Semantic Referencing of Geosensor Data and Volunteered Geographic Information

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Abstract. Georeferencing and semantic annotations improve the findability of geoinformation because they exploit relationships to existing data and hence facilitate queries. Unlike georeferencing, which grounds location information in reference points on the earth's surface, semantic annotations often lack relations to entities of shared experience. We suggest an approach to semantically reference geoinformation based on underlying observations, relating data to observable entities and actions. After discussing an ontology for an observer's domain of experience, we demonstrate our approach through two use cases. First, we show how to distinguish geosensors based on observed properties and abstracting from technical implementations. Second, we show how to complement annotations of volunteered geographic information with observed affordances.

1 Introduction and Motivation

Observations are the principal source of geographic information. Humans share senses[1] and perceptual capabilities [1] that enable them to observe their environment, and thereby obtain geographic information. For example, vision works essentially the same way for all humans. Additionally, humans can easily understand and reproduce observations made by others, because they can understand intentions and join their attention in a scene [2]. If someone tells you that Main Street is closed due to construction works, you can easily understand what was observed without observing it yourself. Some of the authors of this chapter have previously suggested to use perceptual capabilities as common ground to describe geoinformation [3, 4]. In this chapter, we demonstrate how to account for the semantics of geoinformation based on underlying observations. Our approach is general enough to account for observations obtained from technical sensors (such as a thermometer measuring temperature) as well as human observations (e.g., observing the presence of a construction site on Main Street).

Dealing with the semantics of geoinformation in terms of observable properties (such as temperature, precipitation rate, or traversability of a road), we face

[1] With few exceptions, such as disabilities, that do not affect the general case.

the problem of finding an appropriate level of description. This problem is our main focus. It has two aspects. On the one hand, there is a plethora of different sensing procedures for the same property that lead to equivalent results. Hence, their differences are irrelevant for the meaning of the obtained geoinformation. For example, precipitation rate can be measured by a tipping-bucket or a standard rain gauge. However, the meaning of a value of five liters of rainfall in the last 24 hours is independent of the concrete form of the sensor. Therefore, this description is too detailed to describe the property. The problem of having an unnecessarily detailed description of the semantics of geoinformation is called the *abstraction problem*.

On the other hand, we have a *grounding problem* [5]. This problem occurs when it is not clear what kind of observation certain information refers to. One of the most dramatic examples of this was the *moon-alarm* bringing the world to the brink of a nuclear war: On October 1^{st}, 1960, the brand new Ballistic Missile Early Warning System of the United States Air Force took radar signals reflected by the moon for Russian missiles. Luckily, human reason prevented the nuclear "counter"-attack (cf. [6]). Less dramatic, but more frequently, the grounding problem occurs if measurements are only described by SI units[2]. A velocity value of 2 given in meters per second just tells us that there is something moving, but we cannot even tell whether it is a car on the road, gravel on a slope, water in a riverbed, or anything else. Volunteered Geographic Information (VGI) [7], which is publicly available on the Web, faces a similar problem. The most prominent collection of VGI is the OpenStreetMap (OSM) project[3], where users have the opportunity to describe map features via tags. However, the tags that are used to describe points of interest (POI) often do not make clear what the *interest* in a specific point is. That is, they do not provide sufficient information about what is afforded by the POI: The tag `cafe` is used to describe *coffee shops* in New York as well as *Kaffeehäuser* in Vienna. If a user wants to have a beer, a place tagged `cafe` in Vienna is perfectly suitable, whereas a coffee shop tagged `cafe` in New York is not. Here the appropriate level of abstraction would rather be on the level of observed functional properties, like `drinkBeer` or `drinkCoffee`.

State-of-the-art approaches to modeling the semantics of geoinformation do not seem to provide an appropriate level of abstraction. Current top-level ontologies, e.g. the Descriptive Ontology of Linguistic and Cognitive Engineering (DOLCE) [8] or the Basic Formal Ontology (BFO) [9], clarify ontological commitments, but abstract from observation procedures. Therefore, they provide only a partial solution to our problem. Similarly, VGI often relies on user-defined domain specific tags, which lack an unambiguous interpretation in terms of reproducible observations. Current metadata standards, like the Observations and Measurements specification of the Open Geospatial Consortium[4] [10], describe geosensor data at the level of information objects, not of observed properties or objects [11].

[2] Le Système international d'unités, see http://www.bipm.org/en/si/.
[3] See http://www.openstreetmap.org/.
[4] See http://www.opengeospatial.org/.

The idea to use reproducible observations to describe the semantics of geoinformation is not new. Geodesists are routinely grounding coordinates in reproducible measurements of distances and directions. The reference points and parameters for these measurements define *geodetic datums*. We follow here Kuhn's [12] generalization from spatial to *semantic* reference systems to describe the semantics of arbitrary geographic information (not just locations). To construct semantic reference systems in practice, we have suggested conventional semantic datums in terms of repeatable observation procedures [13].

In this chapter we discuss a set of *perceptual types* for describing observations underlying geographic information. Perceptual types are types of entities in an observer's domain of sensory experience. We argue that these comprise *perceptual Gestalts*[5] such as observed bodies, media, surfaces, actions and properties. Grounding our ontology in perceptual types has the advantage that these provide a direct link between the world experienced by an observer and a top-level ontology. We will show that perceptual types neatly fit into DOLCE. Observations also ensure semantic interoperability [14] in the sense that they are easily reproducible by different observers. Additionally, semantic referencing of geoinformation based on observations and perceptual types provides an *appropriate level of abstraction* for annotating and querying geoinformation. Observations and perceptual types allow us to abstract from technical measurement procedures, while differentiating among observed properties beyond SI units and among perceivable functional properties.

Modeling an ontology should be distinguished from implementing it in an encoding language like OWL [15]. To maintain sufficient expressivity when modeling our ontological theory, we use a typed first-order logic with functions. An essential subset of our model can be encoded in RDF[6], allowing to link data to perceived entities and to publish the results on the Semantic Web. Note that this subset in RDF does not exceed the boundaries of existing semantic web technology. Therefore, the paper also demonstrates what can be expressed by current semantic web standards.

The remainder of this chapter is structured as follows. In Section 2 we review background notions to describe human experience. These include affordances, media, and bodies. In Section 3 we introduce perceptual types and operations in a functional first-order style and align them with categories of the top-level ontology DOLCE. In Section 4 and 5 these types are used to describe two scenarios, one concerned with technical sensors and one with Volunteered Geographic Information. We conclude the chapter in Section 6 with a review and outlook.

2 Background

In this section, we make some justifiable claims about what kinds of perceptual capabilities humans have in order to observe geoinformation. Technical sensors are extensions of human senses. They need to be designed, built, calibrated,

[5] For more information on Gestalt perception see [1].

[6] See `http://www.w3.org/RDF/`.

maintained and interpreted by humans. This allows us, in principle, to trace back the observation of technical sensors to human perceptual capabilities. The example of the moon alarm mentioned in Section 1 highlights the necessity of human observers as interpreters and controllers of technical sensors.

2.1 Perceiving the meaningful environment

The ecological psychologist Gibson [16] suggested an informal ontology of elements of the environment that are accessible to human perception and action, called the *meaningful environment*. The three top-level categories of *meaningful things* [16, p. 33] in this environment are *substances*, *media* and *surfaces*.

A medium affords moving through it as well as seeing, smelling and breathing and bears the perceivable vertical axis of gravity (for vertical orientation). According to Gibson, the medium for terrestrial animals is the air. Gibson thought of a medium as something established in terms of *affordances*, i.e. action potentials in the environment. For example, he distinguished liquid media (water) and gaseous ones (air) by what actions they afford to the animal [16, chapter 2]. We have suggested [13] that there may be different kinds of media according to what kind of action they offer to a human being. In this chapter, we restrict our understanding of a medium based on locomotion and action affordances. This view will be explained in the next subsection.

Surfaces are the boundaries of all meaningful things humans can distinguish by perception. This means they are opaque to a certain extent and bound an *illuminated medium*, i.e., a medium for seeing. Surfaces have *surface qualities*, for example a *texture* (including color), and are often resistant to pressure.

Substances are things in the environment that are impenetrable to motion (i.e., are solid) and illumination (i.e., are opaque). Detachable substances are called *objects*, which have further properties, e.g. a shape and a weight. Moreover, substances enable actions: they support movements (the ground), they enclose something as hollow objects, or they allow to be thrown as detached objects.

