Affordances as Qualities

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Abstract. Affordances elude ontology. They have been recognized to play a role in categorization, especially of artifacts, but also of natural features. Yet, attempts to ontologize them face problems ranging from their presumed subjective nature to the fact that they involve potential actions, not objects or properties. We take a fresh look at the ontology of affordances, based on a simple insight: affordances are perceived by agents and may lead to actions, just like qualities are perceived and may lead to observations. We understand perception as a process invoking a quale in an agent. This quale can then be expressed as an action, if it stems from an affordance, or as an observation, if it stems from an other quality. Thus, we see affordances as qualities of the environment, perceived and potentially expressed by agents. We extend our recently proposed ontology of observations to include affordances and show how the parallel between observations (producing values) and affordances (producing actions) provides a simple and powerful ontological account of both.

Keywords. Affordance, Observation, Ontology, Quality, Quale, Action

1. Introduction

Humans judge their environment according to the actions it affords. A river affords swimming and fishing; a house affords protection from wind, precipitation and cold; a chair affords sitting; and a knife affords cutting, vegetables as well as oneself. These affordances determine activities in our lives, ranging from the mundane to spatial planning. Yet, they have received limited attention from information system ontologists. Even though their existence and their importance for categorization has been acknowledged, foundational ontologies and domain ontologies still rest on ontological principles largely developed in ancient Greece, long before the advent of ecological psychology. Affordances are not only perceptual phenomena (depending on perception and influencing behavior), but also *real* action possibilities [38]. This circumstance led Sanders to state that "affordances are ideal primitives for general ontology"[28, p. 103]. Even if one does not want to go that far, it is unfortunate that ecological psychology, which originated the notion of affordance [7], so far enters ontology only through the idea of a niche [34,33]. Affordances are not treated explicitly in ontology and sometimes even get conflated with objects.

From the applied perspective of geographic information systems (GIS), ontologies would benefit from including affordances, given that they are what the environment offers its inhabitants [7]. Yet, information system ontologies typically rest on allocentric

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semantic reference frames [25], with the implicit or explicit assumption that the conceptualizations they specify are agent-independent. For application areas with standardized terminologies (e.g. the *Terminologia Anatomica* in medicine [43]) or relying on conventional technical sensor observations, an allocentric reference frame may be sufficient. For many applications at mesoscopic scales [31] and involving human activities [16], however, the human understanding of an environment is important. Humans share the same physical environment, but perceive it differently. For example, a person in a wheelchair perceives curbstones and stairs differently from a person that can walk; the person in a wheelchair perceives an obstacle, where other people just perceive a step they can climb. An ornithologist perceives and categorizes birds differently from an untrained observer. Such differences are a particular challenge, as well as a chance, for GIS applications: how to integrate information about the same environment, provided by different communities with varying backgrounds [21], possibly distributed all over the planet [3]. The chance for science and society at large is to benefit globally from information provided locally, increasingly also in the form of volunteered geographic information [8].

It is widely accepted that humans do not objectively perceive environmental properties or objects. Perception is determined by interaction capabilities [40,9,41]: humans (and animals) perceive what they can do. We follow Turvey's view that an affordance is a quality of the environment that exhibits a mutual relation to a quality of an agent [38], giving rise to agent behavior [9,37]. Such a view is fully compatible with Gibson's original definition:

> The affordances of the environment are what it offers the animal, what it provides or furnishes, whether for good or ill. [...] I mean by [affordance] something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment. [7, p. 127]
>
> [A]n affordance is neither an objective property nor a subjective property; or it is both if you like. An affordance cuts across the dichotomy of subjective-objective. [...] It is both physical and psychical, yet neither. [7, p. 129]

In this paper, we present an account of affordances for information system ontologies, focusing on their role in perception, observation, and action. The relational nature of affordances suggests to model the environment based on ontologies of its qualities [13, 25] and of human and technical observers [18]. The environment and the observing agent span the space for affordances, which link these two ontological efforts.

