

Space Object Ontology – Toward a Space Domain Ontology

Robert John Rovetto
New York, United States of America
rrovetto@terpalum.umd.edu
University of Maryland, College Park, 2007 Alumnus
University at Buffalo, SUNY, 2011 Alumnus

Keywords. Ontology, computational ontology, formal ontology, philosophical ontology, applied ontology, space object, astronautical ontology, space ontology, space domain ontology, astrodynamics, space situational awareness, astroinformatics

Abstract. This paper develops the ontology of space objects for theoretical and computational ontology applied to the space (astronautical/astronomical) domain. It performs a conceptual analysis and development of key upper-level terms and concepts. It follows "An ontological architecture for Orbital Debris Data" (Rovetto, 2015) and "Preliminaries of a Space Situational Awareness Ontology" (Rovetto, Kelso, 2016) toward a space domain ontology, broadly construed. Important considerations for developing a space object ontology, or more broadly, a space domain ontology are presented. The main category term 'Space Object' is analyzed from a philosophical perspective. The ontological commitments of legal definitions for artificial space objects are also discussed. Space object taxonomies are offered and space object terms are defined. Finally I briefly introduce parts of the applied ontology, the Space Object Ontology, viewable on github.

1. Introduction

This paper develops the ontology of space objects for theoretical and computational ontology applied to the space domain (the astronautical & astronomical domain). The category term 'space object' is analyzed from a philosophical perspective, and alternative space object taxonomies are offered. Given the inherent generality of the term, the semantics of 'space object' is refined for a more thorough taxonomy. Legal definitions are discussed in order to present existing meanings and demonstrate the intricacies of defining the general term. The ontological commitments of these definitions are unpacked as well.

Communities of interest (COIs) include: formal ontology, ontology engineering, astroinformatics, artificial intelligence, and data-fusion, where data annotation, data-sharing, semantic interoperability, and knowledge representation are goals. Specific applications are the space object ontology (SOO), briefly introduced here, and a broader space domain ontology (SDO). This follows ideas from [1] and [2], whose overall concept is the development of an orbital and near-Earth Space environment ontology[24]. A space object ontology is a type of space domain ontology representing space objects.

I begin the paper by providing a synopsis of the field of ontology and the domain to be ontologically represented. I then perform a high-level analysis of the category term 'space object'. Moving on to specific legal definitions, common properties and identity conditions for space artifacts are explicated. Explaining the ontological import of legal definitions demonstrates the link between the space policy, space object, and ontology communities. Following this, I offer some space object taxonomies and qualitative definitions. A space object ontology file has been created and is displayed in section 8. Philosophical category terms are camel-cased, often in bold as well. Corresponding computational ontology categories (ontology classes) are camel-cased with no spacing, and those also in italics are relation terms. Words or phrases only in italics or bold indicate emphasis or key phrases.

2. Ontology

Ontology is the philosophical study of the world or a particular universe of discourse (a domain). *An ontology* is a general theory of a domain, describing the nature, categories and relationships of the entities and phenomena of the domain. For example, it represents and describes actual and potential domain objects and their interrelations.[1] Ontology has since found application in formal and computational disciplines such as formal logic, computer science, artificial intelligence, and informatics.

The result is *computational ontology*, *ontology engineering* [3], or *applied ontology* [25]. This formal and applied research field occasionally uses distinctions and methodologies from software engineering, but also philosophy and formal ontology. *Formal ontology*, a branch of analytic metaphysics, represents an ontology using logics, philosophical methods, and domain-neutral concepts. Philosophical concepts and distinctions such as unity, identity, persistence, whole-part, generality-specificity (e.g. universal-particular) are defined with first-order, modal, and higher-order logics to aid in explicitly characterizing the entities in a given domain, and making knowledge and assumptions explicit. Probabilistic and other non-classical approaches are also employed.

By representing the ontological theory in a computable format, we produce a *computational ontology,* which is a computational artifact that presents an ontology of a given application or domain. It can express the shared knowledge of a domain or an agreed-upon conceptualization. *Domain ontologies* express domain knowledge, e.g., the object dynamics and scientific principles in a specific scientific domain. A*pplication ontologies* have a specific application as a goal and may use domain ontologies in the pursuit of that goal. *Foundational (or top-level) ontologies,* occasionally used as one method[2] to foster data exchange, provide a theory of the most general categories and distinctions in order to classify more specific (or lower-level) ontologies such as domain ontologies. These applied ontologies consist of a taxonomy whose terms have a formal semantics, the totality of which is computable by way of a knowledge representation (or ontology) language, such as Common Logic [4] or OWL. Together with an analytics package, automated reasoning and querying is possible. Some goals of this interdisciplinary field are (Table 1):

Concept(ual) analysis and clarification	Data Annotation	Automated reasoning
Terminology & Taxonomy development	Data-sharing	Knowledge-discovery
Knowledge representation	Semantic interoperability	Database interoperability

Table 1: Goals of Philosophical and Computational Ontology

[1] Due to the fact that astrodynamics involves predicting future behavior of space objects in orbit and events, modality (what is actual and possible) is a vital aspect for space ontology.
[2] These ontologies are not necessary to link ontologies or databases. Mappings between ontologies is another method.

Ontology engineering is the design and engineering process by which computational ontologies are produced and employed. The ontology development process may or may not use specific scientific disciplines to inform its production, but it is necessary if scientific and representational accuracy is desired. The next section summarizes the domain to be ontologically characterized.

3. The Domain: Objects in/and the Space Environment

The domain to be ontologically characterized is that of space objects, broadly construed as objects in astronomical, but at least orbital, space environments. The *space domain* consists of the space environment about the Earth and its phenomena. To formally represent these entities we must know: (I) what space objects there are (and can be), (II) their properties, and (III) how they are related to one another and to their environments, (IV) in what way they interact, and (V) what patterns exist or can develop therein. Given I-V, we therefore begin with some ontological (philosophical) assumptions: the distinctions between properties, property-bearers, their interrelations, and processual entities.

By applying philosophical and computational ontology to this domain we yield a *space domain ontology (SDO),* whose components or modules may be a *space object ontology, a space process ontology, space object behavior ontology,* or otherwise. Because the focus is not on astronomical phenomena, the SDO is more accurately called a space situational awareness ontology [2], a space domain awareness ontology, or an orbital and near-Earth space environment ontology [24].

One question is whether there is a scientifically accurate manner to categorize space objects. Short of this, and in any case, an aim is a classification of space objects that will improve peaceful *space domain awareness* (*space situational awareness*), help solve space domain data problems, and ensure future space travel. Drawing upon reference documents, another aim is to identify (or create) a list of category terms (relation, relata, and otherwise) that will compose a *space object* or *space domain taxonomy*. Philosophy and formal ontology will facilitate this effort.

Figure 1 visually represents the objects in the space domain. Although, the space situational awareness and astrodynamics communities primarily consider artificial space objects, the analysis must consider all objects that would fall under the general category, **Space Object**.

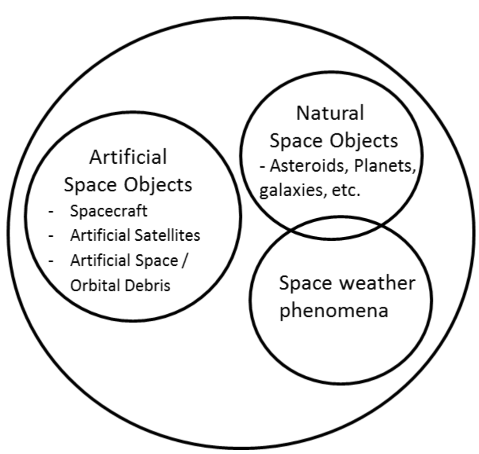

Figure 1: Space domain objects

These space phenomena not only inhabit, but form *part of* that space environment. Relative to our terrestrial home, this includes the orbital space immediately surrounding Earth. The boundaries or divisions of this space can be specified according to contemporary delineations such as Low, Mid, and High Earth Orbit, or according to natural physical thresholds, such as distances from the sun where water ice forms.