One of Gibson's central insights was that the elements of the meaningful environment are inter-subjectively available to human observers in their domain of experience. However, if one does not assume that observers have direct access to external reality [17], this can only mean that they have analogous criteria or capabilities for *identifying and distinguishing* these things. We have suggested [3] that some of these meaningful things could be viewed as results of mental constructions [18] based on preconceptually available Gestalt mechanisms [1], for example identifying and tracking bodies and their surfaces [19]. Complex qualities of bodies can be constructed by performing *perceptual operations* on their surface layout, e.g. by observing their lengths or depths [13]. Movements and other events can be individuated by following these bodies with attention [3]. Media can be individuated based on the affordances they offer an observer [13, 20]. For example the affordance of locomotion identifies the medium that allows you to travel. This can be just the free space of your office, if the door is closed, or extend several kilometers throughout the landscape if you are hiking outside.

Individuation requires criteria of *unity* (i.e., for constructing integral wholes as maximal self-connected sums) and *identity* (i.e., allowing to track entities and distinguish them from each other) [21]. In this chapter, we will assume that there are criteria of individuation available for all perceptual types mentioned in Section 3.2, without discussing how the resulting entities can be constructed in experience[7]. We furthermore presume the existence of reference systems for complex qualities (like velocity, volume or weight).

2.2 Perceived affordance: a simulative account

Affordance is one of the key concepts in ecological psychology. Affordances capture the functional aspect of objects in an observer's environment as well as an observer's opportunities for actions [22]. As Gibson puts it:

> "The *affordances* of the environment are what it *offers* the animal, what it *provides* or *furnishes*, whether for good or ill. [...] I mean by it something that refers to both the environment and the animal [...]." [16, p. 127, emphasis in original]

An observer in this view is not only perceiving but also (potentially) acting. Gibson's own examples of affordances include *action affordances* like climb-ability (walls), catch-ability (balls), eat-ability, mail-ability (postbox), but also so-called *happening affordances* like getting burned (by fire) or falling off (a cliff) (compare [23]).

Viewing affordances as properties of things in the environment [24] seems problematic, because they are also constituted by properties of a particular agent: Stairs are climbable only with respect to an agent's leg length (cf. Warren's experiments [25]). Treating affordances as combined qualities of environments and actors (as proposed in [26]), which seems to work in the staircase example (by relating leg length and riser height), is also problematic. Take, for example the *traversability* of a road. A road is traversable with respect to the velocity of an agent's crossing and the velocity of cars. But traversability is not a combination of a property of the agent with a property of the environment. Rather, it is the interplay of objects which is not reducible to any combination of properties (cf. [27]). We follow Scarantino [23] in that affordances always involve an observer's reaction. We conceive of them as *perceivable potential events*.

But how are potential events perceived? One possible explanation is that perceived affordances are the result of *perceptual simulations*. These were proposed by Barsalou [28] in order to state that human perception and cognition are closely interlinked on the basis of perceptual simulators. They allow humans to imagine and reconstruct formerly perceived sensori-motor patterns of objects, e.g. cars, in new situations, and to reason with them. We suggest to apply this idea to affordances, saying that if pedestrians perceive the affordance of crossing a road, they do so by successfully simulating a crossing event in a given perceived scene. Perceived affordances can be "acted on", i.e. they are a necessary input to

[7] See [13, 20] for examples how this might be done.

human actions, as proposed by Ortmann and Kuhn [29]. Similarly, when placing a rain gauge, we simulate potential raining events in order to set it up in a medium for rain, e.g. in our garden instead of our living room.

Many affordances have a social aspect, in the sense that they involve the interpretation of signs. A prominent example for a so-called *social affordance* [30] is a postbox that affords sending letters. The postbox physically only affords dropping letters (or other similarly shaped objects) through a slot. However, in the social environment that uses the appearance of boxes as conventional signs (blue in the USA, red in the UK, yellow in Germany), this box affords sending letters if the letters are properly labeled and postpaid. Since a simulative account of affordances does not exclude cognition of signs, social affordances are compatible with our approach.

2.3 Structuring perceptual types with DOLCE

We use the Descriptive Ontology for Linguistic and Cognitive Engineering[8] (DOLCE) [8] as a top-level (or foundational) ontology for structuring the perceptual types proposed in Section 3. DOLCE rests on four foundational categories: Endurants, Perdurants, Qualities and Abstracts. *Endurants* are things that are fully present at any moment, but can change over time. Examples of Endurants are all physical objects, such as streets, cars, trees, buildings, as well as amounts of matter (e.g., water, air, sand or concrete), but also features like a crack in a street or a hole in a wall. *Perdurants* are entities that are not fully present at any time. Perdurants occupy a time span. For example, a football match, a thunderstorm or a lunch break all last for a certain time. Endurants typically participate in Perdurants. You, your colleagues and your lunch are participating in your lunch break. Amounts of rain, amounts of air and the city on the ground participate in a thunderstorm. *Qualities* inhere in other entities and are similar to common sense properties. Examples are the height quality of a step, the velocity of a current or the duration of a thunderstorm. In general, all physical endurants have a spatial quality and all perdurants have a temporal quality.

DOLCE has been applied to geospatial ontologies, among others, to describe geographic entities in geology [31], to provide a foundational model of geographic entities [32], to ground the SWEET Ontology [33], as well as to establish semantic reference systems for observations and measurements [34] and to ground an observation ontology [29, 35].

DOLCE has been proposed for developing sound ontologies. For an information category to be *ontologically sound*, identity criteria are required [36]. In our view, the application and combination of perceptual Gestalt operations establishes criteria of identity for environmental entities [3]. It is therefore not surprising that many ontologically sound top-level categories (called *sortals* in [21]), such as the ones of DOLCE [8], can be aligned with this lower perceptual level. This will be demonstrated in Section 3.2.

[8] http://www.loa-cnr.it/DOLCE.html

3 Grounding geospatial data in perceptual types

In the following we introduce and explain basic perceptual types that we use for grounding information in the scenarios of the subsequent sections. Based on the discussion in the last section, we suggest that for all types there are individuation criteria available to human observers, enabling them to track and distinguish instances of a type. Consequently, observations are described from the perspective of a human observer.

3.1 Notation for perceptual operations and types

We use a typed first-order logic for describing an observer's domain of experience, in which types $T_i \in T$ are used in type assignments of the form:

$$
\begin{array}{ll}
f : T_1 \times ... \times T_r \mapsto T_{r+1} & \text{for a function } f, \\
P : T_1 \times ... \times T_r & \text{for predicates } P, \\
c : T_i & \text{for constants } c \text{ or variables.}
\end{array}
$$

Types are introduced with the prescript `type`. Type as well as predicate symbols start with uppercase letters, constants and variables are lowercase. Unary type symbols are used interchangeably with unary predicates, for example $c : T_i$ means $T_i(c)$ where T_i is used as a predicate symbol. Basic types correspond to primitive predicates. We use $\vee$ and $\wedge$ to construct dis- and conjunctive unary types. N-ary types can be constructed using $\times$ (product) and $\mapsto$ (function) type constructors. Perceptual operations are expressed as functions that are applied by an observer to entities and produce entities in his or her domain of experience. They may look like this: $Op : T_i \mapsto T_j$, where T_i is the input type, and T_j is the type of the observation result. If the operator has more than one input of the same type, we may also write $Op : T_i^* \mapsto T_j$ to denote this. Any predicate may also be written as a function that maps to entities of boolean type, e.g. $P : T_1 \times ... \times T_r \mapsto Bool$. We do not intend to list perceptual operations exhaustively, because for every domain, we may have special subtypes of them. Therefore, most of the operations are given as function schemas. Signatures and explanations of these schemas will be given in the text. We introduce perceptual types with a minimal formal apparatus for the sake of demonstration.

3.2 Unary perceptual types and their hierarchy

The entities which can be distinguished in experience come with their categories or unary types. These types can be arranged in a subsumption hierarchy (see Figure 1) aligned with some of DOLCE's top-level categories[9].

The most important types are perceivable *bodies* (`type` *Body*) as self-connected, solid, movable objects. We distinguish `type` *Animate* (e.g. human) bodies and

[9] However, we sometimes divert from strictly following DOLCE and explain this in the text.

`type` *Inanimate* bodies[10]. The empty space that contains these bodies, which is the medium of their movements and actions, is conceived as a maximal part of the environment that affords bodies to move and act in them. We call such an entity a *medium* (`type` *Medium*). We also allow media to afford events for inanimate bodies, e.g. a cliff to afford falling rocks.

Media and bodies have a criterion of unity and are rigid types [36], whose instances can be identified in time. We consider therefore a *physical object* (`type` *PhysicalObject*), in extension of DOLCE, as being either a medium or a body (see Figure 1). One of the perceived bodies is the body of the observer, and one of the media is the one surrounding him or her allowing to move or act. As this medium is identified via an affordance, it moves as soon as the perceived affordance changes its location. For example, if the door is being closed, the medium suddenly reduces to the room.

