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Place reference systems

A constructive activity model of reference to places

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Abstract. Reference to places is a central but largely underexposed problem of information science. Place has been a major object of research in many domains including Geography, Cognitive Science and Geographic Information Science. However, Geographic Information Systems (GIS) have been built solely on *space* reference systems creating a gap between human conceptualization and machine representation. While reference to space only partially captures reference to place, most existing definitions of place either reduce the latter to the former or lack a formal characterization of how places are constructed. In a spatial coordinate system, locations are referenced by angles and distances to other referents. In this paper, we suggest that place reference systems can be built based on localizing things (locatums) involved in simulated activities relative to other involved referents (locators). We propose a formal theory about relevant types of activities and their involved participants, and show how place referents can be identified and localized by choosing locators and locatum among the participants. We formally derive an ontology of places, publish a corresponding OWL version, and demonstrate how to compute a market place and a vantage place in a GIS.

Keywords: Automated place inference, reference system, activities, affordances

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1. Introduction

How can we refer to a place? How can we identify and localize it in an automated fashion? In philosophy, the *problem of reference* addresses how to refer to what a symbol, e.g., a name, stands for Quine (1974). This problem has a practical dimension. What a place name refers to is, by and large, a kind of *practical knowledge* which goes beyond knowing its name.[1] However, in a world of digital information, referential knowledge of places gets lost not only across different communities of practice, but also across different ages of digital heritage (Schlieder, 2010). For cultural heritage data, places often remain the only obtainable referent (Janowicz, 2009). Place-based information integration and retrieval is still in its infancy (Vasardani et al., 2013). In particular, we face the problem of *place reference* as opposed to *space reference*. The latter is a central technology underlying Geographic Information Systems (GIS). The former has, to the best of our knowledge, only rarely been looked at so far.

One reason for the success of GIS technology is that many of its represented phenomena have their own reference systems. The meaning of geographic attributes draws on *measurement scales*, such as temperature in Kelvin, and the meaning of spatial geometries draws on *spatial reference systems*, such as WGS84 (Kuhn, 2003). The former allows us to refer to temperatures in an inter-subjective way, and the latter to locations on the surface of the Earth. Temporal reference systems, such as calendars and clocks,

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[1]Compare the symbol grounding problem (Harnad, 1990).

allow us to refer to time. There are also reference systems for certain kinds of places. For example, certain buildings and plots of land can be referred to by address systems, the latter are used in geocoding. Note that a system of postal addresses is logically independent from a system of geodetic coordinates, even though a geocoder maps the former into the latter (Longley, 2011). It therefore constitutes an *independent system of place reference*, which existed way before any geodetic system of space was invented.

The tendency in GIS as well as in volunteered geographic information (VGI) communities has been to treat places as associations of names with regions in spatial reference systems, e.g., as clouds of geotags (Jones et al., 2008). This has proved a successful pragmatic solution and is the basic idea behind a gazetteer (Hill, 2006). However, places belong to those phenomena whose *identity criteria* (Guarino & Welty, 2000) can only indirectly and insufficiently be captured by spatial reference systems. Humanist geographers have been arguing for decades that the concept of place is multi-faceted and impossible to define in terms of space (Cresswell, 2004; Davies et al., 2009). From a technical viewpoint, this raises the question whether there is an independent procedure of reference which can be used to automatically identify and localize places.

In order to illustrate the challenge, consider the following example, which may serve as a benchmark of place reference. A market place must have a clear identity as well as a name, which allows people to refer to it in a reliable fashion, such that they know where they can find the market. However, constructing a technical procedure for identification and localization of a market place is a big challenge. First, market places are not necessarily permanent and may neither have a static location nor any established boundaries, infrastructure, or signs which could be used for this purpose (Fig. 1). For instance, the Farmers Market on State Street, Santa Barbara, CA, together with all its infrastructure, exists on Tuesdays, but makes way for regular vehicle traffic on other days of the week. The Maeklong Railway Market, Thailand is constantly adjusting its spatial extent by traders having to temporally move their goods and awnings when a train is approaching. During these minutes, customers cannot stand on the tracks and buy goods – consequently, this part of the market is temporally closed (i.e., the space directly

Fig. 1. Maeklong Railway Market, Thailand. Edited picture (original from Fabio Achilli at Flickr); CC BY 2.0. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/AO-140134.)

in front of the train and occupied by the train does not function as market). This immediately shows that places cannot in general be identified via named locations, as this location changes or may be occupied by different places in time. And even though a temporal gazetteer is able to *represent* a moving named location (Hill, 2006), it does not help in *generating* the logical association between place name, time and space. However, the latter is needed to account for place reference.

In this paper, we suggest that these difficulties of place reference may be a consequence of trying to force place into the wrong reference system. We argue that reference to locations and reference to places may be based on two related but independent techniques, which are grounded in different space experiences. Choosing one to represent the other may be therefore ill-conceived, similar to choosing a Celsius temperature scale to represent colors: It is at best a proxy that works only under certain conditions. However, the technical reconstruction of places from their own kind of underlying experience may show a way to an alternative spatial reference system. An important one of these place experiences is a *potential activity*. We explore a first theoretical step into this direction of research, propose a formal theory, and show the principal feasibility of activity-based place inference in a GIS setting, without being able yet to deliver a running implementation.

In Section 2, we discuss related work and, based on this, we suggest general requirements of a place inference system in Section 3. In Section 4, we introduce our idea that place reference may instead be based on involvements of referents in action simulations relative to other referents. In Section 5, we specify a theory of place activities and involvements in higher order logic (HOL), in which place referents can be formally reconstructed (Section 6). In Section 7, we discuss the implementation of activity simulation and place localization based on two simple examples in terms of GIS operations.

2. How to refer to a place

In order to deal with places as digital referents, a computable account of place is missing and required (Goodchild, 2011). In current practice, one tries to associate typed place names with explicit spatial coordinates. Places understood in this way are the content of *gazetteers* such as `www.geonames.org`. A gazetteer represents place as a triple, consisting of a place name, a place category, e.g. town, and a "footprint", i.e., a region or coordinate point in some spatial reference system (Hill, 2006). Using a place name parser (geoparser), it is then possible to locate and compare names in a web page in terms of regions or point clouds in a spatial reference system. One can search and retrieve web resources by their spatial distance. And unknown place names can be localized based on known places (Jones et al., 2008) or tag clouds.

However, a gazetteer entry leaves the underlying place concept ambiguous in many respects, which makes place identification cumbersome.[2] Places frequently have multiple names (synonymy), and can have multiple types as well as multiple footprints (from different sources or for different purposes) (Hill, 2006). Coordinates have uncertainty due to measurement, and places due to inherent vagueness (Montello et al., 2003; Janowicz, 2010). This requires tailored matching algorithms to relate them (Hill, 2006). The underlying difficulty becomes apparent if one uses latitude/longitude coordinates in order to identify a street address, and then realizes that the point is far off any building due to measurement uncertainties such as changes in a reference ellipsoid of the coordinate system (Goodchild, 2011).

At the same time, we know that place is a concept deeply rooted in perception. Authors such as Tuan (1977) and Relph (1976) adopted a phenomenological attitude towards place in an attempt to contrast

[2] Compare Hill (2006), Chapter 5 on Conflation.

with the predominant positivist tradition in Geography. Human geographers have been exploring space experience without the restrictions imposed by existing measurement scales (Cresswell, 2004). Unfortunately, it also leads many to the assumption that place is not at all accessible to technology. Couclelis, in contrast, argued for a more careful technological treatment: "The most significant spaces may never make it into a computer. Even so, the quest for their representation may prove the most exciting kind of geography we've ever done" (Couclelis, 1992). The challenge seems to be that technological space is an abstraction which must proceed from the human body, and not the other way around. *Phenomenology* needs to logically *precede technology*:

> "It is common to assume that geometrical space is the objective reality, and that personal and cultural spaces are distortions. In fact we know only that geometrical space is cultural space, a sophisticated human construct. [...] Original space is a contact with the world that *precedes thinking*. [...] We can say little more than that original space possesses structure and orientation by virtue of the presence of the human body. [...] Space is oriented by each center of consciousness, and primitive consciousness is more a question of '*I can*' than 'I think'." (Tuan, 1979; italics by the authors of this article.)

We follow Tuan (1977) and Seamon (1979) in suggesting that place reference systems, too, need to *proceed from phenomena grounded in certain human abilities*, and cannot take a detour based on space phenomena that are already technologically accessed.

Some researchers hold that a definition of place should, in one way or another, reflect Agnew's (Agnew, 1987) triad of place as *meaningful location*, covering the three aspects *location*, *locale* and *sense of place*.[3] Tuan (1991) adds the institutionalization and narrative of a place as a means of its baptism. While the breadth of these phenomena contributes to the making of place, we believe that not all of them may be necessary in inter-subjectively referring to places.

From a metaphysical perspective, places and space have been a subject of debate regarding their *objective existence* (Poincaré, 1952). Our approach, even though it is based on a method of reconstruction, stays agnostic regarding this question. Regardless of whether places exist independently from humans, as a matter of fact, we only have access to these places via our conceptual and perceptual apparatus. It is this apparatus which serves as a practical tool of reference (Scheider, 2012), and cognitive constructions are part of it. In the same sense, coordinate systems allow us to refer to objective space, even though there is no doubt that coordinates are a result of a sophisticated technical construction, and thus a product of our culture, involving likewise emotional attachment as well as conventions (think about Greenwich and the 0 meridian).

From an information ontology perspective, places have been described as primary means of *localizing* other objects, while at the same time being *in need of localization*. We anchor the location of many objects, e.g., of a rare butterfly species, not directly but relative to places, e.g., relative to a forest (Galton & Hood, 2005). Bennett and Agarwal (2007) have distinguished different ways in which places locate objects: by hosting them in a subspace of a convex hull, e.g. in case of a building, or by remotely anchoring them, e.g. on 'the top of the mountain'. We believe that the localization function of places, i.e., the possibility to be "in" a place, is a central feature of their identity. Furthermore, other locative expressions appearing in texts, such as "between", "near", "on", "at", may be involved in the localization of places relative to known referents (Khan et al., 2013; Scheider & Purves, 2013). Winter and Freksa (2012) recently proposed to localize places negatively, i.e., in contrast to other known places. However, it remains unclear how to precisely interpret locative expressions.

[3] Location refers to the spatial extent of a place, locale to its material layout and object inventory, and sense (or 'meaningfulness') to people's emotional attachment.

