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1992 Complex Systems Summer School

May 31 – June 26, 1992, Santa Fe, New Mexico, U. S. A.

Every year, the Santa Fe Institute organizes for researchers all over the world a summer school, which provides a comprehensive overview of the interdisciplinary scientific field concerning the study of 'complex systems' behavior. The summer schools enjoy great interest – last year it was already the fifths in sequence and over fifty participants took part in it.

The measure of complexity is not generally agreed upon, however there is an intuitive notion of this concept. We can state some basic attributes of complex systems: nonlinearity, adaptation, evolution, self-organization, memory, cooperative behavior of elements, behavior at the edge of chaos. Typical representants of complex systems are cell, brain, ecological systems, economy, typical models are cellular automata, neural nets, quantum field theory, spin glasses, artificial life systems.

Santa Fe Institute is a private independent organization, oriented on interdisciplinary research and graduate education in natural and social sciences and informatics. The motivation for its foundation in 1984 was to get deep insight into fundamental processes in nature and society, to find common underlying rules of processes of evolution and learning, whether in living systems or in world economics. Its aims are to develop new methods for mathematical modeling of nonlinear dynamics, new methods of mathematics and informatics for applied research in physics, biology and social sciences.

The Institute has only little permanent faculty, the research is performed by visiting professors. There is a tight cooperation – joint research and education, with many universities (University of Arizona, University of New Mexico) and other institutions, among others with Los Alamos National Laboratory.

The Fifth Annual Complex Systems Summer School 1992 was located in the campus of St. John's College in outskirts of Santa Fe, New Mexico. The organization was excellent. Six weeks before the event the participants received detailed instructions and a thick package of preliminary reading materials based on lectures of preceding summer schools. The school office was equipped with a xerox machine and a reference library with many related publications was established. The Addison–Wesley publishers accepted orders for the selection of its publications with considerable discount. Besides, the general college library was opened to the participants.

For the participants a computer network of Sun workstations, two powerful Silicon Graphics workstations, two Macintoshes IIci, Next Station and IBM PC AT compatible were available 24 hours a day. The software tools were oriented towards Unix and C language; moreover, Mathematica for Macintosh and Suns was installed. The whole network was connected to Internet via the Santa Fe Institute computer system. The computer lab was invaluable for experiments with theoretically analyzed algorithms. The lecturers intensively exploited videorecorder for presentations of their experiments.

The program was clustered into one-week blocks. Two basic lectures were given in the morning and supporting lectures, seminars of individual interest groups and computer experiments were organized in the afternoon. During the third week the participants could attend The Artificial Life Conference III.

The lectures covered quite a wide field of topics. As well the audience was heterogeneous – from biologists, mathematicians and physicists, to economists and sociologists. It imposed quite hard demands on lecturers to proceed from elementary facts generally known to specialized principles of studied topic in a limited time. The response of the audience in most cases showed that they succeeded.

Before I concentrate on the lectures I wish to express my thanks to the Santa Fe Institute, the Department of the Navy, Office of Naval Research European Office and the

Czech Literary Fund for their support of my stay in Santa Fe.

From the point of view of my interests (optimization, simulation) I divide the lectures into three groups: very interesting lectures with direct impact on my research, lectures, which may contribute to the solution of my problems and marginal topics, which extended my knowledge. The report on the highlights of the summer school deals mainly with first two groups.

Lectures of primary interest

Emerging Science of Complexity (Mike Simmons, the Santa Fe Institute). Mike Simmons gave an excellent introduction to underlying principles of complexity. Complex system is a system which is too complex in its structure or dynamics to be predictable or analyzable. Usually, complex systems are defined by the list of its basic attributes (adaptation in evolution, adaptation at the edge of chaos, self organization, cooperative locally determined behavior, emergent phenomena etc). There are many other different views on what a complex system is. Important tool for their study is computer simulation, analysis of obtained results and generalization.

Genetic Algorithms (Melanie Mitchell, University of Michigan). The series of lectures on genetic algorithms was the backbone of the first week of the Summer School. Genetic algorithms try to simulate natural evolution processes using computers. They utilize abstract principles of evolution for the solution of many problems, where the acceptable or the best variant from a large set of possibilities is to be selected.

