Contextualizing Concepts

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Abstract

The mathematics of quantum mechanics was developed to cope with problems arising in the description of (1) contextual interactions, and (2) the generation of new states with new properties when particles become entangled. Similar problems arise with concepts. This paper summarizes the rationale for and preliminary results of using a generalization of standard quantum mechanics based on the lattice formalism to describe the contextual manner in which concepts are evoked, used, and combined to generate meaning. Concepts are viewed not as fixed representations but dynamically 're-constructed' entities generated on the fly through interaction between cognitive state and situation or context.

Introduction

Theories of concepts have by and large been *representational theories*. By this we mean that concepts are seen to take the form of fixed mental representations, as opposed to being constructed, or 're-constructed', on the fly through the interaction between the cognitive state and the situation or context.

Representational theories have met with some success. However increasingly, for both theoretical and empirical reasons, they are coming under fire (*e.g.* Riegler, Peschl and von Stein 1999; Rosch 1999). As Rosch puts it, they do not account for the fact that concepts "have a participatory, not an identifying function in situations". That is, they cannot explain the contextual manner in which concepts are evoked and used (see also Gerrig and Murphy 1992; Hampton 1987; Komatsu 1992; Medin and Shoben 1988; Murphy and Medin 1985). This contextuality is the reason why representational theories cannot describe or predict what happens when two or more concepts arise together, or follow one another, as in the creative generation or interpretation of *conjunctions* of concepts.

This paper suggests how formalisms designed to cope with context and conjunction in the microworld may be adapted to the formal description of concepts. In this *contextual theory*, not only does a concept give meaning to a stimulus or situation, but the situation evokes meaning in the concept, and when more than one is active they evoke meaning in each other.

The Problem of Conjunctions

We begin by brief summarizing some influential representational theories of concepts and how they have attempted to deal with conjunctions. According to the *classical theory* of concepts, there exists for each concept a set of defining features that are singly necessary and jointly sufficient (*e.g.* Sutcliffe 1993). Extensive evidence has been provided against this theory (see Komatsu 1992, Smith and Medin 1981 for overviews). Two major alternatives have been put forth. According to the *prototype theory* (Rosch 1975a, 1978, 1983; Rosch and Mervis 1975), concepts are represented by a set of, not *defining,* but *characteristic* features, which are weighted in the definition of the prototype. A new item is categorized as an instance of the concept if it is sufficiently similar to this prototype. According to the *exemplar theory,* (*e.g.* Heit and Barsalou 1996; Medin, Altom, and Murphy 1984; Nosofsky 1988, 1992) a concept is represented by, not defining or characteristic features, but a set of *instances* of it stored in memory. A new item is categorized as an instance of a concept if it is sufficiently similar to one or more of these previous instances.

Representational theories are adequate for predicting experimental results for many dependent variables including typicality ratings, latency of category decision, exemplar generation frequencies, and category naming frequencies. However, they run into problems when it comes to conjunctions. They cannot account for phenomena such as the so-called *guppy effect*, where guppy is *not* rated as a good example of pet, *nor* of fish, but it *is* rated as a good example of pet fish (Osherson and Smith 1981). This is problematic because if (1) activation of pet does not cause activation of guppy, and (2) activation of fish does not cause activation of guppy, how is it that (3) pet fish, which activates both pet AND fish, causes activation of guppy? (In fact, it has been demonstrated experimentally that other conjunctions are better examples of the 'guppy effect' than pet fish (Storms et al. 1998), but since the guppy example is well-known we will continue to use it here as an example.)

Zadeh (1965, 1982) tried, unsuccessfully, to solve the conjunction problem using a *minimum rule model*, where the typicality of an item as a conjunction of two concepts (conjunction typicality) equals the minimum of the typicalities of the two constituents. Storms et al. (2000) showed that a weighted and calibrated version of this model can account for a substantial proportion of the variance in typicality ratings for conjunctions exhibiting the guppy effect, suggesting the effect could be due to the existence of contrast categories. However, another study provided negative evidence for contrast categories (Verbeemen et al. in press).

The *generation* of conjunctions is even more problematic. Conjunction cannot be described with the mathematics of classical physical theories because it only allows one to describe a composite or joint entity by means of the product state space of the state spaces of the two subentities. Thus if X_1 is the state space of the first subentity, and X_2 the state space of the second, the state space of the joint entity is the Cartesian product space $X_1 \times X_2$. So if the first subentity is 'door' and the second is 'bell', one can give a description of the two at once, but they are still two. The classical approach cannot even describe the situation wherein two entities generate a new entity that has all the properties of its subentities, let alone a new entity with certain properties of one subentity and certain of the properties of the other. The problem can be solved *ad hoc* by starting all over again with a new state space each time there appears a state that was not possible given the previous state space. However, in so doing we fail to include exactly those changes of state that involve the generation of novelty. Another possibility would be to make the state space infinitely large to begin with. However, since we hold only a small number of items in mind at any one time, this is not a viable solution to the problem of describing what happens in cognition. These issues are hinted to by Boden (1990), who uses the term *impossibilist creativity* to refer to creative acts that not only *explore* the existing state space but *transform* that state space; in other words, it involves the spontaneous generation of new states with new properties.

