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An Ontology for Event Location

Yunpiao BAI [a] and Michael GRÜNINGER [a]
[a] *Department of Mechanical and Industrial Engineering, University of Toronto, Toronto, Ontario, Canada*

Abstract. Space, time, objects, and events are fundamental concepts in ontologies. For substantivalists that believe entities are located at regions (space or spacetime), a key issue to address is the relationship between entities and their located regions. There is rich literature on the ontologies of location and mereology of material objects, as well as their philosophical foundations, but relatively little on events and their location. Most existing event ontologies provide little beyond the signatures and simply associate an event entity to space and time. In this study, we propose a new location ontology for events that formalize the relationship between events and spacetime, where events and spacetime maintain their own mereologies. We also make ontological commitments to support the mereological harmony of events and spacetime and provide the rationale and axiomatization of these commitments.

Keywords. event, location, spatiotemporal, ontology

1. Introduction

The representations and relationships among space, time, physical objects, and events are foundational issues in philosophy and more recently in ontologies. There is a considerable range of theories for representing space-time and location relations among entities (i.e., relations that hold between an entity and a region), such as endurantism, perdurantism, substantivalism, and supersubstantivalism. Many upper ontologies, including BFO, DOLCE, TUpper, have adopted these philosophical stances and provided formalisms of space-time, objects and events.

Although studies over the past decades have established a solid foundation for the formal representation of both space and time, there is still a continuing debate about the three-dimensional (endurantism) and four-dimensional (perdurantism) views on entities. Regardless of these arguments, many theories have recognized that events are four-dimensional entities and are located in spacetime [1,2,3]. Change, such as an event or process, unfolds in time and has temporal parts while physical objects have no temporal parts. Yet most existing event ontologies just simply associate event entities to spatial locations and time [4,5], in which events are not represented as real four-dimensional objects as claimed. Meanwhile, for substantivalists that believe entities are located in regions (space or spacetime), a key issue to address is the relationship between entities and their located regions. However, the majority of the existing work in the field has mainly focused on expressing entities like physical objects and events but disregards or oversimplifies the location relation of these entities. Some attempts have been made to axiomatize "object-to-spatial region" relations [6], in which a physical body is distinct

from the space that it occupies, and there is an occupying relation and structure between the two. Nevertheless, the location representation of physical objects is different from that of events, and the relation between an event and its spatiotemporal location still lacks formalism. Another fundamental topic about the location relation is closely related to mereologies, in which the argument over mereological monism versus mereological pluralism plays a central role in shaping location ontologies. Many existing location ontologies fail to provide or justify the mereological structure of the location relation and its interaction with other mereological relations [6], such as the mereology on space or spacetime; moreover, the existing mereological harmony theory only focuses on the location for physical objects and does not apply to events directly [7].

In our previous research, we introduced a new spatiotemporal ontology based on the mereotopology of RCC and Allen's time algebra [8]. A brief discussion on the philosophical stance of the occupying relation between events and spatiotemporal regions was presented in the paper, but we did not provide any formal ontological commitments and the axiomatization of such relation. The theory proposed in this paper extends our previous study on the spatiotemporal ontology and focuses on the relation between events and spatiotemporal regions. The study aims to provide solid ontological foundations for the location relation between events and spacetime and the corresponding mereological structure. To the best of our knowledge, though there exist some philosophical literature and event ontologies discussing logic foundations or signatures, this paper is the first work to provide an explicit axiomatization of a location ontology for events that also captures the parthood relation for each class of entities. In this research, we develop a scoping scenario and a set of use cases to investigate the requirements and constraints of the proposed ontology. Our ontology is built upon TUpper ontology which is a top-level ontology that contains modules from the ontologies within existing international standards [9]. TUpper covers important concepts and relations for processes and a location relation for physical objects. We reuse these modules together with our spatiotemporal ontology from previous work in the design of the axiomatization; thus, we put our focus of this study on the formalization of the location relation of events.

The remainder of this paper is organized as follows: Section 2 begins with a scoping scenario that captures the importance of relations among space-time, objects, and events, and then we discuss some use case scenarios of our event location ontology. Section 3 introduces the background of TUpper ontology and some important ontological commitments on events and locations we accept within TUpper. Section 4 presents a review of philosophical and ontological work about events and objects in space and time. In Section 5, we justify our ontological choices and commitments of the location ontology and thereby we present our axiomatizations of the proposed ontology based on these commitments in Section 6. Finally, Section 7 briefly demonstrates how our axioms formalize the use case scenarios.

