

Foundations for Digital Twins

Regina HURLEY^{a,b}, Dan MAXWELL^{b,c}, Jon MCLELLAN^{b,c},
Finn WILSON^a, and John BEVERLEY^{a,b,d,1}

^a*University at Buffalo*

^b*National Center for Ontological Research*

^c*KadSci*

^d*Institute for Artificial Intelligence and Data Science*

Abstract. The growing reliance on digital twins across various industries and domains brings with it semantic interoperability challenges. Ontologies are a well-known strategy for addressing such challenges, though given the complexity of the phenomenon, there are risks of reintroducing the interoperability challenges at the level of ontology representations. In the interest of avoiding such pitfalls, we introduce and defend characterizations of digital twins within the context of the Common Core Ontologies, an extension of the widely-used Basic Formal Ontology. We provide a set of definitions and design patterns relevant to the domain of digital twins, highlighted by illustrative use cases of digital twins and their physical counterparts. In doing so, we provide a foundation on which to build more sophisticated ontological content related and connected to digital twins.

Keywords. Digital Twins, Basic Formal Ontology, Common Core Ontologies, directive information, representational information

1. Introduction

The concept of digital twins was first introduced by NASA during the 1960s as part of the Apollo 13 program [1], but decades would pass before the first documented definition was offered by Grieves in 2003 [2]. Grieves envisioned digital twins to be sophisticated virtual representations of physical systems which receive real-time updates from those systems. Digital twins, on this understanding, are used to track, evaluate, and assess physical assets or collections of them. While this characterization has been influential, digital twins have evolved considerably alongside numerous technological and methodological achievements. For example, the emergence in the past decades of the Internet of Things (IoT) brought with it a need for efficient, secure, interactions across interconnected network devices and software systems [3]. Accordingly, researchers observed the value of creating digital twins not only for physical assets and manufactured goods [4], but also manufacturing processes [5], business logic [6], and the environment [7]. Digital twins have seemed to many a path towards more sophisticated integrations of technologies, frameworks, products, and so on. Indeed, the global digital twin market is expected to top 73 billion by 2027, with companies such as Meta and Nvidia capitalizing on this technology [8].

¹ Corresponding Author: John Beverley, johnbeve@buffalo.edu

As with any data-driven endeavor, the specter of semantic interoperability looms over digital twins. A 2020 report by The National Institute for Standards and Technology (NIST) estimated, for example, costs emerging from the lack of interoperability across industrial datasets as between 21-43 billion [9]. Leveraging digital twins in this environment runs the risk of exacerbating the already significant interoperability costs. On the one hand, ambiguity over what counts as a “digital twin” results in what we might call social or communicative interoperability challenges [10, 11]. On the other hand, differing data formats, coding standards, and parochial jargon result in well-known technical interoperability challenges [12]. Symptomatic of each is the presence of *data silos* [13], data sets representing nearby domains that cannot be easily integrated using standard computing techniques. Because digital twins heavily rely on the integration and synthesis of real-time data from disparate sources, data silos are particularly problematic in this context. Achieving meaningful data exchange using digital twins requires overcoming the communicative and technological hurdles that underwrite data silos across researchers and application groups.

Ontologies – controlled vocabularies of terms and logical relationships among them – are a well-known resource for addressing semantic interoperability challenges [12]. Ontologies have been leveraged to support data standardization, integration, machine learning, natural language processing, and automated reasoning [15, 16] in fields such as biology and medicine [16] and proprietary artificial intelligence products, such as Watson [17] and Siri [18]. IoT researchers are well-aware of the benefits of ontologies [19, 20] and digital twin initiatives are not far behind, as evidenced by the World Avatar digital twin project [21] among others [22]. If pursued without oversight, however, combining digital twins and ontologies can easily recreate semantic interoperability problems [13, 23]. This occurs, for instance, when ontologies representing content specific to digital twins are created without reflection on how they might integrate with ontologies covering nearby domains.

Decades ago, recognition of such undesirable consequences led to the creation of ontology ‘foundry’ efforts [24, 25] aimed at creating ontologies in accordance with common standards. Among the principles underwriting most ontology development is that ontologies must extend from a common top-level architecture: Basic Formal Ontology (BFO). BFO [13, 26] is a highly-general ontology designed to contain classes and relations representing content common to all areas of research and investigation - e.g. *object* and *process*. BFO is also designed to be extended to more specific domains, and as such is used in over 600 ontology initiatives, providing a rich ecosystem covering areas such as biomedicine, manufacturing, defense and intelligence, and education, to name a few. We maintain that the best strategy for leveraging ontologies to address semantic interoperability challenges arising from digital twins will be one that leverages BFO. To that end, in what follows we explore common definitions of “digital twin” and identify themes and issues with the goal of constructing an ontologically precise definition for this expression and nearby phenomena. We employ an extension of BFO – the Common Core Ontologies [27] suite – as a foundation on which to construct our definitions, with a particular emphasis on information design patterns characteristic of the suite. In doing so, we provide a firm ontological foundation on which to construct more sophisticated representations of digital twins within the BFO ecosystem.

