Multilevel Approaches to Concepts and Formal Ontologies

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Abstract

In several disciplines there is a divide between advocates of formal, "classical" or symbolic approaches to representation, which can be expressed using standard formal logic, and advocates of biologically inspired, fuzzy or category-based approaches to representation, which can be implemented using fuzzy logic, neural networks, evolutionary computing and similar techniques. This paper argues that these two approaches should not be viewed as two mutually exclusive approaches but instead as two complementary forms of representation which both serve a purpose and can be combined. This is especially important with respect to formal ontologies, which currently only use formal, classical representations but which should utilize both approaches.

1 Introduction

In several disciplines there is a divide between advocates of formal, "classical" or symbolic approaches to representation and advocates of biologically inspired, fuzzy or category-based approaches to representation[1]. In this paper, the first approach will be referred to as "formal" and the second approach as "associative". The basic units of the approaches are called "formal concepts" and "associative concepts", respectively. These terms are used as defined terms in this paper and not in their common sense meanings. Table 1 contains a summary of their distinctive features, which are explained throughout this paper. The table is based on our own research and on Sloman (1996) and Blank (2001).

Formal concepts, which are similar to "classes" in classification research, are precisely defined with rigid boundaries. They usually have an extensional aspect, which is a set of objects they denote, and an intensional aspect, which is a formal definition or set of rules that can be expressed in formal logic. Formal concepts usually require some kind of symbolic representation but not all symbols represent formal concepts. Together formal concepts form a hierarchy, concept lattice or classification system based on the inclusion relation among formal concepts, which is also called ISA relation in AI and in this paper and is called subconcept-superconcept relation or broader term/narrower term relation in other disciplines. Systems of formal concepts are usually modeled or designed based on theories that humans have about the problem domain and the nature of possible solutions. They thus have a "top-down" nature. Formal systems can be evaluated in regards to logical correctness and completeness.

[1]While it could be argued that all representations are "symbolic", in AI the term is usually used with respect to symbols that can be comprehended and manipulated by humans. Neural networks are thus not "symbolic". Examples of "biologically inspired" representations are neural networks and genetic algorithms.

	formal	associative
concepts are ...	precise	fuzzy
generated by	abstraction, design top-down	emergence, gestalt laws ... bottom-up
extensional features intensional features	set of "objects" formal definitions formal logic rules	prototypes, exemplars stereotypes, image schemata family resemblances
relations reasoning	ISA hierarchy/lattice logical, formal causal inference, deduction classification	association similarity, contiguity co-occurrence association, induction clustering
representations	symbolic designed by humans	subsymbolic emergent
in a context that is	formal, general	associative, local
systems are	correct, complete macro-level discrete	probabilistic, dynamic micro-level continuous, "chaotic"
metaphors	information processing	biologically inspired (neural networks, evolution)
implementations	formal logic algorithmic, modular	fuzzy logic learning-based

Table 1

In contrast to formal concepts, associative concepts are fuzzy and without precise definitions or clear boundaries. Their extensional aspects can be modeled as prototypes, exemplars or fuzzy sets. Their intensional aspects can be modeled as schemata or family resemblances. But intensional features are often not known precisely. The only relationship among associative concepts is association (similarity, contrast, contiguity etc). Associative concepts do not usually form a strict ISA hierarchy. For example, an associative concept of "piano" could be subsumed under "musical instrument", "piece of furniture", or many other concepts depending on context. But each of these represents an abstraction of content and thus a formal concept. Associative systems are "bottom-up" because they are trained using examples from which structures emerge.

Associative concepts can serve as a model of how humans imagine concepts, which are called "cognitive concepts" is this paper. But other structures, such as emergent structures in some systems (see below), can also be modeled as associative concepts. There is some evidence from studies in selective brain damage (Damasio & Damasio, 1994) that some clustering or hierarchical organization of cognitive concepts does occur in the brain. For example, there are patients who lose all there knowledge about specific concept groups, such as vegetables, but retain all other knowledge. But there is no evidence that cognitive concepts form rigid ISA hierarchies instead of loose associations.

