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Biological and Chemical Information Technologies

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Abstract

Biological and chemical information technologies (bio/chem IT) have the potential to reshape the scientific and technological landscape. In this paper we briefly review the main challenges and opportunities in the field, before presenting several case studies based on ongoing FP7 research projects.

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1. Background

The capabilities of biological and chemical-based systems are being harnessed for the purposes of radically new forms of computation and nano- and micro scale production. Natural systems are inherently self-organizing, self-repairing, resilient, distributed and adaptive. Importantly they may also be interfaced with traditional, silicon-based substrates to offer the possibility of truly hybrid systems. The growth (and integration) of emerging research areas such as systems- and synthetic biology, artificial cells, chemical information processing, micro-electro-mechanical systems (MEMS), nanotechnology and artificial intelligence means that *biological and chemical information technologies* (bio/chem IT) provide one of the most vibrant and important emerging research domains in recent years. Bio/chem IT is an enabling technology with wide ranging applications areas for current information and communication technologies (ICT) and beyond. The long term potential for creating more life-like and intelligent computational, information processing and production processes will open up applications in most sectors of our society. Possible mid-term application areas for technologies emerging from this work include engineered intelligent diagnostics and drug delivery systems, artificial tissues, nanotechnology for energy and environmental applications, adaptive bioelectronics and molecular synthesis.

2. Bio/chem IT

Traditional information technology (IT) relies on human-engineered solutions implemented on a silicon-based substrate. Although powerful in terms of raw processing capabilities, modern computers lack the *adaptability*, *resilience* and *flexibility* of natural systems. Even the simplest organisms are capable of reconfiguring their internal architectures

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in response to combinations of external signals and internal "programming; a process that is inherently *bio-chemical* in nature. The field of biological and chemical IT (bio/chem IT) seeks to harness the capabilities of natural and chemical systems. Rather than simply *deriving inspiration* from living systems, bio/chem IT researchers seek to *directly use* or *construct* these systems for the purposes of engineering and computation.

2.1. State of the art, and research challenges

Over the past few years, technological advances in chemistry, molecular biology, functional materials and engineering have brought biological and chemical information processing within our control. The ability to build, design and *grow* ICT systems that can exploit these processes will lead to revolutionary advances in the future.

The fundamental challenges facing bio/chem IT revolve around the *evolution*, *construction* and *control* of collections of individual elements, such as bacterial/neural cells, proto/artificial/minimal cells, or functional molecular complexes. These components will be capable of "intelligent" and designer-independent functioning, and be able to respond via self-assembly and/or self-regulation. In order to harness these systems, we require the ability to engineer and control chemistry at the micro-level, as well as being able to understand and control macroscopic, population-level behaviour. This will require a deeper understanding of the extraordinary natural engineering processes by which living cells operate, and how bio-chem elements interact with a MEMS matrix, as well as fundamental insights into the dynamics of large numbers of interacting agents.

2.2. Opportunities and impact

The potential payoff from this field will be information processing systems that are *evolvable*, *self-replicating*, *self-repairing* and *responsive* to their environment (as well as having local intelligence), whilst also being capable of interfacing with existing silicon based ICT systems. Such capacity will open up a radically new form of technology that couples information processing with physical control and production at both the micro- and macro-levels. A breakthrough in this area would allow ICT specialists programmable algorithmic entry to the world of nanoscale chemical processes, as well as the self-organised power of cellular assemblies. In the future, we will require not top-down, directed assembly of structures, but the utilisation of interactions between components to *self-assemble* functional information processing materials of immense complexity.

3. Case studies

In this Section we give brief summaries of the four projects that form the core membership of the COBRA (Coordination of Biological and Chemical IT Research Activities) Coordination Action. COBRA is supported by the EU FP7 Future and Emerging Technologies (FET) Proactive initiative (2010-2013). These projects all contributed short talks to a special *fet*[11] session, organized by COBRA[1]. The plenary talk was given by Dr Farren Isaacs of Yale University. Full details of all constituent projects, including links to websites, are at the COBRA webpage at http://www.cobra-project.eu.

3.1. BACTOCOM

The main objective of the BACTOCOM project is to build a *general-purpose* platform for synthetic biology. Parts of the internal "program" of a bacterial cell (encoded by its genes, and the connections between them) may be "reprogrammed" in order to persuade it to perform human-defined tasks [2]. By introducing artificial "circuits" made up of genetic components, we may add new behaviours or modify existing functionality within the cell. Existing examples of this include a bacterial oscillator, which causes the cells to periodically flash, and cell-based pollution detectors that can spot arsenic in drinking water. The potential for bio-engineering is huge, but the process itself is made difficult by the noisy, unpredictable nature of the underlying material. Bacteria are hard to engineer, as they rarely conform to the traditional model of a computer or device, with well-defined components laid out in a fixed design.