2. Definitions of “Digital Twin”

Many definitions of “digital twin” have been proposed, reflecting a desire among researchers for clarity around the phenomena [28]. Exploring the range of extant definitions reveals common themes as well as challenges. **Table 1** displays 10 sample definitions, several of which are frequently cited in discussions of digital twins.

A theme across most definitions is treatment of digital twins as information or virtual entities designed to represent some physical entity or system; another is that digital twins be designed for synchronization with some physical entity represented. While important, defining “digital twin” as requiring such interaction excludes digital twins that have been created in, say, anticipation of the manufacturing of the corresponding physical entity. However, digital twin “prototypes” are frequently created as blueprints for the physical entities they will ultimately represent [29]. Definitions B, C, D, E, G, and I in **Table 1** require both the virtual representation and the physical entity for something to count as a digital twin, as indicated by an “X” in the “SYN” column.

Definitions differ with respect to scope, some being narrower than others [10]. For example, the restriction to physical manufactured products in definition A excludes digital twins of human bodies [30] and Earth [7], among other natural entities. Similar remarks apply to definitions B, E, F, and G. Definition A is, moreover, too exclusive in another sense, as it requires digital twins “fully” describe a physical entity across all levels of granularity; no digital twin can be so complete. The “SCP” column notes which definitions exhibit scope problems.

Digital twins are fundamentally virtual representations but are often confused or conflated with nearby or related entities [31, 32]. The “TAX” column identifies definitions exhibiting improper taxonomic characterization. For example, digital twins are sometimes conflated with “digital shadows”, but the latter merely provide a copy of a physical state of a given system without reflecting real-time updates. Similar remarks apply to conflation with “product avatars” [33] or “Virtual Factory Data Models” [30]. Moreover, definitions B, H, and I subsume digital twins under “simulation”. While digital twins and simulations share much in common [34], they differ insofar as simulations are often snapshots of a system state used for prediction and analysis, while digital twins are synchronized for real-time evaluation. Definition D exhibits a different issue, as it appears to define digital twins circularly, i.e. as “digital replicas.” Lastly, definition G suggests that digital twins are the combination of a virtual representation and the physical entity represented, which runs the risk of conflating a synchronizing system and one of its parts.

Table 1. Definitions of “Digital Twin”

ID	Definition	SYN	SCP	TAX
A	Virtual information constructs that fully describe potential or actual physical manufactured products from the micro atomic level to the macro geometrical level [2]		X	
B	Integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses...physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin [35]	X	X	X
C	Virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems [36]	X		
D	Digital replica of a living or non-living physical entity...to gain insight into present and future operational states of each physical twin [37]	X		X

E	Virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning, and reasoning to help decision-making [38]	X	X	
F	Comprehensive physical and functional description of a component, product, or system together with all available operational data [39]		X	
G	Functional system formed by the cooperation of physical production lines with a digital copy [40]	X	X	X
H	A safe environment in which you can test the impact of potential change on the performance of a system. [41]			X
I	A simulation based on expert knowledge and real data collected from the existing system [42]	X		X

We consider the definitions in **Table 1** to be a representative sample of those offered in the literature on digital twins. In the creation of our ontologically precise characterizations of digital twins and nearby entities, we thus aim to respect the major themes of these definitions while addressing the identified issues.

3. Ontological Characterization of Digital Twins

The Common Core Ontologies (CCO) suite extends from BFO and so inherits its methodological commitments [26]. CCO ontologies aim to represent entities in reality, rather than merely concepts about them, and are also designed to contain annotations, labels, and definitions reflecting intuitive natural language semantics concerning entities within scope. As an extension of BFO, CCO provides a bridge from the highly general, rather abstract, top-level to the more specific content relevant to digital twins [27]. In what follows, we will introduce ontology elements from BFO and CCO where needed to articulate our characterization of digital twins.

3.1 Digital Twins as Information

Digital twins are plausibly described as *information*; in CCO terms, they fall under the class **information content entity**,² a subclass of the BFO class **generically dependent continuant**, where one finds entities that may be copied across bearers. Distinct computer monitors could bear any of the following distinct patterns: ‘ π ’, ‘pi’, ‘3.14...’, or ‘3.14159265358979323...’, and all of these would convey the same information. In each case that information is said to *generically depend on* respective computer monitors, which we call **information bearing entities** when they enter such a relation. Because **information content entities** in every case *generically depend on* some **information bearing entity**, a given digital twin might be said to *generically depend on* some computer hardware. Dependence in this context being such that if all relevant computer hardware were to cease to exist, then all corresponding digital twins would cease to exist as well. An immediate corollary is that the same instance of a digital twin can depend on multiple computer hardware instances as copies.

²In the sequel, **bold** will be used to represent classes, *italics* to represent relations.

