Genetic Algorithms for Social Innovation and Creativity

Alex Kosorukoff and David E. Goldberg

IlliGAL Report No. 2001005
January 2001

Illinois Genetic Algorithms Laboratory
University of Illinois at Urbana-Champaign
117 Transportation Building
104 S. Mathews Avenue Urbana, IL 61801
Office: (217) 333-2346
Fax: (217) 244-5705

Genetic Algorithms for Social Innovation and Creativity

Alex Kosorukoff and David E. Goldberg
Illinois Genetic Algorithms Laboratory
104 S. Mathews Avenue, Urbana, IL 61801
University of Illinois at Urbana-Champaign
Phone/FAX: (217) 333-2346, (217) 244-5705
{alex3,deg}@illigal.ge.uiuc.edu

Abstract

Since their invention, genetic algorithms have been used primarily for solving problems in different areas of engineering and technology. In most of these areas genetic algorithms were applied successfully and shifted the frontier between what is possible and what is impossible, solving problems that were even hard to approach with conventional deterministic methods. Recent social applications of genetic algorithms challenge our usual way of thinking about social systems. Instead of old concepts of social engineering, based on deterministic mechanical constructivism, genetic algorithms and other methods of evolutionary computation open new approaches to the same issue. These methods allow us to substitute fixed structures of our organizations with free forms which are soft and evolving. This paper contains two examples, and some conclusions from this case study. The main conclusion is that GAs have already passed beyond only their technical applications to artificial systems, they are ready to come into the real world of living systems and even have made the first steps in this direction.

1 INTRODUCTION

The world around us can be roughly divided into the two complementary parts: artificial and real. The former is relatively static and includes material things and artifacts made by people. The latter is constantly changing and populated by living entities. There are many differences between the two worlds, but they can be encompassed in one word 'non-determinism'. Other words will be just another names for the same thing, but they worth mentioning, since each of them gives us another view, and only looking at different facets we can understand this intriguing object we are dealing with. These words are complexity, deceptiveness, irregularity, non-linearity, inseparability. Artificial technical systems are more predictable, regular, linear, and deterministic, while natural ones are deceptive, irregular, non-linear, and complex. Usually, technical systems have bounded polynomial complexity, while natural ones are NP-hard. The parts of technical systems can be viewed and analyzed in separation, while the same method of an atomistic analysis of organs of living systems usually leads us to failure.

Genetic algorithms themselves rather belong to the real world than to the artificial one, they show very complex behavior similar to the one observable in living systems (Kosorukoff, Mittenthal, & Goldberg, 2001). That is why they are used successfully to model living systems in biology, sociology and economics. The idea that genetic algorithms can be a model of human innovation was suggested in (Goldberg, 1983; Holland, 1995; Goldberg, 1998; Goldberg, 2000). In this study we propose that genetic algorithms are not only a model of human innovation and creativity allowing us to study this process, but also a method to achieve innovation, and to boost creativity in real organizations.

Here we present the study of two cases, describing real-world applications of GA to the area of education and knowledge management. These are not a usual kind of computational GAs, because they both rather social than computational. Each of them creates a special form of human organization, based on the principles of evolution, learned from computational GAs. In a sense, the word “form” is not the right word here, because it usually refers to something fixed, while we refer to the kind of a form that is not constant. It is rather a quasi-form, emerging and developing in the process of evolutionary self-organization.

2 CASE STUDY OF TWO APPLICATIONS

In this section we consider two applications of GA in the field of social organization, that appeared independently, but share many common features. The first project “Teamwork for a Quality of Education” is a method to organize an educational process after the model of a genetic algorithm. The second project is “Free Knowledge Exchange”, the web-based virtual organization of several hundreds of people that uses a human-based genetic algorithm (HBGA) for its internal knowledge management and innovation. As you will see the two projects are like-minded and very similar in their spirit. They emphasize different aspects of the general method that can be called *organizational genetic algorithm*.

