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MARCOS LOPES, PAULO E. SANTOS

Looking for a Rational Substratum Constraining the Cognition of Spatial Expressions

Inhabited space transcends geometrical space.

Gaston Bachelard

ABSTRACT: Representing space is very often an attempt of representing some kind of logical meta-theory universally sound and materially adequate – or, to put it shortly, it is an attempt to represent thought itself. It is tempting therefore to investigate the expression of spatial relations in natural language in order to evaluate whether they seem to lie on any rational grounds. And in a somewhat sharp distinction to that, we review some recent Artificial Intelligence proposals for spatial knowledge manipulation whose accent is on formalization, hoping that the contrast between natural language descriptions and formalized models will shed a light on the common directions they both head to and, perhaps more importantly, unriddle the vast amount of work yet to be done.

We discuss some several well-known linguistic and cognitive based contributions on this matter including Levinson's reference frames [1996], Levelt's [1989, 1996] and Talmy's [2000, 2003, 2008] studies focusing mainly on the general "viewer / object / environment" verbalization problem. We argue that these works and many others would benefit with the definition of formal systems constraining the qualitative aspects of spatial expressions. This would provide mathematical tools to verify the hypotheses generated by the language scholars, whereas linguistic studies would render the ecological constraints permeating the use of spatial expressions. The formalization of space is the goal of Qualitative Spatial Reasoning, a part of an Artificial Intelligence sub-area called Knowledge Representation. However, the cross-fertilization between Qualitative Spatial Reasoning formalisms and field-research in cognitive linguistics is yet to be bridged.

KEY WORDS: spatial expressions, natural language, spatial cognition, knowledge representation, qualitative spatial reasoning

Spatial expressions as a means to mind and reasoning

Spatial relations have always been used by philosophers and scientists alike to represent conceptual relations. In grammar, for instance, the etymological motivation for the word “substantive” is “to stand under”. In psychoanalysis, Freud has conceived the psychic apparatus in different “topoi”: Id, Ego and Superego (the “super” part is to be noticed, or its equivalent in German, *Über*). In the middle 1900s, Bachelard wrote *La Poétique de l’espace*, depicting oneiric and phenomenological determinants of architectural space.

But perhaps no author brought spatial relations so explicitly to the center of the very possibility of thought as Frege with his *Begriffsschrift*. To clearly state how concepts relate one to another, Frege created bi-dimensional diagrams and special symbols aimed at visually exhibiting inclusion, exclusion, negation, quantification and so on. In these diagrams, horizontality (i.e., horizontal strokes) represents concepts, whereas verticality (vertical strokes) represents judgements [1, §2]. In this way all logic should be represented spatially in the *Begriffsschrift.* It is worth pointing out the existence of some pre-Fregean diagrammatical reasoning, as cited in [Bocheński, 1961].

Representing space is thus representing some kind of metatheory as universally sound and materially adequate; or, to put it shortly, it is to represent thought itself.

It is tempting therefore to investigate the expression of spatial relations in natural language in order to evaluate whether they seem to lie on any rational grounds. And in a somewhat sharp distinction to this, we review some recent Artificial Intelligence proposals for spatial knowledge manipulation whose accent is on formalisation. May the contrast between natural language descriptions and formalized models shed light, or so we hope, on the common directions they both head to and, perhaps more importantly, unriddle the vast amount of work yet to be done.

Space mapping in natural languages

Some authors conceive spatial expressions (particularly locatives) as a means to reduce the uncertainty of some object position or a given point in space [Miller & Johnson-Laird, 1976, *apud* Coventry, Garrod, 2004, p. 21]. It is possible to implement such conceptions in computational systems *via* probabilistic methods for determining locations in space [see, for ex., Tellex *et al*., 2011] and, furthermore, to use those methods to equip vision-capable robots and, through supervised learning, enhance the accuracy of their interpretation of natural language concerning locatives [Walter *et al*., 2013]. Although such methods may reasonably fit for many specific robotic navigation and localization tasks, it seems to leave aside some distinctive features of representing space in human communication. We take it as highly disputable whether humans would put probabilistic models to use in order to determine the meaning of spatial expressions – or any other kind of expressions. On the other hand, the idea of mapping space directly from perception, however fairly more plausible, does not suffice to explain all spatial expressions on its own. Let us examine this further.