Table 2. BFO and CCO Elements Leveraged

Label	Definition
<i>continuant</i>	An entity that persists, endures, or continues to exist through time while maintaining its identity
<i>occurrent</i>	An entity that unfolds itself in time or is the start or end of such an entity or is a temporal or spatiotemporal region
<i>process</i>	An occurrent <i>p</i> that has some temporal proper part and for some time <i>t</i> , <i>p</i> has some material entity as participant
<i>stasis</i>	A process in which one or more independent continuants endure in an unchanging condition
<i>history</i>	A process that is the sum of the totality of processes taking place in the spatiotemporal region occupied by the material part of a material entity
<i>generically dependent continuant</i>	An entity that exists in virtue of the fact that there is at least one of what may be multiple copies which is the content or the pattern that multiple copies would share
<i>x generically depends on y</i>	<i>x</i> is a generically dependent continuant & <i>y</i> is an independent continuant that is not a spatial region & at some time <i>t</i> there inheres in <i>y</i> a specifically dependent continuant which concretizes <i>x</i> at <i>t</i>
<i>information content entity</i>	A generically dependent continuant that generically depends on some information bearing entity and stands in relation of aboutness to some entity
<i>material entity</i>	An independent continuant that has some portion of matter as continuant part
<i>material artifact</i>	A material entity designed by some agent to realize a certain function
<i>environmental feature</i>	A material entity that is either a natural or man-made feature of the environment
<i>change</i>	A process in which some independent continuant endures and 1) one or more of the dependent entities it bears increase or decrease in intensity, 2) the entity begins to bear some dependent entity or 3) the entity ceases to bear some dependent entity.
<i>descriptive ice</i>	Information content entity that consists of a set of propositions or images that describe some entity
<i>directive ice</i>	Information content entity that consists of a set of propositions or images that prescribe some entity
<i>representational ice</i>	Information content entity that represents some entity
<i>information bearing entity</i>	Object upon which an information content entity generically depends
<i>x represents y</i>	<i>x</i> is an instance of information content entity, <i>y</i> is an instance of entity, and <i>z</i> is carrier of <i>x</i> , such that <i>x</i> is about <i>y</i> in virtue of there existing an isomorphism between characteristics of <i>z</i> and <i>y</i>
<i>x describes y</i>	<i>x</i> is an instance of information content entity, and <i>y</i> is an instance of entity, such that <i>x</i> is about the characteristics by which <i>y</i> can be recognized or visualized
<i>x prescribes y</i>	<i>x</i> is an instance of information content entity and <i>y</i> is an instance of entity, such that <i>x</i> serves as a rule or guide for <i>y</i> if <i>y</i> an occurrent, or <i>x</i> serves as a model for <i>y</i> if <i>y</i> is a continuant

Digital twins often represent some existing physical entity. A digital twin might, however, serve as a prototype that prescribes how a physical entity might be manufactured in the future. Noting this, Grieves and Vickers distinguish between Digital Twin Instance (DTI) – which describes a physical product to which a digital twin remains linked throughout the life of the product – and Digital Twin Prototype (DTP) – information needed to produce a physical product meeting the specifications of a digital twin [2]. **Table 3** displays how we may respect this distinction by leveraging specializations of **information content entity** which characterize information that is prescriptive – such as the information comprising a blueprint – or representational – such as the content of a photograph. DTIs are plausibly understood as at least representational, and so falling under **representational information content entity** in CCO. **Representational information content entities** represent in a variety of ways. For example, the content of a painting of Napoleon Bonaparte represents the former emperor since the content *generically depends on* the painting which in turn bears some similarities to Napoleon. Similarly, a digital twin represents some physical entity insofar as it *generically depends on* computer hardware that bears similarity to that physical entity. Appeal to “isomorphism” in the definition of *represents* is understood as relative to the type of entities involved. In other words, an isomorphism for one pair of entities need not share much in common with an isomorphism between a distinct pair of entities. The arrangement of Napoleon’s body parts in a painting by Jacques Louis David was meant to reflect the actual arrangement of his body; the arrangement of computer hardware circuitry on which a digital twin generically depends is not obviously, in contrast, meant to reflect the arrangement of parts of the corresponding physical entity. Nevertheless, there exists some manner of isomorphism between the circuitry and the corresponding physical entity, such that were the circuitry to be physically altered in some manner then the resulting digital twin might no longer represent the physical entity.

DTIs need not be solely representational. A given DTI may, for example, have parts that *describe* or *prescribe* other entities. For example, the digital twin of Truist Park [44] includes descriptions of historical baseball players as well as directions for how to navigate the park. In this respect, the digital twin both represents the park as a whole while having parts that are not merely representational.

In contrast to the preceding, DTPs do not have any corresponding physical entity they may properly be said to represent. In CCO, the *represents* relation holds between instances.³ If there is no instance for a DTP to *represent*, then that DTP cannot be a **representational information content entity**. This seems the right result since DTPs are better understood on the model of plans or blueprints rather than as representational entities. In CCO, prescriptive entities of this sort fall under the class **directive information content entity**, which in every case *prescribe* some instance. While this intuition seems correct, our path forward is once again blocked. In our envisioned scenario, there is no instance that a DTP can be said to *prescribe*.