We furthermore assume that there is a range of independent *subtypes of media*. These depend on the type of object and the type of motion or action the medium affords to the object. For example, a water body is part of a general motion medium for inanimate bodies, including the air but excluding the ground. For instance, a stone can fall through water and air, but not through the ground. The *water unit* part of this medium[11], on the other hand, is by itself a medium for fish or divers. Likewise, the upper part of the ground is a medium for a mole, and a snowpack is a medium for rescue dogs or snow stakes. Part of the reason why media afford a certain type of motion is their low physical resistance to movement and tensile stress, i.e., their *viscosity*. Therefore, we suggest that it is the affordance of a certain kind of "forceful" motion allowing observers to categorize media of `type` *Fluid*. Fluids can be recognized depending on their resistance to stress applied by an object moving through it. The concept of a medium can also be used in its normal context of human actions. We may perceive certain media in the environment based on *social affordances*. These allow people to act based on the interpretation of social conventions and signs, e.g. to drive on a certain marked surface identified as a lane of a road [20].

We assume that the observer's domain of experience also contains distinguishable parts of bodies and media on which to focus one's attention. Some of these parts are what DOLCE calls *features* (`type` *Feature*). Features have their own criterion of unity, but depend on another physical object, their "host". While a feature needs a host, it does not need to be part of it. Perceivable features of a cup, for example, are its handle but also its opening. The opening of a cup would not exist without it, but is not a part of the cup. A feature of a building is the opening of its entrance. Another important feature is the *surface* of an object

[10] For simplicity reasons, we do not consider animate (agentive) objects as constituted from inanimate (non-agentive) ones, as DOLCE does [8], but see them as subcategories of bodies distinguished according to perceived intentionality. Intentionality is thus constitutive for perceived actions, and actions for animates.

[11] In the remainder, we use the term "water unit" or "unit of water" for any fluid medium consisting of water, regardless of its size. The term "water body" is commonly reserved for large water units that are physiographical features.

(`type` *Surface*), which, in the sense of Gibson [16], can be conceived as the border of a surrounding illuminated medium that affords seeing. Surfaces are themselves hosts for surface qualities like texture and color. In accordance with DOLCE, the experiential domain must also contain arbitrary sums: for example the sum of cars driving past a house and the sum of their wheels. These dependent entities are of `type` *Plurality*. All these entities, physical objects (bodies and media), features, and pluralities, are of `type` *PhysicalEndurant* in the sense of DOLCE, as they exist at any moment of their lifespan and have a spatial extension. In accordance with the axioms about physical endurants in [8], we assume that all physical endurants have a region in space at any time instant of their existence. We also assume that there is a perceivable temporal parthood relation P among physical objects, features, and pluralities, which implies parthood (co-location) of their corresponding spatial regions [8].

The domain of experience is also populated by *perdurants* (`type` *Perdurant*), that is, events, states and processes which are constructed by focusing on the behavior of objects[12]. For example, instances of `type` *Motion* and `type` *Resting* are the result of the observer following already identified objects moving or resting in time and space. In accordance with DOLCE, we assume that all perdurants occupy a region in time. Note that determining whether some object moves or not is always observer-relative. A resting therefore simply denotes objects at rest from the perspective of some spatial reference system. If the observer imputes *an intention* to the object involved in a perceived event, this event is of `type` *Action*.

We assume that the observer can determine the *location* of a physical endurant in a spatial reference system, and the *time interval* of a perdurant in a temporal reference system. The observer has also reference systems for certain other quality types, such as the volume of an endurant, or the area of a flat object, or the color of its surface patch. Their values are of `type` *AbstractRegion* and are part of a quality space [8, 11].

There is a last important category of DOLCE which we conceive as a perceptual type, namely the `type` *Amount*[13]. This notion can be applied to individual portions of matter contained in some object, e.g. the portion of clay of which a statue is made, or the portion of water flowing through some river into the sea. The authors of DOLCE did not consider unity or identity criteria for amounts [8]. Moreover, amounts do not seem to be directly perceivable, since we cannot identify portions of matter as such. One can see this by the fact that we perceive snow packs and lakes in terms of their surfaces, while the matter they contain constantly keeps being exchanged by melting, evaporation or discharge without notice. Nonetheless, we follow Guizzardi [37] and assume that amounts can be *identified indirectly* via objects with a unity criterion (e.g. a certain water unit with perceivable surfaces) and their perceived histories. This assumption is vital

[12] We do not distinguish here between state, process and event perdurants as in DOLCE, also because we are unsure of whether our perceptual types should be regarded as cumulative or not, compare [8].

[13] Known as "amount of matter" in DOLCE.

in order to deal with the observation of river flow, as we will see in Section 4.4. We will discuss perceptual operators for amounts in Section 3.4.

All these entities are related as shown in the subsumption hierarchy depicted in Figure 1.

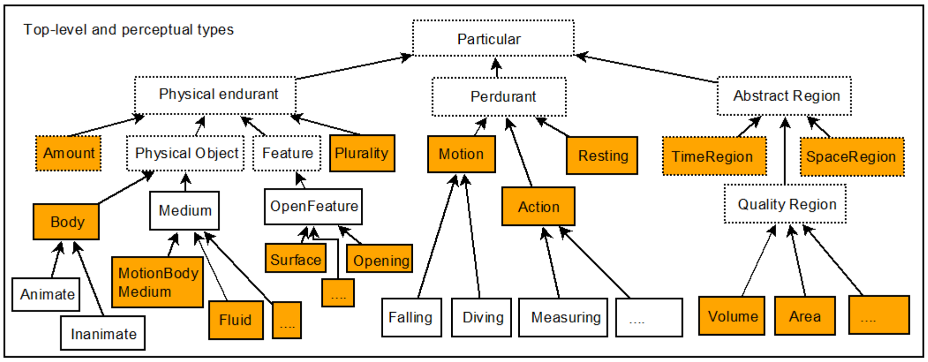

Fig. 1. Subsumption hierarchy of perceptual and top-level types. *Basic types* with identity criteria are highlighted in orange. The dotted boxes correspond to top-level categories of DOLCE.

3.3 Basic types and perceptual operations

Our idea is that perception is the key to distinguish, i.e. to identify, entities. In some sense this means that it accounts for how experiential entities come into being.

This aspect is reflected in our type hierarchy, because some types come with their own identity criterion. These types are basic in that they *carry their own criterion of identity (IC)*, while their subtypes only inherit these criteria, and their supertypes are just aggregations (disjunctive types) without any such criterion. For example, we can distinguish one person from another on the level of their bodies ("this body is distinct from that one"), but not on the level of *Animate* (subtype, inherited IC) or *PhysicalObject* (supertype). These types may be called *basic types*[14] or *true sortals* [36] and are highlighted in the hierarchy of Figure 1. In the same sense, the concrete kind of perceived affordance, differentiated by the type of body and the type of motion or action involved, gives an identity criterion for media subtypes (see Figure 1). Therefore the basic types of media are given on the level of the subtypes of the type medium. For example, a *MotionBodyMedium* has a different identity criterion than a *FallingBodyMedium*,

[14] In the spirit of basic-level categories [38]. But this notion also stands for non-constructed types. Since our basic types correspond to primitive predicates in our theory, both senses are applicable here.

but the type *Medium* itself does not have any IC. Since ICs define identity (=) between entities of a basic type, we can assume that *all basic types are mutually exclusive*, because there cannot be identical entities across those types. This applies also to media, because even though every *Falling* is an instance of *Motion*, a *FallingBodyMedium never is* a *MotionBodyMedium*. However, since a place that affords falling also affords moving, and media are constructed out of such affordances, a *FallingBodyMedium always implies* a larger *MotionBodyMedium* of which it is a part[15].

We will not discuss how basic types can be constructed from perceptual mechanisms, i.e., how these identity criteria are actually established. But we will introduce *perceptual operations* as functions in order to highlight how they depend on each other. The formal properties of these functions will be discussed now.

A perceptual operator function is not necessarily *total*, so for some input it may produce errors[16]. This corresponds to the fact that not every observable input of an observation process gives rise to a certain kind of observation result. For example, not every observable object has a length or is involved in a perceived movement or action.