2.1 Teamwork for a Quality Education (TQE) project

The TQE project was an application of the basic concepts of a genetic algorithm to create a more efficient educational environment (Goldberg, Hall, Krussow, Lee, & Walker, 1998). It introduced teamwork and design across the curriculum enlivened by a spirited, yet friendly competition among teams. It also defined the principles, projects and the rules of the competition.

The program was initially implemented in the Department of General Engineering in the spring of 1997 and has continued in some form to this time.

TQE is a department-wide competition of student-led teams, each team consisting of freshmen, juniors, and seniors together with faculty and staff advisors. Each team is charged with obtaining the highest quality education possible for its members, and this goal is actuated through the series of competitions in three broad categories: (1) academics, (2) service and design, and (3) summer job placement. Like little-league sports, TQE teams have corporate sponsors, usually employers of engineering graduates, with each corporate sponsor giving both in-kind and financial support toward the success of its team and the program.

TQE main principles are the following:

- **Pervasive Teamwork** To achieve higher quality delivery of engineering education, integrated teams should be employed throughout the engineering academy as they have been employed in industry.
- **Minimal Marginal Costs** Whatever reforms are proposed for the engineering academy, they must be designed to use existing or reduced faculty-staff resources with a minimum of marginal costs.
- **New Revenue Streams** Widespread reform efforts should generate sufficient new revenue streams to ultimately cover a significant fraction of their marginal costs.

- **Student Power and Light** Insofar as possible, students should be empowered to run new reform efforts, seek a quality education, and have fun.
- **Faculty facilitation** Each team must be facilitated by an experienced faculty member.
- **Minimal Marginal Credit** Because of the fullness of the existing curriculum, an engineering education reform effort should require minimal additional hours of credit.
- **Friendly Competition Among a Population of Teams** Participation and excellence should be driven by a friendly competition among a population of teams to win team awards based on excellence in academics, projects, and other categories.

In the common academic approach faculty, staff, and students are like billiard balls that collide with one another when a course, advising episode, or other event calls for it. Under TQE program, the same collisions would take place, but the individuals would also be supported by a quasi-permanent interpersonal infrastructure of teamwork (Goldberg, Hall, Krussow, Lee, & Walker, 1998).

Additional information can be found elswhere (Goldberg, Hall, Krussow, Lee, & Walker, 1998), but for the purpose of this paper the key thing to keep in mind is that the TQE was conceived partially because of the second author's experience with GAs. In other words, the very notion of a population of teams, a competition, a fixed (and multiobjective) "fitness function" were drawn from the example of GAs. Additionally, it was assumed that teams would emulate one another, thereby promoting a kind of crossover. It was also assumed that a team member would spontaneously generate new and useful ideas, a kind of smart mutation.

While common academic approach is oriented on the development of individual abilities of a student, TQE emphasizes the development of cooperative skills. Individual grading, the fitness function of usual education, is replaced with team grading, so the educational process optimizes the performance of a team rather than the peak performance of an individual. This produces diverse teams capable of solving tasks the complexity of which is beyond abilities of an individual specialist.

Main lessons learned from this implementation are the following:

- The method appears to work: the participants are satisfied, useful projects get accomplished, and lessons are learned
- Participatory system works better than obligatory
- Teamwork is more important then individual grading
- Smaller team sizes work better, they are easier to get moving.

The TQE project was inspired by a genetic algorithm, and there is a strong correspondence between its concepts and the concepts of a GA. This is represented in the following table:

GA	TQE
Gene	Member
Chromosome	Team
Population	Population of teams
Fitness function	Judging + grades
Generation	Semester
Initialization	Team formation
Selection	Team competition
Crossover	Team swaps + informal exchange
Mutation	New idea of a team member

Most of the table is self-explanatory. New idea creation by a team member is analogous to a mutation of one gene, which is a team member in this case.