The issue we are encountering is not new. There are known challenges to characterizing what unrealized plans and blueprints are about in BFO and CCO [45]. CCO maintains an extension – the Modal Relations Ontology (MRO) [43] – that was developed to partially address this issue. To that end, MRO introduces *modal object property* and creates duplicates for every relation in CCO as sub-relations; users can then

³CCO development was driven largely by real-world use cases within the constraints of the Web Ontology Language (OWL) 2 with direct semantics. Consequently, all object properties in CCO are intended to hold between instances.

use queries to separate actual from merely possible entities as desired. To apply this strategy to modeling DTPs, one would effectively need to create an instance which the DTP possibly *prescribes*. While this is perhaps a practically useful strategy, it suggests a misunderstanding of unrealized plans and blueprints. A given DTP does not, we argue, prescribe a specific instance nor does it prescribe a merely possible instance, whether modal, conceptual, fictional, or otherwise. Unrealized plans and blueprints are, of course, about possibilities, but they are not obviously about possible *instances*.

Rather than possible instances, we maintain that a given DTP is intended to prescribe possible arrangements of classes and relationships among them. A DTP for a planned motorcycle series is not about any particular motorcycle that might emerge from production, though it does prescribe arrangements of portions of rubber and metal, properties of shape, size, and thermal conductivity, relations of parthood and dependence, and so on. This does not mean that a given DTP prescribes anything regarding some specific instance of, say, a portion of metal; there may be no such portion of metal having quite the characteristics prescribed by the DTP. The prescription exhibited by DTPs aims at the class-level rather than instance-level.⁴ We note that this proposal would require changes to the CCO relation *prescribes*, which has range instances of the class **entity**. This is warranted, we maintain, as our proposal more accurately reflects the intentions behind unrealized plans or blueprints than alternatives like that found in MRO. One may nevertheless be unmoved given that implementing this proposal seems to require using OWL Full, since OWL 2 with the direct semantics does not permit class-level relationships. For those who prefer practicality over accuracy, the MRO strategy remains an option, with DTPs defined as prescribing some possible instance.

Pursuing either path leads to DTPs counting as prescriptive entities – or **directive information content entities** - insofar as they serve as a model for the creation of an entity that would plausibly serve as a physical twin. This strategy allows, additionally, for a DTP instance to also be a DTI instance, which is to say a digital twin **directive information content entity** may also be a **representational information content entity**. This is meant to track the intuition that when a physical entity is created satisfying a DTP prescription, the prescription now operates as a representation of the entity created. Altogether, we can respect the insights of [2] by distinguishing DTIs and DTPs as representational information on the one hand and prescriptive information on the other.

3.2 Counterparts of Digital Twins

DTIs have in every case some counterpart, for example, the real-world wind turbine represented by a wind turbine digital twin. DTIs should not be restricted to physical entities though, as researchers often construct digital twins for manufacturing [40] and design processes [12, 46]. Relevant here is that CCO adopts BFO's fundamental division between **occurrent** and **continuant**. **Occurrents** are extended over time and have temporal parts, such as eating or walking, each of which is an example of the **process** subclass of **occurrent**. Instances of **continuant** lack temporal parts, endure through time, and *participate in* instances of **occurrent**. CCO extends **process** to a variety of process types, such as natural processes, agential acts, mechanical processes, and so on. CCO

⁴Modulo relations involved, our proposal seems fully general. The comic book character Superman, for example, describes a human-like individual bearing qualities no known human bears, but which are themselves arrangements of familiar classes, such the ability to fly, emit laser beams, and so on.

and BFO thus provide the resources needed to distinguish physical counterparts from process counterparts of digital twins.

Because one may create a digital twin to *represent* or *prescribe* just about any sort of **process**, it would be unwise to introduce an ontology class such as ‘process digital twin’ which contains all such **process** counterparts, since such a class might collapse into **process**. There is nevertheless a need to connect digital twins, where possible, to relevant counterparts. Our strategy is to introduce sub-properties of *represents* reflecting representation, tracking, and synchronization. Specifically, we introduce *is counterpart process* with range **process**. Similarly, we introduce *is counterpart material entity* since physical counterparts of DTIs plausibly fall under the BFO **continuant** subclass **material entity**, instances of which have matter as parts. CCO provides resources to draw a further distinction between **artifacts**, **material entities** that have been designed to achieve some function, and **environmental features**, **material entities** such as rivers, wind, Earth, and so on. This is an important distinction to draw noting that DTIs may have manufactured and engineered counterparts, i.e. **artifacts**, as well as natural phenomena counterparts, i.e. **environmental features**.

Our proposal thus provides ontological resources for distinguishing among the wide variety of digital twin counterparts, whether natural, manufactured, or processual. Moreover, because **material entities** often *participate in processes*, there is a clear line connecting digital twin representing processes to digital twins representing the physical entities that participate in them.

3.3 Twinning

Digital twins are often updated with real-time information about changes in the corresponding physical counterpart. Alterations to counterparts can be accounted for in CCO using the class **change**, roughly, a **process** in which a **continuant** gains or loses one or more properties. CCO contains a rich hierarchy reflecting varieties of such gains and losses. For example, if a vehicle *participates in* an increase of its thermal energy, this amounts to a **change** in which one temperature quality of the vehicle is replaced by another. **Figure 1** below illustrates the scenario.

