CHAPTER 6

SIMULATIONS OF EMBODIED EVOLVING SEMIOSIS

It is one simple idea that unites the present work: *Embodied Evolving Semiosis* (EES). It takes the form of Selected Self-Organization in the study of biological systems, and Evolutionary Constructivism in the study of Cognitive Systems. EES defines an inclusive position between that bridges the self-organizing with the symbolic paradigm. It asserts that the modeling of living phenomena cannot do without some account of both self-organization and symbolic representation (genetic or cognitive). EES understands the living organization to be comprised of self-organizing principles, which in (situated) interaction with an environment define inert (stable) memory structures that can be used to classify such interaction (see chapter 2). The particular material, situated interaction with an environment defines the universe of possible inert structures which determines the universe of constructed classification. In other words, the living organization requires embodied semiosis with an environment which in turn requires the notion of semantic emergence in addition to mere self-organizing emergence as discussed in chapter 2.

If the inert structures have more explicit symbolic attributes beyond dynamic classification, then the evolutionary potential of embodied semiosis becomes open-ended (see chapter 2). That is, if the classification of the situated interaction between living system and environment is based on local and not distributed memory, and is tied to a selection mechanism, we reach EES. In biological systems this is achieved with the description-based self-reproducing scheme of Von Neumann which effectively describes genetic-based natural selection. In cognitive systems, linguistic categorization may offer a similar selection mechanism which is based on social consensus.

In summary, EES requires:

1. Material self-organization in situated interaction with an environment
2. Semantic emergence: classification based on structural perturbation of self-organizing dynamics by inert memory structures that define a material symbol system
3. Selection in an environment leading to open-ended evolution

The first point implies the notion of embodiment. 1 and 2 imply the notion of emergent classification (semantics), that is, classifications are relative to the situated interaction of a living system with its environment and its ability to construct internal stabilities. Point 2 refers to the establishment of a descriptional syntax necessary to achieve open-endedness. Point 3 effectively grounds the personal, situated construction of points 1 and 2 in a particular environment which is common to other living systems. It is therefore a pragmatic dimension that leads living systems' classifications to be coherent with their environments in order to survive or effectively communicate. Genetic based natural selection evolves organisms that can coherently classify their environments well enough to persist. Linguistic interaction establishes a consensual selection of the personal constructions of cognitive systems so that they can coherently interact with one another. Points 1, 2 and 3 establish a complex system's semiosis with its environment by defining a pragmatic semantics of situated interaction. Syntax is defined by the mechanisms that manipulate the necessary internal inert structures.

Though allowing for open-ended evolution (as described in chapter 2), material symbol systems are nonetheless constrained in what they can describe. This point refers to the parts problem as stated by Von Neumann, and it was computationally modeled with the Contextual Genetic Algorithms experiments of chapter 5. This point was defended only for biological systems, since we have no evidence of the mechanisms that actually implement a system of linguistic structural perturbation in cognitive systems which can "rewire" cognitive emergent classification. In biological systems we have recognized the genetic system as the mechanism of structural perturbation which allows us to discuss its limitations in terms of the Parts Problem. Until more knowledge is gained about language and the brain the argument for EES in cognitive systems is more restricted than the one for biological systems (more on this in the next section). Notice that the application *Talkmine* developed in chapter 5 as a model of cognitive categorization, does establish an adaptive mechanism to "rewire" its long-term associative structure as it is perturbed by a system of linguistic interaction with its users based on short-term categorization. What was not studied were the limitations of such a "rewiring" mechanism. Figures 1 and 2 depict the skeleton of the arguments developed in this dissertation for selected self-organization and evolutionary constructivism respectively.