2. Motivating Scenarios

To capture the major concepts and requirements for the representation of event locations, we develop a scoping scenario that comprehends the motion of moving objects with respect to occurring activities, also known as a semantic trajectory. In such a context, knowledge about space, time, physical objects, and events as well as relations among

them are instrumental in representing the scenario. Though some philosophers argued that some events do not have a spatial location or explicit temporal boundaries [1,3], such as a murder investigation or a train leaving the station, which are ordinary and nonmental events, it should be noted that this research is only interested in expressing the spatiotemporal aspects of events rather than determining an event's location.

2.1. Scoping Scenario

> *Alice leaves her house in Riverdale and crosses the Don Valley to Leaside. She purchases plumbing supplies at Canadian Tire (825 Eglinton Avenue East) and bathroom tiles at the Home Depot that is nearby on Wicksteed Avenue.*

In order to represent this scenario, one of the fundamental notions that we need to cover is Alice's trajectory, which consists of a series of activities ordered in time at different locations, including moving from her house from Riverdale to Leaside, purchase of plumbing supplies at Canadian tire and bathroom tiles at the Home Depot. To further conceptualize and break down the trajectory, it can be treated as tracks of Alice's movement (a moving object) plus a sequence of activities while the object is moving along a spatial path. In that case, we need two sets of ontologies to represent the locations of objects and events respectively. This paper focuses on the location relation of events [1]. As mentioned earlier, events are recognized as four-dimensional entities, so the location of an event should be a spatiotemporal region rather than a spatial region like physical objects. Thus, the two key questions to investigate are:

- What is the relation between an event and a spatiotemporal region?
- What is the mereological structure of this relation and how does it interact with mereologies of events and spatiotemporal regions?

To address these questions, we present two common-use scenarios where the location ontology of events can be applied.

2.2. Use Case Scenario

Scenario 1: Event at scattered locations. 2012 Summer Olympics was held from 27 July to 12 August 2012 in London, England. Canoeing is one of the sports programs, and it was contested in two main disciplines: canoe slalom, from 29 July to 2 August at Lee Valley White Water Centre, and canoe sprint, from 6 to 11 August at Eton College Rowing Centre.

Scenario 2 Motion event. A man is walking to the station, but before he gets there, he turns around and goes home.

In both scenarios, we have a complex event that consists of several sub-events as its parts, which is very common in the real world. Though we say that the 2012 Olympics occurs from 27 July to 12 August 2012 in London, it does not hold 24 hours per day continuously, and it does not occupy the entire City of London. Thus, we would like to explore and formalize what is the relation between the location of a complex activity and its parts' location. Meanwhile, the Olympics is composed of many sports games

[1] How physical objects participating is future work and is not discussed in the paper

that occur during different time periods at different locations, and these games may or may not necessarily bear a certain relation to the others. [2]. For example, slalom and sprint are both part of the canoeing game, and the two events just simply took place independently at two disconnected locations during different time intervals. It should be noted that the relations between sub-events in Scenario 1 are quite different in Scenario 2. Regarding the motion event, there is a continuous spatial change of the man's location during his movement, and all its sub-events must be self-connected. The man's initial walking, his turnaround, and his walking toward home must be continuous both spatially and temporally. This is because no teleport is allowed in our real world, and all parts of a motion must be connected. On the contrary, there is no such constraint on events that occurs at scattered locations like Scenario 1. Taken together, the proposed location ontology at least needs to be able to represent:

- What is the location relation between a complex event and its sub-events?
- For continuous motion, what relation must be held between the parts of a motion event?

3. Background:TUpper Ontology

The TUpper Ontology is a top-level ontology that contains modules from the ontologies within existing international standards. TUpper is the union of a set of modules that are themselves generic ontologies that cover the concepts related to time, process, and space. The TUpper module $T_{pslcore}$ [3]axiomatizes the relations between activities and activity occurrences[4], which are required for reasoning about processes. An activity may have multiple occurrences, or there may exist activities that do not occur at all.

Activities can be composed together to construct complex activities. Occurrences of complex activities correspond to sets of occurrences of their subactivities. Different occurrences of complex activities may contain occurrences of different subactivities or different orderings on the same subactivity occurrences.

