SNAP and SPAN: Prolegomenon to Geodynamic Ontology[1]

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Current approaches to the formal representation of geographical reality are characterized by their static character. GIS representations are representations of the world at a given time, reflecting the fact that geographic information systems have their roots in printed maps. Yet, geographical reality, like all other domains of reality, is essentially dynamic. We here outline a theory that is designed to preserve what is of value in current representation schemas while addressing the need for dynamics. Our position is that a good ontology must be capable of accounting for reality both synchronically (as it exists at a time) and diachronically (as it unfolds through time), but that these are two quite different tasks. Our approach is capable of accomplishing this via what might be described as a joint venture between the so-called three-dimensionalist and four-dimensionalist perspectives current in contemporary philosophical ontology. Briefly, we shall propose a modular formal ontology with two components, one for geographic objects and one for geographic processes.

1 Introduction

Reality is described in the first place by means of natural language. But natural language is of course not without its defects as a tool for description. In order to understand and safeguard against such defects we need a standard of correctness, some ground for speaking about reality – which means a theoretical understanding of reality as it is in itself. It is just such a theoretical understanding which ontology in the philosophical sense is designed to provide. Ontology in this sense concerns itself with the question of what there is. It purports to produce an account of the token entities existing in the world, of the types or

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categories under which these entities fall, and of the different sorts of relations which hold between them.

This philosophical task of working out the types and relationships among entities must of course at some point join up with the work of scientists. The full task of ontology is then a matter of going back and forth between the formulation of philosophical theories on the one hand and the testing of such theories against what we know about reality, above all from the work of scientists, on the other.

Ontology produces theories about the world formalized in some logical language. Such a theory typically includes a taxonomy of categories with accompanying axioms and definitions. The virtue of formalization is first of all that of enforcing a certain degree of clarity. Another virtue is that it makes theories readily accessible, evaluable, and re-usable by other communities of researchers. Additionally, formalization makes it possible for us to exploit some of the power of logic when using ontologies in reasoning systems.

Methodology. Our methodology, defended in (Smith, 2003) and (Grenon, 2003a), is realist, perspectivalist, fallibilist, and adequatist. *Realism* asserts that reality and its constituents exist independently of our (linguistic, conceptual, theoretical, cultural) representations thereof. *Perspectivalism* maintains that there may be alternative, equally legitimate perspectives on this reality. Perspectivalism is then constrained by realism: thus it does not amount to the thesis that just any view of reality is legitimate. To establish which views *are* legitimate we must weigh them against their ability to survive critical tests when confronted with reality, for example via scientific experiments. Those perspectives which survive are deemed to be transparent to reality. This is however in a way that is always subject to further correction. It is a fact that sciences change with time, and thus everything that is said here must be understood against the background of *fallibilism*, which accepts that both theories and classifications can be subject to revision. *Adequatism*, finally, is the negation of reductionism in philosophy. The reductionist affirms that, among the plurality of alternative views of reality there is some one basic view to which all the others can be reduced. We, in contrast, affirm that there are many views of reality, all of which are equally veridical. These are views of entities in different domains or of entities as seen from different perspectives or they are views of what exists on different levels of granularity (microscopic, mesoscopic, geographic). Adequatism is the doctrine that a plurality of such views is needed if we are to do justice to reality as a whole.

An adequatist approach to ontology with ambitions to remain consistent with science will need to be very cautious in sorting out the needed repertoire of mutually complementary perspectives. One perspective might accept as an unchallenged truth the reality of this cup or that chair. Another might seek to do justice to the very same reality in terms of aggregates of atoms or molecules. A third might talk in terms of changes and invariants in the spatiotemporal continuum. Adequatism means that all of these views are tenable within their respective boundaries, and that there is no privileged approach which could justify the reduction of one to another. Adequatism allows us to embrace simultaneously both commonsensical and scientific realism, that is: it allows us to endorse the view that both common sense and science can grant us genuine knowledge of the world.

Formal and Material Ontology. It was Husserl in his *Logical Investigations* (1913/21) who first drew a clear distinction between two kinds of ontological inquiry. On the one hand is what he called *formal ontology*, which is a theory at the highest and most domain-neutral level. Formal ontology deals with the categories and relationships which appear in all domains and which are in principle applicable to reality under any perspective (with some possible additions or subtractions in specific domains or levels). Examples of such categories include: object, relation, group, number, part-of, identical-to. On the other hand are what Husserl called *material* or *regional ontologies*, which are the ontologies of specific domains. There are as many ontologies in this sense as there are subject matters or domains of inquiry. Examples of such domains were for Husserl the domain of space, time and physical things; the domain of organisms; the domain of mind; and the domain of societies.

1.1 Basic Formal Ontology

Basic Formal Ontology (BFO) is a theory of the basic structures of reality currently being developed at the Institute for Formal Ontology and Medical Information Science (IFOMIS) in the University of Leipzig. BFO is a formal ontology in the sense of Husserl and its construction follows the methodological maxims presented above. The enterprise of building BFO is thus motivated on the one hand by the desire to be truthful to reality, and on the other hand by the need to accept a multiplicity of perspectives upon reality which may be skew to each other. IFOMIS and its associates are developing a series of material or regional ontologies, including: MedO (for Medical Ontology), GeO (for Geographical Ontology), and DisReO (for Disaster Relief Ontology). As a formal ontology BFO serves as a reusable template, which can (with some modifications) be used in constructing material ontologies for any and all domains of entities.

Temporal Modes of Being. The central dichotomy among the perspectives represented in BFO concerns the modes of existence in time of the entities populating the world. BFO endorses first of all a view according to which there are entities in the world that have continuous existence and a capacity to endure (persist self-identically) through change. (Here we will use the terms ‘continuant’ and ‘endurant’ interchangeably.) These entities come in several kinds. Examples are: you, the planet Earth, a piece of rock; but also: your suntan, a rabbit-hole, Leeds. All of these entities exist in full in any instant of time at which they exist at all and they preserve their identity over time through a variety of different sorts of changes. You are the same person today as you were yesterday and as you will be tomorrow.

In addition, however, BFO endorses a view according to which the world contains *occurrents*, more familiarly referred to as processes, events, activities, changes. Occurrents include: your smiling, her walking, the landing of an aircraft, the passage of a rainstorm over a forest, the rotting of fallen leaves. These entities are four-dimensional. They occur in time and they unfold themselves through a period of time.

Occurrents are all *bound in time* in the way described by Zemach (1970). This means that each portion of the time during which an occurrent occurs can be associated with a corresponding temporal part of the occurrent. This is because occurrents exist only in their successive temporal parts or phases. Some occurrents – for example beginnings and endings (the initial and terminal boundaries of processes) – are instantaneous. The term *perdurant* is more precisely used for these occurrents which persist (perdure) in time, in other words for those which are extended and not instantaneous. For more background material concerning these notions see (Lowe, 1998; Sider, 2001).

Following (Ingarden, 1964), we shall reserve the term 'process' for extended occurrents. The beginnings and endings of processes and the crossing of transition thresholds within processes – all entities which exhaust themselves in single instants of time – we shall call 'events'. It might be useful to emphasize that the processual entities recognized by BFO are often called 'events' in everyday language.

Spatiotemporal Ontologies in BFO. Continuants and occurrents exist in time in different ways. The challenge is to build a unified framework within which we can do justice to both of these modes of being equally. This framework needs to keep the two corresponding groups of entities clearly separate, since no single inventory can embrace them both. At the same time however we have to find a way of bringing them together: continuants are themselves subject to constant change; occurrents depend on continuant objects as their bearers. In particular, there is an important correspondence between continuants and those special types of occurrents which are their *lives*.

Here again we draw on an intuition of Zemach (1970) to the effect that distinct modes of being generate distinct ontologies. The difference in modes of being of continuants and occurrents corresponds to an opposition between two different ways of existing in time. Accordingly, we distinguish two main kinds of ontologies, called SNAP and SPAN, one for continuants and the other for occurrents. Relations between continuants and occurrents are thus trans-ontological – they are relations which transcend the SNAP-SPAN divide. The resulting framework is a combination, in the spirit of adequatism, of the three- and a four-dimensionalist perspectives, positions which are normally (not least by Zemach) seen as mutually incompatible alternatives.

A reductionist four-dimensionalist asserts that it is possible to translate all talk about three-dimensional entities into talk which refers exclusively to processes. She holds that we can eliminate continuants in favour of four-dimensional spatiotemporal worms. Thus he will accept just the SPAN part of our present framework. A reductionist three-dimensionalist, in contrast, asserts that it is possible to describe the whole of reality by referring exclusively to endurant entities. He can take advantage only of the SNAP part of our framework. Here, however, we shall insist that if we want to do justice to the whole of reality in non-reductionistic fashion, then we need both types of component: SNAP, to do justice to the world of three-dimensional bodies, including the spatial regions at which they are located and all their qualities, powers, functions, roles and other entities existing self-identically from one moment to the next; and SPAN, to do justice to the processes in which such enduring entities are involved and to the spatiotemporal volumes within which such processes occur.

The same two-component structure of BFO is found in a variety of domains and is accordingly reproduced in a variety of material ontologies (compare the distinction in medical science between anatomy and physiology or the distinction between synchronic and diachronic linguistics).

Granularity and Ontological Zooming. Reality can be carved up ontologically speaking in many ways, just as a lump of cheese can be sliced in many ways. The cup on your desk can be apprehended as an object in its own right, or as a structured group of molecules. Each material application of BFO is restricted to some given level of granularity, and each such granular ontology will respect BFO's two-component SNAP-SPAN structure. In practice, granularity reflects those specific ways of carving up domains of reality we associate with different scientific theories.

1.2 Geographical Ontology

A geographical ontology is a theory of those coarse-grained entities and kinds of entities and relations we find in the geographical realm. We will define geographical entities as entities appearing at a certain level of granularity (entities of geographical scale) which have a certain relation to the Earth. These entities – both continuants and occurrents – are as numerous as the objects of the different branches of geography, including not only the sciences of physical and human and political geography, but also geology, geomorphology, climatology, and so forth. A complete geographical ontology should include in addition not only those entities which fall under the purview of such geographical sciences but also those entities at geographical scales which are encountered by human beings conducting their everyday business with the world (Egenhofer & Mark, 1995; Smith & Mark, 1998).

In geographical reality we find first of all continuants such as mountains and lakes, valleys and deltas, land parcels, and cities. We find also armies and their areas of operation; commuters and their patterns of commuting; hospital systems and their patterns of provision of medical services. Mountains, cities, armies are entities with which human beings are involved in their everyday interactions with the world, interactions which are themselves geographical occurrents.

A platoon climbs a hill and fights to defend its summit. Winds blow along the coast creating dunes. Ambulances fan out to deal with the victims of disasters. Our basic assumption in the light of these examples is that reality is made up of objects: platoons, hills, dunes, ambulances, which are involved in a continuous series of processes: climbing, blowing, fighting. Note that terms like 'wind' are ambiguous: they may refer either to movements of masses of air (SPAN) or to the masses of air themselves, which are distributed by these movements (SNAP).

