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The Formal Ontology of Spatio-Temporal Reality and its Formalization

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Abstract

A framework for spatio-temporal reasoning has to account for the variety of modes of existence and persistence in time. It should thus be based on a formal ontology of spatio-temporal reality. For pragmatic reasons, however, it is even better if while being based on a realist foundation, the framework has the potential of being extended and amended contextually. I propose a rich modular framework based on a realist formal ontology of spatio-temporality. I present the ontology as a theory and position it with respect to the variety of spatio-temporal theories. The theory defended has the privilege and strength of being realist, and generates a framework having the potentiality to cope modularly with more exotic theories.

Introduction

This paper is an attempt at constructing a formalized framework for spatio-temporal reasoning based on a formal ontology of spatio-temporal reality. Formal ontology is a branch of philosophy which conducts analysis and produces theories at the highest and most domain-neutral level of generality. The theories produced can themselves be called formal ontologies, there is in particular a formal ontology of spatio-temporal reality. The purpose of a spatio-temporal framework is to account for the diversity of things in their relations to time, change, and persistence. I will start with the observation that there exist two kinds of entities: continuants in time (entities preserving their identity through change) and occurrents (entities which are bound in time and which, when they persist, do so by having successive temporal parts)[1]. Accordingly, there are two genuine modes of being in and persisting through time. These two modes of persistence are unveiled by distinct perspectives upon reality. An adequate formal ontological framework has to do justice to both of these perspectives while respecting their peculiarities. Thus, I shall devise a framework with one component amenable to the ontological treatment of enduring entities and with another amenable to the ontological treatment of perduring ones. This will include the exposition of a basic set of intra-ontological relations for each component. The two components will be articulated at a meta-level, based on a set of trans- and meta-ontological relations (these terms will be defined in due course). The result will be a complete framework for understanding reality which enables us to account for and reason about objects as they are at a certain time, according to the changes they experience through time, and the processes in which they participate. Despite the separation of the components, it is one and the same reality which they depict. However, each component, as a particular perspective upon reality, is transparent to certain constituents of reality and opaque to others. My interest is in the way an ontology (complying with the requirements of one of the components) accounts for reality, how each ontological component is shaped according to the modes of being in time of the entities it has the power to recognize, and how ontologies of different spatio-temporal kinds are related to each other and relate their respective constituents. The detailed layout of the taxonomical structure of the categories of entities in each component is a task I do not address here, leaving room for variations as far as these details go. I will give only high-level features that are relevant to spatio-temporal reasoning. It is hoped that the resulting composite framework articulating two traditionally alternative and complementary views on spatio-temporal reality can provide a basis for integration of prima facie heterogeneous spatio-temporal reasoning systems. In the first part of the paper, I present the philosophical assumptions on which rests the complete framework. I position this theory in the panel of theories of spatio-temporal reality, and provide some preliminary elements of formalization. In the second part, I describe the basics of the first component for enduring entities. I turn to the component for perduring entities in a third part. Finally, I describe elements of articulation of both components.

Basic Structure of the Framework

The complete framework rests on an ontology of spatio-temporal reality which recognizes both enduring entities, such as people, their smiles, tables and their colours or the regions of space they occupy, on the one hand, and, on the

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[1] The terminology of continuants and bound entities in time is borrowed from (Zemach 1970), see (Lowe 2002) for an introductory text, (Simons 1987) for a deeper analysis, and (Smith and Varzi 2000) for more a broad coverage of related issues.

other hand, perduring entities, processes and happenings, such as the smiling of a person, the tarnishing of a table or the reaching the wall of the table which has been moved from the centre of the room next to the wall. Enduring entities are continuants in time, they persist by continuing to exist at different times or during periods of time. They preserve their identity through change. Perduring entities are bound in time, they occur or happen at a time or throughout a period of time. They persist in time by having successively existing (temporal) parts. Entities of each type have a specific relation to time, endurants exist at a time while occurents are located in time, and perduring ones are extended in time. Time is an additional locative dimension for the latter, not for the former.

Given such discrepancy, the challenge for a complete framework is to unify and formalize both of these modes of being in time. The framework has to clearly separate two components, each of which will account for the specificity of one type of entity, and, moreover to articulate these components that have been taken apart for the purpose of analysis and formalization. This split framework can be seen as a form of non-eliminativist three-dimensionalism, according to which there are both endurants or continuants in time and a certain number of perdurants or occurrents in time. This view supports a bi-categorial reading and formalization. Alternatively, it can be seen as an eliminativist three-dimensionalist theory of things coupled with a four-dimentionalist or perdurantist theory limited to events and processes such as they are conceived by common-sense. This is the view I will present here in accordance with the realist perspectivalist methodology advocated in (Grenon 2003a).

