

Foundations for an Ontology of Environment and Habitat

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Abstract. The paper examines the semantics of the terms ‘environment’ and ‘habitat’ and presents a semi-formalised ontological framework in which these concepts are related to the spatial and material structure of the world. Since habitats are essentially associated with lives and behaviour of animals and plants the framework incorporates an abstract model of an organism. This enables the spatial extensions of habitats to be characterised in terms of the possible ‘life trajectories’ of organisms constrained by the physical properties of a geographic region and by the biological requirements for their survival.

Keywords. Environment, Habitat

1. Introduction

The words ‘environment’ and ‘habitat’ are key terms used to describe the world. There is presently an increasing need for us to tackle issues relating to changes in the environment and loss of habitat; but, in order for a computational information system to provide functionality that will help us classify and visualise the world in terms of these concepts, we need a precise model of their semantics. Here we face fundamental problems: What is an environment? What is a habitat?

An extensive ecological literature has developed informal theories for describing and classifying environments and habitats. Such analysis dates back at least to [9] and later [7], who introduced ideas such as the ecological *niche* of an animal, which have played a key role in subsequent theorising [11, 21]. However, as regards the development of formal ontologies, relatively little attention has been given specifically to environment and habitat. A mereological theory of the concept of *niche*, intended to serve as a basic notion in ontologies of ecology and habitat has been developed in [19] and [20]. Their treatment focusses mainly on the expressing topological constraints on a relation $N(x, y)$, read as ‘ x is a niche of (entity) y ’. More general requirements of ecological ontologies were investigated in [8] and [14]. Issues specifically relating to representation of the *niche* concept were further examined in [15] and [16].

Ecological concepts are perceived as being difficult to pin down and geographic ontology development has already encountered huge problems in establishing robust semantic models of seemingly more straightforward concepts [13, 6]. Many of these problems appear to be rooted in deep philosophical problems concerning the meanings of

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geographic and ecological terminology [22, 4]. Despite these difficulties, the EnvO environmental ontology network [1] has recently made some progress in constructing an ontology covering a wide range of environmental concepts, which is primarily intended for supporting annotations for data and samples collected by researchers in the biological, medical and environmental sciences.

As the foundation of our theory, we assume a formal language capable of describing geometrical properties and ‘matter types’ (see Sec. 3.5 below), which could in principle be given a fully formal model-theoretic semantics along the lines of [2]. The more abstract ecological concepts with which we are here concerned could then be axiomatised relative to these spatial and material primitives.² Our aim at this stage of development is not to give a fully axiomatised ontology, but rather to identify the types of entity that should be present in an ontology of ‘environment’ and ‘habitat’ and analyse the relational dependencies between them. Nevertheless, a certain amount of formalism will be presented to illustrate how a more rigorous theory could be constructed.

The structure of the paper is as follows: in the next section we consider some general problems of ambiguity and indeterminism confronting the formalisation of precise ontologies that seek to describe the semantics of natural language terminology. Our aim is to motivate an approach in which a term may be characterised by a combination of a number of distinct though strongly correlated modes of definition. In Section 3 we outline a background theory of space, time and material entities, that will underpin our subsequent analysis. Section 4 examines the nature of geographic regions, giving a semantics in terms of more basic spatial and material concepts. In Section 5 we analyse the term ‘environment’, identifying three different ways in which the concept can be defined and examining the relationships between them. Section 6 discusses the formal treatment of the concept of the *ecological niche* of a species and shows how this can be used to derive the *potential habitat* of the species. Finally, Section 7 is our conclusion.

2. Conceptual Ambiguity and Modes of Definition

In order to develop an ontology, we need to establish interpretations of the key terms that are sufficiently precise that we can, at least approximately, characterise their relationship to the world and to the meanings of other conceptual terms. This will enable us to specify a structure of conceptual relationships and axiomatise semantic constraints on these relationships. To achieve this we often need to disambiguate distinct senses that are conflated by the variegated usages of natural language terminology.

Even where a natural language term seems unambiguous, when we try to pin down its semantics we often find that there are a number of different ways that the term could be defined. A typical example would be the case of an artifactual physical object such as a cup. Some might argue that the concept referred to by the word ‘cup’ is best defined by means of material and geometrical properties, whereas others might say that a satisfactory definition must be formulated in terms of the intended purpose of the artifact. This

²We presume that since they are essentially determined by configurations of matter environmental concepts are definable from spatial and material primitives. However, concepts related to ‘habitat’ are likely to be difficult to define since they depend on biological phenomena, which have an extremely complex dependence on physical properties. Thus it is likely to be expedient to treat certain biological concepts as additional primitives.

phenomenon is discussed in some detail in [3], which introduces the idea that a term can have multiple *modes* of definition.

It should be understood that the notion of distinct modes of definition does not mean simply that there are different ways of defining the same thing. The possibility of giving different but necessarily equivalent definitions applies to all terms even they are completely unambiguous; whereas, with terms affected by mode ambiguity there are alternative definitions that are not strictly equivalent. For instance, in the case of ‘cup’, there could be objects whose material, geometric (and indeed functional) characteristics satisfy any reasonable materialistic definition of ‘cup’, and yet the object was not intended to be used as a cup (it might not even be an artifact).