Two Modes of Cognitive Processing

Why would representational theories be so successful for modeling some aspects of cognition, and so poor for others? It is widely suggested that there exist two forms of cognition (*e.g.* James 1890; Johnson-Laird 1983; Neisser 1963; Piaget 1926; Sloman 1996). The first is a focused, evaluative, *analytical* mode, conducive to analyzing relationships of cause and effect. The second is an intuitive, generative, *associative* mode that provides access to remote or subtle connections between features that may be *correlated* but not necessarily causally related. We suggest that while representational theories are adequate for describing the analytical mode, their shortcomings are revealed when it comes to describing the associative mode.

A Formalism that Incorporates Context

This story has a precedent. The same two problems—that of conjunctions of entities, and that of contextuality—arose in physics in the last century. Classical physics had done exceedingly well at describing and predicting relationships of *causation*, but it was stumped by the results of experiments that required sophisticated ways of describing relationships of *correlation*. It could not explain what happens when quantum entities interact. According to the dynamical evolution described by the Schrödinger equation, quantum entities spontaneously enter an entangled state that contains new properties the original entities did not have. To describe the birth of new states and new properties it was necessary to develop the formalism of quantum mechanics.

The shortcomings of classical mechanics were also revealed when it came to describing the measurement process. It could describe situations where the effect of the measurement was negligible, but not situations where the measurement intrinsically influenced the evolution of the entity; it could not incorporate the context generated by a measurement directly into the formal description of the quantum entity. This too required the quantum formalism.

First we describe the pure quantum formalism, and then we briefly describe the generalization of it that we apply to the description of concepts.

Pure Quantum Formalism

In quantum mechanics, we choose the set of *actual properties* of a quantum entity that we are interested in. These constitute the *state* of the entity. We also define a *state space*, which delineates, given how the properties can change, the possible states of the entity. A quantum entity is described using not just a state space but also a set of measurement contexts. The algebraic structure of the state space is given by the vector space structure of the complex Hilbert space: states are represented by unit vectors, and measurement contexts by self-adjoint operators. One says a quantum entity is *entangled* if it is a composite of subentities that can only be individuated by a separating measurement. When a measurement is performed on the entangled entity, its state changes probabilistically, and this change of state is called *quantum collapse*.

In pure quantum mechanics, if H_1 is the Hilbert space representing the state space of the first subentity, and H_2 the Hilbert space representing the state space of the second subentity, the state space of the composite is not the Cartesian product, as in classical physics, but the tensor product, *i.e.*, $H_1 \otimes H_2$. The tensor product always generates new states with new properties, specifically the entangled states. Thus it is possible to describe the spontaneous generation of new states with new properties. However, in the pure quantum formalism, a state can only collapse to itself with a probability equal to one; thus it cannot describe situations of intermediate contextuality.

Generalized Quantum Formalism

The standard quantum formalism has been generalized, making it possible to describe changes of state of entities with *any* degree of contextuality, whose structure is not purely classical nor purely quantum, but something in between (Aerts 1993a; Aerts & Durt 1994a, 1994b; Foulis and Randall 1981; Foulis, Piron, and Randall 1983; Jauch 1968; Mackey 1963; Piron 1976, 1989, 1990; Pitowsky 1989; Randall & Foulis 1976, 1978). The generalization discussed here, uses instead of Hilbert space, the lattice formalism. The lattice description of the states and properties of physical entities is referred to as a *state property system*.

The motivation behind these general formalisms was purely mathematical. They describe much more than is needed for quantum mechanics, and in fact, standard quantum mechanics and classical mechanics fall out as special cases (Aerts 1983b). It is slowly being realized that they have relevance to the macroscopic world (*e.g.* Aerts 1991; Aerts et al. 2000), and that they can be used to describe the different context-dependent states in which a concept can exist, and the features of the concept manifested in these various states.

One of the first applications of these generalized formalisms to cognition was modeling the decision making process. Aerts and Aerts (1996) proved that in situations where one moves from a state of indecision to a decided state (or *vice versa*), the probability distribution necessary to describe this change of state is non-Kolmogorovian, and therefore a classical probability model cannot be used. Moreover, they proved that such situations *can* be accurately described using these generalized quantum mathematical formalisms. Their mathematical treatment also applies to the situation where the state of the mind changes from thinking about a concept to an instantiation of that concept, or *vice versa*. Once again, context induces a nondeterministic change of the state of the mind which introduces a non-Kolmogorivian probability on the state space. Thus, a nonclassical (quantum or generalized quantum) formalism is necessary.