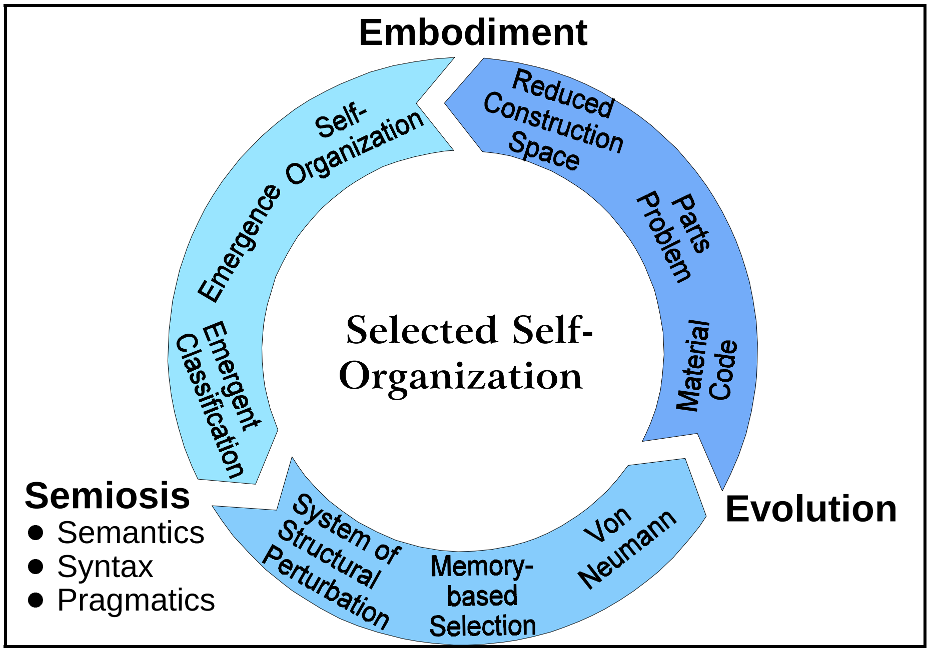

Figure 1: Skeleton of argument for EES in biological systems: Selected Self-Organization

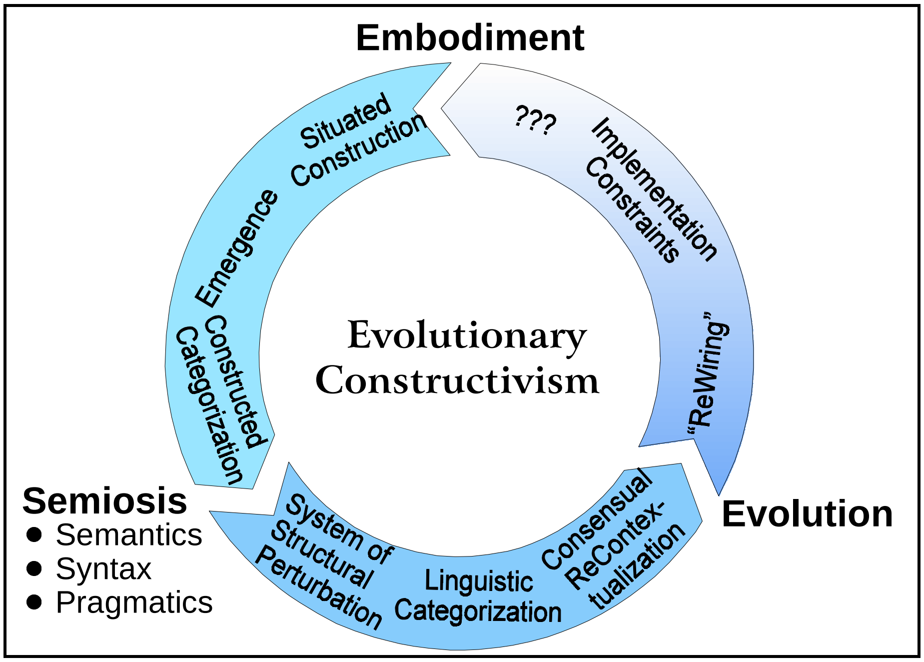

Figure 2: Skeleton of the argument for EES in cognitive systems: Evolutionary Constructivism.