The question immediately arises as to why a language should employ terms that have multiple distinct meanings. How are they interpreted? And, how are the different senses related? We suggest that the meanings of a term according to different modes of definition are related by being *naturally correlated*. Such correlation occurs because the physical laws of the universe and the particular properties of our world ensure that in ordinary circumstance the different modes of definition characterise concepts that (although logically distinct) are highly interdependent. A particular form of this interdependence, dubbed *exemplar clustering* is discussed in [3]. This refers to the fact that, because of the physical constraints of the world, the examples found in nature that satisfy a given concept definition constitute only a limited sample of the range of logically possible instances of the concept. Moreover, these examples will often share properties that are not necessary consequences of the definition itself. Because of this ‘clustering’ of exemplars it can often turn out that two logically distinct concepts have in reality exactly (or almost exactly) the same set of instances (see [12, part 6]). E.g., we might define the term ‘bicycle’ either as a physical object with certain material and kinematic properties, or alternatively as a type of artifact constructed by intelligent agents for a particular purpose. Because it is highly unlikely that an object with the physical characteristics of a bicycle could occur naturally, without intelligent design and construction, both definitions would apply equally to the same class of real objects. Nevertheless, the two definitions are logically distinct because it is possible, albeit vanishingly unlikely, that an object with the physical form of a bicycle could arise from some freak natural process.³

In the current paper we propose a more general notion, which includes exemplar clustering as a special case. By *natural correlation* we mean any interdependence between defined concepts that arises from those conditions of reality that are predominant in the actual world, although they are not strictly logically or physically necessary. For this to occur, the concepts need not have the same instances, but the instances of one concept must determine or partially determine the instances of the other and vice versa.

Returning to the questions about how and why multiple modes should arise in natural language semantics, we can explain this as follows. In the case of clustering of exemplars, we see that, for nearly all practical purposes, the instances to which a term can be applied are the same irrespective of the mode of definition that is adopted. Hence it is not surprising that the same term is used to cover the different modes. With respect to language learning and interpretation it is almost impossible to distinguish the alternative meanings since these processes are conditioned primarily by reference to actual examples rather than abstract definitions.

³In the terminology of [3], a bicycle-like object of this kind is called an *artifable* as opposed to an artifact.

Regarding the more general case of natural correlation, where one aspect of reality is interdependent with another, information about one aspect will imply information about another. Hence, when a term is used to refer to one aspect, a person interpreting the term is likely to think of the other correlated aspects. Since the term evokes consideration of several aspects, it is not surprising that they all become part of its meaning, albeit an ambiguous meaning that moves between different senses. (E.g. a political party may be identified either as a set of doctrines, an institutional organisation or a group of people.)

3. Background Theories

Despite their subtlety, it is clear that concepts of environment and habitat are interpreted in relation to properties of the physical world. Hence, any satisfactory ontology explaining the meanings of these terms will also make reference to concepts of space, time, matter and physical objects. The ontology presented here assumes a background theory that is largely the same as that proposed in [2], although somewhat simplified. However, it should be possible to adapt the central parts of our formalisation that deal with environment and habitat to work with other ontologies of space and matter. In the rest of this section we give a concise overview of the main elements of our background theory.

3.1. Space

We take a classical Cartesian view of space, modelling it as a set of points $S = \{\dots, p_i, \dots\}$, over which a primitive function $d(p_1, p_2)$ gives the Euclidean distance between points p_1 and p_2 . We also assume that the standard topological notions of open and closed sets and of regularity are defined in the usual way. We assume that space is characterised by a reference frame that is fixed in relation to the Earth. Thus for the purpose of this paper we ignore the Earth's rotation and its motion in space.

The predication $\text{Reg}(r)$ asserts that r is a (*purely*) *spatial region* — a part of the universe considered only in terms of its spatial extent and geometrical properties. We shall also refer to lines, surfaces and volumes. These can be considered as subsets of the domain of spatial regions. For convenience, we introduce a function $\text{surf}(r)$ which maps any regular 3-dimensional region to its surface.⁴ We envisage that a mereo-topological language such as that of [18], would be used to specify qualitative relationships between spatial regions. Since such theories are now well-known, we do not go into details here.

3.2. Time and Spatio-Temporal Regions

We model time as an ordered set of points. No particular assumptions are made about the nature of this set and its ordering, although we have in mind a continuous linear ordering. A *convex temporal interval* is the closed set of all time points between and including a beginning and an ending time point.

We shall also sometimes want to refer to spatio-temporal regions. Such a region can be modelled as a set of pairs $\langle p, t \rangle$ consisting of a spatial and a temporal point, meaning

⁴ surf is a partial function over the domain of regions. We note that while notationally convenient, partial functions can be tricky to handle in a formal system and would probably be best avoided in a fully formal extension of the framework presented here.

that the spatial point is within the region at time t . We allow that the `surf` function be applied to a spatio-temporal volume to yield a spatio-temporal surface.

3.3. Physical Regions

A *physical region* is a part of the universe considered both as spatially extended and as possessing material and dynamic characteristics. We assume there is a 1-to-1 correspondence between spatial and physical regions and to formalise this relationship we introduce two functions `phys(r)`, mapping spatial region r to a physical region and `ext(ρ)`, mapping physical region ρ to its purely spatial extension.

