Chapter 12
Encoding and representation of information processing in irregular computational matter

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Abstract Representation is a crucial concept in classical computing. Unconventional computational devices pose a series of challenges to representational issues, including unary analogue encodings, the representation of inputs and outputs, and sometimes the inaccessibility of internal states. Of particular interest are successive representational adaptation and refinement in relation to natural information processes, both during biological evolution and in evolving material and smart microparticle systems. Some examples are discussed in this chapter.

12.1 Introduction

There are three important questions for the usability of unconventional computing (UCOMP): how to represent data and information in unconventional computational material; how to encode specific values and programs in that representation; for autonomous systems, how to decide on which information needs to be resolved. The first two are related: representations need to be implementable, and encodings targetting those representations need to be feasible.

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In this chapter, we discuss some potential issues with encoding values in UCOMP devices, and then discuss three particular systems highlighting the third issue: evolution *in materio*; biological encoding; and encoding in microscopic electro-chemical systems.

12.2 Digital and analogue encodings

One primary data type that needs to be represented in a computational system is the *number*, be it integer- or real-valued. The same number (say, four), can be logically represented in many ways: decimal digits ('4'), binary digits ('100'), Gray coded ('110'), unary encoding ('1111'), even Roman numerals ('IV'). The logical representation needs a corresponding physical representation. Indeed, the logical representation in the previous sentence is described by means of the physical representation of symbols on paper or screen.

A classical *digital* computer is so called because its basic representation is of the binary *digits* 0 and 1, typically represented by two distinct physical voltages. Larger values are represented by combinations of these physical 0's and 1's, with intervening levels of abstraction ('4' represented abstractly as '100', in turn represented as three physical voltages).

This is a based representation. In everyday life, we use base ten. Most digital computers use base two. Some unconventional digital devices use other bases, such as three (either as $-1, 0, 1$, or as $0, 1, 2$). An important feature of a based representation is that the length of the represented number (number of digits needed) is *logarithmic* in the size of the value of the number. It exploits the combinatoric possibilities of strings of symbols to achieve this compression.

Single stranded unmodified unfolded DNA could be considered to be a degenerate form of base four representation, with symbols (rather than digits) A, C, G, T, encoding $4^3 = 64$ possible values per triplet, with the genetic code then mapping each value to one of twenty amino acids. These triplet codons have a 'most significant' and 'least significant' base within the genetic code, with the value of the least significant base having a restricted effect on the represented amino acid.

Many analogue computers instead represent numerical values by some continuous quantity (say, voltage). So the value '4' would be represented by $4k$ volts (or metres, or kilograms, or...), where k is some problem-dependent scaling factor; the value 'x' would be represented by xk volts. This is a *unary* encoding: the size of the encoded value is proportional to the size of the encoding value. Hence such an analogue representation is *exponentially larger* than a corresponding digital representation.

This feature of unary representation can be an issue for some forms of UCOMP. Values have to be scaled to ensure they are representable. And in particular, there is a precision issue. To add one more place of (binary) preci-

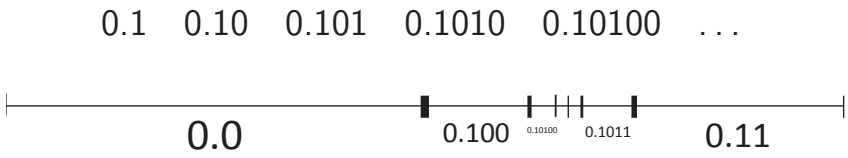

Fig. 12.1 Increasing precision (top) encoding a real number value as a binary number. Doubling precision involves adding one extra binary digit to encode the number; (bottom) encoding a real number value as a position on a line. Doubling precision requires halving the region of the line used to encode the number.

sion to a binary-encoded value, a single extra digit is needed. To add one place to a unary-encoded (analogue) value, that value must be set or measured with double the precision (fig. 12.1), and there is a (typically quite small) limit to the precision with which physical values can be set or measured.

