Toward an Ecological Theory of Concepts

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Abstract

Psychology has had difficulty accounting for the creative, context-sensitive manner in which concepts are used. We believe this stems from the view of concepts as identifiers rather than bridges between mind and world that *participate* in the generation of meaning. This paper summarizes the history and current status of concepts research, and provides a non-technical summary of work toward an ecological approach to concepts. We outline the rationale for applying generalizations of formalisms originally developed for use in quantum mechanics to the modeling of concepts, showing how it is because of the role of context that deep structural similarities exist between the two. A concept is defined not just in terms of exemplary states and their features or properties, but also by the relational structures of these properties, and their susceptibility to change under different contexts. The approach implies a view of mind in which the union of perception and environment drives conceptualization, forging a web of conceptual relations or ‘ecology of mind’.

Keywords: concepts, context, entanglement, exemplar, prototype, quantum structure

Toward an Ecological Theory of Concepts

This paper reviews the history of concepts research over the last thirty years, summarizes outstanding problems in the field, and suggests how these problems can be addressed through an approach to concepts that is ecological in character; that is, an approach that emphasizes how concepts are derived from and function as participatory elements of the life activities in which humans engage. This may seem like a strange move to some, given the emphasis in ecological psychology on percepts rather than concepts (Heft, 2003). However, the distinction between the two is not so great as once thought, and we see much to be gained by making not just action but complex thought (which in turn governs more complex action) amenable to an ecological approach. Not only could this result in a richer, more embodied theory of concepts, it may also result in a richer view of what an 'ecological approach' could mean for psychology. Specifically, we envision that something akin to the food chains and webs of interrelations that one sees in ecologies may potentially come to be as much a part of ecological psychology as situatedness. The insights of Shaw, Rosen, and others about incorporating 'relation' into theories of living agents are potentially applicable to the conceptualizations that emerge through interactions between mind and world, as well as the 'life' of concepts interacting with one another within the mind.

Concepts are generally thought to be what enable us to interpret situations in terms of previous situations that we judge as similar to the present. They can be concrete, like CHAIR, or abstract, like BEAUTY. Traditionally they have been viewed as internal structures that *represent* a class of entities in the world. However, increasingly they are thought to have *no* fixed representational structure, their structure being dynamically influenced by the contexts in which they arise (Riegler, Peschl & von Stein, 1999). This is evidenced by their flexibility to change their structure in an infinite variety of ways, given the infinite number of context that can affect them. For example, the concept BABY can be applied to a real human baby, a doll made of plastic, or a small stick figure painted with icing on a cake. A songwriter might think of BABY in the context of needing a word that rhymes with *maybe*. And so forth. Moreover, while in the past, the primary function of concepts has been thought to be the *identification* of items as instances of a particular class, increasingly they are seen not just to identify but to *actively participate* in the generation of meaning (Rosch, 1999). For example, if one refers to a small wrench as a BABY_WRENCH, one is not trying to identify the wrench as an instance of BABY, nor identify a baby as an instance of WRENCH. Thus concepts are doing something more subtle and complex than internally representing things in the external world. What this 'something more' is and how it functions may well be the most important task facing psychology today; it is vital to understanding the adaptability and compositionality of human thought.

We begin by briefly summarizing the history of attempts to formalize what is meant by a concept and how situations get classified as instances of a concept. Then we outline some key problems that have arisen accounting for the contextual nature of concepts, what happens when two or more concepts combine, and the role of similarity in categorization. This is followed by a summary of what we see as feasible steps toward an approach to concepts that is ecological in character, sing the State-COntext-Property or SCOP, theory of concepts. We show how such an approach can provide a means for handling problems of context, concept combination, similarity judgments, and compositionality. Specifically we discuss an approach that applies generalizations of mathematics originally developed for quantum mechanics to the description of concepts (Gabora & Aerts 2002; Aerts & Gabora 2005a, b). This is not the first or only application of concepts and formalisms first used in quantum mechanics to psychology (*e.g.* Bruza & Cole, 2005; Busemeyer *et al.* 2006; Busemeyer & Wang, 2007; Gibson & Crooks, 1938; Kadar & Shaw, 2000; Nelson *et al*. 2003; Nelson & McEvoy, 2007; Turvey & Shaw, 1995; Widdows, 2003; Widdows & Peters, 2003). We will argue that the persistence of such attempts may reflect that the two domains (quantum mechanics and the psychology of concepts) have a shared underlying structure, and that this is related to inescapably strong effects of context.

In fact what we do with SCOP is somewhat contrary to how usually theories arise in science. Usually, theories arise first as specific, rather ad hoc models, which over time give rise to abstract theories (such that the first ad hoc models come out as special cases of the abstract theory). By introducing SCOP we go immediately to the abstract theory, though it is specified within SCOP how to work out specific concrete models. There are other examples in the history of science where it happened this way. For example, Einstein's relativity theory was from the start the most general theory, and its validity was slowly confirmed over decades by people working out specific models for specific situations using the general structures given by Einstein's theory. But even now after 80 years this is still an ongoing process, still provoking debate over certain aspects of the general theory. Newton's work also had a flavor of this approach (first the general abstract theory, and then concrete special cases), and there are many other examples in science. In a similar fashion, with SCOP we aim at a general theory of concepts incorporating contextuality as an intrinsic, not ad hoc element. There is however a specific remark we want to make in relation with the fact that SCOP is a generalized quantum theory. Many theories that were historically part of physics have now been classified as part of mathematics, such as geometry, probability theory, and statistics. At the times when they were considered physics they focused on modeling parts of the world pertaining to physics. In the case of geometry this was shapes in space, and in the case of probability theory and statistics this was the systematic estimate of uncertain events in physical reality. These originally physical theories have taken now their most abstract forms and are readily applied in other domains of science, including the human sciences, since they are considered mathematics, not physics. (An even simpler example of how a theory of mathematics is applicable in all domains of knowledge is number theory. We all agree that counting, as well as adding, subtracting, and so forth, can be done independent of the nature of the object counted.) It is in this sense that we use mathematical structures coming from quantum mechanics to build a contextual theory of concepts without attaching the physical meaning attributed to them when applied to the micro-world. As always in science when starting from the general theory, the value of this approach must be apparent in its applications, i.e. specific models worked out for specific situations. Toward the end of the paper we mention some applications of SCOP to specific situations arising in concepts research that are worked out in detail in other papers.

A BRIEF HISTORY OF CONCEPTS RESEARCH

We now examine some predominant theories of concepts that have emerged, in roughly chronological order.

The Classical View

Concepts and categorization are the areas in psychology that deal with the ancient philosophical problem of universals; that is, with the fact that unique particular objects or events can be treated equivalently as members of a class. Most philosophers since Plato have agreed that experience of particulars as it comes moment by moment through the senses is unreliable; therefore, only stable, abstract, logical, universal categories can function as objects of knowledge and objects of reference for the meaning of words. To fulfill these functions, categories had to be exact, not vague (i.e. have clearly defined boundaries), and their members had to have attributes in common that constituted the essence of the category, e.g. the necessary and sufficient conditions for membership in the category. It followed that all members of the category were equally good with regard to membership; either they had the necessary common features or they didn't. Categories were thus seen as logical sets, and the mathematics of classical set theory were assumed to apply to them.

This view of categories entered psychology explicitly in the form of concept learning research in the 1950s, led by the work of Jerome Bruner and associates. In one study (Bruner, Goodnow, & Austin, 1956), subjects were asked to learn concepts which were logical sets defined by explicit attributes such as RED AND SQUARE, combined by logical rules, such as 'and'. Theoretical interest was focused on how subjects learned which attributes were relevant and which rules combined them. In developmental psychology, the theories of Piaget and Vygotsky were combined with the concept learning paradigm to study how children's ill-structured, often thematic, concepts developed into the logical adult mode. For linguists, the relationship between language and concepts appeared unproblematic; words simply referred to the defining features of the concepts, and it was the job of semanticists to work out a suitable formal model that would show how this relationship could account for features such as synonymy and contradiction. Artificial stimuli were typically used in research at all levels, structured into micro-worlds in which the prevailing beliefs about the nature of categories were already built into the stimuli and task (for examples, see Bourne, Dominowski, & Loftus, 1979). Thus early empirical research could not refute the classical view since the view was built into the structure of experiments. Although since then ample evidence against the classical view has been gathered (Komatsu, 1992; Rosch, 1999; Smith & Medin, 1981), it has remained a persistent and pervasive force in Western treatments of concepts.

