

## The evolution of emergent computation

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**ABSTRACT** A simple evolutionary process can discover sophisticated methods for emergent information processing in decentralized spatially extended systems. The mechanisms underlying the resulting emergent computation are explicated by a technique for analyzing particle-based logic embedded in pattern-forming systems. Understanding how globally coordinated computation can emerge in evolution is relevant both for the scientific understanding of natural information processing and for engineering new forms of parallel computing systems.

Many systems in nature exhibit sophisticated collective information-processing abilities that emerge from the individual actions of simple components interacting via restricted communication pathways. Some often-cited examples include efficient foraging and intricate nest-building in insect societies (1), the spontaneous aggregation of a reproductive multicellular organism from individual amoeba in the life cycle of the *Dictyostelium* slime mold (2), the parallel and distributed processing of sensory information by assemblies of neurons in the brain (3), and the optimal pricing of goods in an economy arising from agents obeying local rules of commerce (4). Allowing global coordination to emerge from a decentralized collection of simple components has important advantages over explicit central control in both natural and human-constructed information-processing systems. There are substantial costs incurred in having centralized coordination, not the least being (i) speed (a central coordinator can be a bottleneck to fast information processing), (ii) robustness (if the central coordinator is injured or lost, the entire system collapses), and (iii) equitable resource allocation (a central controller must be allocated a lion's share of system resources that otherwise could go to other agents in the system) (e.g., see ref. 5). However, it is difficult to design a collection of individual components and their local interactions in a way that will give rise to useful global information processing. It is not well understood how such apparent complex global coordination emerges from simple individual actions in natural systems or how such systems are produced by biological evolution. This paper reports the application of new methods for detecting computation in nonlinear processes to a simple evolutionary model that allows us to address these questions directly. The main result is the evolutionary discovery of methods for emergent global computation in a spatially distributed system consisting of locally interacting processors.

We use the general term "emergent computation" to describe the appearance of global information processing in such systems (see refs. 6 and 7). Our goal is to understand the mechanisms by which evolution can discover methods of emergent computation. We are studying this question in a theoretical framework that, while simplified, still captures the essence of the phenomena of interest. This framework requires (i) an idealized class of decentralized system in which global information processing can arise from the actions of simple, locally connected units; (ii) a computational task that neces-

sitates global information processing; and (iii) an idealized computational model of evolution.

One of the simplest systems in which emergent computation can be studied is a one-dimensional binary-state cellular automaton (CA) (8)—a one-dimensional spatial lattice of  $N$  identical two-state machines ("cells"), each of which changes its state as a function only of the current states in a local neighborhood of radius  $r$ . The lattice starts out with an initial configuration (IC) of  $N$  cell states (0s and 1s). This configuration changes in discrete time steps according to the CA "rule"—a look-up table mapping neighborhood state configurations to update states. At each time step, all cells examine their local neighborhoods (subject to specified boundary conditions), consult the look-up table, and update their states simultaneously. The CA's radius places an upper boundary on the speed of information transmission through the lattice. It also limits the sophistication of the local dynamics: the number of look-up table entries is  $2^{2r+1}$ . Thus, fixing  $r \ll N$  constrains the sophistication of a CA's explicit information processing.

A simple-to-define computational task for CAs that requires global information processing is deciding whether or not the IC contains more than half 1s. We call this the  $\rho_c = 1/2$  task, with  $\rho_c$  denoting a threshold density of 1s in the input. If  $\rho_0$  denotes the density of 1s in the IC, the desired behavior is for all cells to quickly change to state 1 if  $\rho_0 > \rho_c$  and to quickly change to state 0 if  $\rho_0 < \rho_c$ . The  $\rho_c = 1/2$  task requires global communication, since  $\rho_0$  is a global property of the entire lattice; no linear combination of local computations—such as the cells computing the majority of 1s in their neighborhood—can solve this problem. Designing an algorithm to perform the  $\rho_c = 1/2$  task is trivial for systems with a central controller of some kind, such as a standard computer with a counter register or a neural network with global connectivity. But it is difficult to design a decentralized, spatially extended system such as a CA to perform this task, since there is no central counter or global communication built in. It can be shown that no finite-radius CA can perform this task perfectly across all lattice sizes (9, 10), but even to perform this task well for a fixed lattice size requires more powerful computation than can be performed by a single cell or any linear combination of cells. Since the 1s can be distributed throughout the CA lattice, the CA must transfer information over large space-time distances ( $\sim N$ ), and information from distant parts of the lattice must interact so as to perform the computation. With  $r \ll N$ , such information transmission and interaction can be accomplished only through the coordination of emergent high-level signals. Thus, this task is well suited for investigating the ability of an evolutionary process to design CAs with sophisticated emergent computational abilities.