Reality is essentially dynamic; it involves a continuous succession of processes; but these are, in the domains that concern us here, in every case processes in or involving objects. Objects and qualities are grasped (for example through sampling) as they exist at some given instant of time; processes are grasped (through extended observation) as they unfold through some given temporal interval. A geographical ontology cannot be limited to objects but must make room for processes also. Indeed, geographical sciences are interested precisely in those SPAN entities which are patterns of development of geographical objects over time.

GeO, our ontology of the geographical realm, will reproduce in its structure the main formal-ontological divides between SNAP and SPAN. Because we are interested in this paper primarily in entities on the single geographical level of granularity, we will not dwell on the issue of scale and granularity here, but will concentrate instead on seeing how the SNAP-SPAN distinction informs the regional ontology of geography.

2 Spatiotemporality in BFO: The SNAP-SPAN Distinction

Given the two-ontology structure of BFO, we need some framework to lay down each of the SNAP and SPAN perspectives and to tie them together. Our framework draws on ideas introduced in (Grenon, 2003b; 2003c). The basic idea is that the variables of the theory range over both ontologies and the entities they recognize. Entities and ontologies are not however on a par with each other. Entities are in the world of what happens and is the case. Ontologies are analogous to mathematical structures such as groups and vector spaces. They are not themselves entities which are recognized by some further, higher-level ontology, but can rather be understood as ways in which reality and the entities in reality are structured.

We use a first-order language for our formalization, employing the following symbols: $\sim$ for negation, $\wedge$ for conjunction, $\vee$ for disjunction, $\rightarrow$ for implication, $\leftrightarrow$ for equivalence, $\exists$ and $\forall$ for the existential and universal quantifiers, and ι for the definite description operator.

We introduce italicized symbols of variables and constants denoting entities and ontologies. x, y, z, … are variables ranging over spatio-temporally existing entities, and a, b, c are constants denoting such entities. ω, ω', ω'', … are variables ranging over ontologies, and α, β, γ, … are constants denoting ontologies. We introduce special constants denoting certain designated entities, such as *space*, *earth*, *mountain*, *lake*. Symbols for functors (*sum-of*, *spatial-location-of*, *surface-of*, *life-of*, etc.) are also symbolized by means of lower-case italicized Latin letters.

All symbols for predicates have initial capital letters. We use monadic predicates (Substance, SpatialRegion, Entity) exclusively in order to capture membership in formal categories. We use polyadic predicates such as Identity, Part and Instantiation exclusively in order to capture formal relations. Instantiation of a material universal is symbolized by means of the formal relation Instantiation, thus: Instantiation(a, *mountain*) means: a instantiates the material universal *mountain*.

We assume all the tautologies and the standard rules of inference of classical first-order logic. We number formulae in the order of their appearance, putting an ‘A’ next to the number when the formula is an axiom, a ‘D’ when it is a definition, and a ‘T’ when it is a theorem. Unbound variables are assumed to be within the scope of universal quantifiers.

2.1 Entities and Ontologies

Everything which exists in the spatio-temporal world is an *entity*. ‘Entity(x)’ stands for: ‘x exists in the spatio-temporal world’.

An *ontology* is a depiction of the entities which exist within a given portion of the world at a given level of generality. It includes a taxonomy of the types of entities and relations which exist in the world under a given perspective. Recall that ontologies are not themselves entities within the context of this framework. 'Ω' is the symbol used for the predicate applying to ontologies; thus '$\Omega(\alpha)$' stands for: 'α is an ontology'. In due course, we shall introduce more specific predicates in order to designate ontologies of specific types.

A *constituent* of an ontology α is an entity whose existence is recognized by α. We call the relation between an entity and an ontology recognizing its existence is that of ontological constituency. 'Constituent(x, α)' stands for: 'x is a constituent of α'.

We now lay down a few of the basic axioms of our framework.

Ontologies and entities are distinct:

(A 1) $\sim (\Omega(\omega) \wedge \text{Entity}(x) \wedge \omega = x)$

The only constituents of an ontology are entities and entities are constituents of ontologies only:

(A 2) $\text{Constituent}(x, \omega) \rightarrow (\text{Entity}(x) \wedge \Omega(\omega))$

There is no empty ontology, i.e. there is no ontology of nothing:

(A 3) $\Omega(\omega) \rightarrow \exists x\, (\text{Entity}(x) \wedge \text{Constituent}(x, \omega))$

Conversely, any entity in the domain of our theory is a constituent of some ontology:

(A 4) $\text{Entity}(x) \rightarrow \exists \omega\, (\Omega(\omega) \wedge \text{Constituent}(x, \omega))$

Recall that ontologies are in essence ways in which reality is structured. It follows that there is at least one ontology:

(T 5) $\exists \omega\, \Omega(\omega)$

Ontologies and Ontology Forms. Each depiction of the world is such that the entities depicted fall under certain formal categories, and the latter are related together in a specific way, which we call an *ontology form*. Each ontology instantiates a certain ontology form. So far we have distinguished two ontology forms, of SNAP and SPAN, respectively. The different SNAP and SPAN ontologies are indexed in various ways, reflecting the different sorts of perspectives to which they correspond. Each SNAP ontology is indexed by some time instant. The default time-index for SPAN ontologies is the whole of time, or in other words that maximal time-interval which corresponds to the duration of the history of the universe. Both SNAP and SPAN ontologies are indexed by domain and by level of granularity. The default SNAP domain is: everything, the universe in its entirety, the mereological sum of all continuants existing at some given instant of time. (Note that since we will here be dealing with SNAP ontologies focused on coarse-grained entities on or near the surface of the Earth, we can here set aside issues of the relativistic frame-dependence of simultaneity.) The default SPAN domain is the history of the universe in its entirety. All SNAP ontologies instantiate the same ontology form, though they differ in the material they recognize and in the perspectives they are associated with, including their granularity level. A SNAP ontology of the zoological domain recognizes the corresponding endurant entities as they exist at some given instant of time; a SNAP ontology of the zoological domain with index *now* would contain no entity instantiating the material universal *dinosaur*.

Since we here assume a single level of granularity – the level of geographical scale entities – we shall need to represent only the temporal index of ontologies. The relation between an ontology and its temporal index is captured via the relational predicate 'TemporalIndex'. The sentence 'TemporalIndex(α, t)' stands for: 't is the temporal index of the ontology α'. TimeRegion is the predicate applying to regions of time of arbitrary length, including temporal instants. We then have the following constraints:

(A 6) $\text{TemporalIndex}(\alpha, t) \rightarrow (\Omega(\alpha) \wedge \text{TimeRegion}(t))$

Material Universals. Material universals correspond to the real invariants or patterns in the world apprehended by the material sciences. They are in every case *universals in re*, which means that they exist in their instances (Smith, 1997). Material universals are multiply instantiated: they exist in toto at different places and different times in the different particulars which instantiate them (Grenon & Johansson, 2003). The relation between universals and particulars is one of *instantiation*. 'Instantiation(a, u)' stands for: 'particular a is an instance of the material universal u '.

Given any material universal u we can form a constructed predicate U* such that an entity falls under U* if and only if it is an instance of u. Formally, we write:

$$U^*(x) \equiv_{def} \text{Instantiation}(x, u).$$

Uses of such constructed predicates are always trivially eliminable. The corresponding formulas are mere abbreviations for statements of instantiation relations between instances and universals. The genuine predicates of our theory, in contrast correspond in every case to formal categories and relations. That is, they correspond not to universals *in re* but rather to structural features of reality. Where material universals and particulars are analogous to the pieces of a jigsaw puzzle, structural features are analogous to the connections between the pieces which hold the puzzle together.

Material universals are reflected by referring terms such as '*mountain*', '*lake*', and so on. While it is common in formalized theories to allow the unrestricted definition of ever more complex predicates via Boolean composition, we claim that the realm of universals is not structured in this Boolean fashion. There may be mountains and there may be oceans, but there is no universal *mountain-or-ocean*. We thus accept a sparse theory of universals, a theory of the type embraced by realist ontologists from Aristotle to Armstrong (1978) and Lewis (1983), who hold that the question as to which universals exist in reality is a matter for scientists, not for ontologists, logicians or linguists, to determine.

Taxonomies of Universals in BFO. Each SNAP and SPAN ontology is an ontology of particulars, but each deals also as it were on the side with the universals which such particulars instantiate. Each SNAP or SPAN ontology may be understood as a window on a certain portion of the world. We can look through this window in a way which selects particulars or in a way which selects universals.

Each BFO ontology includes taxonomies of various sorts. A taxonomy is a tree whose nodes correspond to material universals, organized into branches of greater and lesser generality. We introduce the terms 'genus' and 'species' to refer informally to universals at higher and lower positions within such trees. A geological taxonomy recognizes the genus *rock* and the species *igneous rock*, *metamorphic rock*, *sedimentary rock*. Each of the latter is an immediate sub-species of the single genus *rock*. The species on any given level are pairwise disjoint (no rock falls under more than one of these species). In insisting that every taxonomy is structured as a tree we are insisting in effect that every species in a hierarchy satisfies this condition of pairwise disjointness. The genus *rock* satisfies also a second condition, which is that its immediate species jointly exhaust the genus. When all species in a hierarchy fulfil these conditions, the hierarchy has the structure of what we call a partitioning tree. Observe that our insistence on such structural constraints is yet another reason for our rejection of arbitrarily composed categories, such as *mountain-or-ocean*. Allowing such composition would be tentative to building hierarchies of universals of lattice form; BFO requires its hierarchies to be partitioning trees. With this understanding, we will dispense in what follows with axiomatic representations of taxonomies and rely instead on their corresponding labeled diagrams.

2.2 Mereology

Mereology, the theory of the part-whole relationship (see Simons, 1987), will be our basic tool for understanding the domains of SNAP and SPAN ontologies. We write 'Part*(a*, *b*)' for '*a* is a (proper or improper) part of *b*' and use 'ProperPart' as the symbol for the *proper part* relation. The parthood relation is reflexive, transitive, and antisymmetric:

(A 7) $\text{Part}(x, x)$

(A 8) $(\text{Part}(x, y) \wedge \text{Part}(y, z)) \rightarrow \text{Part}(x, z)$

(A 9) $(\text{Part}(x, y) \wedge \text{Part}(y, x)) \rightarrow x = y$

The proper parthood relation is the irreflexive form of parthood:

(D 10) $\text{ProperPart}(x, y) \equiv_{\text{def}} \text{Part}(x, y) \wedge x \neq y$

Overlap obtains when two entities have a part in common:

(D 11) $\text{Overlap}(x, y) \equiv_{\text{def}} \exists z\ (\text{Part}(z, x) \wedge \text{Part}(z, y))$

With this, we may define the operator *sum-of*, which yields the sum of two entities, defined as the entity which overlaps anything which overlaps either entity:

(D 12) $\textit{sum-of}(x, y) =_{\text{def}} \iota z \forall w\ ((\text{Overlap}(w, x) \vee \text{Overlap}(w, y) \leftrightarrow \text{Overlap}(w, z))$

Using the schematic letter '**P**' as a stand-in for a given genuine or constructed predicate, we give the following definitions adapted from (Simons, 1987):

(D 13) **P** is *dissective* when all parts of any instances of **P** also fall under **P**:

$(\mathbf{P}(\text{x}) \wedge \text{Part}(y, x)) \rightarrow \mathbf{P}(y)$.