Graded Structure

A major challenge to the classical view came in the 1970s in the form of evidence that actual categories in use are not the bounded, clearly defined entities required by classical logic. This was first shown with respect to colour (Rosch, 1973). Consider: is red hair as good an example of RED as a red fire engine? Most people answer ‘no’ to this question, and to other questions of this sort. However if categories were the sorts entities entailed by classical logic, it would not be possible for one instance to be a better or worse example than another. With examples of this sort it was shown that instances are judged to have differing degrees of membership in the category, and that colour categories have neither criterial attributes nor definite boundaries. Furthermore, psychological representation of the category appeared to be concrete rather than abstract – e.g. people universally agree that some colours match their idea or image of that colour category better than others. An extensive program of research has demonstrated that the same form of graded structure applies to categories of the most diverse kinds: perceptual categories such as colours and forms; semantic categories such as FURNITURE, biological categories such as a WOMAN, social categories such as OCCUPATION, political categories such as DEMOCRACY, formal categories that have classical definitions such as ODD NUMBER, and *ad hoc* goal derived categories such as THINGS TO TAKE OUT OF THE HOUSE IN A FIRE. Furthermore, gradients of membership must be considered psychologically important because such measures have been shown to affect virtually every major method of study and measurement used in psychological research: learning, speed of processing, expectation, association, inference, probability judgments, natural language use, and judgments of similarity (Rosch, 1999; see also Markman, 1989; Mervis & Crisafi, 1982; Mervis & Rosch, 1981; Rosch, 1973, 1978; Rosch & Lloyd, 1978; Smith & Medin, 1981).

Rosch’s theory of graded structure categorization, in its most general form, was that concepts and categories form to mirror real-world structure (of both perception and life activities) rather than logic. More specifically:

1) *Prototypes*. Categories form around and/or are mentally represented by salient, information rich, often imageable stimuli that become "prototypes" for the category. Other items are judged in relation to these prototypes, thus forming gradients of category membership. There need be no defining attributes which all category members have in common, and category boundaries need not be definite. Sources of prototypes are diverse: while some may be based on statistical frequencies, such as the means or modes (or family resemblance structures) for various attributes, others appear to be ideals made salient by factors such as physiology (good colors, good forms), social structure (president, teacher), culture (saints), goals (ideal foods to eat on a diet), formal structure (multiples of 10 in the decimal system), causal theories (sequences that "look" random), and individual experiences (the first learned or most recently encountered items or items made particularly salient because they are emotionally charged, vivid, concrete, meaningful, or interesting).

2) *Basic-level Objects*. What determines the level of abstraction at which items will be categorized? Rosch, Mervis, Gray, Johnson & Boyes-Braem (1976) argued that there is a basic level of abstraction (e.g. CHAIR, DOG) that mirrors the correlational structure of properties in the object's real-world perception and use. Categories form, are learned, and are perceived first at this level, then further discriminated at the subordinate level (e.g. KITCHEN CHAIR, SPANIEL) and abstracted at the superordinate level (FURNITURE, ANIMAL). Within a given category, this same process of maximizing information through correlational structure leads to the formation of prototypes. One of the most philosophically cogent aspect of prototypes and

basic objects is that, far from being abstractions of a few defining attributes, they are rich, imagistic, sensory, full-bodied mental events that serve as reference points in all of the kinds of research effects mentioned above.

A very important finding about prototypes and graded structure is how sensitive they are to context. For example, while dog or cat might be given as prototypical PET ANIMALS, lion or elephant are more likely to be given as prototypical CIRCUS ANIMALS. In a default context (no context specified), coffee or tea or coke might be listed as a typical BEVERAGE, but wine is more likely to be selected in the context of a dinner party. Furthermore, people show perfectly good category effects complete with graded structure for ad hoc, goal derived categories such as GOOD PLACES TO HIDE FROM THE MAFIA. In fact, the effects of context on graded structure are ubiquitous (Barsalou, 1987; Nelson *et al*., in press). In the classical view, from the time of its origin in Greek thought, if an object of knowledge were to change with every whim of circumstance, it would not be an object of knowledge, and the meaning of a word must not change with conditions of its use. One of the great virtues of the criterial attribute assumption for its proponents had been that the hypothesized criterial attributes were just what didn't change with context. Barsalou argued that context effects show that category prototypes and graded structure are not pre-stored as such in the mind, but rather are created anew each time on the fly from more basic features or other mental structures. The extreme flexibility of categories to context effects may have even more fundamental implications.

Mathematical Models Incorporating Graded Structure Effects

Many reactions to the above view of categorization consisted primarily of attempts to deal with the empirical data from graded structure research without changing one's idea of the real nature of categories as fundamentally classical (or at the very least, requiring some sort of essentialist classical mental representation structure mediating them). Rosch's prototype theory was not presented in the form of a mathematical model and, indeed, challenged the appropriateness of set-theoretic models used by the classical view. In an influential paper, Osherson and Smith (1981) modeled prototype theory using Zadeh's (1965) fuzzy set logic, in which conjunctive categories are computed by a maximization rule, and showed that prototypes do not follow this rule; the typicality of a conjunction is not simply a function of the typicality of its constituents. This has come to be called the 'pet fish problem' because *guppy* is rated as a good example, not of PET, nor of FISH, but an excellent example of the category PET FISH. They took this critique of Zadeh's fuzzy set logic as a refutation of graded structure and prototypes.

Another set of models, called probabilistic models, re-define graded structure as the probability of an item's being classified as a member of the category. These kinds of probabilities are not actually an appropriate measure for graded structure; they do not capture the fact that people universally judge items both to be definite members of a category, and to have definitely differing degrees of membership, some better examples than others. Nor does it capture the fact that people judge some items to be factually not members, i.e. to genuinely straddle two or more categories. (Shortly we will give a more formal argument for why such statistical probabilities are inappropriate for modeling concepts.) Furthermore, in most probabilistic models, artificial categories are once again the stimuli with the same difficulties cited with respect to this strategy when we discussed the classical view.

One main issue of debate in the early models was the level of abstraction and/or detail that need be assumed in the category representation. Extreme prototype-as-abstraction models assert that only a summary representation preserving the central tendencies among category exemplars is necessary. Fairly extreme exemplar views argued that the memories for all individual exemplars are combined whenever a category judgment is made. Other investigators modeled the category representation in the form of a frequency distribution which preserves not only the central tendencies, but also some information about the shapes of the distribution and the extent of variability among exemplars. (See Barsalou, 1990; Neisser, 1989; Smith & Medin, 1981 for summaries.)

Another class of models, called decision bound or *rule-based models*, represent categories as regions in multidimensional space separated by a decision rule or boundary (Ashby & Maddox, 1993; Maddox & Ashby, 1993). Although in theory these boundaries can assume any form, they are assumed to be linear or quadratic, because this provides regions that are simple enough to be realistically learnable, and most likely to match the boundaries of natural categories. (Thus for example, stimuli might consist of a set of lines that vary in length and orientation linearly separated in such a way that the subject must take both length and orientation into account to decide whether a given stimulus belongs to category A or B.) This is a provocative approach, though the type of data such models can account for is limited; for example, they cannot handle category conjunctions. Furthermore, there is a lack of evidence that subjects use all-or-none cutoffs even in artificial categories (Kalish & Kruschke, 1997) much less in real-world categories.