While it is beyond dispute that spatial language is somehow to be grounded in perception, it is no less true that perception alone does not suffice to justify the meaning of the spatial expressions we use in everyday life. As Jackendoff puts it, "by the time visual information is converted into shape information, its strictly visual character is lost – it is no longer retinotopic, for example" [Jackendoff, 1996]. Coventry & Garrod [2004, p. 128] point out that "what a spatial preposition means in a specific context is a function of information present in the visual scene, knowledge of the objects in that scene, and an appreciation of how those objects are functioning in that particular context". As for proximity terms like "near" and "far", for instance, it is evident that not only the distance between two objects is relevant but also the size of the objects; and, in the case of (at least one) moving object, speed also affects judgements of proximity. In a series of experiments with functionally-related objects, like a couch and a TV set, Ferenz found that objects whose fronts were facing each other were significantly considered closer one to another than if they were oriented otherwise, or if functionally unrelated objects (like a bicycle and a cooker) were facing each other [Ferenz, 2000, apud Coventry & Garrod 2004, pp. 116–117]. This interestingly seems to make clear that social habits or perhaps the customary usage of objects at least partially determines proximity judgements. Finally, as indicated by Coventry & Garrod [2004, p. 114], "small objects are also usually located with reference to larger objects […] and mobile objects are usually located with reference to immobile objects, but not *vice versa*".

Idiosyncratic constraints also play a role in how space is expressed in different languages. "Spatial prepositions", Coventry & Garrod [2004, p. 4] say, "are among the hardest expressions to acquire when learning a second language [because] languages differ in the way in which they map linguistic terms onto spatial relations". It is enough to keep referential-based theories at bay especially considering this assertion is true even for a single preposition of a single language, provided that this preposition can be used in dissimilar contexts. Take the English "in", for example. It allows divergent spatial interpretations when put to use in sentences like "The star looked very high in the sky" and "I shut my thumb in the car door". In every natural language the same difficulties are supposed to arise, since a characteristic feature of all of them is that there is no formal homology between a phonological and syntactical *type* and its semantical *tokens* (its meanings), which varies depending on the usage contexts. Even for identical combinations between a preposition and its nominal complements we should expect the interpretation to be identical as well. Insisting on the "in the car door" example, the interpretation of what "in" means sticks out when the syntactic subject changes: "A scratch in the car door" *vs.* "A bullet in the car door".

One of the most influential conceptions on expressing the location of a focalized object ("figure") against some non-focalized object ("ground") is that of Levinson's [1996] "frames of reference", which can be:

1) Intrinsic (using features from the ground)
2) Relative (to the viewer's body)
3) Absolute (not from some viewer's perspective, neither bound to the ground)

Levelt's [1996] contribution on this matter was also to become widely spread. He also conceives it as a three-fold "perspective system", namely:

1) Deictic perspective (speaker centered)

2) Intrinsic perspective (*relatum* centered)

3) Absolute perspective (neither of the above)

Language deeply influences the choice for one perspective or another. So, as Levelt notes, "Speakers of Guugu Yimithirr are exclusive users of an absolute perspective system, Mopan speakers are exclusive users of an intrinsic system, Tzeltal uses a mix of absolute and intrinsic perspectives, and English uses all three systems". And on the top of this, there is still some room for speaker's choices based on the situation or style criteria; in one word, "there is a pragmatics of perspective systems" [Levelt, 1996].

Interestingly, Carlson-Radvansky and Radvansky [1996] experiment-tally found that people tend to favour the intrinsic reference frame over any other possibility when functionally related objects were presented to them (e.g., "The mail carrier is in front of the mailbox"), whereas they would do the contrary for functionally unrelated objects.