1. What Would Invalidate EES?

For EES to be wrong, one of the three points discussed above would need to be proved false. Ample evidence has been given for the self-organizing characteristics of living systems in interaction with an environment [e.g. Kauffman, 1993; Goodwin, 1994; Salthe, 1995] in what is often referred to as the structuralist position. Much evidence has also been compiled for the self-organizing characteristics of cognitive systems [e.g. Churchland and Sejnowski, 1991; Varela, Thompson, and Rosch, 1991; Clark, 1993] in connectionist cognitive science.

That natural selection occurs in living systems is rarely disputed even by the most ardent structuralists. What may be debated is the extent of its influence. This is largely irrelevant for EES as it implies a case by case credit assessment of different aspects of living systems (see chapter 2). Much evidence has also been given for the mechanisms of social consensual selection of cognitive classifications (cognitive development) in education theory and psychology [e.g. Piaget, 1971; Pask, 1975; von Glasersfeld, 1993].

The second point may require more caution. It is the existence of material inert memory structures functioning as symbols that are used in the classification of an environment, as well as in establishing a relation to dynamic building blocks that eventually construct a self-organizing classification. If no such inert structures are proved to exist in biological and cognitive systems, then EES as described in the present work is not a valid systems theoretic framework to study the living organization, biological or cognitive.

In biological systems, the existence of these inert structures is well established. Indeed, the genetic system defines an effectively symbolic coded relation between genes and aminoacid chains that develop into phenotypes. Genes, though probably more dynamic than usually thought of, are based on DNA molecules which naturally have some dynamic properties. However, when used as descriptions of aminoacid chains

DNA molecules are essentially inert information carriers, since their function in the genetic system is not defined by their minimal reactive chemical characteristics but by the sequence of constituents (nucleotides) they are comprised of. Changing this sequence does not change the reactive, dynamic, characteristics of the DNA molecule, but it changes the information it carries to the genetic decoding machinery. It is also understood that genes act as the vehicles of descriptional variation necessary to define von Neumann's scheme of open-ended evolution. Therefore, for biological systems EES has been all but proved, even though the advantages of using such complete semiosis in living organisms are usually not fully understood. The Contextual Genetic Algorithms presented in chapter 4 and 5 aim precisely at the exploration of these advantages whose results are discussed in the next section.

In cognitive systems the story is quite different since no such inert structures have been found. I am convinced that some form of such structures will one day be discovered, but if the reverse is eventually proved, that is, that no such structures exist, then EES will not be valid for cognitive systems. We have plenty of evidence for the self-organizing, connectionist, attributes of cognition, which is effectively non-symbolic [Varela, Thompson, and Rosch, 1991]. However, all current models of connectionism are very incomplete at describing cognitive behavior, in particular its metaphoric characteristics and open-ended associative power. This leads some [e.g. Clark, 1993] to defend that connectionism is only part of the story, and that cognition cannot be completely characterized by non-representational, action-reaction, self-organizing situated interaction. Since connectionist models cannot efficiently deal with open-ended contextual dependencies and metaphor, all bets are still open as to what constitutes the nature of cognitive behavior, at least until we learn more about the brain.

In Chapter 3 and 5 I developed a model of cognitive categorization using evidence sets, which culminated in the *TalkMine* application. This model proposes that prototype linguistic categories function as a temporary system of structural perturbation of an array of context-specific dynamic networks that keep long-term associations in a connectionist manner. The consensual selection of these categories by the environment eventually adapts the long-term associations to such environment. It is a representational mechanism of structural perturbation and, given a large number of context-specific networks, offers the ability of open-ended, multi-context, categorical constructions. The long-term connectionist networks can be seen as the dynamic building blocks necessary for environmental classification, while the short-term categories offer the ability to harness such dynamics, with a specific syntax defined in *TalkMine* by Evidence Sets. Furthermore, these categories offer a selection mechanism in consensual environmental interaction through conversation with other categorizing systems. If such a system of structural perturbation does occur in the brain, then some sort of information carrier for these short-term categories will have to be found.