Exemplar Theories

In yet another class of models, *exemplar models*, a concept is represented by a set of instances or exemplars of it stored in memory (Medin, Altom, & Murphy, 1984; Nosofsky, 1988, 1992; Heit & Barsalou, 1996). Thus each exemplar has a uniquely weighted set of features, and a new item is categorized as an instance of the concept if it is sufficiently similar to the most salient previously encountered exemplars. The exemplar model has met with considerable success at predicting experimental results (*e.g.* Nosofsky, 1992; Tenpenny, 1995); however, it does not fully reproduce individual differences in the distributions of responses across test stimuli (Nosofsky *et al*., 1994), and cannot account for certain base-rate effects in categorization (Nosofsky *et al*., 1992). Moreover, the choice of concepts used in experiments that support the exemplar theory obscure the counterintuitiveness of the assumptions underlying it. They typically come from perceptual data, rather than data obtained using abstract concepts such as BEAUTY or THE NUMBER FIVE. Surely when employing the concept FIVE, one does not calculate how different the current situation is from previously encountered instances of FIVE, such as, say, your five cousins, the five trees in your backyard, and the five buttons on your favorite shirt. One appears to have abstracted something essential out of such instances to form a concept FIVE that no longer has much to do with the irrelevant details of particular situations. Moreover, to define a concept in terms of weighted averages for certain features presupposes that it is possible to state objectively what the relevant features *are*. Unless a context is specified, there is no basis for supposing that one feature is more relevant than another; otherwise one might just as well reason that because Ann could sit in either chair A, chair B, or chair C, Ann can be defined as some sort of average of a human sitting in each of these three chairs. Clearly, Ann is more than this, much as BEAUTY is more than an average taken across certain features of salient instances of BEAUTY. This sort of problem also plagues a related approach to concepts in which they are viewed as *perceptual symbol systems*, that is, simulators of sets of similar perceptually-based memories (Barsalou 1999).

Concept as Core (Essence) + Processing Heuristics

Yet another class of models accounts for graded structure by dividing a concept into its *core* *concept* and *processing heuristics*. In this approach, the actual meaning for category terms is a classical definition onto which is added a processing heuristic or identification procedure that accounts for graded structure aspects (Osherson & Smith, 1981; Smith, Shoben & Rips, 1974). In this way, for example, ODD NUMBER can 'have' both a classical definition and a prototype. This distinction between core concept and heuristics is also central to Wisniewski's (1996, 1997a, b) dual process model of concept combination, which assumes that the combination process involves comparing and then aligning potentially complex but nevertheless incomplete summary schemas of the concepts being combined. This is a dangerous move, for it decouples theory from any empirical referent. The actual meaning of a category term becomes a kind of metaphysical classical entity known by logic alone that is unassailable by data, data being assigned to the peripheral processing heuristics.

All of these theories incorporating graded structure effects have a somewhat analogous problem rendering it difficult, if not impossible, to distinguish between them on the basis of empirical evidence. Each contains a model of storage that is always presented with complementary processing assumptions, which allow it to match any kind of experimental data (Barsalou, 1990). This fact, along with the difficulties cited earlier such as the inappropriate use of probabilities and the reliance on decontextualized artificial stimuli and tasks, seems to indicate that a new type of modeling is called for.

Concepts as Theories

Such a new vision of concepts and categorization would seem to be offered by the view of concepts as theories (Medin, 1989; Medin & Wattenmaker, 1987; Murphy & Medin, 1985)[1]. The

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[1] In the theory theory in developmental psychology, theory is defined as scientific theory and examples such as the

theories view appears to capture an important intuition that people have about concepts and categories, which is that concepts do not stand apart independently but belong to systems larger than themselves. By conceiving of concepts as theory related, the theory theorists are able to avoid talking about attributes, whether criterial or not, or about the problems of defining and measuring similarity, difficult issues for the previous views. On the other hand, context dependent effects in categorization are readily incorporated. For example, the context dependent finding that GREY CLOUDS are judged more similar to BLACK CLOUDS than to white clouds but GREY HAIR more similar to WHITE HAIR than to BLACK HAIR is accounted for by saying that we have different theories about CLOUDS and HAIR. An additional virtue of the theory view is that the persistence of the classical view of categories can be incorporated; it is seen as a persistent theory that we have about categories that children develop with age (Keil, 1989; Medin & Ortony, 1989).

There are several difficulties with the theories view (Komatsu, 1992; Fodor, 1994; Hayes et al. 2003; Rips, 1995; Rosch, 1999). One problem is that conceptual change often happens incrementally, “without a radical restructuring of ones’ beliefs or knowledge” (Hayes et al. 2003). Moreover, theory theorists never define or describe what they mean by theory, and offer not a single example of an actual theory from which findings, even one finding, in categorization research could be derived. Nor is there any attempt to show how attributes, similarity, or context (for the lack of account of which they criticize other views) could be derived from theories, either in the abstract or from specific theories. What is meant by a theory? Explicit statements

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child’s development of biological knowledge are provided (Carey, 1985; Gopnik & Meltzoff, 1997; Keil, 1979). However the aims of the developmental use of theory are somewhat different from the categorization theorists relevant to our present topic.).

that can be brought to consciousness? Any item of world knowledge? The complete dictionary and encyclopedia? Any expectation, habit, belief, desire, skill, custom, value or observed regularity? Any context? It is hard to escape the impression that for the theory theorists, absolutely anything can count as a theory, and that the word *theory* can be and is invoked as an explanation of any finding (somewhat like the proliferation of *instincts* and *drives* in an earlier, now defunct, psychology). If we look more closely at the experiments claimed as support for the theories view, they are primarily demonstrations of what is elsewhere in psychology called *context effects*. Words and concepts are interpreted differently depending upon the environments or contexts in which they occur.

The Geometrical Approach

Gärdenfors (2000a, b) has introduced a provocative geometrical approach to concepts. He considers not just binary features or properties, but dimensions (e.g. color, pitch, temperature, weight). Like theory theory, it exploits (to a limited extent) how attributes *relate* to one another. He distinguishes between *integral dimensions*, for which one cannot assign a value on one dimension without assigning a value on the other (e.g. hue/brightness, or pitch/loudness), and *non-integral dimensions*, for which one can assign a value on one dimension without assigning a value on the other (e.g. hue/size or pitch/brightness). This leads him to define *domain* as a set of integrable dimensions that are separate from all other dimensions. A property (generally an adjective, *e.g*. red) is defined as a convex region in a domain. Formally this means that if two objects v_1 and v_2 are both members of a concept to a certain degree then all items between v_1 and v_2 also satisfy this criterion, e.g. the property ‘red’ is a convex domain in a region defined by the integrable dimensions hue, saturation, and brightness. Properties generally refer to a single domain, and are thus considered properties, while concepts (e.g. CAT) generally refer to many domains. A concept is defined as a set of convex regions in a number of domains (where a domain is a set of integrable dimensions that are separate from all other dimensions, as defined above), together with a salience assignment to the domains, and information about how the regions in different domains are correlated. Concept combination is then modeled as combining of these sets of convex regions. Thus XY = region for some domain of modifier X replaces corresponding region for Y. This ‘modifier + modified’ relationship is very language specific. For example, in RED BRICK, one replaces the original (generic) region for color for the concept BRICK with the corresponding region for RED. A problem with this approach is that the geometries can be very complex, and change in a context-dependent way, so it is still difficult to describe even the most mundane, everyday creative acts in terms of this model.

Ecological View: Concepts as Participatory

An ecological view was first introduced in psychology in regard to perception (Brunswik, 1944) and developed by J. J. Gibson (1979) into a system of ecological optics, which re-described both perceiving organism and perceived environment so that they formed a single unit. In Gibson’s ecological optics, light, space, motion, and other abstract properties are necessarily designated in organismically relevant and dependent ways, and the perceiving organism is necessarily described in environmentally relative and dependent ways. Perception of oneself and one’s environment are, so defined, inseparable: “The supposedly separate realms of the subjective and the objective are actually only poles of attention.” (Gibson, 1979, p. 116). More recently, other cognitive scientists have argued for the inclusive organism-environment field as the basic unit of the science. Combining physiology and philosophy, Skarda (1999) has shown in detail how dualistic perception can arise from the unbroken field of a perceptual event. Jarvilehto (1998a, l998b) reconceptualizes the relationship between organism and environment as a single system both at the micro (neural) and macro (behavioral) levels. In Trevarthen's concept of *intersubjectivity,* interactions between people are codependently defined, experienced, and acted out (Trevarthen, 1993).