Candidates for the solution are iteratively generated using genetic operators (mutation and crossover) applied randomly on randomly selected parents. The selection is done with respect to a defined fitness function. Time consuming exhaustive search which definitely leads to the solution is thus substituted by the genetic algorithm aiming to get good approximation of the solution in a reasonable time. Tested alternatives can be evaluated in parallel.

Application area comprises problems with complex structure or problems with a structure, which is not fully understood. Concrete examples are biological, economical or complex technical systems. The algorithm is expected to search large spaces for good solutions with high efficiency. This is often proved by computer experiments.

The result is a good solution, not the optimal one. There are also problems where we seek any acceptable solution, e. g., in automatic programming, financial market prediction, protein structure prediction, economic models, ecological models etc. There is usually no criterion, when to terminate the search.

The algorithm itself is quite simple, however there is a great variety of possibilities how to apply it to a particular problem. The formulation of the problem seems to be crucial for the overall efficiency of the method. It defines the space of acceptable alternatives and "organizes" that space in the way that certain individuals are close to each other and others are far. Such ordering of the space greatly influences the solution process.

However extensive the experiments with this approach are, still the mechanism of its operation is not theoretically well analyzed. There were several reported research fields, where these algorithms were applied:

Automatic programming. GA were used to synthesize a Lisp program for the solution of simple problems. There are many questions connected with this approach; described solution is highly dependent on suitable problem formulation and the solution space is obviously dense with correct answers. Scaling up to bigger programs still remains unsolved.

Analysis of complex data (time series prediction, speech recognition, protein structure prediction).

Neural networks training. An example of training a feed forward neural net was shown. A comparison with a simple backpropagation weights updating resulted in favor of GA. Interesting (and probably less favorable for GA) would be comparison with more sophisticated training methods. Other application of GA is for evolving neural network topology. Topology is changed via GA, weights using backward propagation.

Traveling salesman problem. This is classical NP-complete classical problem in computer science with many applications (VLSI design). It is a typical example, where problem representation is crucial for efficient solution.

Dynamic behavior of cellular automata. As cellular automata are not widely known, a short excursion to that field preceded the GA application (one-dimensional cellular automata and their Wolframs classification, dynamic behavior on the edge of chaos, their capability to perform complex computations). In the demonstrated example GA was applied to find cellular automata which perform according to prescribed rules.

Implementation of the basic procedures is quite simple. The difficulty lies in proper selection of problem representation. For numerical optimization Gray coding may seem to be suitable, as adjacent integers are only one bit apart. For other classes of problems, other representation may be applicable – e. g. tree representations for automatic programming or list representations.

There are many modifications of basic GA. Different types of reproduction rules (roulette wheel selection of offspring, sigma scaling, tournament selection, rank selection with elitism, or steady-state GA) may be advantageous. Also different types of genetic operators may be used (one-, two- or multi-point crossover, uniform crossover). Their applicability depends on problem encoding. Further effort to experiment with the operators on the basis of real genetics rules can be followed.

As in the case of other computational algorithms, GA parameters influence decisively the efficiency of its performance. The setting of their values is still done empirically; adaptive parameter setting with regard to operator performance (assigning of usefulness to operators), meta GA, or other ways are rare.

Simulation of evolution in GA may help to analyze evolution in nature. In that way the reverse influence of computer science on life sciences is exhibited. Simple demonstration of Baldwin effect (learning can guide evolution even if there is no direct genetic transmission) using GA was performed.

Main unresolved questions are connected with the notion of schemas. Schema is a representative of a class of individuals. GA can proceed by approaching the solution by narrowing a selected and updated set of schemas (templates, building blocks). The role of schemas is not yet well understood.

Another still not resolved question is a characterization of fitness function – 'landscape' suitable for application of GA. It is in close relation with the selection of proper problem representation, that is with a navigation in the space of problems, which are equivalent to the original one.

The most promising seems to be combination of GA with other solution methods. GA should resolve only a part of the overall problem – that one, which is complex and hard to be understood, and which would otherwise have to be solved by e. g. exhaustive or random search.