Our view of affordances as qualities is not new. For example, Vieu et al. [39] discuss the closely related (but simpler) idea of capacities:

> The notion of capacity is taken from Cummins [...] and characterizes the dispositions [...] or behaviors a physical endurant is able to express, independently of any agent, even in the specific case of artefacts. Capacities are a type of DOLCE individual *qualities* possessed by elements in (at least) categories Amount of Matter, Non-agentive Physical Object, and Physical Artefact. [39, p. 125]

The abstraction of capacities from agents, however, leaves out a key ingredient of affordances. A pen, for example, only has the capacity to write or to fit a hand for humans or humanoid agents. Affordances can be seen as extensions of capacities (including an explicit agent), and as qualities at the same time. A key contribution of our work is this explicit modeling of agents. With it comes a connection to the ontology of perception and observation and the inclusion of inanimate observers, covering the affordance notion used in robotics [26].

Our formal account of affordances builds on the definition by Turvey [38]. We add the formal link to observations as well as to actions based on them. Our formalization uses the functional language Haskell[2], because our primary goal is understanding and modeling, rather than encoding for machine reasoning. In addition to its higher order modeling power, Haskell offers the advantage of an executable model of an ontology, which serves for testing during development. Once an agreement has been reached on a particular ontological model, expressing it in any ontology encoding language (such as OWL) is straight-forward. As we are more interested in human understanding than in machine reasoning at this point, we provide a UML visualization of some key concepts.

The remainder of this paper reviews a recently proposed ontology of observations (in section 2), discusses its extension to include affordances (in section 3) and illustrates the ideas through the prototypical affordance example of stair climbing (in section 4), before presenting the formalization (in section 5) and concluding with open questions and plans for future work (in section 6).

2. Observations

Observations link information to reality and provide the building blocks of all conceptualizations. As such they ground communication and relate data in information systems to the world and to its observers. Yet, basic ontological questions like "what can be observed" or "how do observations relate to entities in reality?" cannot yet be answered today, neither by providers nor by users of observation data [23]. With sensor observations becoming ubiquitous and major societal decisions (concerning, for example, climate, security, or health) being taken based on them, an improved understanding of observation as the source of information has become imperative. Many current research issues in information science and the social web (for example, concerning quality, trust, and reputation) also require an improved understanding of observation processes and results. The point of this paper is, furthermore, to show that an adequate ontology of observations can also help to understand affordances.

The ontology of observation has been hindered by, among other factors, the idea that measurement instruments are objective reporters of a mind-independent state of the world. This commonly held view neglects the fact that instruments are built and calibrated by human beings. Neither the choice of the observed entity, nor the quality assigned to it, nor its link to a stimulus, nor the value assignment to the quality are mind-independent. All of them involve human conceptualizations, though these are clearly more amenable to grounding and consensus than anything else in an information system.

Our observation ontology (published in [18], available in revised and simplified form from http://musil.uni-muenster.de/publications/ontologies) specifies observations as processes and defines the semantics of their results by the qualities, endurants, perdurants, and abstracts involved. It generalizes from technical and human sensors [8] to observing agents in general. This generalization of observation and sensing behavior, where people, devices, sensor systems and sensor networks can all observe, has been shown to simplify and improve software architectures in the sensor web area [1,35]. Based on Gibson's

[2]For more information on Haskell and to download the free compilers and interpreters visit http://www.haskell.org (last accessed: 14.2.2010)

ecological psychology [7], we have published a first account of how observations relate to endurants and perdurants in [29], and extended it in [30].

We adopt DOLCE's four top level categories of particulars [20]: endurants, perdurants, abstracts, and qualities (which can be physical, temporal, or abstract). Endurants, for example lakes, participate in perdurants, for example storms. Qualities inhere in particulars, with physical qualities inhering in physical endurants and temporal qualities inhering in perdurants. For example, a temperature quality inheres in an amount of matter, such as an amount of air, and a duration quality inheres in an event, such as a storm. Quality universals shall be admitted, so that a quality can be abstracted from multiple instances to a quality type (e.g., air temperature) and even further to a quality kind (e.g., temperature). Observations result from detectable changes in the environment (stimuli), which involve endurants and perdurants, and have values as results, which stand for qualities inhering in these endurants and perdurants.