Gibson introduced the term *affordances* to refer to the functions that the perceived world offer the organism. For example, the ground affords support, enclosures afford shelter, and elongated objects afford pounding and striking. Because it is an organismically meaningful world that is perceived and acted upon, form and function are as inseparable and co-defining as perceiving subject and perceived object, and this is the information that constitutes both perception and action. "The act of throwing complements the perception of a throwable object. The transporting of things is part and parcel of seeing them as portable or not." (Gibson, 1979, p. 235). Yet it is very obvious that the perceiver and the world perceived are experienced as different and separate. What gives?

This is where we see concepts coming into the picture. To apply an ecological approach to not percepts but concepts may seem unusual. However, we believe that the distinction between percepts and concepts may reflect what the researcher is focused on as much as it reflects what is happening for the subject. More importantly, it is only once objects in the world have been *conceptualized* that they are charged with the potential to dynamically interact in myriad ways with conceptions of other objects as well as with the goals, plans, schemas, desires, attitudes, fantasies, and so forth, that constitute human mental life. And it is through these interactions that their relations are discerned, and together they thereby come to function as integrated internal model of the world, or worldview. Thus it is when stimuli in the world come to be understood in conceptual terms that they acquire the web-like structure and self-organizing dynamics characteristic of an *ecology*. It is therefore our view that an ecological treatment of concepts opens up the possibility of making not just action but complex thought processes amenable to a more ecological approach (as suggested by Gregory Bateson (1973) some time ago). Rosch (1999) argues that it is the role of concepts to provide a bridge between what we think of as mind and what we think of as world, and has articulated this position in terms of its implications for concepts. Concepts and categories do not represent the world in the mind, as is generally assumed, but are a participating part of the mind-world whole. Therefore, they only occur as part of a web of meaning provided both by other concepts and by interrelated life activities. This means that concepts and categories exist only in concrete complex situations.

The three major types of concept and categories approaches (classical, graded structure, and theory) may now be examined in relation to situations and context: Giving dictionary style definitions of concepts is the *sine qua non* of the classical view, but even such activity occurs in a particular situation, a situation in which the entire background of practices, understandings and explicit teachings with which we have been raised in our culture come into play to yield a correct answer which is generally an Aristotelian criterial features, genus and differentia, classical category definition. Note that the very attributes used in this kind of definition of concepts are themselves concepts that can be pointers to affordances and life activities, and how they are organized and understood by the mind.

Prototypes both vary across situations and show inter-situation consistency. Such consistency is a clue to more general life activities. Prototypes with their rich non-criterial information and imagery can indicate, on many different levels, possible ways of situating oneself and navigating complex situations. Basic level object research (Rosch *et al*, 1976) indicated that category formation is not arbitrary but takes place in such a way as to maximally map the informational structure of the world. What is referred to as a *basic level category* such as CHAIR seems more like the object's real name than FURNITURE because it categorizes the object at the level of detail that is most useful for conveying and interpreting meaning, given the forms of living in our culture – a level which would be expected to differ with age, expertise, social structure, and culture. If categories ultimately arise from life activities, basic level categories could provide an entry to the events and processes that produce them. And as a worldview builds up from basic level categories to include more detailed as well as more abstract levels of conceptualizing, it becomes more interconnected, more of an ecology, that comes increasingly to reflect what is unique about the circumstances and idiosyncrasies of the individual.

The examples used in theories arguments typically point to situational variations. For example, a DRINK might mean BEER in the context of truck drivers, MILK in the context of a school lunch, and WINE in the context of a dinner party. This is attributed to the theories that we have about these matters. We argued earlier that the word *theory* may be little but a place holder for an explanation that is still forthcoming; here we can see how it might point toward the life activities that give rise to inter-situational consistencies. The question to ask with respect to all three views of categories is: what are the relations between perceptual, functional, and causal properties in concrete real-world life situations that are searched out by individual learners and honed in on by the languages and cultures of the world to form maximally useful and meaningful categories?

THE NEED FOR A NEW APPROACH

We have examined the merits and pitfalls of several approaches to concepts, focusing on how they combine and change under the influence of a context. Let us now summarize what we see as the major unsolved issues to be accounted for by a theory of concepts.

1. Contextuality

We have seen that the situation or context influences the meaning in the concept, and for this reason we need to give place to the context in the description of a concept. It is however impossible to circumscribe in advance the diverse situations to which a given concept will be applied, and the unique slants it can be given in unexpected circumstances. For this reason, many express the concern that current theories of concepts get us no closer to understanding the contextual manner in which concepts are actually evoked and used in everyday life (Gerrig & Murphy, 1992; Hampton, 1997; Komatsu, 1992; Medin & Shoben, 1988; Murphy & Medin, 1985; Rosch, 1999).

The problem is analogous, indeed virtually identical, to arguments about whether or not and in what way one needs to include world knowledge in formal semantic models (Fodor, 1998; Rips, 1995). The paradox in most works on this topic is the tacit recognition that it is both necessary and impossible to include such knowledge. Rips (1995), for example, claims: “...part of the semantic story will have to include external causal connections that run through the referents and their representations” (p. 84), but in the same work asserts with his *No Peeking Principle* that we cannot be expected to incorporate into a theory of concepts how they interact with world knowledge (what Hampton, (1997), refers to as *extensional feedback* and Searle, (1993), expresses in his *ceteris paribus* argument). The idea that this is impossible stems from the fact that one cannot incorporate into a model of concepts how a concept would manifest in every possible context. An accurate mathematical description of the concept BABY for example, would have to incorporate not only the most typical attributes of BABY, nor even attributes of BABY that are occasionally present, but attributes of BABY that might cause it to be elicited spontaneously in response to some unforeseen context. The concept BABY might be most commonly evoked by situations that involve typical BABY features such as the context of hearing a BABY cry. A criminal might think of BABY in the context of distracting a maternal woman’s attention away from events connected to a crime. And so forth.

2. Concept Combination

Theories of concepts have been relatively successful at describing and predicting the results of cognitive processes involving relationships of cause and effect using artificial stimuli where the effects of background information and nuances of personal meaning are minimal. Difficulties arise when it comes to natural categories, one classic problem being what happens when concepts interact to form a conjunction, or in more complex sorts of combinations such as sentences. As many studies (*e.g.* Hastie *et al.*, 1990; Kunda *et al.*, 1990; Hampton, 1997) have shown, a conjunction often possesses features that are said to be emergent: not true of its constituents. For example, the properties *lives in cage* and *talks* are considered true of PET BIRDS, but not true of PETS or BIRDS. Representational theories are not only incapable of predicting what sorts of features will emerge (or disappear) in a conjunction, they do not even provide a place in the formalism for the gain (or loss) of features. This problem is hinted at by Boden (1990), who uses the term impossibilist creativity to refer to creative acts that not only *explore* the existing state space (set of all possible states) but *transform* that state space. In other words it involves the spontaneous generation of new states with new properties. One could try to solve the problem *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; for instance, whenever a conjunction like PET BIRD comes into existence. However, this happens every time one generates a sentence that has not been used before, or even uses the same sentence in a slightly different context. 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.

3. Similarity, Compatibility, and Correlation

Theories of concepts often employ a notion of distance based on similarity in terms of shared features. Recognition of similarity and difference between things and responses to the things based on that recognition is a universal function of organisms. Behavior on the basis of similarity has been a basic principle in psychology from its earliest beginnings in associationism and Pavlovian conditioning up to its most current techniques in psychophysics. But no one has been able to define or explain similarity in a manner that cannot easily be struck down (Goldmeier, 1972; Tversky, 1977, and see Medin, 1989, for a critique of Tversky). The problem is that definitions of similarity tend to be circular; items are defined as similar that are judged to be similar. Moreover, similarity-based theories of concepts have difficulty accounting for why items that are dissimilar or even opposite might nevertheless belong together; for example, why WHITE might be more likely to be categorized with BLACK than with FLAT, or why DWARF might be more likely to be categorized with GIANT than with, say, SALESMAN. Wisniewski's would answer that it is because DWARF and GIANT are 'alignable' with respect to the dimension of size, but his (1997a,b) dual process theory does not go the next step and show what kind of mathematical space concepts must 'live' in to spontaneously, with incomplete knowledge of one another, become aligned. We provide an approach to resolving this after introducing the relevant formalism.