The distinction between formal and associative concepts is similar to but broader than Sloman's (1996) rule-based and associative forms of reasoning. Sloman's research is restricted to human cognition whereas the notion of formal and associative concepts can also be applied to systems. Furthermore, Sloman does not discuss connections such as emergence (see below). The distinction is also similar but not identical to Jacob's (1991) distinction between classes and categories. Formal and associative concepts are different models of representation (a structural distinction) whereas categories and classes tend to have ontological differences. Formal concepts do not need to be "mutually exclusive" because that would require a tree hierarchy. In a concept lattice, formal concepts are precisely defined but can be overlapping. For example, "dog" and "pet" can be precisely defined within a formal context but they can be overlapping. Whether "pet" is a formal or associative concept depends on how it is modeled in context. This is in contrast to Jacob's "categories" and "classes" where "pet" would usually be a category.

Both formal and associative approaches have advantages and limitations. Many arguments against formal concepts are based on psychological evidence (eg. Rosch (1973)) or linguistic evidence (eg. Wittgenstein). It is argued (Lakoff & Johnson, 1999) that formal concepts are insufficient because human cognition is embodied and situated. Further evidence against formal approaches is that classification systems are often unsatisfactory to users (compare Yahoo! with Google) because classification presupposes precise contexts but designers and users of a system are not usually in the same context. Associative approaches can avoid that problem by assuming that context itself is an associative (thus flexible) entity. In AI, more than 15 years of manual labor invested in the formal ontology[2] CYC (2001) have not yielded a universally useful and acceptable knowledge representation tool - most likely because the tool is formal and not situated or embodied.

On the other hand, Medin (1989, p.1476) states that "despite the overwhelming evidence against the classical view, there is something about it that is intuitively compelling". People want rigid organization. Patrons do not want to return to a library to discover that all books have been slightly moved over night because today's fuzzy representation is slightly different from yesterday's. Furthermore, the formal approach is computationally easy to implement because computers employ formal logic. While associative concepts in the form of neural networks have been successfully applied to small scale robotic or perceptual tasks such as face recognition, applications that combine a multitude of robotic, perceptual and cognitive tasks are not yet in sight. Even though CYC and similar formal ontologies are not perfect, they are frequently used in language processing and comprehension applications (such as on the WWW) because there is no equivalent tool based on associative concepts available.

So, if both formal and associative approaches have limitations but also show promise, it seems reasonable to consider combining both into a "multi-level approach". This is not a just a two-level approach because further levels, such as a linguistic level or a physical level, might need to be added (see below). Human reasoning does in fact appear to encompass several of these levels (Sloman, 1996) because humans are both capable of processing in an association-based mode and employing logical reasoning. Several cognitive scientists (Sloman (1996), Pinker (1991), and to some degree Clark (1997)) have recently been supporting models that are based on such a combination.

With respect to classification systems and formal ontologies this implies that it is time

[2]It should be noted that the term "ontology" in this paper is used in its AI or WWW meaning as defined, for example, by www.ontology.org and not in its original sense as used in philosophy.

to integrate the situated, embodied, contextual and perception-based nature of information into these systems. Of course, this requires some formal methods or models that describe how this integration could be achieved. The current dilemma of classification theory is that all existing classification schemes are based on formal concepts but the theoretical research in this area (eg. Jacob (1991) and Olson (1999)) emphasizes a criticism of the formal approach. There has been at least one implementation of a system (Ruiz & Srinivasan, 1999) that represents the nodes of a thesaurus (i.e. a formal structure) as neural networks (i.e. associative concepts). But this is not the only system that is conceivable.

This paper argues that if formal knowledge systems, such as classification schemes and formal ontologies, are ever to overcome their current shortcomings, they need to incorporate associative concepts. To achieve that they need to employ emergent structures (Clark (1997) and see below) and dynamic interactions (see below). This may not be an easy task. Essentially the problem of integration is equivalent to the gap between quantum mechanics (an associative system) and classical mechanics (a formal system), which has been studied since Einstein and is still unsolved. But there may be partial solutions, such as Ruiz & Srinivasan's system, that can prove successful and hopefully superior to contemporary, inflexible classificatory structures.