In terms of parthood relations, TUpper accepts that there are multiple distinct parthood relations for different classes of entities, known as mereological pluralism, instead of mereological monism which uses a single parthood relation to specify various parthood relationships. Of particular interest in this paper is the mereology on activity occurrences that is specified by the *subactivity_occurrence* relation and axiomatized in T_{mereo_subocc}[5]. This theory is synonymous with the axiomatization of atomic mereology in which arboreal activity occurrences are atoms in the mereological structure of activity occurrences.

[2]There are certain conditions that must be satisfied between games, such as qualifying games and knock-out games. In this paper we do not study these condition relations between games

[3]https://github.com/gruninger/colore/tree/master/ontologies/psl_core/psl_core.clif

[4]The axiomatization of TUpper allows one to specify alternative approaches to the distinction between processes and events that arise from the diverse ways in which these terms can be interpreted in natural language. Within the current paper, we will treat "event" as being equivalent to activity occurrences within T_{psl_core} because it is activity occurrences which are located in time and space.

[5]https://github.com/gruninger/colore/tree/master/ontologies/psl_actocc/mereo_subocc.clif

$T_{spatiotemporal}$ is a spatiotemporal ontology[6] that we developed in the previous study, in which spatiotemporal regions are disjoint from spatial regions and time intervals, and each class of entities has its own mereotopology (pluralism). The module provides the weakest mereotopology for spatiotemporal regions based on the product of the mereotopologies of RCC and Allen's time algebra.

4. Related Work

4.1. Events and Objects in Space and Time

Material objects and events are two foundational topics in philosophy and ontologies. Arguments on the differences between objects and events are commonplace in literature. Material objects, such as stones, are said to exist, yet events are neither substances nor do they exist, and instead, the "being" of events is to take place or occur [10]. Meanwhile, some researchers have also noted the discrepancies between events and objects in terms of their relationships to space and time. For example, material objects have explicit boundaries in space and take full occupancy of the space (no two distinct objects can occupy the same place at the same time) while events are located in spacetime and are not full occupants of space and time as compresence of events is allowed [11,1]. Events have temporal relations to others (e.g., a person eats before drinking water), but objects usually do not stand in temporal relation to other physical objects[11]. It has also been argued that objects are endurants (continuants) that persist by being wholly present at the time in which they exist, referred to as three-dimensionalism or endurantism, and events, persisting over time and having temporal parts, are perdurants (occurrents) [12]. Although some philosophers have posited that objects are perdurant, (an approach referred to as four-dimensionalism or perdurantism) many foundation ontologies, such as BFO, DOLCE, UFO, etc., make a distinction between objects and events. These upper ontologies accept that objects are endurants that occupy spatial regions while events and processes are perdurants that occupy spacetime.

Overall, many researchers have acknowledged that objects are occupants of three-dimensional space, and such occupancy is unique and exclusive, which has led to attempts to axiomatize an occupying relation between objects and spatial regions. Casati and Varzi [13] proposed a location ontology adopting the system of General Extensional Mereotopology with Closure Conditions (GEMTC). Suggested Upper Merged Ontology (SUMO) captured three locative primitives for the location of physical objects: located, exactlyLocated, and partlyLocated [14]. Aameri and Gruninger [6] developed an occupy ontology based on mereological pluralism, in which there are different meretopologies for objects and space.

4.2. Event location

It is commonplace in the literature that events are not in space in the same sense in which objects are. Events have temporal boundaries but their connection to space is less obvious. A number of philosophers have attempted to explain the location relation of events.

[6] https://github.com/gruninger/colore/blob/master/ontologies/spatiotemporal/st_mereotopology.clif

The Particularist Theory of Events argued that events are unique, unrepeatable entities that have a spatiotemporal location [3]. Dretske [15] claimed that events cannot move, and the temporal segments of an event can locate at different regions. Some studies attempted to capture events' locations by referring to their participants' locations. According to Davidson and Lombard an event's precise location corresponds to the location of its smallest participant [2]. Borghini and Varzi [16] also suggested a principle that "the location of an event is the mereological sum of the locations of its minimal participants" and provided some extensions of the principle to allow approximation and indeterminacy in event semantics. Meanwhile, another group of researchers tried to articulate the location of events by postulating spatiotemporal analogies to the spatial location of material objects. For example, Casati and Varzi [2] established some principles of event location by analyzing a structural similarity between objects' locations and events' locations.