RATIONALE FOR USING THE GENERALIZED QM FORMALISM

To accomplish all that we expect of a theory of concepts, it must be a mathematical theory. The formalisms used have tended to be limited in scope or inappropriate to the general approach being tested; often they are examples of the tail wagging the dog. The ecological situational approach, though conceptually appealing, is mathematically challenging due to the lack of fixed reference points for concepts and the element of novelty and creativity in concepts that it encompasses. This suggests that a mathematics entirely new to psychology is called for. The state of concepts research today is in some ways reminiscent of that of quantum mechanics a century ago. Quantum mechanics was born as a discipline when experiments on micro-particles revealed, for the first time in history, a world that completely resisted description using the mathematics of classical mechanics that had been so successful until then.

One point of similarity between quantum entities and concepts is that both differ from entities that can be described by classical physics, for which if a property is not actual then its negation is actual. If the property ‘not green’ is true of a particular ball, then the property ‘green’ is not true of that particular ball. However, for concepts, as in quantum mechanics, a property and its negation can *both* be potential. Thus for the *concept* BALL, if nothing is specified for the colour, ‘green’ and ‘not green’ are both potential. One could refer to this as a *problem of nonclassical logic* for concepts.

A second similarity between the quantum entities and concepts is: much as properties of a quantum entity do not have definite values except in the context of a measurement, properties of a concept do not have definite applicabilities except in the context of a particular situation. In quantum mechanics, the states and properties of a quantum entity are affected in a systematic and mathematically well-modeled way by the measurement. Similarly, the context in which a concept is experienced inevitably colors how one experiences that concept. One could refer to this as an *observer effect* for concepts. We will show that a generalization of the mathematics of quantum mechanics can be used to describe the effect of context on concepts.

These problems – nonclassical logic and the observer effect – generated in physics the need for a new kind of probability model, i.e. a nonclassical probability model[2]. The only type of non-classical probabilities that are well known in nature are the quantum probabilities. This suggests that to develop a theory of how concepts interact with the inevitably incompletely specified contexts that evoke them we should look to the quantum probability model, for such a theory cannot be provided by approaches that assume a standard classical probability model such as neural networks, Bayesian networks, and the formal models discussed earlier in this paper. Indeed the spreading activation hypothesis assumed in most such models is not supported empirically (Nelson *et al*., 2003, in press; Nelson & McEvoy, 2007). According to the notion of spreading activation, activation travels through a fixed associative network, weakening with conceptual distance. That is, it spreads from a target concept to directly associated concepts, to less directly associated concepts, and so forth, such in order for the activation of the target to remain strong there must be a return route for the activation to get back to the target. Nelson and colleagues tested the classic spreading activation hypothesis against another hypothesis they

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[2] It was proven that any process that involves interaction with an incompletely specified context (and thus nondeterminism) entails a non-Kolmogorovian probability model (Pitowsky, 1989). (A classical probability model is said to be Kolmogorovian because it satisfies the axiomatic system for classical probability theory developed by Andrei Nikolaevich Kolmogorov. In a classical (Kolmogorian) probability model, the fact that we are dealing with probabilities reflects a lack of knowledge about the precise state of the system. If, however, these inequalities are violated, no such classical (Kolmogorian) probability model exists. The probability model is said to be nonclassical, or non-Kolmogorovian.) Pitowsky's proof makes use of Bell inequalities, which are mathematical equations that constitute the definitive test for the presence of quantum structure. Pitowsky proved that if Bell inequalities are satisfied for a set of probabilities concerning the outcomes of the considered experiments, there exists a classical probability model that describes these probabilities. Hence, the violation of Bell inequalities shows that the probabilities involved are non-classical (non-Kolmogorovian).

refer to (after a phrase coined by Einstein) as the ‘spooky activation at a distance’ hypothesis. It predicts that the target activates its network of associates in synchrony, and that each link in the associative set contributes additively to the net strength of their activation. In other words, activation strength is determined not by the spread of activation but by the number and strength of links. A key difference between these two hypotheses is that according to spreading activation, the activation of the target will depend on how many associate-to-target links there are, whereas according to spooky activation, activation of the target can be strengthened by associate-to-associate links even in the absence of associate-to-target links. They found that their experimental results supported the spooky activation at a distance hypothesis and not the spreading activation hypothesis.

An extreme kind of contextual interaction occurs when entities acting as contexts for one another influence each other to such an extent that the interaction results in a new entity with properties different from either of its constituents. Their degree of merger may thereafter be such that after the interaction one cannot manipulate one constituent without simultaneously affecting the other. Quantum mechanics provides a means describing such mergers as a compound of two entities. Two quantum entities can become *entangled* when they encounter one another, and in this new entangled state they behave as one quantum entity. A state of entanglement can be mathematically described using the tensor product. The tensor product always allows for the emergence of new states --- the entangled states --- with new properties. Specifically, if H_1 is the Hilbert space describing a first sub-entity, and H_2 the Hilbert space describing a second sub-entity, then the joint entity is described in the tensor product space $H_1 \otimes H_2$. The formalisms developed to describe quantum phenomena have limitations that make their application specific to quantum mechanics. However, these formalisms have been generalized to apply to other situations exhibiting a similar kind of abstract structure, as discussed shortly. With respect to cognition, we can refer to this need to be able to describe what happens when concepts combine to become a single unit of meaning as an *entanglement problem for concepts*.

THE STATE-CONTEXT-PROPERTY (SCOP) FORMALISM

We now outline a theory of concepts that we believe can tackle the problems presented in the previous sections. With it one can begin to investigate the ecology of concepts: the structure of concepts, how they manifest in the context of other concepts, and how they participate in the world of which they are a part. A similar approach is being used to model contextual effects on word meanings (Bruza & Cole, 2005; Widdows, 2003; Widdows & Peters, 2003) and in decision making (Busemeyer *et al.* 2006; Busemeyer & Wang, 2007).

We noted that there exists a mathematical framework for describing the change and actualization of potentiality that results from contextual interaction in quantum mechanics, specifically one characterized by extreme susceptibility to change. A limitation of this framework is that it applies to the extreme case, when the response of the entity is *maximally* contextual. However, the development of generalizations of mathematical structures originally developed for quantum mechanics has provided tools to describe intrinsically contextual situations in not just quantum mechanics but other fields. In other words, these mathematical theories lift the quantum formalism out of the specifics of the microworld, making it possible to describe nondeterministic effects of context in other fields (Aerts, 1993; Aerts & Durt, 1994a, 1994b; Foulis & Randall, 1981; Foulis *et al*., 1983; Jauch, 1968; Mackey, 1963; Piron, 1976, 1989, 1990; Pitowsky, 1989; Randall & Foulis, 1976, 1978). The original motivation for these generalized formalisms was theoretical (as opposed to the need to describe the reality revealed by experiments) but (as is often the case) they have eventually been found to be useful in the description of real world situations.

The formalism we use is one of these generalizations. It is called the State Context Property (SCOP) formalism (described in detail in Gabora & Aerts, 2002a,b; Aerts & Gabora 2005a,b), an elaboration of the State Property formalism (Beltrametti & Cassinelli, 1981; Aerts, 1982, 1983, 1999, 2002). SCOP allows us to explicitly incorporate the context that evokes a concept and the change of state this induces in the concept into the formal description of a concept. With SCOP it is possible to describe situations with *any* degree of contextuality. In fact, classical and quantum come out as special cases: quantum at the one end of extreme contextuality and classical at the other end of extreme lack of contextuality (Piron 1976; Aerts 1983). The rationale for applying it to concepts is expressly because it allows incorporation of context into the model of an entity[3].