2 Features of formal and associative approaches

The features in table 1 are prototypical for formal and associative approaches. That means that not all approaches or systems necessarily have all the above mentioned features. Instead the features indicate a tendency because systems have a tendency to have either formal or associative features; a degree because the features can be gradual or overlapping; or a viewpoint because a single system can be analyzed from a formal or associative viewpoint. In the following sections, emergent structures, concept formation and definition, reasoning mechanisms and the use of symbolic representations are investigated in more detail. They describe important features of formal and associative approaches and reasons why they are so different.

2.1 Emergent and designed structures

The search engine Google is an example of the effective use of emergent structures. Clark (1997, p. 110) defines emergence by stating that "a phenomenon is emergent if it is best understood by attention to the changing values of a collective variable" and "emergent phenomena ... are thus the products of collective activity rather than of single components or dedicated control systems". Emergent structures require some complex structure from which they can emerge in a manner that cannot be explained by a single variable. They are beyond direct control and thus in contrast to designed structures.

Yahoo!'s hierarchy is entirely manually designed and has no room for emergent structures at all. Search engines, such as Lycos, Altavista and Google, use emergent structures because the outcome of a search is not explicitly stored in a database but instead generated at the time of the search based on the parameters of the search. But there is a fundamental difference between traditional search engines, such as Lycos and Altavista, and Google.

Traditional search engines are designed based on Salton's vector space model of information retrieval with some additional models of natural language processing, parsing, ranking and so on. The human involvement in creating these systems is significantly smaller than in Yahoo! but the assumptions that are implicitly contained in the model are quite complex. The emergent structures in these systems depend on occurrence of terms in documents and on the dynamics of natural language because they are highly affected by the polysemy and synonymy of natural language expressions. Experienced users can successfully find information if they are aware of language dynamics and formulate their queries accordingly (by using "and" and "or" to account for polysemy and synonymy, respectively).

In comparison to traditional search engines, Google uses a different framework for emergent structures. Its primary retrieval and ranking algorithm is not based on Salton's vector space model but instead directly exploits the WWW's network character, which is represented by which and how many pages link to a page and by the context generated by the anchor text of links. Thus although Google employs some algorithms for parsing and other natural language processing techniques, it is not the dynamics of term occurrence and natural language that is primarily responsible for the emergent structures but instead it is the dynamics of the WWW linkage structure itself that is responsible.

This does not imply that in general WWW dynamics are more effective than term occurrence or natural language dynamics. The success of a structure is context- and purpose-dependent. According to Clark (1997), it is difficult to explain why structures emerge and predict which structures emerge and thus even more difficult or impossible to engineer emergent structures. In this case in the comparison between traditional engines and Google, the effectiveness of Google's structures corresponds inversely to the complexity of the underlying model. That means that the system (Google) that uses an underlying model that is simpler (because a network is a mathematically simpler structure than a vector space) is also more effective. Again it is not known whether that is a general rule or just a coincidence.

Emergent structures are a characteristic of associative approaches because formal approaches contain rigid relations whereas the relations among associative concepts are associative and thus open to flexibility and discovery. While Yahoo! is a manually designed classification system, the WWW linkage structure that underlies Google is flexible, dynamic and unpredictable. At the same time the WWW linkage structure is not directly accessible to human analysis. There have been approaches to visualize the WWW linkage structure (compare www.cybergeography.org) but such maps represent associative structures and concepts, not formal concepts or classification structures. In a sense, Google presents successful results but it is difficult to explain exactly why that is the case. Again according to Clark that is typical for emergent structures.

To create a more transparent environment for users, a formal system could be added on top of the emergent structures. Search engines, such as Northernlight, appear to do that to some extent by providing an automatically generated folder hierarchy. To summarize, in the case of search engines it has proven successful to start with an associative approach (WWW structures) instead of a formal approach (Yahoo!'s classification scheme) but that does not mean that users would not like to see a formal perspective (in the form of an emerging classificationary structure) on top of the emergent structures. Formal and associative approaches are thus not exclusive but instead may be combined with each other in a multilevel approach.