As in [25], an observation process is seen as invoking first a "quale", i.e., an analog signal in an observer's mind or technical sensor. This notion of quale is slightly different from that in [19], but in line with the one in philosophy of mind[3]: it denotes a quality experience by an observer and is not abstracted from the carrier of the quality. The red of the rose experienced by an observer belongs to the rose as well as to the observer; it cannot be abstracted from either. Thus, observation involves firstly the production of a quale and secondly its symbolization - a sequence of impression and expression.

The core concepts in our observation ontology are those of quality, stimulus, agent, quale, and value. They have been chosen and defined with the goal to remain as compatible as possible with existing observation and measurement standards as well as with the literature (such as [42]) and with ordinary language.

A **quality**, physical or temporal, can be observed. Examples are the temperature of an amount of air (physical) or the duration of an earthquake (temporal). The choice of a quality bearing entity (say, of an air mass surrounding a thermometer or an earthquake) gives a rough account of the spatial or temporal resolution of an observation.

Since qualities as such cannot be detected (how would information about them enter an observer?), a **stimulus** is needed, generating the analog signal in the observer. It can be defined as a "detectable change in the internal or external environment" of an observer[4] or as a "physical or chemical change in the environment that leads to a response controlled by the nervous system"[5]. Examples of stimuli are the heat energy flowing between an amount of air and a thermometer or the seismic waves of an earthquake. Stimuli need to have well-defined physical or chemical relationships to the observed qualities.

We adopt the term **agent** from artificial intelligence:

> An agent is anything that can be viewed as **perceiving** its environment through **sensors** and **acting** upon the environment through **effectors**. [27, p. 31]

This notion of agent allows us to talk about humans, other animals, sensors with display or actuating capabilities, and robots.

Our conceptualization of observation processes, thus, involves two steps performed by agents. First, they generate a **quale** for the observed quality from stimuli. Second, they express the quale by symbols standing for the observation **value**. This account makes the

[3] for a good overview, see http://en.wikipedia.org/wiki/Qualia (last accessed: 14.2.2010)

[4] http://en.wikipedia.org/wiki/Stimulus_(physiology) (last accessed: 14.2.2010)

[5] http://www.emc.maricopa.edu/faculty/farabee/BIOBK/BioBookglossS.html (last accessed: 14.2.2010)

elements determining the semantics of observation values explicit: the reference to what is being observed and the symbolization of the result. It is consistent with the definitions of observations in standards for sensors and for geographic information, such as OGC's Observations and Measurements standard ("An Observation is an action with a result which has a value describing some phenomenon."[2]) or OGC's Reference Model ("An observation is an act associated with a discrete time instant or period through which a number, term or other symbol is assigned to a phenomenon."[24]).

Some examples of technical and human agents taking a variety of observations shall illustrate the notions. Each example identifies an observing agent, the observed quality, stimulus, signal, and value.

A **thermometer** measures the temperature of an amount of air using heat flow as stimulus. The heat expands an amount of gas by some amount, which is the signal that gets converted to a number of degrees on the Celsius scale.

A **sonar** measures water depth of a lake, generating sound waves as stimulus, and converting the time until they return from the ground (signal) into a distance value.

A **CCD camera** observes its visible environment using sunlight reflected from surfaces as stimulus. It integrates the received radiation intensity per spectral band at each of its pixels over some time interval (signal), and returns an image as value.

A **weather station** reports a type of weather by combining temperature, pressure, and humidity measurements (each of them a signal) and returning an aggregated value.

A **sailor** observes wind speed by watching the frequency and size of ripples on the sea (stimulus) and reporting a Beaufort number (value) expressing her impression of wind force.

A **nomad** reports the presence of water in a desert well by observing reflected sunlight (stimulus), getting the impression that there is some water, and sending a text message from his cell phone signifying "water available"[12].

A **doctor** observes a patient's mood by talking to the patient and describing her impressions (qualia) obtained from the patient's behavior (stimulus).

