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Contributions to the formal ontology of functions and dispositions: an application of non-monotonic reasoning

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ABSTRACT

We introduce a basic ontology of functions and dispositions. The theory we suggest is compatible both with major philosophical theories of biological functions and with most top-level ontologies. The particular focus of the suggested formalism is on the inference of causal relationships from functionality and the explicit formalization of the normative character of functions using non-monotonic forms of knowledge representation.

1 INTRODUCTION

The question of functions in biology is a major topic in the philosophy of biology and continues to be of importance to biological science as well. Identifying the functions of proteins, DNA or RNA fragments, as well as the ontogenesis of their functions throughout evolution, remains an important subject of investigation. Inquiries into the nature of functions can reveal methods for determining the functions of specific entities, for distinguishing multiple functions of one entity, or may provide frameworks for describing the evolution of functions over time.

While scientific discussions are dominated by scientific and epistemic questions regarding *function*, it is nevertheless important to consider the ontology of *function*: what is a biological function? Answering this question is important to understand the implications of scientific findings regarding *function*. It is also a necessary step to achieve or increase interoperability between established and new ontologies that include the concept of *function*.

Theories pertaining to the ontology of *function* range from reductions to causality [Wright, 1973] to explanations based on social ascription [Searle, 1997]. In the context of formal ontology, *function* is represented in several top-level ontologies, such as BFO [Arp and Smith, 2008] and GFO [Herre et al., 2006]. We provide here an extension of the ontology of functions [Burek et al., 2006] which is compatible with several top-level ontologies. We investigate the difference between dispositions and functions and propose a means to interrelate both kinds of entities using methods from artificial intelligence research, in particular non-monotonic reasoning.

2 BACKGROUND

Several ontological theories for biological functions have been proposed. The main distinction is between theories that reduce *function* to causality (the etiological view), and theories that emphasize a social ascription of *function*. The main proponents of the first view are Wright [1973] and Millikan [1988], while the second view is advocated by Searle [1997]. We discuss these views before prodiving our own formal account of *function*, which interrelates these.

2.1 Etiological explanations of function

The major proponent of an etiological view of *function* in biology is Wright [1973]. The basic definition Wright gave for function is:

DEFINITION 1. *The function of X is Z means*

1. *X is there because it does Z,*
2. *Z is a consequence (or result) of X's being there.*

For examples, "the function of the heart is to pump blood" means that (1) the heart is present (now) *because* it pumps blood (and pumped blood in the past), and (2) that the pumping of blood is a consequence of the presence of the heart. The first part of this definition explains why hearts are present now (because they pump blood, and pumped blood in the past). The second part explains the causal relation between hearts and the pumping of blood (hearts cause blood to be pumped, in the right circumstances). This definition allows the answer of two questions: *why* hearts exist, and *why* blood is being pumped. Wright emphasizes this explanatory power of statements like "*X* has the function to *Z*".

A formal analysis of this definitions requires at least a **causes** relation. Wright does not provide an analysis of causality. Likewise, we will assume such a relation throughout this paper without thorough analysis.

Wright does not distinguish between the category *Heart*, and the instances of this category. Furthermore, in the definition of function, "doing Z" can refer to either a category (of processes of the kind *Z*) or instances. Therefore, several possibilities for interpretation arise out of this definition of *function*. The first version assumes that the definition refers to instances. In particular, function bearers (*X*) refer to individual objects, and their activities (*Z*) refer to individual processes.

However, the instance-reading of Wright's definition does not lead very far. In particular, entities can have a function without it ever being realized, which is not possible if Wright is read as refering to instances. It is therefore necessary to extend the definition to a category-reading. One option would be to assume that whenever instances of the category *X* have the function *to Z* (*Z* being a category of processes), the following holds: (1) One reason (*cause*) for the existence of the instance of *X* is that other instances

of *X* have caused instances of *Z in the past*; and (2) the instance of *X* has the capability to cause instances of *Z*.