Although we allow physical regions of any dimensionality (even irregular regions of mixed dimension), we will typically be interested in 3-dimensional physical volumes and 2-dimensional orientable physical surfaces. A physical surface is manifest in the physical entities (chemical molecules, photons) and forces (gravity, electro-magnetism) that impinge upon or cross the surface. For present purposes, we will not need to construct explicit models capturing all the details of physical surfaces, but we suggest that they might be modelled by means of vector fields. We write `surf(ρ)` to denote the physical surface enclosing a regular physical volume ρ (i.e. `surf(x)` is a spatial surface if x is a spatial volume but a physical surface when x is a physical volume).

oriented physical surfaces, are physical surfaces considered as viewed from one particular side. By orienting a surface we can describe properties such as the direction of heat flow across a surface. We may model an oriented surface as a pair consisting of a surface and a triple of three points on the surface given in clockwise order.

We also include spatio-temporal physical regions, which are just temporally indexed versions of ordinary physical regions.

3.4. Individual Physical Objects

We use the term *individual* to refer to an object that persists in time in accordance with certain identity criteria [10]. This means that spatial and physical extensions of an individual depend on a time parameter. We represent these extensions using the functions `ext(i, t)` and `phys(i, t)`. The *trajectory* `traj(i)` of an individual i is a spatio-temporal volume, whose spatial extension varies continuously (in the topological sense) over time and is self-connected at each moment in time. Also, its spatial extension is non-empty at every time point within a durative convex temporal interval `span(i)`, and is empty at every other time point. The physical region `phys(traj(i))` will be abbreviated as `life(i)`.

3.5. Matter Types

A distinctive feature of the proposed ontology is that, following [2], we place emphasis on the ontological category of *matter type*. These correspond to the referents of natural language *mass nouns* (e.g. ‘water’, ‘wood’, ‘grass’), which differ from *count nouns* (aka common nouns) in respect of their individuation criteria. A count noun refers to a set of individual objects and not to any proper sub-parts of these individuals; whereas a mass noun refers to a continuous expanse of stuff and to any portion of that stuff. A coarse classification of physical matter is given by dividing it into three general matter types: **solid**, **liquid** and **gas**. For present purposes we shall not go much beyond this, although a fully fledged environmental ontology would clearly require a detailed classification.

We assume that matter types form a lattice structure so that for every pair there is a union $\mathbf{m}_1 \sqcup \mathbf{m}_2$, which refers to the sum of matter of either type (e.g. **fluid** = **liquid** \sqcup **gas**, and an intersection $\mathbf{m}_1 \sqcap \mathbf{m}_2$ (e.g. **liquid** \sqcap **metal**), which refers to matter that manifests the characteristics of both matter types. In the latter case where the characteristics of \mathbf{m}_1 and \mathbf{m}_2 are not found together in any portion of matter, $\mathbf{m}_1 \sqcap \mathbf{m}_2$ will refer to the empty (or non-existent) matter type \mathbf{m}_\perp .

We adopt Quine's suggestion for the semantics of mass nouns, which is that they function similarly to proper nouns, in that they refer to a unique individual [17]. This individual is manifested by that part of the physical universe consisting of the sum of all regions exhibiting particular (typically physical) characteristics associated with the meaning of the mass noun.⁵ Under this analysis, the denotation of the mass term 'water' would be the physical totality of all water in the universe. This semantics means that mass noun symbols are subject to the same semantic functions as individual constants, so we can refer to $\text{ext}(\mathbf{m}, t)$, $\text{phys}(\mathbf{m}, t)$ and $\text{traj}(\mathbf{m})$.

As well as giving a plausible (or at least seemingly consistent) account of the semantics of typical mass nouns referring to types of physical substance (such as water, sand, wood etc.), the Quinean approach also seems to be well suited to apply to environmentally related mass-noun-like terms such as 'rainforest'. Thus, this term would refer to the totality consisting of all physical regions occupied by rainforest.

In fact we shall use the word *totality* in a technical sense. Let $\phi(r)$ be a property of regions — i.e. a formula with a free region variable r . Then the term $\text{totality}_r[\phi(r)]$ denotes the largest region r^* satisfying $\phi(r^*)$. More precisely:

$$(r^* = \text{totality}_r[\phi(r)]) \equiv_{\text{def}} (\phi(r^*) \wedge \forall r'[(\phi(r') \wedge \text{Part}(r^*, r')) \rightarrow r^* = r'])$$

The subscript r in the operator totality_r is used to indicate the variable in $\phi(r)$ relative to which the totality is derived. This is needed in case $\phi(r)$ contains additional variables other than r . This notation does not take us beyond first-order logic, since the definiens is a standard first-order formula.

4. Geographic Regions and their Properties

In this section we define a certain kind of geometric entity that will be taken to correspond to 'geographic regions'. Thus, according to our semantics, any term referring to a geographic region will have such an entity as its denotation. It should be noted that the particular formalism presented here is by no means the only possibility, and may not be the best. But it does demonstrate how complex geographic entities and properties can be defined using set theory and geometry from a relatively limited base of primitives.

Informally, one might define a geographic region to be a part of the Earth's surface, perhaps satisfying some further conditions. However, since the Earth is in many places covered by water or other non-rigid substances such as mud or sand, there is some indeterminism as to what actually counts as its surface. Further ambiguity arises due to the presence of overhangs and cavities. Yet another complication is that, in many contexts, a geographic region is not treated as a mathematical surface of zero thickness but more like a 3-dimensional volume that can contain material objects such as trees or buildings.