Applying Contextual Formalism to Concepts

In our approach, concepts are described using what to a first approximation can be viewed as an entangled states of exemplars, though this is not precisely accurate. For technical reasons (see Gabora 2001), the term *potentiality state* is used instead of entangled state. For a given stimulus, the probability that a potentiality state representing a certain concept will, in a given context, collapse to another state representing another concept is related to the algebraic structure of the total state space, and to how the context is represented in this space. The state space where concepts 'live' is not limited *a priori* to only those dimensions which appear to be most relevant; thus concepts retain in their representation the contexts in which they have, or even could potentially be, evoked or collapsed to. It is this that allows their contextual character to be expressed. The stimulus situation plays the role of the measurement context by determining which state is collapsed upon. Stimuli are categorized as instances of a concept *not* according to how well they match a static prototype or set of typical exemplars, but according to the extent to which categorization involves collapse of that part of the lattice structure associated with the concept. (As a metaphorical explanatory aid, if concepts were apples, and the stimulus a knife, then the qualities of the knife determine not just which apple to slice, but which direction to slice through it: changing the context in which a stimulus situation is embedded can cause a different version of the concept to be elicited.) This approach has something in common with both prototype and exemplar theories. Like exemplar theory, concepts consist of exemplars, but the exemplars are in a sense 'woven together' like a prototype.

We now present three sources of theoretical evidence of the utility of the approach.

A Proof that Bell Inequalities can be Violated by Concepts

The presence of entanglement can be tested for by determining whether correlation experiments on the joint entity violate Bell inequalities (Bell 1964). Using an example involving the concept cat and instances of cats, we proved that Bell inequalities are violated in the relationship between a concept and specific instances of it (Aerts et al. 2000; Gabora 2001). Thus we have evidence that this formalism reflects the underlying structure of concepts.

Application to Pet Fish Problem

The contextual approach has been applied to the Pet Fish Problem (Aerts et al. 2000; Gabora 2001). Conjunctions such as this are dealt with by incorporating context-dependency, as follows: (1) activation of pet still rarely causes activation of guppy, and likewise (2) activation of fish still rarely causes activation of guppy. But now (3) pet fish causes activation of the potentiality states pet *in the context of* pet fish AND fish *in the context of* pet fish. Since for both, the probability of collapsing onto the state guppy is high, it is very likely to be activated. Thus we have a formalism for describing concepts that is not stumped by a situation wherein an entity that is neither a good instance of *A* nor *B* is nevertheless a good instance of *A* AND *B*.

Note that whereas in representational approaches relations between concepts arise through overlapping context-independent distributions, in the present approach, the closeness of one concept to another (expressed as the probability that its potentiality state will collapse to an actualized state of the other) is context-dependent. Thus it is possible for two states to be far apart from each other with respect to a one context (for example 'fish' and 'guppy' in the context of just being asked to name a fish), and close to one another with respect to another context (for example ‘fish’ and ‘guppy’ in the context of both ‘pet’ and being asked to name a ‘fish’). Examples such as this are evidence that the mind handles nondisjunction (as well as negation) in a nonclassical manner (Aerts, Broekaert, and Gabora. 2000).

Describing Impossibilist Creativity

In (Gabora 2001), the contextual approach is used to generate a mathematical description of impossibilist creativity using as an example the invention of the torch. This example involves the spontaneous appearance of a new state (the state of mind that conceives of the torch) with a new property (the property of moving fire).

Empirical Research (in progress)

We are comparing the performance of the contextualized theory of concepts with prototype and examplar theories using previous data sets for typicality ratings, latency of category decision, exemplar generation frequencies, category naming frequencies on everyday natural language concepts, such as ‘trees’, ‘furniture’, or ‘games’. The purpose of these initial investigations is to make sure that the proposed formalism is at least as successful as representational approaches for the simple case of single concepts. Assuming this to be the case, we will concentrate our efforts on conjunctions of concepts, since this is where the current approach is expected to supercede representational theories. We will re-analyze previously collected data for noun-noun conjunctions such as ‘pet fish’, and relative clause conjunctions such as ‘pets that are also fish’ (Storms et al. 1996). A new study is being prepared which will compare the proposed approach with representational approaches at predicting the results of studies using situations that are *highly* contextual. Typicality ratings for conjunctions will be compared with, not just their components, but with other conjunctions that share these components. (Thus, for example, does ‘brainchild’ share features with ‘childbirth’ or ‘brainstorm’? Does ‘brainstorm’ share features with ‘birdbrain’ or ‘sandstorm’?)

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