However we are to ontologically characterize the space environment, environment and objects are to be asserted in *mutual causal interaction*, in accordance with the dynamics expressed by scientific physical principles. That is, the ontology should reflect the *mutual causality* and *interrelational* aspect of reality. This is necessary if we are to identify patterns of interaction. The environment, e.g., space-time, and material objects are not isolable. As such, I assume a contemporary physics understanding of space and time (not necessarily a 4D or block universe view, mind you) such that the universe is dynamic and changing. This is in opposition to the simplistic Newtonian (and earlier but related Aristotelian) container or "billiard-ball" view of space and time. The latter does not do justice to the dynamic nature of reality. Although it may be a useful fiction or heuristic, from scientific and philosophical perspectives Newtonian and Aristotelian conceptions are lacking, both in philosophy and science. Existing ontologies (foundational or otherwise) that adopt such Aristotelian thinking should therefore be avoided.

Moving on, the next section presents an analysis of the category of **Space Object**.

4. The Category of *Space Object*

'Space object' has been a term used in the space community since approximately 1966 [6, p.6]. In what follows I will analyze its meaning and its referents from an ontological (philosophical) perspective. As part of the conceptual analysis for this domain, ask the following questions prior to defining 'space object'.

- What are our intuitive and *prima facie* conceptualizations/meanings of 'space object'?
- What is the *intended* meaning of 'space object'?
- Does the intuitive meaning match the intended meaning?
- What do we mean by 'space'?
- What do we mean by 'object'?

The second question cuts to the chase, but each is important in establishing consistency and clarity of meaning. Once the sense of the term is established, it will later be formally represented. In answering these questions we answer:

- What are the referents (if any) of 'space object'? (What is its extension or denotation?)

By answering the last question, then proceed to identify the defining properties of the referents. This helps in distinguishing the various *sorts, classes*, or *types* of space object.

Like other highly general terms, 'space object' is inherently ambiguous. Its meaning is grasped in context, but more often than not it refers to objects in orbit or somewhere in space beyond Earth's atmosphere. As used in some space communities the term is for artificial space objects in the orbital and near-Earth environments. What more, each specific space community may have its own sense that constrains the sorts of object being referred to (Table 2).

Space Community	Extension of 'space object'
Astronomy	All natural *celestial bodies* and *phenomena* in the universe: galaxies, stars, planets, moons, asteroids, magnetic fields, gravity waves, etc.
Astrodynamics	Artificial space objects in orbital space: telecommunications satellites, spacecraft, etc. Astrodynamic physical principles (e.g., laws of nature)[3]
Space Situational Awareness / Space Domain Awareness	Those space objects of astrodynamics, of the orbital and near-Earth space environments. Both artificial and natural.
Astroinformatics	Data elements referring to actual space objects, or the space objects themselves

Table 2: Discipline-specific scope of 'space object'

It is doubtful that the SSA and astrodynamics community are interested in atomic nuclei, gravity waves, and Galaxies being classified as Space Objects. By contrast, the astronomy community would. The former disciplines have a smaller scope of objects (spacecraft, artificial satellites, etc.) than the latter. It forms a subset of the broad category of Space Object. In other words, the extension of 'space object' for the astrodynamics community is arguably smaller than that of astronomy.

For astrodynamics and SSA communities, the ontology in question is more precisely an: *orbital object ontology*, of which an *orbital debris ontology* [1] is a part. A SSA ontology [2] has a scope large enough to encompass each ontology. As outlined in [1], modular domain- and sub-domain specific space ontologies combine to form a holistic environmental picture of the overall space environment domain.

Although a particular community may use the term to denote only certain sorts of objects, *the term is in fact more general*. It is certainly wider in extension if we assume that its meaning comes from the meaning of its constituent terms. That is, part of the generality may come from that of 'space' and 'object', terms that often reflect domain-neutral concepts and ontological categories from the history of philosophical and scientific thought.

Space (and/or space-time) is oft-considered fundamental in philosophy (e.g., metaphysics, ontology) as well as physics. It is commonly treated as a foundational concept in psychology, and some philosophical and applied ontologies, but has a rich theoretical history, being a subject of much intellectual debate. From a linguistic perspective, the word 'space' has multiple meanings, but the intended meaning at hand is that of *astronomical space*. Again, our domain objects are those of the space environment in which Earth resides and beyond Earth's atmosphere.[4] In itself, this is a rather wide scope: all objects in the entire spatiotemporal universe are included unless we assert constraints, such as a narrower meaning for 'object' or 'space object'. We also run into the problem of granularity or scale (e.g., are atoms composing a meteor space objects?).

[3] These laws should be represented in a space object ontology.
[4] I use the word 'of' to express the causal interconnection of environment (e.g. space-time) with the objects.

The category of Object, likewise is inherently broad. Independent of context, the word 'object' is also ambiguous and flexible in meaning. As an ontological category, Object is often considered domain-neutral [12]. Just like the term 'entity' (which is here used as the most general term), we may use 'object' to describe: astronomical objects, biological objects, social objects, historical artifacts, etc. It will therefore be a matter of explicitly constraining the extension of the term and scope of the domains. To complicate matters further, some of the phenomena under study in Astronomy beg the question: *what is an object*? This question inevitably comes up, in part, because traditional ontological categories are limited in their ability to represent complex and dynamic entities that appear to have properties each category, e.g., modern astrophysics and general physics. Phenomena such as magnetic fields, storms, and gravity waves may not be accurately characterized using the traditional categories and distinctions of continuant vs. occurrent, object vs. process. New categories may be called for. Advancing formal ontological analysis of the space domain thereby serves to pave new ground for conceptual and philosophical innovation.

To clarify the sense of 'object' consider a bottom-up approach: look at the domain objects and science to be described and identify common general properties. The intended sense of 'object' vis-à-vis space objects are at least **spatial** or **physical objects**. That is, they are *spatio-temporal* (at least spatial), being spatially and temporally localizable, and have or can have dynamic and energetic properties. Specific types of objects of interest for space object and SSA communities are satellites, spacecraft, space debris, orbital debris, and asteroids. Thus, these space objects are physical, but also **material** objects: they have some material composition.

However, for the widest sense of 'space object' a material object category is too restrictive: astronomy and astrophysics study entities in the universe that do not have material parts (matter), but consist of energy, fields, or some combination thereof. At one of the highest levels of ontological abstraction, the category of Endurant (or Continuant)[5] is an applicable foundational (top-level, domain-neutral) category to classify material space artifacts such as spacecraft[6], but depending on its definition may not be appropriate for the category of Space object in its widest sense due to exotic astronomical phenomena.

The ambiguities of the term 'space object' and 'space object ontology' are apparent. A problem is resolving the mismatch between the implicitly broader sense of the term 'space object' with the narrower sense of the term as used in a given space discipline or community. This can be solved by not using the phrase/title 'space object ontology' unless 'space object' is used in its broadest sense. Alternatively, one should explicitly state that the ontology uses the term in a narrow sense, e.g., as space artifacts. I do not recommended the latter for three reasons. The first reason is the complexities mentioned earlier, e.g., the term is inherently ambiguous can be rightly ascribed of objects beyond the the would-be narrower sense. The second is without using the category of Space Object it will suffice to assert more precise (lower-level) category terms representing the specific sub-types of space objects of

[5] The philosophical category of Endurant/Continuant encompasses those property-bearing entities that continue to exist (persist) through time whether or not they undergo change.
6 An important fact to keep in mind is that as we move to high-level (more abstract) concepts and category terms, we will be moving closer to arbitrary definition and philosophical theories of the particular sort entity.

interest, e.g. Space Artifact. If need be, an upper-level category of Physical Object can be used instead. Finally, if we use 'space object' in its broadest sense, we avoid confusion and proceed to assert more specific categories as needed. Some properties of some space objects, such as artificiality, facilitate this specialization.