⁵This semantics is adopted primarily for technical simplicity.

4.1. Interpretation of Geographic Regions

Because of the ambiguities just noted, we define a precise class of entities, which will constitute the domain geographic regions in our formal semantics. We call these entities *geo-reg*s, and write $\text{GeoReg}(\rho)$ to assert that ρ is an entity of this kind.

Geo-scientists often describe regions on the Earth in terms of their coordinates relative to a *reference ellipsoid*, a mathematical idealisation of the surface of the planet.⁶ In our ontology we take the surface of the Earth's reference ellipsoid as a primitive entity, denoted by 'res'. We write cres to refer to the point at the centre of res . We can use res to define identity criteria for geographic regions. First we introduce a primitive function $\text{resProj}(\rho)$, mapping each geo-reg to a regular closed subsurface of res . Intuitively $\text{resProj}(\rho)$ consists of all those points on res that lie above or below or are coincident with some point that is considered to be within the physical region ρ , along a line passing through the centre of the reference ellipsoid.

A necessary and sufficient identity criterion for geo-regs is that two geo-regs are identical if and only if they have the same projection onto the reference ellipsoid:

$$\forall \rho \rho' [\text{GeoReg}(\rho) \rightarrow ((\rho = \rho') \leftrightarrow \text{resProj}(\rho) = \text{resProj}(\rho'))]$$

Whereas $\text{resProj}(\rho)$ is a purely spatial region, geographic regions are more naturally thought of as being a kind of physical region. But given the difficulty, mentioned above, of identifying what should count as the Earth's surface, it is not obvious what should be considered as the spatial extension of a geo-reg. In fact, this is not really a substantive issue: since geo-regs are already a technical construct, we can make any reasonable stipulation, as long as it fits in with the rest of our ontology. For definiteness, we make the following stipulation, which, although somewhat arbitrary, is fairly easy to work with: the purely spatial extension $\text{ext}(\rho)$ of a geo-reg ρ is a regular closed subset of space including all those points that are less than 10,000 km from cres and lie on any half-line originating at cres and passing through any point of $\text{resProj}(\rho)$. The physical region ρ itself is then given by $\rho = \text{phys}(\text{ext}(\rho))$. The constant maxGeoReg will be used to denote the 10,000 km radius ball of physical space that is centred at the centre of the Earth (this is the maximal geo-reg entity).⁷

Clearly, those points of a geo-reg that lie within the Earth's core or way off in the exosphere are not relevant to most descriptions of geographic regions. However, including them in the formal denotation of a geo-reg will not cause any harm, since, whenever we want to represent anything specific about a geographic region, we can employ functional operators that map geo-reg entities to other more limited kinds of physical region. Some of these will be explored in the following subsections.

4.2. Geographic Surfaces

We shall often want to refer to certain types of surface that occur within the extension of a geo-reg. Surfaces of interest can often be described in terms of the vertical ordering of matter types within a geo-reg. Hence we define:

⁶Several different reference ellipsoids have been proposed. We assume that some standard has been adopted.

⁷The particular shape and size of maxGeoReg do not matter as long as it definitely includes any point that is incident with any of Earth's geographic regions and excludes points incident with any other celestial body.

- $\text{GeoAbove}(p_1, p_2) \equiv_{\text{def}} (\text{d}(p_1, \text{cres}) > \text{d}(p_2, \text{cres}))$
- $\text{GeoBelow}(p_1, p_2) \equiv_{\text{def}} (\text{d}(p_1, \text{cres}) < \text{d}(p_2, \text{cres}))$

We can now define the *global upper surface* of a given matter type \mathbf{m} to be the surface of those points furthest from the centre of the Earth that have points of matter type \mathbf{m} immediately below them:

$$\begin{aligned} \text{globalUpperSurface}(\mathbf{m}) &=_{\text{def}} \\ \{p \mid p \in \text{ext}(\text{maxGeoReg}) \wedge \forall q[\text{GeoAbove}(q, p) \rightarrow \neg(q \in \mathbf{m})] \wedge \\ &\quad \exists p'[\text{GeoBelow}(p', p) \wedge \forall q[\text{GeoAbove}(q, p') \wedge \text{GeoBelow}(q, p) \rightarrow (q \in \mathbf{m})]]\} \end{aligned}$$

Thus, $\text{globalUpperSurface}(\text{solid})$ denotes the upper surface of the solid mater of the Earth, while $\text{globalUpperSurface}(\text{solid} \sqcup \text{liquid})$ refers to what we might call the cartographic surface of the Earth, which incorporates the surfaces of both water bodies and (non-submerged) land-forms. We define:

$$\text{cartSurf} =_{\text{def}} \text{globalUpperSurface}(\text{solid} \sqcup \text{liquid})$$

The cartographic surface of a given geographic region ρ is then simply given by $\text{cartSurf}(\rho) = \rho \cap \text{cartSurf}$.

From any geographic surface s we can derive the geo-reg within which it is situated. The term $\text{geoReg}(s)$ denotes the minimal geo-reg that contains all points of s .

