Unconventional Computation: Quo Vadis?

Conference Report

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Executive summary

It is generally expected that without disruptive new technologies beyond multi-core systems, the current pace of progress in computer science will eventually reach a plateau within 5-10 years. The goal of the "Unconventional Computation: Quo Vadis?" conference was to look beyond the horizon and to delineate promising future research directions. The main outcome is threefold: (1) highly specialized, niche, and application-specific approaches are more likely to be successful than general purpose architectures; (2) most problems can be boiled down to the largely unsolved challenge of programming and controlling massively parallel ensembles of simple computing elements; and (3) rethinking computation is a necessary, promising, and long-term research agenda which addresses a broad spectrum of challenges.

Motivation and background

Unconventional computation (also *non-classical* or *emerging computation*) is an interdisciplinary research area with the main goal to enrich or go beyond the standard models, such as the von Neumann computer architecture and the 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 observations:

- there is a huge gap between information processing in nature and in artifacts [2, 3], i.e., machines are good where nature isn't and vice versa;
- existing formalisms and computational paradigms are often not suitable to describe, predict, and control the complex information processing in biological, chemical, and physical systems;
- the downfall of Moore's law [5] and sky-rocketing chip foundry costs ask for new fabrication approaches;
- a drastic increase in complexity and the number of individual components involved due to ongoing miniaturization and novel computing substrates (e.g., nano-scale and molecular electronics, *in vivo* or *in vitro* biological devices);
- a drastic widening of the "design gap," i.e., our ability to design and program computers is not keeping up with the number and the complexity of the individual components available [4];
- the increasing need to deal with defect and unreliable components due to miniaturization, novel materials, novel manufacturing techniques, and larger numbers of components involved;
- the difficulty to program massive parallel, fine-grained, and spatial computing ensembles;
- more dynamic, complex, and harsher environments (e.g., radiation) due to an increasing pervasiveness of computing machines, i.e., computers will literally be everywhere (ubiquitous computing), but increasingly invisible (disappearing computers).

Generally speaking, the hope is that the above challenges might be tackled more efficiently by alternative paradigms. For example, developments in synthetic biology, biochemistry, neuroscience, statistical mechanics, or optics, show that complex computations are omnipresent in physical systems, but that they cannot always be easily described, reproduced, or used for specific purposes in the context of standard computing models. Given a physical, biological, or chemical system, the question is whether such a system computes, and if yes, then what and how? What are the limits and characteristics of such a computation? And how could we "exploit" and "program" the system to perform a specific task in an efficient manner for the purpose of computation?

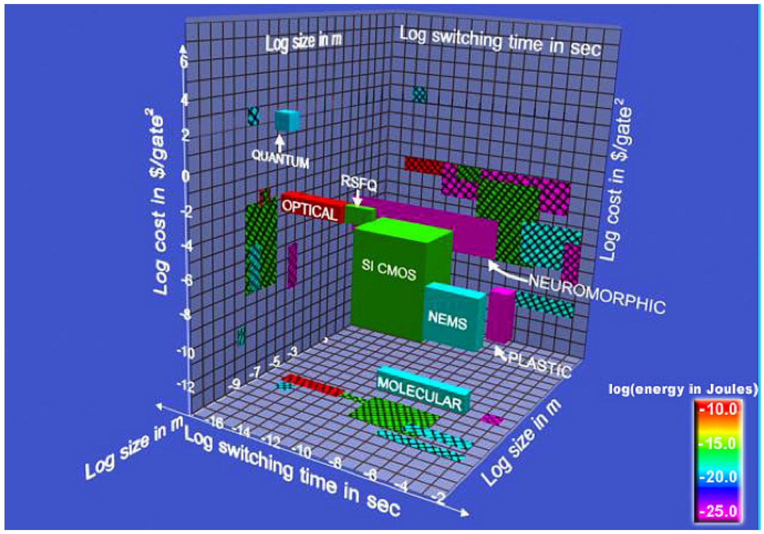

Figure 1: ITRS [1] technology matrix. Silicon CMOS lies in a "sweet spot" in terms of cost, size, speed, and energy consumption. *RSFQ* stands for *Rapid Single-Flux-Quantum* devices, where digital bits are coded in statics by the single quanta of magnetic flux. This technology is based on superconductors and such circuits can reach clock frequencies of well above 100GHz. *Plastic* stands for plastic electronics.

Conference contents and outcomes

The conference brought together a unique and highly multidisciplinary core of scientists. The single-track program (http://cnls.lanl.gov/uc07/Agenda.html) 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 included all major aspects of unconventional computation, including for example self-assembling nano-scale electronics, computation with living *Physarum Polycephalum* slime-molds, self-assembling software, unconventional programming paradigms based on chemical paradigms, analog, DNA, and quantum computation. In addition, one afternoon was entirely 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 "does the brain 'compute'?" If so, "in what sense?" If not, "what forms of non-computational information processing does the brain perform?" Are there "computational primitives" for the brain that represent first-level abstractions for the brain in the same sense that binary arithmetic and Boolean algebra are "computational primitives" for von Neumann architectures?

As Figure 1 illustrates, silicon technology—which is based on more than half a century of research—currently lies in a "sweet spot" in terms of cost, size, speed, and energy consumption. But, alternative technologies, such as molecular electronics or quantum computers, bear unexploited potential that will be available only with the maturation of these approaches (see Figure 2).

