

The Niche

BARRY SMITH
SUNY, Buffalo

ACHILLE C. VARZI
Columbia University

Abstract

The concept of niche (setting, context, habitat, environment) has been little studied by ontologists, in spite of its wide application in a variety of disciplines from evolutionary biology to economics. What follows is a first formal theory of this concept, a theory of the relations between objects and their niches. The theory builds upon existing work on mereology, topology, and the theory of spatial location as tools of formal ontology. It is illustrated above all by means of simple biological examples, but the concept of niche should be understood as being, like concepts such as part, boundary, and location, a structural concept that is applicable in principle to a wide range of different domains.

1. Introduction

In his *Axiomatic Method in Biology* of 1937, J. H. Woodger seeks to apply the tools of mereology, or the formal theory of part and whole, to the field of biology. More precisely, Woodger seeks to give exact formal specifications of such biological notions as gamete, zygote, allele, and so on, and to utilize these formal specifications in order to illustrate how, on his view, a scientific theory should be constructed. Woodger's project is significant because it represents a detailed attempt to apply mereology in the extramathematical sphere.¹ Unfortunately, however, Woodger's actual theory is of little interest. Its formalizations rest on a version of genetic theory that is long since outdated; they involve a confusion between formal notions (such as *part*) and material notions (such as *cell*), all of which are listed by Woodger among the ten 'biological primitives' of his theory; and the theory brings little in the way of conceptual clarification.

What follows is an attempt to take up once again the project of applying mereology in the extramathematical sphere, but with strict adherence to the idea of mereology as a formal theory. We see mereology, more precisely, as a formal or domain-independent ontology along the lines sketched by Husserl in his *Logical Investigations*²—a theory of certain formal structures (namely: structures of part and whole) which are realized or exemplified across a wide range of material domains. The tools of formal ontology will be applied not, as in Woodger's case, to mimic individual special sciences in specific stages of their development. Rather, they will be applied to the task of clarifying the basic concepts shared by a range of disciplines, concepts so fundamental that they are not themselves an object of study in those disciplines.

In order to make way for interesting applications along these lines, however, mereology must be supplemented by other concepts and principles of formal ontology—most notably by concepts and principles of topology and of the theory of location.³ As mereology is formalized in terms of the single primitive relation, *part of*, so mereotopology is obtained by adding a further primitive relation, *boundary for*, and the theory of location by adding a third relational primitive, *located at*. On this basis, it is possible to define a number of structural properties—such as connectedness, compactness, regularity, spatial coincidence—which prove to be of central ontological importance. Consider, for example, the task of characterizing individual integrity, the nature of artifacts, or the distinction between identity and coincidence for events.⁴ Even domains traditionally outside the scope of ontological theorizing may benefit from such extensions of mereology to topology and the theory of location. Consider the geographer's concern with such questions as the relationship between a nation (a city, a parcel of real estate) and a physical territory; the dependence of these entities on their borders; or the representation of boundaries which—as in the case of Wyoming, or Utah—may lie skew to any qualitative differentiations or spatial discontinuities in the underlying territory.⁵ Of course, not everything is settled once clear definitions of such concepts as *territory* or *border* are provided. But further questions cannot even be addressed without agreement as to the meanings of such fundamental terms.

In order, now, to do justice to a range of further central formal-ontological properties of the world we live in, we shall argue that, in addition to *part*, *boundary*, and *location*, a fourth primitive relation is needed, which we shall characterize via the concept of *niche*. This concept will be illustrated above all by means of simple ecological and biological examples. But it should be understood as being, like part, boundary, and location, a formal concept, one that is applicable in principle to a wide range of different domains, from economics⁶ to the theory of network security.⁷ The concept of niche and its cognates are indeed already employed ubiquitously in many disciplines, from evolutionary biology to context-based semantics. Yet the underlying principles have thus far been investigated not at all from the formal point of view. This is in part because the mereotopological tools needed for such an investigation have been developed only recently. But it is in part also a consequence of the fact that formal ontologists have tended to

shun holistic structures, preferring to conceive reality in terms of what can be simulated via (normally set-theoretic) constructions from out of postulated atoms or *Urelemente*. The account presented here, in contrast, will be resolutely me-reotopological: it will proceed from the idea that there are structured wholes, including the medium of space, which come before the parts that these wholes contain and that can be distinguished on various levels within them.

2. The ecological background

Standard treatments of the relevant categories (of niche, habitat, ecotope, biotope, microlandscape) in the ecological literature distinguish between the niche as the function or position of an organism or population within an ecological community and the niche as the particular place or subdivision of an environment that an organism or population occupies.⁸

The functional conception, associated primarily with the work of Charles Elton and other more traditional ecologists, is illustrated by phrases like: “The niche of the Dipper or Water Ouzel (*Cinclus sp.*) is: fast-running mountain streams with rapids and waterfalls, where they dive under the water to catch insects on the bottom.” We can think of the functional niche as a way of making a living in an organic community:

When an ecologist says ‘there goes a badger’ he should include in his thoughts some definite idea of the animal’s place in the community to which it belongs, just as if he had said ‘there goes the vicar’. (Elton 1927, pp. 63f.)

From Elton’s point of view the world of functional niches might be conceived as a giant evolutionary hotel, some of whose rooms are occupied (by organisms which have evolved to fill them), some of whose rooms are for a variety of reasons unoccupied but can become occupied in the future.

More recently however, primarily as a result of criticisms of the functional conception by Richard Lewontin (see Lewontin 1979, Sterelny and Griffiths 1999), the environmental niche conception has come to enjoy a position of dominance in the ecological literature. In the formulation advanced by G. E. Hutchinson (1978, p. 159), the environmental niche is a volume in an abstract space determined by a range of physical parameters pertaining to food, climate, predators, parasites, and so on.

Our theory in what follows will take as its starting point the environmental niche conception as defined by Hutchinson. We shall aim, however, to be more explicit than is customary in the ecological literature as concerns the ontological marks of the entities with which we have to deal. Specifically, we shall focus our attention on the concrete niche (token)—the habitat, location, or site—that is actually occupied by a given organism or group of organisms on a given occasion. We shall hereby assume that each functional niche, to the extent that it is realized at all, is realized in (or as) some concrete environmental niche or habitat. The

niche or habitat occupied by a given organism is thus to be understood not as a mere location, but rather as a location in space that is defined additionally by a specific constellation of environmental variables such as degree of slope, exposure to sunlight, soil fertility, foliage density, and so on.

How, then, are we to set about providing a theory of the niche as thus conceived? The ecological psychologist J. J. Gibson provides one important indication as to the nature of the task in hand:

According to classical physics, the universe consists of bodies in space. We are tempted to assume, therefore, that we live in a physical world consisting of bodies in space and that what we *perceive* consists of objects in space. But this is very dubious. The terrestrial environment is better described in terms of a *medium*, *substances*, and the *surfaces* that separate them. (Gibson 1979, p. 16)

Gibson seeks accordingly, in the section entitled “Surfaces and the Ecological Laws of Surfaces,” ‘a theory of surface layout, a sort of applied geometry that is appropriate for the study of perception and behavior’ (p. 33). This theory would investigate concepts such as: ground, open environment, enclosure, detached object, attached object, hollow object, place, sheet, fissure, fiber, threshold, and so on. It would take account not only of the systems of barriers, doors, pathways, to which the behavior of human beings is specifically attuned, but also of the many different sorts of phenomena—for example, temperature gradients and specific patterns of movement of air or water molecules—that produce surface layouts with which the behavior of other organisms is correlated. Note that some of these concepts refer to what we might call ‘positive’ features of the environment (to predators or prey, to dials and levers in the airline cockpit, to obstacles like rivers or mountains); but some of them refer to what we might more properly think of as negative features: to gaps in space, or in some medium (e.g., hollows for shelter, escape, protection; chasms, corridors, conduits, thermoclines).⁹

What Gibson attempted informally for humans, Jakob von Uexküll conceived in relation to the entire range of animal species. The ‘first principle’ of Uexküll’s *Umweltlehre* (1934) reads as follows: all animals, from the simplest to the most complex, are fitted into their unique worlds with equal completeness. A simple world corresponds to a simple animal, a well-articulated world to a complex one (p. 10). Unfortunately, Gibson, von Uexküll, and their followers were not in a position to make use of the tools made available by recent work in formal ontology in describing the environments or worlds in which organisms live. Some applications of such tools may be found in certain areas of artificial intelligence and the information sciences,¹⁰ but the legacy of the strong association between these disciplines and concern with human reasoning has meant that these tools have not been utilized for the formal-ontological investigation of non-human animal behavior and cognition. The simulations of ecological structures of the type generated by Artificial Life programs¹¹ are similarly of no use for our present purposes, since they yield nothing in the way of conceptual explication.