A more precise formulation of *function* which is similar to the approach taken by Wright is that put forward by Millikan [1988]. Millikan's definition is a biological one, borrowing many terms from the theory of evolution. The definition of a *proper function* is as follows:

DEFINITION 2. *Where m is a member of a reproductively established family R and R has the reproductively established or Normal character C, m has the function F as a direct proper function iff:*

1. *Certain ancestors of m performed F.*
2. *In part because there existed a direct causal connection between having the character C and performance of the function F in the case of these ancestors of m, C correlated positively with F over a certain set of items S which included these ancestors and other things not having C.*
3. *One among the legitimate explanations that can be given of the fact that m exists makes reference to the fact that C correlated positively with F over S, either directly causing reproduction of m or explaining why R was proliferated and hence why m exists.*

This restricts and refines the definition of Wright in an important way. First, several counter-examples to Wright's definition are excluded (e.g., [Boorse, 1976, Smith, 1993]). But more importantly, Millikan provides an analysis in terms of categories and instances (labeled classes and their members), and goes as far as restricting the kind of categories to which function-bearing entities must belong (categories that are established through acts of reproduction). For the remainder of this paper, it is important to note that Millikan uses the notion of *normality* in two places of her definition: explicitly as *Normal character*, and implicitly in the definition of *reproductively established family* (which is defined using *Normal explanation*s in [Millikan, 1988]).

2.2 Social ascription of function

In contrast to causal explanations of function, Searle defends an inherently social view of biological functions [Searle, 1997]. Searle describes an account of functions that differs fundamentally from the account given by Wright or Millikan. Accordings to Searle, functions are never intrinsic of any entity, but are ascribed to entities by a conscious observer. Functions are therefore always *observer-relative*. Underlying the function of the heart ("to pump blood") is the fact about a causal process in which the heart plays a specific role (the *brute fact*). This process is then situated against a system of values, intentions and beliefs of an observer, and through this it is assigned a function. While there are many causal processes the heart is involved in (e.g., creating thumping noises, producing heat), assignment of function selects one or some of these causal processes and situates them against a system of background values and intentions: pumping of blood contributes to survival, and survival of an organism is *good* with respect to the values held by the observer; pumping of blood *explains* the development and presence of the heart best with respect to current scientific knowledge and theories. While causal facts are observer-independent (*brute*), functional facts are always dependent on an observer.

It must be emphasized that this does not imply that function ascription is not based on a causal component or has causal implications. Social ascriptions are not arbitrarily made, especially in a field like biology, where functions play a central role in scientific theories and have specific meanings. They are used in causal explanations and a statement about functions conveys information about physical, observer-independent phenomena. We believe this property to be of paramount importance for any ontological theory of functions: sentences about functions convey information about causal relations.

A further analysis of functionality is due to Hartmann [1966], who analyzes three requirements for some entity to obtain the function F with the goal T_{goal} (illustrated in figure 1). First, an agent establishs a goal T_{goal} which lies in the future. This first step requires free movement in "mental time" (*Anschauungszeit*), because it establishs a *future* goal. Setting this goal belongs to the mental stratum of reality [Gnoli and Poli, 2004], where free movement in time is possible. In particular, this step cannot be performed in material reality alone. This establishment of the goal by a mind is also the source of the intensionality[1] and referential opacity[2] of statements pertaining to functions [Searle, 1997].

Second, the agent generates a plan on how to achieve the goal. For this purpose, the agent goes backward in *Anschauungszeit* starting at the time of the goal and ending at an earlier time. This planning or design process is directed backward in time. It is this "going backward in time" from the goal to the present which determines a process – the realization of the function, once it is established – from its end, and therefore making them teleologic in nature. The result of the second step, if successful, is the establishment of a structure or situation that is able to **cause** the goal established in the first step.

Third, the final component is the causal process which starts at the present and ends with the achievement of the goal (i.e., reaching a situation which instantiates T_{goal}).