3. Affordances

The idea underlying the notion of affordances goes back to ecologist J. von Uexküll, who stated that sensory impression is overridden by the capabilities for interaction ("Das Wirkmal löscht das Merkmal aus", [40, p.27]). This eminent insight gave rise to a new paradigm for understanding environments of humans and animals. Possibilities for interaction started to be seen as individually different, following not only environmental characteristics, but also physical and biomechanical capabilities of humans and animals. The experience and exploration of the environment became subjective, together with the underlying and resulting conceptualizations. The coupling between sensors and actuators at the psychological level has meanwhile also been found by neuroscientist at the physiological level [14]. Sensory impressions as well as motor expressions are processed in close proximity in the brain. However, this insight has so far not been exploited in ontologies of agents and their environments.

Addressing this omission, we now address two questions that remained open in our past theory of observation [18]. The first is "what can be perceived?" We now suggest not only that agents perceive qualities, but that **affordances are qualities**. Affordances are complemented by an agent's capability to act on them [40,7,38], just like other qualities are complemented by an agent's capability to observe them. Secondly, we ask "what is the result of perceiving qualities, including affordances?". In analogy to the behavior of producing observation values, we introduce actions into the observation ontology, as behavior afforded to agents by environments. Perceiving any quality, thus, can be seen as producing an action potential, whether for expressing an observation value or for acting in the environment. Our current ontology does not yet include this generalization, but treats observations and actions in parallel.

A tenet of ecological theories is that there can be no environment without agents and no agent without an environment; environment and agent imply each other [10,40,7]. The notion of "fitness" describes this dependance: an animal *fits* into an environment if the environment affords living to the animal and survival to its whole species, i.e., if the environment affords nourishment, protection, mating and breeding. Applied to the level of species instead of individuals, this set of livability affordances forms the ecological niche [7,34,33]. Gibson assumes an environment that is shared across animals [7], and his remarks on this topic allow the conclusion that only animals of the same species share an environment. Von Uexküll provides a stricter view of the environment, distinguishing also between agents of different age [40]. The correspondence he assumes between agent and environment even allows for a solipsist interpretation. However, for a general theory of observations in information systems, assuming a private environment is not practical. Therefore, we adapt the notion of niche as described in [34,32,33]. The environment as the niche is the physical world surrounding the agent into which it fits according to its sensors, actuators, requirements and possibilities.

A first formal definition of affordances was provided by Turvey, more than two decades after Gibson's coining of the term [38]. Turvey matched affordances, as properties of the environment, with effectivities, as the corresponding properties of the agent:

> Let W_{pq} (e.g., a person-climbing-stairs system) = $j(X_p, Z_q)$ be composed of different things Z (e.g., a person) and X (e.g., stairs). Let p be a property of X and q be a property of Z. Then p is said to be an affordance of X and q the effectivity of Z (i.e., the complement of p), if and only if there is a third property r such that
>
> (i) $W_{pq} = j(X_p, Z_q)$ possesses r
> (ii) $W_{pq} = j(X_p, Z_q)$ posseses neither p nor q.
> (iii) Neither Z nor X posseses r
> [38, p. 180]

In this definition the thing X is part of the environment of the agent Z, and the affordance is a dispositional property. This view is supported by Warren's stair-climbing experiments, that showed that humans perceive the climbability of stairs very accurately [41] (cf. Section 4). Turvey's definition is fully compatible with Gibson's notion and the underlying system view of agents in environments particularly acknowledges von Uexküll's insights. Affordances are, thus, qualities of objects in the environment of an agent. This does not require that affordances must be perceived, nor that they can only be perceived by the agent [7,22]. Affordances can be said to exist independently of perception and one can distinguish perceived from hidden affordances [6].

As a first conclusion on the ontological nature of affordances, we can, thus, say that affordances are those qualities that emerge from fitting a quality of an object in the environment to a quality of an agent. For example, the climbability of a step for a person emerges from the mutual relation that the riser height of a step exhibits with the person's leg length. Here, we focus on physical affordances, i.e. affordances that depend on physical qualities in the environment complemented by an agent's physical qualities. An agent's physical, physiological or biomechanical quality enables controlled movements of his body or of parts of his body as well as other actions. However, the notion of affordance and our approach to its formalization covers any qualities in the environment of an agent, including those of social or mental objects.

