Computational Modeling of Linguistic Pragmatics from a Complex Systems Perspective

(a career development position paper)

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Abstract

Current Natural Language Processing (NLP) systems face a variety of problems involving linguistic pragmatics, e.g., contextual effects and other language "use" issues, commonly observed in areas such as reference resolution, dialogue modeling, discourse structure, and information structure. These complex problems do not easily lend to purely symbolic or purely non-symbolic (e.g., statistical, connectionist) approaches, and current approaches fail to attain sufficient accuracy.

This project explores the following hypothesis: the above-mentioned difficulty arises because pragmatic phenomena emerge as the behaviors of complex systems. A complex system consisting of interacting components often self-organizes to show certain regularities but may also exhibit unpredictable behaviors. To examine this hypothesis, we will model certain pragmatic phenomena, i.e., information structure and context, and compare their behaviors with linguistic data as well as known properties of complex systems. In order to evaluate the generality of the principles in complex systems applied to linguistic pragmatics, we will also analyze the applicability of the principles to other complex phenomena in computing, biological, cognitive, and social sciences. In addition, the proposal is also extended to explore the possibility of applying the same principles to science education. In response to problems with undergraduate science education, e.g., declining enrollment and interests, it has been pointed out that science needs to be learned in more realistic contexts relevant to students' lives. The educational component of this project is to improve science and other undergraduate courses by organizing materials so that scientific ideas can be seen in the context of complex real-world problems.

The intellectual merit of the project is as follows. By computationally modeling pragmatic behaviors as complex systems consisting of interacting components, we aim to explain the source of the difficulty with purely symbolic and purely non-symbolic approaches. The current pragmatic research tends to be informal and descriptive, while formal approaches focus on more rigid aspects of linguistics such as phonology and syntax. This project attempts to bridge these two extremes by offering a platform for simulation and evaluation focusing on pragmatic phenomena. Our conclusion may well be that the pragmatic components of NLP systems must be built around principles in complex systems. Furthermore, by comparing the properties of linguistic pragmatics with other complex systems, we can open up the possibility of applying principles in complex systems in a broader range of phenomena.

The broader impacts of the project are as follows. Compared to more traditional, reductionistic approaches in science, the complex systems approach has a greater potential to appeal to all students including non-science majors, because this approach is to face real-world phenomena surrounding all of us. Reflecting this point, the author will incorporate principles in complex systems in virtually all of his courses, often pointing out how science would affect social and other complex phenomena. This is an essential element in his efforts to enhance liberal learning courses. Continuing his current practice, the author will publish all of his course materials on-line so that the information can be shared by anyone who is interested. The author will also continue mentoring undergraduate students on research topics related to this project. These activities are expected to make an impact on this primarily undergraduate teaching institution.

1. Introduction

Context of the Project

Current Natural Language Processing (NLP) systems still face a variety of pragmatic problems, e.g., contextual effects and other language "use" issues. As a result, computational analysis of linguistic pragmatics is an active area of research. Main areas of research include reference resolution (e.g., Mitkov et al., 2002), dialogue modeling (e.g., Allen and Perrault, 1980), discourse structure (e.g., Grosz and Sidner, 1986), information structure (e.g., Hajicová et al., 1995), and so forth. For example, with the understanding of "information structure" (i.e., the old/new contrast in each sentence as in Lambrecht, 1994, Vallduví, 1990), we can improve NLP systems with respect to a number of aspects such as generation of contextually appropriate intonation in speech applications (Prevost and Steedman, 1994), choice of context-dependent words in machine translation (Sgall et al., 1986), and analysis of text readability (Komagata, 1998).

Research and Educational Problems

The two mainstream approaches to NLP, including pragmatics, have been symbolic (e.g., rule-based as in Hajicová et al., 1995) and non-symbolic (e.g., statistic/connectionist as reviewed in Manning and Schütze, 2000), reflecting the second artificial intelligence debate (e.g., Chalmers, 1990, Fodor and Pylyshyn, 1988). However, many pragmatic phenomena, including information structure, escape purely symbolic or purely non-symbolic analyses. For example, while it is possible to analyze information structure fairly well using a symbolic approach, it would be difficult to exceed an accuracy of 85% for a specific task, as shown by the author (Komagata, 1999). On the other hand, non-symbolic approaches would face the problem of extracting and using rules or principles which can be processed symbolically. For example, complex linguistic structures in English that signals an "old" or "new" component would not easily be captured by approaches such as the Hidden Markov Models. One possibility would be to use the hybrid of symbolic and non-symbolic approaches (e.g., Sun and Bookman, 1994). Although such an approach could improve the performance of certain systems (e.g., Wermter, 1994), there will be new issues with interfacing the two qualitatively distinct components and difficulty with seeing underlying principles. The main research question of this project is to identify the underlying principle behind linguistic pragmatics which could potentially mediate the chasm between the symbolic and non-symbolic theories.

On a seemingly distant front, we often notice articles about problems with science education in this country (e.g., Broad, 2004a, b). In fact, there are science teachers who argue that the traditional approach to education is part of the problem (e.g., Heller and Heller, 2004, Narum, 2004). As a faculty member at a teaching institution, the author takes this educational problem as seriously as the above-mentioned research problem. While these problems might appear unrelated, this proposal addresses an approach that would tackle both of these problems with a common theme.

Research and Educational Goals

Since purely symbolic and non-symbolic analyses both have their limitations, we adopt an approach that has been used for various phenomena at the border between order and chaos, i.e., complex systems. That is, if linguistic pragmatics can be modeled as a complex system, it may well exhibit behaviors at the edge of chaos, which is neither completely regular nor completely irregular. Complex systems are also known to exhibit properties such as sensitivity to the initial conditions and emergence of often unpredictable properties (e.g., Auyang, 1998). Thus, the main hypothesis examined in this proposal is whether linguistic pragmatics can be modeled as a complex system with observed properties commonly associated with such a system. A complex system is generally perceived as a system of interacting components. For linguistic pragmatics, we might consider a system of individuals, e.g., who speak and/or listen. Although such ideas have been proposed (e.g., Halliday, 1978), they have not been analyzed as complex systems.