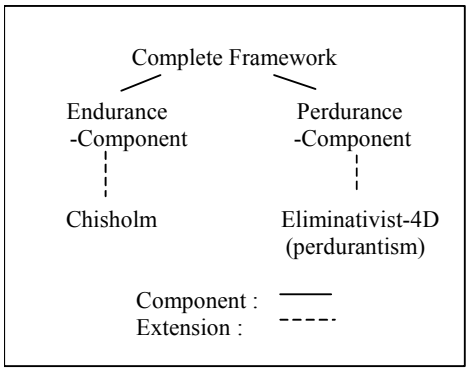

Figure 1. Partial lattice of spatio-temporal theories.

Such a framework will thus contain the required formalism for handling both endurance and perdurance. It is noticeable that a radical (eliminativist) perdurantist reconstructing endurants as four-dimensional entities in space-time, with temporal parts and not as continuants in time, could just preserve the relevant part of the framework. In the meantime, the Chisholm approach to endurants in terms of instantaneous (or short-lived) entities related via temporal counter-parthood relationships in lieu of identity could take advantage of the basic part of the other component. However, both views, in their own way, give up on continuants in time. The complete framework is thus here at the top of a lattice of theories of which the components form the two first main branches (figure 1). The two main components of the framework are each maximally adequate to the aspects of reality they are intended to capture.

Entities, Ontologies, and their Constituents

I present now the primitives of the complete framework, and introduce some predicative and relational notations for the meta-ontological notions of entities, enduring and perduring ones, ontologies and ontological constituency (predicates are capitalized, relations are not). A first-order language should suffice for this purpose. I shall use x, y, z as variables ranging over spatio-temporally existing entities, and a, b, c will be constants denoting such entities. I will use ω, ω', ω'' as variables ranging over ontologies, and α, β, γ will be constants denoting ontologies. These terms shall be defined shortly and if any addition to the language is needed, I shall indicate this in due course. In the remainder, unbound variables are assumed to be within the scope of universal quantifiers. I denote numbered axioms with an A, (A2) is the second axiom, definitions with a D and provable propositions with a P.

Existent. Everything which exists in the (spatio-temporal) world is an existent. I shall use the predicate Existent in order to denote entities, thus 'Existent(x)' is to be read 'x exists in the spatio-temporal world'. I could also have chosen to name the predicate in order to capture the intuition that all entities are persisting through time (with the obvious exception of instantaneous entities, which can, however, be seen as degenerate cases). However, if as I contend theoretical constructs (such as temporal parts of persons) are to be handled as fictions of a sort, it is useful to already introduce, if only implicitly the distinction between real and fictional entities.

The first axiom of the theory is that there is at least one existent:

(A1) $\exists x$ Existent(x).

Enduring and Perduring Entities. The theory recognizes both enduring and perduring entities as fundamental constituents of reality. I shall use the predicate 'Endurant' and 'Perdurant' in order to denote enduring and perduring entities respectively. Thus, 'Endurant(x)' is to be read 'x is an endurant' and 'Perdurant(x)' is to be read 'x is a perdurant'.

Four basic axioms are immediately expressible:

(A2) Existent(x) $\leftrightarrow$ (Endurant(x) $\vee$ Perdurant(x))
(A3) $\sim$ (Endurant(x) $\wedge$ Perdurant(x))
(A4) $\exists x$ Endurant(x)
(A5) $\exists x$ Perdurant(x)

Either (A4) or (A5) in conjunction with (A2) entails (A1). I chose to present (A1) as an axiom because it is emblematic

of the most basic intuition of realism, namely, that there is something which exists in the world and that this intuition is prior to any other consideration about what existing things are like. However, it could be pointed out that for the sake of an axiomatic theory, despite the order of appearance, (A1) is but a theorem. Moreover, one could remark, the conjunction of (A4) and (A5) is more truthful to other assumptions of mine according to which there are genuinely two kinds of things in reality, persisting through time in their own way, namely, endurants and perdurants. Observe nonetheless that only (A2) and (A3) allow us to enforce the claim that this is a partition of reality by (A3) and that this partition is exhaustive (A2). In the following, this partition will appear to us as the motivation for the meta-ontological distinction between the two components of our framework. An immediate corollary of (A2) is that both endurants and perdurants are existents.