Space artifacts are often referred to by the category term 'space object', making artificiality an important property to semantically capturer. Not only do space objects such as satellites and spacecraft have physical and material properties, they be modeled as have **artificial properties**. They are artificial or artifactual, i.e., created by persons. The category of **Artificial Space Object** or **Space Artifact** encompasses most objects referred to by use of the term 'space object' in the SSA and astrodynamics community. It does not include **Natural Space Objects** (or **Astronomical Objects**), e.g., asteroids, however. The inherently broad sense of 'space object' requires addressing both natural celestial bodies as well as artificial bodies. The natural-artificial distinction allows us to group space objects such as asteroids and planets in one category; and telecommunications satellites, orbital debris, and spacecraft in another.

The following taxonomy uses this distinction, and is implicitly structured using the class-subclass (subsumption or 'is a') relation, whereby a subclass inherits the properties of its superclasses. Indentation indicates class subsumption, and forward slashes ('/') synonyms or co-extensional classes. A computable assertion in a subject-predicate-object form would be: Artificial Space Object is_a Space Object.

- Physical Object
  - Space Object
    - Natural Space Object
    - Artificial Space Object / Space Artifact

With the preceding in mind, I offer some options for qualitative definitions of 'space object': the most general (1A) to the more specific (1C) according to the above constraints. This definitional form is used: an A is a B that C's. Various formal relations and terms can be asserted to describe the state of motion, and the relationship between the space object and its environment. Some relations, formally expressible and computationally implementable as n-ary predicates in a knowledge representation language include: ***Inhabits***, ***Interacts in***, ***Located in***, ***Positioned in, Occupies,*** and ***Moves in/through***. Some may be synonymous, others co-extensional[7]. For the sake of brevity, I use 'inhabits' as a catch-all after DEF-1A. If space or the space environment is asserted with its own category, then either it should be left as a primitive or both a formal theory of space-time and the dimensions of the space should be asserted. In addition to the above relations, the categories **Space, Object,** and **Space Environment** are left undefined.

Space Object =def.

an object inhabiting, interacting in, occupying, located in, or moving through space (DEF-1A)

[7] For example, that which moves through space is located in (broadly construed) space.

an object inhabiting the space environment (DEF-1B)
an object inhabiting the orbital or near-Earth space environment (DEF-1C)

1A to 1C vary in their description of the spatial regions. 1C is the most specific, where the space environment extends to a to-be-specified distance from Earth. Without further qualifications 1A and 1B encompass all objects in the universe. Everything from drifting hydrogen molecules, to GPS satellites, planets and Galaxies and perhaps objects on the surface of a celestial body, can be classified as space objects.[8] Accepting the preceding taxonomy, constrain the meaning further in the following manner.

Space Object =def.

a Physical Object (natural or artificial) inhabiting space (DEF-2A)
a Physical Object (natural or artificial) inhabiting the space environment (DEF-2B)
a Physical Object inhabiting the orbital, near-Earth or deep-space environments (DEF-2C)

Only 1C and 2C constrain the position of the space object to the spatial neighborhood of Earth. From a relative perspective, an object is a space object relative to some reference frame or observing location. However, the generality of 'space object' suggests it should be applicable to *any* planetary body. The Earth itself is a space object, after all. All but 1C and 2C are general enough to convey a less relative sense of 'space object', unless 'space environment' is defined for Earth.

These definitions use the physical nature of the referents of the term 'space object' as a guide to classifying space objects. As such they attempt a more objective definition. It is perfectly reasonable, however, that the category or concept of Space Object is not a natural mind-independent ontological category, but one that is attributed by persons in certain social contexts. Let us explore this alternative: classifying Space Object as a type of social or object role.

5.1 Space Object as a Role played by Physical Objects and Material Artefacts

The category of **Space Object (SO)** can be categorized as a type of **Role**, yielding a **Space Object Role** category. Roles are existentially dependent entities that are *held*, *borne by*, and *played* by some role-bearer or role-player, and *realized in* certain circumstances and processes. The holder of the role stands in certain relationships to other entities and performs certain activities to play and realize that role. The most easily recognizable roles are social roles held by persons, such as Astronaut, Aerospace Engineer, and Professor, but it is conceivable to assert roles held by material objects in space. The role is attributed to the space object under an interpretation according to which the category Space Object is socially-constructed or relative to some social context. A ***plays***, ***has_role,*** or ***bears*** relation relates the material object (material space artefact) with the role. These roles are not essential properties of the material object itself.

[8] This raises the question: are grains of sand, or cars in the street, space objects?

Consider a scenario in support of this approach. Is a space telescope not yet launched into orbit a Space Object? On the one hand, we have the intuition that it is a space object even when sitting on Earth. This intuition exists because the telescope was *intentionally designed* to operate in space. It has been produced to have a physical structure that affords its operation in the space environment. It has been given the function to operate in space. Thus, according to intention-, design-, or function-based criteria, it is reasonably classified as a Space Object. Position in space beyond Earth's atmosphere is not a necessary condition, but could be a sufficient condition to be a Space Object.

On the other hand, there is the intuition that only when in orbit (or otherwise in space) is it properly classified as a SO. Being located in the space environment is an essential identifying property of the category (as definitions 1A-C emphasizes). Therefore, according to this location-based criterion, the telescope is not a type of Space Object at that time. It is not an object of interest for space sensors and their operators…yet. A formal approach addressing this intuition is to assert the telescope as a Space Object at one time but not at an earlier time. To avoid this category change, however, assert the individual telescope (SpaceTelescope1) as bearing the Space Object Role when in orbit around earth, but not when on the surface.

If taking this role approach, the term **Space Object Contact** (asserted as a type of **Role**) is appropriate for space communities, observing orbital and Near-Earth space. Only when the object is observable in space that it is deemed a Space Object. For example, when the sensor detects an object, and it is processed (and made aware by human operators), it can be classified as a Space Object Contact. Once further data is gathered and analyzed the specific type of space object can be determined. A ***detected*** relation holds between the detected object (the contact) and the sensor or observing entity. Two alternative definitions of these role categories are below, followed by a role-based definition of 'Space Object'.

Space Object Role / **Space Object Contact Role** =def.

- A role held by a physical object that inhabits the space environment. (DEF-3)
- A role held by a physical object that has been *detected* in the space environment. (DEF-4)

From here assert more specific space object roles, such as Space Artefact Role.

An alternative is to define SO in the following way (DEF-5). **Space Object** =def. a Physical Object (the role-player/bearer) that plays the Space Object Role when located in the space environment.

Finally, the category of **Payload** (or **Space Payload**, more specifically) is arguably best asserted as a type of Role. The Hubble space telescope, for example, played the **Payload Role** during a past **Launch Process** until its deployment process (or **orbit insertion event**). After that point in time, it ceased to bear the **Payload Role**. At all times, however, it persists as an instance of the category **Space-based Telescope** (or **Astronomical Telescope**).

* * *

Part of distinguishing one sort of space object from another involves identifying that which distinguishes it from another sort of entity. Differentiae may be aspects or properties of the space object, its involvement in (or enactment of) some process, some relationship(s) to other entities, or patterns thereof. Differentiae in class definitions of the form **An A is a B that C's** (the genus-species-differentia form, assumed here) take the place of C. This is the subject of the next section.

