# An Axiomatic Approach towards Interoperability of Data in Intermodal Transport: The Intermodal Core Ontology

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## 1. Introduction

Data Exchange between companies within the transport sector can be a challenging task from a technical standpoint. Firstly, the semantic description and terminology can vary even within the same domain. Secondly the data format for the same terms might differ due to different restrictions in the individual modes of transportation. For example, while the routes for road-based and rail-based transport can be given by the individual infrastructure elements the vehicles traverse, the air- and maritime transport sectors can only rely on the geospatial coordinate system to describe the precise routes taken from one infrastructure element to another. Since supply chains often rely on multiple modalities, not only the data exchange among stakeholders in the railway community should be aligned, but it should also be enabled to be interoperable with other sectors. Ontologies have proven their strength in facilitating data interoperability by virtue of their clear hierarchical structure, axiomatic approach of describing the different concepts needed and ability to be designed in a modular fashion [1] [2]. This paper proposes the *Intermodal Core Ontology (io-core).* The aim of the ontology can be summarized in the following points:

- **Simple User Experience**: The ontology provides the user with a basic set of vocabulary that is necessary to describe a journey and is shared across all modes of transportation. This allows for easy modelling of new ontologies and simpler data comparability and transfer due to a clear hierarchical structure.
- **Modular Ontology Design**: The *io-core* is built on top of standards in the ontology domain. Therefore, the user is encouraged to reuse other existing ontologies and model their specific use case in a modular fashion.
- **Reasoning Capability**: The ontology allows the user to implement sophisticated, use case–specific reasoning operations. This enables the implementation of multiple tasks such as optimal rail infrastructure utilization by inferring the workload of the individual network elements.

The *io-core* is an ontology, that is independent of the modality and therefore contains no terms, that are specific to one single mode of transportation. This allows the user to integrate existing modality specific ontologies into the *io-core* while minimizing synonyms and redundancy. The *io-core* additionally provides the necessary vocabulary to write new modality specific ontologies efficiently. This reduces time and effort needed in the development of new ontologies as well as to align two ontologies built on the *io-core*. To facilitate easier alignability with other (potentially traffic unrelated) ontologies and allow for a more complex axiomatic description of all processes involved in intermodal transport, the *io-core* builds on the *Basic Formal Ontology (bfo[1])* [3] and the *Geospatial Ontology (geo)* from the *Common Core Ontologies (cco)[2]* [4]. This allows users of the *io-core* to e.g. model energy consumption or similar indirectly traffic related issues by importing existing ontologies. Overall, the reuse of ontologies[3] is encouraged by simplifying alignment processes across the board.
This paper is structured as follows: In section two, existing work on ontologies in transport will be described. This will lay the groundwork for the decisions on the imported ontologies and describing the process of building the *io-core*. Finally, the process of integrating existing ontologies is demonstrated by aligning the railway specific *ERA*

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[1] BFO-ontology/BFO: BFO repository including source code and latest documents
[2] CommonCoreOntology
[3] The Reuse of ontologies is a broad issue as can be seen in [15] or more recently [16]

*ontology*, an ontology built by the European Union Agency for Railways, that gives all necessary railway specific terms. To refer to a specific ontology, a short reference title will be provided as listed in the glossary. Since the *bfo* and *geo* ontologies use identifiers in their IRIs to name classes, such as "BFO_0000001" for the class with the label "entity", that class will be referred to as *bfo: entity* if this mapping is unique. Otherwise, the identifier will be used and a more human readable version will be specified in a footnote.

# 2. Building the Ontology

Ontologies contain formal and machine-readable definitions of concepts and how they are related. Commonly the *Web Ontology Language* (*owl* [5]), a W3C standard is used to build ontologies. The semantics of *owl* allow ontology developers to infer knowledge from given data. This is known as reasoning. *owl* can be used in different levels of expressivity, the most complex being *owl full*, an undecidable[4] variation of first order logic[5]. Since allowing for reasoning tasks is a core aim of the *io-core*, it is expressed in *owl dl*, a decidable subset of *owl*[6].