Mereological Features. $\leq$ (respectively, $<$) is the (respectively, proper) part-to-whole relation. I take these mereological relations to be of the highest level of generality, their domain and range are the whole domain of existents. However, some restrictions which guide the structuring of our components exist.

Given a predicate P, I say that:

(D1) P is dissective *iff* $(P(x) \wedge y \leq x) \rightarrow P(y)$
(D2) P is cumulative *iff* $(P(x) \wedge x \leq y) \rightarrow P(y)$.

The predicates Existent, Endurant, and Perdurant are dissective and cumulative. Thus, on the one hand, all parts of an existent (respectively, an endurant or a perdurant) are existents (respectively, endurants or perdurants), and on the other hand, existents (respectively, endurants or a perdurants) are parts of existents (respectively, endurants or perdurants) only.

Ontology. A token ontology is formed by a depiction of the world from the standpoint of existence. In particular, an ontology is not the mereological sum total of the entities it depicts. In contradistinction to the sum of all the entities in the world, an ontology does not exist in the world, and thus is not an existent.

The above is a working definition and it is one of the purposes of this paper to elaborate on this rather intuitive starting point. I shall note that ontologies are here conceived as meta-ontological objects, but nonetheless as first-order objects in the domain. I shall use the predicate Ω in order to denote token ontologies, thus '$\Omega(\alpha)$' is to be read 'α is a token ontology'. When using English paraphrases, in non ambiguous contexts I will drop 'token'. The use of the term token is made here to convey the distinction between a depiction of the world and a categorial regimentation of existing entities (a categorical taxonomy). I insist on the particularity of a token ontology, but of course many different token ontologies could actually recognize entities falling under a similar taxonomic structure.

Let's register the fact that existents and ontologies are different:

(A6) $\sim (\Omega(\omega) \wedge \text{Existent}(x) \wedge \omega = x)$

Constituent. A constituent of a given ontology token α is an existent whose existence is recognized by α. I will write 'const(x, α)' which is to be read 'x is a constituent of α'.

The only constituents of an ontology token are existents and existents are constituents of ontologies only :

(A7) $\text{const}(x, \omega) \rightarrow (\text{Existent}(x) \wedge \Omega(\omega))$

Now, the following truths can be formulated. There is no empty ontology, that is there is no ontology of nothing.

(A8) $\Omega(\omega) \rightarrow \exists x\, (\text{Existent}(x) \wedge \text{const}(x, \omega))$

In addition, any existent is a constituent of at least one ontology.

(A9) $\text{Existent}(x) \rightarrow \exists \omega\, (\Omega(\omega) \wedge \text{const}(x, \omega))$

From (A1) and (A9), it follows that there is at least one ontology.

(A10) $\exists \omega\, \Omega(\omega)$

Types of Relations

I am basing my classification of relations on four distinctions. I will essentially discuss elementary relations, which could be used in order to define more complex ones. For the sake of simplicity, I take as paradigmatic the case of binary relations, the material presented generalizes more or less trivially to relations of higher arity (the language could contain sequence-variables for instance) .

Distinction by Signature. I distinguish between three main types of relations in the framework:

1. intra-ontological: a relation between existents that are all constituents of a given ontology α.

2. trans-ontological: a relation which obtains between existents that are constituents of distinct ontologies.

3. meta-ontological: a relation that obtains between ontologies or between an ontology and an existent (no matter the order of the relata), const is an example.

Categorial Distinction. Intra-ontological and trans-ontological relations can be further classified into intra-categorial (the relata belong to a common category) or cross-categorial (the relata belong to two disjoint categories). $\leq$ has two forms respectively in the domain of endurants and perdurants and both forms are intra-ontological and moreover intra-categorial forms at these levels.

In as much as constituents of an ontology are by definition indexed to a given ontology, intra- and trans-ontological relations themselves will always have to be understood as dependent upon that ontology or these ontologies of which the relata are constituents. This yields further specific types of relations according to the types of their relata. Although this feature is essential to reasoning based on the framework developed, it is parasitic to its exposition. Whenever discussing explicitly relations susceptible of an ontology-index, I shall drop this index. I shall wait until the last section before discussing its nature.

Internal and Material Relations. I distinguish between internal and material relations. Internal relations are grounded in their relata, they are such that no extra entity is needed in order for them to obtain, ≤ (part-whole) is such an example. Material relations require additional entities linking their relata, they are grounded in an extra relational entity. For instance, when John kisses Mary, he is related to her, the relation is grounded in their kissing (interestingly, the kissing on the one hand, and John and Mary on the other hand belong to two different components). In the remainder all the relations I will discuss are internal in the sense explained here.