Among contemporary linguists, Leonard Talmy is well-known for his semantic studies on spatial expressions schematization. These are abstract configurations that share certain topological properties such as "magnitude neutrality", "shape neutrality", and "bulk neutrality" [Talmy, 2008]. Magnitude neutrality, for instance, means that a spatial schema may be used when referring to objects of any length as in "The ant crawled across my palm / The bus drove across the country" [Talmy, 2003].

Roughly speaking, there should be two main features in studying spatial expressions from a cognitive point of view. First, this is so because of the (hypothetical, at least) universality of the concepts these expressions bring about; second, because "the findings on how languages represent space are taken as a particular case of the system by which language represents meaning in general" [Talmy 2000, p. 178].

Some examples from the author will hopefully make this clearer. In English, a rider is said to be "*in* a car", whereas if she takes a bus she would be "*on* it". That is because English requires the car to be schematized as an *enclosure*, while the bus is schematized as a *platform.* Still in

English, one person can pass a ball to another *under* the table, but in Atsugewi (a Palaihnihan language from California, USA), players would describe passing the ball *through* the table. This reveals different geometric conceptions of what the table is. For English speakers, it is mostly a top board supported by (accessory) legs; for Atsugewi speakers, on the other hand, it is conceived to have a "volumar configuration" [Talmy, 2003].

Languages thus reveal different geometric frames regarding the conception of objects. Though these frames are not identical translinguistically, they do not contradict each other. In the latter example, the tabletop is absolutely crucial in the English speakers geometric configuration and has a secondary role in the Atsugewi's, but it is still part of it. And in any case, in any configuration, languages reiteratively depict some rational ontology guiding the conception of spatialized objects.

Perspective turns out to be a challenging feature of spatial expressions in natural languages. Perception seems to be always implied in spatial expressions since speakers utterances bring up some visible object in contrast with some visible ground. Following some more of Talmy's examples, saying that "'The bike is in front of the silo' means that the bike is between the silo and the speaker/hearer, while 'The bike is behind the silo' means that the bike is on the opposite side of the silo from the speaker/hearer" [Talmy, 2000, p. 211]. Thus the meanings of "front" and "behind" change according to the speaker's perspective. Therefore a "third component" must very often be taken into account when apparently describing two spatialized objects like the bike and the silo in situations like this: the *observer*, who is also the enunciator describing what he sees. He describes not what it is, but what his point of view allows him to.

A common source of misunderstandings in communicating spatialized objects from a speaker to a hearer is associated with their own situation inside the spatial frame being described. Emile Benveniste [1966, p. 252] points out that the specific point referred to as "here" (or any other in contrast to it, like "there") indicates the location of the speaker during a correspondingly determined amount of time (referred to by "now") and thus changes dynamically even during a conversation.

The role of the enunciation scene, i.e., the dynamical selection of who might be the speaker, the hearer, and the subject of conversation, is of utmost importance for spatial expressions. Levelt [1989, p. 103] notes that there are languages whose deictic proximity system is twofold, like English or Dutch, where a “proximal / medial” distinction applies (namely in words such as *here* and *there*). But in contrast there are others relying on tripartite systems, “proximal / medial / distal”, such as Japanese and Spanish, the latter opposing, for example, *aquí – ahí – allí* for proximity deictics. These are bi- and tripartite paradigms indeed, but the distance from the speaker does not always fit the criterion for what expression to choose. This would accommodate bipartite paradigms but not the tripartite ones. In Spanish it may well be that *allí* is closer to the speaker than *ahí* – for instance, in a telephone conversation with the speakers placed miles away one from another, the speaker will refer to the hearer’s place as *ahí* and to his neighbour’s living room as *allí*. What characterizes the use of these adverbs is, again, their position relatively to the enunciation scene, not to physical distance: *aquí* (and *here*) is the speaker’s space; *ahí* is the hearer’s, and *allí* is the space of someone or something not participating in the enunciation. *There* is suitable for both the latter cases. So enunciation is the key to elucidate the usage of spatial adverbs in conversation, not distance, and this is typically an illustration of how much of spatial expressions can rely on communication, not topography determiners. An enunciation-based approach (like Benveniste’s cited above) not only encompasses all spatial expressions of this kind but is also capable embracing Levelt’s three-fold paradigm for perspective: instead of *deictic*, there is the speaker’s perspective (and Levelt [1996] already acknowledges this one explicitly as he also calls it a “speaker-centered relative system”); instead of *intrinsic*, the hearer’s perspective; and, finally, instead of *absolute*, the perspective of the “out-of-enunciation” participant, which is neither the speaker nor the hearer, and therefore must be superposed to both of them.