In some cases, the operators express *existential dependence* of outputs on inputs. Another way of stating existential dependence (compare [8]) is to say they are *surjective*, so if there exists an instance of their output type, then there must also exist a corresponding instance of the input type that has generated the output. For example, a process only exists insofar as its participating objects exist, and a feature only exists insofar its host exists. Furthermore, a feature only has one particular host, and a process only has a fixed set of objects that generate it (*injectivity*). Together these properties are called *bijectivity* and allow the observer to distinguish the generated entities via the inputs to the perceptual operator. We assume bijectivity only for those operators *Op* whose output O is a subtype of a basic type of *Perdurant* or *Feature*. The individuation of bodies, media, qualities and amounts of matter is more complicated and out of the scope of this chapter.

3.4 Some basic examples of perceptual operations

In the following, perceptual operations are introduced using type signature schemas. In these schemas, [[T] *Type*] is a meta-variable ranging over all subtypes of a type T. For example, [*MotionType*] ranges over subtypes of *Motion*. Concrete signatures and axioms are obtained by substituting these subtypes.

Operation for perceiving parthood among (non-amount) endurants. This is an operation that allows the observer to relate endurants which are not amounts in

[15] This can be inferred formally if media are defined as maximal integral wholes (i.e., connected sums) of places affording motions/actions [20]. In this case the place must be part of two integral wholes.

[16] We assume that there is one standard error element produced by every function in that case.

the perceived environment, i.e. objects, features and pluralities. It corresponds to DOLCE's temporal parthood [8]. P is therefore a mereological operator which is *not extensional*[17], as two different objects, e.g. two media, may have the same parts and may be co-located, and objects may change parts. P also implies spatial inclusion among the object's locations [8].

(1) $$\text{(temp. parthood)}P : \mathit{NonAmountE} \times \mathit{NonAmountE} \times \mathit{TimeRegion} \mapsto \mathit{Bool}$$

The notion $\mathit{NonAmountE}$ stands for the type $\mathit{PhysicalObject} \vee \mathit{Feature} \vee \mathit{Plurality}$. If we omit the temporal parameter of this predicate, we simply mean that parthood is observed continuously, i.e. for every possible time interval.

Operations for perceiving perdurants. These operations take one or several endurants and a time interval and produce a movement or action perdurant in which the endurants participate. They are similar to DOLCE's *participation* relation [8], but allow to distinguish intentional (actions) from non-intentional events. They may also involve many endurant instances as arguments. In order to express that the observer's attention follows objects for an interval in time and identifies one of their movements, we use the operator *move*. We distinguish kinds of movements by inserting the movement type into the operation name. For example, we assume the movement type *Diving*, and so we can express observed divings by the operator *moveDiving*:

(2) $$\mathit{move}[\mathit{MotionType}] : \mathit{Endurant}^* \times \mathit{TimeRegion} \mapsto [\mathit{MotionType}]$$

We follow animate bodies producing actions by the operator *do*. Actions are not necessarily associated with movements. We assume that the first parameter of *do* is the actor's body, and that there may be further optional endurants involved in that action:

(3) $$\mathit{do}[\mathit{ActionType}] : \mathit{Animate} \times \mathit{Endurant}^* \times \mathit{TimeRegion} \mapsto [\mathit{ActionType}]$$

For example, we will make use of the action type *Measuring*, and thus a particular measuring action can be expressed by the operator *doMeasuring*. Another operation called *rest* observes some endurant at rest:

(4) $$\mathit{rest} : \mathit{Endurant} \times \mathit{TimeRegion} \mapsto \mathit{Resting}$$

As discussed in Section 2.2, there are cases in which observers do not watch body movements or actions being performed explicitly (or watch others performing it), they only simulate them in the perceived environment in order to find out whether they are afforded. For example, in order to guess whether it is possible to climb over a fence, or whether a stone would fall into a well. The output of these simulations are also action perdurants. We assume that every type of observable action or movement can be simulated. For the sake of simplicity, we do not distinguish here whether actions and movements are simulated or actually performed.

[17] See Section 3.3 in [39].

Operations for measuring time intervals of perdurants. We measure time in terms of temporal reference systems. These scales are based on calibrated clocks and calendars. The observation process needs a perdurant as input, whose temporal extent is measured. We call this operation *time*:

(5) $$time : Perdurant \mapsto TimeRegion$$

Another operation allows for measuring durations of time intervals. This is done by subtracting the beginning from the end of a temporal region, which produces just another time interval which denotes the duration (compare also Figure 3).

(6) $$duration : TimeRegion \mapsto TimeRegion$$

Operations for measuring locations and other qualities of endurants. The first operation localizes the spatial region that corresponds to a certain physical endurant in a spatial reference system at a certain time. The other operations are examples for basic observations of qualities. All of them correspond to DOLCE's physical qualities [8]. They produce an output region whose temporal resolution depends on the input time interval. For example, observing the location of a moving object for an interval results in an extended region that encompasses this movement.

(7) $$location : Endurant \times TimeRegion \mapsto SpaceRegion$$

(8) $$volume : Endurant \times TimeRegion \mapsto Volume$$

(9) $$area : Endurant \times TimeRegion \mapsto Area$$

Insofar as the quality regions are part of certain *structured space*, we assume the usual operators on them. For example, ratio scaled spaces like volumes and lengths are equipped with arithmetic operators for multiplication, addition and a fixed 0 element on atomic regions. Non-atomic regions are arbitrary subsets of the ratio scale. We furthermore assume that regions on the same level of measurement can be combined by operators into derived quality spaces [40].

Operations for identifying affordances in the environment. For example, operations identifying whether a place in a shop (endurant) affords to buy coffee (perdurant).

(10) $$Affords[PerdurantType] : Endurant \times [PerdurantType] \mapsto Bool$$

We conceive of an affordance as a boolean operation that decides whether a part of the environment (an endurant) allows for a simulated movement or action or resting. This means that such a simulation has successfully taken place in it, and that it is the minimal place necessary for the simulation. The endurant (e) thus identified gives rise to, and is part of (P), a larger medium (m) for the same kind of movement or action or resting (p):

(11) $$Affords[PerdurantType](e, p) \rightarrow \exists m.Medium(m) \wedge P(e, m, time(p))$$

Note that if the involved perdurant is an action, e.g. $doMeasuring$, then the person acting also exists. Due to formula 3, an animate body is involved in generating this action. This body is logically necessary by surjectivity of the *do* operator, as required in the last paragraph of Section 3.3.

Operation for observing kinds of media in the environment. The $Medium$ operator is parameterized with a type of endurant and perdurant. The idea is that the perdurant, e.g. a simulated action, is afforded by integral parts of the medium, while the endurant, e.g. an object, participates in that perdurant.

$$[\mathit{PerdurantType}][\mathit{EndurantType}]\mathit{Medium} : \mathit{PhysicalObject} \mapsto \mathit{Bool} \tag{12}$$

A medium for motion, for example, has parts that afford motion of some type of endurant (see Equation 13). Media for actions and restings have a corresponding usage. Note that media are rigid categories (not roles) just like bodies, because they cannot lose their affordance without disappearing. The underlying idea is that media are identified as integral wholes unified by affordances[18]. The following description captures only a necessary aspect of this idea, namely that a motion medium has a part that allows an endurant to perform a type of motion in it:

$$\begin{aligned}&[\mathit{MotionType}][\mathit{EndurantType}]\mathit{Medium}(e) \rightarrow \\ &\exists p, b, t. P(p, e, t) \wedge [\mathit{EndurantType}](b) \wedge \\ &\mathit{Affords}[\mathit{MotionType}]\,(p, \mathit{move}[\mathit{MotionType}](b, t))\end{aligned} \tag{13}$$

For example, a fluid is a medium with respect to a diving body,

$$\mathit{Fluid}(w) \leftrightarrow \mathit{DivingBodyMedium}(w) \tag{14}$$

that is an integral part of the environment that affords a certain “low resistance” or “forceless” movement of this body.

As argued in [41], the notion of *place* can also be understood in terms of a medium, namely one which affords *containment* for animate bodies. Containment has many metaphorical meanings, but seems to be a central Gestalt schema of human cognition [42]. We conceive of it here as the human act of staying in a perceivable relation to a “container” in some physical sense. This can be a physical enclosure like a building or a conventionally demarcated place such as a bus station. For example, humans are inside a building if they stay in a certain relation to its inner surfaces, and they are at the bus station if they stay in a certain distance to the station sign.

$$\mathit{Place}(b) \leftrightarrow \mathit{ContainingAnimateMedium}(b) \tag{15}$$

[18] More specifically, we conceive of them as maximal wholes self-connected by affordance relations among its parts [13].