Formal and Basic Formal Relations. I distinguish between formal and basic formal relations. Formal relations are relations which belong to formal or domain-neutral ontology. They can be applied at the higher most level in a given ontological component. There are also formal relations that may be applied in more than one component (this makes salient that the formal ontology given here is an ontology of the whole of reality, despite its respect of the divide in reality). I call these basic formal relations. Thus, const is a basic formal meta-ontological relation, and we see now that ≤ is an internal basic formal relation.

Ontology of Endurance

I am primarily interested in dealing now with the realm of endurants or continuants in time. A maximally adequate framework for continuants is one relying on presentism as its guiding assumption. Presentism is the doctrine according to which all entities which exist, exist at the present time. This is a meta-ontological claim and thus it will have to be handled by features that in an adequate framework are meta-ontological. Accordingly an ontology of continuants will always have to be temporally indexed. Here I will only address the issue of temporal indexing, leaving somewhat aside presentism. Indeed, I want to preserve the ability to speak of past, present, and future entities. However, this is already too broad an issue to be handled here. I will keep as a tacit background understanding the privileged standpoint of the now, namely that all there is exists really now, and thus an ontology accounts for things there are as they are now. However, for our purpose, this merely means at a time.

Endurance-ontology

An ontology of enduring entities is formed by the depiction of the world as it is at a given time from the perspective of enduring entities. I shall use the predicate Ωe in order to denote ontologies of enduring entities, thus 'Ωe(α)' is to be read 'α is an ontology of enduring entities' or 'α is an e-ontology'. For the sake of clarity, I emphasize that endurants are those objects which are constituents of some e-ontology. I shall refer to endurants as 'e-entities'.

Thus, endurants are constituents of e-ontologies only:

(A11) $(\text{Endurant}(x) \wedge \text{const}(x, \omega)) \rightarrow \Omega e(\omega)$

And reciprocally, only endurants are constituents in a e-ontologies:

(A12) $(\text{const}(x, \omega) \wedge \Omega e(\omega)) \rightarrow \text{Endurant}(x)$

Since it is necessary to be able to refer to past objects or to existing objects as they used to be, and, similarly, to future objects or objects as they will or might be, the framework will allow such references. S*tricto sensu*, such references are not ontological, in a technical sense, they are meta-ontological. In the present context, reference to non present entities is done by considering those entities in their being constituent of a temporally indexed ontology of enduring entities.

Temporal Index. A token e-ontology α is always given at a time t. I will write 'index(α, t)' which is to be read 't is the time-index of α'. I will discuss time for itself in the next section and here only introduce the predicate Time denoting regions of time.

(A13) $\text{index}(\omega, x) \rightarrow (\Omega e(\omega) \wedge \text{Time}(x))$

In addition, here x is to be taken as a time-point. Indeed, I rely on a presentist intuition from which it follows that real existence is at a moment. Although nothing forbids (indeed many things would seem to suggest, as (Ingarden 1964) shows) having extended but atomic momentary times (such as now). For the sake of explanation, it is just as convenient here to treat instantaneous times as mathematical points (an extended moment would contain many such points). In addition to a presentist motivation, it is necessary that at least elementary e-ontologies be instantaneous in order to prevent the co-temporal obtaining of two contradictory propositions about a given existent. Actually, the framework could probably be extended algebraically such that more abstract or general e-ontological structures over periods of time could be defined. I leave these issues open for now and reserve their treatment for future work.

Existence. Reasoning with enduring entities will require summoning a given (or many) e-ontologies of which the entity is a constituent, and thereby their respective time indexes. It thus appears that being a constituent of a time-indexed ontology amounts to existing at the time of the index. I will write 'exists-at(x, y)' and read 'x exists at y'. This relation is not restricted in principle to endurants and instants of time only, thus the following broad constraints:

(A14) $\text{exists-at}(x, y) \rightarrow (\text{Existent}(x) \wedge \text{Time}(y))$

However, it has a clear meaning and (partial) definition when x is an endurant.

(D3) $(\text{exists-at}(x, y) \wedge \text{Endurant}(x)) \leftrightarrow (\exists\omega\ \text{const}(x, \omega) \wedge \text{index}(\omega, t))$

Mutatis mutendis, the same remark as concerning the duration of temporal indexes for e-ontologies could be made about existence at a time (or over a period of time).