5. Properties of Space Objects

Properties, features, attributes, qualities, or characteristics distinguish one object from another. They may be physical, structural, social or otherwise. We may distinguish static and dynamic properties as well. Properties help ontologically characterize a given object. They are sorts of **Dependent Entity** in the sense of being mutually existentially dependent on some property-bearer. A property is ***had*** or ***borne by*** a property-bearer (such as a material object). These minimally binary predicates can be asserted to relate the property-bearer and the property: for some particular GPS satellite and mass, we assert GPS-Sat1 ***has_property*** Mass1. Material objects, such as asteroids and spacecraft, are examples of property-bearers: they bear properties such as mass, charge, etc.

Essential properties help describe the *identity* of an object. An essential property is a property without which the property-bearer would not be the type of entity it is. For example, from a functional perspective, an optical space telescope is essentially a telescope whose function[9] is to collect photons from interstellar space. The **function** (also a dependent entity) is an essential property of this space artefact. Table 3 presents a list of category terms to characterize space objects.

Physical, Material, Dynamic & Relational Properties	**Misc.**	**Legal & Social Entity Terms**
Mass	Length	Owner
Shape	Width	Nationality
Material composition	Height	Manufacturer
Albedo	Cross-Section	Operational Status
Velocity, Rotation	Launch Date	Mission
Ballistic Coefficient	Reentry Date	Operator
Keplerian Orbital Elements	Function	
State Vector	Coordinate frame	
Solar Radiation pressure	Visual Magnitude	

Table 3: Property classes to characterize space objects

Space artifacts are essentially artificial and artifacts bear these properties: being human-made, and thus having a historical human-made origin, being intentionally designed, and having one or more specific function. The function exists not only because it is intentionally ascribed/attributed by persons, but also because the artefact was constructed in such a way that it is physically able to perform that function. It has the physical capability to do so, and that capability (and function) is in part due to its

[9] Note that there is growing literature on the ontology and philosophy of function, but for lack of space and time I cannot consult them for this paper.

material structure, a structure that is the manifestation of human intentions and actions. Some space artefacts, particularly whole spacecraft and satellites, have one or more **intentionally designed functions**[10] as essential properties of the spacecraft as a whole. A functional approach is helpful for classifying types of space artifacts such as space vehicles, and artificial satellites with their sub-types (telecommunications, GPS, search and rescue satellites, etc.). Not all space artifact objects necessarily have functions, however.

Consider shards of spacecraft (a **space artifact part**) from orbital collisions. The shards (**space debris**) themselves do not have a function in isolation, but the whole of which they were once a part did. In other words, since space debris do not appear to have a function in themselves separate from the whole artefact, *having a function* is neither a necessary condition nor an essential property for every space object.

As we will see in the section on taxonomies, we need not explicitly use the terms 'artificial', 'artefact' and 'natural' in space object categories. Rather than using the natural-artificial distinction, we may instead distinguish space object categories by using some combination of physical parameters and other sorts of property. This includes using the above-mentioned properties common to artificial objects. So long as terms such as 'artificial' and 'artefact' are used, however, the ontology should develop or adopt a theory of artifacts, intentionality, and function, but I cannot discuss this here.

Although agreement as to defining properties of space object types may ultimately be an arbitrary decision (if only in part), it is best achieved by consulting both a variety of scientific and philosophical viewpoints and reference documents. For the general term 'space object' defining features can also be drawn from legal definitions. I analyze some existing legal definitions, next.

6. Legal Definitions of 'space object' and their Ontological import

This section discusses some legal definitions of 'space object' toward a formal ontological definition, drawing out their ontological commitments. **Ontological commitments** [13] are that which a theory or statement explicitly or implicitly implies to exist or that could exist. Given that ontology is concerned with actual and potential existence, the inquiry is relevant. The type of space objects these definitions refer to are primarily **artificial space objects** tracked by the SSA community.

Christopher M. Hearsey [6] provides an informative survey of the legal definitions of 'space object'. He notes its various senses: "the treaty definition of space object represents specific meanings under different treaties", and aims to find "those common elements that give meaning to the term space object under general international law"[6, p.4]. Finding **common elements** is one task of ontological (philosophical) inquiry. These elements may serve to characterize artificial space objects in particular. Hearsey asks when an object becomes a space object, and what makes an object a space object. In philosophical jargon, these questions are about the **identity conditions** of space objects: what

[10] We may distinguish types of function, e.g., an engineering design function for artefacts.

must be the case, what properties the object must have, and what relationships it must stand in to be classified as a space object.

As noted in section 6, to answer these identity questions (and toward stable definitions[11]), use **physical**, **material** and **functional** properties to describe categories of space object. This includes spatio-temporal, structural, chemical, and dynamic properties. Social properties will also characterize the objects, providing insights into the wider socio-political interrelations between space actors, their space assets in orbit, and activities they can or should engage in (e.g. space debris removal). "The term ['space object'] itself activates obligations, affects treaty rights, and other rights and duties under international law." [6, p.3] An ontology of space objects should therefore make reference to the appropriate legal and **social entities**, e.g., **rights**, **duties**, **obligations**. They can help differentiate one category from another.

Various treaties have defined or used 'space object' in a like manner, the common thread being that the objects in question are primarily artifacts such as spacecraft, satellites and space debris. That being said, although "most states [at least 88] [6, p.24] promulgate the term space object in close conformity to the article I definition of the Liability and Registration Conventions" [6], making it reasonable to use it to inform (but not determine) an ontological definition, we must be aware of at least two limitations. First, "the definition of space object, as expressed in article I of the Liability and Registration Conventions, provides only a basis in which to understand the meaning and scope the terms legal effect under international law."[6, p.23] and two, it is circular.

[6, p.7-8] quotes [7], writing that two definitions of 'space object' were considered: (L1) "the object itself and its component parts, as well as the means of delivery and its component parts" and (L2) "articles on board the space object and articles detached, thrown or launched from the space object. The former was chosen, resulting in the circular definition (L3): "The term 'space object' includes component parts of a space object as well as its launch vehicle and parts thereof" [8][9].

By using 'space object' in its own definition, a common principle of formal definitions is violated: non-circularity. It is true that context and intuitions help us grasp the intended meaning. It is also true that there are different sorts of definition, and it is certainly possible that this principle only applies to some formal definitions, but I assume circularity is best avoided for these analytical applications where conceptual clarity is desired and computation is the applied goal. I therefore proceed as if this principle is worth adhering to for the present inquiry.

Note also that L3 excludes objects mentioned in L2 that can rightly be called space objects by the SSA community. Another limitation is that the definition does not explicitly state the type of space object in mind. We need a definition that makes explicit what is implicitly assumed. The second use of 'space object' in L3 implicitly means **artificial space objects** or **spacecraft**. Granting this, another principle is violated: the definiens should contain terms that are simpler (conceptually less complex) or broader in meaning than the definiendum. As we have established, however, 'space object' is broader

[11] Also note that even though we seek a physics-based ontological definition, the term 'space object' is sufficiently generic to resist such a definition.

than ‘spacecraft’ and ‘artificial space object’. L1 correctly uses ‘object’ as the term more general than the definiendum: a Space Object is indeed a type of Object. Let us consult other definitions.

We read the following qualification to the above definition: “Thus any object without which the spacecraft would be regarded incomplete, may be taken to be a component part.” [6, p.8] This is ontologically significant because it references the **structural** and the **functional composition** of the artificial space object.