2.2 Concept formation and definitions

Many animals clearly distinguish between male and female members of their species, between members and non-members of their species, between food and non-food and so forth. No matter in what manner animals actually mentally perceive this information, these are examples that can be modeled as associative or cognitive concepts. Clark (1997) emphasizes that there is no clear distinction between cognition and the external world. He states (p. 69) that "brain and world collaborate in ways that are richer and more clearly driven by computational and informational needs than was previously suspected." The following example illustrates that. The squirrels at my home have learned to beg for food by jumping onto the window sill to get my attention and then running to the door to accept walnuts. But it is very difficult to feed them anywhere else in the garden. This can be modeled as an associative concept of me as a food donor. But the concept includes the environment where the activity is happening and ritualized behavior by the squirrels that initiates the feeding activity. Associative concepts can thus be complex entities based on activities and associations.

Formal concepts on the other hand are more abstract and precisely defined. They are still dependent on context but the context itself can be formally described. For example, whether a tomato is a fruit or vegetable depends on whether the formal context is biology or cooking. In a cooking context, vegetables can be formally defined as elements of the main course. The tomato is thus a vegetable. In biology fruits are defined as containing seeds. The tomato is thus a fruit. As mentioned before, mutual exclusivity is not required as long as the definitions are precise but allow for overlap. This could, for example, be achieved by using a faceted classification (Priss & Jacob, 1999).

Formal definitions give rise to formal concepts with clearly defined extensions, i.e. sets of objects which they denote, and clearly defined intensions, i.e. the formal properties that are contained in the definitions. Formal concepts form an ISA hierarchy based on the rule that the extensions of subconcepts are contained in the extensions of superconcepts and the intensions of superconcepts are contained in the intensions of subconcepts. This hierarchy can be a tree-hierarchy or a concept lattice (compare Ganter & Wille (1999a) or Priss & Jacob (1999)).

Formal systems can be inconsistent, if there are contradictory definitions for items, and incomplete, if relevant information about the classification of elements is missing. But if a formal system is neither inconsistent nor incomplete, which can be achieved for fixed, limited contexts within specific domains, then the concepts are neither fuzzy nor prototypical as associative concepts are. This is because a formal system is an abstraction and corresponds only more or less well to associative or cognitive concepts. In some domains, such as the sciences, there exist large systems of formally defined concepts which function reasonably well for their purposes. Rosch's and Wittgenstein's criticism of the classical theory of concepts does thus not show that formal concepts are incorrect but instead it shows that they are entirely different from associative concepts.

Humans can think of "flying" as a prototypical activity of birds even though not all birds fly. If asked to define "bird", humans (at least in some cultures) produce a precise definition which is appropriate to their current context and which could be "birds are flying animals". If then prompted about a contradiction, such as "but not all birds fly", there are two choices: it could either be concluded that concepts are fuzzy and cannot be formally defined or the definition can be adjusted. In many cases the second choice prevails. That means even though Wittgenstein-Rosch followers are correct in stating that cognitive concepts are fuzzy, when prompted humans may abstract their cognitive concepts into formal concepts. This process is so seamless that humans may not even be aware of the difference between cognitive concepts and formal concepts as represented in formal definitions. This is an acquired and culturally-influenced preference because linguistic investigations (Iris et al, 1988) demonstrate that there are cultural differences in the degree of formality of concepts. Their study shows that the use of formal definitions is more prevalent in cultures with written languages compared to cultures without a tradition of writing.