There are at least two possibilities how the first two conditions can lead to an entity's becoming functional: an agent creates an object to bring about a change from the situation types T_{req} to T_{goal}, or an agent selects an object to bring such a change about. In the first case, an entity has the function F because it was created to bring about this change. In the second case, an entity has the function F because it is (currently) intended to achieve T_{goal} from T_{req}. Understanding function in the first sense does not permit an entity's losing its function, while in the second case an entity can lose and acquire functions over time.

The second condition explains why an object that has a function F with a goal T_{goal} has a specific structure: it must be able to cause the goal, and its structure may be a result of the planning process with the aim to cause the goal established as the first condition.

We extend the Ontology of Functions (OF) [Burek et al., 2006] and add several axioms to the OF that relate functions to facts involving causality. We do not, however, propose a full

[1] Intensionality is the opposite of extensionality.

[2] A term t is referentially opaque in a statement C, if t cannot be replaced with a co-referential term s in C without changing the truth-value of C [Quine, 1964].

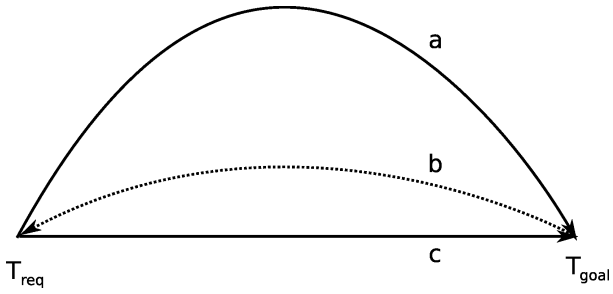

Fig. 1: Three conditions for function ascription. First (a), a goal is established *in the future*. Second (b), the means for achieving the goal are selected or created. Finally (c), the goal is realized by causal means.

axiomatization or definition of *function*, but rather what we believe to be necessary conditions that any ontological account of *function* must satisfy. The theory of function presented here can be extended by a more specific theory if desired.

3 A FORMAL ONTOLOGY OF FUNCTIONS

Functional knowledge can be represented and described independently of the realization of function in the Ontology of Functions (OF) [Burek et al., 2006]. A function structure is described by a label, requirements, a goal and a functional item. The label is a non-formal name or description of the function. The requirement is a situation type T_{req} that must be realized for every realization of the function. The goal is a situation type T_{goal} that describes the state of the world that the function is supposed cause or otherwise bring about. The functional item is a *view* on the entities that can have the functions, selecting all features of the entity that are essential to the function realization.

Both T_{req} and T_{goal} are *situation types* (categories that have situations as their instances). Situations are a "part of the world that can be comprehended as a whole" [Devlin, 1991]. We use the notion of situation types for an understanding of *goals* and *requirements*. In ontological frameworks that do not employ situations, they can be understood as complex states of affairs (in DOLCE) or *n*-ary properties (in BFO).

We model the requirements and the goal of the function as situation types and their realizations (instances) as situations. We consider functions as a special kind of properties. This entails that functions are individuals that inhere in their bearers, and it becomes important to distinguish between an individual function and a function category.

The theories on function differ in how the function's goal is established. For example, following Searle, functions are always observer-dependent: they come into being through a relation between an object and a concious observer [Searle, 1997]. However, there are causal facts that should be exhibited before a function is ascribed to some entity by an agent. That which all the discussed theories of functionality have in common is that the function bearer must *normally* be able to **cause** the goal of the function given the requirements of the function.

If an entity is unable to **cause** a process that ends in the goal of the function, we call the entity *malfunctioning*. When an entity is malfunctioning, the conditions that lead to the entities' obtaining the function (whether through reproduction, evolution or social ascription) remain valid, yet it lacks the *causal powers* to realize the function.

