Standpoint semantics for polysemy in spatial prepositions

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Abstract

In this paper, we present a formalism for handling polysemy in spatial expressions based on supervaluation semantics called standpoint semantics for polysemy (SSP). The goal of this formalism is, given a prepositional phrase, to define its possible spatial interpretations. For this, we propose to characterize spatial prepositions by means of a triplet ⟨image schema, semantic feature, spatial axis⟩. The core of SSP is predicate grounding theories, which are formulas of a first-order language that define a spatial preposition through the semantic features of its trajector and landmark. Precisifications are also established, which are a set of formulae of a qualitative spatial reasoning formalism that aims to provide the spatial characterization of the trajector with respect to the landmark. In addition to the theoretical model, we also present results of a computational implementation of SSP for the preposition 'in'.

Keywords: Supervaluation semantics, spatial prepositions, polysemy

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1 Introduction

The ability to relate with objects in space is one of the most basic skills required of a living organism [1], and being able to describe where objects are located using simple locative descriptions is considered one of the most important capabilities for any speaker of a language [2, 3]. Spatial expressions are present in everyday life and occur in a wide variety of contexts, such as object localization, scenario representation and understanding of the placement of objects. For a large number of natural languages (including Indo-European languages), spatial descriptions involve the use of prepositions. Nevertheless, prepositions do not fully specify all the possibilities of spatial localization, being therefore necessary to assign for the same preposition different senses depending on the context. This is polysemy. The diversity of senses can lead to misleading communication between humans and between human and robotic agents. The general purpose of this paper is to provide a formal and computational way of addressing the diversity of senses.

Spatial prepositions are polysemous words [4, 5]. They are also part of a set of expressions that, together, act as an organizing structure for other material concepts [6, 7]. In cognitive linguistics, spatial expressions can be considered as primary structuring tools for other areas, hence the extensive use of spatial metaphors [8]. Moreover, from a semantic point of view, spatial prepositions are in some way related to the descriptions of scenery and, therefore, to the measurable characteristics of the world [9].

Generally, relations between objects are conveyed by non-quantitative expressions (e.g. ‘the cup is on the table’ or ‘the chair is in the room’) rather than by quantitative terms. This calls for the use of qualitative predicate terms to represent and formally define spatial relations. The area of artificial intelligence that investigates these formalisms is called qualitative spatial reasoning (QSR).

According to [10], QSR is a subarea of knowledge representation in artificial intelligence whose goal is to formalize space in terms of elementary entities and primitive relations in order to approximate a commonsense contextualization of space. QSR abstracts metric details from the physical world and allows computers to make predictions about spatial relations even when accurate quantitative information is unavailable [11]. From a practical point of view, QSR is an abstraction that summarizes similar quantitative states in a qualitative characterization. A complementary view from a cognitive perspective is that qualitative methods compare resources within the object domain rather than measure them by means of some artificial external scale.

A particular QSR formalism named region connection calculus (RCC) is used in this paper [12]. RCC is based on a reflexive and symmetric primitive relation (C) between pairs of spatial regions, representing region connectivity. In this paper, the concept of image schema [13] is used to apply QSR by instantiating spatial expressions appropriately.

Once the image schemata related to spatial expressions are defined, RCC is extended to model spatial relations with unambiguous formal definitions. One problem to be addressed here is that some terms representing spatial relations between objects may have more than one meaning, leading thus to potentially ambiguous interpretations. In order to deal with this issue, this work uses a supervaluation-semantic model named *standpoint*. In supervaluation semantics, a language is interpreted as a set of distinct meanings called precisifications [14]. A standpoint can be modelled by a structure encompassing three sets: (i) *possible worlds* compatible with the agent’s beliefs, (ii) *precisifications* acceptable to the agent and (iii) *predicate grounding theories* that specify different ways in which vague terms can be represented in relation to some logical combination of restrictive thresholds [15, 16]. It should be noted that a standpoint was originally designed to handle vague terms [15]. In this work, this idea is extended to facilitate its application to polysemous terms.

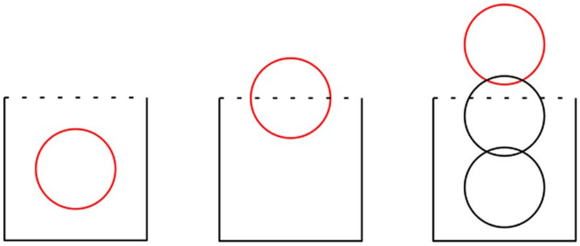

FIGURE 1 Proto-scene examples.

Standpoint semantics for polysemy (SSP), introduced in this paper, proposes some new definitions of the concepts of possible worlds, predicate grounding theories (PGT) and precisifications, compared to standpoint semantics as introduced in [15]. Possible worlds in this work are obtained by mapping spatial expressions in the language to a combination of image schemata, spatial axes and semantic features (semes). This mapping may lead to worlds where the preposition may (or may not) hold. Possible worlds define the use-types of a spatial preposition. For example, in the phrase ‘the ring is in the box’, the preposition ‘in’ refers to the *containment* schema, whereas in the phrase ‘the nail is in the wall’ the schema is of *wrapping*. There are cases in which the image schemata are the same, but the *spatial axis* represented is different. Take for instance the phrases ‘the vase on the table’ and ‘the picture on the wall’. In both cases, the image schema is that of *support*, that is, both the wall and the table support the weight of the frame or vase. However, in the first sentence there is a relation of verticality that does not occur in the second example. PGT take into account the semantic features of the trajector and the landmark in a phrase to determine their spatial relation. It is the PGTs that lead one to conceive the ‘table’ object as a horizontal surface and ‘wall’ as a non-horizontal surface. Finally, precisifications define the possible distinct spatial arrangements that a spatial expression can represent.

In this work, an algorithm is implemented over the SSP definitions in order to extract the interpretation of a sentence containing a spatial expression. More precisely, after pre-processing (tokenizing and pos-tagging) the sentences from the corpus, all phrases with preposition ‘in’ are selected, and the nominal arguments from them are used as inputs to the main algorithm, which returns a set of interpretations and proto-scenes representing these interpretations as outputs. The proto-scenes are graphical representations of the interpretations based on the semantic features of the terms that accompany the spatial preposition and the spatial mereotopology representation obtained using RCC [12]. The main motivation for the implementation of this algorithm was to investigate ambiguities in the interpretation of spatial expressions and how to solve this using the qualitative spatial configurations of such expressions. For example, in the phrase ‘the pear is in the basket’ there are three possible interpretations: (i) the pear is fully enclosed in the basket, (ii) the pear is partially enclosed in the basketand (iii) the pear is out of the basket, but in contact with some other object (other pears or something else) included inside the basket. Figure 1 illustrates the proto-scenes related to this phrase.

The algorithm was implemented using the Python natural language processing module NLTK. Among other features, NLTK incorporates an English language lexicon database called WordNet that allows the extraction of the semantic features of words [18, 19].

Beyond the interpretation of prepositional phrases and sentences, we are mainly concerned with formalizing a feature-integrating unit represented by the spatial description of scenes as a whole.

It would be tempting to say that we depart from full utterances down to simpler components, but this would be misleading. Based on Coventry [1], Johnson [20] and others, we adopt a multimodal view of speakers' utterances, embracing their linguistic, visual and functional aspects. None of those aspects would comprise all of the relevant scenario features on its own. The spatial configurations elicited by the prepositional phrases 'A nail in the wall' and 'A nail in the box' bring out an important positional difference between the nails. If the first one is graphically depicted or verbally described, the nail will most probably be represented in a perpendicular position to the wall. In the latter, the nails in the box take positions inside it. In the first scenario, the wall serves as a surface to accommodate the nail, whereas in the latter, the box is usually a container for the nails. These differences cannot be captured by a purely compositional semantics, without additional machinery to process polysemy. Similarly for most topological or mereological characteristics of objects in spatial configurations. Our proposed formalism provides that machinery; afterwards, compositional semantics can be applied.

This paper is structured as follows. Section 2 describes related work. Section 3 presents RCC, which is the basis for the precisifications and definitions of the spatial location of the trajector in relation to the landmark. In Section 4, we introduce the supervaluation semantics for polysemy, based on a previous work by Bennett [15]. Section 5 presents the implementation of SSP for the preposition 'in' and, finally, Section 6 presents discussion and conclusions.

2 Related work

In this section, we give a brief description of some related work on modelling the semantics of spatial prepositions.

The research reported in [21] defines a semantic representation model of spatial prepositions such as 'near', 'far', 'inside' and 'above' based on physical properties such as area and distance. An approach to the semantics of spatial locative and directional prepositions for conceptual spaces is presented in [22].

In [23], a semantics is described for modelling the meanings of spatial prepositions by means of two distinct approaches: regions and vectors. The author argues that region-based semantics are effective in dealing with prepositions involving contact, contiguity and inclusion, such as 'in', 'on' and 'at'. The vector approach would be more appropriate for projective prepositions, such as 'in front of', 'behind', 'above' and 'below'.