The conclusion of this section is that both associative and formal concepts play a part in human rationality and humans can shift between both seamlessly and unconsciously. The differences between both types of concepts can be gradual. The shift from associative to formal concepts is a form of abstraction because the intension of a concept is specified (eg. "tomato ISA fruit"). A shift from a formal to an associative concept can occur, for example, if a word that denotes a formal concept in some context is uttered and invokes an associative concept in the mind of a listener. Any formal system can give rise to emergent structures (i.e. associative concepts) if the system is too complex and dynamic to be completely understood in terms of a fixed set of variables. Thus shifting the viewpoint on a system from formal to associative can provide new insights. This is further elaborated in the section on dynamic interactions below.

2.3 Reasoning mechanisms and contexts

Goldstone & Kersten (in press) state that "an extremely wide variety of cognitive acts can be understood as categorizations". The formal equivalent to this statement is that formal logic can be understood as an elaboration of formal concepts. This is because the logical assertion that "a implies b" can be formulated as "there is a formal concept which has property a and which is a subconcept of a formal concept which has property b". Ganter & Wille (1999b) provide the mathematical details that show that any logical clause can be represented as implication among attributes in a formal concept lattices. The "cognitive acts" related to formal concepts are thus classification, logical inference and causality. Associative concepts do not support these types of reasoning, which is why formal logic may fail if applied to them. Instead the main cognitive acts related to associative concepts are associations based on similarity, dissimilarity, co-occurrence and so on.

The two levels of formal and associative approaches are often complementary. Human cognitive acts are usually neither solely associative nor formal but instead a combination of both. The research by Chierchia et al. (1998) presents an example that supports this idea. They investigate the use of logical AND, OR, and NOT. A commonly held belief is that humans do not use these operators in the sense of formal logic. For example, if someone is asked whether they want tea or coffee then "both" is an unacceptable answer even though logical OR would allow this. Chierchia et al. point out, however, that in hypothetical and future-related contexts humans do use logical OR in the formal logical sense. For example, if someone bets \$10 that it will rain or snow tomorrow, this person will want to have the money even if it both rains and snows. There are thus some cases in which humans use the logical operators in their formal logical sense. Whereas in other situations the operators are overwritten by pragmatic rules that depend on the associations of the context. “Both” is an unacceptable answer for present tense OR-questions not because it is perceived to be illogical but because its association is pragmatically unacceptable in these situations. Humans easily shift between the different uses of logical operators in natural language. They only encounter problems if the operators are to be used in a strict formal sense in the context of search engines or programming languages which is in contrast to conventional associations.

To facilitate the integration of such multilevel approaches, clear representations of “context” are required because both associative and formal concepts are context-dependent. But the types of contexts are different. Formal contexts are abstract. Anything formulated with respect to a formal context is valid globally in the whole context if the formal system is consistent. Associative concepts are more detailed and “holistic” in that they contain many possible associations of a concept. But these associations are not globally valid. On an associative level (or in common sense arguments), contradictions can occur as long as they relate to concepts in different associative contexts. It may be acceptable to state that “birds fly” with respect to a local, associative context but not with respect to a global, formal context of biology. There has been a substantial amount of research in AI concerning contexts and shifting among contexts (compare Benerecetti et al. (2000) for an overview). Examples of specific theories are CYC’s micro-theories and dimensions (CYC, 2001) and Devlin (1991) and other’s situation theory. But these theories are too focused on the formal side and mostly ignore associative concepts and contexts.

Devices that support human cognitive processes, such as search engines, classification systems or programming languages, could be improved if they paid more attention to the differences between associative and formal concepts. These systems should have some flexibility to shift among representations. Both associative approaches and formal approaches, such as formal logic and other well-defined mathematical structures, should be employed by such systems.

2.4 Symbolic and other levels of representation

Another difference between formal and associative approaches is their use of symbolic representations. Examples of symbolic representations are natural or artificial languages or symbol systems. Presumably a significant difference between humans and other animals is the human use of symbolic representations. Experiments have shown that some animals, such as gorillas, are capable of learning more than 1000 signs of the American Sign Language (PBS, 2001). But that is only a fraction of the number of symbols that humans can acquire. Thus animal cognition cannot be primarily symbolic in the manner of human language-based cognition.