A promising way of accounting for a variety of experiences underlying place, including their localization function, is to understand them in terms of *potential activities*, in a way which resembles the notion of *affordances* (Jordan et al., 1998; Kuhn, 2001).[4] It is known that reference to place is tightly coupled with observing routine activities. The latter provide reliable patterns of orientation in space which can serve as anchor-points for place experience (Relph, 1976; Seamon, 1980). This is demonstrated by their important role in contemporary place extraction technology. For example, by their role in automated text extraction methods associating frequent activities with place types (Alazzawi et al., 2012), or in ubiquitous computing of places from trajectories (Aipperspach et al., 2006) or mobile fingerprints (Hightower et al., 2005). However, a principle problem of this approach is that it relies on performances of activities, and thus cannot account for the enduring property of places. If we derive place referents based on activities, then the former existentially depend on the latter. Once the activity stops, or in case the activity was only planned but never carried out, place referents cease to exist, too. However, we know that there are many relevant types of places which exist only because we know that some activity can *potentially* be carried out. Think about a restaurant without any guests, e.g., on the first day of its opening. It needs to be identifiable as a restaurant, even though constituting activities such as eating and conversation have never been performed there. A solution to this problem is the notion of an action potential. The latter competence basically allows people to project potential activities into their perceived environment. If this can be done in a reliable fashion, then, we argue here, it can be used as an anchor-point for constructing place referents.

Regarding the scope of this approach, we do not believe that activity-based place reference is the only way to refer to a place. We are aware that there are place categories which do not lend themselves to reference by activity, and thus need to be based on some other method of reference. Furthermore, there is a difference between a (technical) place referent and an established place. Convention and habit selects among available referents and introduces common names for them. This process is not reflected in our theory and requires human beings.

3. Requirements for place reference systems

What precisely are requirements for place reference systems? Which kind of knowledge should they allow one to infer? One method to make this precise is to formulate *competency questions* which a formalism should allow to be answered (Gangemi & Presutti, 2010). Based on the discussion above, we identify a number of questions which should be answerable by a place reference system, compare Fig. 2. These questions help us design place reference systems and, at the same time, help evaluate this design. Note that most of these questions are *temporal*, in the sense that answers are true only for a certain time, which corresponds to the notion of places as idle but versatile human constructs (Tuan, 1977). Place reference systems thus need to be able to account for temporality. In particular, place reference systems should come with an *inference mechanism* which allows one to *decide* about the following:

Place localization. Places need to be localizable in space (at a certain time). That is, we need to be able to decide *where a place is located at that time*. The temporal parameter of place localization is essential since places exist and cease to exist or may change their location in time (Kauppinen & Hyvönen,

[4]Gibson (1979) called action potentials in the human environment affordances. Note that we divert from the dominant objectivist view in environmental psychology, which takes an affordance as an objective quality of the human environment (Stoffregen, 2003). While affordances are normally associated with the functionality of a specific object, we use the term in a wider sense, as a general action potential which is projected into the perceived environment.

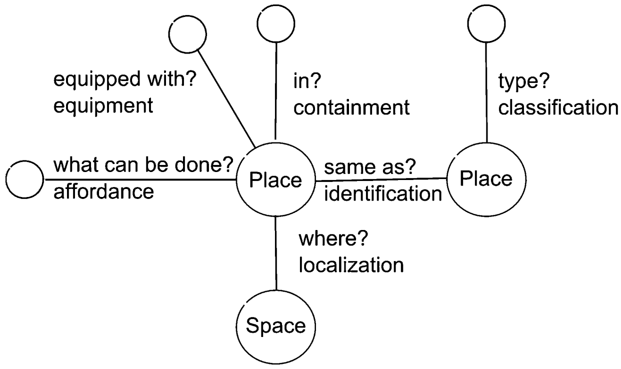


Fig. 2. Essential kinds of place inference.

2007). Place localization also involves uncertainty, which has been a subject of research over many years (Bennett & Agarwal, 2007). However, in this paper, we do not focus on the aspect of uncertainty.

Place containment. As argued above, an essential function of places is that they *serve to localize other things.* How exactly does one determine whether a particular object is *in* a particular place? How can different objects be in the same place? This basically allows the use of places as referents for other things, since the latter can be linked to their places (at a certain time). Note that since places are different from locations, as argued above, localization *of* places and localization *of other things via* places (which we call "containment" here, in order to tell one from the other) need to be distinguished.

Place affordance. Places afford humans to do something. This makes them primary objects of their interest. Therefore, we need to be able to infer what can be done in a place (at a certain time).

Place equipment. Places are interesting also because they are associated with a certain layout and are equipped with certain objects. This does not mean that these objects are necessarily in the place, they may be also outside. Place reference systems should allow one to infer how a place is equipped.

Place identification and classification. We need a procedure that allows us to decide whether something is a place, what kind of place it is, and whether some place is the same as another one.

There are many further questions which may be addressed by place research, for example, concerning the spatial and temporal relation between places (split, merge, overlap). However, we hold that the kinds of inference listed above cover an essential range of information needs about place. In the following, we will suggest a construction of place reference systems which is able to account for the formal inference of answers to these questions. However, this is only up to a certain extent and restricted to a number of place scenarios. In order to provide for answers in general, considerable future work is required. In particular, this paper does not address how humans are actually answering these questions in their daily practice. It rather suggests a new way to answer them by technological and ontological means.

4. Activity-based place reference in a nutshell

In this section, we explain our idea in an informal manner, before we dive into a formalism which accounts for all the details. In Scheider and Janowicz (2010), we suggested to regard places as media in the sense of Gibson (1979), i.e., as media for human activities. In this paper, we go a step further and

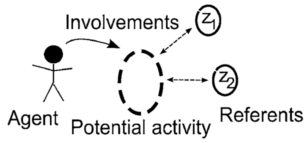


Fig. 3. Schema of involvements in potential activities.

propose that *to be in a place is to act relative to certain referents involved in this act*. Some of these referents serve to *localize* others in this act, including the agent. Places are then treated as logical reifications of involvements in *potential activities*. They are thus not dependent on the existence of actual performances. Place localization is similar to space localization in that it needs referents, however, it is not based on relative distances as in the case of spatial coordinate systems, but on involvements in potential activities. To be in a place simply means to actually perform corresponding actions. Furthermore, since a simulation can correspond to a number of actual performances of actual agents, it allows many referents to be in a place, taking corresponding roles in corresponding actions. And last but not least, whether a phenomenon referenced in this way is denoted by a place name depends on a conventional baptism.

4.1. Involvements in potential activities

Figure 3 illustrates the idea of involvements. Potential activities are projected into the perceived environment of some observer. They are depicted as dotted ovals. In analogy to performed actions, we assume that potential activities can likewise have participants. For example, agents, which are depicted as stickmen. In general, referents can be any perceivable phenomena, such as objects or surfaces, which serve as reliable anchor points via their participation in the potential act. The involvement of agents and other referents is depicted by corresponding arrows.

Since places are logically dependent on action potentials, their existence is independent from performances, as required. At the same time, involvements account for *place containment* and *equipment*: We may say that something is *in* a place, if it is involved in a certain manner in an action which is afforded by the place. For example, a human can be said to be in a vantage place because he or she is the agent of some afforded sighting. The sighting is performed by the human and it corresponds to some potential activity afforded by the place. Correspondences of potential and actual activities can be based on involved participants, action types and spatio-temporal coincidence. Furthermore, the things which participate in the activity, e.g., a sighted monument, can be considered part of the equipment of the place.

How can potential activities be perceived? There is no question that this is a central human competence, which is illustrated by many cognitive and neuronal studies.[5] This means we could rely on a human observer to provide the necessary observation data regarding potential activities in order to technically reconstruct places. However, our approach also suggests a further option.

4.2. Potential activities as simulations

We have suggested in Scheider (2012), Scheider et al. (2011) to follow Barsalou (1999) in regarding potential activities as *action simulations*. Cognitive simulations have recently been considered the central mechanism behind human-level intelligence (Hawkins & Blakeslee, 2004). Performed actions and

[5] Compare, e.g., Chapter 2 in Rizzolatti and Sinigaglia (2008).

activity potentials are then two sides of a coin of action types: the former is a performance, while the latter is a simulation of a type of action. This allows us to handle potential activities as a practical human expertise, and draws them away from metaphysical dispositions. One advantage is that this expertise may be mimicked by technical means. *Technical simulations* on sensor outputs may be used in order to *approximate* cognitive ones, which may help us refer to places even if no human observer is present. The question is which technical simulators can be used for this purpose. Other fields of technical simulation (Zeigler, 1976) suggest that in order to be useful, simulation models do not need to mimic internal processes, only their behavior. Useful technical simulations of cognitive processes can therefore range from very simple inference procedures to sophisticated algorithms with feedback loops. The quality of such simulators can be judged based on whether they serve to approximate human competences. Cognitive studies help in identifying human spatial competences (Klippel, 2011). However, this goes well beyond the scope of this paper, in which we propose very simplistic action simulators in order to make the case. Note also that this paper does not discuss how activity simulations could be computed. It rather focuses on how we can proceed once simulations are available.

4.3. Situated simulations, absent referents and dummies

A simulation of an activity involves agents as well as other referents. A simulation is *situated* if referents involved are present in the perceived environment in which the simulation is run. For example, if I imagine myself sitting down on a particular chair, then this chair and I are perceived and present, even though my sitting action is not. Simulations, however, can also be run *without the presence* of involved referents. For example, I can imagine Goethe sitting down on the chair. This explains how it is possible that traders on a market place can leave the market: traders can be part of a trading simulation which allows identifying a market place even in their absence. Think about the closed booths on a Christmas market. If I can imagine how they are used for trading, I will be able to identify the market even though it is closed. Whether this works well depends on the particular simulator. Furthermore, in this example, concrete knowledge of particular participants is not available at all. Simulations, however, are often run with *descriptions of referent properties*, in the same sense in which car crashes are simulated using crash test dummies. Dummies are substitutable for a range of concrete participants, such as persons of a certain size. In this way, it becomes possible to extend the validity of a single simulation to sets of participants instead of particular ones. This is important if simulations are used for categorization, as in our case. One may perhaps say: the less a simulation is based on the presence of particular referents and the more it uses dummies, the less it can be called "situated". In this paper, we model dummies as *logical referent descriptions*. The latter involve all referents in a simulation which fit the description, regardless whether they are present or not. We assume that activity simulations always have referent descriptions for each kind of involvement, where some of these descriptions fit none or particular referents (i.e., they are definite descriptions or names), while others may fit larger sets.