Formal models and machine learning techniques are applied in [24] to map spatial semantics in natural languages into qualitative spatial representations. In particular, it is investigated whether and how well linguistic features can be classified, automatically extracted and mapped to region-based qualitative relations using corpus-based learning.

For the use-types of prepositions, we rely on work from cognitive linguistics such as [1, 25, 26]. Herskovits [25] proposes an analysis of locative expressions in English whose goal is to place the study of linguistic expressions (in particular, spatial expressions) within the broader context of language usage and the conventions associated with communicating goals and beliefs. Thus, work on linguistic expressions should be evaluated from the perspective of cognitive science as an interdisciplinary field and not simply as a linguistic treatise on prepositions or a computational model of a subset of natural language. Tyler and Evans [26] proposed a model called principled polysemy where a semantic network of spatial prepositions is explained with one central meaning, all of the polysemous spatial prepositions exhibiting a semantic network with motivated extended meanings. Coventry and Garrod [1] suggest that 'our use of spatial prepositions carries an implicit understanding of the functional relationships both between objects themselves and human interaction with those objects'. They present functional and geometric constraints on which comprehension and human action on spatially related objects are based. These works served as a basis for establishing the types of use of the preposition 'in' in the present paper, as described in Section 5.

Inspired by the work reported in [27], which uses the theory of Brunet [28] to obtain visual descriptions through texts, SSP also presents visual descriptions of arrangements of objects from texts containing spatial expressions. Chang *et al.* [29] introduces a set of annotated 3D scene data with natural language descriptions for learning how to base textual descriptions on physical objects, while in [30] the authors feature a system called *WordsEye* to automatically convert text to representative 3D scenes. This system relies on a database of 3D models to map entities and their relations. Each 3D model can have shape, labels and related functional properties.

In [31], the authors describe a system that automatically converts domain-specific narratives to 3D scenes. The texts, written in Swedish, describe road accidents. One of the main features of the program is that it generates scenes using temporal relations between events. The system consists of three modules: natural language interpretation based on information extraction methods; a planning module that produces a geometric description of the accident; and a visualization module that renders the geometric description as animated graphics. The authors in [32] have developed a system for generating 3D visual simulations of natural language motion expressions. To do so, they use a game engine called Unity[1] to generate the graphics and process the inputs and outputs. Inputs are simple annotated natural-language sentences that are handled by external processors, such as the parser ClearNP, and that are referenced to objects in a scene. Pustejovsky and Krishnaswamy [33] provides the specification of a modelling language called VoxML, which encodes semantic knowledge of real-world objects represented as 3D models, as well as events and attributes related to those objects. The goal of VoxML is to overcome limitations in visual markup languages by enabling the coding of a wide range of semantic knowledge that can be exploited by a variety of systems and platforms, leading to multimodal simulations of real-world scenarios using conceptual objects that represent their semantic values.

Bateman *et al*. [34] put forth an extension of a linguistic ontology (generalized upper model) specifically adapted to deal with spatial expressions. As we do in the present article, the authors base their work on linguistic features rather than on geometric or logical features of spatial expressions. They also acknowledge the problem of artificially separating semantic and contextual interpretations for spatial expressions, which is a very common issue with many theoretical proposals that start from relying on simple semantic mappings of expressions but end up failing on most contextual interpretations.

Dobnik and Cooper [35] use type theory with records to provide a computational modelling of spatial descriptions involving perception, movement and natural language. One important feature of their proposal is the ability to deal with low-level perceptual judgements as well as with conceptual judgements. In contrast, even though the present work involves experimental data, it does not focus on actual perceptual concerns but rather on semantic issues such as accessibility (via possible worlds) and supervaluation of meaning (via precisifications). Those issues may contribute to the discussion of other topics laid out by Dobnik and Cooper, namely, 'to find a mapping between a [. . .] geometric representation of a scene with continuous parameters [. . .] to cognitive categories that are reflected in language' and the representation of gradience and vagueness, for which, according to them, possible worlds could be employed.

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[1] https://en.wikipedia.org/wiki/Unity_(game_engine), accessed on 11th of November 2019.

TABLE 1 RCC relations.

Relation	Meaning
$DC(x,y) \equiv_{def} \neg C(x,y)$	x is disconnected from y.
$P(x,y) \equiv_{def} \forall z(C(z,x) \rightarrow C(z,y))$	$x$is part of y.
$PP(x,y) \equiv_{def} P(x,y) \wedge \neg P(y,x)$	x is a proper part of y.
$EQ(x,y) \equiv_{def} P(x,y) \wedge P(y,x)$	x is equal to y.
$O(x,y) \equiv_{def} \exists z(P(z,x) \wedge P(z,y))$	x overlaps y
$PO(x,y) \equiv_{def} O(x,y) \wedge \neg P(x,y) \wedge \neg P(y,x)$	x partially overlaps y.
$DR(x,y) \equiv_{def} \neg O(x,y)$	x is discrete from y.
$EC(x,y) \equiv_{def} C(x,y) \wedge \neg O(x,y)$	x is externally connected to y.
$TPP(x,y) \equiv_{def} PP(x,y) \wedge \exists z(EC(z,x) \wedge EC(z,y))$	x is a tangential proper part of y.
$NTPP(x,y) \equiv_{def} PP(x,y) \wedge \neg\exists z(EC(z,x) \wedge EC(z,y))$	x is a non tangential proper part of y.

2.1 Standpoint semantics for polysemy

SSP, introduced in this work, is a formalism based on the supervaluation semantics proposed by Bennett in [15] for addressing vagueness. As in SSP, Bennett defines the set of interpretations of a sentence based on possible worlds, PGT and precisifications. In that work, possible worlds are real-number assignments to measurement functions related to vague expressions (e.g. ‘height’); PGTs are first-order formulas that define a vague predicate, such as ‘high’ or ‘low’, and the precisifications are assignments of values to the thresholds that define a vague predicate. For example, a precisification for the vague term ‘tall’ could be any value greater than 1.80 m, i.e. people above 1.80 m could be considered tall. In contrast, the SSP introduced in this paper characterizes possible worlds by means of image schemata, spatial axes and semantic characteristics (semes); PGTs define semantic features, and precisifications represent the various possible attributions of QSR formulas to spatial prepositions.

The next section presents one of the key QSR formalisms applied in this work called RCC [12].

3 Region connection calculus

This section presents the RCC and some of its derived definitions, such as the convex hull of regions [12, 17, 36]. RCC is used in this work to define the precisifications of SSP, facilitating the description of spatial relations between objects.

3.1 Connectivity

RCC is built upon the primitive dyadic relation $C(x,y)$ read as ‘x is connected to y’, where x and y are regions in the Euclidean space with at least one point in common. The relation C is axiomatized as reflexive and symmetric. A set of dyadic relations are defined in the Table 1 using C.

The inverses of the relations $P, PP, TPP, NTPP$ are denoted as $Pi, PPi, TPPi$ and $NTPPi$, respectively. In [12], a set of Boolean functions for union ($sum(x,y)$), intersection ($prod(x,y)$) and difference ($diff(x,y)$) between two regions is defined, along with the complement ($compl(x)$) of a region with respect to a universal region U on which all regions are connected. Because of the possibility of joining any two regions, this can result in topologically connected (i.e. a single indivisible part) or disconnected (divided into several parts) regions.

TABLE 2 Relations based on convex hull.

Relation	Meaning
$INSIDE(x,y) \equiv_{def} \neg P(x,y) \wedge P(x, conv(y))$	x is inside y.
$P\text{-}INSIDE(x,y) \equiv_{def}$ $\neg P(x,y) \wedge PO(x, conv(y)) \wedge \exists z(P(z, conv(y)) \wedge \neg P(z,y) \wedge PO(z,x))$	x is partially inside y.
$OUTSIDE(x,y) \equiv_{def}$ $\neg P(x,y) \wedge \neg\exists z(P(z, conv(y)) \wedge \neg P(z,y) \wedge PO(z,x))$	x is outside y.

DEFINITION 3.1
$CON(x)$, read as 'x is an indivisible region formed by a single piece', is defined as: $CON(x) \equiv_{def} \forall yz(sum(y,z) = x \rightarrow C(y,z))$.

This relation is used to define inclusion relations, as described further in this paper.

3.2 Convex hull

In [17], a primitive function $conv(x)$ that returns the smallest convex region of x is introduced. The predicate $CONV(x)$ denotes that x is a convex region. In addition, the function $conv(x)$ is used to define a set of relations representing inclusion and exclusion between regions (Table 2).

The inverses of the relations in Table 2 are denoted by *INSIDEi*, *P-INSIDEi* and *OUTSIDEi*. In [17], the functions $inside(x)$, $outside(x)$ are defined to represent, respectively, the internal and external regions of x.