(D 14) **P** is *cumulative* when the sum of any two instances of **P** also falls under **P**:

$(\textit{sum-of}(x, y) = z \wedge \mathbf{P}(x) \wedge \mathbf{P}(y)) \rightarrow \mathbf{P}(z)$.

For instance, the constructed predicate Cup* is neither dissective (a part of a cup is generally not a cup) nor cumulative (the sum of two cups is not a cup). However, the constructed predicate Water* is both, though its dissectivity holds only down to parts of a certain molecule-sized level of granularity. Entity is dissective absolutely.

Mereology and Universals. For each material domain, each level of granularity, and each perspective, we can distinguish a number of basic universals whose instances are the basic building blocks of reality as captured by the corresponding SNAP and SPAN ontologies. Generally, these universals – for example *molecule*, *cell*, *organism*, *city*, *nation* – will be neither cumulative nor dissective. Instances of basic universals we call basic entities. In addition to the basic entities, there are also aggregates, fiat parts, and boundaries of basic entities. You are a basic entity in the SNAP ontology of common sense, your digestive system is, within this ontology, a fiat part. You and your hat are basic entities, the sum of you and your hat is an aggregate. The categories of aggregate, fiat part, and boundary are genuine formal categories which appear in an ontology as soon as the basic entities themselves are recognized. However, aggregates, fiat parts, and boundaries are not themselves extra entities; rather they reflect merely different possibilities for slicing up the reality constituted by the basic entities that are yielded by our framework.

2.3 Formal Relations

Our framework is so conceived as to comprehend a number of different types of formal relations. Here we shall focus on binary relations, but the treatment can be extended to relations of higher arity. The most important types are:

Intra-Ontological Relations. A relation between entities all of which are constituents of a single ontology is called intra-ontological. An example is the relation of part to whole (between entities of a single granularity). This is because an object is never part of a process, a process is never part of an object. Since in BFO there are two main types of ontology, SNAP and SPAN, there are also two main types of intra-ontological relations.

Trans-Ontological Relations. A relation between entities that are constituents of distinct ontologies is called trans-ontological. Consider the relation of *participation* between an object and a process (as when an army participates in a manoeuvre). The number of types of trans-ontological relations we have to consider depends on the number of types of ontologies our theory needs to relate. Trans-ontological relations will be needed to relate also entities in distinct ontologies of the same type (for instance to relate an army that is recognized by a succession of SNAP ontologies with distinct time indexes). There will be four main types of binary trans-ontological relations, having signatures: (SNAP, SPAN), (SNAP, SNAP), (SPAN, SNAP), and (SPAN, SPAN), respectively.

Meta-Ontological Relations. A relation that obtains between ontologies or between an ontology and an entity is called meta-ontological. Examples are the relation of constituency or the relations of temporal order between ontologies.

Ontological Indices of Relations. The relations which hold among entities are intimately tied to the ontologies which recognize these entities. It could be that two entities are recognized by two distinct ontologies but that they are differently related in each (in one ontology, for example, the relation of *being on* between the cup and the desk is recognized, in another it is not).

When a relation **R** obtains between entities a and b in a single ontology α, we write '$\mathbf{R}(a, b, \alpha)$'. In the case of trans-ontological relations, there might be as many ontologies mentioned as there are relata. We then write for example '$\mathbf{R}(a, \alpha, b, \beta)$' for: '**R** obtains between a in α and b in β'. In practice, when the context is clear we shall omit ontological indices and assume the following constraints:

$$\mathbf{R}(x, y, \omega) \rightarrow (\text{Constituent}(x, \omega) \wedge \text{Constituent}(y, \omega))$$

$$\mathbf{R}(x, \omega, y, \omega') \rightarrow (\text{Constituent}(x, \omega) \wedge \text{Constituent}(y, \omega'))$$

3 SNAP

SNAP ontologies are intended as a framework for representing the ontological nature of continuants. The philosophical doctrine of presentism propounded by (Brentano, 1976) or (Chisholm, 1989; 1990) holds that all entities which exist exist *at the present time*. Each SNAP ontology is thus a presentist ontology relative to some specific temporal instant. The ontology then recognizes just the enduring entities existing at that time, entities which of course have existed already for some time in the past (unless they are precisely being created) and will go on existing in the future (unless they are precisely being destroyed). The entities recognized by SNAP ontologies are in other words no instantaneous entities. A SNAP ontology is analogous to a snapshot (or to the results of a process of sampling), and a series of such ontologies must be used in order to represent change. However, changes themselves are external phenomena from the SNAP perspective. They belong rather to the domain of the SPAN ontology.

3.1 Kinds of SNAP Entities

We shall use the symbol 'SnapEntity' for the predicate under which SNAP entities fall. This predicate is both dissective and cumulative. We can represent subsumption among top-level categories in SNAP as follows:

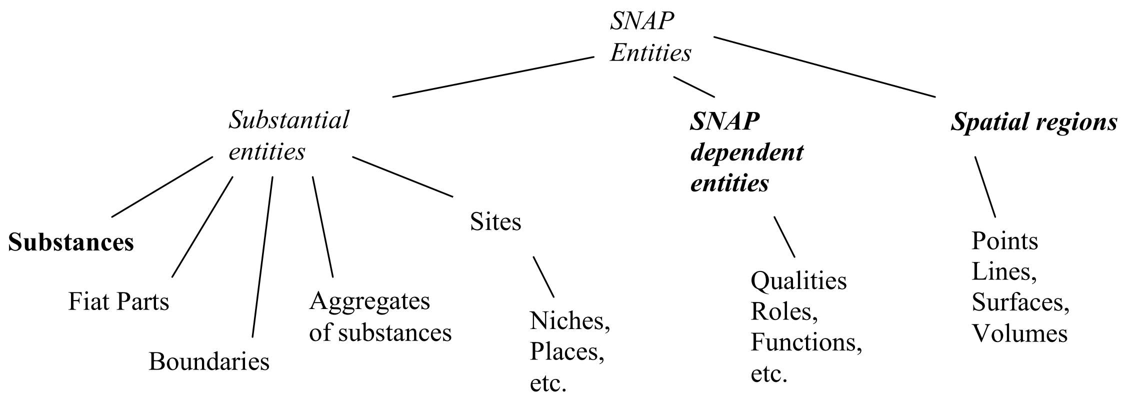

Figure 1. The main formal categories of SNAP entities. Italicized items are dissective and cumulative categories. Bold items are categories of basic entities.

3.2 Spatial Regions

We embrace a so-called absolutist view on space, sometimes called a container view of space. That is, we hold that there are spatial regions, which are endurants and which are such that other SNAP entities can be located at or in them. (The phenomenon of vacuum shows that some regions need not have any entity located at or in them.) There is one distinguished spatial region, namely s*pace* or the entire spatial universe (the maximal spatial region). All spatial regions are parts of *space*, and we may define the predicate SpatialRegion as follows:

(D 15) SpatialRegion(x) $\equiv_{def}$ Part(x, *space*)

SpatialRegion is trivially dissective and cumulative.

We may study *space* at a variety of levels, by means of topological and geometrical theories. In addition, *space* supports a rich variety of qualitative reasoning (Cohn & Hazarika, 2001; Galton, 2001). Thus, we may extend the taxonomy of spatial regions in a variety of ways, for example by reference to qualitative topological categories such as self-connected, convex, holed, and so on.

Space, here, is understood as the locational substrate for material objects and for a range of other SNAP entities. *Space* exists – in conformity with the absolutist view – independently of the things which are located at its parts. On the other hand however we will need to do justice also to certain intuitions underlying the relational conception of space. On the relational view spatial regions exist only in virtue of certain relations among objects. We shall see that some varieties of spatial entities – here called *sites* – are of just this sort.

3.3 Substantial Entities

The category of *substantial entities* is a non-basic formal category comprehending the categories of substances, their fiat parts, aggregates, and boundaries. It can be seen as a generalization of the category of substances resulting from the relaxation of the mereotopological constraints of boundeness and connectedness. The predicate Substantial is both dissective and cumulative. We can distinguish the following sub-categories of substantial entities:

Substances. Substances are maximal connected substantials. They are those substantial entities which enjoy a certain rounded-offness or natural completeness. In addition to material objects such as cups, rocks, and planets, organisms are the prototypical examples of substances. We treat substances in BFO along the lines presented in (Smith, 1997). Substances have the following main features:

- (i) Substances do not depend for their existence upon other entities.
- (ii) Substances are the bearers of qualities and are subject to qualitative change.
- (iii) Substances are enduring entities: they preserve their identity over time and through changes of various sorts.
- (iv) Substances have a location in space.
- (v) Substances are self-connected wholes with *bona fide* boundaries (Smith and Varzi, 2000).

The predicate Substance is neither dissective nor cumulative.

The term ‘substance’ is used here as a count noun, in keeping with the philosophical tradition stretching back to Aristotle. In ordinary English the term ‘substance’ has of course also a mass sense, the treatment of which is however in part a matter of shifting granularities and thus falls outside our purview here. On any given level of granularity, the parts and aggregates of substances are not themselves substances.

Fiat parts. For a theory of fiat parts we refer to (Smith 1995; Smith & Varzi, 2000; Smith 2001b). It is possible to carve out zero-, one-, two- and three-dimensional fiat parts of the Earth. This is what is done when we demarcate the North Pole, or the Equator, or when a parcel of land is demarcated on a cadastral map, or when a certain volume beneath the surface of the Earth is demarcated for purposes of mining exploration. The Earth’s atmosphere, too, may be taken as a substance on an appropriate level of granularity, and we may carve out fiat portions of the Earth’s atmosphere, too, including those masses of air which in motion correspond to winds.

Boundaries. Boundaries are lower-dimensional parts of spatial entities (Smith, 1997; Smith & Varzi 2000). The boundary of the Earth is a closed two-dimensional surface. Boundaries as we conceive them depend on the entities they bound as parts depend on wholes.

Aggregates. Aggregates of substances are mereological sums comprehending separate substances as parts. In contradistinction to substances, aggregates may be scattered and thus have non-connected boundaries. Aggregates on one level of granularity (for example a collection of soldiers) may correspond to substances (for example an infantry battalion) on another level of granularity.