We will often be interested in the properties of the cartographic surface, such as the distinction between land surface and water surface. Rather than defining these directly, it will be useful to define the concept of the *exposed surface* of a matter type \mathbf{m} . This is that part of the upper surface of \mathbf{m} , such that all points above it are within the **gas** matter type (i.e. it is the upper surface separating \mathbf{m} from the Earth's atmosphere):

$$\begin{aligned} \text{exposedSurface}(\mathbf{m}) &=_{\text{def}} \{p \mid p \in \text{globalUpperSurface}(\mathbf{m}) \wedge \\ &\quad \forall p'[\text{GeoAbove}(p', p) \rightarrow (p' \in \text{gas})]\} \end{aligned}$$

It is then simple to define:

- $\text{landSurface} =_{\text{def}} \text{exposedSurface}(\text{solid})$
- $\text{waterSurface} =_{\text{def}} \text{exposedSurface}(\text{water})$
- $\text{landReg} =_{\text{def}} \text{geoReg}(\text{landSurface})$
- $\text{waterReg} =_{\text{def}} \text{geoReg}(\text{waterSurface})$

4.3. Deriving Regions from Surface Point Properties

One method of defining geographic regions is to identify those regions such that all points on their cartographic surface satisfy some particular property. For example, we might want to identify hot regions by specifying a minimum temperature for their surface points. To this end we define the operation $\text{RSSPP}_p[\rho, \phi(p)]$, to be read as ‘region ρ satisfies surface point property ϕ ’:

$$\text{RSSPP}_p[\rho, \phi(p)] \equiv_{\text{def}} \forall p[(p \in \text{cartSurf}(\rho)) \rightarrow \phi(p)]$$

We can also define the *totality* (i.e. the largest region) satisfying a surface point property ϕ by:

$$\text{tsspp}_p(\phi(p)) =_{\text{def}} \text{totality}_\rho[\text{RSSPP}_p(\rho, \phi(p))]$$

5. Environment

As the reader may have inferred from the discussion in Section 2, our view is that the terms ‘environment’ and ‘habitat’ are significantly affected by mode ambiguity. Hence, rather than try to give a single definition characterising the semantics of ‘environment’ we begin by identifying aspects of environment corresponding to different modes of identification. We shall then look into the natural correlations between these modes, which will give a more comprehensive picture of the meaning of the natural language term ‘environment’. We begin with three aspects that we consider to be of primary significance:

- Immediate Environment: the factors that affect a particular *subject* by directly impacting the subject’s outer surface,
- Affective Environment: collection of objects and/or quantities of substance identified relative to a given *subject*, such that these objects each contribute to and jointly determine the immediate environment of the subject,
- Local Environment: the physical region proximal to the subject (this is vague as the degree of proximity is unspecified — the local environment of an organism could be related to the range over which it can move during one day),
- Global Environment: a physical totality characterised in terms of physical characteristics that determine a range of immediate environments that are possible within the region of that totality.

The informal definitions of *immediate* and *affective* environment refer to a *subject* relative to which the environment is determined. The subject would typically be a living organism. However, we allow that the subject might also be an inanimate object. Fig 1 illustrates the distinctions we are making. The diagram shows a lizard situated in a rocky desert environment. Various elements of its affective environment are shown (the sun, the local atmosphere, gravity and the rock on which it is standing). These elements together determine the lizard’s immediate environment, which is the inward oriented physical surface within which the creature is enclosed.

5.1. Immediate Environment

The concept of an organism’s *immediate environment* plays a key role in our analysis. We define the immediate environment of an organism to be the *inward oriented physical surface* that encloses the organism. Across this surface come a variety of physical entities/stimuli: chemicals, photons, forces etc. Clearly these will have an effect on the organism, and different species of organism will be adapted to functioning in different kinds of environment. We can consider the immediate environment of an organism either at a single point in time, or over some period (up to its whole life). Hence, our ontology contains two types of entities corresponding to *instantaneous immediate environments* and *temporally extended immediate environments*.

For obvious reasons we do not normally describe the environment of an organism in terms of a surface of impacting forces/chemicals. This would be too detailed and

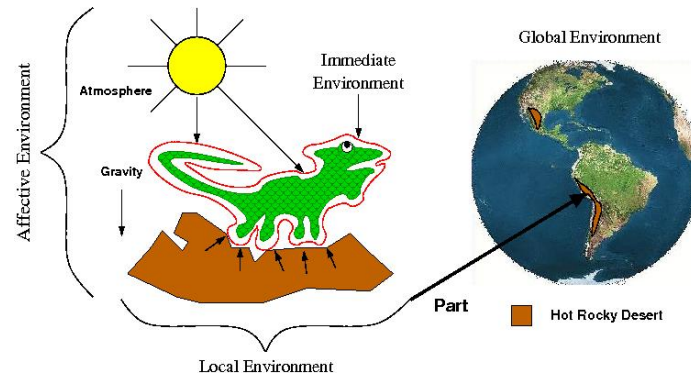


Figure 1. Four Modes of Environment: Immediate, Affective, Local, Global.

complicated to be practical. Instead descriptions of environment usually rely on the fact that the immediate environment is largely determined by objects and forces in the vicinity of the subject and by average properties that hold in the region where it is located.

5.2. *Affective Environment*

In describing a subject's environment, we typically look beyond the animal's skin to the terrain, vegetation, weather conditions etc. in which it lives. These factors will determine typical or average properties (or ranges of variation) of its immediate environment.