[1] Full session details, including resources, at http://www.cobra-project.eu/fet11.html.

We use the inherent randomness of natural processes to our advantage, by harnessing it as a framework for biological engineering. We begin with a large number of simple DNA-based components, taken from a well-understood toolbox, which may be pieced together inside the cell to form new genetic programs. A population of bacteria then absorbs these components, which may (or may not) affect their behaviour. Crucially, the core of our bacterial computer is made up of engineered microbes that can detect how well they are performing, according to some external measure, such as an oscillation period [1]. By performing massively-parallel bacterial random search, we quickly obtain functional devices without "top down" engineering.There are many potential benefits to this work, from both a biological and computing perspective. By uncovering new functional structures, we gain insight into biologicalsystems. This, in turn, may suggest new methods for silicon-based computing, in the way that both evolution and the brain have already done. In building these new bio-devices, we offer a new type of programmable, microscopic information processor that will find applications in areas as diverse as environmental sensing and clean-up, medical diagnostics and therapeutics, energy and security.

3.2. NEUNEU

This project will develop and produce a robust and adaptable substrate for computing. *Droplets* containing a chemical reaction system enclosed in a lipid membrane are the basic computational units. These units can store chemical energy and can repeatedly respond to input signals with a change in their chemical state. The droplets communicate by exchanging signalling molecules that diffuse across membranes or move through transmembrane channel proteins, much like cells in a tissue. Architectures of interconnected droplets can emulate the switching networks of conventional information technology,albeit at a much slower speed. Their natural mode of operation, however, is fundamentally different from semiconductor-based technology, and more akin to nature's information processing mechanisms. The analogy with biological architectures extends beyond information processing, to their chemical energy supply, and also to the production of the units (for example, self-organisation of lipids at a water-oil interface constructs a self-healing membrane around the droplets).

Currently the NEUNEU project studies the properties of basic droplets in the wet-lab [8]. This study has identified configurations and parameter ranges suitable for information processing. Furthermore, novel microfluidic devices are built by rapid prototyping for automatic generation of droplets. *In silico*, simulators are constructed for different levels of abstraction. These facilitate modelling of the internal dynamics of droplets, in order to study approaches that make use of wave propagation within droplets [5]. For droplets with homogeneous internal activity and self-assembly processes, a novel rule-based approach is developed, which allows the simulation of relatively large architectures in three-dimensional space.

3.3. ECCell

ECCell is an EU sponsored project funded in the ICT Future Emerging Technologies by the FET-Open program (2008-2011). The aim of the project is to establish a novel basis for future embedded information technology by constructing the first electronically programmable chemical cell. This will lay the foundation for immersed micro- and nanoscale molecular information processing with a paradigm shift to digitally programmable chemical systems (Figure 1).

ECCell is employing novel families of fully synthetic hybrid informational polyelectrolyte copolymers (not simply DNA), which simultaneously support all three cell functionalities. Their self-assembly under electric field control is the primary information processing mode of this technology [3]. Electrochemical reactions at digitally controlled electrodes regulate pH, microfluidic flow and metabolite concentrations. The research will establish an effective IT interface between microelectronic and molecular information processing, by demonstrating its use to achieve a hard chemical synthetic systems objective (an artificial cell) opening a platform for programming a novel chemical Living Technology at the microscale.

3.4. MATCH-IT

The full integration of programmed chemical synthesis and complex nanoscale function is a hallmark of information processing in living systems. In eukaryotic cells, the subcellular matrix involves a highly modular chemistry in which