Gain or loss of properties is not the only way in which physical counterparts might change. For example, a wind turbine plausibly *participates in* a change when one of its fan blades is replaced by another. This involves the replacement of a material part of the turbine, rather than the replacement of its properties. Following CCO, this manner of change can be captured by observing that the change of material parts of a physical counterpart will in every case involve a change in properties. The wind turbine initially, say, had a worn blade that is later, say, replaced by a fresh blade. Properties may come and go while the material parts of a given physical counterpart remain; but change of physical part leads to change of properties.

Changes to digital twins owing to changes in physical counterparts involve an update **process** through which the digital twin receives an instigating signal triggered by a **change** in the physical counterpart. Supposing a given sensor system is working correctly, a **change** in a physical counterpart will initiate a signal-sending **process**, during which a signal will be sent to and received by the corresponding digital twin. Because the digital twin is an **information content entity**, updating the digital twin requires updating the computer system on which it *generically depends*. Like the physical counterpart of the digital twin, updates to the computer system can be represented as a **change** during which properties are gained or lost. For example, suppose

a decelerating vehicle is the physical counterpart of a digital twin that is updated with information regarding velocity. Circuitry within the relevant computer hardware *participate in* some **change** during which qualities of the hardware are replaced with others. The corresponding digital twin that *generically depends on* the hardware may then have updated parts, such as a **descriptive information content entity** that *describes* the velocity of the vehicle as decelerating.

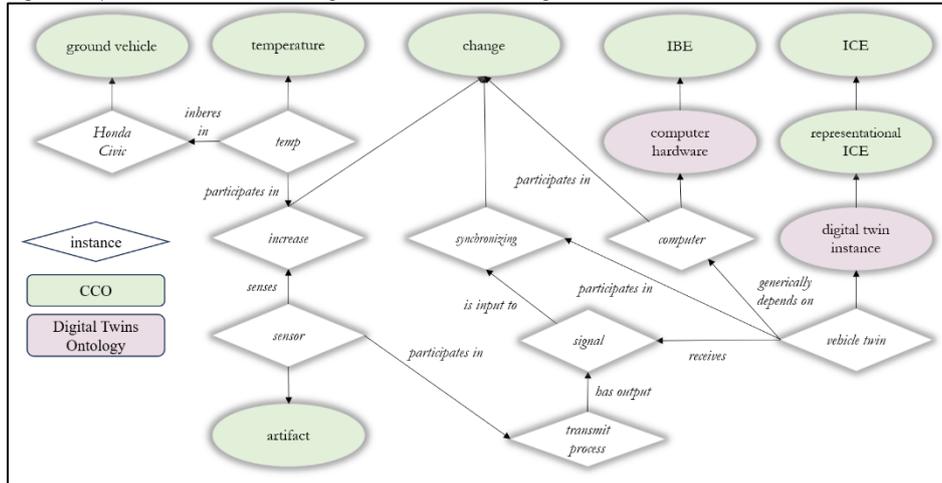
Table 3. Digital Twins Ontology Elements

Label	Definition
<i>digital twin</i>	An information content entity that represents an entity relative to some granularity and is designed to mirror updates of the entity or that prescribes relative to some granularity and is designed to model an arrangement of classes and relation to mirror updates of some entity.
<i>digital twin instance</i> ⁵	A digital twin that represents some material entity or process
<i>digital twin prototype</i>	A digital twin that prescribes classes and relations be arranged in such a manner as to produce a digital twin instance
<i>synchronizing process</i>	A change during which a digital twin instance is updated based on real-time information transmitted from the entity it represents
<i>x is counterpart material entity y</i>	x represents y, x is a digital twin instance, y is a material entity, and x and y participate in a synchronizing process
<i>x is counterpart process y</i>	x represents y, x is a digital twin instance, y is a process, and x participates in a synchronizing process that overlaps with y
<i>twinning rate</i>	A ratio measurement content entity that is a measurement of the rate at which synchronization occurs between a digital twin instance and the entity it represents
<i>fidelity</i>	A measurement information content entity that is a measurement of the number of information types, their accuracy, generality, and quality transferred between a digital twin instance and what it represents
<i>digital twin instance lifecycle</i>	A process that consists of all and only processes in which either 1) a digital twin instance and the material entity it represents participate or 2) a digital twin instance participates and the process it represents is proper process part of

Figure 1 illustrates a digital twin instance updating to reflect a change in temperature from the ground vehicle which it represents, which involves synchronization, or the real-time updating of the digital twin instance based on changes in its counterpart. Unlabeled arrows indicate that some entity is a member of a class. An important feature of this relationship is the so-called ‘twinning rate’ at which real-time updates can be conducted and sustained over time. CCO provides resources for the measurement of such rates within scope of its measurement unit module.

⁵The logical axioms governing digital twin instance entail it is an inferred subclass of representational information content entity; those governing digital twin prototype entail it is an inferred subclass of directive information content entity.

Figure 1. Synchronization between a ground vehicle and its digital twin instance.