Sites. Sites are holes, cavities and similar entities (Casati & Varzi, 1994), for example the holes formed by aggregates of cliffs, walls, floors, together with associated fiat boundaries, which we call piazzas, canyons, atriums. A room in a house is a site, as also is a landing strip, a meadow, the interior of your car or of your airline cockpit. The corner of a room is a site, as also is your alimentary tract or the interior of an oil pipeline. Some sites are formed by sums of sites of these kinds (holes) and of the substantial entities which surround or bound them. A rhinocerus’s body is a site for the small creatures which live upon it. The addresses where people live and work are labels not of spatial regions but rather of the sites which they characteristically occupy. As substances are located in space, so also are the sites associated with them. In addition to being located at spatial regions, substantial entities may also be located at or in sites in virtue of their relations to certain other objects. Sites sometimes act as *surrounding spaces* for other entities (Smith & Varzi, 2002), and as we shall see below, they do this in different ways. Sites are generally filled by a medium such as air or water. The medium is then itself one of the parts of the site.

Boundary-Free and Physically Bounded Sites. Sites are typically a compound of rigid surroundings and fluid medium. Some sites, however, are defined in whole or in part in terms of fiat boundaries: for instance fiat parts of the atmosphere such as air traffic corridors. Sites whose boundaries are partly or wholly solid we call ‘physically bounded’; others we call ‘boundary-free’. Your nostril is a partly physically bounded site. Your office, when the door and windows are closed, is a wholly physically bounded site.

Niches, Environments. Niches are special sorts of sites, marked out by their capacity to be occupied by substantial entities of other sorts. A stagnant pond may be a site of this kind insofar as it is inhabited by microbial organisms. Niches are typically made of a medium enclosed by a mix of fiat and bona fide boundaries (Smith & Varzi, 2002). It is the medium which enables the niche to sustain the occupant (Smith & Varzi, 1999). The media of niches are marked by SNAP dependent entities such as qualities of air pressure and temperature, density and chemical constituency of nutrients, which together help to constitute the niches appropriate for given sorts of tenants.

Places. Places – the Grand Canyon, the Piazza San Marco – are those special sorts of sites which stand to human beings in something like the relation to which niches stand to non-human organisms. Places are characteristically bounded by material objects such as, at the geographical scale, buildings, streets, roads, and other landmarks. In addition, we can define a functional notion *place-of*, which yields for each substantial entity the minimal site which that entity currently occupies. For an object to be in its place, in this sense, is for it to exclude other objects from occupying that same place. If you want to put your book on the table in the place where the cup is, you have to move the cup. If you want to build a monument in the place where the building sits, then you have to move or destroy the building.

3.4 SNAP Dependent Entities

SNAP dependent entities are endurant entities which depend for their existence on the substances which are their bearers. They include: particularized *qualities* (the colour of this tomato, the ambiant temperature in this room), *functions* (the function of the canal to enable transportation), *roles* (as student, as captain of a soccer team), *dispositions* (of the vegetables, that they are prone to rotting), *powers* (of the refrigerator, to slow the decay of vegetables), *liabilities* (of the vegetables, to be affected by the functioning of the refrigerator). These entities all endure in time. But they are all dependent for their existence upon the substances which are their bearers. The particular colour of this tomato would not exist without the tomato which it is the colour of.

The terminology is very hard to fix here, and the types we have distinguished by way of example are not themselves clearly separated. We avoid the terms ‘property’ and ‘attribute’ (and also the terms ‘individualized property’, ‘individualized attribute’) because they are too closely associated with a traditional reading of the term ‘predicate’ in predicate logic – a reading which rides roughshod over the distinctions of importance to us here. We reject also Aristotle’s ‘accident’ and Husserl’s ‘moment’ and the term ‘trope’ used for instance by (Campbell, 1990; Simons, 1994; Lowe, 2002). This is because each of these terms refers to a mixed group of entities which traverse what is for us the crucially important divide between SNAP and SPAN. In what follows we shall use the term ‘quality’ as a convenient shorthand for ‘SNAP dependent entity’, employing the predicate

SnapDependent in formal contexts. The particular redness of this ball is a quality that is dependent upon the ball to which it belongs. Other types of SNAP dependent entity include: *states* or *conditions*, *shapes, plans*, *laws, norms, tasks*, *rules*, *laws*, *natural languages*, and *algorithms*. All of these have in common the feature of enduring through time while requiring a basis in SNAP independent entities in order to exist.

There are both monadic and polyadic or relational SNAP dependent entities. Examples of monadic SNAP dependent entities include qualities dependent on one substance only such as the mass of this apple. Examples of relational SNAP dependent entities include entities which depend upon a multiplicity of substances, which they serve to relate together, such as a treaty between two countries. The treaty itself depends for its existence upon the countries involved. The copies of the treaty document are SNAP independent entities. They are representations of the agreement and of the act by which it was initiated. The term 'relation' is commonly used to refer to a complex congeries of entities of different types, of which SNAP dependent relations are only one example. In addition, there are purely formal relations such as *constituency*, *parthood* and *non-identity*, as well as comparative relations such as *is taller than*, and so forth. There are also other types of relational entities, including SPAN relational processes such as kissing and kicking, which require a different treatment.

3.5 Universals

Going downward in the hierarchy of kinds of being, we can introduce further predicates which are specializations of those surveyed here. Eventually, we move from the domain of formal categories to the domains of material universals belonging to the different material regions as they are apprehended at different level of granularity. Finding out which are the genuine formal categories is the job of the ontologist. Finding out which are the material universals is the job of the specialist scientist.

SNAP material universals fall into two main families:

Substantial universals. These are the universals instantiated by substantial entities. For instance, substance universals such as *ball*, *body*, *planet*; site universals such as *valley*, *bay*, *cave*; universals under which fiat parts of substances fall such as *leg*, *hilltop*, *mound*; universals instantiated by aggregates of substantials such as : *family*, *mountain-range*, *fleet*.

Quality universals. These are the universals instantiated by SNAP dependent entities. Recall that on our view SNAP dependent entities – qualities, conditions, functions, roles, dispositions, powers, liabilities, etc. – are particulars, which instantiate corresponding kinds of universals. There is a universal *colour* or *shape*, instantiated by the colour and the shape of this ball. The universal *red* is a determinate of the determinable universal *colour*, (see Johansson, 2000). We call such universals 'quality universals'.

By combining substantial and quality universals (or their associated defined predicates), we may build further constructed predicates *a volo*, (Grenon and Johansson, 2003). For instance, RedBall* applying to red balls. This does not correspond to any material universal, but it nonetheless applies by definition to all those balls in whose surface there inheres (the *inherence* relation will be introduced formally shortly) an instance of the quality universal *red*.

4 Reasoning in and with SNAP Ontologies

A SNAP ontology is formed through the depiction of the enduring entities existing at a given time (and, more precisely, in a given domain at a given level of granularity). '$\text{Snap}\Omega(\alpha)$' stands for: '$\alpha$ is an ontology of enduring entities' or 'α is a SNAP ontology'. Constituents of SNAP ontologies are SNAP entities:

(A 16) $\text{Constituent}(x, \omega) \rightarrow (\text{Snap}\Omega(\omega) \leftrightarrow \text{SnapEntity}(x))$

Each SNAP ontology is indexed to some specific instant of time:

(A 17) $(\text{Index}(\omega, x) \wedge (\text{Snap}\Omega(\omega)) \rightarrow \text{TimeInstant}(x)$

Being a constituent of a SNAP ontology thus amounts to existing (as a continuant) at the time of the ontology's index. When a SNAP entity a exists at an instant t, we write '$\text{ExistsAt}(a, t)$', defined as follow:

(D 18) $\text{ExistsAt}(x, t) \equiv_{\text{def}} \exists\omega\, (\text{Snap}\Omega(\omega) \wedge \text{Index}(\omega, t) \wedge \text{Constituent}(x, \omega))$

Enduring entities exist continuously during extended periods of time even while undergoing certain sorts of changes (for instance, changes of temperature or mass or height). We may thus speak about *existence during* a period of time by integrating across the instants of time in which endurants are captured by corresponding SNAP ontologies. To this end we define a relation between a SNAP entity and an extended period of time during which it exists. '$\text{ExistsDuring}(a, b)$' stands for: '$a$ exists during the period of time b':

(D 19) $\text{ExistsDuring}(x, y) \equiv_{\text{def}} \text{TimeRegion}(y) \wedge \forall z\, ((\text{TimeInstant}(z) \wedge \text{ProperPart}(z, y)) \rightarrow \text{ExistsAt}(x, z))$

4.1 Reasoning within SNAP ontologies

Reasoning within a single SNAP ontology is prototypically a form of spatial reasoning. Our logical machinery for intra-ontological reasoning in SNAP will include:

Theory of Location. This will relate substantial entities, including sites, niches, and places, and also the monadic SNAP dependent entities (MSnapDependent) which inhere in them, to the regions of space at which they are located. To this end, we introduce a new primitive relation of spatial location, symbolized: 'SpatialLocation' (called exact location by Casati & Varzi, 1996).

(A 20) $\text{SpatialLocation}(x, y) \rightarrow ((\text{Substantial}(x) \vee \text{MSnapDependent}(x) \vee \text{SpatialRegion}(x)) \wedge \text{SpatialRegion}(y))$

(A 21) $((\text{Substantial}(x) \vee \text{MSnapDependent}(x) \vee \text{SpatialRegion}(x)) \wedge \text{Constituent}(x, \omega)) \rightarrow \exists y\, \text{SpatialLocation}\,(x, y, \omega)$

(A 22) $(\text{SpatialLocation}(x, y, \omega) \wedge \text{SpatialLocation}(x, y', \omega)) \rightarrow y = y'$

(A 21) and (A 22) ensure the claim that SpatialLocation is a function, so that we can introduce a functional notation in order to denote the spatial location of an entity a in an ontology ω: '*spatial-location-of*(a, ω)'. We then have:

(A 23) SpatialLocation(x, *spatial-location-of*(x, ω), ω)

Theories of Spatial Relations. There are synchronic spatial relations which obtain between the entities located at spatial regions at any given time in virtue of the relations which exist between the regions themselves. Some of these are mereotopological, some are distance and orientation relations. Thus we need to have the resources to say, for example, that an airplane is above the city of Carlin, NV or that Carlin is situated along Interstate 80, or that it is more than 2000 miles west of New York.

We introduce the relation of *occupation* (OccupiedBy), which relates a site with one of its substantial occupants. We then have:

(A 24) OccupiedBy(x, y) $\rightarrow$ (Site(x) $\wedge$ SpatialRegion(y))

(A 25) (OccupiedBy(x, y, ω) $\wedge$ SpatialLocation(x, x', ω) $\wedge$ SpatialLocation(y, y', ω)) $\rightarrow$ Part(x', y', ω)

We introduced *place-of* earlier; this is a function from substantial entities to places.