This proposal will look at this point carefully. Then, seen as a complex system, the interaction of even deterministic agents could exhibit unpredictable behaviors, sensitive to the initial condition.

We can also view the educational problem in a related way. There has been an increasing emphasis on learning in realistic context, including social and civic ones. Instead of the traditional, more reductionistic ways of teaching/learning, we may need more holistic approaches. Such approaches are consistent with ideas in complex systems. That is, in order to appreciate the usefulness of science in action, students cannot avoid the complexity and unpredictability of many real-world phenomena. Then, principles in complex systems must be useful for science teachers to understand and design courses without the fear of discussing real-world problems. In summary, this project puts forward the following main goals, tied together by means of complex systems.

Main Goals

A. Advance our understanding of linguistic pragmatics in human and machine language processing through the development of models that can demonstrate observable properties useful for evaluation, by applying principles in complex systems.
B. Evaluate the applicability of principles in complex systems across phenomena mainly in human language and communication in general, but also across computational, biological, cognitive, and social sciences.
C. Develop and disseminate new approaches and materials to integrate science and its context within a diverse range of existing and new courses appealing to a broader range of students through ideas in complex systems.

Significance of the Project

If we can successfully model certain pragmatic phenomena as the behavior of a complex system, we would be able to explain why and how a rule-based approach has difficulty converging on a result consistent with real data. This reflects the organization of a complex system, where the interaction of its components is often unpredictable, sensitive to the initial condition. At the same time, such a system may still cause certain statistical regularities to emerge due to self-organization. This would suggest that a pragmatic component of NLP systems must fine-tune its performance through interaction with the environment (including other participants). If an evolutionary or learning component is essential for practical NLP systems, the usefulness of pre-defined NLP systems would be very limited. This could potentially affect the design and implementation of future NLP systems. Furthermore, the proposed approach could shed new light on the contrast between "competence" (knowledge of language) and "performance" (language use), as often discussed in linguistics, also related to the contrast between "genotype" and "phenotype" in biology. That is, the project has a potential to bridge linguistics and other fields, e.g., cognitive/behavioral science, robotics, operating systems, networks, and databases, through common principles in complex systems. In addition, the educational components of this project can also be designed and implemented through the same set of principles. In contrast to traditional, more reductionistic approaches, various parts of complex systems can be integrated in a diverse range of courses, which will be beneficial for the author who needs to teach various courses at a teaching institution (cf. research universities).

Organization of the Proposal

This proposal is organized as follows. Section 2 describes the background of the project. Section 3 explains the organization of the project. Sections 4 through 7 discuss four parts of this proposal in detail. Section 8 concludes the proposal with final notes on the author's career development and future directions.

2. The Current State of Research and Education

2.1 Linguistic Pragmatics in Computational Linguistics

Linguistic Pragmatics

The success of NLP systems depends more and more on pragmatic aspects of computational linguistics with representative areas of applications, such as discourse structure analysis, discourse segmentation (e.g., Passonneau and Litman, 1997), reference resolution, inference analysis (e.g., Dale and Reiter, 1995), presupposition (e.g., Beaver, 1997), and information structure. In all of these areas, the basic research activities touch the essence of how humans use language, also involving cognitive and social aspects. For example, it has been noted that language can actually perform certain functions in our society (speech act as in Austin, 1975, Searle, 1969). Researchers have also noted that language is a cooperative action involving inference (e.g., Grice, 1975). This idea is still actively debated (Asher et al., 2001, Lindblom, 2001, Mooney, 2004). Gradually, a more complex view of language has developed as both individual and joint action (e.g., Clark, 1996). It has also been argued that a pragmatic notion of relevance is crucial for language use (Sperber and Wilson, 2001)

The field of linguistic pragmatics is still full of questions. This project focuses on two aspects, information structure and context, as described below.

Information Structure

As mentioned earlier, information structure, an organization of "old" and "new" components in each sentence (the same contrast is also called "topic" and "focus," or "theme" and "rheme"), can be used to improve NLP systems with respect to intonation, word choice, etc. The following question-answer pair demonstrates a relatively clear case of information structure in the response.

Q: What did you buy yesterday?
A: $[\text{I bought}]_{\textbf{old}}$ $[\textbf{a house}]_{\textbf{new}}$.

The new component, often accompanied with a high pitch tone in spoken English (Steedman, 2000), provides the missing element in the question. The phenomenon of information structure is robust, observed in every language, but its linguistic marking is highly language-dependent and also exhibits different levels of grammaticalization, i.e., development of grammatical forms (Hopper and Traugott, 1993).

For the past several years, the author has been working on various issues of information structure. As pointed out earlier, information structure is an important element of readability analysis (Komagata, 1998). However, one of the main problems with the notion is that the old-new distinction is by no means clear-cut. For example, analysis of information structure in a narrative, especially in a complex sentence, is a challenge. The author argued that the information structure can be analyzed in a way analogous in both simple and complex sentences (Komagata, 2001, 2003b). While it is possible to computationally analyze information structure with a reasonable accuracy, it becomes exceedingly difficult to increase the accuracy, as discussed in the author's PhD dissertation (Komagata, 1999). Thus, it is not likely that we can explain the phenomenon purely based on rigid rules. This situation is partly because of the involvement of other pragmatic components such as inference. Another crucial point is that the definition of and the real force behind information structure are still not completely understood. In this connection, the author recently made the following contribution (Komagata, 2003a). First, he argued that information structure reduces the burden on the listener in terms of processing effort and that such an effort can be measured in terms of entropy. He then explained the tendency of old-to-new ordering of information structure observed in many languages including (the written form of) English. Interestingly, the analysis is also consistent with potential exceptions and unclear cases.