More positive guidance is provided by the anthropological literature on the phenomenon of territoriality, a phenomenon that arises whenever there obtains a type of relation between an individual or group and an area of space which is of such a sort that the former will seek to *defend* the latter against invasion by other conspecific individuals or groups.¹² Anthropologists have shown that in the case of both human and non-human animal species, a nested hierarchy of types of site must be distinguished around any given individual or group. The force of territoriality then diminishes with increase in group size and spatial area. In the first place there are territories in the narrow sense, the characteristically tiny areas in relation to which the occupying individual or group demands exclusive use. This central area is then extended to comprehend various attached regions, for example watering holes, where desirable resources are available on a routine basis. Finally we have the *home range*, that larger surrounding area within which the group spends almost all of its time.¹³ This idea—that niches (territories, settings) form a nested hierarchy around an individual or group at its center—will play a crucial role in the theory that follows.

3. Places

One philosophical progenitor of our theory is the ontology of *places* sketched by Aristotle in his *Physics*. What is it for a substance to be (or to fit snugly) *in* a location or context? Each substance has its place, Aristotle tells us, and the place of a substance is ‘neither a part nor a state of it, but is separable from it. For place is supposed to be something like a vessel’ (209b26f). Place cannot be a type of body, however, for if it were, then two bodies would be in the same place, and this Aristotle holds to be impossible. Place has size, therefore, but not matter. It has shape or form—exactly the shape or form of the thing that is located in it—but it lacks divisible bulk.

What, then, is place?

We say that a thing is in the world, in the sense of in place, because it is in the air, and the air is in the world; and when we say it is in the air, we do not mean it is in every part of the air, but that it is in the air *because of the surface of the air which surrounds it*; for if all the air were its place, the place of a thing would not be equal to the thing—which it is supposed to be. (*Physics* 211a24–28, italics added)

A place *contains* its body, in Aristotle’s view. The body relates to its place in something like the way the liquid in an urn relates to the urn, or the hand relates to the glove, or a precisely engineered Russian doll relates to the immediately circumjacent Russian doll. A place exactly surrounds the thing, but the place does not depend specifically upon the thing, since the latter can be replaced by another thing, which is then said to be in the same place. A place exactly surrounds the thing, but not in the sense in which the white of an egg exactly surrounds the yolk, for the two are here such as to form a single continuous whole. A place exactly

surrounds the thing, rather, where the thing is separate from but yet in perfect contact with its surrounding body, the latter being therefore marked by a certain sort of interior cavity or hole. The external boundary of the thing then exactly coincides with the internal boundary of that which surrounds it. Thus when a thing is in a surrounding body of air or water 'it is primarily in the inner surface of the surrounding body.' The boundaries of the two—the outer surface of the thing and the inner surface of its surrounding body—exactly coincide (211a30-33).

This, then, is place, on Aristotle's view: *the place of a substance is the inner boundary of the immediately surrounding or containing body.*

There are a number of problematic consequences of Aristotle's theory. For one thing, it is topologically incoherent, at least on standard views of contact and separation, since the boundaries of distinct things never coincide in the way required by Aristotle's theory.¹⁴ Moreover, the theory implies that proper substantial parts of bodies (for example: your leg, my arm) are not, in fact, in place—they are only potentially so: they will actually be in place only if they are transformed into substances in their own right by separation. For these reasons, the account of niche that we are after will deviate in crucial respects from Aristotle's account of the relation of place and body.

4. Physical-behavioral units

Another important progenitor of the theory that follows is the account of settings elaborated in great detail by the ecological psychologist Roger Barker. Think of a performance of a Wagner opera, a lecture on Hegel, a garage sale. Wholes of these types, which Barker calls physical-behavioral units, are of importance not least because *almost all human behavior occurs within one* (or in what turns out to be a nested hierarchy of such wholes).

Consider, on the one hand, the recurrent settings that serve as the environments for the everyday activities of persons and groups of persons. Examples are: my swimming pool, your favorite table in the cafeteria, the 5pm train to Long Island. Each of these is marked by certain stable arrays of physical objects and physical infrastructure, by 'surface layouts' in Gibson's terms. But each recurrent setting is associated, on the other hand, with certain stable patterns of behavior on the part of the persons involved. Physical-behavioral units are the conjunct of these two aspects. They are built out of both physical and behavioral parts.

As Barker puts it, physical-behavioral units

are common phenomenal entities, and they are natural units in no way imposed by an investigator. To laymen they are as objective as rivers and forests—they are parts of the objective environment that are experienced directly as rain and sandy beaches are experienced. (Barker 1968, p. 11)

Each physical-behavioral unit has two sorts of components: human beings behaving in certain ways (lecturing, sitting, listening, eating), and non-psychological

objects with which behavior is transacted (walls, chairs, paper, electricity, etc.). Each physical-behavioral unit has a boundary that separates an organized internal (foreground) pattern from a differing external (background) pattern. This boundary, too, though it may be far from simple, is an objective part of nature, though it may change according to the participants involved or according to the nature or phase of the relevant activity. Each unit is further circumjacent to its components: the former surrounds (encloses, encompasses) the latter: the pupils and equipment are *in* the class; the swimmers are *in* the swimming pool.

Many units occur in assemblies, as a chick embryo is constructed as a nested hierarchy of organs, cells, nuclei, molecules, atoms, and subatomic particles.

A unit in the middle range of a nesting structure is simultaneously both circumjacent and interjacent, both whole and part, both entity and environment. An organ—the liver, for example—is whole in relation to its own component pattern of cells, and is a part in relation to the circumjacent organism that it, with other organs, composes; it forms the environment of its cells, and is, itself, envired by the organism. (Barker 1968, p. 154)

Physical-behavioral units, too, may be nested together in hierarchies in this way. There are typically many units of each lower-level kind within a given locality, and these are typically embedded within larger units, as a game is embedded within a match. Conversations, hunt meets, weddings, each of these are physical-behavioral units in Barker's sense. By contrast, a randomly delineated square mile in the center of a city is not a physical-behavioral unit, and nor is the mereological sum of its Republican voters; the former has no self-generated unity; the latter has no continuously bounded space-time locus.¹⁵

5. Towards a formal theory

We can now summarize the ontological marks of environmental settings or niches as Aristotle and Barker might conceive them, as follows:

(i) An environmental niche takes up space, it occupies a physical-temporal locale, and is such as to have spatial parts. Within this physical-temporal locale is a privileged locus—a hole—into which the occupant of the niche fits exactly.

(ii) Environmental niches are unitary. A typical niche enjoys a certain natural completeness or rounded-offness, in contrast to its arbitrary undetached parts and to arbitrary heaps or aggregates of niches.

(iii) An environmental niche has an outer boundary: there are objects which fall clearly within it, and other objects which fall clearly outside it.

(iv) Environmental niches may have actual parts that are also environmental niches, and they may similarly be proper parts of larger, circumcluding environmental niches.

(v) An environmental niche is not simply a location in space; rather, it is a location in space that is constrained or marked by certain functional properties (of temperature, foliage density, federal jurisdiction, etc.).

(vi) An environmental niche may overlap spatially with other environmental niches with which it does not share common parts.

We may now proceed to setting forth a formal theory.