The affective environment of a subject consists of a collection of entities and quantities of material which affect the subject in some way. These entities can be of a variety of forms, including forces and fluid media as well as physical objects and their surfaces. Some of the main categories of affecting entities are the following:

- the atmosphere or fluid in which the subject exists,
- the sun,
- objects and matter constituting the surface upon which the subject resides,
- objects and their surfaces contributing to the visual perception of the subject,
- gravitational force (or material objects contributing to gravity local to the subject).

Our current model of affective environments is rudimentary. We suggest that an affective environment may be characterised by an *effect function*, which specifies the degrees to which each object in the universe has some effect on the subject's immediate environment. Each of the modes of affectation listed above would involve particular laws by which properties of the affecting objects govern the way that they will affect the immediate environment of any subject in their vicinity.

5.3. *Local Environment*

Intuitively, the local environment of a subject is a physical region within which the subject is located. But how large should this region be? One idea is that it should be large enough to include all those objects that have some affect on the subject. But if we were to include all effects (such as gravity) this would take in the whole universe. To counter this, one might propose to include only the region comprising objects that have a suffi-

ciently strong effect on the subject, but then ‘local environment’ would be a somewhat redundant concept as it would be completely determined by the affective environment.

Our suggestion is that, the local environment is indeed closely related to the affective environment, but also involves a distinction between local and non-local effects. Since, gravity acts approximately uniformly over the Earth’s surface it is not considered as contributing to the local environment. The sun and atmosphere would be discounted for similar reasons. Since the criteria for identifying a local environment are unclear, it may be that this concept should be further dissected into more precise modes. However, for present purposes the main thing that we require is that a local environment is a physical region that is proximal to the subject. For instance we could just take it to be a geographic region whose surface is a disc of some fixed radius (say 100m) centred on the subject.

5.4. Global Environment

According to the immediate, affective and local approaches to characterising environment, the notion of environment is associated with a subject (usually an organism) upon which the environment acts. Nevertheless, there are many contexts in which it is common to use the term ‘environment’ without specifically indicating any particular subject. Thus, we might describe the Sahara desert as a harsh environment without mentioning a particular organism or species that is to be found there. In fact we can describe an environment even where there are no organisms present: “The surface of Venus is an extremely harsh environment, which is incompatible with life (as we know it).”

For many purposes the subject need not be specified, since within a geographic region that is uniform in relevant characteristics, all organisms will tend to experience similar immediate environments. Of course this will depend to some extent on the particular behaviour of the organisms. Moreover, this observation also begs the question as to what characteristics are ‘environmentally relevant’. But given that we have a more or less precise definition of *immediate environment*, we can characterise environmentally relevant characteristics as those properties of a geographic region that impose constraints on the possible immediate environments that can be experienced within that region. Typical characteristics of this kind would be the average temperature or humidity of a region.

We propose to represent global environments as special kinds of matter type (albeit ones that can refer to rather heterogeneous portions of matter). Hence, in its global sense, a term such as ‘rainforest’ will be treated as of the same logical type as ‘wood’. So, under this analysis the semantics of “This area is rainforest” would be analogous to “This chair is wood”. As was explained in Section 3.5, we model matter types as individual constants referring to the physical region that includes the totality of regions satisfying given conditions. For example, the term ‘desert’ might be defined as a region satisfying conditions regarding its temperature and precipitation. Since these conditions related to measurements made at surface points of a putative desert region, we can employ the $\text{tsspp}_p[\phi(p)]$ function, introduced above, to provide a concise definition:

$$\text{desert} = \text{tsspp}_p[(\text{avTemp}(p) > 15^\circ C) \wedge (\text{avPrecip}(p) < 20\text{mm per month})]$$

Since ‘desert’ is a vague term, there are no standardly agreed thresholds for the levels of temperature and precipitation that constitute desert. Such, vagueness is intrinsic to many environmental terms. Addressing this issue is beyond the scope of the current paper, but the *standpoint semantics* approach proposed in [5] might be used.

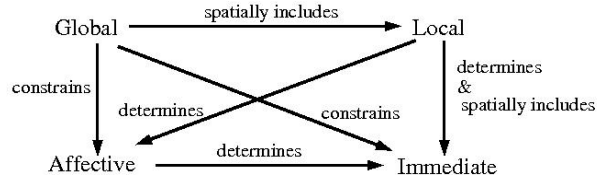


Figure 2. Interactions between the four modes.

5.5. Interaction Between Different Modes

The modes of identification for environments are highly interconnected because of exemplar clustering and other forms of natural correlation. Interaction among modes is illustrated in Figure 2. The conditions that define a global environment induce restrictions on what kinds of affective environment can satisfy those conditions and hence indirectly constrain the immediate environment. The spatial extension of the global environment includes the local environment. The affective environment fully determines the immediate environment (but not vice versa). The local environment also fully determines both the affective and immediate environments, because if we are given a specific physical region of the world centred on the subject, we can determine conditions at that location.

6. Species, Niches and Habitats

Whereas the concept of environment can be used without reference to any particular life form, it is apparent that the term ‘habitat’ is typically used to refer to aspects of the world that are intimately related to living things. Hence, before attempting to explain the semantics of habitat we first examine the nature of species and organisms, focusing especially on characteristics that govern their interaction with environmental conditions.