Mereotopology of Spatial Regions and of Sites. The mereotopology of spatial regions gives us the resources to speak about the connectedness and separation of spatial regions, and also to speak about both fiat boundaries – *space* calls for a fiat mereotopology – and other related notions (Cohn, Bennett, Gooday, & Gotts, 1997; Smith, 1997; Smith & Varzi, 2000; Galton, 2001; Cohn & Varzi, 2003). But we shall need a second such theory for talking about analogous relations involving sites, where bona fide boundaries will play an important role. See, in addition, Casati & Varzi (1999) and Smith & Varzi (1999; 2002). It will prove crucial when dealing with geographical entities that we are able to deal with the surfaces of substances and not only with the regions in which such surfaces are located (Stroll, 1988; Casati & Varzi, 1994).

Inherence is an intra-ontological relation between a SNAP dependent entity and its substantial bearer. The *redness* of the ball inheres in the ball; the *elevation* of a summit inheres in the summit; the shape of a landform inheres in the landform. Inherence is a form of *existential dependence* (Husserl, 1913/21; Simons, 1987; Smith, 1997). It is such that the first of its relata (in the case of *inherence*, the SNAP dependent entity) exists only in virtue of the existence of the second (the bearer). There are other forms of dependence relations and dependence alone does not suffice for the relation of inherence to obtain. Here we use the symbol 'InheresIn' for this relation:

(A 26) InheresIn(x, y) $\rightarrow$ (SnapDependent(x) $\wedge$ Substantial(y))

(A 27) (InheresIn(x, y, ω) $\wedge$ SpatialLocation(x, x', ω) $\wedge$ SpatialLocation(y, y', ω)) $\rightarrow$ Part(x', y', ω)

4.2 Trans-SNAP Ontology: Tracking Change

The above is limited to reasoning within a single SNAP ontology. Normally, however, when reasoning within the SNAP framework we need to manipulate a plurality of SNAP ontologies in order to do justice to changes in the entities they recognize, for example changes recorded through successive instances of sampling. A depiction of the world over time from the SNAP perspective involves taking a succession of temporally indexed SNAP ontologies into account. As single SNAP ontologies are akin to snapshots of reality, so a succession of such ontologies is akin to a slide show. Change is then reflected in discrepancies between temporally separated snapshots.

Three main types of change can be captured in this fashion:

Qualitative Change. Qualitative change is change in the qualities inhering in a SNAP entity. At any given time certain qualities inhere in each given substance. At any subsequent time a number of different qualities may inhere in the same substance. *Pace* (Loux, 1979) there is no inconsistency in ascribing contradictory properties to the same object. Such ascriptions pertain to distinct ontologies, and there is no single perspective within which they conjunctively obtain. (The need to become clear about the existence of such distinct perspectives is the principal message of realist perspectivalism.)

There are various modes of qualitative change:

Change in determinables: In many cases a SNAP dependent entity will instantiate different *determinates* of the same *determinable* quality universal at different times. The colour of this table becomes tarnished over time. The colour changes; yet there is still something which remains the same and which is the subject of such change: a token determinable remains the same while transitioning through successive token determinates or values. This is the most common type of qualitative change in the geographical context: it is illustrated by change in ambiant temperature, elevation, vegetation coverage, and so on

Qualitative creation: A SNAP dependent entity that is not present in one ontology appears in later ontologies. This is what happens when Jacques Chirac takes on the role of President of France, or when a desert area is irrigated and thereby acquires a new dispositional quality of supporting vegetation coverage.

Qualitative destruction: A substance has a certain SNAP dependent entity for a certain interval of time but not at later times. This is what happens when a substance loses powers or functions, as when Jacques Chirac ceases to be President or when a ground area is classified as not suitable for development.

Spatial and Locational Change. In one SNAP ontology the cup is on the table, in a later SNAP ontology it is on the floor. In one SNAP ontology Danzig is a part of Germany; in a later SNAP ontology it is part of Poland.

Substantial Change. Substantial change occurs when substances are created or destroyed, as when a substance is divided up in such a way as to produce a plurality of substances or when a plurality of substances are fused or merged. The Kingdom of Saxony was once one nation; currently its territory is divided out among several administrative regions of a new and more comprehensive state. We can distinguish in this connection the following simple types of *substance formation* (following Smith & Brogaard, 2003):

Budding: a part of a substance becomes detached, forming a new substance while the original substance goes on existing; rock erosions form an example here; cf. also the formation of colonies, or of effluents of streams, or of new streets emanating from existing ones.

Absorption: one substance ceases to exist after becoming absorbed into a second substance; as in the annexion of one piece of territory by another country, cf. also the formation of confluences of streams and of glaciers and sedimentary strata.

Separation: parts of a substance are transformed into entities in their own right, as when the territory of the former Czechoslovakia becomes separated into those of the Czech and Slovak Republic or when Algeria gaines its independence from France.

Unification: separate substances join to form a new substance: two army regiments are unified to become one; two newspapers are merged.

Genidentity. In order to account for such kinds of changes, it is useful to introduce the trans-ontological relation of *genidentity*, which is 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 rubber into two, the sum of the separated pieces is exactly physically genidentical to the chunk as it existed before the cutting). On the varieties of *genidentity* see (Lewin, 1922) and the discussion in (Smith & Mulligan, 1982).

Changes are not Entities in any SNAP Ontology. The SNAP framework allows us to keep track of change, but it does not give us the facility to handle changes as entities in their own right. An account of the world merely in terms of what can be grasped at single instants of time thus falls short of doing full justice to the dynamic features of reality.

5 SPAN

It is in the SPAN ontology that we find changes as entities in their own right. SPAN ontologies are precisely a matter of what spans time; they comprehend spatiotemporally extended regions and the occurrents which such regions contain.

SPAN is the ontology of those entities which unfold themselves through time in their successive temporal parts. (SNAP entities do not have temporal parts: your youth is not a part of you, but a part of your life.) In regard to SPAN, a form of methodological eternalism is appropriate. Eternalism is the philosophical doctrine according to which all times (past, present, and future) exist on a par. Occurrents are extended in time; they have temporal parts, and thus they can be partitioned via partitions of the temporal dimension. *Time* itself is a constituent of the reality that is captured by SPAN. Occurrents are structured also along the spatial dimension; however, the real substrate for location here is no longer *space* but rather *spacetime*, which is itself a SPAN entity.

5.1 Kinds of SPAN Entities

Processes are occurring entities, they unfold themselves through time. However, there exist within the realm of SPAN also the instantaneous boundaries of processes and the instantaneous transitions within processes, here called *events*. Some extended processual entities are apprehended as event-like changes because they involve sudden qualitative or other jumps which seem to divide temporal reality into two parts. Truly instantaneous events are often created via fiat. The ceasing to exist of the German Democratic Republic occurred precisely at midnight on October 2, 1990.

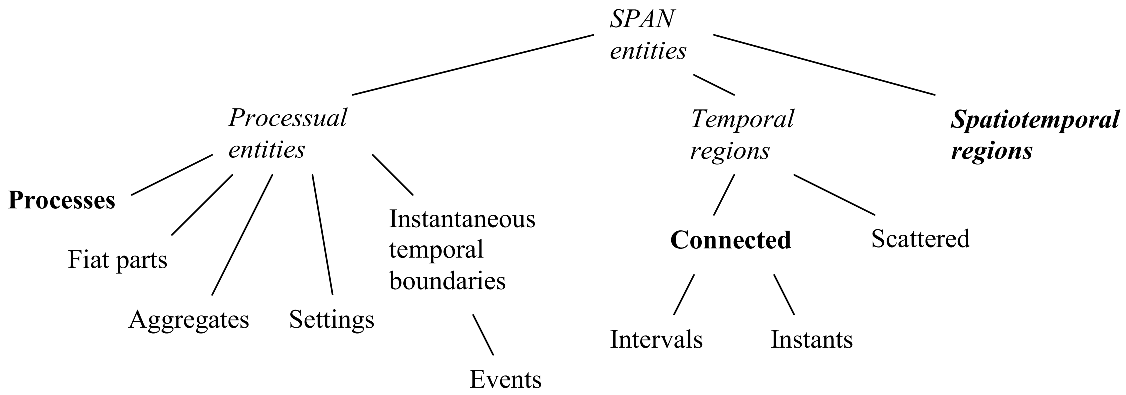

Figure 2. Taxonomy of SPAN entities. Italicized items are for dissective and cumulative categories. Bold items are for categories of basic entities.

5.2 Processual Entities

These are entities which stand to processes as substantial entities stand to substances. Processuals are occurrents or happenings; they involve participants of a SNAP kind and they are dependent on their participants. They occupy spatiotemporal regions. Processuals comprehend not only processes but also the arbitrary fiat parts, aggregates and boundaries thereof. The predicate Processual is both dissective and cumulative. Processuals may have more or less complex structures. However, in contradistinction to what obtains in the realm of substances, there are few clean joints in the realm of processes. Processes merge with each other in a variety of ways to make larger process-wholes, to the degree that the SPAN realm is in large part a realm of flux. When you breathe and your friend talks then these two processes become merged together in a way that has no counterpart in the SNAP realm of substances. When talking about processes as unitary entities we are often in fact engaging in the sort of gerrymandering alluded to in (Quine, 1960; §36, p. 171). Notice, however, that we here depart from Quine, who propounded a four-dimensionalist ontology. Processes, for us are precisely occurrent entities in which substances and other SNAP entities participate. Processes are the entities revealed when we adopt a certain special (SPAN) perspective on reality. But the orthogonal (SNAP) perspective is no less faithful to what exists.

Types of processual entities include:

Processes. We say that processes exist in time by occurring and that they persist in time by perduring. They are natural units in the processual dimension in that they have beginnings and endings corresponding to real discontinuities, which are their bona fide boundaries.

Instantaneous transitions within the interiors of processes – for example the transition in your life which marked your becoming 4 years old – are fiat temporal boundaries. Within the eternalist framework of SPAN, all of the parts of any given process exist on a par with each other.

Just as the category of substances in SNAP is defined in such a way that its instances are mereotopologically connected wholes, so also processes in SPAN are required to be spatiotemporally connected, which means that they involve no gaps. A given process may not be occurring at two distinct times without occurring also at every time in the interval between them. Similarly a process may not occupy two spatiotemporal regions separated along the spatial dimension without occupying also every intervening spatiotemporal region bridging them. (See Cohn & Varzi, 2003). In case a given processual entity is affected by gaps of this sort, we are dealing not with one single process but rather with a process-aggregate. As we see when examining for example movements of air fronts, tornadoes, combustion processes within a forest fire, troop movements, epidemic transmissions of diseases, what is a process and what is an aggregate of processes often depends on the chosen level of granularity.