2. What Does EES Have to Offer to AI and AL?

Besides identifying the concept of EES in its varieties of Selected Self-Organization and Evolutionary Constructivism as a systems theoretic framework for biological and cognitive systems, the purpose of this dissertation is to actually propose models for AI and AL that take advantage of the EES concept. Figure 3 shows the layout of the dissertation in trying to achieve this. In chapter 2 EES was explored philosophically, while chapters 3 and 4 approached the subject from the point of view of cognitive and biological systems respectively. Chapter 5 described the computational applications that can be built from the EES framework with significant practical application potential.

2.1 Evolutionary Constructivism and AI

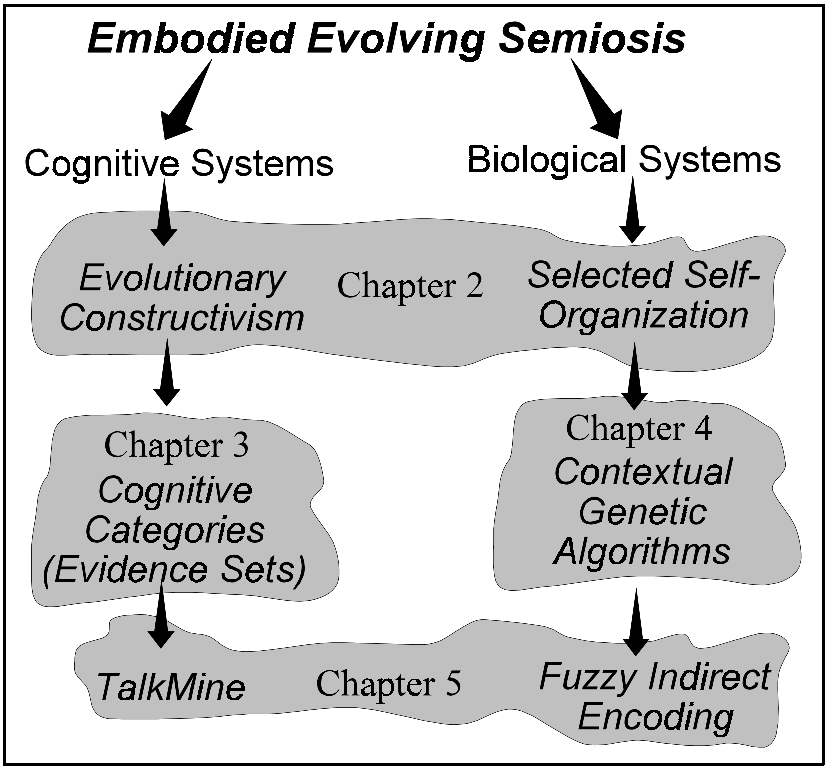

Figure 3: The Exploration of Embodied Evolving Semiosis undertook in the present work

Evidence Sets were proposed as models of short-term prototype categories in an Evolutionary Constructivist framework that assumes a connectionist, self-organizing, long-term memory organization. Evidence Sets model the subjective, context-dependent, uncertain, linguistic categories that are to be used in a socially consensual system of structural perturbation of long-term networked memory. These ideas are then implemented in the *TalkMine* application of Chapter 5. *TalkMine* does not use distributed connectionist networks for its long-term memory banks but a relational database structure which captures many of the desired characteristics of connectionist machines (see chapters 3 and 5). In this sense, it offers a hybrid architecture which simulates both the personal, self-organizing, construction of long-term associations and the communicatable, short-term, categories that allow the system to adapt to its environment as it interacts with its users. This defines the desired Selected Self-Organization or Evolutionary Constructivism in a computational environment.