Collectively, these studies outlined a critical role of connecting events to spatiotemporal regions with solid philosophical stances; however, none of them provided systematic axiomatizations of their proposed theories. In contrast to material objects and their locations, there are relatively few studies on formalizing the relation between the event and its located spacetime region. Raimond and Andallah [5] developed an event ontology but contained little beyond the signature and simply connected an event entity to a spatial feature and a temporal entity. Guizzardi [4] provided an ontological foundation for the conceptual modeling of events based on Unified Foundational Ontology (UFO), which contains an atomistic mereology for events, participation of objects in events, and temporal relations between events. However, instead of treating events as four-dimensional objects that relate to spacetime, the researchers assumed that all spatial properties of events are defined in terms of the spatial properties of their participants. Galton has conducted a series of studies and explored multiple possibilities to model events and the relations to space and time [17,18,19]. In these studies, Galton investigated both "three plus one" dimensional and four-dimensional approaches to expressing changes and motions of objects, but these representations focused more on objects and their attributes in change rather than events or processes themselves. Moreover, the interaction between location and parthood is completely ignored in these models, and no formalisms were provided in his papers. In terms of formal axiomatizations, Basic Formal Ontology (BFO) developed spatiotemporal modules and recognized that a spatiotemporal region is an occurrent entity that can be occupied by other occurrent entities [20], such as processes. However, BFO fails to provide a complete mereotopology of spatiotemporal regions and events/processes, assuming all four-dimensional entities including spatiotemporal regions only have one type of parthood relations. Meanwhile, the ontology temporalizes most relationships among entities in order to interconnect continuants and occurrents, which is redundant for four-dimensional entities that have temporal parts.

5. Ontological Commitments

Two fundamental issues of our event location ontology are the relation between events and spatiotemporal regions, and the interaction between such relation and mereologies of events and spatiotemporal regions. This section discusses some ontological commitments we make prior to the design of the axiomatization.

5.1. Occupying Relation

Substantivalists believe that entities are located at regions of space or spacetime, as opposed to the supersubstantival view in which located entities are identical to their locations. Following substantivalism, this study distinguishes entities and the region they occupy, and occupy is the relationship between an object and its located regions. The motivation is that the basic properties of a spatial or spatiotemporal region are quite different from an object, and it is less acceptable to say a region is a physical body or an event in semantics. There are some location ontologies for the physical object where spatial regions and physical bodies are distinct entities, each having its own mereotopology (mereological pluralism), and occupy is a relation between a physical body and a spatial region [6]. We believe there is a spatiotemporal analogy between event locations and the spatial occupying relation of physical objects; thus, we make the following commitments:

- *An event occupies a spatiotemporal region, and it is distinct from the spatiotemporal region it occupies.*
- *Event and spatiotemporal regions maintain their own mereologies just as the mereotopologies of physical bodies and the occupied spatial regions are distinct.*

Though these two types of location relations are comparable, the occupy relation of events differs from the occupation of physical bodies in several important ways. First, when a material object (all its parts are self-connected) occupies a spatial region, it takes full occupancy of this region, and more specifically it occupies a continuous tract of space. However, given a spacetime region that an event occupies, it is not always the same. This is evident in the use case of the Olympic games that we discussed in the motivating scenario section. A complex event might have several time gaps, yet we still describe its occurrence as a continuous time interval semantically (i.e The London Olympics occurred from 27 July to 12 August). Another important distinction is that the occupation of a physical body is exclusive, implying that any spatial region that is currently occupied by an object cannot be occupied by other physical entities (if no interpenetration of objects). In contrast, concurrent events can occur at the same spatiotemporal region, such as a globe that can spin and get hot at the same time.

In summary, we design the ontology for the occupy relation and the mereological structure of an event and its located spatiotemporal region by analogy to the ontologies for the spatial location of physical objects. Meanwhile, it should be noted that not all principles and constraints of existing location ontologies of physical objects can be applied and translated to the location relation of events.