The Five Elements of a SCOP Description of a Concept

Using the SCOP formalism, a description of a concept consists of the five elements:

- A set $S = \{p, q, \ldots\}$ of states the concept can assume.
- A set $\mathcal{M} = \{e, f, \ldots\}$ of relevant contexts.
- A set $\mathcal{L} = \{a, b, \ldots\}$ of relevant properties or features. (Note that contexts can be concepts, as can features.)
- A function ν that describes the applicability or *weight* of a certain feature given a specific state and context. For example, $\nu(p, e, a)$ is the weight of feature a for the concept in state p under context e.

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[3] SCOP is a general mathematical structure that grew out of (but differs from) the quantum formalism, where the context (in this case measurement context) is explicitly incorporated in the theory. Note that this kind of generalization and re-application of a mathematical structure has nothing to do with the notion that phenomena at the quantum level affect cognitive processes.

• A function μ that describes the transition probability from one state to another under the influence of a particular context. For example, $\mu(f, q, e, p)$ is the probability that state p under influence of context e changes to the state q, giving rise to the new context f.

An astute reader will recall that the entire set of relevant states and contexts is unlimited. Clearly it is not possible to incorporate all of them in the model, and moreover some degree of subjectivity is inevitable in the choice of relevant states and contexts. The model is an idealization of the concept. However, the more states and contexts included in the model, the richer it becomes[4]. What is important is that the potential to include this richness is present in the formalism, i.e. there is a place in it to include even improbable states, and largely but not completely irrelevant contexts. As a SCOP model grows to incorporate more and more concepts, the sets of states and contexts included in the model of any one particular concept will grow accordingly. Each concept (or constellation of concepts) can be considered a context (however unlikely) of another, and highly probable states of one concept can become included as improbable states of another.

Let us now see how these five elements come into play in the description of a concept.

Ground States, Superposition States, and Collapsed States

Inspired by how the problem of context is approached in physics, in the SCOP approach to concepts we have introduced the notion 'state of a concept'. For any concept there exists an

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[4] This is the same methodology as that used to describe the (usually infinite) number of different states for a physical system in physics. The paradox, namely that it is impossible to incorporate all potential contexts into the description, is resolved in a similar way as it is resolved in physics. For concrete mathematical models, one limits the description to a well-defined set of the most relevant contexts, hence a corresponding well defined set of states for the entity. But in principle it is possible to refine the model indefinitely, and hence incorporate ever more contexts and states.

infinite number of possible states it can be in. Each state p in Σ has unique typicality values for exemplars (instances) and applicabilities of properties. If a state of a concept is not affected by a context it is said to be an *eigenstate* for this context. Otherwise it is a *potentiality* (superposition-like) *state* for this context, reflecting its susceptibility to change. Note that a state is only a potentiality state with respect to a particular context. A potentiality state has the capacity to change in different ways under the influence of that context, but not necessarily for any other context. Similarly, a state is only an eigenstate only with respect to a particular context.

An important notion introduced in the SCOP approach is the *ground state* of a concept. This is the 'undisturbed' state of a concept; the state it is in when it is not being evoked or thought about, not participating in the structuring of a conscious experience. The ground state of a concept can be retrieved only as a theoretical construct that we know through how the concept interacts with various contexts (possibly other concepts).

The Role of Context

We say that a context e evokes a change of state in the concept, from a state p to a state q. For example, p could be the concept TREE, which under the context 'desert island' might change to state q, which is PALM TREE. Thus it is through the effect of e on p that sensitivity to context is incorporated, and this is what enables a SCOP model of a concept to be the rich, imagistic, unbounded mental construct that research has revealed concepts to be.

Borrowing terminology from quantum mechanics we refer to this change of state as *collapse*. A change of state of a concept that occurs during collapse may in turn change the context. This can continue recursively, until the concept enters a state that is an eigenstate with respect to that context, at which point it is not susceptible to change. (Of course inevitably another context comes along, in which it may well once again become susceptible to change.)

Actuality and Potentiality of a Concept

We mentioned that much as properties of a quantum entity do not have definite values except in the context of a measurement, properties of a concept do not have definite applicabilities except in the context of a particular situation. Let us examine carefully how this kind of problem can be dealt with, first in quantum mechanics and then in SCOP. If a quantum entity or concept, prior to a measurement or context is in an eigenstate of this measurement or context, then the measurement or context does not change this state, but just 'detects' what is 'in acto'. If the quantum entity or concept, prior to the measurement or context, is in a state of potentiality with respect to this measurement or context, then the measurement or context changes this state (collapse), and also changes what is actual as well as what is potential. Some features that were actual now become potential and *vice versa*. Note that in the formalism of quantum mechanics, a superposition state is not an absolute type of state; it is only defined with respect to a measurement. Concretely this means if measurement A is performed, then with respect to this measurement, 'each possible state of the quantum entity under consideration' will be either a superposition state (with respect to this measurement) or an eigenstate (with respect to this measurement). If it is a superposition state, this means that (most) quantities to be measured by the measurement under consideration are potential (not actual, i.e. do not have a specific value). If it is an eigenstate, this means that the quantities to be measured are actual (do have a specific value). The effect of the measurement is to change a superposition state to an eigenstate, hence to make quantities that were potential before the measurement acquire actual values, and to make quantities that were actual before the measurement taken on only potential values. In other words, the measurement also changes former eigenstates into superposition states.

Let us give an example of how this applies to concepts. Consider the concept CAT, and two contexts: (1) 'is hungry and meowing to get food', and (2) 'eats its food'. The feature 'is meowing' is actual for CAT in the state which is an eigenstate of the first context. In an eigenstate of the second context, as the cat starts to eat, this feature becomes potential. Another feature 'is chewing', which was potential for an eigenstate of CAT in the first context, becomes actual for an eigenstate in the second context. It is this dynamics of actualities becoming potential and potentialities becoming actual that is described using the quantum formalism.

Having examined this shifting between actual and potential, let us return to the problem of context. We noted that for each concept there exists one specific state, which we call 'ground state', the state where there is no influence of any context. When a concept interacts with a specific context, it is immediately projected out of the ground state to another state. This means that the ground state is a theoretical construct, such as for example the state of a physical system in empty space. Indeed, one never experiences a concept in its ground state, since always there is some context present. It is similar to the fact that a physical system is never in empty space. The properties that are actual in the ground state are the characteristic properties of the concept. The influence of context on the state of a concept can be such that even characteristic properties of a concept disappear if the concept is transformed into a new state under the influence of a context. For example, consider the concept ISLAND. The property 'surrounded by water' is a characteristic property, indeed actual in the ground state of ISLAND. But if we apply the context 'kitchen' to island, and hence consider the 'kitchen island', then this state of island does not have the property 'surrounded by water' as an actual property (or hopefully not).

Thus the SCOP a model of a concept is able to incorporate the different contexts by means of the different states of the concept. Concrete workable models will have a concrete set of states available for the concept; that is, a state space, with (usually) an infinite number of possible states. Of course, models with a more limited numbers of states can be made, which are then idealizations of the concept, as discussed earlier. In a model of a concept (as in a model of a physical entity) the level of refinement is determined by the specific role the model needs to play. The more states or contexts associated with any given concept are included, the more states and contexts associated with other concepts are included. Referring back to Rips' No-peeking principle, one could say that in the SCOP approach there is *always* peeking, and the more detailed the model the more peeking there is. Indeed peeking defines the structure of the concept.