Mereology—the theory of parts and wholes [14]—will be useful for ontological descriptions, as will distinguishing types of part: structural parts, functional parts, etc. It is important to describe the **mereological structure** of space objects, and their historical development (provinence). For example, we must know whether an **orbital debris object** was ***part of*** a GPS satellite, a space shuttle, or other space object. This partonomic knowledge plays a part in determining origins and thus legal considerations such as ownership and responsibility. By formally representing the parts (components and otherwise) of a space artefact, an automated reasoner will infer that an identified space object of a particular component class belongs to a particular class of, say, spacecraft.

According to L1 and L3, the **component parts** of a space craft are space objects. Some or all of these components are ***proper parts*** in the sense of mereological ***parthood.*** Without them a spacecraft would not be whole or structurally complete. In functional terms, the function of the spacecraft is not ***achievable, actualizable*** or ***realizable*** until the spacecraft is structurally and functionally whole. That is, all its component parts are in place, and all are capable of performing their function. This forms the artefactual unity—the whole—that is the spacecraft. One mereological question is: are parts of space objects themselves space objects? I would say no because the context of the domain is representing, observing, and predicting the behavior of *entire* space objects. We are concerned with the whole and when an object is observed or detected it is the whole that is observed. Only when a part separates from the whole and thereby itself becoming a whole (and subject to detection) is it a space object.

Cheng’s description of ‘space object’, as quoted in [6 p.8-9], explicitly references the space environment (an essential aspect not mentioned in L3, but mentioned in the section 5 definitions): “any object launched by humans into outer space, as well as any component part thereof, together with its launch vehicle and parts thereof.” A functional definition by Belgium that combines various identity conditions, including component parts and launch vehicle being space objects (the latter two not quoted here), is:

> "Any object launched or intended for launching on an orbit around the Earth or to a destination beyond Earth orbit; […] Such a device shall also be considered a spacecraft even where it is operated experimentally for the purposes of its development or validation stage." [10]

Mention of ‘device’ and ‘spacecraft’ makes the intended meaning once again clear: space artifacts. The novel conditions are intention to launch and experimental operation.

We also read this scope-defining statement in a proposal by some nations: “For the purpose of [the] Convention, the term ‘space object’ also includes […] all component parts on board, detached or torn from the space object." [6, p.8] This particular definition ensures the scope includes certain types of **space debris**, namely **spacecraft fragments** and **separated components**. [6, p9] mentions Gal's [11] definition, which adds an important relational aspect: **the type of motion**.

> "only those objects can be regarded as space objects which perform an orbiting movement round the earth or other celestial bodies, or which have been launched with that purpose,"

Here, actual and intended orbital motion are necessary conditions for an object to be a space object. An approximate first-order logic translation would be:

$$\forall x \, [\, instance\_of(x, SpaceObject) \longrightarrow orbits(x, Earth) \lor orbits(x, y) \land instance\_of(y, CelestialBody)]$$

For all objects x, if x is an instance of the class SpaceObject, then x orbits Earth or x orbits y, and y is an instance of some celestial body.

Notice, that although artificial space objects are the focus, without explicitly stating the artificial nature of the object in question, this definition remains broad enough such that the Moon and other natural satellites satisfy its conditions.

The ontological commitments of these definitions are to: the space object, space object parts, launch and delivery vehicle, objects onboard, orbital motion, celestial bodies, purpose, and function. In a similar vein, Hearsey [6, p.21] identifies these common elements among legal definitions of 'space object'.

(1) object
(2) intent to launch
(3) launched
(4) launch vehicle
(5) payload
(6) component parts and parts thereof
(7) satellite

I will now discuss these common elements from an ontological (philosophical) perspective. Many if not all have either corresponding or subsuming ontological categories. As such, these entities serve to identify types of space object. **Object** was discussed at the beginning of this investigation (section 5), but is a necessary condition: if x is a space object, then x is an object.

The intent to launch, (2), is an **intention**, which is a **mental entity** or **cognitive entity**. It is quite possibly a **collective socio-psychological entity**. That is, aside from intentions held by individual human beings, we may assert **collective intentionality**. On this, [6, p.25] has a helpful condition that we can adopt for describing this space object property. We read: space objects are "intended to be launched into outer space by an authorizing government, as registered, or by way of a national activity". This quotation arguably ontologically commits the speaker to:

- **Intention**(s)
- At least one **holder** or **issuer of the intention**, i.e., human beings, perhaps governments;
- *A* **registered document** that concretely *expresses* the intention, and/or
- Some **national activity** (e.g., a process) which helps manifest or execute the intention

The intention temporally precedes launching, but exists during the conceptual development and design phase of the space artifact. It continues to exist, if not through the lifetime of the space object, then at least until launching. These considerations are about the **persistence** of the entity in question.

Having been launched (3) can be ontologically represented as a **historical property** or **event**. During its occurrence, however, it is an occurring event or process (e.g., a **Launching Process**). At some time t, space object x was launched, and at some later time t+n x was inserted into orbit. During the interval [t, tn] a launching process in which x was involved was occurring.

Launch vehicles, payloads, component parts and their parts, and artificial satellites (4-6) are **Material Artifacts** and **Material Objects**. According to legal definitions they are artificial space objects. As [6, p.21] notes, spacecraft crew and other occupants would not be component parts.[12] Likewise for fuel exhaust.

Taken together, 1 through 7 more precisely characterize the category of **Artificial Space Object** or **Space Artefact**. Being artefactual, the category of **Function** and its subtypes are relevant. If **Space Object** is treated as a type of **Social** or **Legal Entity**, then it will change as legal definitions do. A social or legal entity is one whose properties are socially or legally determined, rather than physically or naturally determined. If "national legal requirements seem to limit generally the scope of the type of object a space object can be" [6, p.13] and a space object ontology uses legal definitions as an authoritative source, then it would also seem that the subclasses of SpaceObject would be dictated by the types of space object specified by those legal requirements. I do not recommend this strategy since it contradicts intuitions on, and ordinary usage of the category of space object. It might be relevant to a role-based representation of the category of Space Object, however.

If we seek a physics-based definition of 'space object', then an ontological definition should not change when legal considerations do, but when physical science is corrected or otherwise updated. The latter approach has been assumed thus far, but the generality of the term appears to require a degree of arbitrary ascription, which gives us cause to consider the Role approach (section 5.1). Moving on, the next section offers some space object taxonomies and definitions of key terms.

8. Types of Space Object and Space Object Taxonomies

The following space object taxonomies are structured according to the class subsumption relation, also called the 'Is a' relation. For example, the class Telecommunications Satellite is a subclass of Artificial Satellite**.** The latter is more general (more encompassing) than the former, carrying less properties that characterize it. As mentioned in the section 7, **partonomies**, which are taxonomies structured with parthood relations ('is part of', 'is proper part of', etc.) along the lines of *General Extensional Mereology*, will be helpful for describing the composition of space artefacts.

[12] One may argue, however, that some sorts of space artifacts (e.g., shuttlecraft)—where human operation is required—calls for human beings to play a Role of a functional, agentive and non-integrative part of the spacecraft. Note that persons should not be represented as subtypes of the category of Object because of the implicit non-human, and often dehumanizing, association of the term 'object'.

Some dimensions to classify space objects are: function, physical properties, spatial location (e.g., at a particular orbital altitude), and motion (e.g., orbital motion, on an interplanetary trajectory, etc.). The most general space object classes use a locational aspect, whereas the most specific artificial space object classes are easily classified according to design or operational function.

The natural-artificial distinction is an intuitive starting point to help organize a space object taxonomy (Table 4), but class terms need not explicitly include the words 'natural', 'artificial' or 'artefactual'. 'Natural space object' refers to what have historically been called **celestial bodies**, the objects of study in astronomy. For this communication, we may substitute 'body' by 'object' with no loss in meaning.

