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Synthetic signalling protocell networks as models of neural computation

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Introduction

Modern conventional computers are programmable, predictable and relatively easy to understand and engineered —at least compared to most complex non-linear systems. These properties are the result of various dynamical constraints that are universal to conventional computers, such as the clock mechanism that synchronises the update of logic gates and other components; the ubiquitous discretization steps (where continuous values are discretized into binary 1s and 0s); and the almost complete isolation of internal processes of computers from the environment of the computer. We are investigating an alternative computational medium composed of signalling synthetic protocells to explore the implications of relaxing some of these dynamical constraints that are typical of conventional computers. Is it possible to build useful and/or programmable computers out of unconventional media such as protocells that do not have a synchronizing clock? Or that do not employ a conventional representation of 0s and 1s? Or that are less decoupled from their environment?

The protocells that we are investigating are aqueous droplets suspended in oil. Each droplet contains the reagents for the Belousov-Zhabotinsky (BZ) oscillating chemical reaction (Zhabotinsky, 2007), resulting in self-exciting dynamical units that, when in contact with each other, are capable of propagating signals similar in some respects to signal transduction in biological neurons. Networks of these signalling protocells are therefore a kind of *wet* artificial neural network, sharing more in common with biological nervous tissue than conventional computer electronics.

It is envisaged that in the future more advanced protocells will be employed to make self-organising computers, or computers that can operate within the human body. But first it is necessary to develop a better understanding of how complex non-linear systems can be harnessed to accomplish useful or "minimally-cognitive" tasks (Beer, 2003) such as categorical perception, boolean logic, and dynamical control.

Moreover, by learning how to construct or assemble networks of complex non-linear units like the BZ-protocells we also gain insight into how other complex and non-linear "computational" media (such as nervous tissue) can conduct, modify and modulate signals and information, and how it can play an important role in the sensorimotor loops of a situated and embodied agent (Stewart et al., 2011). This bottom-up approach to the construction of alternative computational media is an important complement to the more widespread top-down neuroscience where biological neural networks are slowly being reverse engineered.

With these long and medium-term goals in mind, we have set out to (i) design functional collections of signalling protocells (comparable to the logic gates of conventional computing) that could be combined to produce more complex networks, (ii) identify effective signal encoding(s) that facilitate the transmission and manipulation of the signal by protocell networks, and (iii) identify design techniques and methodologies for creating functional signalling protocell networks out of complex non-linear media. To accomplish these goals, we are taking a three pronged approach involving *in vitro* experimentation, simulation and modelling to investigate the dynamical properties of the protocells and networks thereof; and experimental computer-aided design and machine-learning techniques to partially automate the development of functional protocell networks. We now briefly summarize our published results, before describing our current efforts.

Summary of published research

To elucidate the experimental foundations of working with wet chemical computers on microfluidic chips (King et al., 2012), the NeuNeu project consortium (www.neu-n.eu) has conducted various research projects involving simulation, modelling and experimentation. One branch of this research involves the investigation of droplet networks, where the droplets are assumed to be small enough that internal spatial dynamics can be ignored. In this vein, the computing potential of two-droplet systems has been demonstrated in experiment and simulation (Szymanski et al., 2011) and differential equation models have been identified that allow us to accurately describe droplet dynamics and interactions (Szymanski et al., 2011). More abstract simulation models have also been developed to make possible faster and larger-scale simulations (Gruenert et al., 2013), allowing us to analyse higher-level design principles and questions pertaining to system architecture, such as possible benefits of moving beyond naive or simple signal encodings (e. g. high firing-rate = 1, and low firing-rate = 0) to explore various alternatives (Gruenert et al., 2012).

In a parallel branch of simulation and experimental work, our collaborators have been investigating more spatial forms of computing, involving larger reservoirs containing sub-excitable BZ medium. In these conditions, isolated spatial propagating waves can form, combine and interfere in spatial and geometrical ways to accomplish computation-like tasks, such as logic gates (Holley et al., 2011; Adamatzky et al., 2012).

Ongoing research

Information measures for analysing and guiding the artificial evolution of unconventional computational media.

Following information theory (Shannon and Weaver, 1948) and information dynamics measures (Lizier, 2013) in cellular automata and in neural networks (Vicente et al., 2011), which help to identify information propagation, storage and modification systems, we are developing analysis tools for understanding the information flows of experimental and simulated droplet systems. These tools are intended to aid in the tracking and understanding of the flow of information through unconventional computational media, in a way that is largely independent of the encoding of the information and to thereby facilitate the search for complex and potentially useful system behaviours in random or evolved droplet networks, which are inherently less modular and decomposable than conventional engineered computational systems. We are also exploring the use of information theoretical measurements to constrain the design of functional networks. By identifying necessary changes in the state of information at different stages of computation, we believe it may be possible to guide machine-learning algorithms to more effectively design functional networks.

Defining computational-unit fitness implicitly using tautological closed loops.

To facilitate the artificial evolution of of Basic Composable Units ("BCUs" – c.f. logic gates) for unconventional computational media, we are developing a novel technique in which optimal BCU behaviour is defined not explicitly ("given this input, the unit should produce that output"), but implicitly, through its influence on network properties in a closed network consisting of multiple instances of the unit. The network is designed in such a way that only if the units are performing the desired task (e. g. acting as a NAND gate), will certain network properties hold (e. g. dynamics at two points in the network should be similar to each other and different to a third point), and machine-learning techniques tune the BCU properties maximise these network properties. In this way, we implicitly describe the desired behaviour of the units without overly constraining their design, allowing the artifical evolution to concurrently design the BCUs and the encoding of the signal that they operate upon.

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