6. Mereology

For simplicity, we shall assume a standard mereological background.¹⁶ The primitive relation ‘ x is part of y ’ we symbolize by ‘ $P(x, y)$ ’, which we take to be true when x is any sort of part of y , including y itself. The relation of *proper* part can be defined accordingly:

$$D1 \quad PP(x, y) := P(x, y) \wedge \neg x = y. \quad \textit{proper part}$$

It will be understood that variables range over individuals—individual bodies, individual boundaries, and individual instances of a range of other categories, as well as the individual parts and aggregates of these.

The ‘is’ in ‘ x is part of y ’ is to be given a tensed reading. Thus our mereological framework embodies a synchronic theory, a theory of the part-whole relations existing *at some given time*. If we now define overlap as the sharing of common parts:

$$D2 \quad O(x, y) := \exists z(P(z, x) \wedge P(z, y)), \quad \textit{overlap}$$

then the axioms for standard mereology can be formulated as follows:¹⁷

$$\begin{aligned} A1 & \quad P(x, x) \\ A2 & \quad P(x, y) \wedge P(y, x) \rightarrow x = y \\ A3 & \quad P(x, y) \wedge P(y, z) \rightarrow P(x, z) \\ A4 & \quad \forall z(P(z, x) \rightarrow O(z, y)) \rightarrow P(x, y) \\ A5 & \quad \exists x(\phi x) \rightarrow \exists y \forall z(O(y, z) \leftrightarrow \exists x(\phi x \wedge O(x, z))). \end{aligned}$$

Parthood is, accordingly, reflexive, antisymmetric, and transitive, a partial ordering. In addition, A4 ensures that parthood is extensional (two things cannot consist of the same parts) and the schema A5 guarantees that for every satisfied property or condition ϕ (i.e., every condition ϕ that is true of at least one individual) there exists an entity consisting precisely of all the ϕ ers.¹⁸ This entity is called the sum or fusion of the ϕ ers and will be denoted by ‘ $\sigma x(\phi x)$ ’. It is defined as follows:

$$D3 \quad \sigma x(\phi x) := \iota y \forall z(O(y, z) \leftrightarrow \exists x(\phi x \wedge O(x, z))), \quad \textit{sum}$$

where, for simplicity, the definite descriptor ‘ ι ’ is assumed to be contextually defined in Russellian fashion:

$$D4 \quad \psi(\iota x(\phi x)) := \exists x(\forall y(\phi y \leftrightarrow y = x) \wedge \psi x).$$

The mathematical properties of this mereological theory are well known and correspond to those of a Boolean algebra with the null (zero) element removed. Given D3, the analogues of the ordinary Boolean operators are easily defined:

$$\begin{array}{lll} D5 & x + y := \sigma z(P(z, x) \vee P(z, y)) & \text{binary sum} \\ D6 & x \times y := \sigma z(P(z, x) \wedge P(z, y)) & \text{binary product (intersection)} \\ D7 & x - y := \sigma z(P(z, x) \wedge \neg O(z, y)) & \text{difference} \\ D8 & -x := \sigma z(\neg O(z, x)). & \text{complement} \end{array}$$

In addition, we can associate the general sum operator σ with a general product operator π : the product of any number of overlapping ϕ ers is the sum of all those things that are part of every ϕ er:

$$D9 \quad \pi x(\phi x) := \sigma z \forall x(\phi x \rightarrow P(z, x)). \quad \text{product (intersection)}$$

Of course, since A5 is in conditional form, this operator may fail to be defined if the ϕ ers have no parts in common. The operators introduced in D6–D8 may likewise fail to be defined for some of their arguments. This is because there are no null individuals in our theory, no analogues of the empty set.

7. Topology

We should like to talk of things that are connected, or of a piece, on the one hand, and distinguish them from scattered groups or aggregates and other gerrymandered beings, on the other. It is impossible to account for this difference on the basis of mereology alone. More generally, mereology cannot account for some very basic spatial relations, such as the relationship of continuity between two adjacent parts of an object, or the relation of one thing’s being entirely inside or surrounded by another. To provide a systematic account of such relations will require a topological machinery.

We shall assume here an apparatus closely corresponding to ordinary topology, though constructed on a mereological basis.¹⁹ The central concept is the concept of boundary as illustrated by the outer surface of a sphere, the edge of a table, or the borders of Japan. As a primitive, we assume ‘ x is a boundary for y ’, which we symbolize as ‘ $B(x, y)$ ’. We say *boundary for*, rather than *boundary of*, to allow for boundaries that are not maximal (corners, edge segments, parts of

surfaces). The maximal boundary of x is then immediately defined, using AP5, as the sum of all the boundaries for x :

$$D10 \quad b(x) := \sigma y B(y, x). \quad \text{maximal boundary}$$

Again, note that this notion may not be defined for every value of ‘ x ’. Some objects, for instance the universal object (definable as the sum of all self-identical things), may lack a boundary.

For the sake of perspicuity, it is convenient to introduce also a closure operator:

$$D11 \quad c(x) := x + b(x). \quad \text{closure}$$

This is a mereologized version of the standard, point-set-theoretic operator of topological closure. We may then formulate our axioms by mereologizing the standard Kuratowski axioms (1922), in the obvious way, as follows:²⁰

- A6 $P(x, c(x))$
- A7 $P(c(c(x)), c(x))$
- A8 $P(c(x), c(x + y))$
- A9 $P(c(x + y), c(x) + c(y))$.

(In view of D11, axiom A6 is actually derivable from A1 but we list it here for ease of reference.) The axioms imply that ‘ B ’ satisfies certain familiar conditions. In particular, boundaries are always transitive and disjunctive (i.e., they only have boundaries as parts):

- T1 $B(x, y) \wedge B(y, z) \rightarrow B(x, z)$
- T2 $P(x, y) \wedge B(y, z) \rightarrow B(x, z)$.

They are also symmetric, in the sense that a boundary for a given entity is also a boundary for that entity’s complement:

$$T3 \quad B(x, y) \rightarrow B(x, -y).$$

The axioms also allow us to define:

- D12 $IP(x, y) := P(x, y - b(y))$ *interior part*
- D13 $C(x, y) := O(x, y) \vee O(c(x), y) \vee O(c(y), x)$ *connection*
- D14 $EC(x, y) := C(x, y) \wedge \neg O(x, y)$ *external connection*
- D15 $Cn(x) := \forall y \forall z (x = y + z \rightarrow C(y, z))$ *self-connectedness*
- D16 $CP(x, y) := Cn(x) \wedge P(x, y)$ *connected part*

Note that ‘IP’ and ‘CP’ are both transitive and antisymmetric, while ‘C’ is reflexive and symmetric and ‘EC’ is irreflexive and symmetric. We then require, for self-connected boundaries, the existence of self-connected wholes which they are boundaries for:

$$A10 \quad \exists y B(x, y) \wedge Cn(x) \rightarrow \exists y (B(x, y) \wedge Cn(y) \wedge \exists z IP(z, y)).$$

This corresponds to the Aristotelian thesis that boundaries are ontologically parasitic on (i.e., cannot exist in isolation from) their hosts, the entities they bound—a thesis which stands opposed to the ordinary set-theoretic conception of boundaries as, effectively, sets of independent points, each one of which might exist though all around it be annihilated.²¹

Finally, we define:

D17	$i(x) := x - b(x)$	<i>interior</i>
D18	$e(x) := i(-x)$	<i>exterior</i>
D19	$Op(x) := x = i(x)$	<i>open</i>
D20	$Cl(x) := x = c(x)$	<i>closed</i>
D21	$Ro(x) := x = i(c(x))$	<i>regular open</i>
D22	$Rc(x) := x = c(i(x))$	<i>regular closed</i>
D23	$Rg(x) := Ro(i(x)) \wedge Rc(c(x)).$	<i>regular</i>

These definitions provide a natural mereotopological analogue of standard topological notions.²² For instance, the notion of regularity captured by D23 corresponds to that of a regular set. We shall impose on niches and their occupants the constraint of regularity in order to exclude from the orbit of our theory space-filling curves, deleted Tychonoff corkscrews, and other topological monsters. A regular object is, roughly speaking, an object which does not possess outgrowing boundary “hairs,” it does not lack a single interior point, it does not consist of two or more voluminous parts connected by interiorless filaments, and so on.

