

A Formal Representation of Affordances as Reciprocal Dispositions

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Abstract. Notwithstanding its centrality to agency and cognition, the concept of affordance is notoriously difficult to model computationally, partly owing to its conceptually multifaceted character. This paper elaborates on previous formal-ontological studies of disposition by proposing a theory of reciprocal dispositions, and formalizes affordances and effectivities as reciprocal dispositions, contributing to the development of an ontological module for generic affordance representation.

Keywords. affordance, disposition, causal power, agency, parthood

1. Introduction

Since its invention by Gibson [1], the notion of affordance has played such a key role in exploratory discussions about agency, cognition, and action that its computational model would have wide implications for practical implementation of intelligent perception and behavior, e.g., in robotics [2,3]. Classical examples include hiding afforded by gaps and climbing afforded by stairs. It is nonetheless a fairly challenging task to model affordance formally, partly because its conceptual features are too diverse to be considered with an integrated theoretical framework.

This paper furthers the project (originally sketched out by Toyoshima [4]) to provide a formal representation of affordance based on the present conceptual and logical development of the notion of disposition. More concretely, we focus on Turvey's [5] conception of affordance as a disposition of the environment and its logical specification. We also hint at the extensibility of our proposal to other conceptions of affordance, thereby showing the explanatory force and practical utility of recent reconceptualization of the disposition concept in formal ontology.

The paper is organized as follows. Section 2 explains our basic methodology and our theory of dispositions in detail. Section 3 presents a general overview of our dispositional approach to affordance and provides a formal characterization of some core notions therein. Section 4 is devoted to the discussion. Section 5 concludes the paper with some brief remarks on future work.

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2. Methodology and the theory of dispositions

2.1. Justifying a dispositional methodology

A cloud of suspicion hangs over dispositions in formal ontology (see e.g., [6]), notwithstanding its active usage in the biomedical [7,8,9,10] and engineering [11] domains. One common doubt arises as to the apparent specific commitment to dispositions as a *bona fide* entity. As a result, the disposition category has not been adopted by some upper ontologies, including the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) [12], although it has been adopted by others, including Basic Formal Ontology (BFO) [13] (as realizable entities) and the Unified Foundational Ontology (UFO) [14] (as intrinsic moments).

To dispel this worry, we need to remind first the general theoretical setting into which the notion of disposition is inserted. In philosophy, dispositions are usually taken to be one of the topics that are loosely grouped under the heading of “natural necessity”. When one says that it is necessary for a glass to be broken when pressed with a certain force, for instance, one is speaking of the kind of necessity supplied by “nature” rather than by e.g., logic or mathematics (compare: “Necessarily, two plus two equal four”). Major issues of natural necessity are listed below with their elucidation by the example of (Newtonian) force and pressing:

- *Laws of nature*: any object has an acceleration given by the ratio of the resultant force applied on it divided by its mass (Newton’s Second Law of Motion).
- *Causation*: pressing with a certain force caused a glass to be broken.
- *Dispositions*: a fragile glass is disposed to break if pressed with a certain force.
- *Counterfactuals*: if a glass were pressed with a certain force, the glass would break.

It has been of primary philosophical interest to determine which is most fundamental among those concepts of natural necessity. Some may wish to take laws of nature to be most basic and have an eliminativist or reductionist approach towards dispositions. Others would counter that dispositions grounds all other notions of natural necessity and claim that both the truth of counterfactuals and causal relations between processes are determined by dispositions.

Most importantly, the notion of disposition is indispensable for a comprehensive description of reality, in order to account for notions such as fragility, inflammability, solubility, or arguably even physical entities such as Newtonian forces [15], *irrespective of the question of which is the most primary concept of natural necessity*. For instance, BFO would seem to be fundamentally committed to dispositions and DOLCE to laws of nature.³ This does not require however that dispositions be outside the scope of DOLCE; rather, as we will now argue, every upper ontology would have to account for dispositions based on its ontological choice [12] about natural necessity.