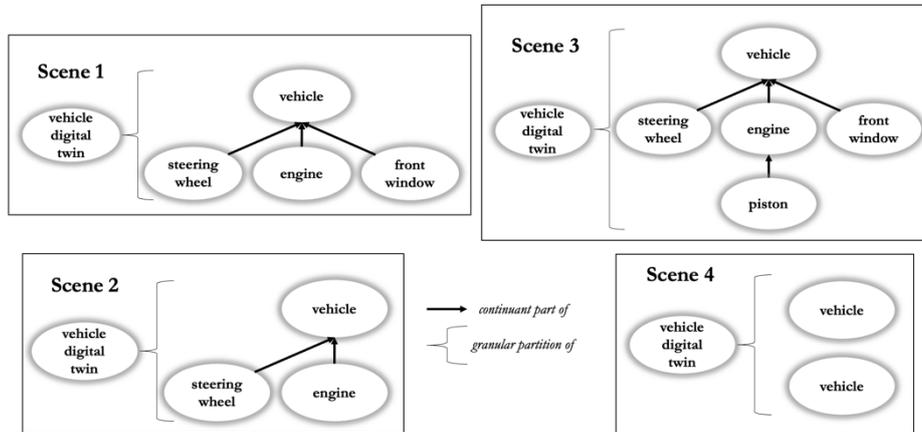


3.4 Fidelity as Granularity Partitions

When constructing a digital twin, there is an immediate need to identify the degree of *fidelity* desirable between the virtual representation and what it represents. The degree to which a digital twin mirrors its physical counterpart trades on a balancing act between the cost of creating and maintaining a digital twin compared to how the virtual representation is to be used [10, 11]. Digital twin development is often pursued in an iterative manner, where sub-components of the twin are added or refined in response to changes in the physical counterpart. Additionally, the use of a given digital twin may change to emphasize different levels of fidelity and relationships among them. In either case, mereological relationships appear important for ontologically precise characterization of the phenomena.

The lines along which we characterize fidelity can be seen in the *theory of granular partitions* [47]. Suppose the digital twin of a vehicle has a part representing the vehicle's engine but does not represent any proper parts of the engine, such as its pistons or cylinders. We might think of this virtual representation of the engine as a *granular partition* or a projection onto a whole that does not project onto all of its parts [47]. In this case, the digital twin of the vehicle projects onto the steering wheel, front window, engine, and so on but does not project onto all proper parts of these objects. In this manner, the digital twin instance represents aspects of the vehicle important to users of the twin for the purposes of synchronization. Scene 1 of **Figure 2** illustrates.

Figure 2. Three granular partitions of a ground vehicle.



As illustrated in scene 2 of **Figure 2**, a granular partition of the vehicle and its engine might not project onto all other parts of the vehicle, such as the front window. In this case, we might say the granular partition is *selective*, which is “a partition does not project onto all objects” within its scope [47]. Scene 3 **Figure 2** illustrates a scenario in which a new material entity is added to the engine, namely, a piston where this addition is of interest for monitoring by a digital twin. From the perspective of granular partitions, this would be a *proper refinement* of the digital twin partition, in which “the object targeted by the root cell...remains the same” [47]. Lastly, the root of the digital twin granular partition could itself be extended. Scene 4 **Figure 2** illustrates such a case in which a given digital twin represents more than one vehicle, perhaps for the sake of modeling autonomous vehicles navigating by one another safely. We have thus extended the granular partition, where “the target of the original root cell is always a proper part of the extension’s root cell” [47]. Moreover, we observe that the relationships across granular partitions, namely, those of parthood, provide a means by which to explain connections within and across partitions. A digital twin of an engine has a digital twin of a piston as part under some granular partition specification because the material entity counterpart of the engine has a piston material part.

We observe that the fidelity of a digital twin can be characterized on the model of granular partitions, which provide a high-level guide for ways in which fidelity might change during the use of digital twins. Fidelity on our construal is best understood as a measurement of the types of information transferred between a digital twin instance and what it represents [48, 49]. This might include information regarding the digital twin counterpart’s temperature, overall health, production capabilities, weathering capability, and so on. In each case, the degree of fidelity is relative to a granular partition of interest as contrasted with the granular partitions that are not of interest. For example, we might say the granular partition of the vehicle referenced above does not intuitively exhibit a high degree of fidelity, as can be seen in contrast to the granular partitions exhibited in other scenes.

We should take care, however, as fidelity cannot be obviously reduced to the number of parts and subparts of interest in a given granular partition. For example, a granular partition that covers the transmission of information regarding both the temperature and

weight of an engine has a higher fidelity than a granular partition that covers only the transmission of temperature. This raises no special modeling problem, however. Just as, according to our ontological design patterns, the engine would be part of the vehicle, we can say that parts of the vehicle bear qualities such as temperature and weight. Moreover, different granular partitions will contain material entities that bear different qualities, much like different granular partitions contain material entities having different parts.