One class of computational models of evolution are genetic algorithms (GAs) (11), which evolve a population of candidate solutions to an optimization problem by propagating the most "fit" candidates to the next generation via genetic modifications. We carried out a set of experiments in which a GA was used to evolve one-dimensional binary-state  $r = 3$  CAs (with

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Abbreviations: CA, cellular automaton; IC, initial configuration; GA, genetic algorithm.

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# Emergent Computation Emergent Computation

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## **Emergent Computation Emergent Computation:**

**Emergent Computation** Andrew Adamatzky, 2016-11-04 This book is dedicated to Professor Selim G Akl to honour his groundbreaking research achievements in computer science over four decades The book is an intellectually stimulating excursion into emergent computing paradigms architectures and implementations World top experts in computer science engineering and mathematics overview exciting and intriguing topics of musical rhythms generation algorithms analyse the computational power of random walks dispelling a myth of computational universality computability and complexity at the microscopic level of synchronous computation descriptiveness of error detection quantum cryptography context free parallel communicating grammar systems fault tolerance of hypercubes finite automata theory of bulk synchronous parallel computing dealing with silent data corruptions in high performance computing parallel sorting on graphics processing units mining for functional dependencies in relational databases cellular automata optimisation of wireless sensors networks connectivity preserving network transformers constrained resource networks vague computing parallel evolutionary optimisation emergent behaviour in multi agent systems vehicular clouds epigenetic drug discovery dimensionality reduction for intrusion detection systems physical maze solvers computer chess parallel algorithms to string alignment detection of community structure The book is a unique combination of vibrant essays which inspires scientists and engineers to exploit natural phenomena in designs of computing architectures of the future      **A Mathematical Structure for Emergent**

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**Emergent Computation** Stephanie Forrest, 1990      **Emergent Computation** S. (ed.). Forrest, Los Alamos National Laboratory, NM (USA). Center for Nonlinear Studies, 9. Annual international conference on self-organizing, collective and cooperative phenomena in natural and artificial computing networks, 1990      The Evolution of Emergent Computation in Cellular Automata Rajarshi Das, 1998      **From Parallel to Emergent Computing** Andrew Adamatzky, Selim Akl, Georgios Ch. Sirakoulis, 2019-03-13 Modern computing relies on future and emergent technologies which have been conceived via

interaction between computer science engineering chemistry physics and biology This highly interdisciplinary book presents advances in the fields of parallel distributed and emergent information processing and computation The book represents major breakthroughs in parallel quantum protocols elastic cloud servers structural properties of interconnection networks internet of things morphogenetic collective systems swarm intelligence and cellular automata unconventionality in parallel computation algorithmic information dynamics localized DNA computation graph based cryptography slime mold inspired nano electronics and cytoskeleton computers Features Truly interdisciplinary spanning computer science electronics mathematics and biology Covers widely popular topics of future and emergent computing technologies cloud computing parallel computing DNA computation security and network analysis cryptography and theoretical computer science Provides unique chapters written by top experts in theoretical and applied computer science information processing and engineering From Parallel to Emergent Computing provides a visionary statement on how computing will advance in the next 25 years and what new fields of science will be involved in computing engineering This book is a valuable resource for computer scientists working today and in years to come