Note that it follows from D14 that two entities can be in contact (externally connected) only if one of them is not closed:

$$T4 \quad EC(x, y) \rightarrow (Cl(x) \rightarrow \neg Cl(y)).$$

Thus, if Bill and Monica are topologically closed, then genuine contact between them is impossible if contact is understood in terms of external connection (EC). In general, the surfaces of distinct physical bodies cannot be in contact topologically, though bodies may of course be so close to each other that they appear to be in contact to the naked eye.²³

8. Location

Before proceeding to the formal theory of niches proper, we still need to draw a distinction between the part-whole relations that apply to entities in space and

those that apply to the spatial regions these entities occupy. This distinction would not be necessary if we could assume that the relation of spatial location is exclusive—that no two entities may share the same spatial location at the same time. We shall, in fact, assume that this principle holds of organisms; but it is not true in general. There are relations of spatial overlap which do not imply corresponding relations of mereological overlap. If you put a stone in a hole, then the stone occupies a region of space which is also occupied by the hole; and yet the stone and the hole do not share any parts.²⁴ Likewise, we want to say that there may be objects located inside the region where a niche is located that are not part of or connected to the niche. The niche around the sleeping bear is full of flies, but the flies themselves are not a part of the niche.²⁵ We also want to say that a niched object does not overlap its niche, not only in the mereological sense of not sharing any part with the niche, but also in the purely spatial sense of not sharing any common location. This, too, cannot be expressed in purely mereotopological terms. Finally, the ecological literature makes it clear that niches are bounded not just spatially, and not just via physical material (the walls of the cave), but also via thresholds in quality-continua (for instance, temperature). Distinct niches, therefore, may occupy the same spatial region. And we may want to say that different organisms, or organisms of different types, are able to find niches within the same spatial region without thereby implying that they share a niche. A niche for the fly on the bear's nose is not a part of the niche for the bear (or at least: we need not assume that it is).

All of this suggests that we introduce, in addition to our mereotopological primitives of part and boundary, a primitive concept of spatial location. We shall use the notation ' $L(x, y)$ ' to indicate that x is located at y , that x stands to y in the primitive relational tie of *exact location*. Other locative relations, such as partial and interior location, can easily be defined in terms of this primitive together with our mereotopological apparatus, but we shall have no use for them for our present purposes.²⁶

As basic axioms for L , we assume the following:

$$\text{A11} \quad L(x, y) \wedge L(x, z) \rightarrow y = z$$

$$\text{A12} \quad L(x, y) \rightarrow L(y, y).$$

By A11, a single entity cannot have two distinct locations: L is a functional relation. By A12, L behaves as a reflexive relation whenever it can: all (and only) those things are located at themselves at which something is located. We shall assume, further, an axiom to the effect that every entity has a location:

$$\text{A13} \quad \exists y(L(x, y)).$$

This is obviously very strong: it implies that entities lacking spatial location (such as numbers) are excluded from the domain of our theory. It brings however the

compensating advantage that it allows us to speak of *regions* as just those things at which something (not necessarily something *else*) is located:

$$\text{D24} \quad \text{Re}(x) := \exists y(\text{L}(y, x)). \quad \textit{region}$$

The region at which an entity x is located we shall call the *location of x* :

$$\text{D25} \quad \text{l}(x) := \iota y(\text{L}(x, y)). \quad \textit{location}$$

The uniqueness of $\text{l}(x)$ follows directly from the functionality postulate, A11, while A12 ensures further that l is idempotent:

$$\text{T5} \quad \text{l}(\text{l}(x)) = \text{l}(x).$$

On the other hand, nothing guarantees that the domain of regions is mereologically well-behaved in the sense that every part of a region is a region, and that the sum of any regions is itself a (possibly disconnected) region. To this effect, the following axioms must be added explicitly:

$$\text{A14} \quad \text{Re}(x) \wedge \text{P}(y, x) \rightarrow \text{Re}(y)$$

$$\text{A15} \quad \forall x(\phi x \rightarrow \text{Re}(x)) \rightarrow \text{Re}(\sigma x(\phi x)).$$

At this point we obtain a more adequate theory of location by adding principles connecting the axioms for L with our basic mereotopological apparatus:

$$\text{A16} \quad \text{l}(x + y) = \text{l}(x) + \text{l}(y)$$

$$\text{A17} \quad \text{l}(\text{b}(x)) = \text{b}(\text{l}(x)).$$

These two principles ensure that the mereotopology of things is in the appropriate way mirrored in the mereotopology of their corresponding regions. By A16 the location of a sum of parts is the sum of the locations of the parts, and by A17 the location of an entity's boundary is the boundary of that entity's location. This implies that the locations of a thing's parts are parts of the thing's location, and the locations of a thing's boundaries are boundaries of the thing's location:

$$\text{T6} \quad \text{P}(x, y) \rightarrow \text{P}(\text{l}(x), \text{l}(y))$$

$$\text{T7} \quad \text{B}(x, y) \rightarrow \text{B}(\text{l}(x), \text{l}(y)).$$

Moreover, A17 implies that a similar result holds when 'b' is replaced by the closure or interior operators:

$$\text{T8} \quad \text{l}(\text{c}(x)) = \text{c}(\text{l}(x))$$

$$\text{T9} \quad \text{l}(\text{i}(x)) = \text{i}(\text{l}(x)).$$

A16, in turn, can be strengthened to cover infinitary sums—the location of a sum of ϕ ers is the sum of the locations of the ϕ ers:

$$A16' \quad I(\sigma x(\phi x)) = \sigma z(\exists x(\phi x \wedge z = I(x))).$$

9. Niches

We are now ready to proceed to the basic principles of the theory of niches. Formally, this may be thought of as a theory of certain sorts of neighborhoods. We shall formulate it with the help of a new primitive relational predicate ' $N(x, y)$ ', to be read: ' x is a niche for y ' (we shall call y the *tenant* of x). Again, the 'is' here is to be given a tensed reading: we are concerned with the panoply of niche-tenant relations at a given time. For simplicity, we shall initially suppose that all tenants are *compact*, in the sense that they have no internal cavities. Later we shall see how the account can be extended to the case of tenants with cavities.

The mereotopological conditions on niches are fixed by the following set of axioms, which we shall explain and justify in the sequel.

A18	$N(x, y) \rightarrow \neg O(I(x), I(y))$	<i>disjointness</i>
A19	$N(x, y) \rightarrow IP(I(y), I(x + y))$	<i>spatial containment</i>
A20	$N(x, y) \rightarrow C(x, y)$	<i>connection</i>
A21	$N(x, y) \rightarrow CI(y)$	<i>closure of tenant</i>
A22	$N(x, y) \rightarrow Cn(x)$	<i>connectedness of niche</i>
A23	$N(x, y) \rightarrow Rg(y)$	<i>regularity of tenant</i>
A24	$N(x, y) \rightarrow Rg(x)$	<i>regularity of niche</i>
A25	$N(x, y) \wedge N(x, z) \rightarrow y = z.$	<i>functionality</i>

The first three axioms fix the basic spatial relationships between niches and their tenants. A niche is a type of perforated or deleted neighborhood of its tenant. Thus, we require that the location of the niche should not overlap (A18) but rather surround (A19) that of its tenant, and that the niche itself should be connected to its tenant (A20). It follows that a niche is always externally connected to its tenant and therefore that N is irreflexive (since nothing is externally connected to itself):

T10	$N(x, y) \rightarrow EC(x, y)$
T11	$\neg N(x, x).$

A result stronger than T10 is in fact provable, namely, that every boundary of a tenant is also a boundary of its niche:

$$T12 \quad N(x, y) \wedge B(z, y) \rightarrow B(z, x).$$

(It is here that our supposition concerning the lack of interior cavities becomes explicit. The presence of a cavity would split the boundary of the tenant into two

disconnected parts, only one of which—the exterior one—can be shared by the niche. We shall come back to this in Section 11 below.)