For the sake of further elucidation, it would be useful to draw a sharp distinction [16] between *dispositions* and *causal powers*. Almost any predicate (e.g., “is green or

³ In explaining DOLCE as compared to BFO, Guarino [6, p.14] says: “The connection between a particular kind of crystalline structure and the corresponding conditional behavior is given by a law of nature, whose ontological presuppositions do not require the existence of other specifically dependent continuants besides the crystalline structure itself. Of course, it may be important, for scientific reasons, to be able to *represent* such laws of nature, but this is not a good reason to introduce an ad hoc ontological category.”

not green”) can define a so-called “predicatory” property, which can be interpreted as a *façon de parler* without any ontological seriousness. Since dispositions are associated with dispositional predicates (“if x would be in situation T , it would R ”), they can be interpreted as predicatory properties. Causal powers are, by contrast, *bona fide* “ontic” properties with a dispositional essence that constitute their distinctive ontological category. When one simply says that a fragile glass is disposed to break, for instance, one is neutral on whether the fragility of the glass is only a disposition or also a causal power.

Because dispositions constitute a central notion in the context of natural necessity, any formal ontology should clarify their status. BFO seems to adopt an ontology of causal powers, whereas DOLCE does not. DOLCE must nonetheless provide its own treatment of dispositions, which would in turn necessitate the DOLCE conception of lawhood.

All these discussions would offer a fresh perspective on prior formal-ontological works [8,17,18,19] on dispositions that have accumulated for the last decade. Indeed, ontology of dispositions has been so far investigated carefully in the context of BFO, where dispositions are grounded in the ontology of causal powers. A general framework for dispositions (which we will detail below) *per se* is nonetheless adaptable to a wide array of upper ontologies (including DOLCE) because it can be well interpreted independently of whether or not one does accept causal powers.

We will attempt a formal specification of affordance on the basis on the above-mentioned formerly developed theories of dispositions. As we argued, this formalization could be articulated with a large range of upper ontologies, whatever their stance is concerning the fundamental nature of dispositions.

2.2. Theory of dispositions

Our formalization will be written using first-order logic, with occasional use of the Manchester Syntax [20] for OWL 2 Web Ontology Language (OWL 2). The formal underpinning of OWL 2 is a variant (i.e. SROIQ [21]) of description logic, which is a decidable fragment of first-order logic. This approach could therefore have a practical virtue when it comes to its implementation in the future. Particulars and relations will be written in bold, and classes in italic.

A disposition is a property that is linked to a realization, namely to a specific behavior of an independent continuant that is the bearer of the disposition. To be realized in a process, a disposition needs to be triggered by some other process: for example, to account for the fragility of a particular **glass₀**, it will be stated that a particular **strong_shock₀** can trigger the disposition **fragility₀** of **glass₀** (**fragility₀ has_trigger strong_shock₀**) which is then realized by a process **glass₀_breaking** (**fragility₀ has_realization glass₀_breaking**) – where “**has_trigger**” and “**has_realization**” are primitive relational predicates.

The fragility of a glass exists because of a certain molecular structure of this glass. The electrical resistivity of a material exists because of its physical constitution. We endorse here the notion of *categorical basis* [17,19] of a disposition: a quality (or a sum of qualities) of the disposition bearer. The categorical basis of the glass fragility is the sum of qualities of the glass that make it fragile, and the categorical basis of its electrical resistivity is the sum of qualities of the glass that make it electrically resistive.

Following Röhl and Jansen [17], we consider here a single-track disposition **d** that has **x** as a bearer, *R* as a class of realizations and *TR* as a class of triggers, and which can thus be described as “a disposition **d** of **x** to *R* when *TR*”. To keep things manageable,

we will ignore here the distinction between a trigger (such as a match being struck) and background conditions (such as the presence of oxygen).

We will use a recent theory of mereology among dispositions [18] which introduces several kinds of parthood relations among dispositions, including the relations **mod-part_of** and **add-part_of**. For example, the disposition to attract another magnet when facing an unlike pole and the disposition to repulse the very same magnet when facing a like pole are mod-parts of a magnet’s ferromagnetic disposition. And the disposition to dissolve of the left half of a tablet and the disposition to dissolve of the right half of this tablet are add-parts of the whole tablet’s disposition to dissolve.