The Structure of Natural Relations

We saw how basic level categories (e.g. CHAIR, DOG) mirror the correlational structure of properties as they are perceived, learned, and used by individuals acting in the world, and how further discrimination occurs at the subordinate (e.g. KITCHEN CHAIR, SPANIEL) and the superordinate (FURNITURE, ANIMAL) levels. The structure of this hierarchy of concepts is modeled in SCOP by deriving the structure of natural relations for sets of states Σ, contexts $\mathcal{M}$, and properties $\mathcal{L}$ of a concept (Aerts & Gabora, 2005a). Concretely this means the following. If a state p is more constrained than a state q (*e.g.* SPANIEL is more constrained than DOG) we say that p 'is stronger than or equal to' q, thereby introducing a partial order relation in the set of states Σ. Similarly, if a context e is more constrained than a context f (*e.g.* 'in the big box' is more constrained than 'in the box') we say that e 'is stronger than or equal to' f, thereby introducing a partial order relation in the set of contexts $\mathcal{M}$. Next we incorporate more of the complexity of the natural world (and our imperfect internal mirrors of it) into the model by introducing 'and' and 'or' contexts. For example, given the contexts 'in the box' and 'on the table' we can construct the contexts 'in the box and on the table' and 'in the box or on the table'. Technically we say that by adding the 'and' and 'or' contexts, M obtains the structure of a lattice. Next we introduce the 'not' context, resulting in the production of contexts such as 'not in the box'. Technically we say that through this introduction of the 'not' context, an orthocomplementation structure is derived for $\mathcal{M}$. An orthocomplemented lattice structure is also derived for the set of properties $\mathcal{L}$, making it possible to construct a topological representation of a SCOP in a closure space. The important thing from a non-technical point of view is that the states and contexts one experiences in the course of real-life situations and actions in the world are not the only ones that participate in our thoughts. Our minds are capable of constructing a multitude of deviations from these original or 'raw' states and contexts, and SCOP is able to model this.

HOW SCOP MEETS THE NEED FOR A NEW APPROACH

The section titled 'The need for a new approach' summarized what we see as the major unsolved issues to be accounted for by a theory of concepts: 1. contextuality, 2. concept combination, and 3. Similarity, compatibility, and correlation. Let us now return to these issues and see how they are dealt with in SCOP.

1. Contextuality

We report briefly on some experimental tests of the theory that demonstrates its ability to account for context effects. One might expect empirical testing of an ecological theory of concepts to involve experimental support for the view that concepts are grounded in real world situations. That concepts are tethered to perception and action has been demonstrated elsewhere (for an overview see Barsalou, 1999), and we take it as a given that this is the case. However, to claim that all concepts are mere rearrangements of percepts is like claiming that a plant is just seed + water + sunlight. Basic level concepts are directly grounded in experience; subordinate, and superordinate concepts are grounded too, but less directly. To gain insight into the ecological nature of not just basic level concepts like DOG but abstract concepts like DEMOCRACY requires that we investigate not just the interaction between mind and world but the interaction between one concept and another within the mind. This does not mean that the concepts live untethered in a world of linguistic abstraction; it means that they are grounded as in 'growing *from* the ground', not grounded as in 'completely underground' (Gabora, 1999a). Just as a seed transforms into a sprout, which emerges from the ground as a plant, an abstract concept can originate through, or be grounded in, perceptual experience, yet turn into something quite different from anything ever directly perceived. This is why in order to determine whether the approach described here is promising it was necessary to perform experiments that test whether the structure of relationships *amongst* concepts as they are used by and interacted with by human subjects is such that the formalism can model them.

The first experiment is outlined in detail elsewhere (Aerts & Gabora, 2005a). The goal of this experiment was to test the prediction that applicability of *each* property varies for *each* context-driven transition from one state to another, as does the typicality of each exemplar. Each subjects was given a questionnaire with a list of fourteen exemplars (i.e. states) of PET, such as DOG and PARROT, and seven possible contexts for PET, such as 'the pet is chewing a bone' and 'the pet is being taught to talk'. They were instructed to rate on a 7-point Likert Scale the likelihood with which a given exemplar of pet might be encountered in each context. In SCOP, states of PET were represented by vectors, and contexts were represented by projectors. The formalism determines the formulas that describe the transition probabilities between states, and the formulas for calculating the weights of properties, allowing us to predict typicality of exemplars and applicability of properties. If the numerical values obtained in the experiment with human subjects had turned out to be statistically different from those calculated when the quantum calculus was applied to these vectors and projectors, this would have indicated that we were on the wrong track and that SCOP does not provide a good model of concepts. However this was not the case; the numerical values obtained in the experiment with human subjects were statistically equivalent to those that resulted from the calculation. This was replicated in another experiment (the results of which are not published elsewhere) with different subjects using a different concept, the concept HAT. Subjects were given five different contexts involving HAT, *e.g*. 'hat worn to be funny' or 'hat worn for protection', and asked to rate (1) the typicality of various exemplars (states), such as helmet or coonskin cap, and (2) the applicability of various properties, such as 'hard' or 'has a brim'. For both concepts, statistically significant differences were found in the ratings for both typicalities of exemplars and applicabilities of properties for different contexts.

Another experiment (the results of which also are not published elsewhere) was performed to determine if effect of context is observed when subjects *generate* exemplars and properties (not just rate their typicality). Subjects were given five different contexts involving GAMES, such as 'games played with the family' or 'games for smart people'. They were instructed to give (1) one appropriate examplar (state) of a game, *e.g*. chess, and (2) one applicable property of games, *e.g*. funny. Statistically significant ($p < .001$) differences were found in the generation of different states and properties for different contexts. For example, when asked for an exemplar of HAT given the context 'worn at a rodeo', most subjects respond COWBOY HAT, but a small percentage respond BALL CAP. Similarly when asked to give a property of the concept HAT given the context 'worn at a rodeo', many subjects respond 'wide brim', but a small percentage respond 'pointy'. It is important to note that these findings do not simply support the hypothesis that context affects typicality of states and applicability of properties. They support the prediction of SCOP that the applicability of *each* property varies for *each* context-driven transition from one particular state to another, as does the typicality of each exemplar.

2. Concept Combination as a State of Entanglement

A state space enables us to describe the various states of an entity. We need a state space that is able to express states of potentiality, superposition states, and collapsed states. In (Aerts & Gabora, 2005b) we embed the sets of contexts and properties in a much less abstract, more constrained mathematical structure, the *Hilbert space*, which is a vector space over the field of complex numbers[5]. A state is described by a unit vector or a density operator, and a context or property by an orthogonal projection (Figure 1).

[INSERT FIGURE 1 ABOUT HERE]

By embedding concepts in complex Hilbert space it was possible to prove that the combining of concepts can be mathematically modeled as entanglement, accounting for the emergence of new properties, resolving the PET BIRD and TOY DWARF effects mentioned previously (Aerts & Gabora, 2005b). As mentioned earlier, if H_1 is the Hilbert space describing a first concept, and H_2 the Hilbert space describing a second concept, the conjunction of these concepts is described in the tensor product space $H_1 \otimes H_2$. The resulting spontaneously generated entity is said to be the *compound* of the individual Hilbert spaces of its two constituents. It consists of both (a) *product vectors*, and (b) *non-product vectors*, which describe states of entanglement that can exhibit a gain or loss of properties compared to its constituents. We saw how the pet fish problem has resisted explanation because theories of concepts have had no means to describe dynamical change of state under the influence of a context and thus account for phenomena such as loss or gain of properties, or unexpected typicality of exemplars when concepts combine. In

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[5] The complex numbers are the field of numbers of the form $x + iy$, where x and y are real numbers and *i* is the

the SCOP formalism this is tackled as follows, as explained in detail elsewhere (Aerts & Gabora, 2005b). We take 'The pet is a fish' to be a context of the concept PET, and 'The fish is a pet' to be a context of the concept FISH, and look at the change of state they mutually provoke in one another. An experiment was performed to obtain numerical data to plug into the infamous entanglement equations in order to test the theory that concept combination can be modeled as a state of entanglement. Subjects were given the contexts *e1* 'the fish is a pet' and *e2* 'the fish is a fish', and asked to rate the typicality of various states of FISH such as GOLDFISH and SHARK. Vectors were used to represent the different states of the concepts tested, and projectors used to represent the contexts. A non-product vector describes the conjunction PET FISH as an entangled state of PET and FISH. The tensor product procedure also allows the modeling of other combinations of concepts such as 'a pet and a fish'. In this case, product states are involved, which means that the combining of concepts employing the word 'and' does not entail entanglement. When the quantum calculus in Hilbert space was applied (exactly as is done in quantum mechanics), the weights yielded by the calculation matched the weights measured in the experiments ($p < .0001$). Thus numerical support was obtained for the theory that concept combination can be modeled as a state of entanglement. The mathematics extends readily to more complex combinations of concepts; thus the approach has clear implications for the productivity of spoken and written language.