Operations for identifying features. Features [8] are perceivable parts of a body or medium identified with respect to a host object. An example is the opening of a funnel or the edge or surface of a table. In the first case, the feature, the opening, is not part of its host, the funnel, but part of the medium surrounding the funnel. But media can also be hosts for features. For example, a water body is a medium with a visible surface. Since there are different feature types an observer can distinguish, *identify* is an operator schema with a wildcard for subtypes of $Feature$. The most important feature is a *visible surface*, denoted by the type *Surface*:

$$(16) \qquad \mathit{identify}[\mathit{FeatureType}] : \mathit{PhysicalObject} \mapsto [\mathit{FeatureType}]$$

Due to surjectivity (Section 3.3), a feature always has a host body that generates it[19]. Features may be parts of bodies or media. We call the features that are part of a medium $OpenFeature$.

Operations for observing surface qualities. Many substances in the environment are specified by the surface quality of an object which is "made" of this substance. This may include texture and color, but also transparency. As an example, we introduce surface qualities as predicates over surfaces that allow to distinguish substances like snow from water:

$$(17) \qquad \mathit{Water} : \mathit{Surface} \mapsto \mathit{Bool}$$

$$(18) \qquad \mathit{Snow} : \mathit{Surface} \mapsto \mathit{Bool}$$

Operations for observing amounts. Amounts, like the amount of water contained in a bottle, must be observed based on other physical endurants with a unity criterion, e.g. physical objects, features or pluralities [37]. We have to identify an amount of water via the water unit that contains it at a certain moment in time, not vice versa. Furthermore, we track this amount through its various states, e.g. through merging or splitting into other objects. For example, when a statue is smashed, we track the amount of clay of this statue in terms of a remaining heap of clay. Sometimes, even the amount contained in a stable object keeps being exchanged, as in the case of a lake. In any case, amounts are first identified (and located) in terms of a temporal slice of an endurant (e.g., the statue before smashing, or a river part at t_n), and then need to be tracked through other temporal slices of other endurants (the lump after smashing, or another river part downstream at t_{n+1}). For the first task, we introduce a perceptual operation called *containsA*, which identifies the amount of matter of a (non-amount) endurant in a time moment. Because different endurants can contain the same amount of matter, and every amount is contained by an endurant, this operation

[19] In DOLCE, while the authors seem to assume that features are existentially dependent on a host, it is left unspecified [8].

is not injective, but surjective[20].

(19) $containsA : NonAmountE \times TimeRegion \mapsto Amount$

(20) $P_A : Amount \times Amount \mapsto Bool$

(21) $Amount_{Fluid}(x) \leftrightarrow \exists y : Fluid, t.P_A(x, containsA(y, t))$

The second operation for tracking amounts through endurant time slices is expressed by the parthood predicate P_A[21]. In contrast to parthood among non-amounts (Equation 1), parthood among amounts is extensional (for extensional mereologies, see [39]), so amounts are identical if they have the same parts, as argued in [37]. This means that subamounts cannot be exchanged. Since parts of an amount are not exchangeable, P_A should be conceived as an atemporal relation. As in DOLCE, amounts and their time-slice containers are always *co-located*, and temporal parthood among endurants implies parthood of their contained amounts [8]. The two operators can be used to introduce *amount subtypes* such as the amount of a fluid $Amount_{Fluid}$ in Equation 21 (we will refer to other amount subtypes in an equivalent way).

After having introduced and discussed unary perceptual types, their subsumption hierarchy and their interrelatedness via perceptual operations, we can now proceed to describe our first scenario in terms of such types and operations.

4 Technical sensors

The challenge addressed in this section is how to describe measurement results of sensors in such a way that the observation process can be understood and in principle repeated by a user. It is particularly important that such a description is independent of technical implementations to be used for comparison, but specific enough to distinguish between different kinds of sensors. This has been identified as the major challenge by OGC's observation and measurement specification (O&M) [10], which states the need for an ontology describing properties:

> "A schema for semantic definitions of property-types is beyond the scope of this specification. Ultimately this rests on shared concepts described in natural language. However, the value of the observed property is a key classifier for the information reported in an observation. Thus, in order to support such classification, for use in discovery and requests, an ontology of observable property-types must be available." [10]

[20] The operation corresponds to DOLCE's triadic "constitution" relation K between physical endurants restricted to amounts [8], but as constitution encompasses also abstract relations whose perceptual grounding remains unclear, we chose to use our own notion.

[21] Perceiving parthood among amounts could be based on following histories of endurant time slices (as in the case of rain drops falling into a lake), or on detecting exchange of matter among them (as in the case of flowing water). In every case, it is based on a very complex perceptual inference task on the part of the observer, which is not further discussed here.

4.1 Grounding technical sensors: volumetric flux and volume flow rate

Many important measurements in hydrology, climatology and other geosciences are based on the idea of a flow of some fluid. Examples include measurements of precipitation conducted by a rain gauge and the flow rate of a river. Volumetric flux and volume flow rate are closely related properties, as each one can be derived from the other. In terms of SI units, volume flow rate is represented as the rate of volume flow across a given area, whereas volumetric flux is additionally normalized by this area:

$$vflowrate = \frac{m^3}{s} \qquad vflux = \frac{m^3}{m^2 * s} = \frac{m}{s} \tag{22}$$

Both qualities are derived from the same kinds of measurement of volumes, areas and times. Volumetric flux sometimes can be reduced to the measurement of a length and a time (e.g. $\frac{mm}{h}$). From a semantic viewpoint, the problem is that this kind of description hides essential features, for example the fact that volumetric flux involves observing a certain kind of process in which a movement of fluids is involved, and the distinction of this quality from arbitrary measurements of velocities. Furthermore, SI units do not say much about other measurement parameters involved: The location of measurement, or the object this quality inheres in. In the following analysis, we focus on volumetric flux, but the same constituents are involved for measuring volume flow rate.

4.2 Describing the observation procedures underlying volumetric flux

Volumetric flux is obtained via the following procedures expressed in terms of perceptual operations.

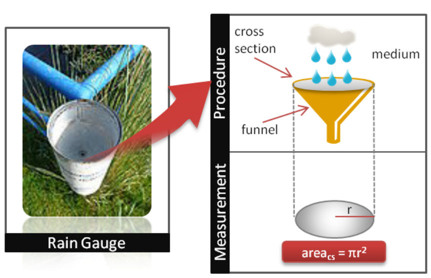

Fig. 2. Identifying an open feature (e.g. an opening) of a funnel to get a cross-section (the feature's location) and its area.

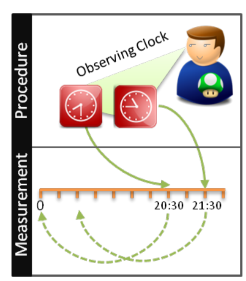

Fig. 3. Identifying a measuring action and measuring its duration.

Identify a resting open feature. For measuring volumetric flux we need to identify an amount of fluid moving through a cross-section. This cross-section is a location in a medium for fluid amounts, and it may be identified by placing a collector instrument, e.g. a funnel, which has an open feature indicating a free space, into such a medium (see Figure 2). It is the open feature that indicates the reference location in the environment, and it is this location that the volumetric flux quality inheres in. This feature needs to be an $OpenFeature$, as the cross-section must be part of a medium, and not part of a body. The medium is one where *amounts of fluids*, for example amounts of rain or flowing water, can move through. This can either mean that the amount moves with its associated container[22], as in the case of rain drops, or it moves autonomously, as in the case of waterflow in a river.

- Input: Collector object ($collector$) and time during which the collector rests in the medium ($restingtime$).
- Output: A cross-section as a location in a medium for fluid amounts.

Identify an open feature...

$$identifyOpenFeature(collector) = openfeature \tag{23}$$

...which rests for a certain time...

$$rest(collector, restingtime) = resting \tag{24}$$

...in a medium which affords movement of fluid amounts.

$$\exists m.P(openfeature, m, restingtime) \wedge MotionAmount_{Fluid}Medium(m) \tag{25}$$

The location of the collector's open feature is:

$$location\left(openfeature, restingtime\right) = crosssection \tag{26}$$

Measure the area of the open feature. There are different operations for measuring areas of open features. For example, we can measure the radius of a maximal idealized circle located in the cross section, inferring its area using π.

$$area\left(openfeature, restingtime\right) = area \tag{27}$$

Identifying a measuring event and its duration.

- Input: The $observer$, the time during which the collector rests in the medium ($restingtime$), and the time interval of measuring ($measuretime$).
- Output: The duration of the measuring action performed during resting (see Figure 3).

$$\begin{aligned} &doMeasuring(observer, measuretime) = measuring \wedge \\ &measuretime \subseteq restingtime \wedge \\ &duration(measuretime) = duration \end{aligned} \tag{28}$$

[22] These exist because of surjectivity of $containsA$.