The relations for (geometric and topological) containment introduced in [17] are also important in the precisification models of SSP. These relations are defined as follows:

DEFINITION 3.2
$TOP\text{-}INSIDE(x,y)$ read as 'x is topologically inside y' is defined as:

$$TOP\text{-}INSIDE(x,y) \equiv_{def} INSIDE(x,y) \wedge \forall z((CON(z) \wedge C(z,x) \wedge C(z, outside(y))) \rightarrow O(z,y)).$$

DEFINITION 3.3
$GEO\text{-}INSIDE(x,y)$ read as 'x is geometrically inside y' is defined as: $GEO\text{-}INSIDE(x,y) \equiv_{def} INSIDE(x,y) \wedge \neg TOP\text{-}INSIDE(x,y)$.

Figure 2 shows an example of the relations $TOP\text{-}INSIDE(x,y)$ and $GEO\text{-}INSIDE(x,y)$.

DEFINITION 3.4
$topinside(x)$ is the function that returns the internal topological region of x.

DEFINITION 3.5
$geoinside(x)$ is the function that returns the internal geometric region of x.

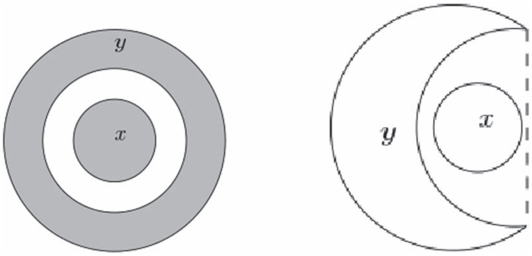

FIGURE 2 **TOP-INSIDE** and **GEO-INSIDE** relations.

In [17], the authors argue that the notion of 'geometrically inside' is not sufficient to represent the idea of containment, which could be more appropriately represented with the following definitions:

DEFINITION 3.6
$LID(w,y,x)$ read as 'x is contained in the sum of the y and w regions' is defined as:

$$LID(w,y,x) \equiv_{def} CONV(w) \wedge P(x, geoinside(y)) \wedge P(x, topinside(sum(w,y))).$$

The relation *LID* represents the situation where a region x is geometrically contained in a region y and y represents a 'capped' region. Therefore, in the $LID(w,x,y)$ relation, the region x is contained in the union of the regions w and y, where w is a 'cap' of y.

The relation *CONT* (defined below) is used when a region x is geometrically included in a capped region y.

DEFINITION 3.7
$CONT\text{-}INSIDE(x,y) \equiv_{def} P(x, geoinside(y)) \wedge \exists w(LID(w,y,x))$.

As stated above, the precisifications of SSP are QSR formulas assigned to spatial predicates. For example, the preposition 'in' can be represented by the relations $IN(x,y)$ (read as 'x is contained in y') that can be precisified as follows:

$$IN(x,y) \equiv TOP\text{-}INSIDE(x,y).$$

A second precisification for $IN(x,y)$ can be obtained assuming that y represents a liquid. This precisification takes the form of:

$$IN(x,y) \equiv CONT\text{-}INSIDE(x,y).$$

The concepts introduced in this section are used in the precisifications for the preposition 'in' in Section 5. The next section discusses the formal definitions of SSP, where the relations described in this section form the basis for defining the precisifications of a spatial precisification model.

4 Standpoint semantics for polysemy

This section introduces formally SSP. As mentioned above, this formalism is based on the supervaluation semantics as proposed by [15]. Thus, the present work shares some of the original formal definitions. The fundamental distinction of this work with respect to [15] is the concept of spatial feature of an expression, which is defined here by the triplet $\langle$image schema ($\mathscr{I}$), semantic feature (Σ), spatial axis (X)$\rangle$, defining *possible worlds* that take part of the description of the basic meaning of prepositions.

An image schema represents a category or a concept, and it is associated with the capacity of abstraction or schematization that allows us to form patterns referring to the use of the language. Schemata are abstract structures, since they do not have characteristics that are specific to the objects they are associated with. These schemata are organized into basic computational Gestalt principles [37], such as similarity, proximity, continuity and alignment.

Johnson [20] considers image schemata conceptual primitives and spatial relations in a given language can be decomposed into these schemata. This concept has become important for the study of polysemy. Based on the ideas presented by [20, 38–42], the image schemata are grouped according to the following categories:

1. Space: Up, Down, Front-Back, Left-Right, Near-Away, Centre-Periphery, Contact, Upright, Straight;
2. Scale: Course;
3. Container: Containment, Inside-Out, Surface, Full-Empty, Content;
4. Strength: Against Strength, Compulsion, Restriction, Unlock, Block, Deviance, Attraction, Endurance, Balance;
5. Unity/Multiplicity: Fusion, Collection, Separation, Reiteration, Part-Whole, Countless-Count, Link;
6. Identity: Combination, Overlap;
7. Existence: Removal, Delimited Space, Cycle, Object, Process;
8. Locomotion: Impulse, Origin-Path-Objective;
9. Balance: Axis, Double Equilibrium, Equilibrium.

Image schemata are analogous representations of sensor-motor experiences and are represented by the use of two constructs called *trajector* and *landmark*. The former is the element of greatest prominence, whereas the latter is the object of reference. In general, the trajector is more mobile, smaller and sometimes more difficult to locate, while the landmark tends to be fixed, larger in size and easier to locate [34]. The concepts of trajector and landmark are essential to the theory proposed in this paper; therefore, they are introduced as definitions further in this section.

Semantic features come from information in dictionaries of English language, dictionaries of synonyms and WordNet. Semantic features represent the basic conceptual components of meaning for any lexeme (entry in a dictionary) [43]. An individual semantic feature takes part of the *intension* of a word, which is the inherent meaning or concept evoked by the word [44]. In addition to the semantic features of prepositions, a set of semantic superordinate terms, called *hypernyms*, are established. Hypernyms can be used to disclose many of the semantic features a lexeme sits on: for instance, in WordNet a ‘pear’ is an {edible fruit}, whereas a ‘basket’ is a container {container}. However, hypernyms in WordNet are exclusively applicable to content words (such as nouns, verbs and so on) and not to stop words (like prepositions, pronouns and determiners), so for the preposition ‘in’ we shall use a set of semantic features instead of hypernyms. The semantic features set for ‘in’, according to [25, 26], is given by {Inclusion, Surrounding, Encapsulation, Adherence}, which shows its polysemous character. In ‘the pear is in the basket’, the phrase evokes the concept of Inclusion (‘the pear is contained within the basket’), whereas in the phrase ‘the microphone in hand’, the understanding is not as if the ‘microphone’ were inside the hand, but rather wrapped by it.

Spatial axes are divided into vertical (up/down), lateral (left/right), front (front/back), proximity (far/close) and content (inside/outside).

Image schema, semantic features and spatial axes are used to define the concepts of possible worlds and spatial structure, as presented below.

DEFINITION 4.1 (Possible worlds).
Let ϵ be a spatial expression, $\mathscr{I}$ be the set of the image schemata of ϵ, Σ the set of semantic features of ϵ and X the set of spatial axes of ϵ. A possible world w is defined as a mapping from ϵ to an element of the set of triples $\langle \mathscr{I}, \Sigma, X\rangle$ defining a proposition:

$$w : \epsilon \rightarrow \langle \mathscr{I}_i \times \Sigma_i \times X_i \rangle,$$

for $\mathscr{I}_i \in \mathscr{I}, \Sigma_i \in \Sigma, X_i \in X$.

A proposition can be identified usually as the set of possible worlds where it is true. However, in contrast with the semantics that does not handle polysemous or vague terms, the formal definitions we propose in this paper need additional machinery. Therefore, in this work possible worlds, as presented in Definition 4.1, are defined as assignments of semantic features, image schemata and spatial axes. The semantic features, image schemata and spatial axes taken together map each expression to a semantic value. If the expression is a sentence, then the semantic value is a proposition. That proposition is a set of possible worlds.

A central difference between this definition and Bennett's work [15] is that the latter defines the possible worlds as valuations of functions of measurements over a domain D to a real number $\mathbb{Q}$. Since the purpose of Bennett's work is to treat vagueness, a spatial structure is used to measure physical observable features, such as size, mass, volume or speed, for example. In the present work, we adapt the concept of possible world to be a mapping from spatial expressions to a structure representing spatial features. This work could be made closer to [15] if the geometric part of the meaning of spatial relations were directly linked with the real values within a spatial coordinate system. However, this would limit the expressivity of the language, since situations such as those exemplified by the phrase 'the pear is in the basket' do not have a clear geometric definition.

The various uses of a spatial expression are represented by the concept of spatial structure defined below.

DEFINITION 4.2 (Spatial structure).
A *spatial structure* denotes the spatial uses of any spatial expression ϵ in relation to image schemata, semantic features and spatial axes. Formally, a spatial structure is a tuple:

$$\langle D, \mathscr{I}, \Sigma, X, W\rangle, \tag{1}$$

where:

- D is the domain of entities (the terms that represent the objects of a given scenario);
- $\mathscr{I}$ is the set of the image schemata;
- Σ is the set of semantic features related to spatial expressions;
- X is the set of spatial axes;
- W is the set of all possible worlds w.