Context

The role of context is crucial in many pragmatic phenomena including information structure, e.g., the effects of context on word order as investigated by the author (Komagata, 2003a). In particular, context is relevant to virtually all aspects of language processing, including interpretation and disambiguation. As it is relevant to many fields, it is studied from different perspectives. For example, context has been defined as a set of presupposed propositions (as context set, Stalnaker, 1991), with more recent derivatives are reviewed in Kadmon (2001), as an abstract "object" that makes a proposition true (McCarthey and Buvac, 1997), or a "situation" (Barwise and Perry, 1983, Devlin, 1991). These approaches still exhibit paradoxical cases (Akman and Surav, 1996) and real interpretation would also involve intention (e.g., Neale, 1997). The current formal approaches may simply involve too many unknowns (Akman, 2000).

In contrast, in communication, context is understood more heterogeneously (e.g., Infante et al., 1997) and more strongly associated with pragmatic aspects (e.g., Adams, 1997). Such an approach must go beyond Shannon's communication model (Weaver and Shannon, 1949), because it is not always possible for the receiver to completely understand the sender's intention and thoughts (Bickhard, 1987). If the notion of context must capture the connection between the speaker's and listener's intention, we need to analyze how communication is coordinated (Shailor, 1997). In fact, there also is a long tradition of considering language as a social construct (Fussell and Kreuz, 1998, Guerin, 1997, Holtgraves, 2002, Mey, 2003, Thomas, 1995, Vygotsky and Kozulin, 1986). However, this tradition has not developed a precise formulation of ideas.

2.2 Complex Systems

General Background

Modern approaches to complex phenomena, initiated by pioneers in chaos theory, fractals, and dynamical systems (Lorenz, 1963, Mandelbrot, 1967, Mandelbrot, 1983, May, 1974, Nicolis and Prigogine, 1989), have been applied to diverse areas: sand piles (Manna, 1999), earthquakes (Bak, 1996), biological behaviors (Camazine et al., 2001), biological evolution (Kauffman, 1993), evolutionary computation (Fogel, 2000), theory of computation (Goldin and Keil, 2001), cellular automata (Wolfram, 2002), engineering (Kennedy et al., 2001), human cognition (Ward, 2002), neuroscience of child-caregiver attachment (Siegel, 1999), sociological problems (Eve et al., 1997), social and other networks (Watts, 1999), human rationality and organizational problems (Simon, 1957a), competition and cooperation (Axelrod, 1984, 1997), music (Manaris et al., 2002), and so forth.

For such a broad range of phenomena, it is possible to see common themes such as: the whole is greater than the sum of parts, sensitivity to the initial conditions, emergence of often unpredictable phenomena, and self-organization. One of the most amazing facts is that complex systems do evolve without meticulous design or planning. One approach to explain the evolution of complex systems is "self-organized criticality" (Bak et al., 1987). According to this idea, the interaction of components may propagate to larger areas, based on the current organization of the components. Large-scale interactions are rarer, but they will occur (i.e., scalability, Schroeder, 1991). As a result, such a system would exhibit power law, e.g., an "inverse" relation between earthquake magnitudes and their frequencies, web page statistics and their numbers, etc. The relation can also be represented as follows: $f(x) \propto x^{-1}$, which gives rise to a straight line on a log-log graph. Recently, another idea called "highly optimized tolerance" is proposed to explain more heterogeneous phenomena (Carlson and Doyle, 2002).

The author recently initiated the Complex Systems Research Group at The College of New Jersey, started to collaborate with other faculty members of the group, and has been mentoring undergraduate students on related topics, including chaos theory, cellular automata, fractals, and agent-based simulation.

Connection to Linguistics

Although the connection between complex systems and linguistics has a fairly long tradition (Ruben and Kim, 1975), its relatively recent activities primarily focus on the study of language evolution (Brooks and

Wiley, 1986, de Boer, 2000, Hashimoto, 2002, Kirby and Hurford, 2002, Nowak et al., 2000, Oliphant, 1996, Smith et al., 2003, Steels, 1997). Another well known classic connection is Zipf's law, closely related to power law (Li, 2002). Zipf's observation was that virtually any text follows the formula of Zipf's law: $\textit{word frequency} \propto \textit{rank}^{-1}$ (Zipf, 1949). He also tried to explain the phenomenon based on least effort, which drew a lot of attention (Cherry, 1978, Mandelbrot, 1965, Miller, 1954, Miller and Chomsky, 1963).

The present work at the intersection of linguistics and complex systems centers around phonetics/phonology, morphology, syntax, limited semantics, and lexicon. Although more and more emphasis has been placed on pragmatics (Bates, 1976, Haslett, 1987, Ninio and Snow, 1996), it is still listed as one of the main areas for future work in recent work (Steels, 2003). The development of the social view of pragmatics is also a growing trend. However, it has not been related to the complex systems approach.

The author has been focusing on the connection between computational linguistics and complex systems and is preparing papers entitled "Pragmatic Phenomena as Living Fossils of Language Evolution" and "Characterization of Context in the Context of Emerging Communication."

2.3 Science Education

There have been multiple efforts to enhance science education at the national level (e.g., National Research Council, 1997, National Research Council, 2000) and on-going activities such as Science Education for New Civic Engagements and Responsibilities (SENCER), an NSF-funded project of AAC&U, and Project Kaleidoscope (PKAL). One of the common themes proposed by these organizations is to teach/learn science in context, also emphasized across disciplines, e.g., Learner-Centered Psychological Principles of the American Psychological Association (APA) and National Learning Infrastructure Initiative (NLII). In this connection, it has also been argued that goals, assessment, and activities must be aligned (Fink, 2003) and evaluation must also be done in context (Huba and Freed, 2000).