To formalize these observations, we use an additional entity in the ontology of functions. We call this a *disposition*. An individual e has the disposition d to cause T_{goal} iff e **causes** a situation $s :: T_{goal}$ to become realized whenever e is placed *in the right circumstances*. We formalize "being placed in the right circumstances" using a situational role[3] [Loebe, 2007] and an additional universal. This universal identifies the structural features of the entity with the disposition that are necessary to realize the disposition.

The terminology to describe a disposition category D is:

- $T_{req}(D)$ is the requirement situation type of D,
- $T_{goal}(D)$ is the goal situation type of D,
- $R(D)$ is a situation role and
- $U(D)$ is a category of material objects (e.g., a category with material objects as instances).

Using dispositions, we can define malfunctioning: an entity e is malfunctioning, $mf(e)$, if it has a function $f :: F$ but does not have the disposition to cause $T_{goal}(F)$, i.e., is unable to realize the function.

A relation must be established between functions and dispositions, so that assertions about functions permit inferences about causal relations. We consider two possibilities to create such a relation. The first is to require that functions are subclasses of dispositions, and the requirement and goal of the function are the requirement and goal of the disposition. Then, every function $f :: F$ with goal $T_{goal}(F)$ and requirement $T_{req}(F)$ is a disposition with goal $T_{goal}(F)$ and requirement $T_{req}(F)$.

The difficulty with this approach lies in the treatment of malfunctionings. If functions are sub-categories of dispositions, it is not possible to assert that an entity has a function, but is malfunctioning. Instead, it must be denied that a malfunctioning entity has the function if it cannot cause the goal of the function.

Therefore, the second approach we suggest treats functions and dispositions as ontologically different entities, i.e., as disjoint categories, and establishes a relation between them explicitly. We suggest that every entity which has a function $f :: F$ with requirement $T_{req}(F)$ and $T_{goal}(F)$ *normally* has a disposition $d :: D$ with $T_{req}(D) = T_{req}(F)$ and $T_{goal}(D) = T_{goal}(D)$. Formally, we first define the formula $A(mf)$:

$$\begin{aligned} A(mf) = hasFunction(e,f) \wedge f :: F \wedge \neg mf(e) \rightarrow \\ \exists d(d :: D \wedge isa(D, Disposition) \wedge inheresIn(d,e) \wedge \\ T_{req}(F) = T_{req}(D) \wedge T_{goal}(F) = T_{goal}(D)) \end{aligned} \quad (1)$$

The predicate mf is an abnormality predicate. In order to treat $A(mf)$ in formula 1 as a default, the extension of the mf

[3] A situational role is the role that an entity plays in a complex situation. If situations are not permitted in the ontology, they can be considered a complex state of affairs, i.e., a complex of instances of relations. In this view, a situational role is a (complex) relational role.

predicate must be minimized in every model. This is achieved by circumscribing [Mccarthy, 1986] mf in $A(mf)$ using *predicate circumscription*. The circumscription of mf in $A(mf)$ is the second-order formula:

$$A(mf) \wedge \forall P((A(P) \wedge \forall x(P(x) \rightarrow mf(x))) \rightarrow (\forall x(P(x) \leftrightarrow mf(x)))) \quad (2)$$

This circumscription formula first requires that $A(mf)$ holds as an axiom. The second part states that every predicate P, which can replace mf in $A(mf)$ and implies $mf(x)$, is equivalent to $mf(x)$. In other words, mf is smaller than or equivalent to $(mf(x) \leftrightarrow P(x))$ any predicate P which satisfies all the conditions that mf satisfies.

Alternatively, a formula in default logic [Reiter, 1980] can be chosen to replace axiom 2 (see [Hoehndorf, 2009] for details). However, a non-monotonic form of knowledge representation is necessary to consistently model functions and malfunctionings. The need for nonmonotonic reasoning in representing functioning and malfunctioning was already recognized by Mccarthy [1986].

As a corollary from this axiom, malfunctioning entities continue to have a function but not a corresponding disposition. This axioms permits the inference of causal relationships from assertions about functions. We believe this to be useful particularily in the biological and medical domain, where functionality is commonly used to describe and infer causal relations.