In this paper, we assume a constant domain, so that all features are considered to be present in the formalism. Relaxing this constraint, specially with respect to real applications where the agent may have a partial model of the world, is the subject of future work.

Next, we introduce the notions of *trajector*, *landmark* and *spatial indicators* that are used in the formal languages defined below.

DEFINITION 4.3 (Trajector).
The trajector (*tr*) is the entity whose location is relevant and can be static or dynamic, a person or an object. In this work, the trajector will always be a static object.

DEFINITION 4.4 (Landmark).
The landmark (*lm*) is the reference entity in relation to the location or trajectory of the trajector.

DEFINITION 4.5 (Spatial indicator).
The spatial indicator is a term that represents a spatial relation between trajector and landmark (e.g. spatial prepositions). The set of spatial indicators is represented by R.

Based on the definitions above, a first-order language for spatial expressions can be established that can be interpreted in terms of a spatial structure.

DEFINITION 4.6
The language $\mathscr{L}_1(S, V)$ is defined as the set of formulae of a first-order logic involving relations for the hypernyms $S = \{S_1, \ldots, S_i\}$, and a set of variable symbols related to the terms of a sentence $V = \{tr, lm\}$.

The atomic formulae for the language $\mathscr{L}_1$ are defined as $S_i(x)$, where $x \in V$ and $S_i \in S$. Complex formulae are defined in the usual way.

Each of the language formulae characterizes the hypernyms of the trajector or the landmark extracted from WordNet and organized according to [25, 26]. For example, in the sentence 'the pear is in the basket', the trajector is represented by the word 'pear' while the landmark is the word 'basket'. Thus, the formula of the language $\mathscr{L}_1$ representing this sentence would be given by $\mathsf{Fruit}(Pear) \wedge \mathsf{Container}(Basket)$. We can now extend the language $\mathscr{L}_1$ by defining new predicates representing spatial indicators (R), hypernyms (S) and qualitative spatial relations (Q).

Let $\mathscr{L}_2(S, V, R, Q)$ be the language obtained by extending $\mathscr{L}_1$ with the inclusion of new (possibly polysemous) spatial predicates for spatial indicators R and qualitative spatial relations Q on spatial regions. PGTs are a set of formulae in $\mathscr{L}_2(S, V, R, Q)$ that relate spatial indicators with qualitative spatial relations whose polysemous character is interpreted in terms of spatial precisification models, as introduced below.

In the next definitions, we use the function $o(d)$ that represents the occupancy region of a domain object d.

DEFINITION 4.7 (Predicate grounding theory).
Let S be a set of hypernyms, Q a spatial relation and R an spatial indicator, a PGT relates the *landmark* (*lm*) and the *trajector* (*tr*) of a sentence in terms of a formula of the language $\mathscr{L}_2$, setting the use cases of a spatial expression. Thus, a PGT is a set of formulae for each spatial indicator $R_i \in R$, according to the schema in Formula 2.

$$\forall lm, tr \exists S_i, S_j \in S \;\; R(tr, lm) \Rightarrow \Phi(S_i, S_j, tr, lm) \wedge Q(o(tr), o(lm)), \tag{2}$$

where Φ is a formula of $\mathscr{L}_1(S, V)$, involving hypernyms $S = \{S_1, \dots, S_j\}$ over elements of V (trajectors and landmarks).

The definition for a spatial indicator is given by the completion of all PGTS (cf. Definition 4.8).

DEFINITION 4.8 (Completion).
Let the set $\Theta = \{\theta_1, \dots, \theta_i\}$ be the set of all PGTs for a spatial indicator R in $\mathscr{L}_2$, a completion of R with respect to Θ is given by:

$$R \Leftrightarrow \theta_1 \vee \cdots \vee \theta_i.$$

We now define a model structure to provide a semantics for $\mathscr{L}_2(S, V, R, Q)$. The model incorporates a spatial structure together with mappings from the language symbols to elements of the spatial structure defining the multiple interpretations (precisifications) over the spatial indicators R. Therefore, while $\mathscr{L}_1(S, V)$ is classical, $\mathscr{L}_2(S, V, R, Q)$ is interpreted over a supervaluation semantics.

DEFINITION 4.9 (Spatial precisification model).
A *spatial precisification model* is a structure

$$\mathfrak{M} = \langle \mathcal{F}, S, T, R, V, \Theta, K, \xi, P \rangle, \tag{3}$$

where:

- $\mathcal{F} = \langle D, \mathscr{I}, \Sigma, X, W \rangle$ is a spatial structure (cf. Def. 4.2);
- S is the set of hypernyms;
- T is the set of qualitative spatial relations;
- R is the set of spatial indicators;
- $V = \{tr, si, lm\}$ is the set of the sentence terms;
- $\Theta = \{\dots, \theta_i, \dots\}$ is the set of predicate grounding theories, where each θ_i is a PGT;
- $K(d) = \{\kappa | \kappa : d \rightarrow S\}$ is the set of hypernyms related to an element $d \in D$;
- $\xi : V \rightarrow d$ maps a sentence term to a object $d \in D$;
- $P = \{p | p : R \rightarrow T\}$ is the set of all mappings from spatial indicators to qualitative spatial relations (P is the set of **precisifications**).

In the model developed in the present work, precisifications are RCC formulae that determine the possible spatial relations between trajector and landmark.

For example, in the phrase ‘the pear is in the basket’, the spatial indicator is given by the preposition ‘in’. According to the schema in Formula 2 and assuming that ‘pear’ is a trajector (*tr*) and ‘basket’ is a landmark (*lm*), one formula of the PGT for the spatial indicator IN is the following:

$$\mathsf{IN}(Pear, Basket) \Rightarrow \mathsf{Fruit}(Pear) \wedge \mathsf{Container}(Basket) \wedge Q(o(Pear), o(Basket)). \tag{4}$$

Here, Container is a hypernym of the landmark (*Basket*), Fruit is a hypernym of the trajector (*Pear*), and Q is a polysemous spatial relation whose meaning is specified by the precisification model described below. The precisifications for the preposition ‘in’ are the various possibilities for the relation $Q(o(Pear), o(Basket))$ described below:

- p_1 : $\mathsf{GEO\text{-}INSIDE}(o(Pear), o(Basket))$: the occupancy region of the pear ($o(Pear)$) is geometrically inside the occupancy region of basket ($o(Basket)$);
- p_2 : $\mathsf{P\text{-}INSIDE}(o(Pear), o(Basket))$: $o(Pear)$ is partially contained in $o(Basket)$;

- p_3 : $\mathsf{OUTSIDE}(o(Pear), o(Basket)) \wedge \exists z((\mathsf{GEO\text{-}INSIDE}(o(z), o(Basket)) \vee \mathsf{P\text{-}INSIDE}(o(z), o(Basket))) \wedge \mathsf{EC}(o(Pear), o(z)))$: $o(Pear)$ is out of $o(Basket)$ but in contact with an object z located inside $o(Basket)$.

In the precisification p_1, the pear is completely contained inside the basket, whereas in the precisifications p_2 and p_3, the pear is in contact with other elements and partially enclosed (p_2) or outside (p_3) of the basket. Thus, for the same sentence we have three possibilities of spatial interpretations.

It is worth pointing out in this example that the geometric features of trajector and landmark cannot encompass all of the senses of the expression. As a matter of fact, *functional* features of the objects are also expected to play an important role in linguistic expressions involving space [34]. In this case, particularly regarding p_3, some of the pears may be geometrically outside the basket and still be said to be in it. In spite of that, the pears keep being *functionally inside* the bowl as long as the global configuration allows to, say, store or carry them without dropping them out of the basket. So there is no paradox in being *geometrically out* and *functionally in* the basket. In addition, functionality also has extensional limits, as well as geometry. This is where precisification comes in to help fine-tuning extensions.

Given a set of PGTs, possible worlds and precisifications, we can use a parallel semantic interpretation function, as introduced in [15], described in Definitions 4.10, 4.11 and 4.12 below.

The semantic interpretation function $[\![\phi]\!]^{w,p,\theta}_{\mathfrak{M}}$ provides the denotation of any spatial sentence ϕ with respect to a precisification model $\mathfrak{M}$, a possible world $w \in W$, a precisification $p \in P$ and a PGT $\theta \in \Theta$.