We also assume, by A21, that all tenants are topologically closed, hence that they contain their boundaries as parts:

$$\text{T13} \quad N(x, y) \wedge B(z, y) \rightarrow P(z, y).$$

This is motivated by our ecological interpretation of ‘N’: the boundaries of a tenant are its surfaces, which face out toward the niche. It also follows that every niche has an interior (has divisible bulk), and therefore that the categories of niche and boundary are mutually exclusive:

$$\text{T14} \quad N(x, y) \rightarrow \neg B(x, z).$$

This is so because, since niches are externally in contact with their tenants (by T10), and since tenants are always closed (by A21), a niche must always be open in the region in which it makes contact with its tenant (by T4, which tells us that, where two entities are externally connected, one must be open and the other closed).

Given T4 and T10, A21 also implies that the tenant of a niche cannot itself be a niche:

$$\text{T15} \quad N(x, y) \rightarrow \neg N(y, z).$$

This in turn implies that N is not only irreflexive (T11) but fully asymmetric and—more generally—that niches cannot themselves be niched:

$$\text{T16} \quad N(x, y) \rightarrow \neg N(y, x)$$

$$\text{T17} \quad N(x, y) \rightarrow \neg N(z, x).$$

This does not exclude an organism from being such as to constitute a niche or natural setting for another entity, for example a micro-organism inside a human body. What it does rule out is that the hosting organism might serve this hosting function by itself. To see what is at issue here, note that, if every organism is closed and every niche open (in the relevant contact area), then it follows that a micro-organism lodged inside your body as a niched entity is not topologically connected to your body: there must be some distance between them, however small. The niche for the micro-organism is thus not your body itself (which is closed), nor a proper part thereof, but rather an entity including also the area immediately surrounding the micro-organism and separating the latter from you.

By A22, all niches are connected. Moreover, the regularity axioms A23 and A24 rule out niches and tenants with strange topologies, for example niches or tenants with outgrowing interiorless boundary hairs. There are, to be sure, organisms that have a quasi-fractal structure (sponges, mosses) and niches whose porosity is im-

portant to their ecological role. The hole-part structure of such entities is enormously complex, but they are nonetheless regular in the sense at issue here.

Our last axiom, A25, says that niches are *exclusive* environmental settings: they cannot be shared by distinct entities (though distinct entities may have overlapping niches, both in the mereological and in the spatial sense of ‘overlap’). Consider the inside of an ant’s nest. This is, no doubt, a niche for a clutch of eggs when they are laid (a disconnected tenant). But is it not also a niche for each separate egg? To see why this is not so, consider that the surrounding environment of each single egg includes, or is determined by, the boundaries of its neighbors. The surface layout of the collective niche is quite different from the surface layout of the niche for each egg taken singly. Similar considerations apply in relation to a pair of twin fetuses inside a mother’s womb. Each fetus helps to determine the niche for its neighbor. The womb as a whole serves as niche for the twinned pair.

Note that our axioms do not guarantee that niches are closed under the basic mereological operations of sum and product. If an object has two niches, their sum need not be a niche, for it might lack the sort of homogeneity that typically characterizes a niche. Likewise, if an object has two niches, their intersection need not be a niche. Consider a group of cows in the middle of a large field with a water tank at each of the two extremities A and B. The whole field is a niche for the cows, as is the middle plus A and the middle plus B. But the intersection of the latter is not a niche, since the cows need water. This asymmetry of behavior with regard to the mereological operations is one respect in which the concept of niche would seem to deviate from the purely topological concept of neighborhood.

There are many other properties of neighborhoods whose analogues for niches have an uncertain status. For instance, should we assume that every two niches of the same tenant have a common part? Should we assume that every niche for a given tenant has a proper part that is itself a niche for that tenant? Should we assume that every niche has a *compact* part that is a niche for its tenant (a niche with no internal holes except those occupied by the tenant)? These are questions that we can hardly address at this stage, and we shall content ourselves, here, with the basic apparatus defined by A18–A25.

10. Vagueness

Our axioms do not imply that niches are dissective: a niche for an entity y may have proper parts that are not niches for y , even if those proper parts fully envelop y . Thus, for instance, no non-regular proper part of a niche ever qualifies as a niche. Our axioms do not imply, either, that niches may be arbitrarily large. Thus, in particular, the mereological complement of an organism (the result of imagining the organism as having been deleted from the remainder of the universe) need not be a niche, according to the axioms here listed.²⁷

What, then, is to be said about the *outer* boundaries of niches? In some cases the surface layout of the surrounding physical environment provides an upper

limit to the niche extension (the worm in its wormhole, the scholar in her cell). In other cases, however (the fish in the ocean, the bird in the sky), no such physical limit may be provided: the outer boundary of the relevant niche is then in some sense vague. We face, here, a range of options which are counterparts of options we face in any account of vagueness. Thus, on the one hand, we might assert that these cases involve a more or less open-ended continuum of nested environments, each of which is in itself perfectly determinate and each of which may claim (possibly to different degrees) to serve as niche for the entity in question. The structure of this continuum would then suggest a postulate of open-endedness along the following lines:

$$\text{A26} \quad N(x, y) \rightarrow \exists z(N(z, y) \wedge PP(x, z)).$$

An even stronger axiom would be density: the nesting of niches always yields mereological intermediates that are themselves niches:

$$\text{A27} \quad N(x, y) \wedge N(z, y) \wedge PP(x, z) \rightarrow \exists w(PP(x, w) \wedge PP(w, z) \wedge N(w, y)).$$

On the other hand, however, we might assert that there is a single niche for the entity in question, but that this niche has an outer boundary that is literally vague or indeterminate. There would then be spatial regions for which there is no objective, determinate fact of the matter about whether they overlap the location of the niche.²⁸ This alternative brings ontological problems of its own and would induce a fuzzification of our basic mereotopological and locative framework. But some might insist that these problems must in any case be solved in an account of the semantics of natural language expressions such as ‘downtown’, ‘Mount Everest’, ‘the hurricane that destroyed the village’, and so on.

We shall here remain neutral with regard to this general issue. Precisely because it is not a problem peculiar to the concept of niche, the theory of niches should not force one account or the other. If there are vague objects, some niches will be among them. If (as we would be inclined to argue) all vagueness is conceptual, then the niche concept will in some cases have vague applications.

11. Cavities

A different sort of question relates to the *inner* boundaries of niches—the boundaries that niches share with their tenants. In presenting our basic axioms, we have assumed that tenants involve no internal cavities. This allowed us to characterize the idea that a niche surrounds the tenant simply by requiring that the location of the mereological sum of niche and tenant includes the location of the tenant as an *interior part* (A19). However, a tenant may itself have interior cavities, and if tenants are to be closed (by A21) and niches connected (by A22), this means that A19 falls short of capturing the relevant sense of ‘surrounds’ in the general case:

the boundary around an internal cavity belongs to the tenant and it therefore cannot be in the *interior* of the sum constituted by the tenant together with its niche (though it would be in the interior of the threefold sum made up of tenant, niche, and cavity).

A19 (and T12) may seem threatened also in cases where the tenant has a connected boundary. All animals are torus-shaped entities, yet it hardly seems reasonable to suppose that every niche of John would snake through his digestive tract. Here three sorts of cases can be distinguished: (i) Cases where the putative hole is, in virtue of the intimate causal interconnection of processes on either side of its boundary, analogous to an organ within the interior of the organism in question. (ii) Cases where the putative hole is a genuine hole, analogous to the hole inside a wedding ring. (iii) Cases which involve a combination of (i) and (ii), perhaps of the sort illustrated by the womb conceived abstractly as dilation in the uterine tract. In type (i) cases, now, the walls of the putative hole are not part of the boundary of the object; their not being in contact with the niche therefore does not contradict T12. Cases of type (ii), in contrast, do indeed allow penetration by a niche into the interior of the tenant (thus we may naturally suppose that the finger through Mary's wedding ring is part of the ring's niche). Type (iii) cases, finally, bring us back once more to the issue of interior cavities, and in order to resolve this issue we need to amend A19 as follows.