The main advantage of GA is universality. The algorithm can be applied to many problems. The result depends heavily on representation and is usually good, yet not the best. The simplicity and straightforward applicability of GA are appealing, yet the best performance is usually achieved with specialized methods, where various characteristic features of the problem are taken into account.

Participants of the course could experiment with two implementations of GA.

Neural Network Computations (Richard Palmer, Duke University, Durham). The lecture was an interesting introduction to the theory and possible applications of neural nets. At the beginning relation of living brain and neural nets was stressed. Basic taxonomy of neural nets was given with short description of their individual features. Different types of learning was described. Some applications of feed-forward networks were shown and back propagation principle was explained in more detail (back propagation principle is well-known for gradient evaluation in systems described by recurrent relations).

Neural networks methods are now penetrating into such fields as optimization and optimal control, too. They provide nonclassical, yet quite fast and computationally efficient way of suboptimal solution of problems.

Introduction to Quenched Disorder (via Spin Glasses) (Dan Stein, University of Arizona). Basics of spin glasses theory were explained. The study of magnetic traits of some alloys led to a theory of systems with many low energy states. Several mathematical models were presented, which result in a large scale problem of combinatorial optimization with many local minima. For such problems the method of simulated annealing is capable to find the solution in reasonable time using the analogy with real physical phenomenon. Impact on other fields of science was shown, e. g. the analogy with Hopfield's neural nets theory. The lecture presented a very interesting problem of high dimensional combinatorial optimization.

The Ecology of Computation (Tad Hogg, Xerox Palo Alto Research Center). The problem of the best utilization of large number of Unix workstations connected to a network was analyzed. System performance maximization for large scale computational tasks (for which system requirements grow exponentially with the size) requires adaptability and dealing with imperfect and conflicting information from many sources. For wide class of problems that are viewed as a search in a large problem space, there is a highly nonlinear increase in performance due to the interactions of agents. A number of experimental results with heuristically guided search were presented. It showed a group of cooperating agents which solves the task faster than the same group of agents working in isolation from each other. The theory can be extrapolated to other real life problems in biology, economy, immunology etc.

As many coming problems are very hard to solve due to extensive demands on computer resources, the need of parallel computers is urgent. Then the reasonable organization of parallel operation is decisive in getting the maximum performance.

The Series of Lectures on Application of Nonlinear Dynamic Systems (Joshua Epstein, The Brookings Institution, Washington DC). The system of first-order ordinary differential equations of Lotke–Volterra predator-prey type was applied to modeling of arms races and wars. The influence of the equations parameters on the model dynamics was studied and their correspondence to the features of real system was sought. Presented relatively simple model is able to generate real life situations, yet the identification of its parameters is very difficult.

Global Information Systems and Nonlinear Methodologies in Crisis Management (Gottfried Mayer–Kress, CCSR Beckman Institute, Urbana). At the beginning the importance of large simulation models of the world was mentioned. Then the impact of micro-relations on global behavior of systems was studied.

Interesting topics

Chaos Concepts (Atlee Jackson, University of Illinois). The lecture dealt with the basic notions of nonlinear dynamic systems theory (conservative and nonconservative systems, state phase portraits, attractors etc.). Deterministic chaos and fractals were introduced.

Global Methods for Cellular Automata (Steen Rasmussen, Los Alamos National Laboratory). Cellular automata due to their simplicity are the favorite object of complex dynamic systems research. Their main features are simple low-level and local rules, which can as a whole perform very complex behavior. They were shown to be able to model many systems in nature (biological, physical). Cellular automata can support complex computation and can be self-programmable.

Self-Programming (Steen Rasmussen, Los Alamos National Laboratory). Using the fact, that computer programs are identical to data, programs alter data and therefore also programs, a self-programming system based on a parallel von Neumann architecture was constructed. One-dimensional memory array was occupied by several types of machine code instructions, that were performed in parallel in the presence of noise. A mutation of machine code programs always yields a new legal program.