## 2.1. Related Work

While ontologies are not entirely new to transport[7], through the growing digitization in the sector and the move towards smart city infrastructure, knowledge representation in form of ontologies has become more prevalent within the transport sector. Katsumi and Fox [6] lay out a description of work related to ontologies in the field of transportation, some of which are specifically tailored to certain aspects of transport, such as the *transport disruption ontology* [7], which lays a framework for the semantic description of disruptions in the transport sector due to different phenomena ranging from social events to natural catastrophes.
As the core ontologies in air and space, the NASA Air traffic management ontology [8] and the SWIM ontology [9] were identified. Maritime transport itself has its own "top level ontology"[8], the MarineTLO [10].
Regarding the rail domain, the RailTopoModel[9] [11] was introduced at the ISWC[10] in 2021. More recent work is done by the European Union Agency for Railways by publishing their own ontology in the rail domain. The core goal of this ontology is to standardise Data within the European railway sector.
However, to the best of our knowledge there is no currently available ontology that can serve as basic vocabulary for the transport sector in the sense of a) being modality independent, b) not explicitly containing traffic unrelated concepts while allowing for these to be integrated and c) using the *bfo* as a top-level ontology.

## 2.2. Design Approach and imported Ontologies

As an overall approach, the *io-core* is built on a top-level ontology and a mid-level ontology. Using a top- and mid-level ontology architecture to build domain specific ontologies has been shown to improve semantic interoperability of data [2]. This simplifies a modular design approach, which allows for a rich description of all necessary concepts while still enabling semantic interoperability and lower cost in computation [1].

The *bfo* has been standardized by ISO[11] and commonly serves as a top-level ontology. The *bfo* lays the groundwork to describe processes, space and time related concepts, roles and other general terms. It serves as the foundation

[4] Undecidable meaning, there exists no algorithm, that can validate every statement.
[5] A formal system used in mathematics and philosophy that deals with quantified variables over non-logical objects, allowing statements about objects and their relationships.
[6] For further information, compare https://www.w3.org/TR/owl-ref/#Sublanguage-def
[7] Some work dates back to 1997, however this work was not done in the web ontology language.
[8] Note, that the term "top level ontology" usually refers to domain independent ontologies, such as the *bfo*.
[9] RailTopoModel
[10] International Semantic Web Conference
[11] ISO/IEC 21838-2

for the mid-level ontology known as the *cco* [4]. The *cco* is built with a modular approach and contains modules that extend many concepts of the *bfo*, such as relations between entities or concepts regarding time and space.
The *cco*'s module GeoSpatial Ontology (*geo)* is imported into the *io-core* to integrate all necessary geospatial concepts needed for the modelling of transportation. *Geo*'s axiomatic approach of describing geospatial relations builds on *'A Spatial Logic Based on Regions and Connection'* [12] and provides a rich interface to model use case specific geospatial terms. The logic serves as a basis to describe the topological properties of transportation networks. *Geo* itself imports the Common Core Module Extended Relation Ontology (*ero*), making *ero* an indirect import in the *io-core*.

## 2.3. Hierarchical Design

To build the hierarchy of the *io-core*, we compiled a set of common terms from the transport domain by taking the terms from ontologies in [6] and the modality specific ontologies mentioned in 2.1.. The main criterium of selecting the terms was, that they needed some bearing on the journey itself. These Terms were then organized into clusters based on their roles or functions[12] within the journey. For definitions, the Aristotelian definition schema was used in combination with a mono-hierarchy approach[13].
First, four disjoint but interrelated concepts were identified and extended as follows:

- **Process**: this term is defined by *bfo*. The core processes that are fundamentally necessary for transport are "*io-core*: journeying", which is composed of "io-core: moving" and "*io-core*: stopping". "*io-core*: journeying" is defined as the process of "one or more Agents changing their location from one point to another"

- **Transportation Task**: the individual roles or functions needed to facilitate the processes required for journeying. The *bfo* defines the concept of a 'role' and a 'function'. The primary difference between the two, is that a "[…] *function is a disposition that exists in virtue of the bearer 's physical make-up, and this physical make-up is something the bearer possesses because of how it came into being either through natural selection (in the case of biological entities) or through intentional design (in the case of artifacts).*" [3]. For example, while an engine - being explicitly built to burn gasoline - bears the function to burn energy thereby enabling a vehicle to drive, a bicyclist pedaling is given that same role, but was not explicitly made for it by biological design. Since "*io-core*: transportation tasks" must contain subclasses or instances of both "*bfo*: role" or "*bfo*: function", it is a subclass of the nearest common parent of "*bfo*: role" and "*bfo*: function" which is "*bfo*: realizable entity".