Suppose, first, that the tenant is a connected object. In that case, the tenant has a cavity if and only if it has a disconnected boundary: the cavity has no contact with the rest of the object's complement, hence its presence splits the object's boundary into two parts. (Equivalently, the presence of a cavity splits the object's mereological complement into two disconnected parts: the one inside, the other outside the object.) Consider now the entity that results (intuitively) when we take the object together with those parts of its complement that lie on its inside—the mereological sum of the object together with its cavities. This can be defined, more technically, as the compact closure of the object—the smallest entity whose boundary is connected and which includes the object as part:²⁹

$$\text{D26} \quad k(x) := \pi y(\text{Cn}(b(y)) \wedge P(x, y)). \quad \text{compact closure}$$

It is easy to verify that this operator is well-defined whenever x is connected. Moreover, the compact closure of a closed object is always closed, and the compact closure of a regular object is always regular:

$$\begin{aligned} \text{T18} \quad & \text{Cl}(x) \rightarrow \text{Cl}(k(x)) \\ \text{T19} \quad & \text{Rg}(x) \rightarrow \text{Rg}(k(x)). \end{aligned}$$

Using this notion we can now reformulate axiom A19 in such a way as to allow for niched objects with cavities. To capture the idea that the niche surrounds the

object, i.e., envelops it *from the outside*, we require the niche to be a deleted neighborhood of *the compact closure of the tenant*:

$$A19' \quad N(x, y) \rightarrow IP(I(k(y)), I(x + k(y))).$$

Of course, this reduces to A19 whenever the tenant has no internal cavities, for in that case the tenant has a connected boundary and thus coincides with its compact closure:

$$T20 \quad Cn(b(x)) \rightarrow x = k(x).$$

On the other hand, given our requirement that niches be always connected (A22), A19' guarantees that, if the tenant of a niche has internal cavities, then these cavities are not a part of the niche. Not every deleted neighborhood is a candidate niche for an entity, but only those that *surround* the entity in the most literal sense.

Note that if we replace A19 by A19', theorem T12—to the effect that every boundary of the tenant is also a boundary of the niche—will fail, though the following will still hold:

$$T12' \quad N(x, y) \wedge B(z, k(y)) \rightarrow B(z, x).$$

A19' is still not general enough, however, since it rests on the supposition that tenants are connected entities. This need not always be the case (think of the niche surrounding John and Mary as they enjoy a romantic candle-light dinner). A tenant may have a disconnected boundary even if it has no cavities, which would make our reference to its compact closure illegitimate. (There is no smallest entity whose boundary is connected and which includes John and Mary as parts.) To capture the idea that a niche surrounds its tenant without requiring that the tenant be connected, we must further require the conditional in A19' to hold, not of the tenant itself, but of each maximally connected part (or 'element') of the tenant. The relevant definition is as follows:

$$D27 \quad E(x, y) := CP(x, y) \wedge \forall z(CP(z, y) \wedge O(z, x) \rightarrow P(z, x)). \quad \textit{element}$$

Informally: an element is a connected part that is maximal in the sense that it contains every connected part that it overlaps. We can finally amend A19 by requiring the niche to surround every element of its tenant, as follows:

$$A19'' \quad N(x, y) \wedge E(z, y) \rightarrow IP(I(k(z)), I(x + k(z))).$$

The analogue of T12 is then provable in the following form:

$$T12'' \quad N(x, y) \wedge E(w, y) \wedge B(z, k(w)) \rightarrow B(z, x).$$

12. Ecological subjects

Return, now, to the rest of the axioms. We have seen that the sum $x + y$ of two niches for an object z need not be a niche for that object. Likewise, we may observe that our axioms do not support the dual principle to the effect that a niche x for a sum $y + z$ is *ipso facto* a niche for each of the summed parts. For instance, if $y + z$ is an individual substance (the head plus the rest of John's body), then it typically has a niche of its own even though the two parts y and z (the head and torso) do not.

We can now distinguish various different sorts of niched entities which are *natural units* in the sense described:

D28	$Ct(x) := Cn(x) \wedge \exists y N(y, x)$	<i>connected tenant</i>
D29	$Su(x) := Ct(x) \wedge \forall z (Ct(z) \wedge O(z, x) \rightarrow P(z, x))$	<i>substance</i>
D30	$Av(x) := \exists y N(y, x) \wedge \exists y (Su(y) \wedge PP(y, x))$	<i>avatar</i>

A connected tenant (D28) is a niched entity which is at the same time not scattered (is not an aggregative or collective tenant). A substance (body, thing) is a *maximally* connected tenant (D29), a tenant which is such that no larger connected tenant includes it as a proper part.³⁰ You are in this sense a substance, but your heart is only a connected tenant within your interior. (Two connected siamese twins are also not substances in the sense of D29, though their sum is.) Finally, an avatar (D30) is a tenant including substances as proper parts. Examples of avatars might include: a shoal of fish in a lake, a herd of buffalo. These are causally integrated and more or less reproductively isolated subpopulations of conspecifics. They play an important role in evolutionary theory in light of the fact that it is avatars, and not whole species, that are the most plausible candidate subjects of selective pressures at the group level.³¹

Note that a connected tenant need not be an element (in the sense of D27), since it may not be maximal. However, every niched element is a connected tenant, and every connected tenant is included in some substance:

T21	$N(x, y) \wedge E(y, z) \rightarrow Ct(y)$
T22	$Ct(x) \rightarrow \exists y (Su(y) \wedge P(x, y))$

In terms of the concept of niche (along with the underlying mereotopological and location-theoretic primitives) we are now able to prove counterparts of a number of propositions central to the metaphysical treatment of substances in the tradition, as also to the treatment of groups or communities and of the associated concepts of natural unit and social whole. For instance, it follows from D29 that substances have a regular topology, that they are closed (i.e., contain their boundaries as parts), and that no two of them can share any parts:

T23	$Su(x) \rightarrow Rg(x)$
T24	$Su(x) \rightarrow Cl(x)$
T25	$Su(x) \wedge Su(y) \wedge O(x, y) \rightarrow x = y$

Thanks to D29, the theory of niches provides the resources also for a more satisfactory formulation of the Aristotelian dependence principle for boundaries (A10). This can now be expressed by requiring every self-connected boundary to be a boundary of some substance:

$$A10' \quad \exists y B(x, y) \wedge Cn(x) \rightarrow \exists y (Su(y) \wedge B(x, y)).$$

Likewise, one may want to strengthen our requirement that substances be maximally connected tenants by further assuming that no substance can be partitioned into connected tenants (otherwise it would be a mere aggregate):

$$A28 \quad Ct(x) \wedge Ct(y) \wedge \neg O(x, y) \rightarrow \neg Su(x + y).$$

More generally:

$$A28' \quad \forall x (\phi x \rightarrow Ct(x)) \wedge \forall x \forall y (\phi x \wedge \phi y \wedge \neg x = y \rightarrow \neg O(x, y)) \\ \rightarrow \neg Su(\sigma x(\phi x)).$$

We believe that these and related principles can aid conceptual clarification in a number of important areas of metaphysics. They can aid our thinking not only in relation to issues pertaining to the nature of species and to the problem of specifying the unit of selection in evolutionary theory, but also, for instance, in the treatment of the metaphysics of the fetus and of the question as to the status and category of the summed fetus+mother pair.

13. Concluding remarks

The theory of niches presented above is of course no more than a first, provisional chapter of a formal ontology of ecological phenomena. It provides a synchronic account only: we still need to introduce the important factor of dynamics and change, and above all to address the issue of the identity of niches and niched objects over time, and issues relating to the movement and interaction of organisms within and between their respective niches. We need to find a place for the special types of causal integrity that characterize niches and niched entities, and for the special types of niche assembly-structure that arise for example when groups of individuals collaborate. We need to consider also the question as to how niches for given objects are determined by the properties of their surroundings. What determines the shape and size of a niche? How do animal niches in this respect relate to those of organisms of other types?