The correspondence between TQE and GA procedures are pretty strong, except for the crossover operator. Usual kind of GA crossover is very difficult to apply to a human team, because team members unlike genes have their own preferences and desires. Therefore, we can't just swap members randomly between two teams. The practice of team swaps is tightly connected with the willingness of particular members to change their team, and usually this process happens actively only at the initial stages of TQE. After the teams become more or less solid, crossover rarely happen, so its combinatorial potential can't be fully explored.

However, the problem with the team crossover is compensated by the crossover happening implicitly at another level: the exchange of ideas and the best practices between members of different teams. This makes the TQE project similar to the Free Knowledge Exchange (FKE) project, which has no evolution of teams at all, putting the main emphasis instead on the evolution of ideas of individual participants. It is described in the next section.

2.2 Free Knowledge Exchange (FKE) project

The Free Knowledge Exchange (FKE) project introduces the concept of evolutionary knowledge management based on concepts of GA. It is an application of multi-level human-based genetic algorithm (HBGA) for the task of collaborative solving of problems expressed in natural language (Kosorukoff, 2000b).

It was established in 1997 as "an organization helping each member to be successful through new forms of cooperation based on better knowledge management." Currently it supports 6 different languages and has about 500 registered members from 92 countries[1]. There is no membership fee and anyone can join this community through the Internet at the website http://www.3form.com

The FKE project uses evolution of natural language strings to arrive at better answers to the problems submitted by its members. It organizes individuals into collaborative community and uses their ability to perform intelligent crossover and selection operators on existing knowledge.

The idea of knowledge evolution in the most explicit form was suggested by Richard Dawkins (Dawkins, 1976). Evolution of natural language was proposed and explored in neuro-linguistic programming (Bandler & Grinder, 1976) and in the evolutionary theory of language (Pinker, 1998). Some web projects implicitly use evolutionary methods to stimulate creativity, and the most relevant example is probably the Global Ideas Bank (GIB). Brian Eno has defined the main idea of it as

[1] Information from Click2net advertising network

collecting more successful and humane ways of doing things, and then re-presenting them in new mixes and matches.

> Instead of an all-embracing ideological overview from which correct behavior is supposed to flow, it takes a case-by-case approach to changing the world. It says "Given what we have and what we now know, wouldn't it be better if we did this particular thing in this other way?" Primarily, it's a work of research - scanning the world for signs of more successful and humane ways of doing things, and then re-presenting them in new mixes and matches. In that sense, it's The Good News, the stuff that doesn't make the headlines, the material of human success. This approach constitutes the proposal that a better world will be achieved not by smashing everything up, but by the accumulation of systems and arrangements that work a little better. It arises out of the expectation that, given the choice, people will make rational and even generous decisions. And it says: it's our responsibility to look after the future (Eno, 1998).

FKE and GIB have the same general idea which is evolutionary, but they differ in the procedure of evolution and its actual implementation. There are two important differences in FKE: support of recombination operator and diploidy of representation.

The use of recombination operator distinguishes it from GIB, the human based recombination distinguishes it from usual kind of Interactive Genetic Algorihtms (IGA) (Takagi, 1998), the use of diploidy distinguishes it from both. Three main distinctions of FKE and their sources can be put into the following table:

Emphasis on Recombination	GA
Human interaction	IGA
Diploidy	Creative questioning

The evolutionary procedure of Global Ideas Bank is based on selection, but doesn't have a recombination mechanism implemented. Likewise, Darwin's theory of evolution was also based on selection, since Darwin was not aware of the genetic mechanism of recombination. Although, the mechanisms of genetic change happen in living and social systems even if they are not implemented (Kosorukoff, Mittenthal, & Goldberg, 2001; Kosorukoff, 2000b). As it was shown for TQE project, the absence of recombination operator in the social system is partly compensated by the crossover at another level of evolutionary process. This implicit process was crucial for the success of the Darwin's evolution theory and the GIB. They both took advantage from natural processes.