- **Geolocations and Time**: the spatial regions and time concepts needed to describe the process of journeying. Since these concepts are all related to the geo ontology or the subclasses of "*bfo*: temporal region", we simply import the necessary ontologies and omit the inclusion of an explicit classes regarding space or time.

- **Agent**: an "*io-core*: agent" is any Entity, that can bear a task. Since the *bfo* restricts its class "*bfo*: spatial

[12] For an explanation behind the semantics of these terms, see the bfo, however a brief explanation is given under "transportation tasks" in 2.3
[13] Each class has exactly 1 direct parent class and the definition of a class A being a subclass of B is phrased by the schema "A is a B with the special property p"

region" from bearing roles or functions[14], "*io-core*: agent" is a subclass of the intersection of "*bfo*: independent continuant" and "not (*bfo*: spatial region)"[15]. More formally:

$$IO - core: Agent \subset bfo: independent\ continuant \cap (\neg bfo: spatial\ region)$$

In its most fundamental form, the *io-core* states, that each journey is a process involving multiple agents, which perform tasks at a certain time and a certain place. In the following, these four upper classes and their respective subclasses will be explained more in depth. Note, that the *bfo* ties processes, time and spatial regions tightly together. Therefore, these concepts are described in a common subchapter.

### 2.3.1. Agents

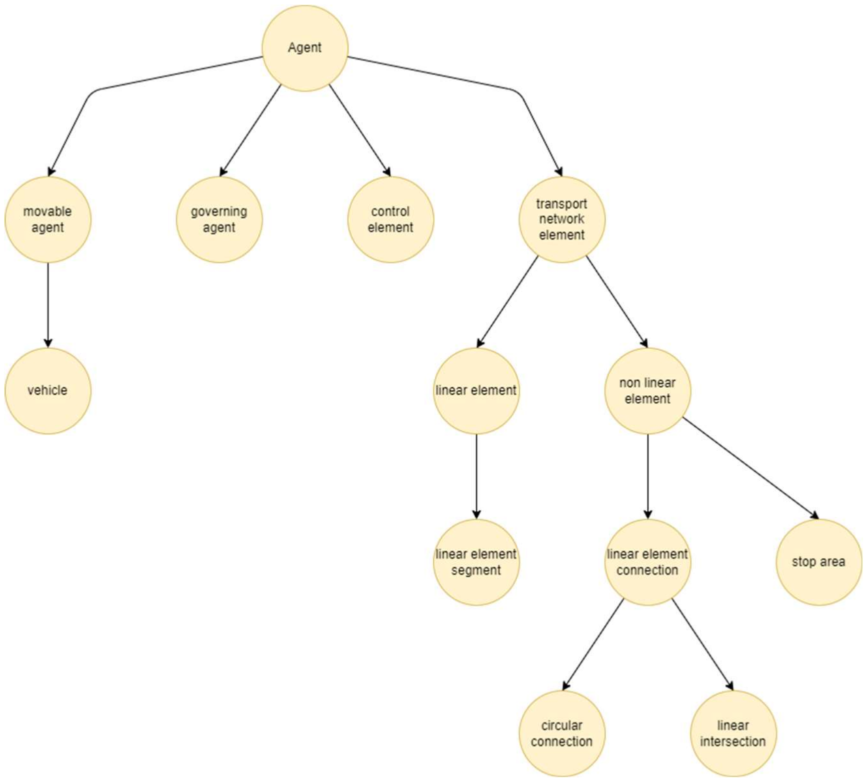


Figure 1 hierarchical structure stemming from the class "*io-core*: agent"

By grouping common objects by their overall role in the journey, four common clusters were identified, namely "*io-core*: governing body", "*io-core*: movable agent", "*io-core:* transport network element" and "*io-core*: control element". These terms can be categorized by their task within transportation. A full hierarchical structure for all descendants of "*io-core*: agent" can be seen in Figure 1.