Several axioms are satisfied by those kinds of disposition-parthood [18]:

- The bearer of a disposition-part (whether mod-part or add-part) is a part of the bearer of the disposition-whole.
- A mod-complex (that is, a disposition that has a proper mod-part) is triggered by a process if and only if at least one of its proper mod-parts is triggered by this process; and it is realized in a process if and only if at least one of its proper mod-parts is realized in this process.
- If an add-complex (that is, a disposition that has a proper add-part) is triggered by a process, then all its add-parts are triggered by a part of this process; and if it is realized in a process, then all its add-parts are realized in a part of this process.

To formalize affordances, we need now to expand our theory of dispositions by introducing the notion of *reciprocal disposition*.

2.3. Reciprocal dispositions

2.3.1. What are reciprocal dispositions?

Reciprocal dispositions have been discussed in philosophy [22] and in formal ontology, under labels such as “complementary disposition” [8] or “reciprocal dependence” among dispositions [13]. Classical examples include a key and a lock such that the former opens the latter: **key₁** has the disposition **d₁** to open **lock₂**, and **lock₂** has the disposition **d₂** to be opened by **key₁**. Those two dispositions have something in common: they are triggered by the same class of process, namely *key₁ pivoting in lock₂*, and they are realized by the same class of realization, namely *lock₂ opening by key₁*.

We will say that **d₁** and **d₂** are reciprocal dispositions and write: “**d₁** **has_reciprocal_disposition** **d₂**”, where **has_reciprocal_disposition** is a symmetrical relation. This relation is anti-reflexive: a disposition is not reciprocal of itself. Similarly, **d₂** is not a reciprocal disposition from the disposition of **door₀**, which is closed by **lock₂**, to be opened by **key₁** (both dispositions are closely related, but their relation is not what we mean by “reciprocal”). Therefore, we endorse the axiom stating that the bearers of two reciprocal dispositions do not have any common part:

$$\begin{aligned}
 &(\text{BEARER}) \mathbf{b} \text{ bearer_of } \mathbf{d} \wedge \mathbf{b}' \text{ bearer_of } \mathbf{d}' \wedge \\
 &\mathbf{d} \text{ reciprocal_disposition_of } \mathbf{d}' \Rightarrow \neg \exists \mathbf{b}'' [(\mathbf{b}'' \text{ part_of } \mathbf{b}) \wedge \\
 &(\mathbf{b}'' \text{ part_of } \mathbf{b}')]
 \end{aligned}$$

2.3.2. Reciprocal dispositions and their complex disposition

We can introduce the mereological sum of **key**₁ and **lock**₂ noted **key**₁+**lock**₂, assuming throughout this paper the standard, classical extensional mereology [23]. This sum is the bearer of another further disposition, namely the disposition **d**₃ of this system that is also triggered by *key*₁ *pivoting in* *lock*₂ and realized by *lock*₂ *opening by* *key*₁. As will be justified below, we will say that **d**₃ is the ‘causally equivalent sum’ of the two reciprocal dispositions **d**₁ and **d**₂, and we will write it using the ternary relation “is_causally_equivalent_sum(**d**₃,**d**₁,**d**₂)”. Introducing the ternary mereological sum relation **is_sum_of** between material objects (such that **is_sum_of**(**b**₃,**b**₁,**b**₂) means that **b**₃ is the mereological sum of **b**₁ and **b**₂), the following axioms are being satisfied:

$$\begin{aligned}
 &(\text{TRIG}) \text{ is_causally_equivalent_sum}(\mathbf{d}_3, \mathbf{d}_1, \mathbf{d}_2) \Rightarrow (\forall \text{tr}, \mathbf{d}_1 \text{ has_trigger tr} \Leftrightarrow \mathbf{d}_2 \\
 &\text{has_trigger tr} \Leftrightarrow \mathbf{d}_3 \text{ has_trigger tr}) \\
 &(\text{REAL}) \text{ is_causally_equivalent_sum}(\mathbf{d}_3, \mathbf{d}_1, \mathbf{d}_2) \Rightarrow (\forall \text{r}, \mathbf{d}_1 \text{ has_realization r} \Leftrightarrow \\
 &\mathbf{d}_2 \text{ has_realization r} \Leftrightarrow \mathbf{d}_3 \text{ has_realization r}) \\
 &(\text{BEARER-SUM}) \text{ is_causally_equivalent_sum}(\mathbf{d}_3, \mathbf{d}_1, \mathbf{d}_2) \Rightarrow \\
 &[\mathbf{d}_1 \text{ has_bearer } \mathbf{b}_1 \wedge \mathbf{d}_2 \text{ has_bearer } \mathbf{b}_2 \wedge \mathbf{d}_3 \text{ has_bearer } \mathbf{b}_3 \\
 &\Rightarrow \text{is_sum_of}(\mathbf{b}_3, \mathbf{b}_1, \mathbf{b}_2)]
 \end{aligned}$$

Barton et al.’s [18] theory of mereology among dispositions can help us formalize the connection between those three dispositions, namely:

d₁ add-part_of **d**₃

d₂ add-part_of **d**₃

As a matter of fact, they satisfy the axioms characterizing an add-part:

- The bearers of **d**₁ and **d**₂ are parts of the bearer of **d**₃.
- If **d**₃ is realized in a process, then both **d**₁ and **d**₂ are realized in a part of this process (namely, this very process).
- If **d**₃ is triggered, then both **d**₁ and **d**₂ are triggered by a part of this process (namely, this very process).

More specifically, we could call this relation between **d**₁ and **d**₃ or **d**₂ and **d**₃ a “causally equivalent add-part”: those add-parts **d**₁ and **d**₂ and their add-sum **d**₃ have the same triggers and realizations, and therefore, we can informally say that they play the same causal role; but they have different bearers (the bearers of the add-parts being a part of the bearer of the add-sum). They also have different categorical bases: the categorical basis of **d**₁ (named “**q**₁”) is formed by **key**₁’s qualities that make it fit with **lock**₂; the categorical basis of **d**₂ (named “**q**₂”) is formed by **lock**₂’s qualities that make it fit with the structure of **key**₁; and the categorical basis of **d**₃ (named “**q**₃”) is the mereological sum of **q**₁ and **q**₂. Barton et al. [19] identified a criterion of identity among dispositions stating that for all practical purposes, two dispositions are identical iff they have the same categorical basis, as well as the same classes of triggers and realizations. Following this criterion, **d**₁, **d**₂ and **d**₃ are different, as they do not have the same categorical bases.

2.3.3. External-particular-dependence

What matters for the existence of **d**₁ (respectively **d**₂) is not only the existence of its categorical basis **q**₁ (respectively **q**₂) that inheres in their bearer **key**₁ (respectively **lock**₂),

but also some external qualities. As a matter of fact, \mathbf{d}_1 also depends existentially on the qualities \mathbf{q}_2 , and \mathbf{d}_2 also depends existentially on the qualities \mathbf{q}_1 . Such qualities are called the “external basis” [15] of the disposition: that is, a quality (or sum of qualities) that does not inhere in the bearer of the disposition, but whose existence is required for the existence of the disposition. Thus, \mathbf{q}_2 is an external basis of \mathbf{d}_1 , and \mathbf{q}_1 is an external basis of \mathbf{d}_2 .

This implies that \mathbf{d}_1 and \mathbf{d}_2 can be subject to so-called “Cambridge change” [24]: if \mathbf{key}_1 (resp. \mathbf{lock}_2) disappears, then \mathbf{d}_2 (resp. \mathbf{d}_1) disappears, although \mathbf{key}_1 is external to \mathbf{d}_2 (resp. \mathbf{lock}_2 is external to \mathbf{d}_1). On the other hand, \mathbf{d}_3 has no external basis, and is not subject to Cambridge change. For this reason, one may doubt whether \mathbf{d}_1 and \mathbf{d}_2 are *bona fide* existing entities, and suggest that only \mathbf{d}_3 exists – but as we are going to see with the example of affordances and effectivities, there are good reasons to maintain the existence of \mathbf{d}_1 and \mathbf{d}_2 . Because \mathbf{d}_1 and \mathbf{d}_2 depend existentially on a particular which has no common part with their bearer, we will say that they are “external-particular-dependent”. The theory of reciprocal dispositions can now be used to formalize affordances.