Natural Space Objects	**Artificial / Artefactual Space Objects**
Asteroids	Spacecraft
Comets	Space Telescope
Moons (natural satellites)	Telecommunications satellite (artificial satellite)
Planets	Space Debris / Orbital Debris
Stars	Space Station

Table 4: Types of Space objects grouped according to the natural-artificial distinction

Naturally formed space objects can be represented using the class **AstronomicalObject**, similar to the IVOA Ontology of Astronomical Object Types (its class term being 'AstrObject').[13] 'Astronomical object' is here synonymous with 'Celestial body', but their corresponding ontology classes are subclasses of NaturalSpaceObject in order to allow for astronomical phenomena that are best categorized as other than a body or object, where *body* and *object* are conceived as some unitary material whole. Pending a review of the IVOA ontology, we may reuse it taxonomy in its entirety or in part. Likewise for the ontology as a whole, importing it into a space object ontology file workspace.

Table 5 presents a space object taxonomy that explicitly includes the natural-artificial distinction. The natural space object classes to the right may be structured similar to, if not reused from, the IVOA ontology. Given the broad nature of the category of Space Object, subsuming Astronomical Object under it is justifiable.

Taxonomy 1	**Natural Space Object Classes**
Space Object	
Natural Space Object	
Celestial Body / Astronomical Object	*Celestial Body / Astronomical Object*
Artificial Space Object	Asteroid
Spacecraft / Space Vehicle	Comet
Space Shuttle	Meteoroid
Space Launch Vehicle	Planetary Body
…	Planet
Artificial Satellite	Moon
<Satellite classes>	Stellar Body
Space Station	Star

[13] This brings up one case: some space debris are natural space objects, a scenario that can be used in favor of categorizing Space Debris as a type of Role played by space objects.

Space Debris	<Stellar classes>
<Debris classes>	Galactic Body
	Galaxy
	<Galactic classes>
	Nova
	Supernova
	<Supernova classes>

Table 5: Space object taxonomy 1 (left) with Natural space object classes (right)

The terms " […]'space vehicle', 'spacecraft', 'spaceship', 'satellite', and 'space station' represent the types of objects launched into outer space"[6 p.7]. They refer to artificial space objects, and have a place in a space object taxonomy, but some should be synonyms, e.g. 'space vehicle' and 'spaceship'. The Space Station class is disjoint from Space Vehicle. Despite the fact that both transport persons or cargo, the former is not designed to travel vast trajectories under their own power, or to be autonomous vehicles on part with shuttlecraft or rockets. Rather, space stations are designed to occupy a position in orbit, to be a human place in space as it were.

Taxonomy 2 below differs by removing use of the term 'natural'. I also use the category of **Space Artefact** and generalize that of **Spacecraft** to be equivalent. The general sense of 'craft' according to which a craft is *any work* by persons is the intended meaning rather than the sense of 'craft' as a 'vehicle'. The result is: any space (astronautical) work by persons. The category of **Space Vehicle** uses the sense of 'vehicle' as an artefactual means for transporting persons or cargo through space.

Taxonomy 3 maintains the generalized Spacecraft sense, but removes Space Artefact and the terms 'natural' and 'artificial'. Instead, it implicitly adopts a strategy according to which we refer to features that characterized artifacts, e.g. being human-made, function(ality), intention, design, historical origins, etc.

Taxonomy 2	**Taxonomy 3**
Space Object	Space Object
Celestial Body / Astronomical Object	*Celestial Body* / Astronomical Object
Space Artefact / Spacecraft	Spacecraft
Space Vehicle	Space Vehicle
Space Shuttle	Space Shuttle
Space Launch Vehicle	Space Launch Vehicle
Artificial Satellite	<Artificial satellite classes>
<satellite classes>	Space Debris
Space Debris	<Debris classes>
<Debris classes>	

Table 6: Space Object Taxonomies 2 and 3

At least two space object classes need further study: satellites and debris. **Natural satellites** are satellites formed by physical processes independent of human action, e.g., moons. **Artificial satellites** are spacecraft that orbit an astronomical body. They come in a variety of types, each designed to perform one or more specific functions. Since orbital motion is the property, state or process common to all satellites, we must distinguish them according to an additional criteria, such as design function. Non-exhaustive taxonomies of human-made satellites, and space debris are as follows.

- Artificial Satellite
  - (Tele)Communications Satellite
  - Navigation Satellite
    - GPS Satellite
  - Search & Rescue Satellite
  - Earth Observation Satellite
    - Weather Satellite
  - Reconnaissance Satellite
  - …

- Space Debris
  - Comet Fragments
  - Spacecraft Fragments
  - Defunct Spacecraft
  - Mission-related Space Debris
  - …

Eliminating **Artificial Satellite** from the taxonomies, but asserting its types yields Taxonomy 3 (and 4). This strategy is supported by the fact that any object can orbit a planet, making orbital motion insufficient to thoroughly distinguish one artificial space object from another. Similarly, we may remove Space Artefact and Artificial Space Object from all taxonomies, and assert their respective types with the appropriate identity conditions: being made by person, having a design function, etc. This strategy is suggested when a philosophical account of artefactuality is either undesired or will complicate either the taxonomy or automated reasoning.

Taxonomy 4 removes SpaceObject, but asserts **SpaceObjectRole** (or SpaceObjectContactRole). Lower-level space object classes are asserted, to be formally related to SpaceObjectRole class by an n-ary (at least ternary) ***has_role*** predicate as described in 5.2. The Spacecraft class serves to group the artificial space objects. SpaceObject can be added and then defined according to definition 5 (DEF-5).

Taxonomy 4

- *Celestial Body* / Astronomical Object
- Spacecraft
  - Space Vehicle
    - Space Shuttle
    - Space Launch Vehicle
    - <Artificial satellite classes>
  - Space Debris
    - <Debris classes>

- Role
  - Social Role
    - Medical Doctor Role
    - …
  - Material Artefact Role
    - **Space Object Role** / **Space Object Contact Role**

Table 7: Space Object Taxonomy 4

Finally, taxonomy 5 eliminates the category of Space Object all together. The resultant types of space object, then, can be classified as Physical or Material Objects. Mention of space object can be relegated to the treatment on roles, e.g., defining each type of space object below as a physical object that bears the SpaceObjectContactRole over a period of time.

Taxonomy 5

- *Celestial Body* / Astronomical Object
  - Spacecraft
    - Space Vehicle
      - Space Shuttle
      - Space Launch Vehicle
    - <Artificial satellite classes>
    - Space Debris

<Debris classes>

Table 8: Space Object Taxonomy 5. No *Space Object* class.

Regardless of the taxonomy, candidate superclasses of artificial space objects include: Space Artefact, Material Artefact, Material Object, Physical Object, Physical Entity, and so on. The last three may serve as superclasses for natural space objects (Astronomical Object) as well. Given the exotic and category-defying phenomena in the universe, I recommend a more general class such as Astronomical Entity, Astronomical Body, or the traditional Celestial Body. The next section proposes some definitions for the main space object classes.

9. Definitions

The following are definitions of the central space object categories. Parenthetical notes indicate if the definitions correspond to the preceding taxonomies or whether they are more generic definitions. As such, I provide more than one definitional option for some terms. A single definition should be chosen for each term, but I provide alternatives. For any given definiendum, bullet points mark variations that may use different parent classes. '…' signify that it uses the preceding definition but with a different superclass. Forward slash ('/') separates synonyms or co-extensional categories.

Space Object =def. a Physical Object inhabiting the space environment (DEF-2B)

Space Object Contact =def. A Physical Object detected in space by a ground or space-based sensor.

Space Object Role / **Space Object Contact Role** =def.

- A role held by a physical object that inhabits the space environment. (DEF-3)
- A role held by a physical object that has been detected in the space environment. (DEF-4)
- A role held by a material object that has been detected in space by a ground or space-based sensor.