Identify the amount of fluid that has passed the open feature during measuring. This can only be done by identifying a part of a fluid fp at a time t, which contains all and only those amounts that passed the open feature during measuring time[23]. Note that this does not necessarily mean that the human observer perceives the movement of an object, e.g. a unit of water. During measuring, the amount of fluid may be contained in a plurality of moving water units, e.g. in rain drops, but it may also be flowing inside one contiguous resting object, e.g. a river.

- Input: *measuretime*, *openfeature*, identification time t
- Output: fp (part of a fluid) identified at time t which contains all and only that amount of fluid that passed the open feature during measuretime.

Equation 29 describes what it means for a fluid part fp to contain *all* the fluid that passed the open feature during measuring (i.e. to be a "passing fluid container"): namely that fp needs to contain the amounts of all fluid parts fp' that where part of the open feature at some time t' during measuring (see Figure 5):

$$\begin{aligned}(29)\qquad & \forall fp, t.PassingFluidCont(fp, t, measuretime, openfeature) \leftrightarrow \\ & \exists w : Fluid.P(fp, w, t) \wedge \\ & \forall fp', t'.(t' \subseteq measuretime \wedge (\exists z : Fluid.P(fp', z, t')) \wedge \\ & P(fp', openfeature, t') \rightarrow P_A(containsA(fp', t'), containsA(fp, t)))\end{aligned}$$

The sought operation must produce the minimal container in that sense, because it needs to contain *only* fluid of that kind. This restriction excludes unwanted amounts of fluid that did not pass the open feature:

$$\begin{aligned}(30)\qquad & \forall fp, t.passingFluidCont_{min}(t, measuretime, openfeature) = fp \leftrightarrow \\ & \forall fp'.PassingFluidCont(fp', t, measuretime, openfeature) \rightarrow P(fp, fp', t)\end{aligned}$$

Measure the volume of this amount of fluid. Depending on the kind of fluid and the way the fluid part is identified, the procedure of measuring volume is different. We abstract from the specific implementation by a single perceptual operation of the volume quality.

$$(31)\qquad volume(passingFluidCont_{min}(t, measuretime, openfeature), t) = volume$$

4.3 Volumetric Flux in a Nutshell

A volumetric flux can be obtained by dividing the measured volume of the fluid amount by the cross-sectional area of the open feature and the measuring duration. Usual parameters of a particular volumetric flux value are its time of

[23] This is a slight oversimplification because it does not account for variations due to water loss or contamination.

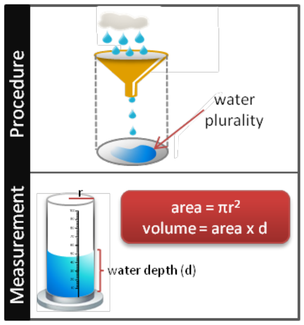

Fig. 4. Identify the amount of fluid that passed the open feature and measure its volume.

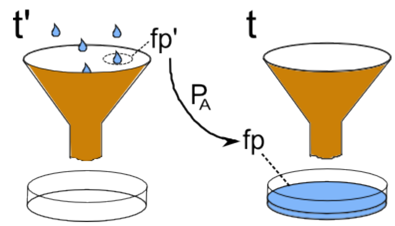

Fig. 5. Explanation of Equation 29.

measuring, the location of the cross-section, and the time of recording $recT$. This is the time all required measurements are available so that the value can be recorded, which is in our case the time of identification of the amount of fluid:

$$volumetricFlux\left(measuretime, crosssection, recT\right) = \frac{volume\left(passingFluidCont_{min}\left(recT, measuretime, openfeature\right), recT\right)}{area(openfeature) * duration(measuretime)} \tag{32}$$

If the reader substitutes all constants in this equation with perceptual function applications where possible, it can be seen that the observer, the resting, measuring and recording times, and the collector are the only free variables in this formula, which corresponds to our intuitive understanding of what setting is needed for observing this quality. It also makes clear that from an ontological viewpoint, the common parameters added to such a quality, like location and time, are only some of the entities involved in the context of measurement.

4.4 Describing and Querying Volumetric Flux Sensors

Each of the operations introduced in the last section is implemented in one or the other way in the following technical sensors. We will indicate the additional types needed in each case in the text.

Example 1: Tipping Bucket Rain Gauge. An example for a *rain gauge* is a tipping bucket rain gauge. This instrument comprises a funnel (i.e., $Funnel(collector)$) which collects the rain drops. The open feature is the opening (`type` $Opening$) of the funnel which allows rain drops to enter it. This means it is placed in a special medium m for "falling water", `type` $FallingAmount_{Waterunit}(m')$[24], where

[24] This medium is implied by a co-located medium for moving water units, `type` $FallingWaterunitMedium(m)$, with $P(m, m') \wedge P(m', m)$, since fluid amounts are co-located (and therefore move) with their containers. In order to draw this inference, a stronger theory of movement would be needed.

the new `type` *Waterunit* means:

$$(33) \qquad \mathit{Waterunit}(w) \leftrightarrow \mathit{Fluid}(w) \wedge \mathit{Water}(\mathit{identifySurface}(w))$$

The rain drops travel down the funnel and reach one of two 'small buckets' balanced on a fulcrum. The water amount passing the funnel during measuring is identified as the amount of raindrops accumulated in the full bucket (fp). When the rain drops fill one of two buckets located inside the gauge, the bucket tips and drains. The second bucket is positioned under the funnel for the next reading. The tipping event ($recT$) actuates a sealed reed switch which is detected by a data logger or telemetry system. The data logger records each individual tip of a bucket attributed to a specific time instant. The measuring perdurant ($measuring$) is simply the event between two tips. Since the bucket is filled and has a known volume (for example, each tip of the bucket represents 0.2 mm of rainfall), volumetric flux of rain can be computed with a constant volume but a varying measuring time.

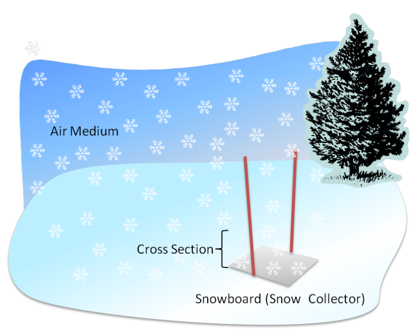

Fig. 6. Snow fall measurement. Starting of the measuring.

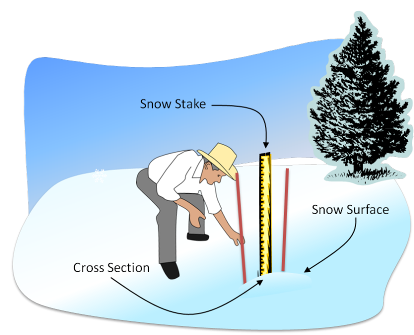

Fig. 7. Snow fall measurement. End of the measuring, recording.

Example 2 : Snow fall measurement. Snow fall is a quality that seems to be conceptually easy, but turns out to be at least on the same level of complexity as rain gauge measurement. It is correctly conceptualized as the volume of snow accumulated on a piece of the ground surface during measuring time. The fluid amount medium is of `type` $\mathit{FallingAmount}_{\mathit{Snowunit}}(m')$ (derived from a medium of falling snowflakes, `type` $\mathit{FallingSnowunitMedium}(m)$), where:

$$(34) \qquad \mathit{Snowunit}(s) \leftrightarrow \mathit{Fluid}(s) \wedge \mathit{Snow}(\mathit{identifySurface}(s))$$

The open feature in this case is a *Surface* feature: it is that part of the visible surface of the snow falling medium (where snow falling ends), which is located directly above the marked board on the ground surface (see Figure 6). Its host is the board, which is at the same time the collector of snow ($\mathit{Board}(\mathit{collector})$)). At the beginning of each measurement event, the board therefore has to be cleared from snow. The measuring event (*measuring*) is any major snow falling event. At the end of such an event ($recT$), the passed amount of snow is identified by that part of the snowpack (*fp*) which is right above the board after measuring time. Its volume is measured by sliding in a snow stake until it reaches the ground or snowboard and measuring depth (see Figure 7). Since the area of the open feature happens to coincide with the bottom area of the accumulated snow pack, and thus disappears from the equation, volumetric flux becomes a velocity.