[14] The domain of "*bfo*: bearer of" is $bfo: indepentent\ continuant \cap (\neg BFO: statial\ region)$

[15] The Complement of the class "*bfo*: spatial region"

- ***Movable Agent***: from an intuitive standpoint, this class encompasses any agent, that can be physically present during the journey, i.e. it can change its location. These can be but are not limited to the vehicles, drivers, passengers[16] or goods being transported. It has one subclass: "*io-core*: vehicle".[17]
- ***Transport Network Elements:*** "*io-core*: transport net elements" are Agents, in which the agents are meant to move or stop. These can include Roads, Rails or Rivers.
- ***Control Elements:*** agents, that control the flow of the transportation. This can include Signs and even groups of people assigned to roles that regulate transportation.
- ***Governing Agent***: the class encompasses any agent, that does not directly participate in a journey, but owns or controls any part of the transportation networks, control elements and/or movable agents, such as the European Union Agency for Railways or European Aviation Safety Agency as core agencies governing the rail and air domains in their respective jurisdiction.

### 2.3.2. Processes, Time and Spatial Regions

The *bfo*'s definition of a process is *"(Elucidation) p is a process means p is an occurrent that has some temporal proper part and for some time t, p has some material entity as participant*". It ties spatial regions and time to processes as can be seen in Figure 2. The Process "*io-core*: journeying" is broken down into the "*io-core*: route" (a descendent of spatial region) and "io-core: journey time slot" (a descendent of temporal region). To tie these concepts together, one additional class is required: "*io-core*: Journey", a subclass of spatiotemporal region. Since the bfo uses a similar approach to tie process boundaries to a time and space, analogous steps were taken to define the process boundaries "*io-core*: arriving" and "*io-core*: departing".

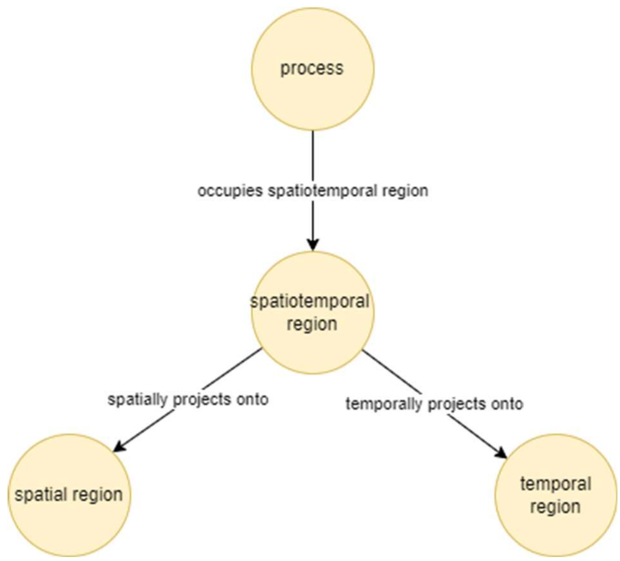


Figure 2: Visualization of *bfo*'s connection for processes, temporal regions and spatial regions. Process boundaries follow an analogous construction.

The core processes necessary for transportation are "*io-core*: moving" and its antithesis, "*io-core*: stopping". "*io-core*: moving" has two subclasses, "*io-core*: rotating" and "*io-core*: relocating" and any instance of moving can be seen as a combination of rotating and relocating.

"*io-core*: relocating" is defined as the process of a material entity changing its location from one point in space to another without stopping, giving us the following equivalence:

$$io - core\text{: } relocating \Leftrightarrow io - core\text{: } journeying \cap \neg(bfo\text{: } has\ occurent\ part(io - core\text{: } stopping))$$

"*io-core*: rotating" is the process of an "*io-core*: agent" changing its orientation relative to a given axis. "*io-core*: rotating" need not entail a change in a material entities geolocation.

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[16] Note, that a driver and a passenger are both (typically) human beings, but receive different tasks within the journey.

[17] A more in-depth hierarchy underneath movable agent will be achieved by alignments to further ontologies to integrate the concept of Person, however since this term is not exclusively transport related, the class was not explicitly added under the IRI of the *io-core*.