*Emergent Computation* Matthew Simon, 2005-11-10 Emergent Computation emphasizes the interrelationship of the different classes of languages studied in mathematical linguistics regular context free context sensitive and type 0 with aspects to the biochemistry of DNA RNA and proteins In addition aspects of sequential machines such as parity checking and semi groups are extended to the study of the Biochemistry of DNA RNA and proteins Mention is also made of the relationship of algebraic topology knot theory complex fields quaternions and universal turing machines and the biochemistry of DNA RNA and proteins Emergent Computation tries to avoid an emphasis upon mathematical abstraction elegance at the expense of ignoring scientific facts known to Biochemists Emergent Computation is based entirely upon papers published by scientists in well known and respected professional journals These papers are based upon current research A few examples of what is not ignored to gain elegance DNA exists as triple and quadruple strands Watson Crick complementary bases have mismatches There can be more than four bases in DNA There are more than sixty four codons There may be more than twenty amino acids in proteins While Emergent Computation emphasizes bioinformatics applications the last chapter studies mathematical linguistics applied to areas such as languages found in birds insects medical applications anthropology etc Emergent Computation tries to avoid unnecessary mathematical abstraction while still being rigorous The demands made upon the knowledge of chemistry or mathematics is minimized as well The collected technical references are valuable in itself for additional reading

**Universality And Emergent Computation In Cellular Neural Networks** Radu Dogaru, 2003-03-13 Cellular computing is a natural information processing paradigm capable of modeling various biological physical and social phenomena as well as other kinds of complex adaptive systems The programming of a cellular computer is in many respects similar to the genetic evolution in biology the result being a proper cell design and a task specific gene How should one program the cell of a cellular computer such that a dynamic behavior

with computational relevance will emerge What are the rules for designing a computationally universal and efficient cell The answers to those questions can be found in this book It introduces the relatively new paradigm of the cellular neural network from an original perspective and provides the reader with the guidelines for understanding how such cellular computers can be programmed and designed optimally The book contains numerous practical examples and software simulators allowing readers to experiment with the various phases of designing cellular computers by themselves Computational Economic Systems Manfred Gilli, 2013-03-09 The approach to many problems in economic analysis has changed drastically with the development and dissemination of new and more efficient computational techniques Computational Economic Systems Models Methods Econometrics presents a selection of papers illustrating the use of new computational methods and computing techniques to solve economic problems Part I of the volume consists of papers which focus on modelling economic systems presenting computational methods to investigate the evolution of behavior of economic agents techniques to solve complex inventory models on a parallel computer and an original approach for the construction and solution of multicriteria models involving logical conditions Contributions to Part II concern new computational approaches to economic problems We find an application of wavelets to outlier detection New estimation algorithms are presented one concerning seemingly related regression models a second one on nonlinear rational expectation models and a third one dealing with switching GARCH estimation Three contributions contain original approaches for the solution of nonlinear rational expectation models

An emergent computation approach to natural language processing Jon Rowe, Paul McKeivitt, University of Exeter. Department of Computer Science, 1991\* Dynamics, Emergent Computation, and Evolution in Cellular Automata Wim Hordijk, 1999 *Applied Computational Intelligence, Proceedings Of The 6th International FLINS Conference* Da Ruan, Pierre D'hondt, Etienne E Kerre, Martine De Cock, Mike Nachtegaele, 2004-08-17 FLINS originally an acronym for Fuzzy Logic and Intelligent technologies in Nuclear Science has now been extended to include computational intelligent systems for applied research FLINS 2004 is the sixth in a series of international conferences covers state of the art research and development in applied computational intelligence for applied research in general and for power nuclear engineering in particular This book presents the latest research trends and future research directions in the field The proceedings have been selected for coverage in Index to Scientific Technical Proceedings ISTP ISI Proceedings Index to Scientific Technical Proceedings ISTP CDROM version ISI Proceedings CC Proceedings Engineering Physical Sciences **Computation at the Edge of Chaos**, 1990 In order for computation to emerge spontaneously and become an important factor in the dynamics of a system the material substrate must support the primitive functions required for computation the transmission storage and modification of information Under what conditions might we expect physical systems to support such computational primitives This paper presents research on Cellular Automata which suggests that the optimal conditions for the support of information transmission storage and modification are achieved in the vicinity of a phase transition We observe surprising similarities