4.4. Place reference and localization

We propose to base place reference on situated simulations of activities which may involve other referents. How can places constructed in this way be localized in space and time? Situated simulations are run on the basis of perceptions, and these perceptions can be localized. Whenever one experiences a phenomenon in one's environment and wants to refer to it, one can utter a *here-now* (deictic) statement about it, such as "here and there continues an activity" (Quine, 1974). In the simplest case, one just

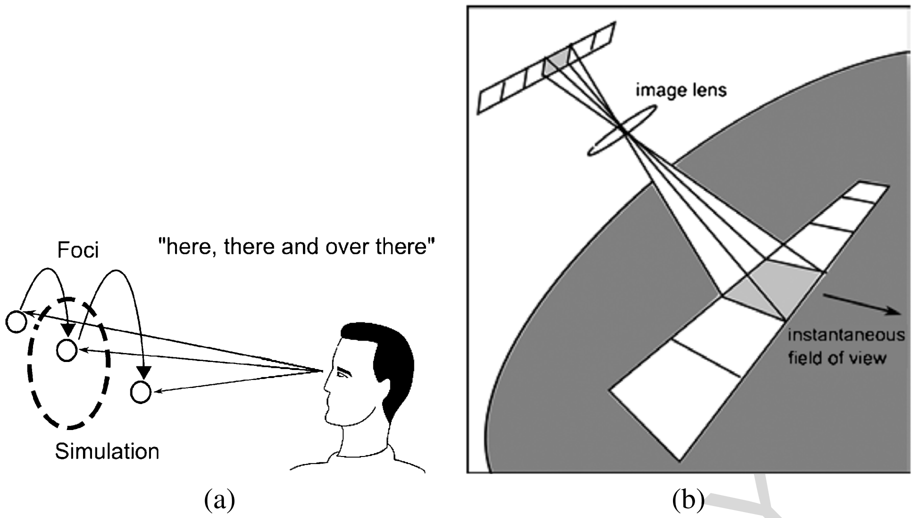


Fig. 4. A *focus* is an abstraction over foci of human attention and spatio-temporal sensor ranges. In both cases, spatio-temporal resolution is a consequence of a shifting observation process, which takes into focus a given excerpt of the environment at a given time. (a) Foci of attention of some human observer. (b) Instantaneous field of view of remote sensor.

points at something. Correspondingly, we know the resolution of a sensor because we are able to follow its sensor range and focus. For example, in remote sensing, a focus corresponds to an *instantaneous field of view*, see Fig. 4. Each instantaneous field of view has a corresponding region in space and an interval in time. We can use sequences of satellite images in order to observe a process, or in order to simulate it based on other observed properties. In this way, foci serve to localize places in space and time: If places are based on activities, activities are simulated at foci, and foci have a spatio-temporal resolution, we can localize a place in terms of those regions which correspond to the set of foci underlying the simulated action (Scheider, 2012). The lowest level information items which can be shared and on which we can build place reference systems are therefore *foci* of an observer or a sensor, i.e., *here-now granules* (Scheider, 2012). They allow us to abstract from human or technical sensing, and they have a spatio-temporal resolution due to the underlying observation process (Frank, 2009). They serve as atoms in terms of which we can express results of observation as well as simulation.

4.5. Inter-subjective place reference and convention

Observations can be understood by other observers because they have the same perceptual competences, and because they are able to *join the attention* of the speaker (Tomasello, 1999). Humans are particularly strong in following the focus of attention of others (Tomasello, 1999). Furthermore, they are equipped (by culture as well as nature) with many equivalent sensors as well as simulators (Hawkins & Blakeslee, 2004). This, in essence, allows them to share categories and views on the world (Tomasello, 1999). Disagreement about the location and identity of places can therefore be at least threefold: it can be a result of using different sensors of different resolution and focus, of using different activity simulators, or of using different place construction principles. All of these give rise to spatial uncertainty of places. On the other hand, place referents can become inter-subjective once their way of construction is mimicked, i.e., if it is the case that observers with equivalent competences join their foci of attention (i.e., focus on the same spots), actions are simulated in the same way (based on equivalent simulators), and places are reified in the same manner.[6] Thus, inter-subjectivity of place reference rests on the assumption that humans can share constructive competences and join their attention. In this, places are not in any way different from other spatial categories (Scheider, 2012). Furthermore, joint attention also accounts for the conventional aspect of places. Once place referents are selected based on joint attention, place names can be established. We do not focus here on this conventional aspect. Note that our theory presented in the next section is only meant as a tool for precisely describing how place referents may be generated, not a tool for establishing place names or conventional habits. In other words, it is not intended as a tool to get rid of the humans in the loop.

5. A theory of place activities and involvements

In this section, we introduce a formal theory of activities which can be used for place reference. The theory was specified in terms of typed functions in HOL and implemented[7] in the theorem prover Isabelle/HOL.[8] Note that functions in Isabelle/HOL are *total*, i.e., they can always be applied to the entire domain. Function applications are left associative, i.e., $f\ a\ b\ c = (((f\ a)\ b)\ c)$. $(x :: X)$ declares x to be of type X. Complex types are built with constructors and embraced by quotation marks. The symbol $\Rightarrow$ is a type constructor for functions, and $\times$ for tuples. Predicates are specified as Boolean functions of type "$X \Rightarrow bool$". We also use Isabelle's sum types "$X + Y$". For reasons of readability, we omit type upcasting in formulas. λ (lambda) is the Isabelle operator for function abstractions. We also use Isabelle's list and set operators, for example set definition $\{x.P(x)\}$. In non-recursive definitions, definiens and definiendum are separated by $==$. Recursive function definitions are introduced by the keyword *fun*.

5.1. Basics of a place activity theory

We assume that the primitive notions in our theory are grounded in *action simulations*. That is, all axioms and ground facts in the theory are considered either a result of performing a simulation of the required type of action in the perceived environment of an observer or a sensor, or of computing abstractions on simulation results (compare Scheider, 2012). We first introduce our domain of discourse by formal types and primitive functions. Then we show how to define relations between activities and compound activities, before introducing relevant primitive kinds of activities which correspond to action simulators.

5.1.1. Formal types and primitive operators

Our universe of discourse consists of potential activities (called affordances[9]), referents, foci, locations and temporal referents, as well as places. Each of these kinds of things is introduced as a formal type in Table 1. Note that types in Isabelle are *mutually exclusive*, so it is never the case that a potential activity is a referent or a place is at the same time a location. The type *Referent* is a shorthand for phenomena which can be directly perceived, such as bodies or surfaces. A *Focus* is a granular entity which is produced

[6] How these equivalences are established is not our concern here, but we believe it is beyond question that humans have equivalent perception and simulation capacities at their disposal.

[7] Specification and proofs are in http://www.geographicknowledge.de/vocab/PlaceAffordanceTheory.thy.

[8] http://www.cl.cam.ac.uk/research/hvg/Isabelle/. HOL allows functions as arguments and recursive definitions, which can be used to specify constructors.

[9] For lack of a better and shorter term. We are aware that this does not fully correspond to the common use of the term.

Table 1
Primitive and defined types of things

Name	Formal type	Instances of this type
Affordance	A	Primitive and compound action simulations
Action	*Action*	Primitive and compound action performances
Referent	*Referent*	Things that can be referenced by perception
Focus	*Focus*	Granular foci of attention of some observer/sensor
Location	*Space*	Regions in a spatial reference system
Time	*Time*	Regions in a temporal reference system
Place	*Place*	Places in a place reference system
Activity	$A' =$ "$A + Action$"	Super-type of potential or performed activities
Activity type	$AType =$ "$A' \Rightarrow bool$"	Predicates denoting subsets of activities
Affordance type	$AfType =$ "$A \Rightarrow bool$"	Predicates denoting subsets of affordances
Involvement	$Involvement =$ "$Referent \Rightarrow A' \Rightarrow bool$"	Involvements of referents in activities
Referent type	$ReferentType =$ "$Referent \Rightarrow bool$"	Predicates denoting subsets of referents

Note: Types of predicates and relations are defined as types of Boolean functions.

Table 2
Primitive operations on foci and activities

Formal symbol	Description
$join$ :: "$A \Rightarrow A \Rightarrow A$"	A semi-lattice on affordances
$join'$ :: "$Action \Rightarrow Action \Rightarrow Action$"	A semi-lattice on actions
$where$ :: "$Focus \Rightarrow Space$"	The spatial resolution of foci
$when$ :: "$Focus \Rightarrow Time$"	The temporal resolution of foci
$leqt$ :: "$Focus \Rightarrow Focus \Rightarrow bool$"	Temporal order on foci

by observation and which has a resolution in terms of some region in spatial and temporal reference systems. *Affordances* are action simulations performed on such foci, as well as results of combining these. *Activities* are performed actions, i.e., ones that are not simulated. Note that both affordances and actions denote concrete events, not activity types. We use a supertype A' to talk about both kinds of events, and often we do not further distinguish between the two. *Involvements* provide the central mechanism for place reference, as we will see in the next section. They express the participation of referents in some activity. For example, the participation of agents (Fig. 3).

Primitive functions on these types are introduced in the following, together with some axioms which describe their behavior. First, we assume that affordances (and, likewise, actions) can be arbitrarily combined into *compounds*, similar to merging parts into wholes. This is expressed by a *join* operation (and a similar $join'$ for actions), compare Bach (1986) (Table 2). It can be axiomatized in terms of a semi-lattice, i.e., a partially ordered set of affordances which has a join (a least upper bound) for any nonempty subset of affordances. We require that this lattice is also *atomistic* and *constructive*. That is, every affordance is guaranteed to be a *least upper bound* (*lub*) of a constructive set of primitive affordances (compare Appendix B). An equivalent lattice exists for actions.

Second, we introduce three functions (compare Table 2) which map foci into regions in spatial (*where*) and temporal (*when*) reference systems and which totally order the foci (*leqt*) according to time.[10] Every

[10]The latter may be defined based on time stamps.

Table 3

Involvements, simulations and purposes of affordances

Formal symbol	Description
agentOf :: *Involvement*	The involvement of intentional agents
objectOf :: *Involvement*	The involvement of targets
supports :: *Involvement*	The involvement of support surfaces
toolOf :: *Involvement*	The involvement of tools
productOf :: *Involvement*	The involvement of generated products
resourceOf :: *Involvement*	The involvement of resources
performedAt :: "$A' \Rightarrow Focus \Rightarrow bool$"	Focus at which an activity was performed
purpose :: "$A' \Rightarrow A'$"	The purpose of an activity is another activity

pair of foci is ordered, however we leave open the possibility of simultaneous (*eqt*) foci. Note that it follows that *leqt* is reflexive.