Most physical and biological systems process information in some way, the question is how these processes can be used and/or interpreted for the specific purposes of computation? How will they enable us to go beyond traditional approaches (in terms of speed, integration density, or power consumption)? What are the limitations? What kind of problems can be solved and how efficiently? There are essentially three ways—all of which were covered during the conference—one can think about computation in the context of physical systems and biological organisms:

- the original process is being interpreted in a particular way,
- a natural system is "modified," or
- a system is engineered synthetically from scratch

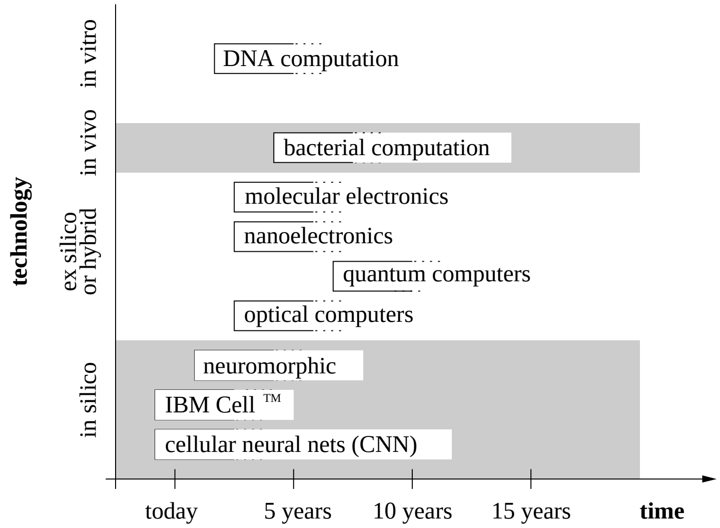

Figure 2: Illustration of the estimated time when different alternative computing paradigms and machines might become mature enough to efficiently solve some large-scale real-world problem. While some technologies are readily available today, others will require many more years of intense research.

to perform specific functions for the purpose of computation. For example, molecular and nano-scale electronics are commonly engineered (or rather "self-assembled") from scratch. In traditional DNA computation as introduced by Adelman, a problem is encoded and its solution interpreted in a particular way, which allows to elegantly solve problems with the natural mechanisms performed by DNA. On the other hand, the bio-chemical processes of biological cells can be modified today rather straightforwardly with bio-engineering methods for the purpose of computation.

The main outcomes of the conference can be summarized as following:

- If we can directly use biological and physical processes to perform computations, we can often solve problems more efficiently compared to traditional approaches. However, only selected problems can be addressed efficiently. For example, neurons are powerful pattern recognizers, but cannot do standard arithmetic.
- Biological (e.g., the brain) and artificial (e.g., molecular electronics) systems—whether traditional or alternative—are composed of huge numbers of simple components that interact in a mostly local manner. The challenge of using them for the purpose of computation can be boiled down challenge of programming and controlling such a massively parallel system. This challenge came up from various perspectives in most of the talks.
- Design tools and languages (e.g., programming languages) lack the ability to express and address the spatial aspects of novel and natural computing substrates. Spatial aspects are irrelevant in von Neumann architectures but play a crucial role in alternative computing devices, where one can often trade space for time due to the massive inherent parallelism.
- The different sub-fields of unconventional computation are in various stages of maturity (see Figure 2) and address different problems by different means. There is no single solution to all challenges and one can therefore see an increasing trend for highly specialized machines.

A special issue of the Physica D journal, which will contain selected and peer-reviewed contributions from the invited speakers, is in preparation (to be published early 2008). The goal is to put together a high-quality publication that contains the state-of-the-art and outlines future research directions in the broad field of unconventional computation.

Impact of research

We are experiencing a "composite revolution" 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. The importance of going beyond existing models and machines is emphasized by a growing international community of researchers that is concerned to keep computer science going at the same pace. Massive and long-term investments are required to rethink computation and to address tomorrow's complex large-scale grand challenges in computer science.

Related links

- "Unconventional Computing 2007," Bristol, UK, Jul 12-14, 2007.
  http://uncomp.uwe.ac.uk/uc2007
- "Unconventional Computation 2007" (UC'07), Kingston, Canada, Aug 13-17, 2007.
  http://www.cs.queensu.ca/uc07
- "Unconventional Computation: Quo Vadis?" Santa Fe, NM, USA, Mar 20-23, 2007.
  http://cnls.lanl.gov/uc07
- Computer Research Association (CRA) conference on *Grand Research Challenges*, "Revitalizing Computer Architecture Research, " 2005.
  http://www.cra.org/Activities/grand.challenges/architecture
- Nature, "2020 – Future of Computing," 2006.
  http://www.nature.com/nature/focus/futurecomputing
- International Journal of Unconventional Computing
  http://www.oldcitypublishing.com/IJUC/IJUC.html

References

[1] International technology roadmap for semiconductors (ITRS). Semiconductor Industry Association, `http://www.itrs.net/reports.html`, 2005.

[2] R. Brooks. The relationship between matter and life. *Nature*, 409(6818):409–411, January 18 2001.

[3] M. Conrad. The brain-machine disanalogy. *BioSystems*, 22(3):197–213, 1989.

[4] J. Henkel. Closing the SoC design gap. *IEEE Computer*, 36(9):119–121, 2003.

[5] L. B. Kish. End of Moore's law: Thermal (noise) death of integration in micro and nano electronics. *Physics Letters A*, 305:144–149, 2002.

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