between the behaviors of computations and systems near phase transitions finding analogs of computational complexity classes and the Halting problem within the phenomenology of phase transitions We conclude that there is a fundamental connection between computation and phase transitions and discuss some of the implications for our understanding of nature if such a connection is borne out 31 refs 16 figs      Super-Recursive Algorithms Mark Burgin, 2006-12-21 Super Recursive Algorithms provides an accessible focused examination of the theory of super recursive algorithms and its ramifications for the computer industry networks artificial intelligence embedded systems and the Internet The book demonstrates how these algorithms are more appropriate as mathematical models for modern computers and how these algorithms present a better framework for computing methods in such areas as numerical analysis array searching and controlling and monitoring systems In addition a new practically oriented perspective on the theory of algorithms computation and automata as a whole is developed Problems of efficiency software development parallel and distributed processing pervasive and emerging computation computer architecture machine learning brain modeling knowledge discovery and intelligent systems are addressed This clear exposition motivated by numerous examples and illustrations serves researchers and advanced students interested in theory of computation and algorithms      Information and Computation Gordana Dodig Crnkovic, Mark Burgin, 2011 This volume provides a cutting edge view of the world's leading authorities in fields where information and computation play a central role      *Handbook of Research on Artificial Immune Systems and Natural Computing: Applying Complex Adaptive Technologies* Mo, Hongwei, 2009-04-30 This book offers new ideas and recent developments in Natural Computing especially on artificial immune systems Provided by publisher      **Unconventional Computation and Natural Computation** Jerome Durand-Lose, Natasa Jonoska, 2012-09-02 This book constitutes the thoroughly refereed post conference proceedings of the 11th International Conference on Unconventional Computation UC 2012 held in Orleans France during September 3-7 2012 The 28 revised full papers presented were carefully selected from numerous submissions Conference papers are organized in 4 technical sessions covering topics of hypercomputation chaos and dynamical systems based computing granular fuzzy and rough computing mechanical computing cellular evolutionary molecular neural and quantum computing membrane computing amorphous computing swarm intelligence artificial immune systems physics of computation chemical computation evolving hardware the computational nature of self assembly developmental processes bacterial communication and brain processes      Emergent Computation Stephanie Forrest, 1991 Researchers in several fields are exploring computational systems in which interesting global behavior emerges from local interactions among component parts an approach called emergent computation In these systems interactions among simultaneous computations are exploited to improve efficiency increase flexibility or provide more realistic models of natural phenomena These 31 essays define and explore the concept of emergent computation in such areas as artificial networks adaptive systems classifier systems connectionist learning other learning and biological networks to determine what properties are required of

the supporting architectures that generate them Many of the essays share the themes of design how to construct such systems the importance of preexisting structure to learning and the role of parallelism and the tension between cooperative and competitive models of interaction In the introduction Stephanie Forrest presents several detailed examples of the kinds of problems emergent computation can address These include showing how emergent computation can lead to efficiency improvements in parallel processing establishing the connection between emergent computation and nonlinear systems and comparing two search techniques to show how the emergent computational approach to a problem differs from other more conventional approaches Stephanie Forrest is Assistant Professor in the Department of Computer Science at the University of New Mexico She is also affiliated with the Center for Nonlinear Studies and Computing Division at Los Alamos National Laboratory

**Parallel Problem Solving from Nature - PPSN III** Yuval Davidor, Hans-Paul Schwefel, Reinhard Männer, 1994-09-21 The challenges in ecosystem science encompass a broadening and strengthening of interdisciplinary ties the transfer of knowledge of the ecosystem across scales and the inclusion of anthropogenic impacts and human behavior into ecosystem landscape and regional models The volume addresses these points within the context of studies in major ecosystem types viewed as the building blocks of central European landscapes The research is evaluated to increase the understanding of the processes in order to unite ecosystem science with resource management The comparison embraces coastal lowland forests associated wetlands and lakes agricultural land use and montane and alpine forests Techniques for upscaling focus on process modelling at stand and landscape scales and the use of remote sensing for landscape level model parameterization and testing The case studies demonstrate ways for ecosystem scientists managers and social scientists to cooperate

**Self-star Properties in Complex Information Systems** Ozalp Babaoglu, 2005-05-24 This book is a spin off of a by invitation only workshop on self properties in complex systems held in summer 2004 in Bertinoro Italy The workshop aimed to identify the conceptual and practical foundations for modeling analyzing and achieving self properties in distributed and networked systems Based on the discussions at the workshop papers were solicited from workshop participants and invited from leading researchers in the field Besides presenting sound research results the papers also present visionary statements thought provoking ideas and exploratory results The 27 carefully reviewed revised full papers presented together with a motivating introduction and overview are organized in topical sections on self organization self awareness self awareness versus self organization supporting self properties and peer to peer algorithms

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