We argue in this paper that the work cited above would benefit with the definition of formal systems constraining the qualitative aspects of spatial expressions. This would give the mathematical tools to verify the hypotheses generated by the language scholars, whereas linguistic studies would provide the ecological constraints permeating the use of spatial expressions. The formalization of space is the goal of the field called Qualitative Spatial Reasoning (described in the next section); however, the cross-fertilization between Qualitative Spatial Reasoning formalisms and field-research in cognitive linguistics is yet to be fully bridged.

Qualitative Spatial Reasoning

Qualitative Spatial Reasoning (QSR) is part of the sub-area of Artificial Intelligence (AI) called Knowledge Representation. The goal of QSR is the development of systems to achieve a level of spatial knowledge manipulation similar to that used by humans on a daily basis. In other words, QSR intends to develop systems able to understand, think and act about relationships between everyday objects, such as “the glass is in front of the vessel”, “Bonito is part of the state of Mato Grosso do Sul”, etc. This type of knowledge is often impossible, and generally computationally infeasible, to be represented with the numerical methods used in the natural sciences. Thus, research on spatial reasoning in AI has largely been developed independently of the areas related to the geometry and topology [Bennett, 1997].

We can trace the origins of spatial reasoning formalisms in AI to the early twentieth century, with Whitehead’s proposal for the development of phenomenological theories to describe (logically) the world as seen by the human perception. In this phenomenological approach, physical objects and events become the primitive elements of a kind of “geometry” whose goal is to formalize the basic laws ruling the relationships of these elements, and to calculate these particular configurations from the basic laws. According to Whitehead:

> We diverge from Descartes by holding that what he has described as primary *attributes* of physical bodies, are really the forms of internal relationships *between* actual occasions. Such a change of thought is the shift from materialism to Organic Realism, as a basic idea of physical science. [Whitehead, 1929, p. 471]

The construction of formal theories about the relations between space and objects is the central goal of the qualitative spatial reasoning field.

In this section we present some of the main formalisms of spatial reasoning in AI. Our goal here is not to do a complete literature review on qualitative spatial reasoning (which can be found in Stock [1997]; Cohn and Hazarika [2001]; Cohn and Renz [2008]; Ligozat [2011]), but rather to present the fundamental concepts of this area.

One of the most well-known theories for qualitative spatial reasoning is the Region Connection Calculus (RCC) [Randell, Cui and Cohn, 1992]. RCC is a many-sorted first-order axiomatization of spatial regions based on a binary primitive relation about the connection between two regions (C/2). Informally, given two regions x and y, the relation C(x, y) ("x is connected to y") is true if and only if the topological closures of x and y have at least one point in common. With respect to C/2, RCC defines a number of mereotopological relations, such as: "x is part of y" (P(x, y)), "x overlaps y" (O(x, y)), "x is proper part of y" (PP (x, y)), "x is disconnected from y" (DC(x, y)), "x is equal to y"(EQ (x, y)), "x overlaps y" (O(x, y)), "x is externally connected to y" (EC (x, y)), "x is tangential proper part of y "(TPP (x, y)), "x is non-tangential proper part of y" (NTPP (x, y)).

The region connection calculus has been applied, for example, to qualitative simulation [Cui *et al.*, 1992], or to the representation of forms [Gotts, 1994], in a qualitative theory movement [Wolter, Zakharyaschev, 2000]; [Muller, 1998] and as the basis for modelling the relationship between the observer and the object, such as occlusion [Randell *et al.*, 2001]; [Randell, Witkowski, 2002].