Online interfaces of GIB show ideas one at a time and allow users to evaluate them, to add new ideas and comments. This process of knowledge evolution is based on selection and mutation. Mutation happens implicitly when one idea inspires another, and the result is submitted to the bank. Experience with GA has shown that this mechanism of evolution produces incremental continuous improvement, but it lacks efficiency without recombination operator (Goldberg, 1998). The FKE project puts much emphasis on the process of recombination as all other genetic algorithm implementations.

Another important thing about Human Based Genetic Algorithm used in FKE is a kind of diploidy it assumes. FKE divides all processed text strings into the two mutually exclusive classes: problems and solutions, as if corresponding to female and male origin. This approach distinguishes it from knowledge processing systems that doesn't make this distinction. This distinction creates two levels of co-evolution in FKE, each having the same recombination methods, but different methods and criteria for selection. The interplay between problems and answers in the FKE create an environment similar to that in the method of creative questioning (Ray & Myers, 1989).

In distinction from the usual kind of interactive genetic algorithm using only human judgment (Takagi, 1998), HBGA uses balanced approach allowing and encouraging both convergent and divergent thinking of participants in the form of evaluation and recombination, correspondingly. This is accomplished by selecto-recombinative interfaces, where a human operator can perform selection or evaluation or both, based on one's preferences at the particular moment. Additional information can be found elsewhere (Kosorukoff, 2000b), but for the purpose of this paper the important thing is that despite major representation and implementation differences, the core concepts of FKE are the same as those of early GAs and most of the theoretical concepts of GAs are applicable to the processes of knowledge evolution happening in FKE.

It can be said that natural language strings have a tight linkage of building blocks, since in the most frequently used patterns of language their constituent parts tend to be located close to each other. Thus our natural language by itself has a good encoding for the purpose of genetic algorithm. We can hypothesize that the structure of language has itself evolved to allow this tight linkage of building blocks. Such a structure makes the evolutionary method of natural language processing efficient.

Here we draw several examples that were evolved in the system. The following question had the highest fitness among English speaking participants at the time of writing this paper (the numbers in the first column correspond to the fitness of answers).

Q	How do you know that you are in the right career to really exceed in life and to do well overall?
18	You are in the right career if you wake up excited to go to work.
12	You need to feel it. If you're enjoying yourself, nothing else matters. As long as the money is enough to live by, you're fine there.
12	Rely on your intuition and senses. It should feel good to be in the right carreer :-)
11	You are in the right carreer if you wake up every day and can't wait to get to work. You spend all day doing what you love and then when its time to go home you really don't want to.
8	What is the definition of the right? If people want, then they can do anything and enjoy doing it. Nobody preassigns you from the birth to be a cook or a janitor, it is a choice which is made based on the life experience and the environment.

Another question clarifies the meaning of "knowledge" in the context of FKE:

Q	What is knowledge?
4	Approximation of the outside world in our local observable vicinity. It is usually expressed in some alphabet of a limited size and doesn't approximate well beyond the local limits.
4	Knowledge is our personal extrapolation of information. Our minds take in information (or data) and spew out knowledge – even when we're wrong.
3	Knowledge is information valuable for us, that we gather, select and generalize throughout our life.
3	Something that keeps us from making the same errors twice.
3	Something very powerful and hard to attain. It is knowledge about things as they are or reality. With the correct knowledge almost everything is possible.

The basis of selection process in FKE is delegated to its participants like in interactive genetic algorithms (Takagi, 1998), but processing of the individual evaluations is different. The system acts as a mechanism that collects, processes and integrates the individual selections made by humans. We assume that humans are error-prone and consider them as unreliable classifiers, so the main purpose of the whole classification system is to minimize the overall error of classification. This purpose can be achieved by different decision making mechanisms: ensemble averaging, arcing and boosting, or cascading classification. Some of them are compared in (Kosorukoff, 2000c). It was found that the fastest method is ensemble averaging, while the most precise method found so far is cascading classification. Both of them are used in FKE, the former is used for classification of problems, the latter is used for classification of solutions. Thus the speed was chosen as the priority factor in problem evaluation, while the quality was chosen as the priority in solution evaluation.