Although it may well be the case that complex, real-world examples would interest students more than simple, textbook-style exercises, it is not sufficient for teachers to simply use complex, real-world examples. As there is a gap between micro and macro levels in complex systems, students need assistance to bridge these two levels (Penner, 2000). We could realize this by, for example, observing and analyzing the difference between novices and experts regarding understanding of complex systems (Hmelo-Silver and Pfeffer, 2004).

The author has been actively involved in providing learning-centered experience. He participated in SENCER Summer Institute 2003. Later, his new liberal-learning course "Introduction to Computational Modeling," which introduces quantitative reasoning to students through computer simulation of social and other complex problems, was reported in the SENCER E-Newsletter, Vol. 2, Issue 6, Jan./Feb., 2004. The author has also developed writing-intensive First Year Seminar courses, "Information, Language, and Computation" and "Family Values and Human Mind," where preliminary ideas of this project were explored.

The recent movement in education is indeed to grasp the educational environment as a complex system, where all sorts of properties of a complex system can be observed. Thus, with a good understanding of complex systems, a teacher would be able to design and run courses more effectively. This point is applicable to virtually any course, regardless of the actual course materials.

3. Organization and Outline of the Project

3.1 Project Parts: Specific Objectives and Their Significance

To achieve the project goals, bridging computational linguistics, complex systems, and education, this proposal defines four parts. Since pragmatics alone is a large, challenging area, the project will focus on two specific sub phenomena: first, information structure (Part 1), extending the author's dissertation work, and then, context (Part 2), a broader notion also closely related to information structure. Building on the examination of these two components, the project will focus on the question of whether pragmatics shares properties with other complex systems (Part 3). Furthermore, ideas in complex systems will be applied to science education (Part 4).

Part 1: Information Structure from a Complex Systems View Point

This part of the project explores the question of whether information structure emerges as a property of a complex system involving the speaker(s) and the listener(s). Like other aspects of communication, we will need to analyze the speaker's and the listener's effort, including the level of competition vs. cooperation involved in the process. An answer to this question will be a key to understanding why information structure is not purely symbolic or non-symbolic, potentially leading to improvements in practical applications and identification of limitations of NLP systems. Our approach for this part will be to develop a model that can demonstrate the emergence of information structure as a result of the speaker-listener interaction. For example, we can analyze whether the speaker actually benefits from processing information structure, corresponding to potentially better understanding of the listener. This can be analyzed by simulation and/or mathematically. The results of simulation/analysis will then be compared with linguistic data involving information structure.

Part 2: Context from a Complex Systems View Point

This part explores a question analogous to **Part 1**, i.e., whether context is a result of a complex system. In particular, we will begin with a minimal communication model as a basis for both human language and communication in general. This will also lead to other questions, including the representation of a context, e.g., as a network with special properties such as "scale free" and "small world" (Watts, 2003). An answer to this question could elucidate the essential properties of context, possibly providing the core ideas for relating different types of analyses. The results would be useful also for designing pragmatic components of NLP systems. Again, we will develop models of context that would exhibit desired properties. We will compare the behavior of the model with linguistic data and properties of complex systems.

Part 3: Connections between Linguistic Pragmatics and Other Fields with Respect to Complex Systems

This part explores the similarities and differences between the models in **Parts 1** and **2** and those used for complex systems in other fields. The strength of being able to model multiple phenomena in different fields is the possibility of gaining a higher explanatory power. If linguistic pragmatics can be analyzed in a way similar to computational, biological, social, and other complex phenomena, we could move closer to finding the unifying principle behind all natural and artificial complex systems involving evolutionary processes. To answer the question, we will identify components and their interaction across fields, e.g., across linguistic evolution and biological evolution. The evaluation of this part will primarily depend on the list of connections among different instances of complex systems.

Part 4: Applying the Complex Systems Perspectives to Education

The main theme of this part is how to apply principles in complex systems to education. In addition, we will also use computational linguistics and complex systems as parts of course materials where appropriate. By designing courses as an activity involving complex systems, i.e., real-world phenomena, we will be able to use more realistic examples. Students must be able to feel that such examples are more relevant to their lives. Although we may not always find answers, cf. well-defined exercises in text books, we will be able to gain opportunities to practice realistic experience. In many courses that deal with complex phenomena, we can emphasize the neglected part of the story, i.e., interaction of components and emergence of often unexpected properties, referring to principles in complex systems. As a part of the evaluation, the author will use a specifically designed student survey in each course. In addition, through a number of take-home exercises, there will be plenty of opportunities to collect a variety of forms of students feedback.

3.2 Outline of the Project

The main strategy to accomplish the project goals is to integrate as much research as possible with course preparation. This will be possible because complex systems ideas are tied to the author's pedagogical philosophy, not just to course materials. Reflecting this strategy, the author proposes to pursue **Part 4** throughout the project period. **Parts 1** through **3** can be tackled more or less sequentially, with considerable overlap, so that the author can progress from more familiar parts of the project to newer areas. As described in the more detailed description of the project, the author will collaborate with his colleagues. The author also expects that there be more collaboration with other faculty members and students who join the Complex Systems Research Group.

4. Part 1: Information Structure

Connection to the Main Goals

This part will contribute to **Main Goal A**. The research in this part will be a stepping stone to study a related but broader problem of context in **Part 2**.

Specific Objectives and Their Significance

The main objective of this part is to examine whether information structure emerges as a property of a complex system, through the following specific research questions:

1. What would be a model of linguistic communication that involves information structure? For example, what would be the role of cooperation and competition among the speakers and the listeners? Furthermore, would the model require fine-tuning by some external force or emerge due to certain underlying principles?
2. If information structure affects the speaker's and the listener's effort to produce and understand speech, respectively, how could we measure and analyze the effort level?
3. What kind of linguistic and/or non-linguistic data should we use to evaluate the model?

Although we can intuitively see that information structure exhibits certain properties of a complex system, a better understanding of the phenomenon would come from modeling it precisely. Unlike previous formalizations of information structure, the research questions above attempt to relate the underlying mechanism and observed phenomena. A reasonable response to the above questions would be a support for the hypothesis that pragmatic phenomena are a manifestation of a complex system. Then, we can extend the discussion to the notion of context in **Part 2** and further connections to non-linguistic phenomena in **Part 3**.