The most established approach is *Niche Theory* [11, 21], where the niche of a species is modelled as a hyper-volume in a space of environmental parameters. This represents the space of possible conditions under which a species can survive (or thrive). The parameters used to characterise a niche may include complex factors such as predation and temporal behaviour patterns. However, many significant parameters relate to environmental properties that can be represented in terms of an acceptable range of some physical measurement (e.g. temperature). Within our framework, a niche described in terms of such parameters can be represented as a conjunction of predicates, which (leaving aside certain granularity issues) can be evaluated at each point of a geographic region.

6.1. Formal Specification of ‘Potential Habitat’

Suppose the environmental niche constraints for species s are specified by a geographic point predicate $\text{Niche_pred}_s(p)$ (and we ignore other factors such as predation), then, using our definition from section 4.3, the geographic region that the species could potentially inhabit will be given by

$$\text{potential_habitat}(s) = \text{tsspp}_p(\text{Niche_pred}_s(p)).$$

We can regard this as a possible way to formally stipulate the *habitat* of species s . According to this mode of specification, a habitat is a type of *global environment*

(in the sense of 5.4), where the defining predicate is derived from the niche parameter constraints of the species. However, it must be realised that ‘habitat’ is deeply affected by mode ambiguity (as discussed in section 2 above). Hence, this is one among several naturally correlated, but logically distinct ways of defining habitat.

6.2. Modes of Habitat

The term ‘habitat’ appears to be subject to even more mode ambiguities than ‘environment’. The conditions under which an individual organism lives or could live are naturally correlated with the average conditions to which a species is adapted. Hence, there is a mode ambiguity between an organism focused interpretation and an interpretation in relation to a species. There is also a deep ambiguity as to whether the concept of habitat relates to the the location of actual, typical, or possible life trajectories.

We identify the following principal mode ambiguities in the meaning of ‘habitat’:

- ‘Habitat’ may be interpreted either as a kind of *global environment* (as per the formal specification given above), or in terms of an organism’s *affective environment* (i.e. a collection of objects which have some effect on the organism). (It seems less natural to conceive of a habitat in terms of a local or immediate environment).
- ‘Habitat’ may be applied to an individual organism or to a species. (It is also possible that one considers an individual in relation to the habitat of its species — e.g. ‘This caged polar-bear is not in its natural habitat’.)
- ‘Habitat’ may refer to the actual environment where an individual or species occurs (its geographic range), or to environments that are typical of a species, or to possible environments that are survivable by an organism/species (potential habitat), or perhaps to environments in which an organism/species is likely to thrive.

As yet, we have only formalised one sense of ‘habitat’ by the predicate `potential_habitat(s)`. But we believe that the primitives and structures identified in our examination of geographic regions, environments and organisms provide a good basis for an constructing ontology within which the other modes could be defined explicitly.

7. Conclusion

In this preliminary investigation we have applied a particular approach to elucidating the meanings of the terms ‘environment’ and ‘habitat’. We have picked apart a range of possible interpretations and examined the relationships that tie these together. Although many details have been glossed over, we believe that the framework provides a useful starting point for a more comprehensive treatment and for the development of a fully formal ontology. As well as contributing to understanding the specific problems that arise in the environmental domain, we believe that the approach is more generally applicable to semantic analysis across a wide range of domains.

Among the many directions in which this work could be extended, the following seem to be particularly important: a) development of a theory of granularity that takes into account the scale-dependent aspects of concepts relating to environment; b) modelling of the phenomenon of vagueness which is pervasive in the meanings of geographic and environmental concepts; c) more detailed consideration of temporal aspects of environment and habitat; d) elaboration of how one can use models of the characteristics of organisms and species in order to derive information about their habitats.

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Appendix

This section has been removed from the paper because of the limited space available.

A More General Model of Organisms and Habitats

Although the model of habitat in terms of niche constraints is a powerful theoretical tool, it does have some limitations. Although we have presented a relatively simple way to derive potential habitat from niche constraints, this only works under the assumption that the niche can be defined purely by means of predicates that apply to geographic regions. Such a model fails to take account of the cumulative effects upon organisms that move through a variety of environmental conditions. For example, an animal might be able to survive in particularly harsh conditions for certain periods, as long as it has intervals where it can recuperate in more favourable circumstances. In this section we sketch a more elaborate model of organisms and their interaction with the environment, which could form the basis of a much more detailed and flexible way of formalising concepts relating to habitat.

Being a variety of physical individual, living organisms are related to spatial and physical regions *via* the primitive functions specified in Section 3.4. In particular $\text{life}(o)$ denotes the physical spatio-temporal volume occupied by organism o over its lifetime. This enables one to refer to the immediate environment of the organism at any given time point during its lifespan.

We identify the following characteristics of an organism that are relevant to how they function and respond to their environment:

- Internal State Parameters — these describe the intrinsic physical condition of the organism.
- Metabolism — organism's *metabolism* can be modelled by a function mapping its environment inputs into outputs.
- Shielding — the capability to block or reflect environmental inputs.
- Tolerance — the range of values internal compatible with the functioning and survival of the organism.
- Mobility — movement capability of the organism.

In order to remain in a stable state (which is normally required for survival) an organism must keep its internal properties more or less constant. Hence, for each transitory factor it must either maintain direct equilibrium, or transform some input into a cancelling output.