Another important family of problems relates to the status of niches when tenants are absent. Are niches essentially dependent entities, as Lewontin would have it? Do we need to distinguish different types of niche, some of which will survive the temporary or permanent departure or replacement of their tenants? What is the relation between my niche and your niche when you occupy a posi-

tion within my niche and I within yours? What is the relation between my niche and yours when we are in conflict, for example when we compete for occupation of a given territory, or when you are predator and I am prey? What, finally, is the biologically very important relation between the *individual* niche or habitat of a single organism or population of organisms and the *niche-type* of the corresponding species? The formal theory outlined in the above will, we hope, provide at least a starting point for providing answers to these questions.³²

Notes

¹Leśniewski's original (1916) formulation of mereology grew out of an attempt to provide a solution to Russell's paradox; Whitehead's formulations in (1919) and (1929) were meant as a basis for his theory of extensive abstraction; and Tarski's (1929) application was to the foundations of geometry.

²See Husserl (1900/1901), 'Prolegomena', Chapter 11. This project of a formal ontology is present also in Leśniewski's later work on mereology (see his 1927/1931).

³On the importance of topology for formal ontology, see Smith (1993, 1997) and Varzi (1994). On the theory of location, see Perzanowski (1993) and Casati and Varzi (1996, 1997).

⁴On individual integrity see, for instance, Cartwright (1975); on artifacts see Simons and Dement (1996); on events see Hacker (1982).

⁵For some applications of ontology to geography see Egenhofer and Mark (1995), Smith (1995, 1999), Frank (1997), and Casati *et al.* (1998).

⁶See e.g. Milne (1990).

⁷See Cardelli and Gordon (1998).

⁸See Whittaker and Lewin, eds. (1975).

⁹The theory envisaged by Gibson would thus be closely related to the mereotopological ontology of holes presented in Casati and Varzi (1994).

¹⁰See e.g. Guarino, ed. (1998).

¹¹Hraber *et al.* (1997).

¹²Sack (1986). Compare also the related psychological phenomenon of 'personal space' discussed in Hall (1966).

¹³See Taylor (1988), pp. 21f.

¹⁴For something like Aristotle's theory to work, we would need to recognize a deviant topology of boundaries of the sort described in Smith (1997) and Smith and Varzi (1999), where topological connection is defined in terms of boundary coincidence. In classical topology, by contrast, connection between two things is explained in terms of intersection (overlap) between one thing and the closure of the other. See section 7 below.

¹⁵See Barker (1968), pp. 11f., 16; (1978), p. 34.

¹⁶For an introduction to standard mereology and its variants, see Simons (1987). Our presentation here follows that of Smith and Varzi (1999).

¹⁷Here and in the sequel initial universal quantifiers are to be taken as understood.

¹⁸' ϕx ', again, is to be given a tensed reading. Hence, the entity in question will consist of those things that satisfy ϕ at some given time, not of those things that satisfy ϕ at some time or other.

¹⁹Here we confine ourselves to a brief review. For more on mereotopology, we refer to Smith (1993, 1997), Varzi (1996a), Cohn and Varzi (1998), Smith and Varzi (1999). For a standard reference on ordinary topology, see Steen and Seebach (1970).

²⁰These axioms are to be understood as holding whenever $c(x)$ is defined. In other words, we read each axiom as involving a tacit antecedent asserting the existence of denotations for its defined terms. For instance, A6 amounts to the conditional $\exists y(y = c(x)) \rightarrow P(x, c(x))$. We shall rely on a similar convention in stating all our theorems and axioms below.

²¹A more general statement of the dependence thesis would assert that the existence of any boundary is such as to imply the existence of some entity of *higher dimension* which it bounds. Here, though, we shall content ourselves with the simpler formulation. For more details, see Smith (1993) and Smith and Varzi (1999).

²²Recall that we are assuming a Russellian treatment of definite descriptions (D4). Thus, 'Op(x)' will be false not only when x is non-identical with its interior, but also when x lacks an interior altogether, i.e., when $i(x)$ is not defined; and similarly for the other definitions listed here and below.

²³There is a compacting of molecules where Bill and Monica kiss, but no part of Bill is ever in contact with any part of Monica. This is in agreement with standard topology, and also with standard physics, but see again Smith and Varzi (1999) for a more detailed account of the underlying issues.

²⁴See Casati and Varzi (1994), ch. 7. Our talk of 'spatial regions' and 'locations' here should not be taken as expressing commitment to an absolutist conception of space: analogous remarks would apply on a relationist conception.

²⁵This suggests a distinction between the narrowly defined concept of *niche* and a wider concept of *environment*, defined as the mereological sum of all that lies within the spatial location of an object's niche. The environment of the sleeping bear would then include the flies as proper parts.

²⁶See Casati and Varzi (1996, 1999) for details.

²⁷The axioms do not however rule this out. Indeed, a straightforward consistency proof for the theory defined by A18–A25 can be obtained precisely by taking 'N(x, y)' to be true if and only if x is the mereological complement of y .

²⁸Niches would thus be vague entities in the sense of Tye (1990).

²⁹In a more sophisticated analysis we would define the compact closure of an object as the sum of the object with its holes (Varzi 1996b). This, however, would require an explicit treatment of the relation ' x is a hole in y ', which cannot be defined in terms of standard mereotopological primitives of the sort available here.

³⁰D29 presupposes that every substance is always in a niche. This may be disputable: a diver crossing the boundary between water and air is arguably not in a niche but rather moving from one niche to another. The issues raised by cases such as this, however, are part and parcel of the general problem of motion and change, which goes beyond the limits of the purely synchronic framework presented here.

³¹See Damuth (1985) and Eldredge (1989).

³²Thanks to David Mark and the National Center for Geographic Information and Analysis (an Organized Research Unit of the University at Buffalo) for valuable support in the present project, and to Ling Bian of the University at Buffalo Geography Department, whose work on fish ecology inspired it. Thanks also to Roberto Casati, Andrew Frank, Michael Ghiselin, Kevin Mulligan, Barbara Nunn, Kim Sterelny, Graham White, Jan Woleński and the referees of *Noûs* for their comments on earlier drafts.

References

- Barker, R. G. (1968) *Ecological Psychology. Concepts and Methods for Studying the Environment of Human Behavior*, Stanford: Stanford University Press.
- Barker, R. G., and Associates. (1978) *Habitats, Environments, and Human Behavior. Studies in Ecological Psychology and Eco-Behavioral Science from the Midwest Psychological Field Station, 1947–1972*, San Francisco: Jossey-Bass Publishers.
- Cardelli, L., and Gordon, A. D. (1998) "Mobile Ambients," in M. Nivat (ed.), *Foundations of Software Science and Computational Structures. Proceedings of the First International Conference*, Berlin and Heidelberg: Springer-Verlag, pp. 140–55.
- Cartwright, R. (1975) "Scattered Objects," in K. Lehrer (ed.), *Analysis and Metaphysics*, Dordrecht: Reidel, pp. 153–71.
- Casati, R., Smith, B., and Varzi, A. C. (1998) "Ontological Tools for Geographic Representation," in N. Guarino (ed.), *Formal Ontology in Information Systems*, Amsterdam and Oxford: IOS Press, pp. 77–85.