Informal Remarks. On this basis, reasoning (exclusively) with endurants will thus amount to manipulating a set of temporally indexed e-ontologies and their constituents.

Tracking changes in an endurant will necessitate considering at least two such ontologies (leaving aside cases of cyclic changes). A picture of the world over time from the perspective of endurants thus amounts to a succession of temporally indexed e-ontologies. E-ontologies thus appear to be metaphorically akin to snapshots of reality (and their succession to a slide show). However, these are rather selective snapshots in that they would not even capture instantaneous slices of a process which rather belong to the ontology of temporally bound together with perduring entities.

Spatial and Locational Change. There are three basic elements of the framework required for reasoning about spatial change (change in relative or absolute location), the first two constitute the core of a theory of location:

1. a category of spatial regions
2. an intra-ontological relation of spatial location between an endurant and a region of space
3. a set of spatial relations which may be either intra- or trans-ontological and that could be defined based on the locational relation and a mereotopological theory of regions of space.

Qualitative Change. Qualitative change is change over time in the quality (particular property) of some existents. The framework has four basic elements:

1. a meta-ontological relation of ontological dependence, which holds when an entity necessitates the existence of another (the token redness of the ball necessitates the ball of which it is the redness)

2-3. two categories of independent (a ball) and dependent (its redness) existents

4. an intra-ontological relation of inherence, which holds between a dependent and an independent (as between the redness of the ball and the ball).

Substantial Change. Substances are both mereological wholes and independent e-entities, they are self-connected and bounded in space. For instance, a ball is a substance. The elements for reasoning about substantial changes are thus essentially mereotopological. In addition, it is useful to introduce the intra-categorial trans-ontological relation of genidentity, which is sometimes explained as a relationship in which one entity stands to another when the latter is such-as-to-have-come-forth-from the former (cut a chunk of matter in two, the sum of the separated pieces is genidentical to the chunk before the cutting). Another trans-ontological relation of temporary parthood could be introduce as well.

Ontology of Perdurance

In the previous section, I presented the elementary structure of the component adequate for the ontology of endurance. I shall now turn to the ontology of perdurance.

Perduring entities occur at a time and unfold through time. In contradistinction with the framework for endurance, a form of eternalism is adequate here. I shall leave essentially open the question of whether full eternalism or a restricted view only taking into account the past and the present moment is to be preferred. Either an all time encompassing or a growing spatio-temporal manifold will do. Reality within the realm of perduring entities is given in a way that outflanks the present time. It turns out that the role of the present or of a particular instant, corresponding to a slice of the spatio-temporal manifold, is of importance when articulating the two frameworks, in particular, when bringing occurrents within reach of the presentist inspired picture of the framework for endurance. But presentism or simply momentary temporal incidence, although adequate for this meta-ontological task, does not leave much room to account for full fleshed perdurants. In a word, the intuition is correct according to which occurrents which are extended in time, have (proper) temporal parts, and know a temporal order. Time itself is a constituent of this reality.

Perdurance-Ontology

An ontology of perduring entities is formed by a depiction of the part of reality constituted by perduring entities throughout time. I shall abbreviate 'ontology of perduring entities' by using 'p-ontologies'. I shall use the predicate Ωp to denote p-ontologies. '$\Omega p\ (\alpha)$' is to be read 'α is an ontology of perduring entities' or in short 'α is a p-ontology'. Let us emphasize for the sake of clarity that perdurants are those entities which are constituents of some p-ontology. I shall call perdurants p-entities.

Thus, perdurants are constituents of p-ontologies only.

(A15) $(\text{Perdurant}(x) \wedge \text{const}(x, \omega)) \rightarrow \Omega p(\omega)$

And reciprocally, only perdurants are constituents of p-ontologies.

(A16) $(\text{const}(x, \omega) \wedge \Omega p(\omega)) \rightarrow \text{Perdurant}(x)$

Mereology and Mereotopology in P-Ontologies. Perduring entities have temporal parts. A temporal part x of a p-entity y is an existent which is a part of y and which overlaps with every parts of y that exist during the existence of x. I will use the relation temporal-part and read 'temporal-part(x, y)' as 'x is a temporal part of y'. This relation is intra-ontological and exclusively intra-categorial among perdurants, it is not basic. Typically, if a perduring existent is extended in time, its temporal parts are extended themselves. However, there are instantaneous temporal parts, called temporal slices. For this purpose, I use the relation temporal-slice. Since it is a more specific form of temporal-part, it inherits its structural features.