Example 3: Stream Discharge Measurement. The stream discharge or streamflow is the volume of water passing a given cross-section along a stream in a unit time, so it is a volume flow rate (see Section 4.1). In case of a river, the medium of interest is a self-connected water unit, $Waterunit(m)$, which is co-located with a medium for flowing water amounts, $FlowingAmount_{Waterunit}(m')$, with $P(m, m') \wedge P(m', m)$[25]. Discharge measurements are based on a cross section of this river. So the open feature (of `type` *Crosssect*) in this case is a cross-sectional part of the water unit of the river, and its host (the collector) is this water unit itself: $identifyCrosssect(m) = openfeature$, with $P(openfeature, m)$. In order to measure the area of this feature, the stream width and the average water depth measured at several locations in the cross-section are multiplied. Then a standard *traveling length* in the direction of flow has to be established. The amount of water passing the cross-section is identified by that volumetric part of the river (*fp*) which starts at the cross-section and extends orthogonally in flow direction for the traveling length (see Figure 8)[26]. The measuring event (*measuring*) is the time a floating object takes to travel along this predefined length. This time indirectly measures how long it takes to fill up the established volume with water and how fast an amount of water is moving. The recording time *recT* is the end of the measuring event, at which *fp* is filled. So the volume in this case is fixed, whereas the measuring duration is variable.

Descriptions like the ones above are on a level of abstraction adequate to express useful differences among sensors based on property or quality types. They could improve queries by abstracting from the technical level of O&M in describing which kinds of qualities and objects are observed. For example, we can compare volumetric flux sensors on the level of types of fluid media, for example on the level of *flowing objects* (amounts vs. bodies of snow or units of water) or on the level of *movement types* (falling or flowing), or based on whether the open feature is fully “drained” in the fluid (river) or not (precipitation). Different implementations of rain gauges (standard rain gauge, tipping bucket, a.s.o) can be subsumed under a common type.

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[25] In this case, the medium for flowing amounts of water is not implied by the other medium, since the water unit itself is not moving. This illustrates the use of distinguishing these different kinds of media.

[26] This is a simplification, since it is assumed that this volume is simply the orthogonal projection of the cross-section in travelling direction.

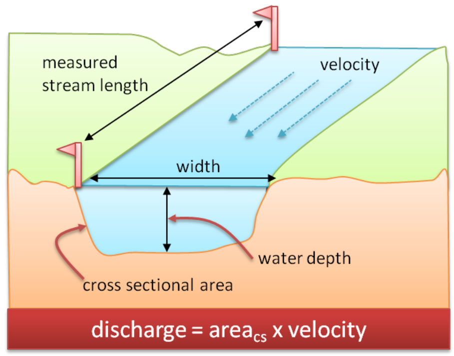

Fig. 8. River discharge measurement.

Furthermore, the instruments and actions (i.e., the resources) involved in such a measurement can be compared in detail. We see that in some cases, a collector instrument (a body with a funnel) needs to be placed somewhere, whereas in other cases the collector is just an existing water body. The operation for identifying amounts and measuring volumes and areas is implemented differently in each case. The measuring event requires to be aligned with different other observations by the observer, like measuring the traveling time of water at a fixed distance, or the duration of a snowfall event. In other cases the event is triggered automatically, as in case of the tipping bucket. The temporal intervals of these measuring events are huge or small and have fixed or open duration depending on these implementations.

How can such queries be implemented? In our scenario we mostly needed sentences with *ground terms* (terms without variables) or existentially quantified variables. This makes it easy to substitute all existentially quantified variables and all function applications by constants, and all functions by relations, in order to represent the resulting ground sentences in a relational scheme, e.g. a relational database or RDF. We then also have to replace Definition 30, which employs a universal quantifier, by a primitive relation, taking a loss on expressiveness. Examples how such a relational scheme can be translated into RDF and how it can be queried with appropriate languages is shown in Section 5.3.

5 Volunteered Geographic Information

In the previous section, we have discussed how technical sensors can be semantically referenced based on the underlying measurement and observation procedures. While this approach targets semantic annotation of sensors and observations at a technical level, the amount of geographic information that is produced by non-technical sensors has grown rapidly in recent years. *Citizens as sensors* [7] produce a range of different kinds of geographic information, with the community-generated world map in the OpenStreetMap project being the most prominent example. Other examples of such Volunteered Geographic Information include maps for local natural hazards (such as bush fires) where the authorities have difficulty in providing up-to-date maps, or services on the Social Web where the location information is produced as a by-product, such as geo-tagged pictures, blog posts or tweets[27].

On the surface, the observation methods applied by human observers that produce such geographic information seem to be fundamentally different from those underlying the technical sensors discussed in Section 4. In this section, we argue that the volunteered observation process can best be described based on the human perception and simulation of possible interactions with the environment. In this respect, technical and human observations have a common root: They can both be described in terms of perceptual types, e.g. affordances, in a shared environment. We show how affordances can be employed to improve the tagging of geographic features. OpenStreetMap serves as a working example in this section, as it provides the largest collection of user-generated geographic information. We discuss an approach to semantic referencing of points of interest in OSM.

5.1 OpenStreetMap: Describing the Semantics of POIs

In a German OSM mailing list[28], people recently discussed how to tag a point of interest where you can mail as well as pick up letters and parcels. Since a lot of automated boxes offering this functionality have been installed in Germany[29] over the past years, people recognized that the commonly used label `post_box` does not specify what is really of interest for the user: can he or she mail or pick up letters and parcel?

Points of interest in OpenStreetMap are currently annotated with key-value pairs such as `amenity=post_office`. This combination of keys and values (also referred to as tags) is not structured in any way. Users can freely assign any tags they consider useful for a POI when they add or edit it. The idea is to reach a consensus on the tags to use by discussions on the OSM wiki and different mailing lists[30]. The tags assigned this way, however, can make it difficult for users to properly annotate their POIs. Places often do not fit into just one of the category values defined by the OSM keys.

For example, many cafés in Europe are open late and also serve alcohol, so that they would be better described as bars in the evening. Annotating such POIs with either `amenity=cafe` or `amenity=bar` therefore only tells half the

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27 See http://twitter.com.

28 See http://lists.openstreetmap.org/pipermail/talk-de/2008-February/007487.html.

29 See http://www.dhl.de/en/paket/privatkunden/packstation.html.

30 In practice, however, the decision on the tags to use is largely influenced by the developers of the different map renderers and editors. They decide which tags are picked for display on the map, and which symbols are chosen for them. Since seeing "your" POI on OSM is a major incentive to contribute, users obviously pick certain tags to describe their POIs.

truth and hides useful information from OSM users. Such conflicts can often be observed, for example when bookstores include cafés, when kiosks serve as pick-up points for parcel companies, or when fully annotating these POIs with all relevant information is only possible with workarounds. Post offices offer a number of different services in Germany, including banking facilities (provided by the Postbank), ATM machines, the opportunity to buy stationary in addition to the common services available at a post office. These come in a number of different combinations, depending on the size and location of the office. Describing such a POI only as `amenity=post_office` does not give credit to all these different functionalities and makes it hard for other users to figure out what kind of services they can expect at this place.

One problem of the OSM data scheme lies in the fact that a place can have a variety of affordances, which may be of varying importance depending on the user. Points of interest in OSM in contrast allow for only one value per `amenity` key, wich implies an a-priori choice. Another problem is that the categories suggested as values are too abstract and ambiguous to give a clear idea of how they should be observed.

To overcome these problems of the current OSM tagging approach, we propose to use tags grounded in affordances. Similar to the affordance-based specification of observation procedures introduced in the previous section, this approach is based on reproducible observation of different functionalities offered by the POIs. We use several examples to illustrate how affordance-based tagging can help with a solution.

5.2 Describing the observation procedures underlying POI affordances

We suggest to conceive of POIs as places equipped with a (potentially long) list of action affordances offered by its parts (compare [43]). These affordances account for the "interest" in a POI. Note that we do not suggest that there is any intrinsic priority ordering among them, for example some prior use. Our view also follows the open world assumption that what volunteers do not know, i.e., the affordances they may not have observed, may nevertheless be existent. In the following, we go through several POI examples (assuming that the unbound variable *poi* denotes any particular one) to demonstrate how the observations underlying POIs could be described.

Restaurants, cafés and bars are places, and some of their parts, namely tables and chairs, afford to eat, drink and talk to each other. There may be also other parts such as a bar, toilets and entrances. Definitions of these place categories would be very complex because of their graded prototypical nature. It is also not recommendable to suggest some "major" type of usage, because restaurants can be used as cafés and vice versa, depending on the intentions of the observer. In some situation, a restaurant may be primarily a place to find a restroom or an open wifi network. It seems therefore more reasonable to add functional descriptions of a *poi* place using affordance operators differentiated by action types, while keeping involved persons, things and times implicit (existentially quantified). Sometimes, explicit parameters may be useful. For example, t in the following example indicates the time of observation of the affordance.