Supplemental Information: *Detection* is either a state or process (but not defined here).

Natural Space Object / **Celestial Body** / **Astronomical Object** =def. a Space Object formed by physical processes according to natural physical principles (laws of nature), independent of human action. (Taxonomies 1-3)
Supplemental Information: it is the space phenomena that forms the subject matter of astronomy.
Examples: planets, stars. *Instances*: Earth, the Sun.

Artificial Space Object =def.

- a **Space Object**, its component parts, portions or parts thereof, and contained articles, created by persons; and intended, designed and physically structured to operate in the space environment (Taxonomy 1)
- A **material object**, …

This definition encompasses whole spacecraft as well as space debris originating from space artefacts. Function is not mentioned in order to include space objects that do not have a function, but are nonetheless artificial. Including functions, we have Space Artefact, below.

Space Artifact / **Spacecraft** =def.

- A **Space Object,** its component parts, portions or parts thereof, and contained articles; that has been created by person; and intended, designed and physically structured to operate in the space environment, and that has one or more specific functions. (Taxonomy 2, 3)
- A **Material Artifact**, …

Space Vehicle =def.

- a **Space Artefact / Spacecraft** designed, and whose function is, to transport persons or cargo (payloads) through the space environment. (Taxonomy 2)
- a **Spacecraft** designed, and whose function is, to transport persons or cargo (payloads) through the space environment. (Taxonomy 3)

Spacecraft / **Space Vehicle** (general) =def.

- a **Space Artefact** whose minimal (at least one) function is to transport persons or cargo in the space environment.
- A **material object** created by persons, whose minimal (at least one) function is to transport persons or cargo in the space environment

Space Station =def. **a Space Artefact** whose minimal function is to provide persons with a long-term and relatively stable/stationary location in the space environment from which to perform various activities such as scientific research.

These definitions do not include legal conditions or properties, but if desired, including conditions such as *being launched by a nation-state* is a matter of course.

10. The Space Object Ontology

Figure 2 displays (in the Protégé ontology editor) space object classes from the Space Object Ontology (SOO) I have under-development. I am considering some permutations of an broader ontological architecture. Given a modular approach in which the overall space environment domain is delineated, and to the extent that an SOO is an ontology unto itself, I consider a it to consist of classes of space objects types. Separate ontology modules would be a space object process ontology, spacecraft operations ontology, space weather ontology, and so on. An orbital debris ontology (ODO) [1] may be a portion of an SOO, where orbital debris objects are types of space debris objects, which in turn are types of space object. An SOO can be part of a broader space ontology, either a space situational awareness ontology (SSAO) [2], an orbital and near-earth space environment ontology (ONESEO), or a space domain ontology (SDO), essentially three names for the same ontology. Alternatively, an SOO can be a portion of the ONESEO or SDO, where the SSAO focuses on awareness entities in the sense of detection, tracking, knowledge, sensor operator operations, and so on.

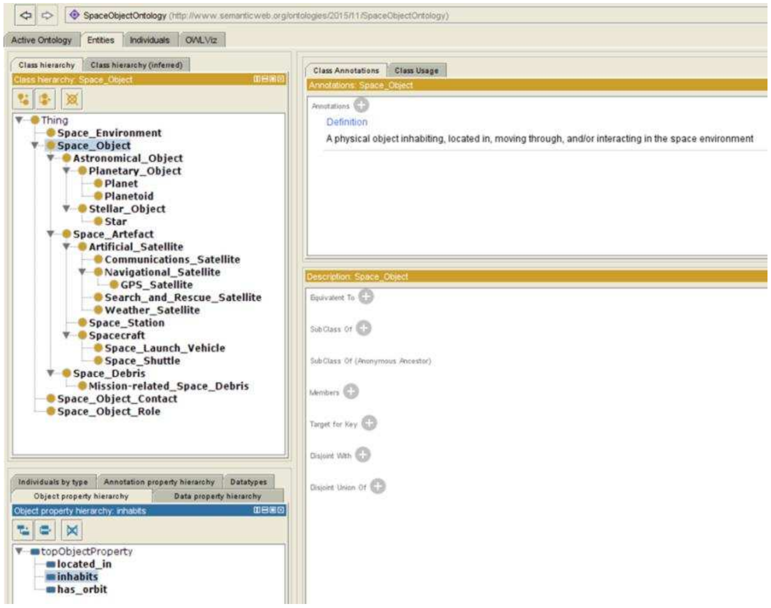

Figure 2. Space Object Ontology in Protégé ontology editor.

To create a veridical space ontology, we must be as scientifically accurate as possible, while accepting that the ontology is subject to revision as our scientific knowledge changes. As such the ontology must have *the open world assumption* as a principle.

10.1 Methodology and Resources

To create a space domain ontology, like any other, I approach the task in the following manner. Note that software development methodologies can guide ontology development, but any well-built computational ontology should include concept(ual) analysis.

- *Identify*: goals, the domain, domain-problems to solve, requirements, and communities of interest
- *Domain Research*: domain reference documents, domain-experts, etc.
- *Terminology & Taxonomy Development*: identify and list key terms; define and structure them into a taxonomy (a part of, and step towards, an ontology), identify subsuming (parent) category terms
- Philosophical and Concep(tual) analysis of key concepts and terms
- Formalization of domain knowledge and term definitions using most expressible logics
- Computational Ontology Development / Ontology Engineering
  - Translate natural language definitions and formal logic definitions to knowledge representation (ontology) languages. The latter should be as expressive as the logics used
  - Taxonomy/Ontology editor applications
  - Query the ontology and automated reasoner
- Informatics, Data-science, Analytics

Drawing on table 1, **domain-specific goals** of the space object ontology are: space domain explication; space object data annotation, space object data sharing; *space object catalog* interoperability; and space object knowledge representation and discovery. The communities of interest (COI) are those of the **space community**, broadly construed to include: astronautics, astrodynamics, space situational awareness (SSA) (or space domain awareness), astronomy, and astroinformatics [5]. The SSA community will find this ontology application useful because in creating a space object ontology, we also create a **space object taxonomy**. SSA communities maintain **space object catalogs**, and a standardized computable and semantically-rich taxonomy (i.e. an ontology) serves to annotate the data elements in catalogs. This will ideally facilitate interoperability among catalogs or SSA databases [1].

To create a scientifically accurate taxonomy of space objects we need to have sufficient scientific knowledge of said objects. This includes general knowledge of their *physical and dynamic properties* (including orbital elements), material composition, and the *causal interrelationships* at work among them and their environment. It will also include more specific knowledge of the space system architectures and functionalities. In pursuit of this domain research, consult SSA data (remote sensing data), experiential data[14] of the orbital and near-earth object population, and domain professionals. Philosophical concepts will help generally categorize and formally describe this knowledge and the corresponding real-world entities. Members of the space community are to provide domain expertise, including verifying the accuracy of the knowledge expressed by the logical formalizations in the ontologies. Domain-specialists, e.g. astrodynamicists, are essential parts of any ontology development process that seeks to produce veridical domain ontologies. *In totto*, this partially constitutes the ontology development methodology.

10.2 Reference Documents

The following non-exhaustive list of domain-specific resources is recommended. They serve as domain knowledge reference sources for the development of a space object taxonomy and the ontology of which it is a proper part. These reference documents help identify the common domain-specific terms and definitions to include in the ontology. To foster automated inference, the definitions may need to be adjusted, however.

- Dictionary of Technical Terms for Aerospace Use (1965) by Allen [20]
- ESA Science Glossary [21]
- Canadian Space Agency Astronautics Vocabulary [22]
- NASA thesaurus [23]
- U.S. Department of Defense Dictionary of Military and Associated Terms (2015)

Existing space and physics-related ontology resources that may also be used, incorporated into, or extended by, a space object ontology are these. Class terms from existing ontologies can be imported into other space domain ontologies and vice versa.

