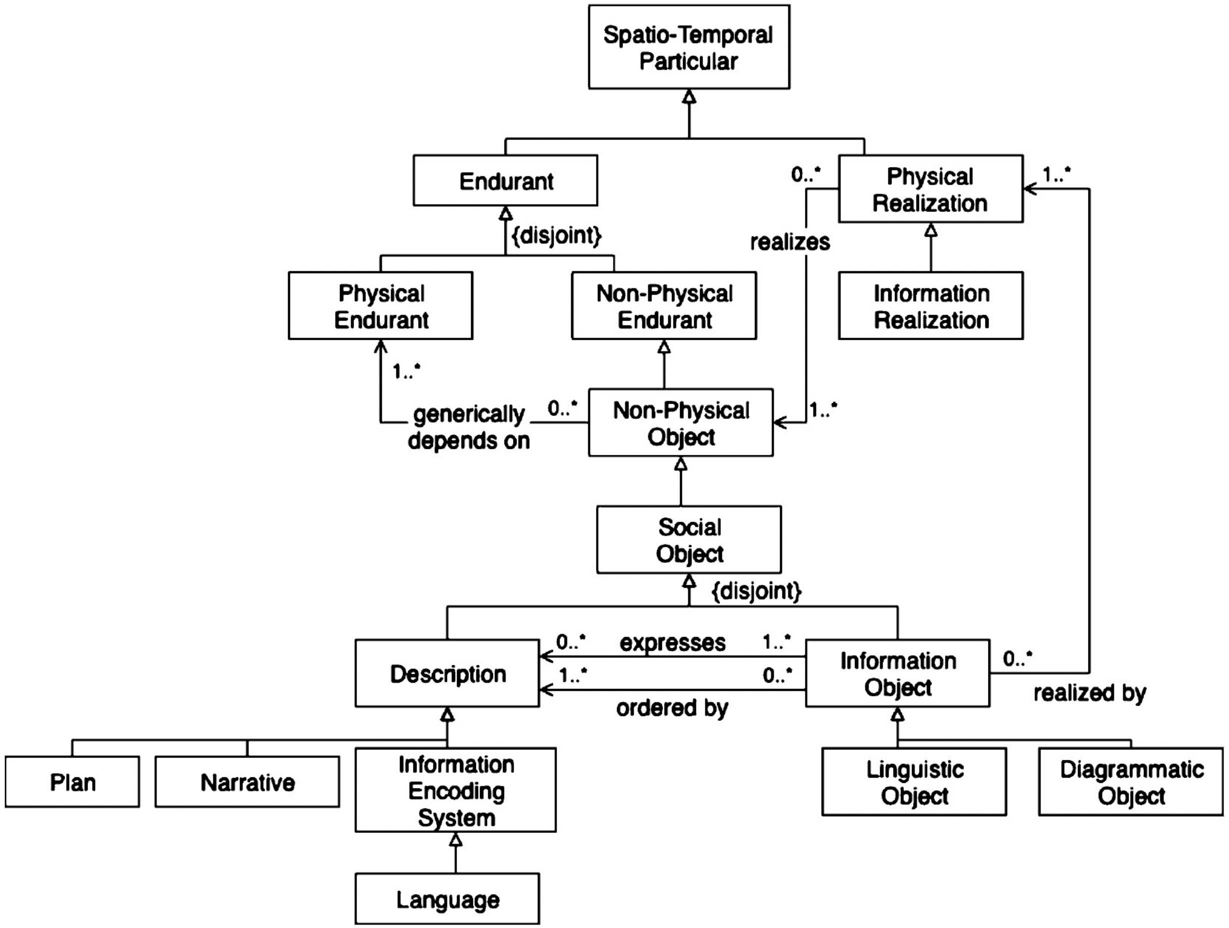
DT'S AS INFORMATION ENTITIES

By looking at the literature in applied ontology, we can single out some properties that are commonly attributed to information entities [Sanfilippo 2021]:

- They are **in time** (created in a point in time), but **not in space** (they are immaterial)
- They are **generically dependent** on another entitiy: in order to exist, they need a **support**
- They can be **realized in different supports**, without reducing to them
- They are **about** something:
  - not necessarily about entities that are **currently present** (also past or fictitious entities)
  - can be about a **broad range** of things (objects, qualities, events, situations)
  - can refer to some entities but **only partially** or from a specific perspective
  - may **lack reference** altogether, as in the case of a product to be fabricated

INFORMATION OBJECT IN DOLCE (?)



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DIGITAL TWIN AS INFORMATION OBJECT IN DOLCE

According to the previous diagram, ideas to be explored:

- DTP: **information object** (sublcass of social object)
- DTI: realization (**information realization**)
- DTI: non physical object that **generically depends** on the PT

An interesting idea that I saw in [Barcelos et al. 2021] is to see Prototype DTs as **variable embodiments** whose **rigid embodiments** are models of the physical twin. Why Prototype DTs and not DTIs? That could capture **change** through time

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A CYBER-PHYSICAL AND SOCIOTECHNICAL PERSPECTIVE

- Cyber-Physical Systems (CPS) may be defined as smart **embedded** and **networked systems** within production systems

- Digital twins together with their physical relata are **cyber-physical systems**, that are not just models, but multiple models [Wagg et al. 2024]

- DTs have obviously to be studied together with the correspondent PTs, with which they constitute a **system**. The system is both **cyber-physical**, given the connection between the DT and its counterpart and **sociotechnical**, given the technological apparatus behind the construction of the system and the influence it has on the social realm. As a matter of fact, DTs are particularly useful in «socially sensitive» settings, where virtual simulation or constant monitoring are required because the action of the PT is potentially dangerous for the community in which it is supposed to be employed.

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