Axiom 1.

$$\textit{Totality}:\quad \forall\,(x :: Focus)\,(y :: Focus).\ leqt\ x\ y \lor leqt\ x\ y$$

$$\textit{Transitivity}:\quad leqt\ x\ y \land leqt\ y\ z \rightarrow leqt\ x\ z$$

Definition 1.

$$\text{Simultaneity}:\quad eqt\ x\ y == leqt\ x\ y \land leqt\ y\ x$$

5.1.2. Involvements in activities

There are a number of participants which are typically involved in activities (Table 3) (compare Smith & Grenon, 2004; Sowa, 1996). The kinds of involvements relevant for us range from agents (intentional bodies), over objects (i.e., things that are targeted by actions), supports (surfaces that support an action), tools (things that serve to do something, but which are not consumed), resources (things that are consumed in an action, i.e., which are no longer available afterwards), to products (things that are generated in an action). As we will see later, the occurrence of involvements depends on the kinds of affordances.

We propose some axiomatic restrictions on these relations which constrain their meaning over all activities. Activities are bound to have agents. Furthermore, activities are performed at some foci. Thus, they have a spatio-temporal extension. And, last but not least, both *involvements* and *performedAt* relations are propagated upwards in a join hierarchy. In consequence, compound activities involve the union of participants and are performed at the union of foci of their components. This allows the preservation of relations from lower to upper levels of abstraction of affordances (equivalent axioms are used for the action lattice).

Axiom 2.

$$\forall\,(x :: A').\ (\exists\, y.\ agentOf\ y\ x)$$

$$\forall\,(x :: A').\ (\exists\, y.\ performedAt\ x\ y)$$

$$\forall\, r\ x\ (y :: A)\ (inv :: Involvement).\ inv\ r\ x \rightarrow inv\ r\ (join\ x\ y)$$

$$\forall\, f\ x\ (y :: A).\ performedAt\ x\ f \rightarrow performedAt\ (join\ x\ y)\ f$$

Furthermore, activities may have purposes. However, goal hierarchies, as discussed in Jordan et al. (1998), can become arbitrarily abstract and complicated. For our purpose, it is sufficient to specify activity goals only on the lowest level. The outcome of an activity is then simply a new activity. Purposes allow the linking of affordances with each other, as we will see later. This is specified in terms of the function *purpose* in Table 2. Actions may or may not have a clear purpose. An example for the latter may be a singing under the shower. We model activities without purpose simply by letting them map $purpose$ to themselves.

5.1.3. Simulation dummies and involvement profiles

While actions always involve concrete referents, activity simulations may also involve *dummy referents* which stand for a set of possibly involved referents, similar to crash test dummies. As argued in Section 4, we model dummies as referent profiles and assume that every affordance has such a profile for each kind of involvement, that is, a logical description of referents which fit the simulation. The latter may be a definite description, e.g., a name, or an arbitrary predicate, or the description may be empty (if nothing is involved). Profiles are provided by the function $inv_{profile}$, which always involves in a given affordance all referents which fit the profile.

Axiom 3.

$$inv_{profile} :: \text{“}Involvement \Rightarrow A \Rightarrow ReferentType\text{”}$$

$$\forall\, x\ (a :: A)\ (inv :: Involvement).\ (inv_{profile}\ inv)\ a\ x \leftrightarrow inv\ x\ a$$

5.1.4. Activity relations and compounds

Given the vocabulary so far, a number of relations and predicates on activities can be defined. These include coincidence, overlap, simultaneity, concatenation, co-agentivity, sequence, and endurance (Table 4). Note the difference between coincidence and simultaneity: the first means equivalence of foci (including space), the second means temporal equivalence. One could similarly define spatial equivalence. A sequence is a coagentive concatenation of affordances, i.e., a “ballet” (Seamon, 1979). An activity is an “endurance” of another activity if the agent of the first activity is object of the second

Table 4
Defined relations between activities

$covers\ b\ a == \forall\, x.\ performedAt\ a\ x \rightarrow performedAt\ b\ x$
$coincident\ a\ b == covers\ a\ b \leftrightarrow covers\ b\ a$
$overlap\ a\ b == (\exists\, x.\ performedAt\ a\ x \wedge performedAt\ b\ x)$
$during\ a\ b == \forall\, x.\ performedAt\ a\ x \rightarrow (\exists\, y.\ eqt\ x\ y \wedge performedAt\ b\ y)$
$simultaneous\ a\ b == during\ a\ b \wedge during\ b\ a$
$endof\ a == \{f.\ ((performedAt\ a\ f) \wedge (\forall\, x.\ performedAt\ a\ x \rightarrow leqt\ x\ f))\}$
$startof\ a == \{f.\ ((performedAt\ a\ f) \wedge (\forall\, x.\ performedAt\ a\ x \rightarrow leqt\ f\ x))\}$
$concat\ a\ b == (endof\ a = startof\ b)$
$coagentive\ a\ b == \forall\, x.\ agentOf\ x\ a \leftrightarrow agentOf\ x\ b$
$sequence\ x\ y == coagentive\ x\ y \wedge concat\ x\ y$
$coobjective\ a\ b == \forall\, x.\ objectOf\ x\ a \leftrightarrow objectOf\ x\ b$
$endures\ y\ x == (\exists\, z.\ objectOf\ z\ x \wedge agentOf\ z\ y)$
$Supported\ a == (\exists\, x.\ supports\ x\ a)$
$Combinat\ a\ x\ y == (x \neq y) \wedge (a = join\ x\ y)$

one, which is a basic mechanism for social activities, as we will see. Based on this, we can generate compound affordances, such as *simultaneous joins* (joins of simultaneous affordances) and *bitasks* (co-agentive coincident joins, i.e., affordances that are performed by the same agent and at the same foci[11]).

Definition 2.

$$\textit{Simult a x y} == \textit{Combinat a x y} \wedge \textit{simultaneous x y}$$

Definition 3.

$$\textit{Bitask a x y} == \textit{Combinat a x y} \wedge \textit{coincident x y} \wedge \textit{coagentive x y}$$

5.1.5. Kinds of activities for place reference

Kinds of activities are modeled as a set of primitive predicates of type *AType* (K_A in Definition 4). They are *conjunctively exhaustive on non-compound activities* (Appendix B, Axiom 9), since every activity is a result of performance or a composition thereof. One may furthermore assume that activity kinds are mutually exclusive, in order to prevent decisions on whether performances can be combined or not.[12] The set K_A is extensible and depends on the application domain. For a certain domain, we can choose primitives based on whether corresponding action competences/simulators are available. The particular list in Definition 4 is needed for the types of places we will construct in Section 6.4.

Definition 4.

$$\begin{aligned} K_A :: \text{“}\textit{AType set}\text{”} == \{&\textit{Standing, Sitting, Walking, Driving, Climbing, Placing, Seeing,}\\ &\textit{Hearing, Talking, Writing, Showing, Giving, Receiving,}\\ &\textit{Manufacturing, Cultivating, } \ldots\,\} \end{aligned}$$

In the following, we describe these kinds of activities in terms of their participants. If something is a standing, a sitting, a walking, a driving, a climbing, or a placing, then it needs to be supported by some surface (Fig. 5(a), (b) and (d)). A placing involves an object (which is placed on a surface, e.g., on the cupboard, see Fig. 5(d)), and a seeing also involves an object (which is seen). Furthermore, manufacturing involves a product (which is generated), a resource (which is consumed), as well as some tools. Cultivation involves an object (the field surface), as well as tools (Fig. 5(c)).

Axiom 4.

$$\big((\textit{Standing x} \vee \textit{Sitting x} \vee \textit{Walking x} \vee \textit{Driving x} \vee \textit{Climbing x} \vee \textit{Placing x}) \rightarrow \textit{Supported x}\big)$$

$$(\textit{Placing a} \vee \textit{Seeing a}) \rightarrow (\exists\, y.\ \textit{objectOf y a})$$

[11] The latter is a simple way to simulate *multitasking*. Another approach would be to merge action simulators directly, instead of only their outputs.

[12] Humans can easily combine certain actions as well as simulators. For example, it is possible to jump on a leg and whistle and to imagine that. However, some combinations seem impossible. For example, humans may have a hard time imagining to jump on one leg and simultaneously jump on the other one. For the sake of simplicity, we model multitasking in this paper simply by unrestricted merging of activities instead of (restricted) fusion of competences. In consequence, some mergers may appear not meaningful. However, the merging just means that we use a single entity to talk about both performances at once.

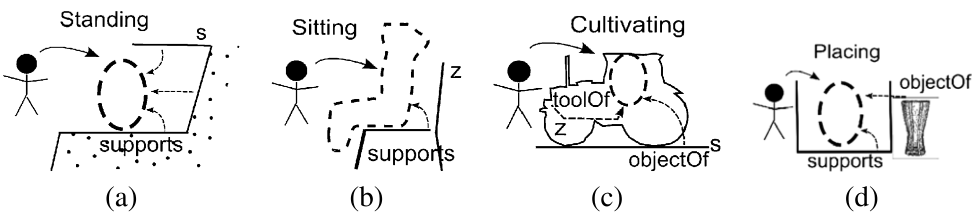


Fig. 5. Some primitive kinds of activities.

$$\textit{Manufacturing } a \rightarrow (\exists\, x\, y\, z.\ \textit{productOf } x\ a \wedge \textit{resourceOf } y\ a \wedge \textit{toolOf } z\ a)$$

$$\textit{Cultivating } a \rightarrow (\exists\, x\, z.\ \textit{objectOf } x\ a \wedge \textit{toolOf } z\ a)$$

The kinds of activities introduced so far are *non-social*, in the sense that in order to perform them, the agents do not need partners. However, many kinds of actions relevant to places are social (Seamon, 1979). In order to specify social activities, we need to define promptings. A *prompting* is a kind of action which *has a different action as purpose* (which is prompted), such that *all of its objects are agents* in the prompted action.