3. Affordances as reciprocal dispositions and their formal characterization

3.1. Background and general idea

The term “affordance” was coined by Gibson [1] to pin down precisely the interaction between animals and the environment: “The *affordances* of the environment are what it *offers* the animal, what it *provides* or *furnishes*, either for good or ill” [1, p.119]. For instance, a gap affords hiding when it is of a certain size relative to the size of a person and a stair affords climbing when it is a certain proportion of a person’s leg length.

A dispositional view of affordance was initially proposed by Turvey [5], which is motivated by an understanding of animal activity in terms of prospective control (PC): “control concerned with future events, usually interpretable as goals to be realized” [5, p.174].⁴ To walk across a cluttered room, for instance, an agent needs to know what (bodily movement) is possible. The ecological approach to PC thus requires that affordances be closely linked with agents’ behaviors enabled by the environment with respect to which PC is conducted.

The crux of Turvey’s argument is that: “An affordance is a particular kind of disposition, one whose complement is a dispositional property of an organism” [p.179]. He also calls the complement of an affordance “effectivity”. For instance, the affordance of the stairs is their disposition to move an organism upward and its complement is the disposition (effectivity) of an organism to move upward. In what follows we elaborate a substantially refined version of this idea of affordance and its formalization, based on the theory of dispositions that was delineated in the last section. In particular, we aim to deploy, for space reasons, a core formal framework for representing affordances (and effectivities), rather than a full axiomatization of them.

The first thing to point out is that Turvey’s usage of the terms “disposition” and “dispositional property” is obscure in light of our distinction between dispositions and causal powers. He assumes “property realism” [Section 3] which would mesh better with the grounding of the disposition concept in an ontology of causal powers; but, he also

⁴ For simplicity we will henceforth refer only to page or section numbers in citing Turvey [5] unless otherwise specified.

argues for “law-based perspective on real possibility” [Section 4] which would favor no ontological commitment to causal powers because it can be read as a fundamental commitment to laws of nature, among the concepts of natural necessity. The latter interpretation serves our purpose of building a general model of affordance, which is acceptable independently of any commitment concerning the existence of causal powers.

3.2. *Affordance and effectivity*

Given Turvey’s key idea that “An affordance is a particular kind of disposition, one whose complement is a dispositional property of an organism” [p.179], we introduce *Affordance* as a subclass of *Disposition*. Most importantly, Turvey’s notion of “complement” remains unspecified. He says: “Given that a dispositional property is not defined (i.e., it is a nonexistent property) when there is no complement, then an affordance is not defined (i.e., is nonexistent) without a complementing animal property and, in like fashion, an effectivity is not defined (i.e., is nonexistent) without a complementing environment property” [pp.179-180]. It requires further elucidation for our goal to characterize precisely in which sense those two dispositions depend existentially on each other.

We formalize it by introducing another subclass of *Disposition* named *Effectivity*, and stating that any effectivity has an affordance as reciprocal disposition:

Effectivity SubClassOf [*Disposition* and (**reciprocal_disposition_of** some *Affordance*)]

A reciprocal axiom, not mentioned by Turvey, must be added, namely that the existence of an affordance implies the existence of an effectivity that is its reciprocal disposition:

Affordance SubClassOf [*Disposition* and (**reciprocal_disposition_of** some *Effectivity*)]

For example, **afford** might be the affordance of **stairs₀** enabling **Mary** to climb it, and **effect** might be the effectivity of **Mary** enabling her to climb **stairs₀**.

3.3. *Affordance/effectivity complex*

Turvey [Section 7] proposes the following formal account of affordances and effectivities (the name of instances are ours). Let **agent** be a particular agent, **env** a particular environmental entity, **effect** a property of **agent** and **afford** a property of **env**. He considers the junction **junction** of **agent** with disposition **effect** and **env** with disposition **afford**. Then, he argues that **afford** is an affordance of **env**, and **effect** is an effectivity of **env** that is the complement of **afford**, if and only if there is a third property **afford/effect** that is possessed by **junction**, and such that **junction** possesses neither **afford** nor **effect**, and such that neither **env** nor **agent** possesses **afford/effect**.