Perceiving affordances generates possibilities for action. Thus, the quale invoked in an agent when perceiving an affordance allows the agent to act upon it. To execute an action, the agent's intention has to complement the affordance [37]. At any given time, there are countless affordances in the environment for the agent, but the number of actual interactions is limited and most affordances are not acted upon. All the pencils and books on your desk afford grabbing, but you will not grab them all or even any. In a theatre, all seats afford sitting, but you will normally only sit on one of them. Life is a continuous perception-action-perception cycle, characterized by conscious and unconscious choices about which affordances are perceived and, among these, which are acted upon. The locomotion affordance, for example, is so basic that humans and animals perceive it unconsciously and act on it all the time.

4. Example: Climbing Stairs

To motivate the example of stair climbing, we emphasize again the determining impact of the human motor system on perception. The observable quality in our example, the affordance of climbability, is the physical quality of a step that human actuators can perceive and act upon based on their abilities. The mode of perception can be visual, haptic or even ultrasonic, resulting in potentially different judgments of action (climbing) possibilities.

Among the first and most prominent experiments on the perception of affordances are those conducted by W.H. Warren [41]. Warren investigated the perception of the affordance to climb stairs. Stair climbing is a trivial everyday activity that most people do not even think about. However, it becomes important in environments of small children and elderly or handicapped people (cf. [15]). The configuration of this agent-environment system is quite simple. Warren showed that stair climbability can be modeled with two qualities only, namely the person's leg length L and the riser height R of the stairs. The climbability affordance can then be derived from the ratio of the values for these qualities. For young adults, Warren's experiments suggest that ratios of $R/L < 0.88$ realize the affordance. This result complies with predictions from biomechanical models. The other result, more relevant to a theory of perception of affordances, was that subjects could easily select, from a set of pictures, the stairs with a maximum climbable height as well as those with an optimal height for them.

Clearly, Warren's model of stair climbability is only a coarse approximation to reality and one can easily think of further pairs of environmental and agent properties to include, such as tread depth and foot length, or stability and weight. Yet, his results show two important things about the perception of affordances. First, he proved that humans perceive affordances, and that this perception indeed depends on the perceiver's physical abilities. Second, the invoked quale is not a boolean value but a gradual analog signal.

Humans can distinguish the most energy-efficient climbability and the least climbable step. It seems likely that humans also distinguish categories of climbing difficulty.

5. Extending the Observation Ontology by Affordances

We now present the extensions to the observation ontology [18] that support the perception of an environment with affordances and implement the example from Section 4. The observation ontology already introduced technical sensors and persons as observing agents. It was written as an algebraic specification in Haskell and continues to serve as both, an ontological specification and a simulation for development and testing. We add the specifications for perceiving affordances and provide the functionality to simulate afforded actions. We will refer to Haskell code[6] in the text using capital true type fonts like `OBSERVATIONS` for Haskell type classes, normal true type fonts like `Climbability` for data types, and lower case true type fonts like `perceive` for operations and individuals. For readers not familiar with Haskell, and for better comprehensibility in general, we provide diagrams of the core parts of the ontology in the Unified Modelling Language (UML). We first introduce the upper-level type classes of the ontology and then the extensions to account for perceptions and actions. After that we state our ontological commitments and show how they are specified in Haskell.

The observation ontology is aligned to the foundational ontology DOLCE with its four top-level notions of *endurants*, *perdurants*, *qualities* and *abstracts*. The expressiveness of Haskell allows us to use language constructs to differentiate the main DOLCE top-level categories. Endurants are implemented as data types of kind *, with an identity. Perdurants are implemented as types of kind *->*, i.e. functions defined for endurance. Qualities, as dependent entities, are modeled as constructor functions applied to their host, i.e., to the entity the quality inheres in. Haskell offers a higher level notion of "class", namely that of type class. A type class unites all types (or tuples of types) sharing some behavior. For example, we define the type class QUALITIES for all tuples of entities and functions returning a certain quality of them. The usual notion of "class" in ontologies is captured by a Haskell data type.