Definition 5.

$$\textit{Prompting } a == (a \neq \textit{purpose } a) \wedge \big(\forall\, b.\ \textit{objectOf } b\ a \rightarrow \big(\textit{agentOf } b\ (\textit{purpose } a)\big)\big)$$

In short, promptings intend other actions whose agents are therefore intended objects. A simple example of a prompting is a *Giving*. A giving prompts a receiving, whose agent is the object of the giving. Without the receiving, the giving is actually unsuccessful. The thing which is given (and received) can be seen as a resource, not an object, since it is consumed in the course of the giving (in the sense that it is no longer available for the agent). For example, money is consumed by spending it (giving it to someone else).

Axiom 5.

$$\textit{Giving } a \rightarrow \textit{Prompting } a$$

$$\textit{Giving } a \rightarrow \textit{Receiving } (\textit{purpose } a)$$

$$\textit{Giving } a \rightarrow (\exists\, y.\ \textit{resourceOf } y\ a)$$

$$\textit{Giving } a \wedge \textit{resourceOf } y\ a \rightarrow \textit{resourceOf } y\ (\textit{purpose } a)$$

Further examples for promptings are *speech acts*. Speech acts are performed in order to prompt corresponding actions of communication partners (Janich, 2006; Kamlah & Lorenzen, 1996). For example, talkings prompt hearings (which may then be called listenings), showings prompt seeings (which are then called watchings) and writings prompt seeings (which are then called readings).

Definition 6.

$$\textit{Speechact } a == (\textit{Showing } a \vee \textit{Talking } a \vee \textit{Writing } a)$$

Axiom 6.

$$Speechact\ a \rightarrow Prompting\ a$$
$$Talking\ a \rightarrow Hearing\ (purpose\ a)$$
$$Showing\ a \rightarrow Seeing\ (purpose\ a)$$
$$Writing\ a \rightarrow Seeing\ (purpose\ a)$$

5.1.6. Correspondence of actions and affordances

We can use the various kinds of activities and their participants as well as the spatio-temporal extent in order to decide whether a performed action corresponds to a simulation. Actions can then be regarded as "realizations" of corresponding activity potentials that are simulated. One can define a correspondence relation as the following definition.

Definition 7.

$$\begin{aligned} corresp\ (a :: A)\ \big(a' :: Action\big) == {} & \big(\forall\ (inv :: Involvement)\ r.\ inv\ r\ a' \rightarrow inv\ r\ a\big) \\ & \wedge \big(\forall\ ak.\ ak \in K_A \rightarrow \big(ak\ a \leftrightarrow ak\ a'\big)\big) \\ & \wedge \big(\forall f.\ performedAt\ a'\ f \rightarrow performedAt\ a\ f\big) \end{aligned}$$

An affordance corresponds to an action iff the affordance shares all involvements of the action, activity kinds apply equally, and the action is performed at the location of the affordance. An affordance may involve more participants than a corresponding action (which is why the first part of the definiens is not a biconditional), because the former involves all referents of the respective involvement profile, whereas the latter involves only particular referents.

5.2. Complex involvements

In this section, we define a number of complex involvements in compound affordances, based on the vocabulary introduced in the last section. These complex affordances are used to reference and identify the types of places in the next section.

5.2.1. Complex involvements with things

If we are accessing a train from a platform, or if we are accessing a room in a house from another room, then we concatenate a standing, a walking and a standing action (Fig. 6(a)). The first and last standing let us stay on the platform or in a room, and the walking shifts us from one opportunity to stay to another. We define this in terms of a sequence of activities in the following definition.

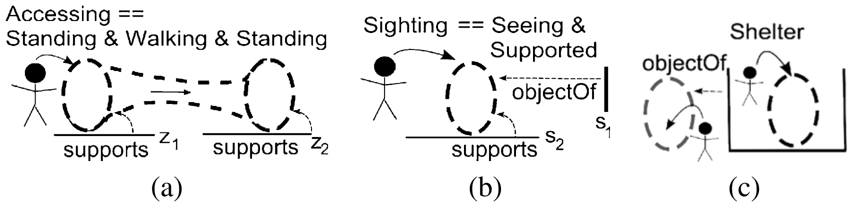


Fig. 6. Some compound non-social activities.

Definition 8.

$$\textit{Accessing } x\ y\ z == \textit{Standing } x \wedge \textit{Walking } y \wedge \textit{Standing } z \wedge \textit{sequence } x\ y \wedge \textit{sequence } y\ z$$

The supports of the two standings allow us to locate the goal and the start, and thus to define what it means that some surface is accessible from where one can stand. Surface r is accessible from some standing x if there exists a chain of corresponding activities in the following definition.

Definition 9.

$$\textit{AccessableFrom } r\ x == (\exists\ y\ z.\ \textit{Accessing } x\ y\ z \wedge \textit{supports } r\ z)$$

Another important complex activity is called a *sighting*. We use this somewhat artificial term to refer to the possibility to see something from a surface, i.e., from a simultaneously performed *supported* act, which allows one to locate the viewer based on a support. The supported act may be a standing, such as in Fig. 6(b), but may be also a sitting or a walking.

Definition 10.

$$\textit{Sighting } a == \exists\ x\ y.\ \textit{Bitask } a\ x\ y \wedge \textit{Seeing } x \wedge \textit{Supported } y$$

A further compound activity is a *shelter activity*. A shelter activity allows one to do something while being sheltered from exposure to another activity, i.e., from being passively involved in another action (Fig. 6(c)). We first define what it means to be *exposed to another activity*, namely that the agent of a supported activity is object of another simultaneous activity in the following definition.

Definition 11.

$$\textit{BeingExposed } a\ x == \textit{endures } a\ x \wedge \textit{simultaneous } x\ a \wedge \textit{Supported } a$$

Definition 12.

$$\textit{ShelterFrom } a\ t == \neg\big(\exists\ a'.\ t\ a' \wedge \textit{BeingExposed } a\ a'\big)$$

For example, the following relation expresses whether one is shielded from the view of other people possibly gazing from somewhere (some surface *r*).

Definition 13.

$$\textit{ShelterFromSight } a\ r == \textit{Shelter } a\ (\lambda\ s.\ \textit{Sighting } s \wedge \textit{supports } r\ s)$$

5.2.2. Complex involvements with people

A simple example for a complex social involvement is the activity of being sighted by other people (Fig. 7(a)).

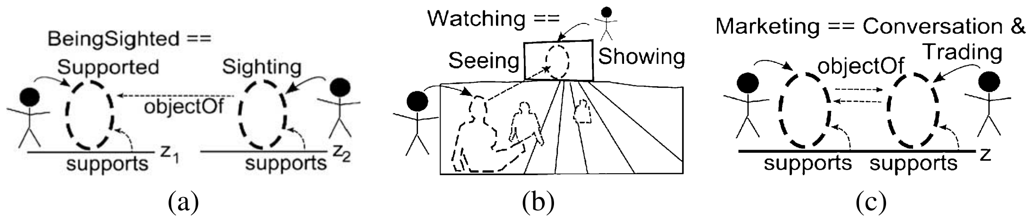


Fig. 7. Some compound social activities.

Definition 14.

$$BeingSightedFrom\ a\ r == \exists\, x.\ BeingExposed\ a\ x \wedge Sighting\ x \wedge supports\ r\ x$$

More sophisticated social activities can be based on promptings. For example, *tradings*, i.e., exchanges of goods, can be defined based on the possibility of mutual *transactions* among agents, where the latter are defined as mergers of simultaneous givings with intended receivings and with respective supported acts in the following definition.

Definition 15.

$$\begin{aligned} &Transaction\ a\ x\ y \\ &\quad == Simult\ a\ x\ y \wedge \big(\exists\, x'\ x''\ y'\ y''.\ Giving\ x' \wedge purpose\ x' = y' \wedge Supported\ x'' \wedge Supported\ y'' \\ &\qquad\qquad \wedge Bitask\ x\ x'\ x'' \wedge Bitask\ y\ y'\ y''\big) \end{aligned}$$

An activity a is a trading of agent ag_1 with agent ag_2 with respect to object ob, iff a is a merger of two supported mutual transactions between these agents and ob is the resource in one of these transactions.

Definition 16.

$$\begin{aligned} &TradingWith\ a\ ag_1\ ag_2\ ob \\ &\quad == (\exists\, x\ x_1\ x_2\ y\ y_1\ y_2.\ resourceOf\ ob\ y_1 \wedge join\ x\ y = a \wedge Transaction\ x\ x_1\ x_2 \\ &\qquad \wedge Transaction\ y\ y_1\ y_2 \wedge agentOf\ ag_1\ x_1 \wedge objectOf\ ag_1\ y_1 \wedge agentOf\ ag_2\ y_1 \\ &\qquad \wedge objectOf\ ag_2\ x_1) \end{aligned}$$

Very similarly, we can define a *conversation* based on the activity of mutually directed and supported speeches. The latter are mergers of speech acts (talkings, showings, writings) with their simultaneous promptings (hearings, seeings).

Definition 17.

$$\begin{aligned} &Speech\ a\ x\ y \\ &\quad == Simult\ a\ x\ y \wedge \big(\exists\, x'\ x''\ y'\ y''.\ Speechact\ x' \wedge purpose\ x' = y' \wedge Supported\ x'' \\ &\qquad\qquad \wedge Supported\ y'' \wedge Bitask\ x\ x'\ x'' \wedge Bitask\ y\ y'\ y''\big) \end{aligned}$$

Definition 18.

$$\begin{aligned}&\mathit{Conversation}\ a\ ag_1\ ag_2\\&\quad == (\exists\, x\ x_1\ x_2\ y\ y_1\ y_2.\ \mathit{join}\ x\ y = a \wedge \mathit{Speech}\ x\ x_1\ x_2 \wedge \mathit{Speech}\ y\ y_1\ y_2 \wedge \mathit{agentOf}\ ag_1\ x_1\\&\qquad \wedge \mathit{objectOf}\ ag_1\ y_1 \wedge \mathit{agentOf}\ ag_2\ y_1 \wedge \mathit{objectOf}\ ag_2\ x_1)\end{aligned}$$

It is now possible to define a marketing activity as a compound (a) of conversation and trading with a trader ag_2 about an object ob.

Definition 19.

$$\begin{aligned}&\mathit{Marketing}\ a\ ag_2\ ob\\&\quad == (\exists\, ag_1\ x\ y.\ a = \mathit{join}\ x\ y \wedge \mathit{Conversation}\ x\ ag_1\ ag_2 \wedge \mathit{TradingWith}\ y\ ag_1\ ag_2\ ob)\end{aligned}$$

The definition clarifies what is needed in order to *simulate a market*: transactions and conversations with salespersons which stand or sit on some surface, e.g., a market street.

