Research Statement

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1 Summary

Although the implementation of Boolean functions in semi-conducting materials is currently dominating the study and practice of computing, I believe it is important to continue searching for new models and new implementation mediums. I consider the study of computation to be tightly connected with the natural sciences since the laws of physics provide hard limits to the potential computing power of an implemented model of computation.

I plan to use my knowledge of computational complexity theory to evaluate physical phenomena so as to deepen our understanding of computation and to push back the boundaries of what we consider "tractable" problems (normally a subset of those problems solvable in polynomial time (the set P)).

2 Recent research

When solving problems with *natural computing*[1] systems, it sometimes seems more intuitive to directly encode a problem instance into the computation machinery. For example, Adleman's ground breaking DNA computer directly encoded an instance of the Hamiltonian Path Problem in strings of DNA, a different set of DNA strings is required when a different instance of the problem is considered. This encoding technique is seen in many other optical, biological and mechanical models of computation. We say a family of devices that solves a problem in this manner is *semi-uniform* if a single algorithm writes out the description of the appropriate device to solve a problem instance when given the problem instance as input.

Other models, Boolean circuits for example, are designed so that there is one device to solve all problem instances of a certain size, if these devices are described by a single algorithm which takes a number representing the input size then it is called a *uniform* family.

Before my research, semi-uniform and uniform families of every model of computation were believed to solve the same class of problems. However, when I examined a model of computation where both uniform and semi-uniform families were believed to characterise P, I noticed that the families were relying on their family constructing algorithm to solve the problem for them! By restricting the power of the family constructing algorithms I accurately characterised the computing power of these systems for the first time. The semi-uniform families are actually restricted to solving a class of problems solvable with very little memory (known as NL) [3, 5]. Even more surprising is that the uniform families are extremely weak, solving a tiny set of problems (at most AC^0) [4].

This result has ramifications for many models of computation, both natural (neural networks, molecular and DNA computers, tile assembly systems computing systems, optical computers and cellular automata) and also "classical" systems such as Boolean circuits and branching programs. We are currently working to understand exactly the conditions where uniformity and semi-uniformity are different.

[1] Natural computing is a catch-all term for unconventional, non-silicon or non-Boolean algebra based models of computation, especially those inspired by biology

This research in complexity theory has been done through an established model of computation known as Membrane Computing (or P-systems) which are models of computation abstracted from the sub-systems of biological cells (with special focus on the cell membrane). By concentrating on a specific feature or sub-system of a cell and using its properties to define a model of computation, we make progress towards understanding the nature of computation within cells without getting paralyzed by their overwhelming complexity.

As an example, it is claimed that the exponential growth provided by membrane division (an model operation reminiscent of mitosis) does not give membrane systems any reliable ability to solve intractable problems in the class NP. I have made significant progress on proving this conjecture (which has been open for 5 years) and have proved that several restrictions of the model can solve no more than the problems in P [2, 7].

My work has brought a new direction to the study of complexity in membrane computing by focusing on (the more realistic and implementable) lower-level complexity classes as apposed to solving NP-hard computational problems, as was the previous trend over a number of years.

Early on in my research I designed a model of analog sorting that characterises how physical laws affect particles according to their properties [1]. We worked with physicists and biologists to implement instances of the model using common laboratory techniques such as chromatography, the diffraction of light, gel electrolysis, and mass spectrometry. Our model of physical sorting naively compares favorably with digital sorting algorithms (which require at least $\Omega(n \log(n))$ time). However, setting up the problem instance and reading off the sorted list are slow operations and reduce the competitiveness of this method of sorting. I also designed a model of computation in which strands of DNA work like Boolean circuits [6].

3 Short term plan

In the immediate future I will continue to investigate what causes uniform and semi-uniform families of some systems to have a gap in their power, this is a fascinating problem and is opening many interesting new avenues of research.

I am also about to start a short-term project to extract information from digital holographic images. From this project I will gain insight into optical computing, holographic storage and parallel computing.

My short term plan is work with the best international research groups on in following topics:

- Complexity theory: I am interested to work with theoretical groups and use my knowledge of natural computing and unusual models to give fresh and unique approaches to explore new terrain in complexity theory.
- Natural computing: I would love to use my expertise in complexity theory to help those implementing models of natural computing devices (biological, chemical, optical, quantum or new silicon technologies) to understand the theoretical computing power of the systems they are building.
- Systems biology: My experience developing algorithms to explore exponential computation trees would be invaluable to a systems biology group. My approach of studying natural processes from the point of view of a computation can give insight as to how to simulate and more accurately predict their behaviour.

4 Long term plan

My long term research plan is to contribute to the research of top international groups working in Computational Complexity, Natural Computing and Systems Biology. While visiting and working with these groups I also want to absorb more of the collective knowledge that scientists have amassed about computing and the physical world. Eventually I will seek a permanent position and found (or join a suitable) research group where I will gather experts and enthusiastic new students to combine knowledge of the physical world and computation to expand our range of computing technology.

One of the features in nature that seems particularly powerful is the natural parallelism that can be found in optics, chemical reactions, biological processes, ant/slime-mold colonies, the robust recognition processes found in immune systems, and of course our own brains.

It is my ambition to one day be able to use deep knowledge of a model of computation and its implementation to allow us to make a new prediction about the physical world.

References

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