More recently (Aerts, 2008) we have been able to provide a quantum interpretation for the experimentally demonstrated overextension and underextension of disjunctions of concepts (Hampton, 1988). For example, subjects reliably rate ASHTRAY to be less a member of the disjunction HOUSE FURNISHINGS OR FURNITURE than of either HOUSE FURNISHINGS

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imaginary unit equal to the square root of -1, √-1.

or FURNITURE. In the quantum interpretation, concepts and conjunctions of them are represented as vectors in complex Hilbert space, and a weight referring to the extent to which an item is an instance of a concept is modeled using quantum weights that are calculated using the standard quantum procedure. It turns out that the quantum effects of interference and superposition are at the origin of the overextension and underextension effects. Interestingly, complex numbers are needed to model these effects; representing the states of concepts as vector spaces over the field of real numbers gave results that did not match the experimental data.

3. Similarity, Compatibility, and Correlation

We have seen that the problem with similarity is that it is context-dependent; similar with respect to *what?* There are always an infinite number of dimensions against which two things can be compared, and thus an infinite number of ways of determining whether two things are similar.

The non-classical quantum-like structure of a concept is revealed in that for two contexts *e* and *f*, a state is not necessarily an eigenstate of the context *e* ‘or’ *f* if and only if it is an eigenstate of *e* ‘or’ an eigenstate of *f*. Moreover, although any state is an eigenstate of *e* or *not e*, it is not so that any state is an eigenstate of *e* or an eigenstate of *not e*. For example, given contexts *e* ‘The man is a dwarf’, and *not e* ‘The man is not a dwarf’, any state of MAN for which size is irrelevant (*e.g*. SALESMAN) is neither an eigenstate of *e* nor of *not e.* As another example, consider the concept PET and *contexts g* ‘runs quickly’ and *not g* ‘does not run quickly’. Any state of PET that does not refer to what the pet is doing is neither an eigenstate of *e* (where PET adopts a state for which it ‘runs quickly’) nor of *not e* (where PET adopts a state for which ‘it is not so that the pet runs quickly’).

The notion of *compatibility* from quantum mechanics is useful here; properties are compatible if they pertain to the same context. This can help us with a certain kind of problematic situation that arises in the study of concepts and categories, as exemplified by DWARF getting categorized with GIANT rather then with SALESMAN. In the SCOP formalism, DWARF and GIANT pertain to the same context, specifically ‘size’. ‘Size’ may not appear at first to be a context; it may seem different from contexts considered earlier, such as the context ‘circus’ as it pertains to ANIMAL, or the context ‘dinner party’ as it pertains to BEVERAGE. But what is the case in all these examples, and what is critical in order for something to be a context, is that it acts on a state of a concept such that the state changes to another state with a different set of properties and a different set of typical instances. Much as in the context ‘dinner party’ the state of the concept BEVERAGE changes from GENERIC BEVERAGE to WINE, if the concept is HUMAN and the context is ‘size’, one’s mind turns from thoughts of a human that is average in size to one that is unusual with respect to size, e.g. DWARF or GIANT. It is because DWARF and GIANT pertain to the same context that they are said to be compatible. Similarly, WHITE and BLACK, although opposite, are compatible properties since they pertain to the same context, namely ‘colour’ (Gabora & Aerts, 2002b). It is interesting to note that one of the basic axioms of quantum mechanics, referred to as ‘weak modularity’, is the requirement that orthogonal properties are compatible. Note that compatibility is thus quite a different kind of similarity from correlation – similarity with respect to values for those contexts. Distinguishing between them gives us a refined notion of similarity, which has been used to develop a context-sensitive measures of conceptual distance (Gabora & Aerts, 2002b).

SUMMARY AND CONCLUSIONS

> The very meaning of “survival” becomes different when we stop talking about the survival of something bounded by the skin and start to think of the survival of the system of ideas in circuit.
>
> -Gregory Bateson, 1973 (p. 483).

Hitherto, most theories of concepts have not strayed far from the image of a concept as something entirely pre-defined which, when used, simply gets turned on, like the starting of a motor or the flicking of a light switch. For example, the sight of a baby is thought to activate a predefined set of graded features, or exemplars, or a theory about what constitutes the concept baby. But to be of significant value in understanding how concepts come into play when we make sense out of real world situations and engage in meaningful interactions, a theory of concepts must incorporate how meaning emerges through interaction with elements generally considered to be external to them, i.e. elements of the context. We view concepts not as fixed representations or identifiers, but rather as bridges between mind and world that *participate* in the generation of meaning. To this end we identified the importance of an ecological approach to concepts and discussed the State Context Property (SCOP) theory of concepts, which uses a generalization of the formalism of quantum mechanics, as a concrete example of this approach. Both quantum mechanics and concepts require a mathematics that provides a place for context in the formal description itself. Much as the state of a quantum system collapses under the influence of a measurement, a concept actualizes in conscious experience when evoked in a particular situation.

Adopting the terminology of the mathematics underlying the quantum formalism, we differentiate between superposition states of a concept with respect to a specific context, which undergo a change of state under the influence of this context, and eigenstates with respect to this context, which do not change under the influence of this context. In a superposition state with respect to a context, the set of relevant features and their values are not actualized, while in an eigenstate with respect to this context they are. In this approach, *peeking* (from either another concept, or an external stimulus) is taking place; concepts require a peek, a context, to actualize them in some form. We investigate the types of situations concepts ‘find themselves in’ and the relationships they forge amongst themselves; in other words, how they manifest *in the context of* one another in myriad ways, giving new shades of meaning to new situations. We distinguish between similarity with respect to which contexts are relevant (compatibility) and similarity with respect to values for those contexts (correlation). The internal structure of a concept is described using a lattice to represent the correlational structure amongst properties (the extent to which one property implies another), and this structure has the flexibility to shift according to context. Conjunctions of concepts are described as states of entanglement using the tensor product. This can be generalized to more complex kinds of conceptual combinations, thus putting us on the way toward a theory of concepts that account for their flexibility and compositionality.

The SCOP approach discussed here is still quite abstract, and work remains to be done to elaborate concrete and apply it to specific situations. But we believe that the ideas put forth in this paper have important implications beyond a fuller understanding of concepts and percepts as elements of cognition. They move us toward a deeper understanding of the mind in relation to its environment, including how it spontaneously reorganizes and refines the particular constellations of concepts employed in the representation of particular situations, thereby weaving and re-weaving internal webs of understanding into a more fitting, pleasing, or consistent whole. This has implications for how the individual achieves his or her own unique style of ‘seeing and being in' the world, his or her own worldview. In keeping with Rosen's (1991) work on closed loops in cognition, and Shaw's (1981) ideas about alleviating endless regress through closure, we are working toward uniting previous work on how a worldview attains an integrated, more or less consistent internally structure through conceptual closure (Gabora, 1999b, 2000) with this quantum inspired theory of concepts (Gabora & Aerts, 2008). Following from the proposal that the worldview is what evolves through human culture (Gabora 1998, 2004, 2007), we believe that the ideas in this paper could play a key role in achieving a deeper understanding of cultural evolution. At the very least we hope that they constitute a step toward a theory of the role of concepts in mediating situation action, and thus of what an "ecology of mind" could be.

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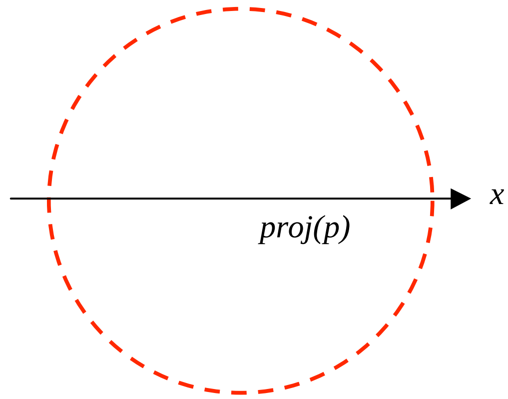

Figure 1. A state *p* is described as a vector in Hilbert space and a context or property by an orthogonal projection, labeled *proj(p)*.