5.2. Motions and Scattered events

In the motivating scenario section, we discussed two different types of use cases: events at scattered regions, and motions. In the real world, it is very common that a complex event has many sub-events that occur at disconnected temporal and spatial regions. We illustrated an example of canoeing sports in the Summer Olympics earlier. A critical consideration is the structure of the spatiotemporal region occupied by a complex activity whose sub-activities occupy disconnected spatiotemporal regions. Since our spatiotemporal ontology is based on Allen's algebra and RCC8, and neither of them entails the existence of arbitrary sums in their mereologies, we then do not require the existence of

arbitrary sums for spatiotemporal regions either. Meanwhile, Allen's algebra is restricted to temporally convex time intervals. In the design of $T_{pslcore}$ within Tupper, the begin and end of a complex activity occurrence are the begin timepoint of its first subactivity occurrence and the endpoint of its last subactivity occurrence. As a consequence, following Allen's algebra and TUpper, we would like to guarantee that time is convex so that the temporal extent of a spatiotemporal region must be convex as well. In the Olympics example, even though the Olympic game is not held continuously 24 hours per day, its occurrence should still be considered to reside in a convex temporal region, both semantically and logically. On the contrary, there is no certainty that the spatial locations of a complex event is connected, and we would allow having scattered spatial regions for an event. Thus, we make the following ontological commitments to the spatiotemporal regions occupied by events:

- *An event occupies a spatiotemporal region whose temporal extent must be convex time interval but its spatial extent can be disconnected.*

In general, there are no constraints on the occupy relation for events with scattered locations, except the principle above. The spatiotemporal locations of disconnected subevents do not necessarily bear a certain relation with each other. On the other hand, a motion activity is the continuous spatial change of a physical object in the physical world, and the physical object cannot shift its location to a region that is not connected to its current spatial location without traveling via the regions in between. In the second use case, if a man wants to get to the station, he has to travel through the regions between his original location and the station. Therefore, all sub-phases of the man's walk and the spatiotemporal regions they occupy must bear the relation that every phase of his motion must be connected. In this context, we propose the following as a commitment to continuous motion:

- *All sub-occurrences of a continuous motion activity are ordered in time, and these occurrences must be connected spatiotemporally.*

5.3. Mereological Harmony

Events and their occurrences have their own mereological structure, and so do the spatiotemporal regions. Thus, it is natural to ask how the location relation of events interacts with these mereologies. Mereological harmony refers to the constraints that the mereological properties between located entities must mirror the mereological properties of the locations for those entities [21]. More specifically in our context, the mereological harmony between events and spatiotemporal regions leads us to explore the question: if an event occupies a spatiotemporal region, must it have the same mereological structure as that spatiotemporal region? There are some principles for mereological harmony of located material objects proposed within the philosophical literature to support the form of mereological pluralism [7,21], but we have not seen either the formalization of these principles in location ontologies of physical objects or comparable principles of located event entities. Since we believe that the location of events is a spatiotemporal analogue to the location of objects, some of these principles for object occupy relation can also be applied to the location of events, though not all types of events. Here we present some principles for mereological harmony and discuss some situations where these principles can be applied. It should be noted that many of these principles are strong constraints,

and the principles may conflict with each other too. In this study, we do not provide an analysis of the reasonableness of these principles, and we just treat these principles as an extension to our location ontology; meanwhile, we provide an option to use these principles as additional constraints and illustrate some possible situations to use them with our proposed ontology.

Principle 1: Basic harmony. *The part of an event occupies part of the spatiotemporal region that is occupied by the event itself.*

Basic harmony is a fundamental constraint for all types of events and the spatiotemporal regions they occupy. It mandates that all spatiotemporal regions that subevents occupy must be part of the spatiotemporal region occupied by the complex event.

Principle 2:Rigid occupy principle. *Two events cannot occupy the same spatiotemporal region when they are the occurrences of the same activity.*

Within the location ontologies developed by Aameri and Gruninger [6], there are some extended axioms to prevent multiple objects from occupying one single spatial region. Although compresent events can be located in the same spatiotemporal region, we cannot have two occurrences of an individual activity located in one region. In the $T_{psl_complex}$ module within TUpper, a complex activity can have multiple possible activity occurrences to represent the change of an event. For example, with use case 2 modeled by TUpper, the man arriving at home is one possible activity occurrence while with another activity occurrence, the man arrives at the station. Although with these two possibilities, we have two different occurrences of the same activity (the man's whole journey), only one of them eventually can occur, and these two possibilities must occupy distinct spatiotemporal regions.