Taking a simpler view on this, our account introduces the mereological sum **agent+env** to play the same role as **junction** in Turvey’s theory. It then states that if **afford** is an affordance and **effect** is the corresponding effectivity, then **afford** and **effect** are reciprocal dispositions; therefore, there exists a causally equivalent sum **afford/effect**. This leads to a proposal slightly simpler than Turvey’s, as it interprets the junction simply

as a mereological sum, but retains its important features: following our theory of reciprocal dispositions, **afford/effect** inheres in **agent+env**, neither **afford** nor **effect** does inhere in **agent+env**, and neither **agent** nor **env** is the bearer of **afford/effect**. We introduce a class *Affordance/effectivity complex* such that **afford/effect** is an instance of this class.

Turvey also states that “an effectivity, as the term suggests, is the causal propensity for an animal to effect or bring about a particular action, to manifest what is needed for [the junction of its effectivity and the environment’s affordance] to be realized” [p.179]. This is accounted for in our theory by the axiom (REAL), which implies that an affordance is realized by a process iff the corresponding effectivity is realized by the same process (and iff the corresponding affordance/effectivity complex is realized by the same process). For example, the class of **Mary** climbing up **stairs₀** (let us call it *Mary climbing stairs₀*) is a realization of the corresponding affordance, effectivity and affordance/effectivity complex.

Similarly, by application of (TRIG), any trigger of an affordance, its associated effectivity or its associated affordance/effectivity complex is a trigger of the two others. For example, the class of **Mary** positioning her feet on **stairs₀**’s surface and contracting her muscles in the adequate way (let us call it a climbing effort by **Mary** on **stairs₀**, or *Mary’s stairs-climbing situation on stairs₀*) is a trigger of the corresponding affordance, effectivity and affordance/effectivity complex (see Figure 1 below).

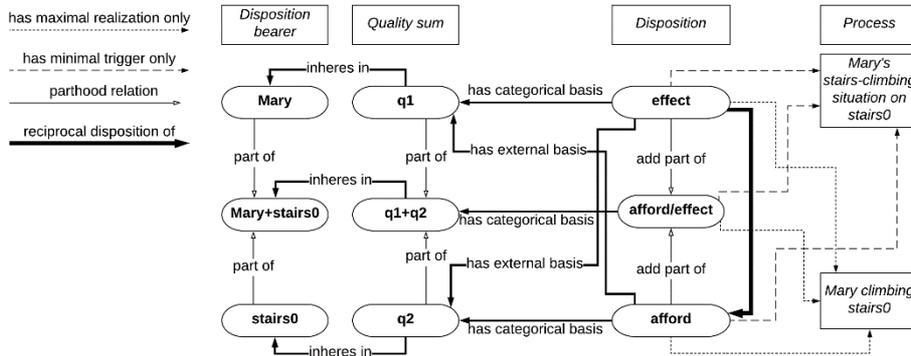


Fig. 1: Affordance, effectivity and affordance/effectivity complex

To illustrate further, consider another example, namely the affordance of **gap₀** enabling **John** to hide (that is, not to be seen from some positions). This affordance is a disposition of **gap₀** that can be triggered by **John** being into **gap₀**, and realized by **John** not being seen from those positions; and its reciprocal effectivity is a disposition borne by **John** that can be triggered and realized by the same respective processes.

4. Discussion

4.1. Extending our approach to other perspectives on affordance

Our proposal is deeply rooted in Turvey’s dispositional account of affordance, which has been nonetheless subject to criticism. According to Şahin et al. [25], for instance, there

are three different perspectives from which to view the affordance notion: the *agent perspective*, the *environmental perspective*, and the *observer perspective*. Turvey's theory captures, as they say, only the second because it regards affordances to be those properties of objects in the environment which are perceivable by the agents. We indicate only briefly, owing to spatial limitations, how the other two perspectives on affordance could be formalized within the present dispositional framework.