An adequate mereotopological apparatus would have the resources to define boundaries of perduring entities, and thus bounded or connected processes, their maximally connected components, etc. With such tools it would become possible to provide precise characterizations of the various sub-categories of that of perdurants:

1. processes, which are extended in time and such has to have a possibly complex structure of their temporal parts
2. events, which are momentary entities and typically boundaries of processes (beginnings and endings).
3. spatio-temporal regions

4. time

The idiomatic use of the terms 'process' and 'event' in this classification is inspired by (Ingarden 1964). I will refer to processual entities (with the predicate Processual) when the distinction drawn is irrelevant. Processual entities include parts (in particular, boundaries) and aggregates of processes. As noted before, events being momentary are not properly speaking persisting in time, they are non persisting occurrents. I will nonetheless allow this abuse of language for the sake of simplicity.

Bound in Time. I will handle temporal location as a form of projection of existents upon time. I call the primitive relation of a perduring existent to a period of time of arbitrary length: at-time. Thus, 'at-time(x, y)' will read 'x is temporally located at y'. It is an intra-ontological relation between a time (instant or extended period) to a perdurant:

(A17) at-time(x, y) $\rightarrow$ (Perdurant(x) $\wedge$ Time(y))

Every perdurant is located at a time:

(A18) Perdurant(x) $\rightarrow \exists$y (Time(y) $\wedge$ at-time(x, y))

Thus, in particular, co-temporality among perdurants is a form of co-location or co-presence. My working assumption for dealing with time is of a substantivalist nature. Time is a genuine existent, although a quite peculiar one, and it is a perdurant.

(A19) Time(x) $\rightarrow$ Perdurant(x)

By (A15), individual times are constituents of p-ontologies, since they are perdurants. Moreover, time is always part of a p-ontology, i.e., there is always an individual time in a p-ontology. Indeed, a given p-ontology α is by definition an ontology, and, by (A8), α has at least one constituent, and thus, by (A18) and the intra-ontological character of at-time, α has an individual time as a constituent.

(P1) Ωp(ω) $\rightarrow \exists$x (Time(x) $\wedge$ const(x, ω))

I shall leave open the question whether there exist empty times, i.e., time but no happening, and therefore a purely temporal ontology. However, I should like to mention the consequences of denying such a claim. Namely, requiring that time is an ontologically dependent p-entity would entail that in any p-ontology there is at least one non purely temporal existent, complementing (P1). An intuition which would fit the understanding of temporal relationalist (time is not an independent existent, but just amounts to an arrangement of concrete happenings). I shall mention for the sake of clarity the relevant assumption (AS).

(AS) Ωp(ω) $\rightarrow \exists$x (Perdurant(x) $\wedge$ ~Time(x) $\wedge$ const(x, ω))

Duration. The duration of a p-entity is the length of the time during which it exists, the measure of that period. The duration of a p-ontology is the duration of the sum total of its constituents.

Spatio-Temporal Location. The real substratum in p-ontologies is the spatio-temporal manifold. Issues of locations always have to be understood in the spatio-temporal framework when it comes to an ultimate account. However, it is possible to distinguish two forms of abstraction with respect to which a sensible and useful apparatus of projective location for p-entities might be elaborated.

1. Spatial and spatio-temporal locations as projections of processes at an instant or over a time period on the spatio-temporal substratum. This is a useful element for a typology of processes according to their shapes in space-time
2. Temporal location as projection of processes upon the axis of time (that I already addressed).

Analogously to the merely spatial case of endurants, we would be able to define based on locational relations and the categories of perduring entities a set of spatio-temporal relations holding between non purely temporal or spatio-temporal entities, i.e., processuals (a set of relations with which would rest content the temporal relationalist). There is, moreover, a form of genidentity which may hold exclusively among perdurants. We see that e- and p-genidentity are but forms of a basic formal relation of genidentity. There are other relations that I do not have the room to discuss here, causal links among processual entities for instance.

Informal Remarks. Within p-ontologies, in contradistinction to e-ontologies, reasoning about perdurants over time can be conducted in a single (p-)ontology. It is possible to reason with a multiplicity of p-ontologies or portions of an all-time-encompassing p-ontology. In as much as ontologies of endurants are analogous to snapshots of reality, ontologies of perdurants are analogous to video, extended in time. This analogy is to be taken with a grain of salt. In particular, p-ontologies should not be taken in analogy to successions of still images, a slide show or a film, and associated with a succession of e-ontologies. The temporally indexed e-ontologies are not parts of temporally extended p-ontologies. An instantaneous restriction of a p-ontology is not an e-ontology. This understanding is captured by (A11-12-15-16). In the following section, I offer a more formal discussion of this feature of the framework.