Principle 3:No Interpenetration Principle. *Events that do not share parts cannot be located in spatiotemporal regions that do share parts.*

The original No Interpenetration principle asserts that it is metaphysically impossible for entities of any kind to "pass through one another" without sharing parts, such as how a ghost might pass through a solid brick wall [7]. As a consequence, if an object x's location is part of y's location, then x is part of y. In general, it is possible for two events located in overlapped or the same spacetime region, such as a globe spinning and turning hot, but in most cases, this is caused by the same object participating in concurrent events or there is a causality between two events. The example of globe spinning and turning hot can be handled in the PSL ontology [9] by modelling it as a concurrent activity that is composed of two sub-activities (spin and turn hot), and there is only one activity occurrence that occupies a spatiotemporal region in this case, which is the occurrence of the concurrent activity instead of two separate occurrences for spinning activity and turning hot activity respectively. Certainly, there are some types of events that do not allow concurrency. To illustrate, for two motion events, if they occupy the same spatiotemporal region, a collision may happen. Moreover, if two meetings are scheduled for the same room at the same time, there is a conflict as well. Such constraints are very common for scheduling problems, in which no two events can occupy the same time and space. In such cases, applying No Interpenetration Principle can help detect and prevent conflicts of activity occurrences.

Principle 4: No Extended Simples Principle. *It is impossible for an atomic event to occupy a complex spatiotemporal region.*

Principle 5: No Gunky Spacetime Principle. *It is impossible for a complex event to be located in an atomic spatiotemporal region.*

A simple entity is considered an entity that has no proper part. On the other hand, an entity whose parts have further proper parts is gunky. Extended simples are those entities that are simple but are located in a region that has proper parts. There are many debates about simple and gunky objects and whether the region occupied by objects should follow the same structure [7,22]. In general, it is still arguable whether a simple material object with a complex location is possible and the same holds for the possibility of a complex material object with a simple location. Within the realm of events, we do accept that events are not gunky and there exist atomic events according to TUpper, but in our study, we neither accept nor deny the simple entities and extended simples for spatiotemporal regions, and we just simply provide a choice for those who would like to have constraints on extended simples and gunk.

Regardless of the plausibility of Principles 4 and 5, there are certain circumstances in which extended simples and gunky spacetime should be avoided. Considering a booking system that only provides fixed time slots and rooms, and each room can only be booked for one hour in the system. In such a scenario, each booking is a simple event, and it can only occupy a room for an hour, in which each time slot has no proper part in the system and must be simple as well. Thus, every booking event needs to be modeled as an atomic event and occupies an atomic spatiotemporal region as there is no spatiotemporal location that can be part of one room and one hour in the system. Furthermore, for an event that has scattered locations, it is impossible for it to be modeled as an atomic event as its located spatiotemporal location has multiple disconnected parts and each part is occupied by an event.

6. The Event Location Ontology

The design of the event location ontology is driven by the semantic requirements extracted from the motivating scenarios and follows our ontological commitments:

1. Activities and activity occurrences are disjoint from spatiotemporal regions.
2. Each class of entities has its own mereology (pluralism).
3. Mereological relations between events and their located spatiotemporal regions match the mereological relations of events (mereological harmony)

Our axioms are built upon TUpper and the spatiotemporal ontology established in our previous research [8]. The TUpper ontology includes basic time, space, and activities(events) modules that are fundamental to representing event locations. Our spatiotemporal ontology provides the weakest mereotopology of the spatiotemporal region which is the product of the mereotopologies for time and space. In this research, we develop a $T_{st\_occupies}$ module that axiomatizes the occupy relation between activity occurrences and spatiotemporal regions. Activity occurrences and spatial regions have their own mereologies respectively, and the mereological relations between activities are preserved in the mereological relations between the spatiotemporal regions that they occupy.

