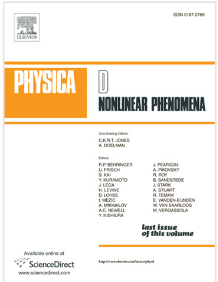
Accepted Manuscript



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PII: S0167-2789(08)00119-X
DOI: 10.1016/j.physd.2008.03.033
Reference: PHYSD 30398

To appear in: *Physica D*

Please cite this article as: C. Teuscher, I. Nemenman, F.J. Alexander, Novel Computing Paradigms: Quo Vadis?, *Physica D* (2008), doi:10.1016/j.physd.2008.03.033

Novel Computing Paradigms: Quo Vadis?

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Introduction

Unconventional computation (also *non-classical*, *novel*, or *emerging computation*) [4, 6, 11, 20] is a broad and interdisciplinary research area with the main goal to go beyond the standard models and practical implementations of computers, such as the von Neumann computer architecture and the abstract Turing machine, which have dominated computer science for more then half a century. This quest, in both theoretical and practical dimensions, is motivated by a number of trends. First, it is expected that, without disruptive new technologies, the ever-increasing computing performance and storage capacity achieved with existing technologies, will eventually reach a plateau. The main reason for this are fundamental physical limits on the miniaturization of today's silicon-based electronics (see e.g., [14]). Second, novel ways to synthetically fabricate chemical and biological assemblies, for example through self-assembly, self-replication (e.g., [9]), or bio-engineering (e.g., [5, 21]) allow one to create systems of unimagined complexity. However, we currently lack the methodologies and the tools to design and program such massively parallel and spatially extended unconventional "machines." Third, many of today's most important computational challenges, such as for example understanding complex biological and physical systems by simulations or identifying significant features in large, heterogeneous, and unstructured data sets, may not be well suited for classical computing machines. That is, while a classical Turing-universal computer, at least from a theoretical perspective, can in principle solve all of these challenging problems (as any other algorithmic problem), the general hope is that unconventional computers might solve them much more efficiently, i.e., orders of magnitude faster and using much less resources.

Not everything that looks like a computation in a physical system is useful and not everything that does some information processing can be used to solve problems. A common, if slightly abused, example is that of a falling ball, which can be interpreted as an "unconventional" computer that solves the second order differential equation of Newton's second law. As a matter of fact, a significant research effort has been spent on similar examples, with the goal to characterize the types of computations, i.e., the laws governing the underlying dynamics behind various physical phenomena. However, a falling ball is a pretty useless computer that can only solve one particular equation with different initial conditions. Interpreting the solution, storing and recalling it, and interfacing the computing unit with other units to perform further computations, is virtually impossible. Thus, while most physical systems solve some equations and most biological organisms process information in some way, we should refrain from calling these systems "computers" until we can harness and interpret the underlying processes with a specific computation in mind. Given a physical, a biological, or a chemical system that is supposed to act as a computer, the question is not only *what*, if anything, this system computes, but also, and more importantly, *What are the characteristics of such a computation? (in terms of speed, size, integration density, or power consumption)? What are the lim-*

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itations? What kind of problems can be solved and how efficiently? How can we "program" the system to perform a specific computation? and *How can we interface the result of the computation with traditional computers to post-process, analyze, and store it?*

The Conference and its Outcomes

Some of the issues raised in the introduction were previously addressed at a conference in Santa Fe, NM, USA, in 2007 [3]. The conference brought together a unique and highly multidisciplinary group of scientists. The single-track program featured 22 invited talks by world-leading scientists, 6 contributed talks, and 17 poster presentations. About 75 registered participants attended the 3-day conference. The topics covered all major aspects of non-classical computation, including for example self-assembling nano-scale electronics, computation with living *Physarum Polycephalum* slime-molds, self-assembling software, chemical programming paradigms, analog, DNA, and quantum computation. One afternoon was dedicated to "computation in the brain," with a special session organized by Chris Wood (Santa Fe Institute). The goal was to address questions such as *In what sense does the brain compute? Are there computational primitives for the brain that represent first-level abstractions in the same sense as binary logic for classical computers? What physical mechanism allows the brain to store new memories quickly (within seconds), yet keep them for a long time (tens of years), and protect them from being overwritten by noise and new memories?* The last question, in particular, is an area of active research in computational neuroscience [10], but has not yet sufficiently been addressed in the broader area of unconventional computation. Thus the goal of the special session was to bridge gaps between disciplines and to focus the research efforts on important common questions.