2.3.3. Transportation Tasks

The core necessity of a "*bfo*: role" or "*bfo*: function" being an instance of "*io-core*: transportation task" is, that they must be realized by one of the processes involved in journeying. This leads to the following equivalent formulation:

$$io - core{:}\, transportation\ task \Leftrightarrow (bfo{:}\, role \cup bfo{:}\, function) \cap (bfo{:}\, has\ realization\ some(io - core{:}\, being\ stationary \cup io - core{:}\, journeying \cup io - core{:}\, moving))$$

"*io-core*: transportation task" has two direct subclasses and one named individual

- "*io-core*: transported agent" is an instance of a "*io-core*: transportation task", that should be given to any material entity being transported, such as goods or people.
- "*io-core*: transporting agent" is a subclass of "*io-core*: transportation task", that serves as the parent for all instances of tasks, that have some bearing on the process of "*io-core*: journeying", such as "*io-core*: means of transportation"[18] or "*io-core*: navigating agent.
- "*io-core*: waypointer" is a subclass of transportation task, that can be indirectly[19] tied to spatial regions for optimized route description by tagging a location with one of its individuals, such as "io-core: right turn point", "*io-core*: origin" or "*io-core*: destination". The class's main purpose is accurate route description and role involvement of the different "*io-core*: transport network elements".

## 3. Integrating the ERA Ontology

The ERA ontology is an ontology, that has been published by the European Union Agency for Railways, the documentation of which can be found online[20]. It imports select terms from the following ontologies:

1. the *Time Ontology*[21] (*time*, created by the W3C) to express time related concepts
2. the *GeoSPARQL Ontology*[22] (*gs*) for geospatial terms
3. the *Core Organization Ontology*[23] (*org*) to coin the term organization
4. the *Friend-of-a-Friend Ontology*[24] (*foaf*) to coin a Person

To establish a common vocabulary, the ERA ontology was aligned into the *io-core*. While ontology alignment is a complex field and can be very time consuming, the hierarchy of the *io-core* allowed for a simplified process in aligning the ERA ontology. The steps taken are described in the following chapters.

[18] Note, that often times this term is used synonymously with vehicle. In our view, this must be a task for two reasons: Firstly, from an intermodal point of view one journey will contain multiple means of transportation. The task therefore can be used to tag which vehicle is used as the means of transportation for a specific leg of the journey. Secondly from an ontological standpoint, vehicles might be a transported agent (e.g. a car on a ship being transported) thus leading to ambiguity of the term "means of transportation" itself, if vehicle and means of transportation are used synonymously.
[19] Indirectly due to the restriction on "bfo: bearer of" mentioned previously.
[20] https://data-interop.era.europa.eu/era-vocabulary/
[21] https://www.w3.org/TR/owl-time/
[22] opengeospatial.github.io/ogc-geosparql/geosparql11/geo.ttl#
[23] w3.org/ns/org#
[24] http://xmlns.com/foaf/spec/

### 3.1.1. Aligning ERA's imported Ontologies

As the first step to align the ERA ontology into the *io-core*, the imported ontologies had to be aligned. Since the ERA ontology only imports the Term "*org*: Organization" from the Core Organization Ontology and creates a class for the role of an organization, the class *org:* Organization was simply added as a subclass of "*io-core*: governing body" and the class "*era*: organization role" became a subclass of "*io-core*: transportation task".
The bfo expresses time in a very fundamental fashion. Therefore, an alignment could be easily achieved by defining select classes such as "*time*: Instant" and "*bfo*: temporal instant" to be equivalent. This allows the use of properties in the time ontology with these classes in their domain or range to be used on the equivalent *bfo* classes. A more complex approach might be necessary, if the time ontology from the *cco* were to be integrated into the *io-core* in the future.
Since "*cco*'s geospatial design patterns resemble those of GeoSPARQL[25] which maintains a vocabulary of points and polygons from which users may construct query patterns concerning spatial location"[26] these ontologies are compatible by design.

### 3.1.2. Aligning the ERA Terminology

Next, the classes of the ERA Ontology and the io-core were aligned. The ERA Ontology itself possesses only those classes needed to describe the rail topology, vehicles and administrative roles and bodies. It predominantly uses *shacl*[27] shapes to describe its classes, compared to object property restrictions used in some other ontologies, such as the *bfo* and *cco*. Due to the structure given by the ERA ontology, most of the classes provided by ERA were simply inserted into the hierarchical structure of the *io-core* similarly to how "*org*: organization" or "*time*: instant" were integrated as described above.
Some more technical work was needed for the integration of the classes "*era*: track", "*era*: switch" and the subclasses of "*era*: net element". Firstly, since the ERA Ontology deals with rail related concepts exclusively, "*era*: net element" was identified as a subclass of "*io-core*: transport net element". Similarly, we identify the following class connections:

- "*era*: linear element" is a subclass of "*io-core*: linear element"
- "*era*: linear element section" is a subclass of "*io-core*: linear element segment"
- "*era*: non-linear element" is a subclass of "*io-core*: non-linear element"

The main difference in the hierarchy of the two ontologies underneath "*era*: net element" and "*io-core*: transport net element" is, that the *io-core* subdivides non-linear elements further based on how these elements are used, i.e. it differentiates between an upper class for train stations, depots and airports ("*io-core*: stop area") vs an upper class for intersections of streets, rails or rivers. Since topologically speaking, a switch is meant to merge two instances of a linear element in the rail topology (or vice versa allow forking one linear element into two) an "*era*: switch" can be considered a subclass of "*io-core*: linear element intersection". Similarly, since the comment in "*era*: linear element" specifically states an "*era*: linear element" to be "Pieces of tracks composing the topology" we consider an "*era*: track" to be equivalent to an "*io-core*: linear element", that is composed of exactly one "*era*: track". "*era*: track" is therefore a subclass of "*io-core*: linear element".

Since most properties in the ERA ontology are given a domain and range, the alignment of the object properties mostly follows trivially from the super classes the *era* classes were aligned to and the object properties provided by *bfo*, *geo* or *io-core*. For example, "*org*: organization" and "*era*: organization role" are connected via the object

[25] https://www.ogc.org/standards/geosparql/
[26] https://commoncoreontology.github.io/cco-webpage/geospatial-tracking/
[27] https://www.w3.org/TR/shacl/

property “*era*: role” and its inverse “*er*a: role of”. These were added as sub properties of “*bfo*: bearer of” and “*bfo*: inheres in” respectively.

## 4. Summary and Future Research

The intermodal core ontology will be extended to a broader ontology, that describes intermodal transportation as a whole. It will contain at least one module for land-, air, water and space-based transport. In the case of land transportation, it is clear that individual modules for rail and road transportation will be necessary. The first step towards developing the rail module has already been initiated through the integration of the ERA Ontology, as outlined in the previous section. This initial integration serves as a critical baseline, enabling the ontology to encapsulate complex railway infrastructure concepts, operational protocols, and regulatory requirements while reusing existing terminology used in the domain. However, it is important to note that the ERA Ontology is still evolving, and future realignments or refinements will likely be necessary to ensure seamless compatibility and to incorporate emerging standards and data structures. For water-based transportation systems a similar dual module approach might be necessary to describe the intricacies of journeys on rivers vs on open waters. Overall, this architecture ties the vocabularies of the different modes of transportation in one common system.

Future work regarding the rail Module will be aimed at using it to describe the topology of the railway infrastructure with a specific emphasis on connectivity of the individual tracks. The goal is to implement a SWRL rule-based approach to infer knowledge about the topology of the transportation network itself. This SWRL-rule based approach will be primarily tested on the Railway infrastructure such as, which parts of the topology are accessible by a vehicle with a given location or which platforms are available upon arrival in the station, given a specific delay of a train.
Additionally, the different modality modules will be connected via properties that act as a translation for the different descriptions and data formats and allow for a precise description of how transported agents are transferred from one mode of transportation to another.

Finally, to enhance the interoperability to other ontology driven systems, such as GTFS [13], further alignments to existing ontologies will be created. Furthermore, a semi-automatic or automatic mapping system using the RDF Mapping language [14] has the potential to lead to a rich, open-source data ecosystem for the transport community. Overall, this approach allows for sharing of data and joint optimisation of multiple aspects regarding the journeys involved in transport systems and supply chains.

## Glossary

Ontologies

- *bfo* = Basic Formal Ontology
- *cco* = Common Core Ontologies
- *era* = the Ontology of the European Union Agency for Railways, synonymously ERA ontology to avoid confusion with the Organization creating the Ontology
- *ero* = Extended Relation Ontology, a module of cco
- *foaf* = Friend of a Friend Ontology
- *geo* = Geospatial Ontology, a module of cco
- *gs* = GeoSPARQL Ontology
- *io-core* = Intermodal Core Ontology
- *owl* = Web Ontology Language
- *time* = Time Ontology as standardized by the W3C

Logical Operators

- $\mathrm{A} \cap B$ = Intersection of classes A and B
- $\mathrm{A} \cup B$ = Union of classes A and B
- $\neg\mathrm{A}$ = the complement of A
- $A \Leftrightarrow B$ = classes A and B are equivalent

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