The selection of problems is performed according to their importance, based on expressed interest of participants in each particular problem. This measure of fitness based on the summed interest of all participants is used to include a problem into the generated web pages shown to people. This process happens in interfaces of HBGA, which generate the interactive WWW pages dynamically. The roulette wheel selection method is used for this purpose. In this way, the problem in which many people are interested will appear in the interfaces more frequently. The frequency of appearance of the particular problem in the interfaces and in dynamically generated WWW pages can be thought as a measure of attention the system pays to a particular problem.

The selection of solutions is performed according to their fitness in the context of specific problem. The method of cascading classification used for this purpose is based on creating optimal classification structure from individual elements and letting solutions propagate through this structure. The method of structure assembly is described in details in (Kosorukoff, 2000a). It is based on evolving the representations of classifying networks with a genetic algorithm to achieve the minimum of the overall classification error.

The interesting thing about the FKE system is that it can define its identity, purpose and evaluate its own performance, evolving the answers to the corresponding questions: what is FKE? what is the purpose of this community of people? is it uselful? what is needed to make it better?

By collecting this information the FKE system becomes 'aware' of what people think about it and which changes and improvements are needed. Most of these self-awareness questions appeared spontaneously in the process of evolution, like the following one.

Q	What is a goal of Formula?
10	Allow people to cooperate effectively, and optimize the technologies of their interaction.
8	To help people
4	Help every member to achieve his/her goal, succeed in his/her enterprise no matter commercial or non-commercial. Success of every member makes our community more successful, and expands opportunities of other members.
4	Attract many people, provide them with effective technology of creative cooperation, test new ideas, develop and implement them, evolve fast to satisfy continuously changing demands of participants.
8	Attract people and increase creative potential of their community.

These questions are circulating through the system, because participants express an interest to them. In this process the questions gather human opinions and evaluations, making the system aware of its purpose. Another self-evaluating question had the second best fitness at the moment of writing this paper. Here is it with a list of the top 5 responses.

Q	What is your impression from this website?
10	It's very unique and really a good thing. This way people won't be afraid to ask.
9	This is a good way to continuously stimulate the thinking brain matters to keep one mentally fit
9	Could be helpful
8	The idea is quite smart. Here's hoping it can succeed, it's certainly got the potential
8	Interesting

It this way, the FKE system becomes aware of its own performance. The satisfaction of people using the system is not a quantitative metric, but it agrees very well with the idea of this social system made for people. It can be said that FKE has no definite purpose. Human participants fill the purpose of FKE with their concerns and problems, and as long as these problems find solutions, the purpose of the whole organization is also fullfilled. It is close in meaning to the known words of Lao Tsu "It has no purpose, but its purpose is fullfilled" (Tsu, 1972).

We still need to learn much about the mechanisms of evolutionary knowledge creation. The FKE project provides us with valuable data for this purpose: statistics about preferences of different people, methods of recombination and evaluation of natural language strings. What is clear by now that FKE interfaces allow co-evolution of related populations of problems and solutions and this evolution results in selection of creative solutions and problems of interest. We believe that this is a sure way to new knowledge and understanding.

Let us outline the correspondence between the FKE project and GA as we did for the case of TQE. We get something like the following:

GA	FKE
Gene	Word of natural language
Chromosome	Text of question/answer
Population	Knowledge base
Fitness function	Human preference
Generation	Meta-interface cycle for solving a set of problems
Initialization	Solicitation of initial answers and migration of them from other populations
Selection	Ideas competition
Crossover	Crossover of answers
	Crossover of problems
Mutation	Random creativity technique

This table looks very similar to the one for TQE. These are the same processes working in a different context. Different levels of evolutionary process are emphasized in these two models. Comparing TQE and FKE, we can see that the former model represents better the processes in the higher levels (group and participating individuals), while the latter pays more attention to the lower levels (individual problems and finding solutions to them). Nevertheless the very same methods work on these levels to achieve the goal of quality of education (TQE) and effective creative problem solving (FKE).