Evaluation and Dissemination

The evaluation of this part will be based on the comparison of the behavior of the model and linguistic data, i.e., real data and/or information extracted from real data. The results will be submitted for publication, e.g., in *Journal of Pragmatics*. Parts of the findings will also be disseminated through undergraduate education, e.g., understanding the mechanism of cooperation/competition and improving the readability of student research papers, which will be discussed in **Part 4**.

Research Activities

The first step of this part would be to identify missing elements in the current theories of information structure. For example, while the linguistic realization of information structure has been studied extensively, its historical and evolutionary aspects have rarely been discussed. Although the study of language evolution is not the focus of this project, there are many relevant factors. For example, certain types of grammaticalization are pragmatically motivated, and distinct forms used by different social classes (e.g., Labov, 1966) are also examples of grammaticalization. As being examined in the author's on-going work, some of these types of grammaticalization are related to information structure. It is also possible to view certain pragmatically motivated grammaticalization as residues of language evolution (Jackendoff, 2002). The author has started to investigate this case as noted in Section 2.2.

Another point was that there has been very limited discussion of how to measure the effort of the speaker and the listener, except some earlier work (Campbell, 1982, Cherry, 1978) and the author's own work on the use of information theory to measure the entropy of information-structure components. Like any other effort of communication, the speaker would make as little effort as possible to obtain the desired effect. For example, individuals would avoid the inference process, if possible, as it will require effort (Kemper, 1988). The situation is comparable to certain male birds (e.g., the starling) adjusting their songs based on the reaction of female birds (West et al., 2003). Unlike many other aspects of communication, however, information structure does not change the message content. Thus, the speaker's effort cannot be measured in terms of informativeness.

Understanding different ways of realizing information structure is also important because we know that the association between the function and the forms of information structure is arbitrary as in the case of word-meaning association. This suggests that our model must be sufficiently general to be able to deal with various aspects of linguistic realization, be it realized phonologically, morphologically, or syntactically.

The next stage, developing a model, will focus on the interaction of the speaker and the listener (Clark and Haviland, 1977). A hypothetical model would draw from the work on cooperation and competition (Axelrod, 1984, 1997, Danielson, 2002, Hammerstein, 2003, Taylor and Day, 2004). For example, such a model can be mostly game-theoretic in that the agents' behaviors are well-coordinated. With appropriate conditions, we may be able to show that the speaker makes some effort to use information structure so that she is understood better by the listener, possibly applying the entropy-based measure of effort mentioned earlier. A simple model would involve as information structure the division between the subject and the predicate. Then, distinct ordering of the subject and the predicate can be compared with respect to the effort of the participants. For this model, we could use simulation and mathematical analysis to some extent.

One potential problem with such a model is that we may need to fine-tune the condition to obtain the expected behavior. Humans are not perfectly rational, and most likely have only "bounded rationality" (Simon, 1969), and thus natural phenomena may not be captured by the conditions expressible in game-theoretic analyses (Bronstein, 2003). Then, we need to search for a more robust model, which does not require fine-tuning. In this proposal, we will examine the idea of "self-organized criticality" and "highly optimized tolerance," as described in 2.2. While it seems possible to model interacting speakers/listeners more or less homogeneously, it is not obvious if there is a relevant property that would exhibit power law.

We will then proceed to develop a model of evolving information structure as an emerging property of multiple linguistic agents, interacting with one another by adjusting their efforts. Since such a model will be more complex compared to game-theoretic ones, the modeling process will most likely be accomplished by computer simulation. Depending on the amount of time spent, the simulation may demonstrate different degrees of using information structure in their communication.

The results of simulation will be compared with linguistic data. For example, the level of developing information structure will be compared with different levels of grammaticalization of information structure in multiple languages. Furthermore, the results can be compared with the level of clear use of information structure in real corpora.

5. Part 2: Context

Connection to the Main Goals

In this part, we extend our scope from information structure to context (**Main Goal A**). Although context is already a major factor in information structure, we attempt to treat context more generally. In doing so, we will focus on the intersection of human language and a primitive communication system (part of **Main Goal B**).

Specific Objectives and Their Significance

The main objective of this part is to examine whether a model of context in a communication system, seen as a complex system, exhibits properties shared by the use of context in human language, through the following specific research questions:

1. What would be a minimal communication model where the notion of context can be defined? Could such a model evolve into more sophisticated ones comparable to human language?
2. What would be an appropriate representation of context that would scale from primitive to complex communication? Furthermore, would the model involve fine-tuning by some external force or emerge due to certain underlying principles?
3. What would be the phenomena that can be used for evaluation of models of context in comparison with real data?

Although the current context research focuses on relatively sophisticated communication systems such as human language, the notion of context must be important to primitive communication systems as well. By identifying such an example, we will be able to delineate the essence of context and how context may have influenced the development of more complex communication systems. If humans can unconsciously learn language as a highly effective communication system (Forsdale, 1981), a model which does not require fine-tuning seems appealing. Again, a reasonable response to the above questions would be a support for the hypothesis that pragmatic phenomena are a manifestation of a complex communication system, in response to **Main Goal A**. In addition, this part will have made the connection between linguistic pragmatics and communication in general, preparing for further connections to non-linguistic phenomena explored in **Part 3**.

Evaluation and Dissemination

The evaluation of this part will be based on the comparison of the behavior of the developed models and information extracted from real data, including linguistic and other forms of communication such as animal communication. If a model is explained by "self-organized criticality," we will be able to find some property that would exhibit power law or Zipf's law (word frequencies vs. ranks). On the other hand, a model based on "highly optimized tolerance" would predict more heterogeneous structure with more robust outcomes of complexity. The results will be submitted for publication, e.g., in *International and Interdisciplinary Conference CONTEXT* and *Evolution of Communication*. Some of the findings will also be disseminated through undergraduate education, e.g., written and oral communication and the use of context, which will be discussed in **Part 4**.