We introduce `AFFORDANCES` as subclass of `QUALITIES` and exemplarily model `Climbability` as a type of `AFFORDANCES` which inheres in a `Step`. The constructor of `QUALITIES` requires a quality like climbability to always be defined with its host. The implementation of `AFFORDANCES` and `Climbability` is shown in Listing 1. For comparison, we also provide the code for `Height` in Listing 2, which is of type `QUALITIES`.

Agents perceive qualities of their environment through stimuli. Consequently, the type class `STIMULI` provides the `perceive` behavior, which is by virtue of its signature a DOLCE perdurant. Perceive relates a quality inhering in an entity to an agent and generates a quale in the agent. Listing 3 shows the specification of the class `STIMULI`. Each pair of a quality type and agent type instantiated to the type class `STIMULI` gets its own implementation of the `perceive`-function, modeling how the quality affects the agent. An agent has a field, such as `pQuale` for persons, whose value changes as a result of perception. When a person perceives the height of a step, a height quale is invoked, i.e.

[6] The current Haskell specification and simulation can be downloaded from http://musil.uni-muenster.de/publications/ontologies/ (Last accessed: 14.2.2010)

Listing 1: The Haskell type `Climbability`.

```
class (QUALITIES affordance physicalEndurant, PHYSICAL_ENDURANTS
    physicalEndurant) => AFFORDANCES affordance physicalEndurant

data PHYSICAL_OBJECTS step => Climbability step = Climbability step
instance QUALITIES Climbability Step
instance AFFORDANCES Climbability Step
```

Listing 2: The Haskell type `Height`.

```
data PHYSICAL_OBJECTS step => Height step = Height step
instance QUALITIES Height Step
```

Listing 3: The Haskell class `STIMULI`.

```
class (QUALITIES quality entity, AGENTS agent)
        => STIMULI quality entity agent where
        perceive :: quality entity -> agent -> agent
```

Listing 4: The Haskell implementation of perceiving height and climbability.

```
instance STIMULI Height Step Person where
        perceive (Height step) person = person{pQuale = riserHeight step}

instance STIMULI Climbability Step Person where
        perceive (Climbability step) person =
        person {pQuale = (riserHeight step) / (legLength person)}
```

written into its `pQuale` field. When a person perceives the climbability affordance of a step, a quale standing for an action potential is written into the same field. In accordance with Warren [41], this quale is a ratio between the leg length of the observer and the height of the stair. The implementation of perceiving height and climbability is shown in Listing 4.

The perception of stimuli by itself does not yet result in a symbol or action. A subsequent phase can express an observation value or an action. Thus, observation as well as action require a preceding perception. We model this dependency by the `observe` and `act` functions calling `perceive` and then determining a value or action from the quale. They are the behavior provided by the classes `OBSERVATIONS` and `ACTIONS`, respectively. An action naturally requires the perception of an affordance, instead of any quality, as shown in Listing 5. The example of the climb action resulting from the perceived climbability affordance is given in Listing 6. The action requires an affordance of a physical endurant, the `Climbability` of a `Step`, and it requires an actor, the agent `Person`. The action is modeled by comparing the perceived climbability quale to the maximal ratio affording climbability. If a step is perceived to be climbable, the actor expresses an action, i.e., climbs the step. The observation of height works analogously. It expresses a perceived height quale in the intrinsic semantic reference system of the observer, distinguishing "low" from "high" by the observer's physical capabilities

Listing 5: The Haskell implementation of the classes `OBSERVATIONS` and `ACTIONS`.

```
class STIMULI quality entity agent => OBSERVATIONS quality entity agent
    where
        observe :: quality entity -> agent -> agent

class (AFFORDANCES affordance physicalEndurant, STIMULI affordance
    physicalEndurant agent) => ACTIONS affordance physicalEndurant agent
    where
        act :: affordance physicalEndurant -> agent -> agent
```

Listing 6: The Haskell implementation of acting on climbability and observing height.

```
instance ACTIONS Climbability Step Person where
        act (Climbability step) person =
        if (pQuale (perceive (Climbability step) person)) < 0.88
        then person {pStep = step} else person

instance OBSERVATIONS Height Step Person where
        observe (Height step) person =
                person {pValue =
                if (pQuale (perceive (Height step) person)) /
                        (legLength person) < 0.26
                then  "low" else "high"}
```