Both associative and formal concepts can be symbolically represented. Symbolic representations can thus be more or less formal. They can be quite informal, such as ambiguous words with multiple meanings, medium formal, such as disambiguated words in a specific context, and highly formal, such as scientific terminology which is consistently defined for use in multiple contexts.

A system of symbols, such as a natural language, essentially represents another level of representation in addition to associative and formal concepts. There are multiple and complex interactions between the different levels. Linguistic phenomena, such as polysemy, synonymy and lexical gaps (i.e. concepts that have a symbolic representation in one language but not in another) indicate that there is no simple one-to-one correspondence between linguistic units and concepts.

A fourth level to be considered is the external world. Independently of whether or in what format an external world may exist, it should be obvious that this level matters. But as Clark (1997) states, humans do not have a complete world model in their minds. That implies that there also cannot be a complete world model represented in language. The model that humans store in their minds is so incomplete that according to Clark it is possible to add, alter or remove objects in a person's visual environment without the person noticing it. The explanation is that the partial model that humans have in their minds is continuously updated by perceptual input. It could be argued that since human cognition involves both the external world and internal representations but language represents, in this case, only internal representations, language cannot adequately represent human cognition.

This poses a challenge for formal knowledge representation systems and formal ontologies, such as CYC. Since these systems store symbolic information, it follows that they can only represent a small proportion of the knowledge in question. CYC explicitly stores information such as "you can see a person's nose but not normally a person's heart" or "a normal face has two eyes and a nose". Humans do not need to permanently store such information if it can be deduced from other knowledge and the external world. In the face-example humans can look at a person present or evoke a mental image of a person.

It is important to note that although words can evoke cognitive or formal concepts in a human mind or represent such concepts in a specific context, in general, words are not equivalent to concepts. Wittgenstein's famous "game" example shows that the word "game" without contextual information is ambiguous. It denotes a fuzzy notion of "game-like". If "game" is uttered in a context, it is mapped to whatever fits best to being "game-like". This also explains metaphoric and creative word use, such as in "game of life". Since all words in a sentence have this incomplete indicative character, ambiguity is only resolved by a combination of words within a context. If the combination of words is sufficiently dense, some of the words become redundant. This redundancy ensures that understanding is even possible if some words are missed because of noise or unfamiliarity with them. For example, in "the XXX of chess", it might easily be guessed that XXX can mean game. Associative or formal concepts are thus not directly represented by individual words or phrases but instead they are associated with them in context. Symbol perception causes cognitive concepts to emerge in the human mind.

Disambiguated symbolic representations are usually more associated with formal concepts than with associative concepts because they are abstract and content-reduced. For example, in "she looked through the window" and "she painted the window", the word "window" refers in one case to the glass, in the other one to the frame. An associative concept of window can have both associations. But a formal concept of "window" would most likely either be in ISA relation to "transparent object" or to "intransparent object" but not to both. Out of context, the word "window" can point to an associative concept, but in the contexts of the two sentences it points to two different formal concepts. Because humans know that one cannot look through paint, it is clear to which formal concept of "window", the word refers in each sentence. But for a formal ontology or for a natural language processing algorithm employed by a search engine, it is difficult to disambiguate the two different senses of "window" because the system would need to have access to knowledge about the external world.

As a solution, an ontology could store as much world knowledge in symbolic form as possible. CYC does that. But even though more than 15 years of manual labor have been invested into CYC so far, its representation of external world knowledge is still not sufficiently complete. And because of the abstract nature of symbolic representations, it probably never will be. A multilevel approach for ontologies would be to combine the symbolic representation of knowledge that can be symbolically represented, such as "2+2 = 4", with a more associative, schematic representation of knowledge that cannot easily be symbolically represented. An ideal version of such an ontology would have a robotic/perceptive interface that could directly interact with the physical world. But that is quite futuristic. A simpler version would represent non-symbolic knowledge in 2- or 3-dimensional schematic simulations, which would be mapped to associative concepts using gestalt principles of perception. Given the modern achievements of robotics and research in gestalt perception, such a system is not quite so futuristic.