Research Activities

The notion of context is extremely difficult to pin down, partly because it is often discussed in conjunction with complex activities, such as human language. As reviewed in Section 2.1, it is necessary to view as a social construct, complementing the shortcomings of current formal approaches. On the other hand, we also desire to pursue the precision of formal approaches. As a starting point, this part will examine a primitive communication model which still can be used to define the notion of context. Then, by applying principles and techniques in complex systems, we will analyze how such a primitive model can evolve into more complex ones.

The primitive communication model might involve a single agent receiving some signal in a simple environment. The agent might behave differently depending on the signal. For example, the agent may have two states corresponding to the two states of the environment. If the agent responds to the states categorically, there is no concept of context. Now, suppose that there is another piece of information in the environment. If the behavior of the agent depends on both of these inputs and the second input is not emphasized for some reason, the interpretation of the first input may be said to depend on the context (involving the second input). Then, we might be able to characterize "context" as inputs necessary for fixing the agent's behavior, i.e., disambiguation, but not explicitly recognized as input. This type of "prominence" associated with the first signal is relative, e.g., to the agent or possibly to another agent who generates these conditions.

This type of simplistic set up may actually be not too far from how simple electric signal functions in the evolution of certain fish (Hopkins, 1999). When we refer to a context, the term is used in contrast to the non-contextual part, say, "foreground." Thus, even in this model, we will need to analyze how the foreground and the context can be distinguished (Goodwin and Duranti, 1992). In fact, it seems to be important to study how non-signal might evolve into signal (Hauser, 1996). If there are multiple pieces of information of various kinds, we might conjecture that the foreground-context distinction be inherently relative to the agents that use the information. Then, the objective separation of foreground and context may not be possible, which may go against proposals which assume such separation (e.g., McCarthey and Buvac, 1997).

The next model would involve two agents who may engage in inter-agent communication. In order for an agent to realize that it is engaging in communication with the other agent, there already are a number of questions we will need to ask. How can an agent know that some signal is generated by the other agent? Thus, there must be additional information to indicate which agent generated the symbol. The interpretation of the same signal will have completely different meanings depending on who generated it. Typically, this information is not explicit in the linguistic form, but it must be obvious in the immediate situation. In general, the speaker's and the listener's beliefs may not coincide (Hirst, 2000). There even may be an ironic case where a vague expression is employed for an effective use of context (Jucker et al., 2003). Furthermore, we even need to be able to explain that real understanding can be achieved through joking (Davies, 2003, Kotthoff, 2003).

Other questions about an agent include the following. Should the agent assume that the other agent has similar properties? In particular, can the agent assume that the other agent will react in the same way to signals with the same communication protocol? Even more sophisticated models would have a certain meta-level capability of processing protocol to adjust its own communication mechanism, possibly with some innate mechanism to bootstrap. Thus, communication is inherently recursive (Krippendorff, 1994). It has been noted that a finite number of exchanges cannot lead to perfect communication (Clark and Marshall, 1981), even if the communication protocol is shared. We also ask how the agent would understand its own, the other agent's, and the joint activities (Clark, 1996). The model must provide data that can be used to analyze these questions.

As we take the position that language is a social activity, we will need to develop a model involving multiple agents. While the two-agent case may be modeled using game theory in the tradition of Wittgenstein (Lewis, 1991, Sally, 2003), the multiple-agent case would require a different approach. We may be able to model such a case as a network of agents, possibly as a "small world" or "scale free" network. Small world networks are highly clustered yet with relatively short distances between any pair, often found in social networks. Scale free networks exhibit a growth pattern such that heavily connected nodes attract more connections (Albert and Barabási, 2002). As the context becomes more and more complex, we will need to organize it in a way that facilitates efficient processing. For example, we might model a complex context as a network of concepts/words (Ferrer i Cancho and Solé, 2001, Motter et al., 2002, Widdows, 2003), again properties such as "small world" or "scale free" might apply.

Analysis of the behaviors of these models will need to be done carefully, mainly through computer simulation. Depending on the model, e.g., self-organized criticality vs. highly optimized tolerance, the model may exhibit power law. For example, Zipf's law as observed on the word count may be considered as a behavior of a language generation system in a dynamic context. Considering a discourse as a context (Zanette, 2004), we could analyze the law as follows: words are repeated with a frequency proportional to the number of previous occurrences; new words are added at some constant rate (Simon, 1957b), critically reviewed in Mandelbrot (1959). This is a special case of analyzing linguistic context. But if we can see an analogous behavior in a more general case, it may suggest that language use in context exhibits power law and thus, the information may be used in support of language evolution through self-organized criticality. Since a connection between Zipf's law and scale free networks has been noted, we will also be able to compare our models of context and related network representations.

The ability to deal with a complex context must robustly evolve from a simple model. Such models can be compared with animals' social communication systems of various complexities. The results can be compared with real data involving miscommunication (Mortensen and Ayres, 1997), which is fairly common. We will also be able to use grammaticalization, as it may have been derived through context change (Heine, 2002).

6. Part 3: Connections

Connection to the Main Goals

This part pursues **Main Goal B** with some connection to **Main Goal A** as the models in **Parts 1** and **2** are also examined.

Specific Objectives and Their Significance

The main objective of this part is to examine the connections between linguistic pragmatics and other complex systems, through the following specific research questions:

1. Do the same principles in complex systems apply to both linguistic pragmatics and other areas including, for example, computational, biological, cognitive, and social sciences?
2. What would be the connections between the evolutionary (diachronic) and the behavioral (synchronic) aspects of complex systems?