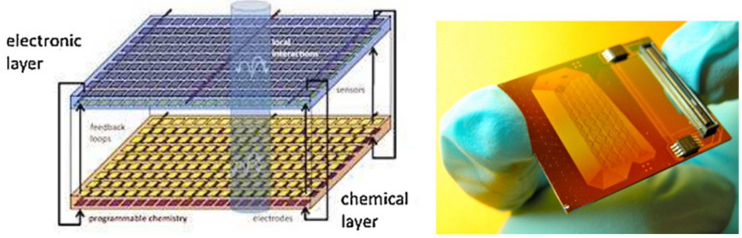

Fig. 1. (Left) Tight local coupling of electronic and chemical layers in the ECCell project as proposed by McCaskill (2008) [7]. Spatially localized cells can grow and proliferate in the hybrid plane. Through the symmetric local feedback coupling, the role of the two layers can be made symmetrical, not just electronics controlling chemistry but also the chemistry controlling the electronics. Electronic chemical cell functionality is divided between the two layers: with both electronic and molecular genomes. (Right) Physical realization of programmable environment for electronic chemical cells. Microfluidic channels at the rear supply a continuous flow of chemicals and the system is connected via CCD cameras and FPGA chip to a monitoring computer. Chemical cells must combine self-replication, self-containment and self-regulation of resources (metabolism) enabling evolution to qualify as alive. Electronic chemical cells will do this in conjunction with a reconfigurable electronic system.

membranes delimit dynamic chemical containers of various sizes and functionalities. Functional units are actively transported by a protein assembly system throughout the cell, depending on the recognition properties of molecules on their surfaces, and the energy that fuels all these processes is embedded within the system. This project will abstract such a high-information-density and modular self-organizing chemical system and realize it in a more programmable way, as an interface connected to traditional computers, making novel use of MEMS technology and chemical addressing via DNA [4]. DNA address tags can be synthetically attached to other chemicals, and hence to a variety of containers. Like computer addresses, they can then be processed, as research in DNA computing has demonstrated.

Self-organizing container addressing allows micro- and nanoscale processing of any collection of chemicals that can be packaged in the containers [6]. DNA-addresses can be used to bring containers together spontaneously exploiting parallel physical self-assembly. Addresses may be resolved with respect to an external address space (e.g. via immobilized DNA on surfaces or in gels) or by specifying binary or higher- order inter-container docking and thence content processing. In the design and analysis of such interactions we will derive inspiration also from membrane computing, a formal framework for information processing via package release chemistry. We aim to show that this concept can be applied to make chemical material processing programmable in a broad range of chemical systems, both in aqueous solution and in hydrophobic solvents. This will lay the groundwork for general addressable-container-based information and production chemistry.

4. Conclusions

Many of the complex challenges facing 21st century society will require solutions that transcend disciplinary boundaries. The focus of bio/chem-IT is the convergence of nanotechnology, information technology, biotechnology and artificial intelligence that is widely predicted to lie at the heart of the next technological revolution. Bio/chem IT science and technology has the potential to *fundamentally transform* healthcare, agriculture, energy, security, environmental science and many other areas of pressing concern.

References

[1] C. Brettschneider, R.J. Rose, S. Hertel, I.M. Axmann, A.J.R. Heck, M. Kollmann, A sequestration feedback determines dynamics and temperature entrainment of the KaiABC circadian clock, Molecular Systems Biology 6 (1) (2010).

[2] J. Carrera, G. Rodrigo, A. Jaramillo, Model-based redesign of global transcription regulation, Nucleic Acids Research 37 (5) (2009) e38.

[3] M. Frasconi, R. Tel-Vered, M. Riskin, I. Willner, Electrified selective "sponges" made of Au nanoparticles, J. Am. Chem. Soc. 132 (2010) 9373–9382.

[4] M. Hadorn, P. Eggenberger Hotz, DNA-mediated self-assembly of artificial vesicles, PLoS One 5 5 (3) (2010) e9886.

[5] J. Holley, A. Adamatzky, L. Bull, B. De Lacy Costello, J. Ishrat, Computational modalities of Belousov-Zhabotinsky encapsulated vesicles, Nano Communication Networks 2 (1) (2011).

[6] S.E. Maurer, M.S. DeClue, A.N. Albertsen, M. Dörr, D.S. Kuiper, H. Ziock, S. Rasmussen, J.M. Boncella, P.-A. Monnard, Interactions between catalysts and amphiphile structures and their implications for a protocell model, ChemPhysChem 12 (2011) 828–835.

[7] J.S. McCaskill Evolutionary microfluidic complementation toward artificial cells. In S. Rasmussen et al., editor, Protocells: Bridging nonliving and living matter, pages 253–295. MIT Press Cambridge, Mass., London, England, 2008.

[8] J. Szymanski, J.N. Gorecka, Y. Igarashi, K. Gizynski, J. Gorecki, K.-P. Zauner, and M.D. Planque Droplets with information processing ability. International Journal of Unconventional Computing, to appear. Preprint at http://eprints.ecs.soton.ac.uk/21840/, 2011.