Furthermore, it is by virtue of this system of short-term construction of categories which perturbs the long-term networked memory banks, that the bringing together of many different contexts is attained. The possibility of utilization of many contexts establishes a virtually open-ended association mechanism capable of relating concepts that would otherwise be highly distinct. Such capability effectively simulates metaphorical categorizations (see chapter 5). The continued development of systems such as TalkMine and Evidence Sets, is necessary in order to lead AI away from fruitless debates over the merits of self-organizing or symbolic paradigms. If we accept cognition to depend on EES, then the future of AI should be on hybrid structures such as *TalkMine* that try to bridge the gap between self-organizing constraints and symbolic open-endedness, and in so doing define very useful applications for data-mining problems.

2.2 Selected Self-Organization and AL

Similarly Contextual Genetic Algorithms (CGA's) were proposed as means to model more accurately the self-organizing, developmental, constraints of genetic driven Natural Selection in a Selected Self-Organization framework. The inclusion of indirect encoding between genetic descriptions and problem solutions in evolutionary computation applications, is an attempt to simulate embodiment in a computational realm. The results obtained with the Fuzzy Development Programs (FDP) CGA's in chapter 5, which allow large information reduction of genetic descriptions, show the advantages of applying the EES concept to evolutionary computation. They also show that the evolution of solutions for a given problem depends on the particular (simulation of) dynamic building blocks of the genetic system. In the FDP CGA's, this means that the pool of Fuzzy Set shapes and operations selected dictates the space of solutions that be constructed. In other words, Fuzzy Sets work as the material building blocks that constrain the evolutionary potential of an (artificially) embodied symbol system.

The CGA model implements both enabling and restraining constraints of evolutionary systems. The existence of a finite number of building block eases the information necessities of genetic descriptions, enabling the construction of complex solutions from simple descriptions. On the other hand, depending on the richness of these building blocks, the space of possible solutions is restrained since not all possible solutions can be reached, but only those that can be built out of these building blocks. If the EES framework is right, that is if evolutionary systems are based on embodied evolving symbol systems, that follow Von Neumann's scheme of descriptional selection but which equally emphasize the dynamic constraints of a symbol system's building blocks (the parts problem), then AL must be preoccupied with models of life-as-it-could-be that explicitly define a particular simulated embodiment from which the living organization is constructed.

The CGA model of chapter 5 shows that genetic driven selection leads evolving symbol systems to seek higher values of fitness only in so far as its specific embodiment can reach them. Evolution is open-ended only in the context of a given set of material building blocks. Thus, AL, like AI, should avoid the fruitless debate over the supremacy of selection or structure, and devote itself to inclusive strategies that incorporate notions from both paradigms. AL can indeed offer the right forum to implement a new synthesis of these two camps of evolutionary thought, by investigating computationally the relative importance of the several factors that define evolutionary systems. In other words, AL is the ideal field to study the credit assignment problem of evolutionary systems. The CGA model developed in chapters 4 and 5 offers the possibility of studying how the same problem (same fitness) can be solved by differently embodied, evolving, symbol systems defined by different sets of Fuzzy Set building blocks. In this sense, the CGA model opens the door to an inclusive, synthetic, theory of Artificial Evolutionary Systems.

3. Limitations of EES

3.1 The Origin Problem

EES as presented in the present work does not address the origin of semiosis itself. It defends that the living organization requires symbolic representation to be accurately simulated, but the arguments on which it is based follow from ample evidence obtained from the observation of biological and cognitive systems – the genetic and natural language systems. The problem of the origin of symbolic representation is not discussed. How is it that symbols appear in the living organization from a non-informational milieu is a question that is beyond the scope of this work. Indeed, such is the main question that any theory of the origin of life or cognition must answer. EES can only stress the central importance of the concept of embodied semiosis. It may therefore offer yet another modest push to direct the research of problems of origin to the mechanisms that would allow the emergence of semiosis from self-organization.