4 DISCUSSION AND CONCLUSION

Closely related to our work is the theory of functions in BFO [Arp and Smith, 2008]. The definition of *function* in BFO is:

DEFINITION 3. *A function f is*

1. *a realizable dependent continuant, which*
2. *has a bearer which is an independent continuant, and*
3. *is of a type instances of which typically have realizations; each realization is (a) a process in which the bearer is a participant, (b) that occurs in virtue of the bearer's physical makeup, (c) this physical make-up is something which that bearer possesses because of how it came into being.*

Biological functions require that they inhere in parts of an organism and that the physical make-up of the function's bearer is a result of the "coordinated expression of that organism's structural genes" [Arp and Smith, 2008]. Because this is a definition, it can also be read in the opposite direction: every realizable dependent continuant satisfying the described conditions is a function. Therefore, in BFO it is a true statement that "the function of the heart is to make thumping noises", because "making thumping noises" satisfies all the conditions for *function*.

Additionally, some conditions appear to be too strong as necessary conditions. For example, many functions are typically *never* realized, such as the function of a sperm, yet the theory in [Arp and Smith, 2008] requires functions to be *typically* realized. Also, that function bearers must be created ready to realize the functions (condition 3c) seems overly strong. Furthermore, a formalization of "typically", used both for defining *function* and *realization* has not been performed in [Arp and Smith, 2008]. We hope that the theory we propose will help to improve other ontological theories on function as well.

The ontological theory of function introduced here is intended to be compatible both with a wide range of philosophical theories on function and with most upper-level ontologies. It permits the inference of causal relations from function ascription, a feature of particular importance in biological ontologies.

REFERENCES

Robert Arp and Barry Smith. Function, role, and disposition in basic formal ontology. In *Proceedings of The 11th Annual Bio-Ontologies Meeting*, 2008.

Christopher Boorse. Wright on functions. *The Philosophical Review*, 85(1):70–86, 1976.

Patryk Burek, Robert Hoehndorf, Frank Loebe, Johann Visagie, Heinrich Herre, and Janet Kelso. A top-level ontology of functions and its application in the Open Biomedical Ontologies. *Bioinformatics*, 22(14), 2006.

Keith Devlin. *Logic and Information*. Cambridge University Press, 1991.

Claudio Gnoli and Roberto Poli. Levels of reality and levels of representation. *Knowledge Organization*, 31(3), 2004.

Nicolai Hartmann. *Teleologisches Denken*. Walter de Gruyter, 1966.

Heinrich Herre et al. General Formal Ontology (GFO) – A foundational ontology integrating objects and processes [Version 1.0]. Onto-med report, Research Group Ontologies in Medicine, Institute of Medical Informatics, Statistics and Epidemiology, University of Leipzig, Leipzig, 2006.

Robert Hoehndorf. *Basic considerations for improving interoperability between ontology-based biological information systems*. PhD thesis, University of Leipzig, 2009. forthcoming: `http://lc2.eu/thesis.pdf`.

Frank Loebe. Abstract vs. social roles - towards a general theoretical account of roles. *Applied Ontology*, 2(2):127–158, 2007.

John Mccarthy. Applications of circumscription to formalizing common sense knowledge. *Artificial Intelligence*, 28(1):89–116, 1986.

Ruth G. Millikan. *Language, Thought, and Other Biological Categories: New Foundations for Realism*. MIT Press, 1988.

Willard V. Quine. *Word and Object*. Studies in Communication. The MIT Press, March 1964.

R. Reiter. A logic for default reasoning. *Artificial Intelligence*, 13 (1-2):81–132, 1980.

John R. Searle. *The Construction of Social Reality*. Free Press, January 1997.

Peter G. Smith. Functions: Consensus without unity. *Pacific Philosophical Quarterly*, 74:196–208, 1993.

Larry Wright. Functions. *Philosophical Review*, 1973.