Given a possible spatio-temporal trajectory of an organism, we can work out what would be the affect of traversing that trajectory on the internal state parameters of the organism. If the values of these parameters vary outside the tolerance of the organism then it will suffer ill health or death. Trajectories over which the organism survives can be regarded as *possible lives* of the organism.

The characteristics of metabolism, tolerance and mobility, determine for each organism and physical region, the set of life trajectories that the organism could possibly act out within that region, in virtue of the survivability of those trajectories. However, there is a forth, less concrete, factor that affects the probability that different life trajec-

tories are adopted. This is what may be called its *behaviour pattern*. In fact it is more reasonable to attribute a behaviour pattern to a species rather than an individual, since the pattern is manifest in a distribution of possible lives. We suggest that the behaviour pattern of a species can be modelled as mapping from geographic regions to probability distribution of all possible lives that individuals of that species could lead within that region. Moreover, by using this approach, we believe that the potential habitat of a species can be modelled much more accurately than would be possible using the simpler parameter-based niche approach.

A. Take-Outs

B. Structural Overview of the Ontology

Our analysis has identified a rather large diversity of different kinds of entity that are relevant to the semantics of environment and habitat. In this section we present a systematic classification of these entity types and of the functions and relations that link these different types.

B.1. Semantic categories

B.1.1. Entity Types

- purely spatial entity
 - * point, line, surface, 3D volume
- purely temporal entity
 - * time point
 - * temporal interval
- physical entity:
 - * instantaneous (SNAP) physical entity
 - * 3D physical volume
 - * $2\frac{1}{2}$ D geographic surface
 - * 2D physical surface
 - instantaneous immediate environment
 - * spatio-temporal physical entity:
 - * temporally extended (SPAN) physical volume (individual)
 - (history of) inanimate object
 - (history of) geographic feature
 - (history of) region type totality:
 - environment type totality
 - (life of) organism
 - * temporally extended physical surface
 - temporally extended immediate environment

B.1.2. Classifier Types

Classifier types identify classes of entities. Or more specifically, at any given time point each classifier refers to the set of entities satisfying certain conditions.

[10]

- Physical object classifier
 - * Geographic Feature classifier
- Spatial Region Classifier
 - * Scale Classifier
 - * Shape Classifier
- Physical Region Classifier
 - * Geographic Region Classifier
 - * Biotic Physical Region Classifier (EcoReg)
 - * Macro Biome (Global Scale EcoReg)
 - * Meso Biome (Local Scale EcoReg)
- Species (organism classifier)

B.1.3. Property Types

- Purely spatial/geometric characteristics
- Organism Characteristic
 - * Individual Characteristic
 - * Skin Barrier — capability to block environmental inputs
 - * Metabolism — ability to convert environmental inputs to outputs
 - * Tolerance — range of survivable internal state parameters
 - * Mobility — determines possible motion trajectories within any given physical region
 - * Species Characteristic
 - * Average Metabolism, Average Tolerance, Average Mobility
 - * Behaviour Pattern — a mapping from physical regions to possible lives

B.2. Syntactic Categories

- count noun
 - * Geographic Feature Type
 - * Species
- mass noun
 - * Environment Type
 - * Habitat Type
- proper noun — a name referring to a particular individual (each individual is an example of a count noun — in fact of many count nouns).

- Quality Predicate
 - * Qualities of Organisms
 - * Qualities of Spatial Regions (geometry)
 - * Qualities of Physical Regions
 - * Qualities of Instantaneous Immediate Environments
 - * Qualities of Temporally Extended Immediate Environments
 - * Max of

B.3. Functions and Relations

Functional Relationships:

- $\text{imEnv}(o) : O \rightarrow TEIE$ denotes the temporally extended immediate environment of individual object o .
- $\text{imEnv}(o, t) : O \times T \rightarrow IE$ denotes the immediate environment individual object o at time t ;
- $\text{imEnvSet}(\pi, \rho)$ — The combination of a behaviour pattern π and a physical region ρ determines a set of possible immediate environments;
- $\text{bp}(s) : S \rightarrow \Pi$ — the behaviour pattern of species s ;
- $\text{range}(\pi, \rho)$ — The spatial range of any species with behaviour pattern π within physical region ρ .

Non-Functional Relations:

- the relation of the particular immediate environment of an individual object (which may be a living organism) to an environment type or habitat type. (This boils down to a spatial inclusion of the immediate environment in the extension of the environment type.)
- a physical region provides for many immediate environments — these are the ways in which the 4D life object of entities could be hosted
- $\text{Part}(x, y)$

B.4. Type and Token

If we examine the usage of terms used to refer to habitats or environments, we find two distinct modes in which they are employed. For example, let us consider the term ‘rainforest’.

Here rainforest seems to be a class of particular regions. “Region X of the Amazon is a rainforest.”

“Rainforest is an Environment.”

“Rainforest is humid.”

“Rainforest is a humid environment”

Here ‘rainforest’ occurs as an (abstract) individual — a member of the class of environments.

B.4.1. Multi-Level Set Theoretic Approach

spatial individuals: purely spatial regions (anchored to the geoid)

(geographic) individuals: particular geographic regions

environment types: sets of geographic regions

The term environment: set of environment types/ set of individual environments