- Casati, R., and Varzi, A. C. (1994) *Holes and Other Superficialities*, Cambridge, MA, and London: MIT Press (Bradford Books).
- Casati, R., and Varzi, A. C. (1996) "The Structure of Spatial Location," *Philosophical Studies* 82, 205–39.
- Casati, R., and Varzi, A. C. (1997) "Spatial Entities," in O. Stock (ed.), *Spatial and Temporal Reasoning*, Dordrecht, Boston, and London: Kluwer Academic Publishers, pp. 73–96.
- Casati, R., and Varzi, A. C. (1999) *Parts and Places The Structures of Spatial Representation*, Cambridge, MA, and London: MIT Press (Bradford Books).
- Cohn, A. G., and Varzi, A. C. (1998) "Connection Relations in Mereotopology," in H. Prade (ed.), *Proceedings of the 13th European Conference on Artificial Intelligence*, Chichester: John Wiley & Sons, pp. 150–54.
- Damuth, J. (1985) "Selection among 'Species': A Formulation in Terms of Natural Functional Units," *Evolution* 39, 1132–46.
- Egenhofer, M. J., and Mark, D. M. (1995) "Naive Geography," in A. U. Frank and W. Kuhn (eds.), *Spatial Information Theory A Theoretical Basis for GIS. Proceedings of the Second International Conference*, Berlin and Heidelberg: Springer-Verlag, pp. 1–15.
- Eldredge, N. (1989) *Macroevolutionary Dynamics Species, Niches, and Adaptive Peaks*, New York: McGraw-Hill.
- Elton, C. (1927) *Animal Ecology*, New York: Macmillan.
- Frank, A. (1997) "Spatial Ontology: A Geographical Information Point of View," in O. Stock (ed.), *Spatial and Temporal Reasoning*, Dordrecht, Boston, and London: Kluwer Academic Publishers, pp. 135–53.
- Gibson, J. J. (1979) *The Ecological Approach to Visual Perception*, Boston: Houghton-Mifflin (reprinted Hillsdale, NJ: Lawrence Erlbaum, 1986).
- Guarino, N., ed. (1998) *Formal Ontology in Information Systems*, Amsterdam and Oxford: IOS Press.
- Hacker, P. M. S. (1982) "Events and Objects in Space and Time," *Mind* 91, 1–19.
- Hall, E. T. (1966) *The Hidden Dimension*, Garden City: Doubleday.
- Hraber, P. T., Jones, T., and Forrest, S. (1997) "The Ecology of Echo," *Artificial Life* 3, 165–90.
- Hutchinson, G. E. (1978) *An Introduction to Population Ecology*, New Haven: Yale University Press.
- Husserl, E. (1900/1901) *Logische Untersuchungen*. Halle: Niemeyer (2nd ed. 1913; Eng. trans. by J. N. Findlay, *Logical Investigations*, Two Volumes, London: Routledge & Kegan Paul, 1970).
- Kuratowski, C. (1922) "Sur l'opération A^- de l'Analysis Situs," *Fundamenta Mathematicae* 3, 182–199.
- Leśniewski, S. (1916) *Podstawy ogólnej teorii mnogości. I*, Moscow: Prace Polskiego Koła Naukowego w Moskwie (Eng. trans. by D. I. Barnett, "Foundations of the General Theory of Sets. I," in S. Leśniewski, *Collected Works*, ed. by S. J. Surma et al., Dordrecht, Boston, and London: Kluwer Academic Publishers, 1992, Vol. 1, pp. 129–173).
- Leśniewski, S. (1927/1931) "O podstawach matematyki," *Przegląd Filozoficzny* 30, 164–206; 31, 261–91; 32, 60–101; 33, 77–105; 34, 142–70 (Eng. trans. by D. I. Barnett, "On the Foundations of Mathematics," in S. Leśniewski, *Collected Works*, ed. by S. J. Surma et al., Dordrecht, Boston, and London: Kluwer Academic Publishers, 1992, Vol. 1, pp. 174–382).
- Lewontin, R. (1979) "Sociobiology as an Adaptationist Program," *Behavioral Science* 24, 5–14.
- Milne, G. R. (1990) *An Ecological Niche Theory Approach to the Assessment of Brand Competition in Fragmented Markets*, Dissertation, School of Business Administration, University of North Carolina at Chapel Hill.
- Perzanowski, J. (1993) "Locative Ontology. Parts I–III," *Logic and Logical Philosophy* 1, 7–94.
- Sack, R. D. (1986) *Human Territoriality. Its Theory and History*, Cambridge: Cambridge University Press.
- Schoggen, P. (1989) *Behavior Settings. A Revision and Extension of Roger G. Barker's Ecological Psychology*, Stanford: Stanford University Press.
- Simons, P. M. (1987) *Parts. A Study in Ontology*, Oxford: Clarendon Press.

- Simons, P. M., and Dement, C. W. (1996) "Aspects of the Mereology of Artifacts," in R. Poli and P. M. Simons (eds.), *Formal Ontology*, Dordrecht, Boston, and London: Kluwer Academic Publishers, pp. 255–76.
- Smith, B. (1993) "Ontology and the Logistic Analysis of Reality," in N. Guarino and R. Poli (eds.), *Proceedings of the International Workshop on Formal Ontology in Conceptual Analysis and Knowledge Representation*, Padova: Ladseb-CNR, 51–68 (revised version as "Mereotopology: A Theory of Parts and Boundaries," *Data and Knowledge Engineering* 20, 1996, 287–304).
- Smith, B. (1995) "On Drawing Lines on a Map," in A. U. Frank and W. Kuhn (eds.), *Spatial Information Theory. A Theoretical Basis for GIS*, Berlin and Heidelberg: Springer-Verlag, pp. 475–84.
- Smith, B. (1997) "Boundaries: An Essay in Mereotopology," in L. H. Hahn (ed.), *The Philosophy of Roderick Chisholm* (Library of Living Philosophers), Chicago and La Salle, IL: Open Court, pp. 534–61.
- Smith, B. (1999) "Objects and Their Environments: From Aristotle to Ecological Psychology," in A. Frank (ed.), *The Life and Motion of Socioeconomic Units*, London: Taylor and Francis, in press.
- Smith, B., and Varzi, A. C. (1999) "Fiat and Bona Fide Boundaries," *Philosophy and Phenomenological Research*, in press.
- Steen, L., and Seebach, A. (1970) *Counterexamples in Topology*, New York: Holt, Rinehart, and Winston.
- Sterelny, K., and Griffiths, P. (1999) *Sex and Death: An Introduction to the Philosophy of Biology*, Chicago: University of Chicago Press.
- Tarski, A. (1929) "Les fondements de la géométrie des corps," *Księga Pamiątkowa Pierwszego Polskiego Zjazdu Matematycznego*, suppl. to *Annales de la Société Polonaise de Mathématique* 7, 29–33 (Eng. trans. by J. H. Woodger, "Foundations of the Geometry of Solids," in A. Tarski, *Logics, Semantics, Metamathematics. Papers from 1923 to 1938*, Oxford: Clarendon Press, 1956, pp. 24–29).
- Taylor, R. B. (1988) *Human Territorial Functioning. An Empirical, Evolutionary Perspective on Individual and Small Group Territorial Cognitions, Behaviors and Consequences*, Cambridge: Cambridge University Press.
- Tye, M. (1990) "Vague Objects," *Mind* 99, 535–557.
- Uexküll, J. von. (1934) *Streifzüge durch die Umwelten von Tieren und Menschen: Ein Bilderbuch unsichtbarer Welten*, Berlin: Springer-Verlag (Eng. trans. by C. H. Schiller, "A Stroll Through the World of Animals and Men," in C. H. Schiller (ed.), *Instinctive Behaviour: The Development of a Modern Concept*, New York: International Universities Press, 1957, pp. 5–80).
- Varzi, A. C. (1994) "On the Boundary Between Mereology and Topology," in R. Casati, B. Smith, and G. White (eds.), *Philosophy and the Cognitive Sciences*, Vienna: Hölder-Pichler-Tempsky, pp. 423–42.
- Varzi, A. C. (1996a) "Parts, Wholes, and Part-Whole Relations: The Prospects of Mereotopology," *Data and Knowledge Engineering* 20, 259–86.
- Varzi, A. C. (1996b) "Reasoning about Space: The Hole Story," *Logic and Logical Philosophy* 4, 3–39.
- Varzi, A. C. (1997) "Boundaries, Continuity, and Contact," *Noûs* 31, 26–58.
- Whitehead, A. N. (1919) *An Enquiry Concerning the Principles of Human Knowledge*, Cambridge: Cambridge University Press.
- Whitehead, A. N. (1929) *Process and Reality. An Essay in Cosmology*, New York: Macmillan.
- Whittaker, R. H., and Lewin, S. A., eds. (1975) *Niche Theory and Applications* (Benchmark Papers in Ecology 3), Stroudsburg, PA: Dowden, Hutchinson, and Ross.
- Woodger, J. H. (1937) *The Axiomatic Method in Biology*, London: Cambridge University Press.