Cross-Component Meta-Ontology

Meta-ontology is the unifying level in the framework, it is motivated by a balance of properly meta-ontological, high-level cross-categorial, and trans-ontological considerations. E- and p-entities are distinct, but they are also related. There is a series of connections between sub-categories in each component. Endurants have lives and histories, conversely, processual entities have participants. Participation (or partaking) is distinct from parthood, and, in particular, temporal parthood. I use the relation part-in for this, and 'part-in(x, y)' is to be read 'x participates in y'. The following provides constraints on the relata:

(A20) part-in(x, y) $\rightarrow$ (Endurant(x) $\wedge$ Processual(y))

There is a family of trans-ontological and cross-categorial relations akin to participation or its converse among which:

initiation, termination, creation, destruction, sustenance, deterioration, facilitation, hindering, other causal roles, etc.

A participant in a process temporally overlaps this process, the former is a constituent of e-ontologies temporally overlapping the p-ontology of which the latter is a constituent. *Inter alia*, each endurant is a privileged participant in a particular perdurant, namely its life.

Given the peculiarity of the respective modes of being of e- and p-entities, it is still puzzling to understand how possibly these existents are brought together in a unified framework. The issue is about the articulation of a present (time-indexed) e-ontology and the part of the p-ontology which recognizes 'actual' (present events, presently ongoing processes) p-entities. Time has to play a cardinal role as a medium. Processes and events are ongoing or happen at a time in a cross section of their p-ontology which is co-temporal with some e-ontology. The p-entities are projectable upon the time which forms the index of the e-ontology, meanwhile, e-entities exist at that same time. The relation exists-at can also be seen as rooted in a form of trans-ontological projection (although in essence meta-ontological). Such common projection upon a time (or common incidence in time) forms the fundament for articulating the e- and p-entities.

Among ontologies, there is temporal co-location of an e-ontology with a cross-section (analogous to temporal slices) at a time of a p-ontology. A cross-section β of a p-ontology α at a time t is a (temporally) restricted ontology whose constituents are those constituents of α that are temporally located at t. I define temporal restriction as a meta-ontological relation between two (p-)ontologies and a time. Thus, restriction(α, β, t) means that α is a restriction of β at t (specifically, it is a cross-section when t is momentary).

(D4) restriction(ω, ω', t) *iff* const(x, ω) $\leftrightarrow$ (const(x, ω') $\wedge$ (at-time(x, t))

(D5) For an e-ontology α and a p-ontology β, such that there exists a p-ontology γ such that restriction(β, γ, t) holds: co-location(α,β) *iff* index(α, t).

Processuals and endurants appear to be connected at an higher level than that of participation. It is not strictly speaking a form of co-presence or co-existence (although they actually are co-present in the real world). Co-presence should be seen as an intra-ontological relation. Rather, among existents, there is temporal co-incidence of e-entities with entities constituting the cross section of a p-ontology (at that time).

(D6) For a, b, α, β such that Ωe(α), Ωp(β), const(a, α), const(b, β): co-incidence(a, b) *iff* co-location(α,β).

Figure 2 illustrates co-location and co-incidence, it can be described in the language developed so far as follow:
-Ωe(α), index(α, t_1), const(a, α), with, in particular, Endurant(a) and exists-at(a, t_1); Ωe(β), index(β, t_2), const(a, β), and exists-at(b, t_2)
-Ωp(γ), const(b, γ), at-time(b, t_1), const(c, γ), at-time(c, t_c), const(d, γ), at-time(d, t_2), temporal-slice(b, c), temporal-slice(d, c)
-restriction(γ, γ', t_2), Ωp(γ'), and const(d, γ')
-co-location(β, γ'), co-incidence(a, b), co-incidence(a, d).
Given these settings, it is possible that part-in(a, c), and, in particular, part-in(a, b) and part-in(a, d). Thus, for instance, c could be the life of a, and b its birth.