The lecture was focused on the fact that this system has the same fundamental property as living systems have – the ability to evolve new properties. This constructive dynamical system was shown to develop complex cooperative structures with adaptive responses to external perturbations. Several experiments with this system were done and emergence of complex functional properties was demonstrated.

The Geometry of Excitability (Art Winfree, University of Arizona). Basic notions of excitability and its impact on analysis of some oscillatory behavior in chemistry and biology were given.

There is still no exact mathematical definition of excitable medium. We can state that 'zero-dimensional dynamical system in a certain range of states, that exhibits large transient excursion before returning to the original state as a response to a small stimulus, is called excitable'. Excitable media have local excitable dynamics and tight coupling of neighboring regions so that excitation in one region can provide its neighbors with the kind of stimulus required to provoke excitation there. In such way they can support propagation of nonlinear waves.

In two dimensional media the right stimulus will create rotating vortices which radiate pulses in every direction, in three dimensional media pivot points of the rotating structure form a line, a vortex filament, that typically closes in a slowly shrinking 'scroll ring'. The creation of organizing centers, their taxonomy and anatomy in topological terms were studied.

The phenomenon was mathematically modeled by parabolic partial differential equations of reaction-diffusion form. An extensive 3D graphical visualization on a computer were shown.The model demonstrated self-organizing objects in three dimensions. The behavior of excitable media can be observed in the Belousov–Zhabotinski reagent; it may be the underlying principle in the life-threatening arrhythmias of heart muscle.

Marginal topics

Protein Biophysics (Robert Austin, Princeton University). The series of lectures tried to explain mechanism of protein synthesis and introduced the theory of spin glasses to biochemistry. Many unresolved questions were posed.

Rhythmic Oscillations of the Brain (Charles Gray, The Salk Institute, San Diego). The series of lectures described experiments with animal brains. Oscillatory behavior and its changes as a response to external stimulation were analyzed. Related problems – description of particular regions in a brain and their function were the topic of the lecture *An Introduction to Mapping the Brain (Charles Wood, Los Alamos National Laboratory).*

Theory of Languages and Automata (Chris Moore, the Santa Fe Institute). The introductory lecture explained the basics of the theory of automata and languages. Corresponding classes of grammars and automata were defined.

Evolution and Optimization: They're not the Same (Marcus Feldman, Stanford University). Major difficulties in attempting to use game theory reasoning to substitute for evolutionary dynamic modeling were explained. There is a question whether it is possible for genes or chromosomes to have individual strategies. The phenomenon of maintaining stable sex ratio 1:1 was explained with two models of its evolution. The problem of evolutionary genetic stability was described.

Evolutionary Phenomena in Simple Dynamics (Kristian Lindgren, the Santa Fe Institute). The author demonstrated evolutionary phenomena using the Prisoner's Dilemma Game. Finite memory deterministic strategies were exposed to selection and mutations. The population dynamics was simulated on a computer.

Biochemical Networks and Antichaotic Behavior. Experimental Artificial Biochemistry (Harold Morowitz). Prof. Morowitz focused on systems of cells, taxonomy of organic matter, stability of bio-systems and their behavior in different environments and a chaotic behavior as a hypersensitivity to parameters. He analyzed life as a regular set of chemical reactions.

Quenched Disorder (Jonathan Yedidia, Harvard University). He gave an introduction to statistical mechanics with necessary definitions. Using variational principles, the shape of polymer was derived minimizing the trial Hamiltonian.

Artificial Life III. Conference. The participants of the school could attend afternoon sessions of the conference. The aim of the conference was to report about the research of artificial systems with behavior characteristic for living systems. The goal of most studies of artificial life systems is to discover general laws of evolution in nature.

Computer experiments were often shown, ranging from simple cellular automata to large complicated simulations on parallel machines. They give straightforward tool for the analysis of modeled principles. Only basic theoretical results were cited and there often seems to be demand for underlying theoretical knowledge.

Conclusion

Complex Systems Summer School has given its participants comprehensive overview of the state of art in the field of complex systems. Among many covered topics it was possible to find new inspiring ones, which brought highly interesting problems and approaches to their solutions.

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