Fiat Parts. The parts of processes on a given level of granularity are by definition fiat parts, for if processes are connected entities then any division into parts must of necessity be a fiat division. Examples are: the first day of the Six Day war, the displacement of an anticyclone during some given 20 minute period. However, when we move to a lower level of granularity, then we often find it possible to recognize bona fide process parts (for example, the movements of individual droplets of water in a rainstorm).

Events. Events are the fiat and bona fide instantaneous temporal boundaries of processes. Examples are: the beginning of a conflict; the ceasing to exist of a country as a result of annexation; the detaching of a portion of rock as result of erosion. Thus they are the temporal analogues in SPAN of the spatial boundaries of substances in SNAP.

Aggregates of processes. Examples of aggregates of processes are: the aggregate of all wars and ethnic conflicts in Central Africa in a given year; the aggregate of all movements of troops in the jungle in a given night. Again: aggregates of processes at one level of granularity may appear as processes in their own right at coarser grains.

Settings (spatiotemporal environments). Just as we distinguished sites within SNAP, so we can distinguish settings (Barker, 1978), their four-dimensional counterparts, within SPAN. Examples are: Tudor England, London during the Blitz, Rouen during the Hundred Years War.

5.3 Spatiotemporal Regions

The totality of spatiotemporal regions reflects the totality of possible fiat demarcations of that maximal region we call *spacetime*. They include in particular those spatiotemporal regions which are the spatiotemporal extensions of processual entities. Processuals then stand to spatiotemporal regions in SPAN ontologies in a way analogous to the way in which substantials stand to spatial regions in SNAP ontologies. Spatiotemporal regions are entities which exist in their own right and independently of any processuals which may be located at or within them. The parts of the spatiotemporal universe all exist on a par with each other (in accordance with the eternalism of SPAN). We use ‘SpacetimeRegion’ as symbol for the predicate applying to spatiotemporal regions. Our framework calls for a fiat mereotopology for spatiotemporal regions. The parts of spatiotemporal regions at which processuals are located generate corresponding delineations of the processuals themselves. Spatiotemporal regions have specific sorts of four-dimensional shapes – for example the characteristic shapes of army manoeuvres or of hurricane movements – and these may be used in the formulation of taxonomies of their processual occupants.

(D 28) SpacetimeRegion(x) $\equiv_{def}$ Part(x, *spacetime*)

5.4 Temporal Regions

Time, the maximal temporal region, is a perdurant, and thus a SPAN entity. A temporal region is a part of *time* and the predicate ‘TimeRegion’ is defined as follows:

(D 29) TimeRegion(x) $\equiv_{def}$ Part(x, *time*)

Instants of time are zero-dimensional boundaries of extended temporal regions. They delineate a cross-section of *spacetime* which is meta-ontologically super-imposable on s*pace* as apprehended by the corresponding SNAP ontology. The relation between the two is then not one of identity – no continuant is identical with any occurrent – but rather one of spatiotemporal co-incidence.

6 Reasoning in and with SPAN Ontologies

6.1 Temporal Apparatus

Temporal order. Our apparatus will require a theory of temporal order reflecting the structure of *time* as a linear continuum. We follow traditional usage and take as our primitive the Before relation, which is a strict total order holding between two time instants when the first is earlier than the second.

Temporal location. Every SPAN entity can be assigned a temporal location. The primitive location relation between a SPAN entity and an (instantaneous or extended, connected or disconnected) region of time is symbolized by ‘TemporalLocation’. We write ‘TemporalLocation(a, t)’ for: ‘a is located at region of time t’. The TemporalLocation relation is analogous to the SpatialLocation of SNAP.

(A 30) TemporalLocation(x, y) $\rightarrow$ (SpanEntity(x) $\wedge$ TimeRegion(y))

Every SPAN entity has a temporal location:

(A 31) SpanEntity(x) $\rightarrow \exists y$ (TimeRegion(y) $\wedge$ TemporalLocation(x, y))

The temporal location of each SPAN entity is unique (it is the location of the whole entity), and TemporalLocation is therefore functional:

(A 32) (TemporalLocation(x, y) $\wedge$ TemporalLocation(x, z)) $\rightarrow z = y$

Thus we may introduce a functional notation for the temporal location of a SPAN entity: '*temporal-location-of*'.

Instantaneous SPAN entities are located at instants of time. 'AtTime(a, t)' stands for: 'a is temporally located at temporal instant t'. It is an intra-ontological relation between a SPAN entity and an instant of time:

(D 33) AtTime(x, y) $\equiv_{\text{def}}$ (TemporalLocation(x, t) $\wedge$ TimeInstant(y))

Temporal relations. We can define a number of temporal relations holding between processuals in virtue of the ordering and mereotopological relations which exist between their respective temporal locations. In particular, the relation of being Cotemporal will hold between SPAN entities which are located at exactly the same region of time.

The relation TemporalPart between SPAN entities can then be defined as follows:

(D 34) TemporalPart(x, y) $\equiv_{\text{def}}$ Part(x, y) $\wedge$ $\forall z$ ((Part(z, y) $\wedge$ Cotemporal(x, z)) $\rightarrow$ Part(z, x))

Temporal parts are thus the sums of cotemporal parts of a SPAN entity located within a given region of time.

Instantaneous temporal parts are also called 'temporal slices':

(D 35) TemporalSlice(x, y) $\equiv_{\text{def}}$ TemporalPart(x, y) $\wedge$ AtTime(x, y)

We may now define the formal predicate Event which holds of instantaneous processuals:

(D 36) Event(x) $\equiv_{\text{def}}$ $\exists y$ (Processual(y) $\wedge$ TemporalSlice(x, y))

By definition of TemporalSlice, events are located at an instant of time. We may now define the relation OccursAt between a processual and a time. It is the relation which holds between a processual entity and an instant of time at which a temporal slice of this processual is located:

(D 37) OccursAt(x, t) $\equiv_{\text{def}}$ $\exists y$ (TemporalSlice(x, y) $\wedge$ AtTime(y, t))

Obviously, in the case of an event e, OccursAt(e, t) is equivalent to AtTime(e, t). A proper mereotopological apparatus will allow us to define self-connected and scattered SPAN entities, and maximally connected parts of SPAN entities.

6.2 Spatiotemporal Apparatus

Spatiotemporal Location. Spacetime constitutes the universal substratum for all SPAN entities and location in SPAN has to be understood in relation to this spatiotemporal framework. We shall use 'SpatiotemporalLocation' to symbolize the relation between a SPAN entity and the region of *spacetime* which it occupies. It is defined by analogy to TemporalLocation. Spatiotemporal location is also a function and so allows the definition of the functor *spatiotemporal-location-of*.

Spatiotemporal Relations. A number of spatiotemporal relations hold between processuals in virtue of the relations between the regions of s*pacetime* at which they are located. Thus there are mereological and mereotopological relations; relations of co-incidence in *spacetime* (when two entities occupy the same spatiotemporal region) and overlap of location (when their respective spatiotemporal regions share parts), and so on. Definitions here follow more or less as in the temporal case.

6.3 Reasoning with SPAN Ontologies

A SPAN ontology is obtained by depicting the reality constituted by those perduring entities that unfold themselves within some determinate interval of time (in some given domain of reality and at some specific level of granularity). As ontologies of endurants are analogous to snapshots of reality, so ontologies of perdurants are analogous to videos spanning time (though the latter analogy has to be taken with a large grain of salt). In what follows, the predicate SpanΩ will apply to SPAN ontologies. 'SpanΩ(α)' stands for: 'α is a SPAN ontology'

(A 38) $\text{Constituent}(x, \omega) \rightarrow (\text{Span}\Omega(\omega) \leftrightarrow \text{SpanEntity}(x))$

Every SPAN ontology contains temporal regions as constituents. An all-encompassing SPAN ontology contains *time* itself as constituent.

(T 39) $\text{Span}\Omega(\omega) \rightarrow \exists x\, (\text{TimeRegion}(x) \wedge \text{Constituent}(x, \omega))$

In contradistinction to what is the case within the realm of SNAP, reasoning about change can be conducted within a single SPAN ontology. We may also form partial SPAN ontologies by restriction to specific intervals of time. If a SPAN ontology β is such that its constituents are the constituents of a SPAN ontology α, where the maximal temporal region of α is a part of that of β, then we say that α is a temporal restriction of β, and write: TemporalRestriction(α, β). When the index of the restriction is an instant of time, we call β: 'the cross-section of α' and write: Section(α, β).

(D 40) $\text{TemporalRestriction}(\omega, \omega') \equiv_{\text{def}} (\text{TemporalIndex}(\omega, t) \wedge \text{TemporalIndex}(\omega', t') \wedge \text{Part}(t, t') \wedge (\forall x\, (\text{Constituent}(x, \omega) \leftrightarrow (\text{Constituent}(x, \omega') \wedge \text{Part}(\textit{temporal-location-of}(x, \omega'), t))))$

(D 41) $\text{Section}(\omega, \omega') \equiv_{\text{def}} \text{TemporalRestriction}(\omega, \omega') \wedge \text{TemporalIndex}(\omega, t) \wedge \text{TimeInstant}(t)$

(T 39) is a theorem since any SPAN ontology is either such as to encompass the whole of time (and thus trivially contains at least one region of time, namely *time* itself) or it is a restriction of such a SPAN ontology and thus contains the relevant temporal part of *time*.

7 Trans-Ontology in BFO

Each SNAP entity is related to a unique SPAN entity which is its *history* or *life*. This is true of both substantial and dependent SNAP entities: each has a life with a beginning and an end. The relation between you and your life is of course difficult to define; however we shall here assume that it is a functional relation (that your life is unique) and that it can be handled through the introduction of the corresponding operator on SNAP entities: *life-of*.

There is a family of further trans-ontological relations between SNAP and SPAN entities, of which not only *participation* but also *initiation*, *termination*, *creation*, *destruction*, *sustenance*, *deterioration*, *facilitation*, *hindrance* are examples (for details, see

Grenon, 2003). Here we lay out the framework of SNAP-SPAN trans-ontology in terms of the prototypical example of *participation*.

A participant in a process exists during a time which overlaps the temporal location of the process. We then have:

(A 42) ParticipatesIn(x, y) $\rightarrow$ (Substantial(x) $\wedge$ Processual(y))

(A 43) (ParticipatesIn(x, y) $\wedge$ ExistsDuring(x, t) $\wedge$ TemporalLocation(y, s)) $\rightarrow$ Overlap(r, s)

Given the peculiarities of the respective modes of being of SNAP and SPAN entities, it might still be puzzling how these entities can be brought together within a single framework. The connection comes about through the fact that both are somehow located at a time (via ExistsAt for SNAP entities and OccursAt for SPAN entities). *Time*, or rather instants of time, thus play a cardinal role as medium of connection between SNAP and SPAN.