The semantic interpretation function can be extended to compound formulae in the standard way:

$$[\![\neg\phi]\!]^{w,p,\theta}_{\mathfrak{M}} = \mathbf{t} \text{ if } [\![\phi]\!]^{w,p,\theta}_{\mathfrak{M}} = \mathbf{f}, \text{ otherwise} = \mathbf{f} \tag{5}$$

$$[\![\phi \wedge \psi]\!]^{w,p,\theta}_{\mathfrak{M}} = \mathbf{t} \text{ if } [\![\phi]\!]^{w,p,\theta}_{\mathfrak{M}} = \mathbf{t} \text{ and } [\![\psi]\!]^{w,p,\theta}_{\mathfrak{M}} = \mathbf{t}, \text{ otherwise} = \mathbf{f}. \tag{6}$$

DEFINITION 4.10
The relation of semantic satisfaction is defined by:

$$\mathfrak{M}, \langle w, p, \theta \rangle \Vdash \phi \text{ iff } [\![\phi]\!]^{w,p,\theta}_{\mathfrak{M}} = \mathbf{t}. \tag{7}$$

DEFINITION 4.11
The interpretation set of a sentence in relation to a model $\mathfrak{M}$ is given by

$$[\![\phi]\!]_{\mathfrak{M}} = \{\langle w, p, \theta \rangle | \mathfrak{M}, \langle w, p, \theta \rangle \Vdash \phi\}. \tag{8}$$

The interpretation set is the set of possible worlds, precisifications and predicate grounding theories in which the sentence ϕ is evaluated as true. Continuing the example of the sentence: $\phi =$ 'the pear is in the basket', the interpretation set of ϕ is $[\![\phi]\!]_{\mathfrak{M}} = \{\langle w_1, p_1, \theta_1 \rangle, \langle w_2, p_2, \theta_1 \rangle, \langle w_2, p_3, \theta_1 \rangle\}$, where the w_1, w_2 are the possible words which mean, respectively, the situations of total inclusion and partial inclusion, p_1, p_2 and p_3 are the precisifications defined above, and θ_1 is the PGT for the predicate IN, given by $\theta_1 : \mathsf{IN}(tr, lm) \Rightarrow ((Container(lm) \vee Vessel(lm) \vee Receptacle(lm)) \wedge (\neg Liquid(tr) \wedge \neg Beverage(tr))) \wedge Q(o(tr), o(lm))$, where *tr* is the pear and *lm* is the basket.

In accordance with the interpretation function $[\![\phi]\!]^{w,p,\theta}_{\mathfrak{M}}$ specified above, the agent's attitude to the meanings of terms is modelled in terms of possible worlds, the PGTs and the choices of precisifications that the agent considers to be acceptable. In other words, PGTs represent object features, precisifications define the distinct arrangements between objects and possible worlds represent characteristics of these arrangements. This paper assumes that these three feature kinds are independent. Thus, they are interpreted in conjunction.

Finally, the agent's attitude with respect to polysemous terms is represented by a structure called standpoint (cf. [15]).

DEFINITION 4.12 (Standpoint).
A *standpoint* characterizes the range of possible worlds and interpretations that are considered plausible or acceptable. Formally, a standpoint is a tuple:

$$\langle B, A, \Psi \rangle, \tag{9}$$

where:

- $B \subseteq W$ is the set of possible worlds that are compatible with the meaning of a spatial expression;
- $A \subseteq P$ is the set of precisifications that are admissible for a spatial expression;
- $\Psi \subseteq \Theta$ is the set of PGT that characterizes all possible definitions of predicates that are considered acceptable.

For any given model $\mathfrak{M}$, the condition for a formula ϕ to hold with respect to a particular standpoint $\langle B, A, \Psi \rangle$ (cf. [15]) is given by:

$$\mathfrak{M}, \langle B, A, \Psi \rangle \Vdash \phi \text{ iff } (B \times A \times \Psi) \subseteq [\![\phi]\!]_{\mathfrak{M}}^{w,p,\theta}. \tag{10}$$

In Bennett's terms, a sentence ϕ holds for a standpoint if it is true in all worlds in the belief set for all admissible precisifications and all acceptable PGTs [15]. In the present paper this statement is still applied, but the agent's beliefs also include the semantic features of the terms and the choice of qualitative spatial relations.

Next section shows an implementation of the spatial precisification model for the preposition 'in' and the standpoints for sentences containing this preposition.

5 Implementation of SSP

In this section, we present the spatial precisification model for the preposition 'in', illustrating the definitions of possible worlds, semantic features and spatial axes.

5.1 Spatial precisification model for the preposition 'in'

The spatial precisification model $\mathfrak{I}$ for the preposition 'in' is given by

$$\mathfrak{I} = \langle \mathcal{F}, S, T, R, V, \Theta, K, \xi, P \rangle, \tag{11}$$

where $\mathcal{F} = \langle D, \mathscr{I}, \Sigma, X, W \rangle$ is a spatial structure (cf. Definition 4.2). Therefore, the model $\mathfrak{I}$ is defined as:

- D are the terms representing the objects of the scenario, defined according to the sentence;
- $\mathscr{I} = \{\text{Containment, Support}\}$ is the set of image schema;
- $\Sigma = \{\text{Inclusion, Surrounding, Encapsulation, Adherence}\}$ is the set of semantic features of the preposition 'in';

- X = {Inside, Outside, Up} is the set of spatial axes;
- W = { is the set of possible worlds
  - – w_1 =(Containment, Inclusion, Inside): the object is contained in a container medium.
  - – w_2 =(Containment, Inclusion, Outside): the object is outside or partly contained in a medium container.
  - – w_3 =(Containment, Surrounding, Inside): the object is surrounded by a container.
  - – w_4 =(Containment, Encapsulation, Inside): the object is encapsulated by another object.
  - – w_5 =(Support, Adherence, Up): the object is being supported by another object.
- – };
- S = { is the set of hypernyms of the sentence and includes:
  - – Container: any object that can be used to hold things;
  - – Vessel: an object used as a container, especially for liquids;
  - – Receptacle: a container that is used to put or keep things in;
  - – Liquid: a substance that is liquid at room temperature and pressure;
  - – Beverage: any liquid suitable for drinking;
  - – Clamp: a device (generally used by carpenters) that holds things firmly together;
  - – Stirrup: support consisting of metal loops into which rider's feet go;
  - – Enclosure: a structure consisting of an area that has been enclosed for some purpose;
  - – Extremity: an external body part that projects from the body;
  - – Pocket: a small pouch inside a garment for carrying small articles;
  - – Bag: a flexible container with a single opening;
  - – Pouch: a small or medium size container for holding or carrying things;
  - – Closet: a small room (or recess) or cabinet used for storage space;
  - – Cabinet: a piece of furniture resembling a cupboard with doors and shelves and drawers;
  - – Car: a motor vehicle with four wheels;
  - – Gondola: the compartment that is suspended from an airship and that carries personnel and the cargo and the power plant;
  - – Pipe: a hollow cylindrical shape;
  - – Tube: conduit consisting of a long hollow object (usually cylindrical) used to hold and conduct objects or liquids or gases;
  - – Trench: a ditch dug as a fortification having a parapet of the excavated earth;
  - – Ditch: any small natural waterway;
  - – Gutter: a channel along the eaves or on the roof; collects and carries away rainwater;
  - – Seat: furniture that is designed for sitting on;
  - – Stool: a simple seat without a back or arms;
  - – Water: an aquatic environment;
  - – Fastener: restraint that attaches to something or holds something in place;
  - – Pan: cooking utensil consisting of a wide metal vessel;
  - – Dish: a piece of dishware normally used as a container for holding or serving food;
  - – Tray: an open receptacle for holding or displaying or serving articles or food;
  - – Oven: kitchen appliance used for baking or roasting;
  - – Fridge: a refrigerator in which the coolant is pumped around by an electric motor;
  - – Home Appliance: an appliance that does a particular job in the home;
  - – Support: any device that bears the weight of another thing;
  - – Wall: an architectural partition with a height and length greater than its thickness; used to divide or enclose an area or to support another structure;
  - – Equipment: an instrumentality needed for an undertaking or to perform a service;

  - Compartment: a space into which an area is subdivided;
  - Luggage: cases used to carry belongings when travelling;
  - Bin: a container; usually has a lid;
- };

T = {DC, P, PP, EQ, O, PO, DR, EC, TPP, NTPP, INSIDE, P-INSIDE, OUTSIDE, TOP-INSIDE, GEO-INSIDE} is the set of qualitative spatial predicates defined in terms of RCC (as introduced in Section 3);

$R = \{\mathsf{IN}(tr, lm)\}$ is the set of predicates (spatial indicators) that represent the uses of the preposition 'in';

$V = \{tr, si, lm\}$ is the set of variable symbols that represent the roles that the terms of the sentence can take;

Θ is the set of PGT for IN given by:

- $\theta_1 : \mathsf{IN}(tr, lm) \Rightarrow ((Container(lm) \vee Vessel(lm) \vee Receptacle(lm)) \wedge (\neg Liquid(tr) \wedge \neg Beverage(tr))) \wedge Q(o(tr), o(lm))$: the landmark is a container and the trajector is a solid object.
- $\theta_2 : \mathsf{IN}(tr, lm) \Rightarrow (Container(lm) \vee Vessel(lm) \vee Receptacle(lm)) \wedge (Liquid(tr) \vee Beverage(tr)) \wedge Q(o(tr), o(lm))$: the landmark is a container and the trajector is a liquid.
- $\theta_3 : \mathsf{IN}(tr, lm) \Rightarrow (Wall(lm)) \wedge Q(o(tr), o(lm))$: the landmark is a wall.
- $\theta_4 : \mathsf{IN}(tr, lm) \Rightarrow (Stirrup(lm) \vee Clamp(lm)) \wedge Q(o(tr), o(lm))$: the landmark has a ring form, such as a stirrup, tweezers or pliers.
- $\theta_5 : \mathsf{IN}(tr, lm) \Rightarrow (Enclosure(lm)) \wedge Q(o(tr), o(lm))$: the landmark is a structure that consists of an area that has been closed for some purpose.
- $\theta_6 : \mathsf{IN}(tr, lm) \Rightarrow (Extremity(lm)) \wedge Q(o(tr), o(lm))$: the landmark is an extremity of the human body.
- $\theta_7 : \mathsf{IN}(tr, lm) \Rightarrow (Pocket(lm) \vee Bag \vee Pouch(lm)) \wedge Q(o(tr), o(lm))$: the landmark is a flexible container with a single opening.
- $\theta_8 : \mathsf{IN}(tr, lm) \Rightarrow (Water(lm)) \wedge Q(o(tr), o(lm))$: the landmark is a liquid medium.
- $\theta_9 : \mathsf{IN}(tr, lm) \Rightarrow (Fastener(tr)) \wedge (\neg Container(lm) \wedge \neg Vessel(lm) \wedge \neg Receptacle(lm)) \wedge Q(o(tr), o(lm))$: the trajector is a fastening element and the landmark is not a container.
- $\theta_{10} : \mathsf{IN}(tr, lm) \Rightarrow (Support(lm)) \wedge Q(o(tr), o(lm))$: the landmark is a holder such as a wall hook.
- $\theta_{11} : \mathsf{IN}(tr, lm) \Rightarrow (Cabinet(lm) \vee Closet(lm)) \wedge Q(o(tr), o(lm))$: the landmark is a storage compartment.
- $\theta_{12} : \mathsf{IN}(tr, lm) \Rightarrow (Car(lm)) \wedge Q(o(tr), o(lm))$: the landmark is a vehicle.
- $\theta_{13} : \mathsf{IN}(tr, lm) \Rightarrow (Tube(lm) \vee Pipe(tm)) \wedge Q(o(tr), o(lm))$: the landmark is a pipe.
- $\theta_{14} : \mathsf{IN}(tr, lm) \Rightarrow (Seat(lm) \wedge \neg Stool(lm)) \wedge Q(o(tr), o(lm))$: the landmark is a seat, except when it is a stool.
- $\theta_{15} : \mathsf{IN}(tr, lm) \Rightarrow (Trench(lm) \vee Ditch(lm) \vee Gutter(lm)) \wedge Q(o(tr), o(lm))$: the landmark is a passage for liquid or a long and narrow excavation in the ground.
- $\theta_{16} : \mathsf{IN}(tr, lm) \Rightarrow (Pan(lm) \vee Dish(lm) \vee Tray(lm)) \wedge Q(o(tr), o(lm))$: the landmark is an open container where normally foods are prepared or served.
- $\theta_{17} : \mathsf{IN}(tr, lm) \Rightarrow (Oven(lm) \vee Fridge(lm) \vee HomeAppliance(lm)) \wedge Q(o(tr), o(lm))$: the landmark is a home appliance.
- $\theta_{18} : \mathsf{IN}(tr, lm) \Rightarrow (Equipment(lm)) \wedge Q(o(tr), o(lm))$: the landmark is a machine or mechanical equipment.
- $\theta_{19} : \mathsf{IN}(tr, lm) \Rightarrow (Compartment(lm)) \wedge Q(o(tr), o(lm))$: the landmark is a compartment within an enclosed area.

  - θ_{20} : $\mathsf{IN}(tr, lm) \Rightarrow (Bin(lm)) \wedge Q(o(tr), o(lm))$: the landmark is generally a capped container.
- $K(d)$ is the set of all hypernyms of $d \in D$. For instance, given a term 'vase' in the expression 'rose in vase', K(vase) is the following set {jar, vessel, container}.
- ξ is the mapping of the terms of a sentence to the roles they carry in the sentence. For instance, considering the sentence 'rose in vase', ξ(rose) = tr, ξ(in) = si, ξ(vase) = lm.
- P is the set of precisifications for the relation $Q(o(tr), o(lm))$, where x, y are respectively $o(tr)$ and $o(lm)$ the occupancy regions of tr and lm:
  - $p_1(x,y) \equiv_{def} \mathsf{GEO\text{-}INSIDE}(x,y)$
  - $p_2(x,y) \equiv_{def} \mathsf{P\text{-}INSIDE}(x,y)$
  - $p_3(x,y) \equiv_{def} \mathsf{CONT\text{-}INSIDE}(x,y)$
  - $p_4(x,y) \equiv_{def} \mathsf{OUTSIDE}(x,y) \wedge \exists z((\mathsf{GEO\text{-}INSIDE}(z,y) \vee \mathsf{P\text{-}INSIDE}(z,y)) \wedge \mathsf{EC}(x,z))$
  - $p_5(x,y) \equiv_{def} \mathsf{PO}(x,y)$
  - $p_6(x,y) \equiv_{def} \mathsf{TPP}(x,y) \vee \mathsf{NTPP}(x,y)$
  - $p_7(x,y) \equiv_{def} \neg\mathsf{INSIDE}(x,y) \wedge \mathsf{VERT}(x,y) \wedge \mathsf{EC}(x,y)$
  - $p_8(x,y) \equiv_{def} \mathsf{TOP\text{-}INSIDE}(x,y)$.

In the spatial precisification model for the preposition 'in' seen above, we establish five possible worlds representing the most typical contexts of application for this preposition, representing its polysemous character. The phrases 'the bowl in the microwave' and 'the window in the wall' represent, respectively, the possible worlds w_1 and w_4. In the first case, the preposition 'in' is used in the sense of containment, i.e. the bowl is inside the microwave, whereas in the second sentence the preposition is used in the sense of involvement, i.e. we cannot say that the window is inside the wall, but rather that the wall surrounds the window. Thus, we say that possible worlds define a first level of polysemy.

Another contribution this paper intends to provide is to establish a second level of polysemy. Consider the following examples:

1. the water in the bottle;
2. the pears in the bowl.

In both cases, the possible world evoked is that of containment (w_1). However, in the first example the trajector ('water') is totally contained in the landmark. In the second example, however, the pear can be physically out of the bowl, but in contact with other pears that are inside the bowl. Thus, we establish the PGT based on the semantic features of the trajector and the landmark. Therefore, each possible world has a set of PGTs associated with it. Finally, each PGT has a set of precisifications. In the example of 'the pears in the bowl', there are three possible locations of the pear in relation to the bowl: fully inside the bowl, partially inside the bowl or outside the bowl, but in contact with other pears inside the bowl. Thus, in establishing the possible worlds, the PGTs and the precisifications, we can establish the different senses of a preposition.

In the next section, we present the algorithm for the formalism introduced so far and the results of its implementation obtained with the preposition 'in'.

5.2 Algorithm for SSP

The algorithm presented in this section implements the spatial precisification model for a given preposition. The algorithm has as input a phrase containing a certain spatial expression and outputs the standpoints, i.e. the set of triplets ⟨possible worlds, PGTs, precisifications⟩ compatible with the expression. The algorithm has a table of PGTs for the preposition, and each PGT has a set of possible

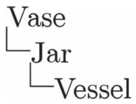

FIGURE 3 Hypernym tree for word ‘vase’.

worlds and precisifications to which it is associated. The set of hypernyms of the trajector and the landmark are determined and checked in the table of PGTs for compactibility with respect to the semantic features. These sets are obtained through a similarity function, which will be explained further in this section.

The algorithm takes the trajector, the landmark and the spatial indicator as inputs. The sets of PGTs, possible worlds and precisifications are given according to spatial precisification model.

In the implementation of Algorithm 1, we used the Princeton WordNet corpus reader of the NLTK module for Python. The sets K_1 and K_2 were determined by a similarity function between the synsets of the terms and the synsets predetermined by the precisification model. This function is given by:

> synset1.path.similarity(synset2): Return a score denoting how similar two word senses are based on the shortest path that connects the senses in a(hypernym/hypnoym) taxonomy. The score is in the range 0 to 1. By default, there is now a fake root node added to verbs so for cases where previously a path could not be found – and None is returned– it should still return a value. The old behavior can be achieved by setting simulate.root to be False. A score of 1 represents identity.[2]

In WordNet, a synset or synonym set is defined as a set of one or more synonyms that are interchangeable in some context without changing the truth value of the proposition in which they are embedded. We choose values above 0.33, which means that a term S is at most two levels up in the hyperonym tree. The terms ‘container’ and ‘basket’ have similarity degree 0.5, because the synset of ‘container’ is directly above the ‘basket’ synset. The similarity function between ‘vase’ and ‘vessel’ returns 0.33 because it is two levels up in the tree. (cf. Figure 3)

The set S is defined by the hypernyms predetermined for the trajector and the landmark. As previously seen, these terms depend on the spatial indicator. In lines 9 to 17 of Algorithm 1, for each such term, the similarity with the trajector and the landmark is tested. The symbol $\odot$ on lines 24 and 36 is used to verify which PGTs are true for a given term. Thus, for each hypernym related to the trajector and the landmark, the algorithm checks what are the compatible PGTs, i.e. the PGTs that return ‘true’. In line 43, a call is made to Algorithm 2 that verifies the possible interpretations for the set of PGTs Ψ and the spatial indicator R. Algorithm 2 is defined as follows.