4.1.1. *Agent perspective*

The agent perspective takes affordances to residing within the agent interacting in the environment through his own behaviors. For instance, Stoffregen [26] argues that affordances are properties of the animal-environment system: they are *emergent properties* that do not inhere in the environment, nor in the animal. In a similar vein, Chemero [27] proposes that affordances be relational properties: relations between the abilities of animals and features of the environment.

We contend that the agent perspective on affordance would be interpretable in terms of the affordance/effectivity complex inhering in the agent-object(s) mereological sum, which grounds the affordance disposition(s) of the object(s) and the effectivity disposition of the agent. Although we formalize affordance as inhering in the environment, and effectivity as inhering in the agent, those dispositions have an external basis – and this form of existential dependence is in line with Stoffregen's and Chemero's above-mentioned positions.

4.1.2. *Observer perspective*

The observer perspective on affordance is “used when the interaction of an agent with the environment is observed by a third party” and “one must also have the capability of taking the observer perspective when perceiving affordances, at least for the agents of the same species as the observer” [25, p.14]. We would prefer to hold that this view pertains to *epistemology* of affordance rather than ontology of affordance. It is nonetheless a noteworthy inquiry to take a dispositional look at the observer aspect partly because of its relevance to the application of the affordance concept, e.g., to robotics [25], partly because of the prior work [28] on the extension of an ontology of observation to Turvey's environmental conception of affordance.

One of the most natural extensions of our dispositional approach to the observer perspective would be arguably to think of the observer conception of affordance (which consists in “the capability of taking the observer perspective”) as the disposition of the agent-object(s)-*observer* system (i.e. the system whose components are an agent, some object(s), and *an observer*) composed by the affordance disposition(s) of the object(s), the effectivity disposition of the agent, and *the observation capability disposition of an observer*. A formal representation of this disposition could be built out within our ontological framework previously given.

Quite importantly, this model assumes that a capability is a subtype of a disposition. We find this premise plausible, although it is difficult to define explicitly a capability (see e.g., [29] for a recent attempt). For one thing, there is an intuitive close connection between a capability and a disposition. For another, a dispositional account of capability has been employed in an ontological analysis of capability-related concepts in the enterprise architecture framework for the defense domain [30].

4.2. Further issues concerning the formalization

Our formalization raises a few issues that could be discussed in future works. First, our ontology introduces the mereological sum **agent+env** as the bearer of the affordance/effectivity complex, but refrains from speaking of the ‘system’ composed by **agent** and **env**. As a matter of fact, it is not straightforward to ontologize the notion of system (see e.g., [31] for some thoughts), and we leave it open here whether the system composed by **agent** and **env** reduces or not to the mereological sum of both.

Second, the notion of causally equivalent sum of two reciprocal dispositions can be compared to the notion of *collective disposition*, which is defined within the BFO framework as follows: “A disposition inhering in an object aggregate *OA* [the BFO category] in virtue of the individual dispositions of the constituents of *OA* and that does not itself inhere in any part of *OA* or in any larger aggregate in which *OA* is a part” [8, p.410]. A crowd has the collective disposition to do the wave in virtue of each individual crowd member’s disposition to stand at the appropriate time, for example [8, p.409]. However, the relation between an affordance and an effectivity on one side, and an affordance/effectivity complex on the other side, is importantly different from the relation between the individual dispositions to stand up and the disposition of the crowd to do the wave. In the latter case, the dispositions of each individual crowd’s member to stand exists independently of each other. On the opposite, if **afford** and **effect** are two reciprocal dispositions, **afford** exists only as long as **effect** exists, and vice-versa. Moreover, the **afford/effect** complex seems to be ontologically prior to the dispositions **afford** and **effect**; whereas the individual dispositions to stand up at the right time seem to be ontologically prior to the disposition of the crowd to do the wave.