Let us assume for instance that two entities are given and known to stand in the relation of participation. We introduced ParticipatesIn as a relation between a substantial and a processual (A42), and this commits us to the trans-ontological character of participation. That is, whenever ParticipatesIn(a, ω, b, ω') holds we have SnapΩ(ω) and SpanΩ(ω') and also Constituent(a, ω) and Constituent(b, ω'). More generally, that a participates in b over a region of time t means that there is a series of SNAP ontologies α_i ($1 \leq i$) covering t, and a SPAN ontology β whose temporal index contains t, such that 'ParticipatesIn(a, α_i, b, β)' is true for all i.

For any given time instant t, if we know that ParticipatesIn(a, α_t, b, β) holds, we know also that a exists and b occurs at t, i.e.that ExistsAt(a, t) and OccursAt(b, t). More generally, for any two separate time instants t_1 and t_2 at which we know that ParticipatesIn(a, b) holds, we also know that a exists during the interval [t_1, t_2] separating t_1 and t_2, i.e.: ExistsDuring(a, [t_1, t_2]). This is because a is a continuant in time. As concerns b we can say only that it has at least two temporal parts overlapping t_1 and t_2, respectively. Strictly speaking, our framework guarantees that b has two temporal slices at these times (by definition of OccursAt). For instance, b might be a scattered processual in which a participates only in each of the beginning slices of its successive phases.)

A participant in an extended process at a given instant participates in the temporal slice of this process located at that instant. Temporal slices are events and they are ordered by the Before relation. This yields a number of possible cases according to the relative position of the temporal slice in relation to the process as a whole, for instance:

(i) when this is the earliest such slice and the substantial initiates the process as when a referee fires the starting pistol in such a way as to initiate the race

(ii) when this is the last temporal slice and the substantial terminates the process as when a car hits a wall

(iii) when this is intermediate and the substantial contributes to the unfolding of the process as when the stream of water contributes to the erosion of a rock face.

To conclude, let us observe that in the case of the relation between a SNAP entity and its life we will always have exact temporal coincidence. In other words, SNAP entities exist for the entirety of the period of time at which their life is located and conversely. Thus on the one hand, there is no temporal part of your life which occurs before or after the period of time during which you exist. On the other hand, your life is occurring at every time at which you exist; lives of continuants may not be scattered processuals entities.

8 Geodynamic Ontology

There are two major types of geographical ontology. On the one hand is the ontology of geographical continuants or endurants; we call it 'SNAPGeo'. On the other hand is the ontology of geographical occurrents, which we call 'SPANGeo'.

Geographical regions are at the heart of our theory of geographical entities, and once we have defined them it will be possible for us to define geographical entities in general as entities which stand in relations of a specific sort to geographical regions.

To begin with we want every geographical SNAP ontology to have one privileged region – the surface of the planet Earth – though we do not want to hold that any ontology which recognizes this surface as an entity is thereby of necessity a geographical ontology. The framework here presented can be generalized in the obvious way to apply to other reference bodies such as the Moon and also (for those who want to investigate the analogies between geography and anatomy) to human bodies.

A geographical ontology takes the Earth as reference body for the location of entities which are located at or near its surface. There are no precise limits to the scope of a geographical ontology, which can extend in principle as far as the upper atmosphere and down into the Earth's core. A geographical ontology must however have the resources to deal with phenomena which causally interact with what exists or takes place at or near the surface of the Earth even where such phenomena do not fall within the scope of geography as narrowly conceived. The Moon, for example, is not a geographical object, but phenomena such as tidal cycles are causally correlated with its position in relation to the Earth. We will leave aside such considerations here, however, and focus exclusively on the ontology of those objects and processes which are located on or near the surface of the Earth and which are standardly understood as geographic.

In a full account of these matters, when we have at our disposal a theory of granularity, we shall need to provide analyses of the two concepts of existing or occurring in proximity to the surface of the Earth and of being of geographical scale. Here, however, we shall take these notions as primitive.

8.1 Geospatial, Geotemporal, and Geospatiotemporal Regions

We have used 'region' as a generic term embracing regions of *space*, of *time*, and of *spacetime*. The term 'georegion' will have the same generic character here. Common to all georegions is that they are of geographical scale and that they are located in proximity to the surface of the Earth (which is not itself a region but the geographical substantial entity *par excellence*).

Geospatial Regions. The Earth itself is not a geospatial region. Rather, it is a substance and its parts (mountains, cliffs, plateaux are substantials. The planet Earth occupies a geospatial region at any time at which it exists. Geospatial regions are regions of *space* at or in which are located parts of the Earth or of the Earth's atmosphere at or near its surface. We shall use '*earth*' in a designated way, analogous to '*time*', '*space*' and '*spacetime*', to denote this substance.

The surfaces of a substance are boundaries. They are what delineates the substance from the rest of the world. In the terminology of (Smith, 1997; 2002), surfaces are boundary-dependent entities. They and all their parts depend for their existence on the substances they bound. Since the relation between a substance and its (maximal, and therefore unique) surface is functional, we use the function *surface-of* in order to denote a substance's surface.

The entity *surface-of*(*earth*) – a constituent of ontologies which have *earth* as a constituent – is then dependent upon *earth* for its existence. *surface-of*(*earth*) is a SNAP substantial entity, and it has a specific spatial location at any given time. We may now define surface geospatial regions as spatial locations of parts of the surface of the Earth:

(D 44) $\text{SurfaceGeoSpatialRegion}(x) \equiv_{\text{def}} \text{SpatialRegion}(x) \wedge \exists y\ (\text{Part}(y, \textit{surface-of}(\textit{earth}, \omega)) \wedge \text{SpatialLocation}(y, x, \omega))$

Reasoning about Geospatial Regions. There are two important modes of geospatial reasoning:

On the one hand is the sort of three-dimensional spatial reasoning about spatial location that we have discussed in the general context of SNAP ontologies. The apparatus already presented needs however to be extended so as to include the means to define for any substance, be it a planet, an apple, or a human body, its surface, interior, and exterior. In the geographical context, we need in addition the concepts of near-surface-interior and near-surface-exterior. These extensions to our mereotopology call for an extended treatment of geographical scale and will not be considered here.

On the other hand is reasoning about the location of geographical entities with respect to surface geospatial regions. This is the type of reasoning we employ when working with two-dimensional maps. We use the functional relation SurfaceLocation in order to relate a spatial entity to its corresponding surface location. This is in fact a ternary relation between a SNAP entity, a spatial region and a substance acting as a reference body, but we can here leave the third term out of account, since we assume in all geographical contexts that the reference body is the Earth. The surface location of a geographical entity is that portion of the location of the Earth's surface onto which the spatial location of the entity projects along the vertical axis at a given time (an entity is spatially located at, under or above its surface location). An airplane flying over a city is spatially disconnected from the city but its surface location is part of (or overlaps) that of the city it is flying over.

Geotemporal Regions. These are temporal regions (GeoTimeRegion) with a specific relation to the Earth. They are the regions of time during which the Earth exists:

(D 45) $\text{GeoTimeRegion}(x) \equiv_{\text{def}} (\text{TimeRegion}(x) \wedge \forall y\ (\text{TimeSlice}(y, x) \rightarrow \text{ExistsAt}(\textit{earth}, y)))$

Since the Earth is a SNAP entity, it has a life, which is a SPAN entity. The Earth exists at any time at which the process we call its life is occurring and conversely:

(T 46) $\text{ExistsAt}(\textit{earth}, t) \leftrightarrow \text{OccursAt}(\textit{life-of(earth)}, t)$

The geotemporal regions are then precisely the parts of the region of time occupied by the life of the Earth:

(T 47) $\text{GeoTimeRegion}(x) \leftrightarrow (\text{TemporalLocation}(\textit{life-of}(\textit{earth}), y) \wedge \text{Part}(x, y))$

Geospatiotemporal Regions. These are spatiotemporal regions (GeoSpacetimeRegion) with a specific relation to the Earth, namely they are regions of *spacetime* which are parts of the spatiotemporal location of the life of the Earth:

(D 48) $\text{GeoSpacetimeRegion}(x) \equiv_{\text{def}} (\text{SpatiotemporalLocation}(\textit{life-of}(\textit{earth}), y) \wedge (\text{Part}(x, y))$

8.2 Geo-Ontologies

We use the symbols 'GeoΩ', 'SnapGeoΩ', and 'SpanGeoΩ' for the predicates under which geographical ontologies fall. Maps are examples of SNAP geographical ontologies in our sense. A SNAP geographical ontology is an ontology whose constituents are spatially located at a geospatial region. A SPAN geographical ontology is an ontology whose constituents are spatiotemporally located at geospatiotemporal regions. These characterizations yield the following definitions:

(D 49) $\text{Geo}\Omega(\omega) \equiv_{\text{def}} (\Omega(\omega) \wedge (\text{Constituent}(x, \omega) \rightarrow \exists y\, (\text{Constituent}(y, \omega) \wedge (\text{GeoSpatialRegion}(y) \wedge \text{SpatialLocation}(x, y) \vee (\text{GeoSpacetimeRegion}(y) \wedge \text{SpatiotemporalLocation}(x, y))))$

SNAP geographical ontologies are SNAP ontologies:

(D 50) $\text{SnapGeo}\Omega(\omega) \equiv_{\text{def}} (\text{Snap}\Omega(\omega) \wedge \text{Geo}\Omega(\omega))$

So, in particular, constituents of SNAP geographical ontologies are SNAP entities:

(T 51) $(\text{SnapGeo}\Omega(\omega) \wedge \text{Constituent}(x, \omega)) \rightarrow \text{SnapEntity}(x)$

SNAP geographical entities are characterized, *inter alia*, by their having a geospatial and a surface geospatial location and by the fact that they exist at geotemporal regions.

(A 52) $(\text{SnapGeo}(x) \wedge \text{Constituent}(x, \omega)) \rightarrow \exists y\, (\text{GeoSpatialRegion}(y) \wedge \text{SpatialLocation}(x, y, \omega))$

(A 53) $(\text{SnapGeo}(x) \wedge \text{Constituent}(x, \omega)) \rightarrow \exists y\, (\text{SurfaceGeoSpatialRegion}(y) \wedge \text{SurfaceLocation}(x, y, \omega))$

(A 54) $(\text{SnapGeo}(x) \wedge \text{Constituent}(x, \omega)) \rightarrow \exists \omega'\, \exists y\, (\text{Span}\Omega(\omega') \wedge \text{Constituent}(x, \omega') \wedge (\text{GeoTimeRegion}(y) \wedge \text{ExistsAt}(x, y, \omega))$

Similar characterizations hold for SPAN geographical ontologies and entities:

(D 55) $\text{SpanGeo}\Omega(\omega) \equiv_{\text{def}} (\text{Span}\Omega(\omega) \wedge \text{Geo}\Omega(\omega))$

(T 56) $(\text{SpanGeo}\Omega(\omega) \wedge \text{Constituent}(x, \omega)) \rightarrow \text{SpanEntity}(x)$

(A 57) $(\mathrm{SpanGeo}(x) \wedge \mathrm{Constituent}(x, \omega)) \rightarrow \exists y\, (\mathrm{GeoSpacetimeRegion}(y) \wedge \mathrm{SpatiotemporalLocation}(x, y, \omega))$

9 The SNAP Geographical Object Ontology

There are five major subcategories of geographical SNAP entities: features, artifacts, agents, places, and qualities.