(35) Restaurant, café or bar:

$$\begin{aligned}&Place(poi) \land \exists eatingplace.P(eatingplace, poi) \land\\&\exists somebody, something, t.Affords(eatingplace, doEat(somebody, something, t)) \land\\&\exists drinkingplace.P(drinkingplace, poi) \land\\&\exists somebody, t.Affords(drinkingplace, doDrinkAlcohol(somebody, t))\end{aligned} \tag{35}$$

Supermarkets. We can distinguish supermarkets from restaurants by asserting that they allow to buy food, but not to eat it there. Since categories like food are themselves observed via affordances such as eatability, this nicely fits into our type schema:

(36) Supermarket:

$$\begin{aligned}&Place(poi) \land \exists pointofsale.P(pointofsale, poi) \land\\&\exists somebody, something, t.Affords(pointofsale, doBuy(somebody, something, t)) \land\\&\exists somewhere, t.Affords(somewhere, doEat(somebody, something, t))\end{aligned} \tag{36}$$

Parking lots are places that allow to place vehicles, which are things to drive with:

(37) Parking lot:

$$\begin{aligned}&Place(poi) \land \exists lot.P(lot, poi) \land \exists car, t.Affords(lot, rest(car, t)) \land\\&\exists somewhere, somebody, t.Affords(somewhere, doDrive(somebody, car, t))\end{aligned} \tag{37}$$

The descriptions above not only highlight which contextual entities need to be observed, but also which entities can be inferred if a POI is being observed.

Evidently, this approach is in stark contrast to the simple key-values pairs currently used in OSM. An affordance-based tagging potentially leads to more complete and appropriate descriptions of points of interest and hence facilitates retrieval, as outlined in the following subsection. The complexity of the underlying formalization, however, may hamper users from contributing to the map. This approach hence requires user interfaces that hide the complexity from OSM users. Furthermore, the complexity of an observed affordance can be hidden by definitions. The general schema of a POI affordance could be shortened, e.g., by the defined binary predicate *HasObservedAction*:

$$\begin{aligned}&\forall poi, action.(poi)HasObservedAction(action) \leftrightarrow\\&\quad Place(poi) \land \exists p.P(p, poi) \land Affords(p, action)\end{aligned} \tag{38}$$

5.3 Querying and visualizing affordance-based POI tags

The immediate advantage of affordance-based descriptions becomes evident when querying over the potential functions and their links to existing entities. In this case, querying for a specific function would result in all unexpected and expected uses of a POI. So a query for the function of drawing money would return bank offices as well as ATM machines. Similarly to the use case in Section 4.4, the sentences above contain only ground terms or existentially quantified variables, and so they can be easily represented and queried in any relational database: Simply replace the existential quantifiers by constant names, convert all terms (constant names and function applications) into keys of a table (one table for every type), and then convert every atomic formula to a table row (one table for every predicate) referencing constant names with foreign keys. It is similarly possible to convert this scheme into a set of RDF triples linked with OWL concepts in order to directly annotate OSM data. In this case, SPARQL technology [44] as well as a RESTful interface [45] can be used to query afforded actions.

The following RDF snippet demonstrates the annotation process for a café in Münster. It uses a vocabulary including the RDF predicate `hasObservedAction` (as defined above) and others from a hypothetical file `http://foo.bar/poi`. Note that the affordance-based tagging does not render existing key-value pairs useless, but should rather complement them[31]. Categories which are currently assigned manually could be defined based on sets of affordances, as outlined in Section 5.2. POIs falling into a specific category could be automatically tagged based on the assigned affordances. In order to keep the set of assigned affordances consistent, recommendations based on existing affordances can be shown to the users [46].

```
@prefix poi: <http://foo.bar/poi#>.
@prefix osm: <http://osm.org/browse/node/>.
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>.
osm:740777363
       poi:hasName "Teilchen und Beschleuniger";
       poi:hasObservedAction
              <poi:doDrinkAlcohol_37>, <poi:doDrinkCoffee_21>, <poi:doEat_42>;
       poi:isAmenity "bar","cafe".
       ...
```

The observed actions, e.g. `doDrinkCoffee`, are instances of more generic action types, e.g. `DrinkCoffee`, as specified in the following excerpt. These action types are `rdfs:subClassOf` the generic type Action. The specific instances are observed at specific time instances, which would allow to infer temporally restricted action potentials (e.g., to deduce opening hours or when food is served only up to a certain time)[32].

```
@prefix poi: <http://foo.bar/poi#>.
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>.
<poi:doDrinkCoffee_21>
```

[31] For an implementation of affordance-based tagging, the OSM restriction of having only one value per key would have to be loosened (which is not an issue in RDF).
[32] See `http://www.w3.org/TR/owl-time/` and its RDF resource under `http://www.w3.org/2006/time`.

```
    poi:observedAt "2010-06-05T18:00:00-5:00"^^<xsd:date>;
    rdf:type <poi:DrinkCoffee>.
```

The following SPARQL code shows a sample query for OSM POIs that afford to eat (i.e., to serve food) within the next two hours. We assume a conversion of the date time at which this action was observed to "hours of day":

```
PREFIX poi: <http://foo.bar/poi#>
PREFIX time: <http://www.w3.org/2006/time#>
SELECT ?cafe ?eat ?now ?inTwoHours
WHERE {
  ?y poi:isAmenity ?cafe;
  ?y poi:hasObservedAction ?eat;
  ?eat poi:observedAtHour ?t;
  ?t time:after ?now;
  ?t time:before ?inTwoHours.
}
```

This approach would also enable a different way to hook OSM data into the Linked Data Cloud, as proposed by the Linked GeoData initiative [47], and semantically enable OSM data for the exchange of spatial information [48].

Evidently, affordance lists are difficult to visualize by icons when rendering the map. Since the affordance-based approach does not exclude existing tags in OSM, the renderer's categories based on these tags can still be represented by the existing icons[33], so that no changes are required at this point. A small extension to the mapping interface would make the novel query functionality accesible for the user: if one searches for functionalities on the map (e.g. "draw money"), the POIs offering this functionality could simply be highlighted. Hence, there is no need for special icons for every affordance.

6 Conclusions and future work

In this chapter, we have made a proposal for describing the semantics of geodata on an experiential level, as a means to resolve its inherent abstraction and grounding problems. These problems become manifest in that geosensors are inadequately described on the level of SI units as well as on the level of instruments, and that useful and consistent tagging of VGI is a matter of choosing a level of categories with clear interpretations.

We propose to add semantic references to such data as a way of enabling users to reproduce the underlying observation processes. To this end, we suggested an operational view of human perception, including basic perceptual types such as media, bodies, features, motions, actions, amounts and quality regions, which can be aligned with top-level categories of DOLCE, and which have criteria of individuation rooted in Gestalt perception capabilities. The proposed types are linked by perceptual operations, e.g. action-, motion-, affordance-, and feature-detectors, which account for the generative dependence among them, and which

[33] See http://wiki.openstreetmap.org/wiki/Rendering.

are also alignable with DOLCE. Criteria of individuation were not discussed here, but might be given in terms of integral wholes, as proposed in [3, 20].

Our main idea is that affordances and the equipment of the meaningful environment, understood as perceptual types, provide a firm basis for semantic referencing of geodata. We demonstrated that volumetric flux sensors, e.g. rain gauges, can be described with the same formal apparatus as Points of Interest (POI) in volunteered information. Thereby, the variety of entities involved in a measurement, as well as the commonalities between instrumental implementations show up. We furthermore found that POI can be adequately modelled as places with lists of affordances related via perceptual operations.

The formal framework for semantic referencing sketched and illustrated in this chapter allows to formulate typed first-order theories about geosensors and VGI, of which we have only scratched the surface. In order to do that, the proposal needs a deeper formal elaboration. The main questions are what sets of axioms consistent with the ones in DOLCE should be added, and what further media, motion, action and quality subtypes are necessary to describe a given domain.

The framework can be used in its current form as a guideline for annotating VGI and geosensors. As we have discussed, subsets of a typed reference theory can be translated into RDF, facilitating queries over VGI and geosensors. It is straightforward to convert the sentences used in the examples into ground terms, substituting existentially quantified entities with object constants, and complex functions with primitive relations. The resulting data scheme is just a simple RDF graph of instances. It can be efficiently handled by standard triple stores, indices, and query engines based on SPARQL.

We consider all these options, as well as the required implementations, as part of future work[34].

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[34] A similar framework was used to implement a tool for evaluating and querying road network junctions in OSM (compare [20]). The tool is freely available as JOSM plugin under `http://wiki.openstreetmap.org/wiki/JOSM/Plugins/JunctionChecking`.

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