The conference resulted in a number of important outcomes. First, if we can directly use biological and physical processes to perform computations, we can sometimes solve problems more efficiently compared to traditional approaches, but that is certainly not true in general. For example, neurons are powerful pattern recognizers, but cannot do standard arithmetic with high precision and reliability as conventional computers can. Some of the participants explicitly addressed the promises and drawbacks of such application-specific realizations. Second, a central challenge for new computers is in controlling and programming massively parallel systems consisting of vast numbers of simple and unreliable components. For example, even if we could fabricate a billion biologically realistic neurons, we would not immediately know how to *program* the resulting network to solve a specific algorithmic problem. The grand challenge of programming massively parallel systems was raised from different perspectives in most of the talks.

This Special Issue in a Nutshell

The field of non-classical computing is broad and fragmented, which is typical for a research area that has not matured yet. In this special issue, we have put together a collection of papers, a subset of all presentations at the conference, that fully reflects this interdisciplinary and broad character. The *leitmotif* for the papers was provided to the authors in the form of eight key questions, that we asked them to address specifically:

- What problems can you solve more efficiently with your approach?
- What are the "killer apps?"
- How do you control and program your system?
- How does the approach scale up to larger system and problem sizes?
- What can be brought to market now? In 5 years? In 10 years?
- When do you expect to be competitive with traditional approaches?
- What are the benefits and drawbacks of your approach?
- What needs to be addressed in the future?

We believe that these questions must be asked for any novel computing machine or paradigm. However, as the reader of this special issue will easily see, most of them remained unanswered in all but a few contributions. This suggests that the field is probably even younger than many working in it believe, and that significant research and investments are required in the next few years to come up with alternative approaches that have the potential to become true competitors of classical computers.

In "The Neglected Pillar of Material Computation," Stepney argues that we should be investigating matter from the perspective of its natural computational capabilities instead of forcing non-classical approaches into a conventional Turing computable framework. Molecular computers that operate and are embedded in a biological environment have a huge potential for medical applications. In their review article "Towards Molecular Computers that Operate in a Biological Environment," Kahan et al. argue that molecular computers are particularly interesting not because of their inherent parallelism but because they can interact directly with a biochemical environment.

Besides biological and molecular computing machines, quantum processes offer considerable potential for computation as well. While the theory is already well advanced, daily real-world quantum computers are still far away. Wiesner and Crutchfield introduce quantum finite-state transducers as representations of quantum finitary processes. They compare them to similar deterministic and nondeterministic stochastic classical automata and summarize their relative computational power in a hierarchy of finitary process languages.

Neural systems, whether biological or abstract, form another class of non-traditional computing devices. In their article "Reliable Computing with Unreliable Components: Using Separable Environments to Stabilize Long-Term Information Storage," Nugent et al. ask how one can store classification over long periods in connectionist networks, which are subject to noisy and changing environments and thus to random fluctuations in individual synaptic weights. They demonstrate that this is possible with an unconventional Anti-Hebbian-And-Hebbian (AHAH) plasticity rule. Siegelmann, on the other hand, addresses the ability of humans to modify memories based on new information, a process called reconsolidation. She proposes a model based on attractor dynamics, which is capable of quick memory updates and long storage. However, grounding the explicit introduction of two time scales in the dynamics in real biological organization of the brain will require further work.

Conventional von Neumann computers are not always well suited for solving complex and ill-posed real-world problems. In their article "Analog Computation Through High-Dimensional Physical Chaotic Neuro-Dynamics," Horio and Aihara explore a new mechanism to address this challenge and present a prototype of a highly application-specific machine. They use quadratic assignment problems as benchmarks for their 300- and 800-dimensional chaotic neural dynamics. Another representative of highly powerful, non-classical, and neurally-inspired machines is a Cellular Neural/Nonlinear Networks (CNNs), which is composed of thousands of massively parallel, locally interconnected analog cells. Ercsey-Ravasz et al. present two examples of stochastic simulations on CNNs: the site-percolation problem and the two-dimensional Ising model in their article "Statistical Physics on Cellular Neural Network Computers."

Analog computing paradigms offer non-classical alternatives to the all-to-present digital paradigms in today's computers. Mills' article "The Nature of the Extended Analog Computer" introduces the Δ-digraph in the context of Rubel's extended analog computer [19]. The Δ-digraph defines the paradigms of analogy and algorithm, illustrates how applications for the EAC are analogies developed by choosing the semantics for a machine configuration, and suggests how partial differential equations might be compiled to EAC configurations.