The goals of the two projects, although formulated differently, can also be viewed in the context of one general perspective. In the process of FKE problem-solving, the participants not only solve their particular problems, but also learn about other problems in a way that is easy and entertaining, they learn to see and to perceive the problems of other people as their own, they also see the effect of mutual help and cooperation of many people. In this perspective, the goals of FKE and TQE seem to be the same and correspond to the ultimate goal of good education.

3 LESSONS FROM THE CASE STUDIES

Our case studies have shown how similar the ideas and the processes behind the TQE and FKE to the main concepts of genetic algorithms. These similarity makes two projects like-minded, so we can view one of them in the context of the other and vice versa. They both can be viewed as application of GAs to the social organization. They are essentially different from the early attempts of social engineering based on mechanistic constructivism. This new approach to social organization is flexible and adaptive, it doesn't reject changes, as did earlier deterministic models. It allows and encourages spontaneous changes and uses them for improvement of the system, realizing creative potential of errors.

We can construct a similar table contrasting these evolutionary approaches to the traditional deterministic system of education: in most of the issues they are opposite to each other.

Traditional system	Evolutionary system
Fixed	Flexible
Obligatory	Participatory
Emphasis on inheritance	Emphasis on diversity
Error correction	Error utilization
Error based	Achievement based
fitness	fitness
Rejects changes	Encourages changes
Everything competes	People cooperate;
	ideas compete
Goal is speed	Goal is quality
External motivation	Internal motivation
Centralized evaluation	Distributed evaluation

We can see that in almost every feature the new approaches contradict to the traditional practice. That is the major reason of difficulty in implementing them, but this kind of difficulty of being different is always associated with any new product or method.

Both organizational genetic algorithms are also different from standard GAs in their purpose. It is clear that convergence is not a goal of organizational GAs. Convergence in the case of FKE would mean leaving a participant without any freedom of choice, and insisting that one 'correct' answer will work for the problem, in the case of TQE convergence would mean that all teams loose their identity, in the pursuit of perfection. That is not what we want in social environment. Looks like in this case any convergence will be premature, because the real-world evolution doesn't stop there. Convergence always means death in the living world, that is why traditional metrics of quality of the genetic algorithm based on time-complexity are inadequate in these cases. They should be extended by the new metrics that have yet to be found. Certainly, one of them can be satisfaction of the participants and human evaluation of the overall performance and usefulness of the system, another one can be the diversity of the system behavior.

The experience with organizational GAs shows that GA must correspond to the area of its application. Technical areas need competent GAs. Social areas need balanced or enlightened GAs (Goldberg, 1989). Competent GAs are designed to achieve fast convergence, balanced GAs should be designed to achieve innovation and creativity as a continuing process. Balanced GAs should always be able to adapt even to the unpredictable environment, they always should check if their assumptions about the world are still valid, and 'unlearn' them if they are not. It is not expected that such procedures will do better than competent GAs in engineering applications, because adaptation always takes time. But it is expected that they will do better in the less predictable real life environments.

4 CONCLUSIONS

Looks like, the area of application of GAs is no longer limited to the design of artificial systems. In the beginning of this paper we suggested the idea that GA will challenge our way of thinking about social systems. We think they will play an important role in our everyday life, affecting the processes in our social organizations. We had reviewed only two examples of such applications, but we are sure that we will not wait too long to see other examples. We expect that in the nearest years GA will introduce big changes in knowledge management, outsourcing and organization structures.