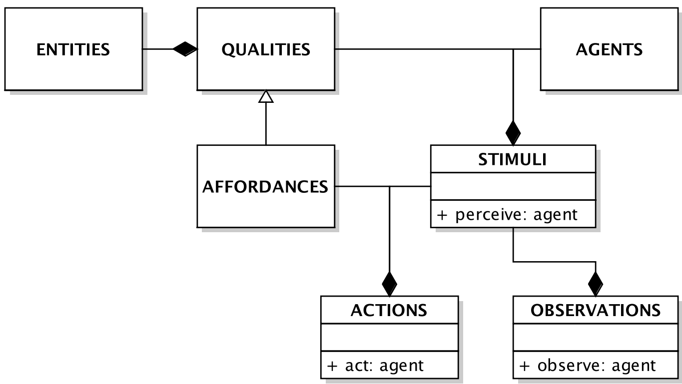

Figure 1. UML class diagram showing the alignment of the `STIMULI`, `OBSERVATIONS` and `ACTIONS` classes to DOLCE. We use composition arrows to denote existential dependence between classes.

(and using the threshold of 0.26 determined by Warren). The specifications of acting on climbability and observing height are given in Listing 6.

Figure 1 shows the core Haskell classes modeling the processes of perception and observation. The "components" (used here for participants) of stimuli are qualities inhering in entities and agents perceiving the qualities. The class `STIMULI` provides the perceive behavior that sets the quale of the agent. The `OBSERVATIONS` class provides the `observe` behavior that sets the observed value for the observing agent. Likewise, the `ACTIONS` class provides the `act` behavior (cf. Listing 3). The classes `OBSERVATIONS` and `ACTIONS` are associated with `STIMULI`, as an observation or action requires the

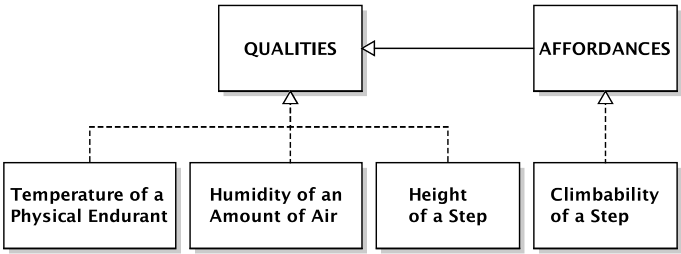

Figure 2. UML class diagram showing the modeled qualities, including the affordance of climbability.

perception of a stimulus. `AFFORDANCES` are a subclass of `QUALITIES`, the `act` behavior can only be executed on the perception of a type of `AFFORDANCES`. The qualities and the affordance we have exemplarily implemented are shown in Figure 2. These qualities participate in the process of perception and invoke a quale in the perceiving agent.

With this account of perception and observations/actions we have completed a model of interacting perception and action. Though there remains a lot of work to do, the current state of the ontology provides a reasonably stable account of the perception and observation of qualities and affordances by humans and technical sensors. The remainder of this section summarizes our main ontological claims. We state each claim, give an explanation or justification for it, and reference the corresponding specification in Haskell.

Affordances are qualities. This claim follows directly from Turvey's definition of affordances [38] introduced in Section 3. Surprisingly, however, it has not been exploited in ontology yet. The class `AFFORDANCES`, as specified in Listing 1 provides the specification how to write an affordance in Haskell. `Climbability` implements this specification.

Affordances are perceptibles. The theories of perception by von Uexküll [40] and Gibson [7] directly imply that affordances are what humans and animals can perceive [36]. Affordances are perceptible because they are required to guide action. They are qualities that suggest a certain action to an agent. Even though their perception and use naturally requires an agent, affordances exist independently of perception [7,22,6] and before they are perceived. An example of this is given in the implementation of the perception of climbability (cf. Listing 4).