6. The construction of place referents

Up to now, we have introduced types of simulated activities and actions and what they involve. Simulated activities provide a basis for constructing place referents. In this section, we suggest how this may be done by choosing involvements of *locatums* (referents which are to be located) in certain types of affordances relative to *locators* (referents which locate the locatums). Furthermore, we show how this allows us to answer the competency questions discussed in Section 3. We also specify a simple model of our theory, which proves its consistency, and suggest a collection of derived types of places.

6.1. Place identification based on locator and locatum

Places can be identified by the set of potential activities of a certain type that involve certain referents in a certain way. A *locator* (the referent which locates a place) and a *locatum* (the referent which is located at a place) are roles played by involved referents. This lets us uniquely identify a single place in terms of a tuple of four elements.

Definition 20.

$$\mathit{Place} :: \mathit{AfType} \times \mathit{Involvement} \times \mathit{Involvement} \times \mathit{Referent}$$

These different ingredients of a place are as follows (where *fst* retrieves the first element of a tuple, and *rest* its rest).

Definition 21.

$$\mathit{Aftype}\ (p :: \mathit{Place}) == \mathit{fst}\ p$$

$$Locatuminv\ (p :: Place) == fst\ (rest\ p)$$

$$Locatorinv\ (p :: Place) == fst\ \big(rest\ (rest\ p)\big)$$

$$Locator\ (p :: Place) == rest\ \big(rest\ (rest\ p)\big)$$

That is, the underlying type of affordance of a place p (*Aftype*), the type of involvement of the locatum in an affordance of this type (*Locatuminv*), the type of involvement of the locator in an affordance of this type (*Locatorinv*), and a referent which plays the role of the locator (*Locator*).

The idea behind this is that we refer to an *individual place* (note: not a place type) by identifying all affordances of the respective type with respect to some concrete involved referent (locator). For example, if the locator is a sighted object, then all possible sightings of this object (i.e., the respective "sites") form a single vantage place. Affordances can be used to localize a place since they were simulated at foci which map into space (as well as time). Figure 8 illustrates the idea. In case there is no corresponding affordance available, the place remains ungrounded (compare next section).

Alternatively, one may also specify *multi-locator places* which take sets of locators instead of a single one, and multi-affordance places, which take arrays of affordance types. For our purpose, this simple definition is enough.

6.2. Place grounding and localization

The logical interconnections between the ingredients of a single place (such that the locator is actually involved in the required sense in an affordance of the respective type) are formally not treated as part of the place type definition, but are added instead as a restriction on *place grounding*.[13] In order to localize a place constructed in this way, we need to be able to ground it into some appropriate affordance.

Definition 22.

$$GroundedIn\ (p :: Place)\ (x :: A)$$
$$== \big((Aftype\ p)\ x \wedge \big(\exists\ locatum.(Locatuminv\ p)\ locatum\ x \wedge (Locatorinv\ p)\ (Locator\ p)\ x\big)\big)$$

That is, the affordance must be of the required type, there must be a locatum involved in the required sense, and the locator must also be involved in the required sense. If a place is grounded in some affordance, then we can localize it easily as follows.

Definition 23.

$$locatedAt\ (p :: Place)\ (s :: Space) == (\exists\ a\ x.\ GroundedIn\ p\ a \wedge performedAt\ a\ x \wedge where\ x = s)$$

6.3. Place containment and equipment

How can this mechanism be used to decide whether something is "in" a place? In our approach, places are *places for locatums involved in corresponding actions*. That is, the referents r involved as locatum in a grounded place affordance are *in* a place p at a certain time t iff they are also involved as locatum in a corresponding action performed at t in the following definition.

[13] This is done because it is easier in Isabelle to have unrestricted types and model restrictions as predicates over them.

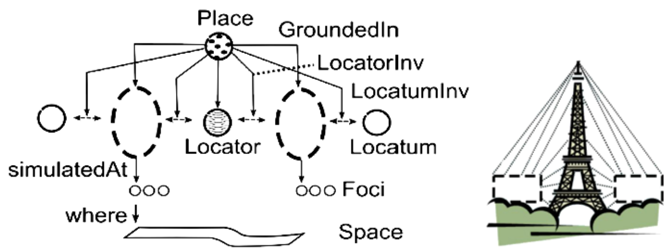


Fig. 8. Schema of place grounding and localization. Affordances which ground a particular place need to be of a particular type and need to involve a particular locator (or a set of locators), such as the Eiffel tower. The locations of those foci at which such an affordance was simulated provides for the location of the place. Note that places may consist of several such affordances. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/AO-140134.)

Definition 24.

$$in_{place}\ (r :: Referent)\ (p :: Place)\ (t :: Time)$$
$$== \exists\ a\ a'\ f.\ GroundedIn\ p\ a \wedge corresp\ a\ a' \wedge (Locatuminv\ p)\ r\ a' \wedge performedAt\ a'\ f$$
$$\wedge\ when\ f = t$$

That is, in order to be in a place, one has to be involved in an action which corresponds to an affordance of that place. Prototypically, locatums are agents. This covers a human-centric usage of the word place. For example, the particular place from which one has a nice view on the Eiffel tower is a place in which only people can be, and which is spread around the tower (Fig. 8). Someone is in this place if he or she is an agent of a concrete sighting of the tower. Even though the Eiffel tower is object of the sighting, as a matter of fact, the tower is not “in” this place (it is not even located where this place is located). There are also places for passive objects, such as cups on a cupboard. Such place categories can be based on alternative locatum involvements. And all other involved referents simply form the equipment of a place in the following definition.

Definition 25.

$$equipment\ (z :: Referent)\ (p :: Place) == \exists\ (inv :: Involvement)\ a.\ GroundedIn\ p\ a \wedge inv\ z\ a$$

A related competency question was *how many people* can be in a single place, and how is it possible to determine this. We have introduced simulation dummies as profile descriptions over possible referents in a simulation. Each locatum involvement profile of an affordance that grounds a given place describes the set of concrete referents which can be in that place. Since an unlimited number of such referents may be involved in corresponding actions, an unlimited number of them may also *be* in that place.

6.4. An involvement-based ontology of places

By constraining the ingredients of our place definition, we can distinguish useful types of places. For example, a *storing place* is a place where objects can be placed onto a surface. A *vantage place* (“SightingPlace”) is a place where agents can see an object while standing. A *shelter from sight* is a place where an agent is sheltered from the sight of another agent (who is the locator). A *manufacture* is a place where an agent can manufacture things with a tool (which is the locator). A *field* is a place of cultivation of an object (the ground surface) (which is the locator). A *station* is a place from which the (interior) surface of a vehicle (locator) is accessible. A *market* is a place in which agents can trade and have a conversation with salespersons (which are the locators).

Definition 26.

$$\begin{aligned}&\mathit{StoringPlace}\ p\\&\quad == (\mathit{Aftype}\ p) = \mathit{Placing} \wedge (\mathit{Locatuminv}\ p) = \mathit{objectOf} \wedge (\mathit{Locatorinv}\ p) = \mathit{supports}\end{aligned}$$

Definition 27.

$$\begin{aligned}&\mathit{SightingPlace}\ p\\&\quad == (\mathit{Aftype}\ p) = \mathit{Sighting} \wedge (\mathit{Locatuminv}\ p) = \mathit{agentOf} \wedge (\mathit{Locatorinv}\ p) = \mathit{objectOf}\end{aligned}$$

Definition 28.

$$\begin{aligned}&\mathit{ShelterFromSightPlace}\ p\\&\quad == \big((\mathit{Aftype}\ p) = \big(\lambda\ a\ .\ \mathit{ShelterFromSight}\ a\ (\mathit{Locator}\ p)\big) \wedge (\mathit{Locatuminv}\ p)\\&\qquad = \mathit{agentOf} \wedge (\mathit{Locatorinv}\ p) = (\lambda\ x\ y.\ \mathit{ShelterFromSight}\ y\ x)\big)\end{aligned}$$

Definition 29.

$$\begin{aligned}&\mathit{Manufacture}\ p\\&\quad == (\mathit{Aftype}\ p) = \mathit{Manufacturing} \wedge (\mathit{Locatuminv}\ p) = \mathit{agentOf} \wedge (\mathit{Locatorinv}\ p) = \mathit{toolOf}\end{aligned}$$

Definition 30.

$$\mathit{Field}\ p == (\mathit{Aftype}\ p) = \mathit{Cultivation} \wedge (\mathit{Locatuminv}\ p) = \mathit{agentOf} \wedge (\mathit{Locatorinv}\ p) = \mathit{objectOf}$$

Definition 31.

$$\begin{aligned}&\mathit{Station}\ p\\&\quad == \mathit{Vehicle}\ (\mathit{Locator}\ p) \wedge (\mathit{Aftype}\ p) = \big(\lambda\ a.\ \mathit{AccessableFrom}\ (\mathit{Locator}\ p)\ a\big) \wedge (\mathit{Locatuminv}\ p)\\&\qquad = \mathit{agentOf} \wedge (\mathit{Locatorinv}\ p) = \mathit{AccessableFrom}\end{aligned}$$

Definition 32.

$$\begin{aligned}&\mathit{Market}\ p\\&\quad == (\mathit{Aftype}\ p) = \big(\lambda\ a.\ \big(\exists\ ob.\ \mathit{Marketing}\ a\ (\mathit{Locator}\ p)\ ob\big)\big) \wedge (\mathit{Locatuminv}\ p)\\&\qquad = \mathit{agentOf} \wedge (\mathit{Locatorinv}\ p) = \big(\lambda\ r\ a.\ (\exists\ ob.\ \mathit{Marketing}\ a\ r\ ob)\big)\end{aligned}$$

6.5. How to identify and localize a vantage place in a simple model

In order to illustrate our theory and, at the same time, to prove its consistency, we introduce a simple model of a vantage place and localize it by proving ground facts about it. The domain of discourse (under the interpretation I of this model) consists of three simulated affordances, three referents, and (for reasons of simplicity) one focus which is mapped into a single location and time (Table 5). Furthermore, there is exactly one place instance for each possible combination of place ingredients, in particular p. Furthermore, under the interpretation I, the primitive functions and relations denote the sets specified in Table 6. A proof that this is actually a model of our theory is in Appendix A. If we introduce corresponding object constants for our domain, i.e., $d^I = d$ for all $d \in A^I \cup \mathit{Referent}^I \cup \mathit{Focus}^I \cup \mathit{Space}^I \cup \mathit{Time}^I \cup \mathit{Place}^I$, and translate Table 6 into ground facts (adding simple closure axioms), then, by drawing on the axioms and definitions introduced above, we can prove the following facts about our model (for details of these proofs, see http://www.geographicknowledge.de/vocab/PlaceAffordanceTheory.thy).