3.2 Computational Limitations

The computational models of EES developed in chapter 5 one way or another struggle with the necessity of simulating a dynamic self-organizing system which is harnessed or structurally perturbed by some representational syntactic manipulations. *TalkMine* uses the language of Evidence Sets to structurally perturb a model of dynamic representation defined by relational databases, leading the associative memory banks to match the expectations of the consensus of its users. The CGA model uses a genetic variation engine to perturb a dynamic system simulated by Fuzzy Sets which can construct solutions for some problem.

The problem of building models of EES such as *TalkMine* and CGA's in an universal computation environment is that, at some level of the simulation, the dynamics of self-organization must also be symbolically computed. In natural EES systems, matter does not have to compute its next state as it self-organizes, but merely follow the laws of physics. When we use universal computers, every single aspect of the simulation must be computed. For instance, natural genetic systems do not have to describe the phenotypes they produce in all their physical details, instead they merely have to describe the set of aminoacid chains that develops into such phenotypes. In other words, the natural embodied semiosis of biological systems utilizes pre-existing order that "comes for free" with the laws of matter. Conversely, computational simulations of these systems must not only describe the genetic descriptions but also the self-organizing dynamics in all of its details, which burdens simulations tremendously.

The models developed in chapter 5 try to simplify the simulation of dynamic interactions as much as possible and still preserve some of the essential characteristics of self-organizing, connectionist, dynamics. *TalkMine* uses relational databases instead of true connectionist machines precisely to avoid the lengthy process of re-training that such systems require, which is nothing more than the simulation of self-organizing classification behavior. This move allows *TalkMine* to maintain the required associative metric produced by connectionist machines with a simpler re-computation algorithm (see chapters 3 and 5). The FDP CGA uses a Fuzzy Set system of representing a dynamical system without actually implementing one also to avoid lengthy computations. FDP's maintain some characteristics of dynamic development (see chapter 4) but are not truly dynamic. In this sense, both *TalkMine* and the FDP CGA's try to streamline as much as possible the computational requirements of EES in a universal computer environment.

In order to build better models of EES we would do well by abandoning the universal computer framework and utilize genuinely hybrid computation environments. In other words, instead of using universal computers we might use problem-specific computers, also known as analogues. Consider the FDP CGA model. If the FDP's instead of being implemented in a program for a universal computer, were actual physical building blocks observing the desired behavior, then the software part would only have to implement the genetic variation engine which would harness such physical building blocks that do not require simulation. If the analogue part is fast enough, then we would save tremendously on computer resources and computation time.

Universal computation environments are based on a hierarchy of virtual machines that eventually produces a sequence of binary operations implemented in silicon flip-flops. As this hierarchy becomes more and more sophisticated, say with the development of visual object oriented programming, the size of the lower level binary operations needs to increase dramatically. By using problem-specific analogues, we can do without this complicated hierarchy at least when it comes to constant aspects of our computations. Universal computation by definition is designed to as independent as possible of physical law, while requiring the highest amount of syntactic description. Problem-specific analogue computation, harnesses more complicated physical processes that spontaneously follow pre-defined, unprogrammed, dynamic behavior thus requiring much smaller descriptions, though, of course, reducing the scope of possible problems that can be computed. In order to simulate complex systems that observe EES we would be better off with such hybrid computational/analogue systems precisely because EES demands the simulation of self-organizing dynamics that analogues could offer without computational expenses. Perhaps in the future, research into molecular computation might establish such a framework.

In the meantime, the FDP CGA model can be made much more effective if the Fuzzy Set building blocks are hardwired into a separate silicon chip that the universal computer can access without simulating it. Once a good pool of Fuzzy Set shapes and operations is found for a set of problems, they can be hardwired so that the software variation engine can act on them to construct solutions in a much faster way. In other words, if the indirect encoding layer of CGA's is substituted by a very fast physical process with some fixed, known characteristics, then the genetic variation engine would only trigger a true material development layer which would be in turn interpretable as a solution. This would establish a hybrid software/hardware system for optimization of informationally expensive problems.