4. Conclusion

The growing reliance on digital twins across various industries and domains brings with it semantic interoperability challenges that ontology solutions are well-suited to address. Given the complexity of the phenomena and interest from so many different disciplines, there is significant risk of reintroducing interoperability challenges at the level of ontology representations. Our goal in this work has been to avoid such potential pitfalls by leveraging and aligning with Basic Formal Ontology and the Common Core Ontologies suite, for ontological characterization of digital twins and nearby entities of interest. In this respect, we envision this work to be foundational for more sophisticated ontological representations of digital twins within the BFO ecosystem. Additionally, what we describe is directly extendable to simulation and many other computer-based analytic techniques where machine to machine interoperability is critical. With that in mind, next steps involve working closely with subject-matter experts in various fields that employ digital twins, identify use cases against which to test our representations, and clarify verbal disputes around this topic while promoting semantic interoperability.

5. Code Availability

BFO is available on the BFO-2020 GitHub repository (<https://github.com/BFO-ontology/BFO-2020>); BFO is maintained under the CC BY 4.0 License. CCO ontologies are available on the CCO GitHub repository (<https://github.com/CommonCoreOntology/CommonCoreOntologies>); CCO is maintained under the BSD-3 License.

6. References

- [1] X. Nguyen, R. Trestian, D. To, and M. Tatipamula. Digital twin for 5g and beyond. *IEEE Communications Magazine*, 59(2):10–15, 2021.
- [2] M. Grieves, *Virtually Perfect: Driving Innovative and Lean Products through Product Lifecycle Management*
- [3] Sampath Kumar VR, Khamis A, Fiorini S, et al. Ontologies for Industry 4.0. *The Knowledge Engineering Review*. 2019;34:e17. doi:10.1017/S0269888919000109
- [4] R. Rosen, G. Von Wichert, G. Lo, and K. D. Bettenhausen, “About the importance of autonomy and digital twins for the future of manufacturing,” *IFAC-PapersOnLine*, vol. 48, no. 3, pp. 567–572, 2015.
- [5] F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang, and F. Sui, “Digital twindriven product design, manufacturing and service with big data,” *Int. J. Adv. Manuf. Technol.*, vol. 94, nos. 9–12, pp. 3563–3576, Feb. 2018.
- [6] H. Ikävalko, P. Turkama, and A. Smedlund, “Value creation in the Internet of Things: Mapping business models and ecosystem roles,” *Technol. Innov. Manage. Rev.*, vol. 8, pp. 5–15, Mar. 2018, doi: 10.22215/timreview/1142
- [7] Li, X., Feng, M., Ran, Y. *et al.* Big Data in Earth system science and progress towards a digital twin. *Nat Rev Earth Environ* 4, 319–332 (2023). <https://doi.org/10.1038/s43017-023-00409-w>
- [8] “Digital twin market - global forecast to 2027.” Accessed: April 18, 2024.