Understanding of common properties among various complex phenomena will let us view these phenomena more systematically. By comparing **Parts 1** and **2** with other areas, we hope to triangulate the appropriateness and applicability of the use of complex systems ideas to linguistic pragmatics. Understanding common principles in complex systems across different disciplines is also important even for students and learners to be able to gain the basic skills to analyze and process complex systems as described in Section 2.3.

Evaluation and Dissemination

The evaluation of this part will be based on how well information can be translated between pragmatics and other areas. We will also examine whether the comparative study would reveal information that confirms and/or rejects the research in **Parts 1** and **2**. Within the proposed five-year project period, the extent of the work in this part will be limited. But it will establish the basis for related future projects. The preliminary results will be submitted for publication, e.g., in *Advances in Complex Systems*. Parts of the findings will also be disseminated through undergraduate education, e.g., analytical approach to complex systems, which will be discussed in **Part 4**.

Research Activities

First, we will investigate the situation associated with computation. Although there is a close connection between linguistic and computer science, the level of complexity that has been focused on so far has been at a fairly low level along the Chomsky hierarchy, i.e., mainly finite-state and context-free. The entire point of this project on linguistic pragmatics is to extend this limit, focusing more on the interaction of multiple agents, which may exhibit potentially unpredictable behaviors. In this respect, even the most powerful model of algorithmic computation, i.e., Turing Machines (TMs) would not suffice, because TM's are completely deterministic and non-interactive (except for the initial input and the final output). Even modern computational problems in the real world, e.g., operating systems, networks, and artificial intelligence, cannot be adequately modeled with a TM. While textbooks in "Theory of Computation" often discuss the equivalence of TMs and modern computers, we must also note that computers are used to simulate complex phenomena commonly thought to be beyond TM computability. The usefulness of modern computers is increasingly dependent on interactivity, which goes beyond TMs (Wegner and Goldin, 2003). It has been pointed out that the TM model is no longer appropriate for dealing with complex real-world phenomena (MacLennan, 2003). There are many proposals to represent "super-TM" computation. One approach is through analog computation (Israel and Goldenfeld, 2004). Another would still use discrete computation with added capability to iterate the process with persistent memory (called Persistent TM in Goldin, 2000) or with an interactive calculus (called pi-calculus Milner, 1993). Yet another possibility is evolutionary computation (Goldin and Keil, 2001). It might be the case that complex systems including super TMs are all equivalent under the "principle of computational equivalence" (Wolfram, 2002). A related point has also been noted in evolutionary biology (Levins, 1973). Through the comparison of these models with the results in **Parts 1** and **2**, we attempt to respond to **Objective 1** of this part.

One of the richest areas in which to review the literature and observe phenomena with respect to both evolutionary and behavioral aspects of complex systems would be biology. For example, evolution has been examined as self-organization and a variety of complex biological behaviors have been modeled. We can naturally compare language evolution and pragmatic behaviors with the biological counterparts. For example, the realization of genetic information in a certain environment can be compared with pragmatic phenomena based on, for example, grammatical information. However, the behavior of living forms may manifest properties that cannot be explained by genetics alone; some of them are social. The situation is analogous in linguistics. Thus, it must be illuminating to compare the animal social behavior and social effects on linguistic pragmatics from complex systems view points.

We will also compare the contrast between "self-organized criticality" and "highly optimized tolerance" discussed in earlier sections with the relevant development in biology. For example, a theory of evolution that biological evolution is not so smooth (i.e., punctured equilibrium as in Gould and Eldredge, 1977) lead to an account based on self-organized criticality, through stages of analyses (Bak and Sneppen, 1993, Flyvbjerg et al., 1993). Note that the appropriateness of the model based on species, not individuals, is debatable (Maddox, 1994). Also, if a hierarchy of heterogeneous objects is the key to understanding evolution (Pattee, 1973), we may need a more general idea, e.g., highly optimized tolerance.

Among the connections with cognition, we will focus on the phenomenon called $1/f$ noise ("pink noise"). $1/f$ noise is a random-looking frequency distribution with more concentration on lower frequencies, observed in certain brain activity (as well as other physical activities). Mathematically, $1/f$ noise corresponds to power law. Thus, the comparison between the sources of $1/f$ noise and the results in **Parts 1** and **2** may bring about new insight. One aspect of cognition which is increasingly emphasized recently is the effects of the environment, i.e., social cognition (Kennedy et al., 2001, Kunda, 1999, Siegel, 1999). Thus, cognitive development must be seen in connection to sociology in general (Eve et al., 1997) and the study of spatial interaction (Batten, 2001, Pacala et al., 1996), which can be modeled as a network. This also relates back to the author's position that language is a social construct. That is, language studies restricted within the individual level will have inherent limitations. In other words, the current position aligns with externalism in philosophy and cognitive science. It is also related with "oracle" computation (Hopcroft and Ullman, 1979). That is, true power of computation might exist outside the computer. By clarifying these connections, we will attempt to highlight the essence of complex systems.

At the end of this part, we will have a mapping between different fields and their implications to **Parts 1** and **2**. Since the allocated time for this part is very limited, it is unrealistic to expect new discoveries. However, making connections will pave the way for the future work in this relatively new area.

7. Part 4: Education

Connection to the Main Goals

This part pursues **Main Goal C**. However, it is also related to **Main Goals A** and **B** in that this part involves computational linguistics and complex systems as potential course materials as well as the principles in complex systems also applied to course development at the pedagogical level.

Specific Objectives and Their Significance

The specific objectives of this part are as follows:

1. Develop new approaches and materials that would integrate science with its contexts more vigorously, in a diverse range of existing and new courses. This is by itself an application of principles in complex systems.
2. Disseminate basic concepts in complex systems, which can be used effectively in various parts of many courses.
3. Disseminate basic concepts in linguistic pragmatics, e.g., information structure and context for the writing segments of various courses.
4. Increase interdisciplinary activities, especially related to various ideas in complex systems.