Hence, in order to pursue richer models of EES, we need to do more than just simulating materiality, but actually use it. Practically, this means leading AI and AL more and more into the area of situated robotics and cognition. This direction of research re-emphasizes the earlier cybernetic vision of hybrid machines that intertwine computation and true self-organization in order to simulate the living organization in embodied interaction with an environment. Pragmatically it requires the investigation of good material substrates that can establish true, fast, self-organizing behavior in order to bypass lengthy hierarchical universal computation that must eventually boil down to the "chunk-chunk-chunk" of silicon 0's and 1's. Being an inclusive idea, EES does not imply the abandonment of symbolic computation, not at all, but it does alert us to a theory of life and cognition that must pragmatically use both universal computation and analogue self-organization in its models as previously defended by Cariani[1989].

4. Future Directions and Conclusions

Several formalisms and models were proposed in this dissertation to establish EES as a systems-theoretic framework for biological and cognitive systems. Even though good computational results were obtained from these models, there is ample room to develop them into richer formalisms.

Many avenues exist to develop and affirm evidence sets as robust mathematical structures to model linguistic uncertainty, a list of a few of these is presented next:

1. The study of information measures developed in section 5 of chapter 3 can address the very recent developments in the measurement of nonspecificity in nonsdiscrete domains, by discussing Klir and Yuan's [1995] Hartley-like measure in terms of the general measure of nonspecificity (11) proposed in section 5 of chapter 3. The computational simplicity of the relative measures of uncertainty developed in section 5.4 of chapter 3 can be evaluated by comparing them to standard measures of uncertainty.
2. A more complete belief-constrained theory of approximate reasoning can be pursued by proposing more operators for evidence sets such intersections and unions with extended range of operations. The combination of the belief qualification of evidence sets can be studied in more detail in order to develop more sophisticated forms of context preservation in linguistic categories.

3. Evidence sets can be compared to additional models of uncertain linguistic categories and belief formalisms such as the possible-world semantics of modal-logics, fuzzy rough sets,

rough fuzzy sets, etc. This study should pay attention to the computational costs of the different approaches as computational models of linguistic categories.

4. The definition of α-cuts for Evidence Sets can be pursued.

Similarly, contextual genetic algorithms can be better established as valid tools for evolutionary computation by pursuing different avenues:

1. More experiments should be made with different classes of computationally demanding problems. Only the repeated success of the scheme when applied to different classes of problems can establish it as a valid evolutionary computation tool.
2. Good pools of fuzzy set operations and shapes for different classes of problems can be investigated. Heuristics should be developed to aid the selection of such pools for particular problems.
3. Once good pools are discovered, they can be hardwired to obtain much faster evolution of solutions for general classes of problems. The software part of the implementation would be responsible for the genetic variation and decoding portions of the algorithm, while the hardwired part would be responsible for the development portions.
4. Artificial life models of environmental influence in genetic transcription and phenotypic development can be implemented and evaluated.
5. Artificial Life models of hierarchical development can be pursued. In this case, the building blocks that build the solutions (the fuzzy sets) should have several stages of development.

I consider the research presented in this dissertation to be an exploration into the coupling of symbolic controls to self-organizing dynamics. Computational models were developed in order to explore the limits of current universal computation techniques as models of EES. Many practical applications spin off this dissertation, which emphasize both the power and limits of symbol manipulation coupled to self-organization. Evidence Sets enlarged the mathematical study of linguistic uncertainty as an extension of Zadeh’s Fuzzy Sets by explicitly formalizing subjective context-dependencies. When coupled to networked memory structures, they also offer a model of cognitive categorization, which is used in the development of the useful database retrieval system *TalkMine*. Contextual Genetic Algorithms enlarge evolutionary computation as proposed by Holland, by including non-linear, self-organizing, relations between genetic descriptions and solutions to optimization problems. The FDP CGA experiments of chapter 5 demonstrate the power of this expansion. The underlying conclusion to the present work is that both symbols and dynamics are important to models of evolving cognitive and biological systems, and that the key to these complex systems is precisely the integration of both of these aspects.