The evolving organizations based on GAs will be non-deterministic, but that brings no danger, since they will be able to maintain dynamic balance between the interests of an organization and people *participating* in it. In deterministic organizations the goals of stability and freedom are always in contradiction. To achieve more stability organizations must take more obligations from you, reducing your freedom. That is why they tend to drift to the state of stability and no freedom. But stability and no freedom is not what we desire, after all. Evolutionary methods are able to make the unity of this contradiction. Evolutionary organization will give both stability and freedom to make choices to all its participants, it will allow participants to be ordinary, i.e. to be themselves and change without putting the whole organization in danger. It will create new ways to learn, based on interest and curiosity, rather than need and necessity. It will give you the right to make errors in your workplace, to have rest when you want it, to make your life more diverse and less stressful, and finally more enjoyable.

Currently, humans have to adapt to fit fixed forms of traditional organizations. Evolving organizations will adapt to fit humans.

Acknowledgments

The authors would like to thank Jay Mittenthal and Chi-Sheng Ho for interesting discussions and contributing valuable ideas to this paper. We are also thankful to the participants of the Free Knowledge Exchange project contributed the material included in this paper and granted the right to publish it under the conditions of the Success Formula Community Agreement.

Professor Goldberg's contribution to this work was sponsored by the Air Force Office of Scientific Research, Air Force Materiel Command, USAF, under grants F49620-97-1-0050 and F49620-00-0163, by the National Science Foundation under grant DMI-9908252, by the U. S. Army Research Laboratory under the Federated Laboratory Program, Cooperative Agreement DAAL01-96-2-0003. The US Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation thereon.

The views and conclusions contained herein are those of the researchers and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Office of Scientific Research, the National Science Foundation, the U. S. Army, or the U.S. Government.

References

Bandler, R., & Grinder, J. (1976). *The structure of magic : A book about language and therapy.* Science & Behavior Books.

Dawkins, R. (1976). *The selfish gene.* Oxford University Press.

Eno, B. (1998). *An incremental strategy for changing the world* (Foreword to Global Ideas Bank Compendium). www.globalideasbank.org /wbi/WBI-1.HTML.

Goldberg, D. E. (1983). *Computer-aided gas pipeline operation using genetic algorithms and rule learning.* PhD dissertation, University of Michigan.

Goldberg, D. E. (1989). Zen and the art of Genetic Algorithms. *Proceedings of the 3rd International Conference on Genetic Algorithms.*

Goldberg, D. E. (1998). *The design of innovation: Lessons from genetic algorithms, lessons for the real world* (IlliGAL Report 98004). Department of General Engineering, UIUC.

Goldberg, D. E. (2000). The design of innovation: Lessons from genetic algorithms, lessons for the real world. *Technological Forecasting and Social Change*. In press.

Goldberg, D. E., Hall, W. B., Krussow, L., Lee, E., & Walker, A. (1998). *Teamwork for Quality Education: Low-cost, effective educational reform, through a department-wide competition of teams* (IlliGAL Report 98005). Department of General Engineering, UIUC.

Holland, J. H. (1995). *Hidden order: How adaptation builds complexity.* Addison-Wesley.

Kosorukoff, A. (2000a). Genetic synthesis of cascade structures for particle classification. In *Late breaking papers of GECCO'2000*, Genetic and Evolutionary Computation Conference Proceedings (pp. 170–174). Las Vegas, Nevada.

Kosorukoff, A. (2000b). *Human Based Genetic Algorithm (HBGA).* http://3form.com/hbga.

Kosorukoff, A. (2000c). Social classification structures. optimal decision making in an organization. In *Late breaking papers of GECCO'2000*, Genetic and Evolutionary Computation Conference Proceedings (pp. 175–178). Las Vegas, Nevada.

Kosorukoff, A., Mittenthal, J., & Goldberg, D. (2001). *Modeling of evolution of signaling networks in living cells by evolutionary computation.* in press.

Pinker, R. (1998). *How the mind works.* W. W. Norton.

Ray, M., & Myers, R. (1989). *Creativity in business.* Doubleday, NY.

Takagi, H. (1998). Interactive evolutionary computation: System optimization based on human subjective evaluation. *INES'98*.

Tsu, L. (1972). *Tao te ching (Gia-fu Feng & Jane English translation).* Wildwood House.