An in-depth discussion of qualitative changes in spatial reasoning is presented in Galton [2000]. In particular the region connection calculus is used in Galton [2000] to represent different types of motion, such as a region entering into another, or two regions (initially disconnected) meeting each other.

The temporal model in Galton [2000] assumes both instants and time intervals. Therefore, a state of the world may hold at an instant or during a time interval, and this distinction is incorporated into the theory by means of two predicates: *HoldsT* which represents a true state at a time instant and *HoldsI* for states that hold during a time interval. From these definitions, eight distinct types of transition between state pairs are defined to cover all the possible combinations between two states in time. The work of Galton pioneered the development of various qualitative theories about movement. Muller [2002] and Muller [1998] introduce qualitative theories of motion where RCC is the basic language in the definition of space-time relations. A family of logics for representing time-space regions is investigated in Wolter and Zakharyaschev [2000], wherein the region connection calculus is defined in terms of the modal system S4 and it is integrated into a temporal logic that formalizes relations such as “since” and “until”.

There is also a number of formalisms for representing the qualitative relations of position or direction. The cardinal direction calculus (CDC) [Frank, 1996] is a formalism for automatic reasoning about directions between spatial objects. The set of basic relations of this calculus is composed of nine relations: north, south, east, west, northeast, northwest, southeast, southwest and EQ (EQ (x, y) means “x is in the same direction y”). The central task of the CDC is to perform inferences about the relative direction between two objects A and B from the direction of A and another object C (distinct from A and B). For example, given that “north(A, B)” and “northeast(B, C)” hold, the task is to calculate the possible relations between A and C. In Ligozat [1998] a binary constraint network is developed for this calculus in which cardinal directions are defined as two-dimensional lines between two point objects in a 2D space. Thus, the problem of reasoning about cardinal directions is reduced to a problem of constraint propagation. Another important formalism about directions is the double-cross calculus [Freksa, 1992; Scivos, Nebel, 2001]. This formalism defines the direction of a point with respect to an oriented straight line by means of 15 ternary relations, listing all the possible compositions of directions between front-back and left-right. A more complex formalization of qualitative spatial directions surrounding the reference points in a three dimensional space are presented in Ragni and Wölfl [2006]; Moratz and Wallgrün [2012], among others. There has been some recent work on bridging the gap between formal systems and language (e.g. [Mart *et al*., 2014; Sprangler and Pauw, 2012; Rodrigues *et al*., 2016]). However, the full complexity of the various space representations used in the natural languages (as pointed out previously in this article) is still to be understood.

Conclusion

This paper has discussed some of the issues related to the linguistic study of spatial expressions and described the key formalisms for Qualitative Spatial Reasoning (QSR), which are just a sample of the methods developed in this field [Cohn, Renz, 2008; Ligozat, 2011].

Although presenting a thorough analysis of the distinct aspects related to space, the linguistic literature lacks a common ground, or a base formalism, with which the mental structures that allow the cognition of space could be built from the observations of the use of natural languages. We believe that this *representational substratum* for such space cognition could at least partially be developed using ideas from the various theories developed in QSR. The field of qualitative spatial reasoning, however, has been developed independently from the study of natural languages and, therefore, currently there is no formalism capable of coping with issues such as vagueness and polysemy, let alone the functional and idiomatic determinants of speech. These are issues common to any (natural) language and, thus, they should be part of the representational substratum for space cognition.

An opportunity thus arises for the application of qualitative spatial reasoning formalisms to constrain the meaning of spatial expressions. Confronting the use of spatial expression in natural languages with the current formal systems for representing space may lead to the definition of new formalisms in order to cope with the various issues related to the natural use of language, a task that has been largely overlooked by the scientific community.

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Paulo E. Santos,
Artificial Intelligence and Automation Lab. Centro Universitário FEI,
Av. Humberto de A. C. Branco, 3972, CEP. 09850-901 São Paulo, SP – Brazil,
psantos@fei.edu.br

Marcos Lopes,
Universidade de São Paulo, Departamento de Linguística,
Av. Prof. Luciano Gualberto, 403 – Sala 16, 05508-010 São Paulo, SP – Brazil,
marcoslopes@usp.br