3 Dynamic interactions between associative and formal levels

As mentioned before, the distinction between formal and associative systems is based on a tendency of systems to have features of either one. But the distinction also depends on point of view. For example, natural language can be viewed as an associative system in that language use evokes cognitive concepts in the language user's mind. But language can also be viewed as a formal system in that dictionaries provide definitions for individual word senses that point to formal concepts.

As another example, formal logic itself is obviously a formal system but it also gives rise to emergent structures (or meta-level expressions) that cannot be explained within the original system. Steels (1994) supports this view by stating that emergent phenomena require description in a new vocabulary. Therefore associative concepts can even emerge from a formal system such as formal logic. Gödel's work also provides evidence for this. He proved that sophisticated mathematical structures, such as formal logic, are as a whole either inconsistent or incomplete. That means they cannot be entirely explained and thus have an associative character and give rise to emergent structures. Kuhn's (1962) paradigms may have the same function: each paradigm starts as a formal system. But viewed from an associative perspective some facts remain unexplained. A new paradigm needs to be formed to explain the emergent structures from a prior paradigm.

An analogy for the shift or rise from an associative level to a formal level is a computer game where players start at level 1 in an open structure and work their way up to a more complete structure. Once that is accomplished, level 2 is reached, which sets the players back to an open structure but on a more challenging level. A shift can start a snowball effect or positive feedback loop. For example, Clark (1997, p. 62) speculates that in the evolutionary development of humans "it may be that a small series of neuro-cognitive differences make possible the origination and exploitation of simple linguistic and cultural tools. From that point on, a kind of snowball effect (a positive feedback loop) may take over. ... It is as if our bootstraps themselves grew in length as a result of our pulling on them". Devlin (2000) speculates on a similar effect of a sudden increase of conceptual development in human evolution which coincides with a sudden increase in human brain matter.

Clark also calls this a "mangrove effect" in analogy to the way mangroves create islands by accumulating debris amongst their roots which in turn provides a substrate for the development of new mangroves. Some mental tasks such as writing poetry or planning activities are best tackled by alternating between a representation in the form of associative concepts, such as brainstorming or imagining, and a formal representation, which can even be external, such as writing or sketching the ideas on a piece of paper. Similar examples of the mangrove effect are the use of diagrams as associative devices in explaining mathematical facts or proofs, even though formal logic should be logically sufficient for explanations; or maps used for navigation, even though algorithmic descriptions, such as "turn right at the next corner", should be sufficient.

With respect to formal ontologies these feedback loops or mangrove effects have two consequences: first, formal ontologies need to provide methods for multilevel representational approaches, and for shifting among them, if the ontologies are expected to reach the complexity of human cognition, emergent structures and the external world. Second, the existence of feedback loops gives rise to the hope that perhaps all that is required to boost formal ontologies is to understand how to integrate formal and associative representations and how to initiate shifting. Once that is achieved the feedback loop between both forms of representation may take off and grow exponentially by itself. But, of course, reaching such an understanding may not be easy. Several disciplines provide hints for solutions: cognitive psychology because it studies how cognitive concepts are formed; several areas in AI and Artificial Life that study self-organizing emergent behavior; Dynamical Systems Theory (compare Clark (1997)); and last but not least Data Mining because it identifies associative concepts in large sets of "raw" data.

4 Conclusion

Several disciplines favor either formal or associative systems and approaches. This paper argues that both approaches need to be combined in the design of formal ontologies. This claim is supported by the fact that the human mind combines both types of representations. Such a combination often initiates a positive feedback loop because the expressiveness of representations increases exponentially. Examples for this kind of growth of expressibility are Kuhn's (1962) paradigm shifts and Clark's (1997) mangrove effects. A conclusion is that once ontology researchers succeed in incorporating associative structures into traditional formal ontologies, the representational capabilities of ontologies may grow exponentially. This task is not easy but systems that implement partial solutions (such as Ruiz & Srinivasan (1999)) already exist and several disciplines, such as psychology, AI, and Data Mining can contribute to solutions.

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