Theorem 1.

$$\mathit{coincident}\ a_1\ a_2 \wedge \mathit{coagentive}\ a_1\ a_2$$

Theorem 2.

$$\mathit{Sighting}\ a \wedge \mathit{agentOf}\ r\ a \wedge \mathit{objectOf}\ ob\ a \wedge \mathit{performedAt}\ a\ f$$

Theorem 3.

$$\mathit{SightingPlace}\ p \wedge \mathit{GroundedIn}\ p\ a \wedge \mathit{locatedAt}\ p\ s$$

Table 5

Domain of discourse D of the model

$A^I = \{a_1, a_2, a, n\}$
$\mathit{Referent}^I = \{r, ob, su\}$
$\mathit{Focus}^I = \{f\}$
$\mathit{Space}^I = \{s\}$
$\mathit{Time}^I = \{t\}$
$\mathit{Place}^I = \{p, \ldots\}$

Table 6

Interpretation of primitive functions and relations

$\mathit{Seeing}^I = \{a_1\}$
$\mathit{Standing}^I = \{a_2\}$
$\mathit{join}^I = \{(a_1, a_2, a), (a_2, a_1, a), (a_1, a, a), (a_2, a, a), \ldots\}$
$\mathit{supports}^I = \{(su, a_2, (su, a))\}$
$\mathit{objectOf}^I = \{(ob, a_1), (ob, a)\}$
$\mathit{agentOf}^I = \{(r, a_1), (r, a_2), (r, a)\}$
$\mathit{purpose}^I = \{(a_1, a_1), (a_2, a_2), (a, a)\}$
$\mathit{performedAt}^I = \{(a_1, f), (a_2, f), (a, f)\}$
$\mathit{where}^I = \{(f, s)\}$
$\mathit{when}^I = \{(f, t)\}$
$\mathit{leqt}^I = \{(f, f)\}$
$p^I = (\mathit{Sighting}^I, \mathit{agentOf}^I, \mathit{objectOf}^I, ob, p)$

Notes: Functions which are not in this list are interpreted into the empty set. The complete interpretation of *Place* and *join* can be computed in a straightforward combinatoric manner and is left open here.

7. Implementation and encoding

The technique of place referencing and localization formalized in the last section, which was based on Isabelle proofs, is semi-automatic, since HOL is undecidable, as well as intractable. Furthermore, it leaves open the computation of action simulations. In order to implement place referencing and localization in a tractable way, we have to provide the following:

(1) A *set of foci* of some observer or sensor together with their known spatio-temporal resolution (*where* and *when*) and further observable attributes.
(2) Either a *human affordance-observer* or a tractable *action simulator* for each primitive kind of affordance in K_A, such that *performedAt*, *purpose* and all *primitive involvements* required for this kind can be obtained.
(3) A *tractable place grounding*, i.e., a translation of *GroundedIn* and *locatedAt* from our theory into an efficient algorithm which grounds and localizes places.
(4) A sharable *encoding* and *automated classification* of places and their relations which can be easily reused by others.

In the following, we discuss each of these requirements and suggest simple and preliminary implementations based on two of our scenarios, namely the *automatic reconstruction of market places* and *places of sight*.

7.1. Observation and generation of foci

In order to simplify things, we use a non-temporal GIS which represents a single spatial snapshot of the ground surface. In this case, our domain of *foci* is *simultaneous* (*eqt*) and maps via *where* to a set of locations in some spatial window. These locations may be cells generated by aerial photography and represented in term of a *grid*. Alternatively, they may be generated by some human observer in terms of a collection of *vector* points of interest. We assume that these foci come with observed information which can be used as input to action simulators. For example, foci may have information about the terrain height or their location in a 3-D urban space. Furthermore, we assume that all required *referents* (surfaces, objects and agents) are identified by similar observation processes, and that their extent can be mapped into the same spatial window.

7.2. Simple standing, trading and sighting simulators in GIS

In the following, we give two examples of very simple kinds of simulators implemented in terms of *standard GIS operations*, namely *visibility analysis*, *slope analysis* and *buffering*. One may think that this contradicts our assumption that place referents should be constructed independently from space. However, basing simulators on *spatial metrics* is just a convenient proxy for the human cognitive competence of imagining corresponding actions, as argued in Section 4: Metric distances and directions allow one to approximate whether it is possible to talk to someone or see something (because these actions depend, among other things, on spatial configurations), and spatial surfaces allow one to estimate whether it is possible to stand somewhere. The fact that we use these approximations does not mean that we assume that humans actually recognize affordances in the same way, or that simulators need to be that simple. Furthermore, as a matter of fact, places constructed in this way are still independent from space in the sense that they are *not referenced in terms of a relative metric location*, i.e. in terms of a coordinate system.

The first example is a simulator for a *Talking* as well as a *Giving* affordance, assuming that all foci are simultaneous. It is an inference rule which generates ground facts in our theory based on checking whether location s_1 is within a buffer around an agent *ag* (the trader of the market) localized by its footprint, which is location s_2. Note that GIS operations are not part of our theory.

Definition 33. *Talking* and *Giving* simulator

$$\begin{aligned}
&X \in \{\mathit{Talking}, \mathit{Giving}\}\text{:}\\
&\quad \big[\mathit{WithinDistance}^{\mathit{GIS}}\ s_1\ s_2, \mathit{footprint}^{\mathit{GIS}}\ \mathit{ag} = s_2\big]\\
&\qquad \Longrightarrow \exists\, a_1,\ a_2,\ f_1,\ f_2,\ \mathit{ag}_1.\ X\ a_1 \wedge \mathit{purpose}\ a_1 = a_2 \wedge \mathit{performedAt}\ a_2\ f_2 \wedge \mathit{performedAt}\ a_1\ f_1\\
&\qquad\qquad \wedge\ \mathit{agentOf}\ \mathit{ag}\ a_2 \wedge \mathit{agentOf}\ \mathit{ag}_1\ a_1\ \mathit{where}\ f_1 = s_1 \wedge \mathit{where}\ f_2 = s_2
\end{aligned}$$

And here is a simulator for a *Standing* affordance, which simply checks whether a location is less inclined than a maximal slope and is located within an area for pedestrian traffic (the latter operation may be generated based on Open Street Map data).

Definition 34. *Standing* simulator:

$$\begin{aligned}
&\big[\mathit{MaxSlope}^{\mathit{GIS}}\ s, \mathit{Pedestrian}^{\mathit{GIS}}\ s\big]\\
&\quad \Longrightarrow \exists\, a,\ f,\ \mathit{ag},\ \mathit{su}.\ \mathit{Standing}\ a \wedge \mathit{performedAt}\ a\ f \wedge \mathit{agentOf}\ \mathit{ag}\ a\\
&\qquad \wedge\ \mathit{supports}\ \mathit{su}\ a \wedge \mathit{where}\ f = s
\end{aligned}$$

We have computed this for the Farmers Market on State Street in Santa Barbara (Fig. 9(a)), which was discussed in the Introduction. Note that traders were distributed in space by us, that is, they are

(a) (b)

Fig. 9. GIS implementations of simulators for marketing and sighting affordances. (a) Market place GIS computation of the Farmers Market in SB, showing point locations for each trader and dissolved buffers for marketing affordances. (b) Visibility analysis of the July column on the "Place de la Bastille", Paris. By kind permission of Fabian Dembski ©, cf. http://fabiandembski.wordpress.com/. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/AO-140134.)

not necessarily present at the market. Since our marketing simulator is based on a buffer around traders localized by points, the marketing affordances map to circular buffer zones. In order to generate a simplified connected spatial region for the whole market, one could also first aggregate traders by their convex hull and then apply the buffer (see larger area in Fig. 9(a)).

Our second example is a *Sighting* affordance and a corresponding vantage place. It can be implemented by standard GIS *visibility analysis*. For example, Fig. 9(b) shows a simulation of the affordance of seeing the July column, which stands on the Place de la Bastille in Paris.

7.3. Simple place constructors in GIS

How to *compute a place referent* based on these affordances? A place tuple can be handled in an efficient way as an array of its ingredients. The computation of *locatedAt* is a bigger challenge, since it involves searching for affordances of the required type over the join lattice. The latter needs to be constructed first over primitive affordances. In general, this is intractable. However, one can efficiently *integrate lattice construction with search strategies*. This immensely speeds up the search process. For example, one can simplify the generation of *multitasking affordances* simply by using *spatial joins* of affordances on foci locations, disregarding agents.

Definition 35. Simplified multitasking rule:

$$[performedAt\ a_1\ f,\ performedAt\ a_2\ f] \Longrightarrow \exists\ a.\ Bitask\ a\ a_1\ a_2$$

From bitasks generated in that way, one can generate *speeches* and *transactions* by their links via purpose, and corresponding *marketings* by linking via agents which are traders. One then needs to search for all marketings in which locator(s) (traders) of the required market place definition are involved as agent, and generate corresponding *locatedAt* relations between the place and the spatial extension of the joined affordances. For example, a spatial join of State Street (simulating *Standing*) with the simulated marketing affordances locates the area of the Farmers Market. If we add foci which range over time, then it becomes even possible to study the appearance/disappearance of the place.

7.4. Encoding of places and automated classification in OWL

We translated a subset of our theory into an OWL 2 vocabulary pattern which is available online.[14] The OWL relations (properties) among affordances, foci and referents are depicted in Fig. 10, and a subset of the class hierarchy is shown in Fig. 11.

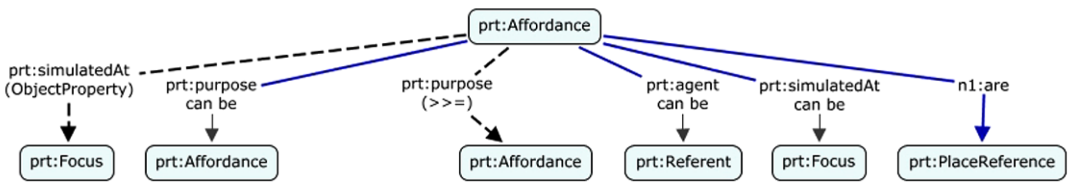


Fig. 10. Relations among affordances, foci and referents in the OWL pattern. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/AO-140134.)