- Ontology of Astronomical Object Types. [15]
- Astronomy/Science Ontology [16]
- NASA Sweet Ontologies [17]
- Quantities, Units, Dimensions and Data Types Ontologies [18]

[14] Experiential data may include experiences with space objects and data from physical experiments.

- “A Space Surveillance Ontology Captured in an XML Schema” [19][15]

A survey and assessment of existing ontologies is critical to assess their quality, compatibility, and degree of domain coverage. For example, the NASA Sweet Ontologies has many terms relevant for a variety of scientific disciplines, but there are a number of undefined categories, some of which have questionable hierarchical placement. Discussion with developers is highly recommended to grasp the conceptualization in mind. The first resource in the list—the Astronomical Types Ontology (IVOA)—appears to also have a thorough taxonomy, one that accurately captures the various sorts of natural astronomical bodies in the universe. Good ontology development practice also calls for defining all terms save any primitives (undefined terms), which should nevertheless have some explicit clarifying remarks. Ontology users must be clear on the intended meaning of terms.

Conclusion

This paper has developed the ontology of space objects, presenting a philosophical and conceptual analysis of the category of Space Object. The ontological commitments of legal definitions were discussed, along with preliminary mention of formal aspects of the broader inquiry, e.g., mereology, functionality, and artifactuality. From this discussion I offered space object taxonomies, and definitions of some central category terms. The Space Object Ontology (SOO) was introduced, an applied ontology to annotate space object data from existing space object catalogs and space situational awareness (SSA) databases. The potential benefit of the application is improving SSA or space domain awareness via data-sharing, semantic interoperability and knowledge discovery.

The preceding has provided much needed theoretical contributions to developing ontologies and taxonomies for the space domain and its objects. Space objects include: artificial objects such as spacecraft, space stations; and natural space objects as studied in astronomy. Physical properties principles (laws of nature, astrodynamics laws, etc.) should be incorporated for a more quantitative ontological representation of space objects and their characterization.

We must bear in mind that “the definition of space object has evolved over time with the innovation in the types of technologies that can be launched into outer space. States have sought to generalize how they define such objects or kept the terminology open-ended.”[6. p.26]. As we advance the state of the art in spacecraft design, astronautics, and space science and development, the amount (and possibly sorts) of space objects will increase. Any definition and formal representation should reflect this generality, not least to ensure the flexibility needed to describe and characterize lower-level domain space objects, such as GPS satellites.

[15] Not an ontology in the modern sense.

References

[1] Rovetto, Robert J. An Ontological Architecture for Orbital Debris Data. Earth Science Informatics, 9(1), 67-82 (Published Aug 6 2015, submitted Dec 2014. Printed Feb 2016).Springer Berlin Heidelberg. URL= http://link.springer.com/article/10.1007/s12145-015-0233-3
DOI: 10.1007/s12145-015-0233-3.

[2] Rovetto, Robert J., Kelso, T.S. Preliminaries of a Space Situational Awareness Ontology. (2016) 26th AIAA/AAS Space Flight Mechanics meeting, Napa, California, Feb 17 2016.

[3] Staab S, Studer R (Ed.)(2009) Handbook on Ontologies, International Handbooks on Information Systems, Springer 2nd ed.

[4] Common Logic - International Organization for Standards. URL= http://www.iso.org/iso/catalogue_detail.htm?csnumber=39175

[5] Borne K.D. (2010) Astroinformatics: data-oriented astronomy research and education. Earth Science Informatics, Volume 3, Issue 1, pp 5-17. URL= http://link.springer.com/article/10.1007%2Fs12145-010-0055-2

__ (2009) Astroinformatics: A 21st Century Approach to Astronomy - Astro2010 State of the Profession Position Paper. URL= http://arxiv.org/pdf/0909.3892v1.pdf

[6] Hearsey, Christopher M. Comparative Study of the Definition of Space Object in National Space Laws and its Legal Effect under International Law, May 2 2012 Univ of Miss school of law. URL= http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2072514

[7] Reynolds, G.H.; Merges, R.P. (1989), Outer Space: Problems of Law and Policy p.210. Westview Press.

[8] Article 1 of Convention on Registration of Objects Launched into Outer Space - The General Assembly, http://www.unoosa.org/pdf/gares/ARES_29_3235E.pdf, http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introregistration-convention.html

[9] "Art 1(d) Convention on International Liability for Damage Caused by Space Objects", http://www.unoosa.org/pdf/gares/ARES_26_2777E.pdf, http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introliability-convention.html

[10] National legislation and practice relating to the definition and delimitation of outer space - Note by the Secretariat-Addendum (28 January 2013), UN General Assembly http://www.unoosa.org/pdf/reports/ac105/AC105_865Add12E.pdf, p.2

[11] Gyula Gal, Thirty Years of Functionalism, 40 PROC. COLL. L. OUTER SPACE 125 (1997).

[12] Laycock, Henry, "Object", *The Stanford Encyclopedia of Philosophy* (Winter 2014 Edition), Edward N. Zalta (ed.), URL = <http://plato.stanford.edu/archives/win2014/entries/object/>. URL= http://plato.stanford.edu/entries/object/

[13] Bricker, Phillip, "Ontological Commitment", *The Stanford Encyclopedia of Philosophy* (Winter 2014 Edition), Edward N. Zalta (ed.), URL = <http://plato.stanford.edu/archives/win2014/entries/ontological-commitment/>. URL= http://plato.stanford.edu/entries/ontological-commitment/

[14] Varzi, Achille, "Mereology", *The Stanford Encyclopedia of Philosophy* (Spring 2016 Edition), Edward N. Zalta (ed.), URL = <http://plato.stanford.edu/archives/spr2016/entries/mereology/>. URL= http://plato.stanford.edu/entries/mereology/

[15] International Virtual Observatory Alliance (IVOA). Ontology of Astronomical Object Types. URL= http://www.ivoa.net/documents/Notes/AstrObjectOntology/

[16] "Astronomy/Science Ontology", Department of Astronomy, University of Maryland, USA. URL= http://www.astro.umd.edu/~eshaya/astro-onto/ , http://www.astro.umd.edu/~eshaya/astro-onto/ontologies/astronomy.html

[17] National Aeronautical and Space Administration (NASA) Semantic Web for Earth and Environmental Terminology (SWEET) Ontologies, Jet Propulsion Laboratory, California Institute of Technology. URL= http://sweet.jpl.nasa.gov/

[18] Quantities, Units, Dimensions and Data Types Ontologies (QUDT) URL= http://www.qudt.org/

[19] "A Space Surveillance Ontology Captured in an XML Schema", October 2000, Mary K. Pulvermacher, Daniel L. Brandsma, John R. Wilson, MITRE, Center for Air Force C2 Systems, Bedford, Massachusetts

[20] Allen (1965), Dictionary of Technical Terms for Aerospace Use. URL= http://er.jsc.nasa.gov/seh/menu.html

[21] European Space Agency (ESA) Science Glossary URL= http://sci2.esa.int/glossary/

[22] Canadian Space Agency Astronautics Vocabulary. URL= http://www.asc-csa.gc.ca/eng/resources/vocabulary.asp

[23] National Aeronautics and Space Administration (NASA) Thesaurus. URL= http://www.sti.nasa.gov/thesvol1.pdf , URL= http://www.sti.nasa.gov/thesvol2.pdf

[24] Rovetto, Robert J. "The Orbital and Near-Earth Space Environment Ontology", Forthcoming, 9th International Conference on Formal Ontology in Information Systems.

[25] Journal of Applied Ontology, URL= http://www.iospress.nl/journal/applied-ontology/