Exploring the fundamental physical limits of computation is an important field as well. Wolpert's article "Physical Limits of Inference" shows that all devices that perform observation, prediction, or recollection share an underlying mathematical structure. He provides various existence and impossibility results about such inference devices, which hold independently of the precise physical implementations.

While non-classical physical devices and computing substrates are key for novel computing machines, programming languages and tools are equally essential for new machines to eventually become competitive with traditional approaches. The last two papers address some of these issues. In their article "The Foundation of Self-Developing Blob Machines for Spatial Computing" Gruau et al. present self-developing blob machines, virtual machines that that run on a physical cellular automaton substrate. Objects are placed in space by simulating physical forces among them, which represents an elegant way to deal with the locality problem of this spatially extended computer.

Finally, Giavitto and Spicher address the importance of explicitly handling spatial relationships with their MGS language (MGS stands for "Modèle Généraliste de Simulation"), which offers topological collections and transformations using the concepts developed in algebraic topology. In their article "Topological Rewriting and the Geometrization of Programming," they show how to use transformations in order to implement a discrete version of some differential operators, and how MGS handles data like fields in physics.

Future Research Directions

We are experiencing a "composite revolution" [18] where the convergence of various sciences, along with their own related inspirations, is more likely to lead us to the destination we seek than any single one of them can. Non-classical computation is a good example, which resides at the interface of various research areas.

We have earlier mentioned a series of questions that we believe should be addressed more seriously by the unconventional computing community. In addition we consider research in the area of the physics of information, information processing, and of algorithms as a key and core to novel computing paradigms and machines. Deep connections have already been discovered between statistical mechanics and computer science. These include the links between phase transitions and complexity in, for example, Boolean satisfiability (SAT) problems, and between the inference on graphs and the statistical mechanics of spin systems [12, 16, 17]. Belief propagation and its generalizations have been related to the hierarchy of variational approaches in statistical mechanics [23] and they provide fast and high quality approximate solutions to computationally hard problems.

In addition to the connections between physics and information, there are a number of outstanding physics questions. For example, in reaction-diffusion systems, one would like to know how stable the patterns (memory) are to fluctuations [7] since this directly impacts the reliability of the memory. One would also like to know how many metastable states the system has (that is, how many memories it can store). And, most important for performing computations, one would like to be able to manipulate and control the transitions between states.

This represents just a small subset of all the open and challenging questions that need to be addressed in the future if we ever want unconventional computing devices and paradigms to become conventional. Clearly, massive and long-term investments are required to rethink computation [1, 2, 13, 22], the way we design and program machines, and the way we think about and control information processing in natural and synthetic systems. Computers as we know them are unlikely to disappear in the near future, however, there is all the reason to expect computers *as we don't know them* to appear *where we don't expect them*. Imagine bio-molecular automata embedded in smart medication, which find their own way to destroy malicious tissue, imagine an Avogadro number (6×10^{23}) of self-replicating bacteria solving an NP-hard graph problem of unimagined size, imagine a trillion cultivated neural cells on a silicon chip that perform facial recognition far more robustly than any classical machine (or a human brain, for that matter).

We would like to encourage the Physica D readership to engage in the computational aspects of nonlinear media and phenomena. Information processing by harnessing nonlinear phenomena in physical systems bears unique opportunities for novel computing devices and paradigms. For example, *transient computation* [8] and *liquid state machines* [15] represent a successful attempt to perform computations with the internal nonlinear dynamics of a system. We believe that the Physica D readership could greatly help in not only understanding experiments, techniques, and ideas of nonlinear phenomena, but to use the toolset and methodologies of physics to harness them for information processing. We hope the readers will enjoy this special issue and that the unique contributions will stimulate new exciting research in the next few years.

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Los Alamos, NM, USA, February 2008

Acknowledgments

The "Unconventional Computing: Quo Vadis?" workshop [3] would not have been possible without generous support from the Center for Nonlinear Studies (CNLS) at Los Alamos National Laboratory (LANL), with additional support from the Information Sciences group (CCS-3) at LANL, the Santa Fe Institute (SFI), and Old City Publishing. We would like to thank (in alphabetical order): Melissa Castaneda, Robert Ecke, Adolfy Hoisie, Stephen Lee, Kelle Ramsey, Adam Shipman, Donald Thompson, Ellie Vigil, Chris Wood, the contributing and invited workshop speakers, all contributors of this special issue, and the numerous reviewers. A special thanks goes to the Physica D editorial members Gary W. Anderton, Arjen Doleman, and Joceline Lega.

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