Geographical Features. Where the entities of table-top scale one first discovers in everyday encounters with the world are material objects – people, chairs, tools and so on – in the realm of geography they are physical features such as hills, mountains, lakes, and rivers. Such substantial entities are the most salient geographical entities for human subjects (Smith & Mark, 1999). In addition, there is a number of fiat geographical features defined by human geography and various branches of the geographically oriented social sciences (geopolitics, demography, etc.), which include: territories of countries, states, and counties, postal districts, and a wide variety of other fiat objects whose demarcation is due to the activities of human being.

Geographical Artifacts include buildings, roads, bridges, reservoirs, cities, towns, etc. These too are substantial entities.

Geographical Agents. A geographical artifact such as a city has a government. Both the city and its government are SNAP geographical entities. Geopolitical agents are tied to certain geopolitical objects, which are tied in turn to certain geographical sites or places. There are also mobile geographical agents, such as an army on the march or the racing pool of the Tour de France. Mobile agents, like other mobile geographical objects, have the capacity to produce *derived* geographical objects: armies produce front lines; aggregates of viral agents produce quarantine zones.

Geographical Places. Objects take up space, they occupy some position, and they thereby help to carve out sites of various sorts, including those special kinds of *sites* we call places, which are occupied by other sorts of substantial entities in their turn. Places – *inter alia*, the places whose names are listed in gazetteers – are organized into hierarchies of increasing size, from the small portions of territory (a street corner, a field) on which one can stand, to countries and continents one can visit. There are also three-dimensional sites such as mine shafts and volumes of the Earth's crust demarcated when mining rights are assigned to underground resources. The family of places includes also cities and towns conceived as geopolitically demarcated sites or locations which one can inhabit (rather than as mere aggregates of material substances).

Boundaries and Geographical Regions. Boundaries of geographical substantial entities are of two sorts: fiat and bona fide. The former reflect human (for example administrative) decisions; the latter are real physical discontinuities. Often some extended substantial will be taken as an indicator of a boundary (a fence, for example, will indicate the delimitation of a property, a river will participate in the physical delineation of the border between two countries).

Geographical Qualities. Here again 'quality' is used as an abbreviation to comprehend also powers, functions, roles and other kinds of SNAP dependent entities. In the geographical realm we are interested in qualities of geographical substantial entities of geographical scale. These include qualities of features (for example the altitude of a mountain peak) and of agents (an army's morale, a government's level of respect for human rights).

10 The SPAN Geographical Process Ontology

Geographical spatiotemporal regions are the parts of *spacetime* properly included within the spatiotemporal region occupied by the life of the Earth. The basic kinds of SPAN geographical entities are the geographic-scale changes which are spatiotemporally located at these regions and which occur on or near the surface of the Earth. They are in every case changes in SNAP entities. Here we describe some of the most salient kinds of processual entities within the geographic domain.

A primary division is that according to the kind of participants involved in those processes, between: *physical processes* such as erosion, water run-off, forest fires, whose participants are exclusively physical objects; and *social processes* such as demographic changes, epidemics. The latter are processes involving aggregates of human beings. We can distinguish also various families of geographical *actions*, which are processes involving either human beings or institutional agents on a geographical scale. Examples are: army manoeuvres, the passing of a re-zoning ordinance.

10.1 Geographical Changes

The main kinds of changes which occur in geographical contexts are:

Substantial Changes. These are events in which geographic objects are created and destroyed, together with related forms of changes for example of the sort discussed in (Hornsby & Egenhofer, 2000). Substantial changes are always instantaneous (compare the way in which two drops of water become one); clearly however they are often associated with extended processes which proceed or follow them, for example processes of political reorganization.

Locational Changes. Some geographical objects are tied essentially to their locations; this holds especially of geographical features such as canyons and mountains. Other geographical objects move through space – this applies for example to thunderstorms and other weather phenomena – or they may be shifted over time – this applies for example to front lines in a war and to city limits. Such geographical motions are locational changes on a geographical scale.

Other sorts of geographical changes include qualitative, structural and morphological changes: for example a change in temperature across a geographical area. Note that the latter is at another level of granularity a (non-geographical) matter of the movements of molecules. This shows the importance of a more general formal apparatus within which macroscopic geographical phenomena can be related to the microscopic processes by which they are constituted (Bittner & Smith, 2002).

10.2 SPAN Patterns and Secondary Taxonomic Distinctions

In all regions of the Earth there are processes which occur with more or less regularity, defining for example seasonal patterns of weather and other processes. Patterns may be correlated with one another via complex relations of causality and dependence – for example in the way in which ocean currents (patterns of water displacement) are correlated with winds blowing over the surface of the water (patterns of displacement of masses of air). In order to describe such SPAN patterns we have to build a framework for describing the characteristic features of processes. Geographical processes have participants, they occur in places, and they typically amount to changes in the SNAP geographical entities participating more or less actively or passively in them.

We can now distinguish two types of secondary distinctions in the taxonomy of processual entities:

Changes of Intensity or Rate of a Process. These give rise to characteristics such as: accelerating, alternating (e.g. tidal variations), gradual, instantaneous, continuous, discrete, regular, zigzagging, cyclical, seasonal (e.g. monsoons), transitional (e.g. exercise of interim governmental power), transient (e.g. lightning), and so on.

Changes in the Geographical Extent of a Process, for example the increase in prevalence of a disease, expansion of commercial penetration, routing of an army.

11 The SNAP Geographical Fields Ontology

Recent work on the ontology of geography has recognized two distinct perspectives, called the *object* and *field* perspectives, respectively (Peuquet, Smith & Brogaard, 1999; Smith & Mark, 2003). The object-perspective is precisely the SNAP geographical framework presented here. The field-perspective involves apprehending reality in terms of distributions of attributes such as temperature, population density, tree-coverage, etc. over a given spatial location. Reflection shows that this field perspective can be combined also with the SPAN framework, when the substratum of location in relation to which attributes are allocated includes in addition the fourth-dimension of time. It is however primarily SNAP geographical fields which are of importance in the literature. SNAP fields are enduring entities which are located at or defined in terms of geospatial regions with which they coincide spatially. Field attributes are dependent SNAP entities which are associated with given locations within the field at given times.

Here, too, we must distinguish between attributes as *determinables* and attributes as *determinates*. The former are universals such as *temperature* or *elevation*. The latter are specific *values* of such universals such as –30°C or 4810 meters. Values of attributes form scales, sometimes demarcated in terms of real numbers, sometimes in term of other cardinal or ordinal measures. Some attributes, for example soil types, have *qualitative* determinables and determinates.

The SNAP field- and object-perspectives in the geographical domain can be directed towards identical portions of reality. It follows that there are a number of trans-ontological relations between the entities recognized by each, discussed by Broogaard in (Peuquet *et al.*, 1999).

A SNAP field ontology recognizes only geospatial regions (as base field) and attributes (SNAP dependent entities); thus it masks all of those entities in the geographic domain which are recognized by SNAP as substances and their substantial parts. There is no planet Earth visible from the field perspective, nor are there mountains and lakes. There are however fields (or parts of fields) which comprehend any relevant aggregation of features associated with the corresponding objects.

Our theory of SNAP geographic fields can be generalized to apply in other domains. A brain scan is a depiction of a SNAP neurological field.

Relations in SNAP Field Ontologies. Fields are related to their attributes in a way that is analogous the inherence relation between SNAP dependent entities and the substantial entities which are their bearers. Attributes in a field are necessarily bound to a given part of the field, and thus to a given spatial location. We use the relation of *attribution* between an attribute in a field and the corresponding field location, abbreviated in the symbol 'AttributedTo'. The SNAP fields and object perspectives are then linked as follows. Whenever *a* is attributed to *b* in a SNAP field ontology and *b* is located at the position *c*, there is in some SNAP object ontology a substance located at *c* in which *a*′, a proxy of *a*, inheres (*a*′ then depends upon *b* in the same way as *a* depends upon *b*).

(D 58) $\text{AttributedTo}(x, y, \omega) \equiv_{\text{def}} (\text{GeoSnapFieldAttribute}(x) \wedge \text{GeoSnapFieldEntity}(y) \wedge \text{InheresIn}(x, y, \omega))$

(A 59) $\text{AttributedTo}(x, y, \omega) \wedge \text{TemporalIndex}(\omega, t) \rightarrow \exists\omega' \, \exists z \, (\text{Snap}\Omega(\omega') \wedge \text{TemporalIndex}(\omega', t) \wedge \text{InheresIn}(x, z, \omega'))$

There are a number of constraints on attribution. For instance, we may only allocate an attribute which depends on a field at a region which is part of that of the field.

(A 60) $(\text{AttributedTo}(x, y, \omega) \wedge \text{SpatialLocation}(x, x', \omega) \wedge \text{SpatialLocation}(y, y', \omega)) \rightarrow \text{Part}(x', y', \omega)$

12 Ontology of Geodynamics

We have presented the main axes of an ontological framework in terms of which it will be possible to capture in a rigorous way the essentially dynamic nature of geographical reality. The SNAP/SPAN distinction allows us to do justice to both sides of geospatial dynamics by allowing us to focus on processes as occurrent entities – entities which evolve through time but in such a way as to involve substantial entities as agents and targets. Thus we can understand the participation of a stream in an erosion process, the initiation of socioeconomic disasters by heavy rainfalls and floods, the destruction of forested areas by acid rains. We can understand how the bed of a stream can survive identically through an interval of time even while it is subject to a constant process of erosion. We can understand also those features of geographical dynamics which pertain to enduring entities capable of motion and locational change, as when armies move across the landscape or the borders of cities or states are displaced.

Our framework allows us also to formulate relations between different ontologies. It is the relations between the SNAP and SPAN ontologies which have been our focus here. But the framework can be readily extended to the treatment of families of ontologies of other types. It can be applied to the treatment of relations between ontologies of different levels of granularity to the treatment of the relations between the ontologies generated by the object- and field-perspectives. It can be provide a tool also for dealing with the relations between distinct culturally-generated perspectives on the geographical domain, of the sort which are studied by linguists and anthropologists. Standardly, of course, such culturally-generated perspectives have been dealt with in relativistic fashion. The members of each cultural group – as it is sometimes said – 'live in different worlds'. Perhaps the most characteristic features of our framework is that it offers a way out of this relativistic trap. It shows how we can deal with pluralities of ontologies which are distinct yet nonetheless directed towards (because they are ontologies of) one and the same reality.

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