Agents perceive qualities through stimuli. Perception is realized through stimuli, i.e., changes in the environment of an agent. Not the quality per se, but the stimulus invokes a quale in the agent. Ontologically, a stimulus (as change in the environment) is a perdurant. The quality perceived (which can be an affordance) and the agent who perceives both participate in the stimulus. This is expressed in the `STIMULI` class with its two parameters for `perceive`, as shown in Listing 3.

Perception of affordances leads to possible actions. The perception of an affordance invokes a quale, which stands for an action possibility. Actions require the perception of an affordance, and every perception of an affordance leads to a possible action. However, not every possible action has to be executed. Therefore the `perceive` operation returns a quale and does not cause a change of the environment. The quale can then be acted upon, for example as an action climbing the step. In the same way, regular qualities lead to the possibility to express a symbol. This is captured by the specifications of stimuli in Listing 4.

Agents act on perceived affordances. The execution of an action follows the perception of an affordance. This is in line with Stoffregen [37], who explains the occurence of an action as the complementation of a perceived affordance with an intention to act. Even though we did not deal with intentions in our ontology, the preceding of perception to action is specified in the `act` function, which calls the `perceive` function. Necessarily this also means that the `ACTIONS` class assumes the `STIMULI` class. Of course, the actions considered here are only those traceable to affordances.

Agents observe perceived qualities. Analogous to acting, agents can express a value as a result of observing a regular quality. We define (following OGC) observation as resulting in a value. The expression of a value requires a quale which is obtained by perception. It can also be interpreted as an illocutionary act [5], but this unification is a topic for future work.

6. Conclusion

We have presented an approach to "ontologize" affordances. Extending an observation ontology that generalizes observation to human and technical sensors, we showed how a twist on observation results allows for capturing observations of regular qualities as well as actions realizing affordances. This led to an ontological account of perception and action in terms of affordances and other qualities. Humans perceive their environment according to their capabilities, i.e., they perceive affordances. Since affordances naturally connect an agent to an environment, we have specified affordances as qualities of the environment of an agent. Thereby we have anchored perceptions in the environment and in the agent's individual qualities. We have then modeled observations as the expression of a perceived quality and introduced actions as expressions of perceived affordances. Using Haskell as ontology modeling and specification language, we have shown that integrating affordances into an observation ontology founded on DOLCE is possible and beneficial. In agreement with Sanders [28] we have found that affordances are at least valuable and beneficial primitives for ontologies and worth considering for information system ontologies.

The presented work suggests several directions for future work, in addition to the previously mentioned generalization of actions to include observations as speech acts. For one, we have focused so far on physical affordances, but the generalization to social affordances appears to be a straightforward extension to the specification. Humans do not only live in physical, but also in social environments. An extended theory distinguishing physical and social affordances, as for example in [11], will also help to improve and extend the observation ontology.

We will explore how the theory and its model can simulate whole cycles of action and perception. An isolated observation is rare and multiple observations are typically happening in parallel and sequentially, with afforded actions leading to new observations, which in turn lead to observable changes. The current ontology presents an ideal starting point for this exciting research direction, as its functional style allows for concatenations of the specified processes.

In previous work, the second author formalized the relation between spatial affordances and image schemas [17]. Connecting that theory to the perception-based formalization of affordances presented here will allow for relating the categorizing role of affordances to observed qualities. This might eventually lead to ontologies that refrain entirely from a priori specifications of types (kinds) and support instead an ad hoc computation of classifications based on observed qualities. Given that consensus on observable qualities is more easily achievable than consensus on object classifications, such an approach has the potential to improve semantic interoperability considerably.

Finally, the ontology assumes precise observations for now. In reality, most observations are imprecise and can only give uncertain accounts of environments. This affects affordances just like regular qualities. If we see a door, we cannot be sure that we can open it. This example also points to so-called false affordances [6]. A theory for perception-based probabilistic reasoning is presented in [44] and appears to supply the necessary mechanisms to account for uncertainty in observation ontologies. The seed for dealing with spatial, temporal, and thematic resolution has already been planted through the explicit modeling of quality bearers and through our work on semantic datums [29]. An additional perspective on this issue is [4], suggesting to specify qualia as convolutions of stimuli over space and time, which would produce resolution and uncertainty measures at once.

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