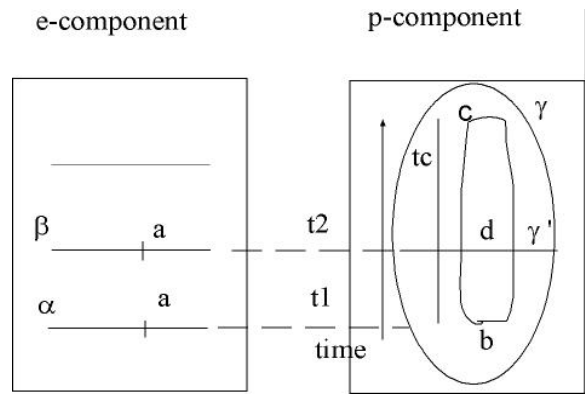

Figure 2. cross-component relations

Ontological Index. The indexing of relations is done by an ontology, and not by any particular element characterizing the ontology, time for instance. There may indeed be other characteristics of the ontology that time alone does not take into account, for instance, granularity. The index for intra-ontological relations will comport the mention of only one ontology, while it will presumably mention as many ontologies as there are relata belonging to specific ontologies in the case of trans-ontological relations. I take the binary case as paradigmatic. If R is a given relation, the indexing will work as illustrated by the following examples:

1. for intra-ontological relations: R(a, b, α)
2. for trans-ontological relations: R(a, b, α, α').

We can see, as with for example co-incidence, that an additional parameter for time would be redundant, at least in some cases, since it is already implicit in time-indexed e-ontologies. With respect to the example of figure 2, the forms co-incidence(a, b, α, γ) and co-incidence(a, b, β, γ) would be sufficient for our purpose.

In the current framework, there will be two types of intra-ontological relations, namely when α is a e-ontology or when it is a p-ontology. There will be up to four types of trans-ontological relations in the binary case of respective signature: (Ωe, Ωp), (Ωe, Ωe), (Ωp, Ωe), and (Ωp, Ωp). Notice that the second and third forms are peculiar in that the signature combine not only different ontologies but different spatio-temporal types of ontologies.

Conclusion, Open Issues, and Future Work

I constructed the basic elements of a framework for spatio-temporal knowledge representation and reasoning based on a realist formal ontology of spatio-temporal reality. This framework is rich enough to account for the variety of modes of existence of individual spatio-temporal existents. I showed whenever relevant the flexibility and modularity of the framework and suggested ways of amending it in order to embed variant or concurrent theories.

The present paper is a generalization and provides foundations for my work on spatiotemporality in the Basic Formal Ontology developed at IFOMIS (Grenon 2003b). BFO is a modular ontology of the sort presented here, its SNAP and SPAN fragments are respectively e- and p-ontologies. I did not treat granularity issues which, in the framework of BFO, are approached in (Bittner and Smith 2003) by defining granular spatio-temporal ontologies in superimposing a partition theoretic apparatus onto the SNAP-SPAN theory.

I left a number of tasks for future work. In particular, the nature of the eternalism endorsed by the perdurantist component should be researched. The importance of the present (and more generally, the nature of instantaneity) has to be assessed, especially in relation to the version of eternalism which holds that dynamic reality is a growing manifold bounded by the present. The treatment of co-presence and co-incidence are thus to be perfected and formalized more extensively.

Furthermore, although rich in essence, the locative apparatus is axiomatically weak. This is a strength of the framework which would be capable of embedding for instance a mereological approach to space and time handling co-temporality or co-spatiality as forms of partial overlap. For space and time, this would amount to a collapse of the locational apparatus into simple mereology. On the other end, introducing such mereological relations suggests a weakening of dissectivity claims in the present theory. The nature of the temporal order is rather uncommitted, and this has the effect of allowing flexibility with respect to these issues. The current treatment of space presents a similar plasticity. The relevant alternatives have to be carved out and positioned within the complete framework.

Finally, the elaboration of a detailed algebra and a typology of ontologies is a promising structural task that has to be pushed forward. It might be useful to approach ontologies as ontological contexts or settings and to type axiomatic fragments (taxonomical, factual and nomological) and their roles. The notion of a constituent of an ontology then appears as fundamental and the question remains open as to which constituents, other than the entities discussed in this paper there might be. In particular, is there room for cross-categorial wholes (again, contravening to existing requirements of dissectivity and cumulativity)? Are these extra entities deserving yet another ontological treatment, and, if so, which is the structure of an adequate ontology?

There are a few foundational issues relating to the capacity of the framework to contribute elements to a definitive upper-level ontology. For instance, are there other divisions (well-founded in reality) in addition to that between pure endurance and perdurance ontologies? Which extensions to the types of ontology (components) presented in this paper are there? What is the potential of domain ontology in terms of extensions or additions to the formal ontological basis of the spatio-temporal framework? How do the putative variety of spatio-temporal ontologies are articulated and how do they compare?

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