$$(\forall st)\, spatiotemporal\_region(st) \supset \neg activity(st) \wedge \neg activity\_occurrence(st) \quad (1)$$

$$(\forall o, st) st\_occupies(o, st) \supset activity\_occurrence(o) \wedge spatiotemporal\_region(st) \quad (2)$$

$$(\forall o, a) occurrence\_of(o, a) \supset (\exists st) st\_occupies(o, st) \quad (3)$$

$$(\forall o, st) st\_occupies(o, st) \supset (\exists i) psl\_interval(o, i) \wedge temporal\_extent(st, i) \quad (4)$$

$$(\forall o,\ st1, st2) st\_occupies(o, st1) \wedge st\_occupies(o, st2) \supset (st1 = st2) \quad (5)$$

$$(\forall o1, o2, st1, st2) subactivity\_occurrence(o1, o2)$$
$$\wedge st\_occupies(o1, st1) \wedge st\_occupies(o2, st2) \supset st\_part(st1, st2) \quad (6)$$

The axioms of $T_{st\_occupies}$ are the weakest relations held between an event and its located spatiotemporal regions. The spatiotemporal ontology we use is independent of the specific axiomatization of the spatial regions and time intervals and compatible with the formalisms typically used for spatial reasoning (RCC8) and temporal reasoning (Allen's Interval Algebra). As a consequence, the axioms are compatible with those using RCC and Allen's algebra in other ontologies.

With respect to mereological harmony principles, rather than debate the reasonableness of the principles, here we just axiomatize these principles and make them extensions to $T_{st\_occupies}$ in case stronger constraints are needed to solve specific domain problems.

T_{rigid_occupy} is the extension of $T_{st\_occupies}$ with the following sentence:

$$(\forall o1, o2, a, st) st\_occupies(o1, st) \wedge st\_occupies(o2, st)$$
$$\wedge occurrence\_of(o1, a) \wedge occurrence\_of(o2, a) \supset (o1 = o2) \quad (7)$$

$T_{no\_interpenatration}$ is the extension of $T_{st\_occupies}$ with the following sentence:

$$(\forall x, y, st1, st2) st\_overlaps(st1, st2) \wedge st\_occupies(x, st1) \wedge st\_occupies(y, st2)$$
$$\supset (\exists z) subactivity\_occurrence(z, x) \wedge subactivity\_occurrence(z, y) \quad (8)$$

$T_{no\_extended\_simple}$ is the extension of $T_{st\_occupies}$ with the following sentence [7]:

$$(\forall o, st) st\_occupies(o, st) \wedge arboreal(o) \supset atomic\_st(st) \quad (9)$$

T_{no_gunky} is the extension of $T_{st\_occupies}$ with the following sentence:

$$(\forall o, st) st\_occupies(o, st) \wedge atomic\_st(st) \supset\ arboreal(o) \quad (10)$$

In terms of continuous motion events, the requirement is that all events are located in strongly connected spatiotemporal regions (that is, if a spatiotemporal region is the sum of two other spatiotemporal regions, then those regions must be connected). Meanwhile, no interpenetration principle should also be applied to a motion event as when two motions occupy the same spatiotemporal location, a conflict or collision will happen. T_{motion} is the extension of $T_{st\_no\_interpenetration}$ with the following sentence:

[7] arboreal(o) means o is an atomic subactivity occurrence in the activity occurrence tree

$$(\forall o1, st1, st2, st3)st\_occupies(o1, st1) \wedge st\_sum(st2, st3, st1) \supset st\_C(st2, st3) \tag{11}$$

7. Formalization in Event Location Ontology

The formalization of the two use cases we introduced in the earlier section involves the specification of events using PSL ontology (the process ontology module in TUpper), our spatiotemporal ontology, and the location ontology we proposed in this paper.

Regarding Scenario 1, there are not many constraints on an ordinary event that occur in disconnected regions. The canoeing game can be modelled as a complex activity and is composed of slalom and sprint. The structure of the events can be represented using the following axioms:

$$(\forall o)occurence\_of(o, canoeing) \equiv (\exists s1, s2)subactivity\_occurrence(s1, o) \wedge subactivity\_occurrence(s2, o) \supset occurrence\_of(s1, slalom) \wedge occurrence\_of(s2, sprint) \tag{12}$$

$$(\forall o, s1, s2)occurence\_of(o, canoeing) \wedge occurrence\_of(s1, slalom) \wedge occurrence\_of(s2, sprint) \supset (\exists st, st1, st2)st\_occupies(o, st) \wedge st\_occupies(s1, st1) \wedge st\_occupies(s2, st2) \wedge st\_part(st1, st) \wedge st\_part(st2, st) \tag{13}$$