As reviewed in Section 2.3, by placing every course, every class meeting, and every problem in context, students must be able to appreciate the meaning of the activities and thus learn more effectively. In addition, by connecting different phenomena through principles in complex systems, students are expected to improve their ability to transfer their knowledge to new areas. By preparing materials that would change students' perception of "traditional" science education, the learning community (department, college, etc.) can move forward to practice more effective science education. In this proposal, complex systems ideas are applied both at the meta-level and at the object level; i.e., the message is that what is learned (object level) must be useful in reality (meta-level). Since this part pursues certain principles across the curriculum, especially in the liberal learning program at The College of New Jersey, the author believes that the impact of the entire project is reasonably broad.

Evaluation

This part will be evaluated by peers through in-class observations and by students through the standard course evaluation and specifically designed student surveys. The author will also self-evaluate his own achievements through reflective essays. All the course materials as well as other general educational materials will be available on-line, as the past materials of the author.

Educational Activities

The College of New Jersey is a primarily undergraduate teaching institution. It offers a sufficiently broad range of programs typical of a college of its size. The college also has a tradition of active undergraduate research, especially in the Department of Computer Science to which the author belongs. However, the author is and will also be active in science and liberal education in a broader sense. This section describes the planned activities in these and other components of undergraduate education.

In many courses that deal with complex phenomena, we can emphasize the neglected part of the story, i.e., the interaction of components and emergence of often unexpected properties, by applying principles in complex systems. We can even discuss classroom dynamics and learning in connection to complex systems. Contrary to the popular belief, it must be possible and even desirable to discuss complex phenomena earlier in a program because of their relevance to our complicated society. Thus, it is possible to pursue **Objective 1** in virtually any course. A plan to integrate complex systems in various contexts is discussed below.

Computer science courses: Based the author's recent experience, two examples where the proposed approach can be integrated includes "Discrete Structures of Computer Science" and "Theory of Computation." In the past instances of Discrete Structure, the author has already started to experiment with novel course materials set in a variety of real-world contexts.

Recently, the author proposed a Theory course which involves ideas in complex systems. As discussed in **Part 3**, algorithmic computation, albeit essential, has severe limitations in terms of its ability as a model for highly complex and interactive modern computing environments. It would be impossible to completely predict the behavior of such a complex system. Instead, we will often need to admit that there are properties that cannot be explained as the sum of the properties of components. Thus, in order to model these complex systems, we will need the concept of complex systems. This approach addresses **Objectives 2**.

In the past, the author has taught a special topic course on Natural Language Processing. If there are similar opportunities, **Objective 3** can be accomplished accordingly.

Computer science student research: So far, the author has been mentoring undergraduate students on topics in computational linguistics and complex systems. The author intends to continue to deal with both fields, meeting **Objectives 2** and **3**. In the Department of Computer Science, mentored research is the capstone experience which involves intensive writing. Therefore, parts of **Objective 3** can also be met through instruction on writing research papers.

Computer science internship: In our department, internship is an alternative capstone experience. Again, parts of **Objective 3** can be met through instruction on writing internship reports.

Systems science minor: With several other faculty members in the Complex Systems Research Group, the author initiated to develop a minor in systems science. Currently, the research group involves the faculty from Sociology & Anthropology, Mathematics, and Computer Science departments, and students mainly from Computer Science. The author intends to accomplish **Objective 4** by extending the faculty and student circle beyond the current state.

Liberal learning courses: As a coordinator for computer science liberal learning, the author has developed "Introduction to Computational Modeling" and is co-developing "Human and Artificial Intelligence" (tentative title). The former course, based on the SENCER ideas, analyzes social and other complex phenomena through computer simulation. Naturally, **Objective 2** is one of the main course goals. As for the latter, we will discuss complex cognitive phenomena, where the author will introduce complex systems ideas.

The author is also involved in writing-intensive First Year Seminar programs. He will be teaching "Family Values and Human Mind," another SENCER-inspired course. The course addresses problems which students would face in daily activities. Both society and cognition will be discussed as examples of a complex system.

Common to all the above educational activities, the author will be practicing an approach in which learning goals, student assessment, and learning activities are intertwined in a highly interactive manner.

Dissemination of the SENCER experience: The author participated in the SENCER Summer Institute 2004 and confirmed the importance of learning in context (reference to **Objective 1**). In addition to developing SENCER-inspired courses as described above, the author also aims to disseminate the idea and the approach to his department and the entire college through informal discussions and workshops.

8. Career Development and Future Plan

Career Development within and beyond the Author's Organization

Consistent with the vision of the teaching institution, the author strives to be an exemplary teacher-scholar through the implementation and evaluation process described in this proposal. The author's role in his department and the college can also be seen from a complex systems point of view. The author continuously attempts to contribute to the department with respect to both research and teaching. By extending the research/teaching area to complex systems, the author expects to teach a variety of courses so that course assignment in the department would be flexible. By volunteering to be the departmental internship supervisor, the author expects to strengthen the internship program and obtain feedback from the industry. Through the participation in interdisciplinary activities such as teaching in the First Year Seminar program, teaching liberal learning computer science courses, and developing the systems science minor (by coordinating the Complex Systems Research Group), the author also expects to contribute to the college. In turn, the department and the school express their support for this project in various ways, e.g., collaboration on research and teaching activities, and support for presenting research papers.

Career Development beyond the Proposed Project

The long-term goal of the author is to advance his research/teaching career further in the area of complex systems in connection to a diverse range of natural and artificial phenomena, extending **Parts 3** and **4** of this proposal. Such an approach would call for a truly transdisciplinary environment. In this regard, the existing highly departmental organization of higher education is not an ideal environment. To complement the current situation, the author believes that everyone must increase her/his awareness of the importance of complex systems. As our society becomes more and more complex, institutions in higher education must also evolve so that the learning process directly addresses complex problems in the real world. Eventually, the approach discussed in this proposal should be disseminated beyond the higher education system as well. It is vital that the entire population has good understanding of how our society works (or does not work).

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