Third, note that two reciprocal dispositions **d₁** and **d₂**, as well as their causally equivalent sum **d₃**, have the same mereological sum of categorical basis and external basis, namely **q₁+q₂**. One could wonder whether this (in conjunction with them having the same class of triggers and the same class of realizations) would imply that **d₁**, **d₂** and **d₃** are, after all, identical – updating the identity criteria among dispositions suggested by Barton et al. [19]. However, the example of affordance and dispositions shows that there are good reasons to consider them as different.

Fourth, we have seen that two reciprocal dispositions **d₁** and **d₂** are external-particular-dependent. However, we can introduce related dispositions that are not so. For this, let us consider *Q₁* the universal of qualities that characterize a key that can open a lock similar to **lock₂**, and *Q₂* the universal of qualities that characterize a lock that can be opened by a key similar to **key₁**, such that **q₁ instance_of Q₁** and **q₂ instance_of Q₂**. Let us consider *Key₁* the class of keys which have a quality instance of *Q₁* (thus, **key₁ instance_of Key₁**) and *Lock₂* the class of locks that have a quality instance of *Q₂* (thus, **lock₂ instance_of Lock₂**). Then, we can introduce additional related dispositions:

- the disposition **d₁’** of **key₁** to open locks instances of *Lock₂*
- the disposition **d₂’** of **lock₂** to be opened by keys instances of *Key₁*

Although they are similar to some extent, **d₁** and **d₁’** are not identical: contrarily to **d₁**, **d₁’** does not depend existentially on **lock₂**. Similarly, **d₂** and **d₂’** are not identical: contrarily to **d₂**, **d₂’** does not depend existentially on **key₁**. That is, neither **d₁’** nor **d₂’** has any external basis: they are not external-particular-dependent.

This strategy can be adapted to affordances and effectivities, since we have defined them as reciprocal dispositions. On top of defining the affordance provided by **stairs₀** to **Mary** to climb it, we could define the affordance provided by **stairs₀** to the general class

and how individual-directed affordances could be complemented by family-directed affordances. This work constitutes the initial step towards the formalization of an ontological module for generic affordance representation.

In the future we will be able to proceed along at least three major lines of research. First, our logical specification of affordance will be richer as our formal understanding of disposition becomes deeper. In particular, a rigorous formalization of the relationship between dispositions and modality [33, 34, 35, 36] would help to harmonize our proposal with a widespread, modal logical approach to agency and cognition (e.g., [37]). This would also contribute to further investigation of implicit ontological assumptions embedded in logical representation languages in general [38, 39].

Second, the interrelationship between agents and the environment would be incompletely accounted for unless we take into consideration not only the capability of the environment to act on agents but also agents' abilities to interact with the environment, the former and the latter being respectively captured foundationally by the theories of affordance and *image schema* [37, Section 2]. Image schemas are, roughly, schematic prelinguistic patterns of cognition that are learnt during infancy: for example, repetitive visual experiences of plates placed on tables form the image schema of "support". Our approach should be thus supplemented by a dispositional interpretation of image schema for a long-term goal to furnish a full-fledged dispositional ontology of agency, cognition, perception, and action. For instance, Galton's [40] view of image schemas as "the affordances of actual exemplars of those schemas" would serve as a useful starting point for our future discussion.

Third and relatedly, a strong correlation between affordance and learning/creativity is well worth pursuing. It has been traditionally worried (as in [41]) that Gibson's original version of affordance may be too deeply rooted in an ecological perspective on perception to be well-suited for considering people's learning and creation of contemporary technologies such as computers. Accordingly, there is a growing demand for a more nuanced notion of affordance in a number of different domains, including communication technology [42, 43]. Building upon Turvey's conception of affordances as reciprocal dispositions of agents' effectivities (the latter of which tend to be dismissed in the relevant literature) in a particular situation, our formal-ontological theory of affordance would be explanatory enough to model perspicuously the dynamics involved in a complex interaction between humans and modern artifacts. It would also enhance an affordance-based approach to creativity because its flexibility can accommodate people's (especially children's) exploratory behaviors to discover "non-canonical" affordances [44, 45], thereby demonstrating the potential to develop mechanical systems (e.g., softwares) guiding humans into cognitively enhanced and imaginative acts [46].

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