In terms of the motion event in Scenario 2, the intended structure and mereology with TUpper are shown in Figure 1. We can represent the man's journey as a complex activity corresponding to the text descriptions. Both walking and turning are subactivities of the journey. Walking home and walking to the station are expressed as two possibilities of the occurrence of the journey. First, the structure of this event description is represented using the following axiom based on TUpper:

$$(\forall o)occurence\_of(o, journey) \supset (\exists s1, s2)subactivity\_occurrence(s1, o) \wedge subactivity\_occurrence(s2, o) \wedge occurrence\_of(s1, walk) \wedge occurrence\_of(s2, turn) \tag{14}$$

Next, we specify the relations between the journey and its subactivities walk and turn. Since this process journey is a continuous motion, all spatiotemporal regions occupied by its subactivities must be connected:

$$(\forall o1, o2, o3)occurrence\_of(o1, journey) \wedge occurrence\_of(o2, walk) \wedge occurrence\_of(o3, turn) \wedge subactivity\_occurence(o2, o1) \wedge subactivity\_occurence(o3, o1) \supset (\exists st1, st2, st3)st\_occupies(o1, st1) \wedge st\_occupies(o2, st2) \wedge st\_occupies(o3, st3) \wedge st\_part(st2, st1) \wedge st\_part(st2, st1) \wedge st\_C(st1, st2) \tag{15}$$

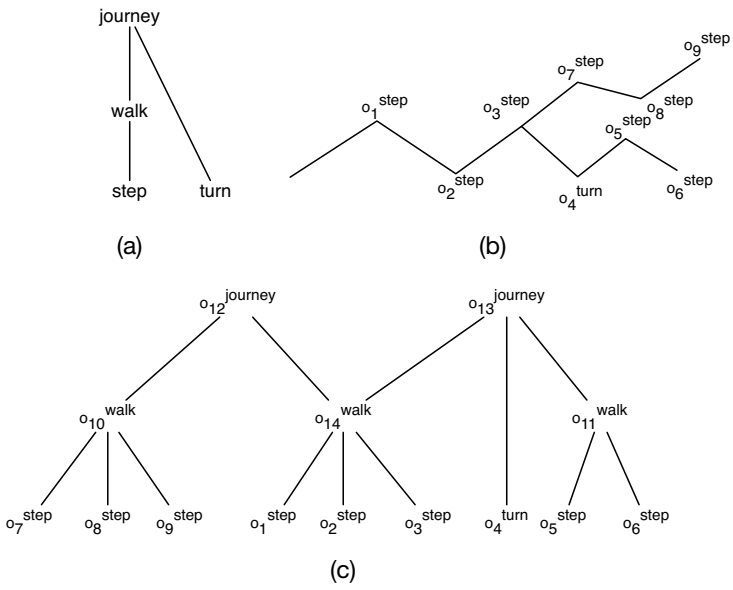

Figure 1. Depictions some of the substructures of a model of the process description for event change use case. (a) The mereology on subactivities; (b) two branches of the activity tree, consisting of an alternative sequence of atomic activity occurrences, together with the timeline; (c) mereology of subactivity occurrences.

8. Conclusions

This study set out to provide the axiomatization of an ontology for event location based on the philosophical stance of mereological pluralism, in which entities maintain their own mereologies. We identify multiple scenarios to justify our ontological commitments and provide extensions of the ontology to support mereological harmony of the location relation of events. It should be emphasized that although we provide a formalization for representing an event's location, our research does not provide a theory of how to locate events (i.e. the relation between the location of participants and the location of events). In this paper, we recognize that material objects are three-dimensional entities that only occupy spatial regions, and events and processes are four-dimensional, taking occupancy on spatiotemporal regions. Meanwhile, we adopt a spatiotemporal analogy to the spatial location of material objects to capture the principles for expressing locations of different types of ordinary events such as the Olympic games and an object's motion. The spatiotemporal occupy ontology proposed in this paper is based on the process ontology of TUpper and the spatiotemporal ontology from our previous study.

It is obvious that there is a relation between an event's location and the spatial locations of the material objects involved in the event – the "participants". For example, the spinning and turning heat of the globe occurs exactly at the location of the globe. However, in many cases, an event location can also refer to the area affected by the event. To illustrate, a natural disaster, such as a wildfire or flood, would affect a specific region for a certain time period. Thus, a natural progression of this work is to represent the relationship between participants' locations and the location of events.

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