[14]http://geographicknowledge.de/vocab/PlaceReferenceTheory.

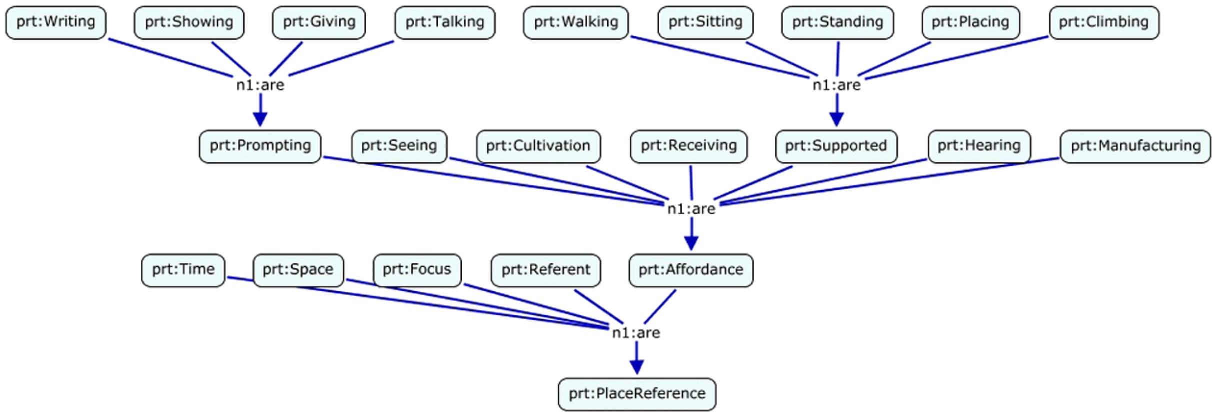
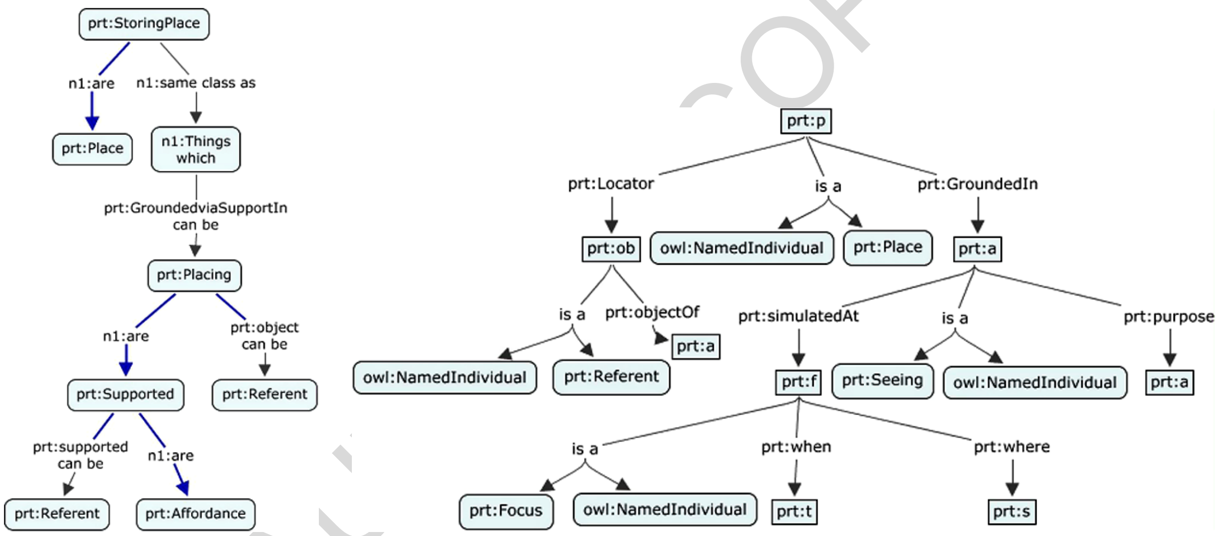


Fig. 11. Subset of the class hierarchy in the OWL pattern. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/AO-140134.)



(a) (b)

Fig. 12. (a) A storing place defined as an OWL class. (b) An example of annotating a vantage place individual with the pattern. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/AO-140134.)

The OWL theory can be used in order to *encode* and share the results of place construction in terms of the relations between specific places, foci, affordances, referents, space and time, see Fig. 12(b). For example, one can use the pattern to *search* for places which are associated with an affordance, as suggested in (Scheider et al., 2011). It can also be used to automatically *classify* certain simple types of places which can be defined in OWL DL using automatic reasoners. For example, in Fig. 12(a), a storing place is defined as that class of places which is grounded in some placing of some object on some surface, the latter serving as locator of the place. Note, however, that while OWL DL can be used to reason about classes of places, it is not expressive enough to define place constructors.

8. Conclusion

In this paper, we have suggested a basis for constructing place reference systems. Place reference systems can be used to identify and localize places by a technique of reference independent from any particular spatial reference system. Our suggestion is based on cognitive capabilities to simulate activities and involvements of referents in the perceived environment. Simulations are situated and thus allow one to localize places relative to involved referents. Depending on the simulation, referents can be present, absent or unknown and described in terms of a profile. Furthermore, one can determine whether a referent is in a place based on corresponding actions. Simulations can be mimicked technically, which allow one to refer to places also in the absence of human observers. Current technical approaches either reduce place to space or presume user generated geotags in order to refer to places. We have specified requirements and competency questions for place inference, formalized a corresponding theory in HOL which provides answers to all these questions, published an OWL pattern as a theory subset which can be used to encode place referents, and discussed approaches to implement place reference systems and simulators in terms of simple GIS operators.

In several respects the work presented here is preliminary and in need of future work. First, there is a need for empirical work which studies the action simulation capabilities of humans with respect to places (compare, e.g., Klippel et al., 2010). This would allow us to understand how human observers are practically referring to a place, and to evaluate the approach empirically. This goes well beyond this paper, which is rather focused on the formal side showing technical feasibility. Second, research is needed that focuses on computable technical simulators for each of the involved kinds of actions. Depending on purpose, these simulators will be more or less complex, and will therefore be more or less able to mimic human perceptual competences. Simple simulators, as the ones proposed in Section 7, may already be very useful. There is also an opportunity to define simulators which infer affordances from place descriptions, e.g., from texts or documents. Third, the place reference theory formalized in HOL needs to be refined and translated into tractable algorithms. In Section 7, we have made a proposal how construction and search over affordance lattices can be made tractable for place constructors and localization functions. The advantage of this theory is its semantic generality, which allows us to abstract away from particular actions, and cognitive or technical implementations. And fourth, a place ontology may be derived bottom-up in the way shown in Section 6.4. This may be used as a grounded place vocabulary in the Semantic Web.

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Appendix A. Proof of consistency

We need to prove that the interpretation I given in Section 6.5 satisfies all axioms. In doing so, we can ignore all axioms which are implications with conditions unsatisfiable under the interpretation, as they are satisfied by default. These are Axioms 5 and 6 as well as those parts of Axiom 4 which are not about *Standings* and *Seeings*.

The remaining axioms are satisfied as follows: The extension of *join* satisfies Axioms 7 by construction of our model. Axiom 8 (atomicity) is satisfied since *primAff* a_1, *primAff* a_2, *primAff n* by Definition 36 and *lub* $[a_1, a_1] = a$, *lub* $[a_1] = a_1$, *lub* $[a_2] = a2$, *lub* $[n] = n$ by Definition 37. Axiom 1 (temporal order) is trivially satisfied by the single fact *leqt f f* on a single focus. We have that *agentOf r* a_1, *agentOf r* a_2, and *agentOf r a*, which satisfies the first part of Axiom 2. We also have that *performedAt* a_1 *f*, *performedAt* a_2 *f*, and *performedAt a f*, which satisfies the second part. All involvements (*agentOf*, *objectOf*, *supports*) and *performedAt* are propagated upwards to *a*, which satisfies the remainder of Axiom 2. Axiom 9 is satisfied by the facts *Seeing* a_1 and *Standing* a_2, since both are in K_A. Axiom 4 is satisfied by *Seeing* a_1 and *objectOf ob* a_1, and *Standing* a_2 and *supports su* a_2.

Appendix B. Activity lattices

We introduce a constructive semi-lattice on affordances (and likewise on actions).

Axiom 7.

$$\textit{associativity}: \quad \textit{join}\ (\textit{join}\ x\ y)\ z = \textit{join}\ x\ (\textit{join}\ y\ z)$$

$$\textit{commutativity}: \quad \textit{join}\ x\ y = \textit{join}\ y\ x$$

$$\textit{idempotency}: \quad \textit{join}\ x\ x = x$$

$$\textit{neutralelement}: \quad \textit{join}\ n\ x = x$$

Note that the neutral element *n* is a particular primitive which serves only the convenient recursive construction of the following list. It does not have any further meaning.

We define primitive (non-compound) affordances as atoms of the lattice and *lub* as a recursive function[15] over lists of affordances using well defined operators.[16]

Definition 36. Non-compound:

$$\textit{primAff}\ a == \forall\ a'\ a''.\ \textit{join}\ a'\ a'' = a \rightarrow \big(a' = a \wedge a'' = a\big)$$

Since every list corresponds to a constructive finite set, and the lattice is made of lists of atoms, it follows that the whole lattice must be constructive, too.

Definition 37.

$$\textit{fun lub} :: \text{“}\textit{A list} \Rightarrow A\text{” } \textit{where lub}\ [\,] = n \mid \textit{lub}\ \big(\textit{Cons}\ s'\ s\big) = \textit{join}\ (\textit{lub}\ s)\ s'$$

[15]Expressed in Isabelle by the keyword “*fun*”, which automatically proves its computability.

[16]Such as *Cons* (constructor for lists), [ ] (the empty list), and *set* (a function that generates sets from lists). For details, see http://www.geographicknowledge.de/vocab/PlaceAffordanceTheory.thy.

Axiom 8. *Atomicity*:

$$\forall\,(a :: A).\ \exists\,(as :: A\ list).\ \big(lub\ as = a \wedge \big(\forall\, a'.\ a' \in set\ as \rightarrow primAff\ a'\big)\big)$$

Furthermore, we assume that all activity kinds (K_A) are conjunctively exhaustive on affordances (and likewise on actions).

Axiom 9.

$$\forall\,(a :: A).\ primAff\ a \rightarrow (\exists\, k.\ k \in K_A \wedge k\ a)$$

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