The lines 5 and 6 of Algorithm 2 give the sets of possible worlds and precisifications, respectively. These sets are based on the predetermined spatial precisification model. The symbol $\oplus$ on lines 10 and 11 is used to check for possible worlds and the precisifications that are associated with a PGT. The correlation between PGTs and possible worlds, and also between PGTs and precisifications, are previously informed. The output of this algorithm is the standpoints, i.e. the set of triplets $\langle$possible worlds, predicate grounding theories, precisifications$\rangle$ compatible with an expression ϕ or ‘incorrect use’ if there is no PGT compatible with the sentence. There are two interpretations for case Ψ to be *NULL*:

---

[2] In http://www.nltk.org/howto/wordnet.html

Algorithm 1 Predicate Grounding Theories

```
procedure PGT($\phi$)
    $tr \leftarrow$ trajector of $\phi$
    $lm \leftarrow$ landmark of $\phi$
    $R \leftarrow$ spatial indicator of $\phi$
    $\Theta \leftarrow$ PGTs of $R$
    $S \leftarrow$ the set of hypernyms of $R$
    $n \leftarrow |S|$
    $i \leftarrow 1$
    while $i \leq n$ do
        if $S_i$.path.similarity (tr) $\geq 0.33$ then
            $K_1(tr) \leftarrow S_i$
        end if
        if $S_i$.path.similarity (lm) $\geq 0.33$ then
            $K_2(lm) \leftarrow S_i$
        end if
        $i \leftarrow i + 1$
    end while
    $i \leftarrow 1$
    $t \leftarrow |\Theta|$
    $m \leftarrow |K_1|$
    while $i \leq m$ do
        $x \leftarrow 1$
        while $x \leq t$ do
            if $K_1(tr)_i \odot \theta_x =$true then
                $\Psi \leftarrow \theta_x$
            end if
            $x \leftarrow x + 1$
        end while
        $i \leftarrow i + 1$
    end while
    $j \leftarrow 1$
    $m \leftarrow |K_2|$
    while $j \leq m$ do
        $y \leftarrow 1$
        while $y \leq t$ do
            if $K_2(lm)_j \odot \theta_y =$true then
                $\Psi \leftarrow \theta_y$
            end if
            $y \leftarrow y + 1$
        end while
        $j \leftarrow j + 1$
    end while
    $I \leftarrow$ Interpretation $(\Psi, R)$
    return $I$
end procedure
```

Algorithm 2 Standpoints Semantics for Polysemy

```
procedure INTERPRETATION($\Psi$, $\rho$)
    if $\Psi = NULL$ then
        return Incorrect use
    else
        $W \leftarrow$ possible worlds of $\rho$
        $P \leftarrow$ precisifications of $\rho$
        $n \leftarrow |\Psi|$
        $z \leftarrow 1$
        while $z \leq n$ do
            $B \leftarrow \Psi_z \oplus W$
            $A \leftarrow \Psi_z \oplus P$
            $z \leftarrow z + 1$
        end while
        return $\{\langle \Psi, B, A \rangle\}$
    end if
end procedure
```

1. The unsual use of a schema, as in ‘The bottle is in the lid’, and
2. use not foreseen in the PGTs, as in the example ‘The knife is in the stone’.

5.3 Results

We have tested the algorithm with 71 prepositional phrases (PP) taken from the Corpus of Contemporary American English (COCA)[3] , arguably the most representative English language corpus available. We have divided the results into the 20 PGTs defined in the spatial precisification model $\mathfrak{I}$, seen in the previous section. Results are exhibited in Table 3. In addition to the PGTs obtained, results show the possible worlds and the precisifications associated with each PGT. Note that nearly half of the PGTs are associated with the possible world w_1, which refers to the inclusion of an object in a container medium. Moreover, 41 sentences tested are associated with the possible world w_1 as well. Thus, the world w_1 can be associated to Herskovits’ [25] *ideal meaning* of the preposition ‘in’, or to Tyler and Evans notion of *proto-scene* of this preposition in a polysemous network of other meanings [26].

Seven out of the total analysed PPs presented more than one possibility for the PGTs. This is because a PGT can provide more than one meaning for a word. The word ‘stirrup’, e.g. is characterized both as a ring format and as a support. In the prepositional phrase ‘the jar in the bin’, the word ‘bin’ was classified as a simple container (PGT θ_1) or a container with a lid (PGT θ_{20}). Nine other prepositional phrases were not classified in any PGTs, namely:

- ‘Sword in the stone’
- ‘Wires in the cable’
- ‘Jewelry in the center of the table’
- ‘Key in the cartouche’

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[3] https://corpus.byu.edu/coca/

TABLE 3 Results by PGT.

PGT	#sentences	Possible worlds	Precisifications
θ_1	15	w_1, w_2	p_1, p_2, p_4
θ_2	3	w_1	p_3
θ_3	4	w_4	p_6
θ_4	1	w_4	p_5, p_6
θ_5	1	w_4	p_8
θ_6	2	w_3	p_5
θ_7	1	w_1	p_1
θ_8	4	w_3	p_5, p_6
θ_9	4	w_4	p_5
θ_{10}	3	w_4	p_5
θ_{11}	4	w_1	p_1
θ_{12}	3	w_1	p_1
θ_{13}	1	w_1	p_3
θ_{14}	1	w_5	p_7
θ_{15}	2	w_2	p_2
θ_{16}	1	w_1, w_2	p_1, p_2
θ_{17}	10	w_1	p_1
θ_{18}	1	w_3	p_5
θ_{19}	2	w_3	p_1
θ_{20}	3	w_1	p_3
Unclassified	9	—	—

- ‘Blade in table saw’
- ‘Jar in the mattress’
- ‘Pans in the sink’
- ‘Bottle in the towel’
- ‘Dried flowers in the book’.

Finally, three expressions tested presented unusual applications of the preposition ‘in’:

- ‘Hat in the head’
- ‘Head in the hat’
- ‘Bottle in the cap’.

A predetermined gold standard was used to evaluate the results, since to the best of our knowledge there is no other software in the literature for this purpose with which our results could be compared. The gold standard was based on dictionaries of use and also on prepositions semantics references, such as [25, 26, 45]. The algorithm had 87.33% of PPs correctly classified and 12.67% not classified, meaning that there was no PGTs compatible with those phrases. Three PPs presented unusual interpretations for the preposition, and yet were properly classified by the algorithm. In this way, a distinction was made between unusual and unclassified cases. The latter, as mentioned above, represent only 12.67% of all the analysed phrases. In addition to these results, a visual representation for each interpretation provided by the SSP algorithm was automatically generated. These are simple figures that represent schematically the use of the preposition in the sentence. The next section describes how they were produced.

5.4 Pictorial representation

Based on the theory of choremes [28] that establishes schemata for representation of direction, and also on the concept of proto-scenes [26, 39], in this work each interpretation is assigned a pictorial representation. In order to do that, each semantic feature is represented by a figure, and the arrangement of these figures is dictated by a combination of PGT and precisification, where the PGT is used to define the format of the trajector and the frame in the image, and precisification is used to establish the location of the trajector with respect to the frame.

Originating from Brunet's work in geography [28], choremes are iconic components that can be used to represent specific spatial configurations as well as prototypical processes in topography. Finally, it is important to point out that in Tyler and Evans's theory [26, 39], the central sense for a preposition such as 'over' is directly grounded in a specific kind of recurring spatial scene. This spatial scene, in which a trajector and a landmark are associated in a particular spatio-geometric configuration, is called a *proto-scene*. While the proto-scene is a type of image schema, it is distinct from the central image schema proposed by Lakoff [13] because it relates to a distinct and discrete spatial scene.

