Klaus-Peter Zauner, invited view at ICT Event, Lyon 25.-27. November 2008, The European Commission's Directorate General Information Society and Media

Bio-chemistry based IT: Prerequisite for a Revolution

Context & Impact

The intricate organisation of a small set of chemical building blocks gives rise to the wide variety of material structures and specialised functions seen in nature. A complexity barrier largely prevents chemists and engineers from entering this design space. When this hurdle can be tackled, however, the technology impact will rival the advent of organic chemistry.

To make the complexification of matter exhibited by nature amenable to engineering, it will be necessary to mimic the molecular level information processing employed by organisms. Living systems are peculiarly organised inhomogeneous arrangements of the very same matter that forms the remaining dead universe. Their highly organised state can be sustained only by active maintenance which in turn necessitates the processing of information—life without computation is inconceivable.

Information processing serving to sustain the complex organisation of an organism faces both the harsh reality of real-time requirements in an open physical world and severe constraints on energy and material that can be expended on the task. The proficiency with which this challenge has been met by evolution is amply demonstrated by single-cell organisms that can maintain their living state under ultra-violet radiation, gamma-radiation, or above the boiling point of water. Being single-cells, all information processing in these organisms is bio-chemistry-based.

In face of the apparent discrepancy between attempts to implement artificial devices with life-like properties (robots, cognitive systems) and the performance of living systems it appears likely that the intertwining of information processing and material processes innate to organisms may confer computational capabilities that in practise surpass conventional computing methods.

Macromolecular information processing therefore plays a dual role:

1. It enables the exploitation of existing and future bio- and nano-materials for enhanced computational capability.
2. It is a necessary step towards opening the engineering path towards the marvellously efficient and complex materials we see in the living world.[1]

Distinctive Characteristics

In the foreseeable future bio-chemistry-based information technology is not likely to supersede solid-state technologies. Its role will likely be complementary and open up new application domains. The unique properties of bio-chemistry-based information technology are therefore more pertinent than the possibility to emulate conventional mechanisms and architectures.[2] Extrapolating from what is known about molecular-level information processing in organisms, some of the features one could expect to be exploited by bio-chemistry-based information technology are:

- Direct use of the physical characteristics of materials for computation to achieve a radical reduction in size and energy requirements for information processors.
- Use of noise, in particular the thermal heat-bath, in a constructive way: bio-molecular interactions profit from the free search that Brownian motion provides. Implementing molecular recognition steps without the benefit of the heat bath would be cumbersome.
- Self-assembly of structures enables the replenishing of components during operation. This confers three advantages:
  1. Components with a limited cycle-time can be used and continually replaced.
  2. Components that are damaged by external factors (e.g., high energy radiation, reactive chemicals, or strongly binding contaminants) can be replaced, affording a first level of self-repair.

3. If all essential components of a system can be replenished the basis for self-reproduction is available. Biased selection (together with ubiquitous noise) would then enable directed evolution.

- The physical and chemical properties of a chemical compound can be radically different from the properties of the reactants that form the compound. Together with the combinatorial space of conceivable macromolecules, bio-chemistry-based IT can rely on a large set of highly specialised components assembled from a small number of building blocks.

Impediments to Progress Present IT is founded on the basis that computation can be formally prescribed independent of its physical realisation. Coercing a physical substrate to obey the formalism, however, comes at the price of a large overhead in material and energy. It will be necessary to both go back to early ideas of information processing architectures (e.g., from the time when components with high signal gain were difficult to achieve, cycle times were limited, analog-digital hybrid systems were in use), and to broaden the notion of computation. Critical will be that such a broadening is not driven by the convenience of formalisms, but instead by the physical reality of biomolecular implementations (e.g., thermal noise, conservation of mass in reaction pathways).

The existing knowledge about biochemistry is heavily biased towards physiological conditions. From on IT engineering perspective this is an unnecessary constraint. Non-physiological biochemistry, such as enzymatic reactions in organic solvents (which have been developed for industrial applications), indicate that the design space may be much wider than what is apparent form standard bio-chemistry text-books.

Challenges Examples of challenges that can be addressed in the near term can make the issues outlines above more concrete:

- Excitable molecular devices (e.g, droplets, vesicles) that act as crude artificial bio-molecular neurons.
  - Repeatable excitation, refractory period, use of chemical energy
  - Interconnection of such devices
  - Specificity of trigger signal and output signal
  - Adaptation of trigger-level and gain (e.g., to mean concentration of input signal)
- Self-Assembly of components with internal states that allow sequencing and check-pointing of the assembly steps. Present self-assembly schemes (e.g. DNA tiles) have very low yield and need to be slow (near equilibrium) to keep error-rates low. State switching in the assembling components (as seen in virus self-assembly) can overcome this limitation.
- The development of a flexible set of molecular building blocks that will facilitate experimental research: DNA is easy to work with but not flexible enough (it is optimised for information storage, not processing—good storage materials resist change), RNA has great functionality but is difficult to work with: can we come up with a few molecules that would provide more convenient building blocks?

Opportunities & Applications Biochemistry-based information processing is complementary to existing technology and will open up application domains that are out of reach for conventional approaches. Future applications will fall in three broad areas:

1. Molecular Co-processors: bio-chemistry based IT interfaced with conventional technology to provide properties that are hard or impossible to implement with solid-state devices.
2. Bio-immersive IT: The application of bio-chemistry based IT to integrate engineered control mechanisms into living cells.
3. Informed Matter:[1] The application of information paradigms to chemistry to enable molecular-level control in the synthesising complex macromolecules.

By far the most exciting opportunity opened up by molecular information technology is its potential to bring us closer to engineering with heterogeneous macromolecules and supra-molecular systems. It would be difficult to overestimate the technology impact this will have.

Before such a general application of information-paradigms on the molecular scale will be feasible, however, more specialised application areas are likely to see the benefit of molecular information technology. Examples range from task-specific processors for complex pattern recognition problems to devices on the cubic-millimetre scale capable of sophisticated real-time response. The latter, together with direct chemical power supply will enable insect-like micro-robots with long endurance.

The compatibility of biochemistry-based IT with living cells enables a novel application scenario for IT: Artificial intracellular controllers for synthetic biology applications such as genetic-control in micro organisms deployed for decontamination of chemical spills are an example. Networks of cells could functionalise surfaces for sensing and do so at very low cost. Micro organisms with artificial molecular controllers could act as actuators in micro devices. On a longer time scale bio-immersive IT may be used for "intelligent" drugs that determine the biochemical state (health) of a cell, before they act on it.[3,4]

Bio-chemistry based control structures that employ ongoing self-assembly processes to actively resist impinging destructive processes open up applications of very small and lightweight devices in harsh environments. Possible applications in this domain are sensor networks that are robust against contamination, or corrosive chemical conditions. But also the replenishment of photosensitive areas and the rerpair of molecular films that are driven through large cycle numbers (e.g., in diplays) can be imagined.

In the this context of self-assembly, it is interesting to note, that historically slower but denser IT technology has won out over faster technology. It is plausible that the high component and connection density that is feasible in a molecular architecture arising from self-assembly and growth processes can compensate for its limited speed. Arguably, therefore, biochemistry-based IT may, in the long-run, also make inroad in some of the established domains of silicon-based information technology.

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