- [9] Inadequate Modeling Data Costs Billions to US Manufacturers. (2020). *NIST*. <https://www.nist.gov/news-events/news/2020/02/inadequate-modeling-data-costs-billions-us-manufacturers>
- [10] Barricelli, Barbara Rita et al. "A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications." *IEEE Access* 7 (2019): 167653-167671.
- [11] Jones, David Edward et al. "Characterising the Digital Twin: A systematic literature review." *CIRP Journal of Manufacturing Science and Technology* (2020): n. pag.
- [12] Thelen, Adam et al. "A comprehensive review of digital twin — part 1: modeling and twinning enabling technologies." *Structural and Multidisciplinary Optimization* 65 (2022): n. pag.
- [13] Arp R., Smith B., Spear A., Building Ontologies with Basic Formal Ontology, 2015, MIT Press
- [14] Kendall, E., McGuinness, D.: Ontology Engineering. Springer, Cham (2022). <https://doi.org/10.1007/978-3-031-79486-5>
- [15] Hitzler, P. "A Review of the Semantic Web Field." *Communications of the ACM* 64 (2): 76–83. (2021).
- [16] The Gene Ontology Consortium. The Gene Ontology Resource: 20 years and still GOing. *Nucleic Acids Res.* 2019; 47:D330–D338. doi:10.1093/nar/gky1055. (2019).
- [17] Ferrucci, D., et al. "Building Watson: An Overview of the DeepQA Project." *AI Magazine* 31, 59 (2010).
- [18] Spivack, N. "How Siri Works – Interview with Tom Gruber, CTO of SIRI." (2010). Accessed May 19, 2023.
- [19] Cao, Qiushi & Zanni-Merk, Cecilia & Reich, Christoph. (2018). Ontologies for Manufacturing Process Modeling: A Survey. In the 5th International Conference on Sustainable Design and ManufacturingAt: Australia
- [20] Sanfilippo, E.M. et al. (2018). Modeling Manufacturing Resources: An Ontological Approach. In: Chiabert, P., Bouras, A., Noël, F., Ríos, J. (eds) Product Lifecycle Management to Support Industry 4.0. PLM 2018. IFIP Advances in Information and Communication Technology, vol 540. Springer, Cham. https://doi.org/10.1007/978-3-030-01614-2_28
- [21] J. Akroyd, S. Mosbach, A. Bhawe, and M. Kraft. Universal digital twin-a dynamic knowledge graph. *Data-Centric Engineering*, 2, 2021.
- [22] A. Erkoyuncu, I. F. del Amo, D. Ariansyah, D. Bulka, R. Roy, et al. A design framework for adaptive digital twins. *CIRP annals*, 69(1): 145–148, 2020.
- [23] De Colle, Giacomo; Hasanzadeh, Ali; Beverley, John. Ontology Development Strategies and the Infectious Disease Ontology Ecosystem. *Proceedings of the International Conference on Biomedical Ontologies 2023*.
- [24] Ameri, Farhad & Sormaz, Dusan & Psarommatis, Foivos & Kiritsis, Dimitris. (2021). Industrial ontologies for interoperability in agile and resilient manufacturing. *International Journal of Production Research*. 60. 420–441. 10.1080/00207543.2021.1987553.
- [25] Drobnyakovic, M., Kulvatunyou, B., Ameri, F. Will, C., and Smith, B., The Industrial Ontologies Foundry (IOF) Core Ontology, Formal Ontologies Meet Industry (FOMI) 2022, Tarbes, FR, [online], https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=935068 (Accessed February 17, 2024)
- [26] Otte NJ, Beverley J, Rutenberg A. (2022) BFO: Basic Formal Ontology. *Applied Ontology*. 17–43.
- [27] CUBCR, Inc. (2019) An Overview of the Common Core Ontologies.
- [28] Semeraro, Lozeche, Panetto, Dassisti, Digital Twin Paradigm, a Systematic Literature Review
- [29] Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems,
- [30] Tang, C., Yi, W., Occhipinti, E. et al. A roadmap for the development of human body digital twins. *Nat Rev Electr Eng* 1, 199–207 (2024). <https://doi.org/10.1038/s44287-024-00025-w>
- [31] Sharma, Angira et al. "Digital Twins: State of the Art Theory and Practice, Challenges, and Open Research Questions." *J. Ind. Inf. Integr.* 30 (2020): 100383.
- [32] Wright, Davidson, How to tell the difference between a model and a digital twin
- [33] K. Hribernik, T. Wuest, and K.-D. Thoben, "Towards product avatars representing middle-of-life information for improving design, development and manufacturing processes," in *Digital Product and Process Development Systems*, G. L. Kovács, D. Kochan, Eds. Berlin, Germany: Springer, 2013, pp. 85–96.
- [34] Wooley, Ana et al. "When is a simulation a digital twin? A systematic literature review." *Manufacturing Letters* (2023): n. pag.
- [35] Glaessgen and D. Stargel. The digital twin paradigm for future nasa and us air force vehicles. In 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA, page 1818, 2012.
- [36] VanDerHorn and S. Mahadevan. Digital twin: Generalization, characterization and implementation. *Decision Support Systems*, 145:113524, 2021.
- [37] Z. Wang et al., "Mobility Digital Twin: Concept, Architecture, Case Study, and Future Challenges," in *IEEE Internet of Things Journal*, vol. 9, no. 18, pp. 17452-17467, 15 Sept.15, 2022, doi: 10.1109/JIOT.2022.3156028.
- [38] IBM. 2024. What is a digital twin? Accessed 4-17-24. <https://www.ibm.com/topics/what-is-a-digital-twin>

- [39] S. Boschert, C. Heinrich, and R. Rosen, "Next generation digital twin," in Proc. TMCE, 2018, pp. 209–218.
- [40] J. Vachálek, L. Bartalský, O. Rovny, D. Šišmišová, M. Morhč, and M. Lokšík, "The digital twin of an industrial production line within the industry 4.0 concept," in Proc. PC, 2017, pp. 258–262, doi: 10.1109/PC.2017.7976223.
- [41] V. Hempel. Healthcare Solution Testing for Future, Digital Twins in Healthcare. Accessed: Oct. 16, 2019. [Online]. Available: <https://www.dr-hempel-network.com/digital-health-technology/digital-twins-inhealthcare/>
- [42] T. Gabor, L. Belzner, M. Kiermeier, M. T. Beck, and A. Neitz, "A simulation-based architecture for smart cyber-physical systems," in Proc. ICAC, Jul. 2016, pp. 374–379, doi: 10.1109/ICAC.2016.29
- [43] Rudnicki, R., Smith, B., Malyuta, T., & Mandrick, W. Best Practices of Ontology Development. CUBRC, Inc. nist.gov. (2016).
- [44] "Atlanta Braves Announce the Creation of Digital Truist Park." *MLB.com*, 15 Feb. 2022.
- [45] ISO/IEC 21838-2:2021. "Information Technology — Top-Level Ontologies (TLO) — Part 2: Basic Formal Ontology." Accessed Feb 19, 2024.
- [46] Perno, Matteo et al. "Implementation of digital twins in the process industry: A systematic literature review of enablers and barriers." *Comput. Ind.* 134 (2022): 103558.
- [47] Thomas Bittner, Barry Smith, and Maureen Donnelly Systems of granular partitions.
- [48] Detzner, Alexander and Martin Eigner. "A digital twin for root cause analysis and product quality monitoring." (2018).
- [49] Rosen, Roland et al. "Next Generation Digital Twin: an Ecosystem for Mechatronic Systems?" *IFAC-PapersOnLine* (2019): n. pag.