The implementation of the proto-scenes was done using the OpenCV library [46]. A set of geometric shapes was preset for each member of the set S, and for a given sentence, the program generates the shapes of the trajector and the landmark. The arrangement between the trajector and the landmark is given by the precisification. For example, Figure 1 presents the proto-scenes for the sentence ϕ = 'the pear in the bowl' whose interpretation set is given by $[\![\phi]\!]_{\mathfrak{I}} = \{\langle w_1, p_1, \theta_1\rangle, \langle w_2, p_2, \theta_1\rangle, \langle w_2, p_4, \theta_1\rangle\}$. Since the PGT is the same in all three interpretations, the landmark has the same format in the three figures. The position of the trajector varies according to the precisification: Figure 1a corresponds to the interpretation $\langle w_1, p_1, \theta_1\rangle$ where the trajector is fully inside the landmark. In the interpretation $\langle w_2, p_2, \theta_1\rangle$ (Figure 1b), the trajector is partially inside the landmark, whereas in the interpretation $\langle w_2, p_4, \theta_1\rangle$ (Figure 1c) the trajector is outside the landmark but in contact with some other object inside of the landmark.

Figure 4 shows all the proto-scenes generated for the preposition 'in'. These proto-scenes were used for the visual verification of the possible world of a given sentence. The algorithm receives an interpretation (according to Algorithm 2) and returns the pictorial representation for this interpretation based on the semantics.

6 Discussion and concluding remarks

This paper introduced a logical formalism called SSP that was developed aiming at providing a formal treatment of polysemy in spatial expressions. This semantics was an adaptation of Bennett's standpoint semantics [15], originally conceived for the treatment of vagueness, where precisifications are assignments of values to thresholds, and vague predicates are defined by PGT, which are formulas of a first-order language involving measurement functions and thresholds. In SSP, precisifications are qualitative spatial relations and PGTs are established according to the semantic characteristics of a trajector and a landmark. These semantic characteristics were defined based on dictionaries and WordNet.

The predicates of the language are the spatial indicators (the terms that relate trajector and landmark). Each spatial indicator has a set of PGTs assigned and also a set of possible worlds, which

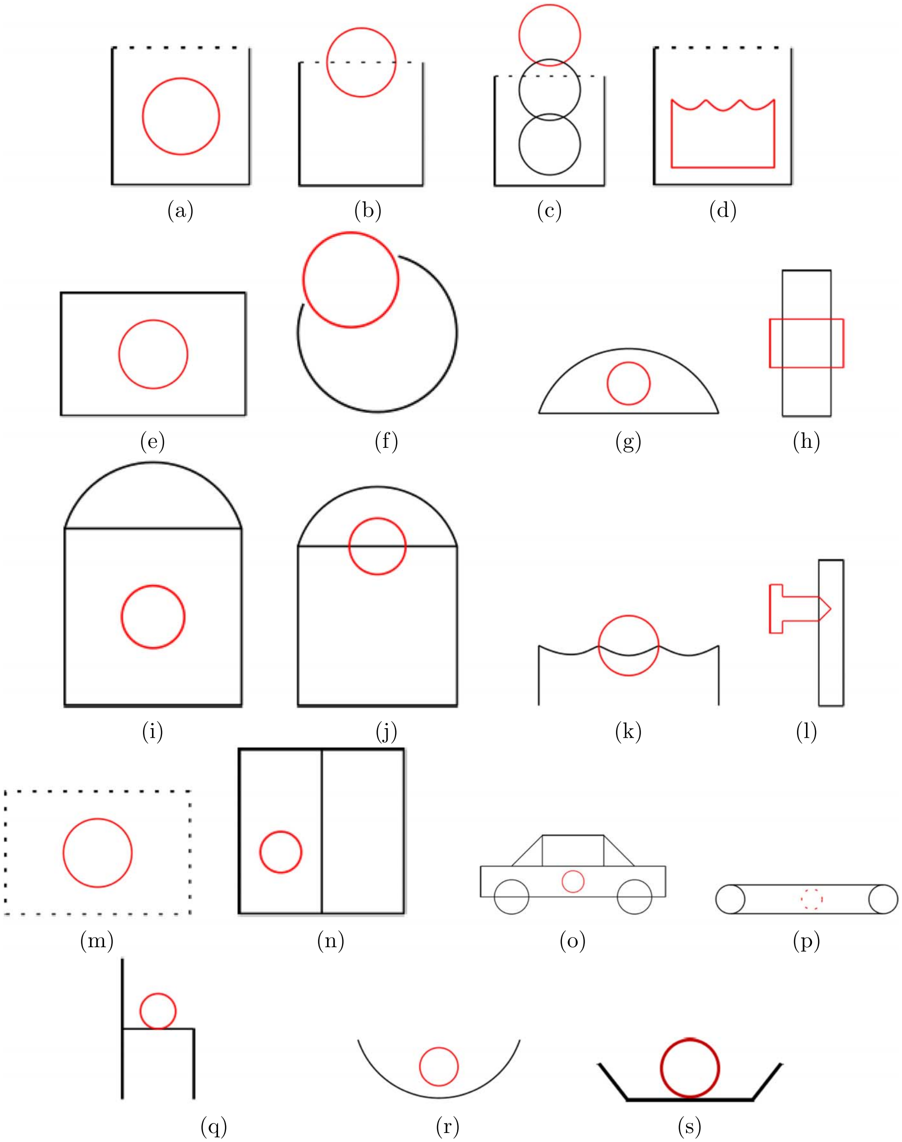

FIGURE 4 Proto-scenes for preposition ‘in’: (a) total inclusion, (b) partial inclusion, (c) inclusion by tolerance, (d) inclusion of a liquid, (e) trajector on a wall, (f) ring-shaped landmark, (g) encapsulation, (h) landmark as end of the human body, (i) total inclusion in a bag, (j) partial inclusion in a bag, (k) inclusion in a liquid medium, (l) trajector is a fixer object, (m) landmark as support, (n) inclusion in a storage compartment, (o) inclusion in a vehicle, (p) inclusion in a tube, (q) landmark as seat, (r) inclusion of a trench, (s) inclusion in an open container.

are the possibilities of using each indicator. The possible worlds are a combination of semantic features, image schemata and spatial axis (following a similar definition proposed in [47, 48]).

Thus, possible worlds define the various senses (polysemy) that a spatial indicator can have. Image schemata define the cognitive categorization of the spatial indicator, i.e. which cognitive role it exerts. Finally, the spatial axes determine the spatial organization expressed by the indicators.

The notion of possible worlds defined in this paper is a set of constraints, evaluated by means of a mapping function that represents states of affairs against which features are evaluated with respect to each world (i.e. some features may be true or false with respect to how they are grounded in the world). In the simplest cases of applications of the ideas of Kripke semantics, everything needed to get a truth value should be bundled into the idea of a world [49]. In the satisfaction relation in this paper, however, the place of valuation is not simply a world, but a triple of world, precisification and predicate grounding theory. Therefore, not everything needed to get a truth value is bundled up into what we call a 'world', but rather the full triple is needed.

In other words, our treatment of polysemy is restricted to the context of the sentence in which spatial prepositions occur. This context encompasses two 'objects', the trajector and the landmark, whose spatial relationship is expressed by the preposition combined with their own hypernyms. This is a token-based approach [50], i.e. we expect a potentially different sense of the spatial preposition in each phrase it occurs. On top of that, the hypernyms of both trajector and landmark, which are also potentially different in every scenario studied in this paper (methodologically depicted in proto-scenes), are explicitly held by the image schemata.

In the proto-scenes, the shape of the trajector and the landmark are determined by the PGTs while the layout in space serves to determine their relative placements. Other theoretical approaches subsuming formal and conceptual structures of interpretation, like the generative lexicon theory [51] or grounded ontologies [34] could also fit the same purpose, and it would certainly be interesting to replicate the results we have achieved so far remodelling the formalism and the algorithms to work with other semantic and computational backgrounds. It should be emphasized that the proto-scenes are rendered based on various qualitative characteristics depicted by the image schemata (shape, size, orientation and so on) combined with the specific semantic input from the prepositions.

In the present work, the term 'proto-scene' is used to represent the arrangement between trajector and landmark, but in a future work, representing the interpretations by proto-scenes may serve as a model for comparisons with real images. The main idea is to transform an image into a schematic representation and then compare it to proto-scenes in order to get mappings between images and natural language phrases.

We chose to make this pictorial representation to better validate the results of SSP against expected outcomes. At this point, it is worth mentioning that the proto-scenes were established by a gold standard test, as we did not find any other work in the literature presenting such classification.

The implementation of SSP was written using the NLTK module for Python to extract the degree of similarity of a term in relation to the predetermined semantic features in the PGTs. The similarity function searches the tree of hypernyms of a term x given a term y, returning a real value between 0 and 1.

In order to test the SSP, 71 phrases were extracted from COCA containing the preposition 'in' linking two objects. The SSP correctly classified 87% of these sentences, whereas for the other 13% there was no similarity with any semantic features with the defined PGTs. However, the main advantage of SSP is that it is an elaboration-tolerant classifier, i.e. we can add new PGTs without necessarily modifying the formal structure. We opted for this classification approach because other classification methods such as deep learning models do not make explicit which features are being used in the classification process. In addition, we did not find in the literature any other methods for classifying polysemous use of prepositions, which then stands as the main contribution of our work.

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