In the systems discussed below, typical continuous signals include voltages, field strengths and chemical concentrations. In the presence of thermal fluctuations, the precision of analogue quantities is limited by the amplitude of fluctuations, e.g. 25.4 mV corresponds to kT for a single (electron) charge. Number fluctuations in equilibrium for molecules limit counting resolution to the square root of the number of molecules in many circumstances.

12.3 Encoding information in evolving material systems

To encode information in a material system requires a way of placing the material in a particular state. For example, while this article is being written this document is being viewed on a liquid crystal display (LCD) device. In a LCD there is a thin layer of liquid crystal held between two sheets of glass each of which is covered with a grid of transparent electrodes. In addition, the electrode-liquid crystal sandwich is placed between two polarizing light filters that are orientated at right angles to each other. The liquid crystal molecules are electrically polarized so they are sensitive to electric fields. Thus when voltages are applied to the electrode arrays, the orientation of the molecules can be changed and this affects the light transmitted.

In LCDs the voltages merely configure (i.e. twist) the molecules to allow us to view text (or images) on a screen. Thus, in general we supply a vector of real-valued voltages and we read (literally) the output from the LCD visually. In many computational problems we would like to obtain a function that can transform a vector of inputs to a vector of outputs. For example in machine learning classification problems one seeks a function that can assign a class to a vector of input values. The idea is that we might learn a function that can predict what class previously unknown instances of input data belong to. Such functions can be extremely useful in many application domains. For instance, the input vector could be a set of medical measurements taken from a patient.

One might be trying to diagnose which of a number of medical conditions a patient is suffering. In machine learning many techniques have been devised to attempt to solve such problems. Such techniques represent a solution (one that predicts successfully new instances) in many ways, however most if not all, reduce to a set of mathematical equations that act on the input data to produce an output vector that predicts the class.

In principle, it is possible for physical materials to provide such functions. To do this one needs a way of transforming input information into a set of input signals that can be applied to a material. This is often called the input-mapping. One also needs to decide how to read signals from the material and how these can be transformed into information that represents a solution to a computational problem. This is called the output-mapping. Finally, one needs a set of configuration signals that can also be applied to the material that affects the behaviour of the material. If the material is to be useful in solving a computational problem we need a method that can allow us to find a good configuration. This is akin to the set of mathematical equations that machine learning techniques devise. The technique known as evolution *in materio* (EiM) (Harding et al., 2008; Miller and Downing, 2002; Miller et al., 2014) uses evolutionary algorithms (Holland, 1975) to search for configurations of a material that allow it to solve computational problems. A schematic showing how EiM can be used to configure materials for computation is shown in Figure 12.2.

One of the first materials investigated in this regard was liquid crystal where Harding and Miller (2004), Harding and Miller (2005), and Harding and Miller (2007) showed that configurations of a LCD could be evolved to allow it to distinguish between different frequency square-waves, control a simulated-robot navigating a simple maze and carry-out logical functions.

Materials have many physical properties and it is not obvious what are the most appropriate and useful ways of presenting and encoding information supplied to a material (binary or floating point representation, encoded in voltages, different frequency waves, light, and so on). Let us consider evolution *in materio*, of carbon nanotube systems (Miller et al., 2014; Mohid and Miller, 2015; Mohid et al., 2015), to give a specific example. Here, inputs, outputs, and configurations are supplied as voltages to an array of electrodes embedded in the computational material. Such voltages can encode analogue values, or, by thresholding, digital values. Figure 12.3 shows an electrode array connecting to a sample of carbon nanotubes embedded in an insulating polymer.

Another material system used for EiM was gold nanoparticles on an electrode array (see Figure 12.4). It was found that configurations of voltages could be found that made the system compute any two-input Boolean function.

If some problem is being tackled by 'analogue' computation, in the original sense of the computational process being 'by analogy' to the original problem, then the input and output values can themselves be the direct analogues of the

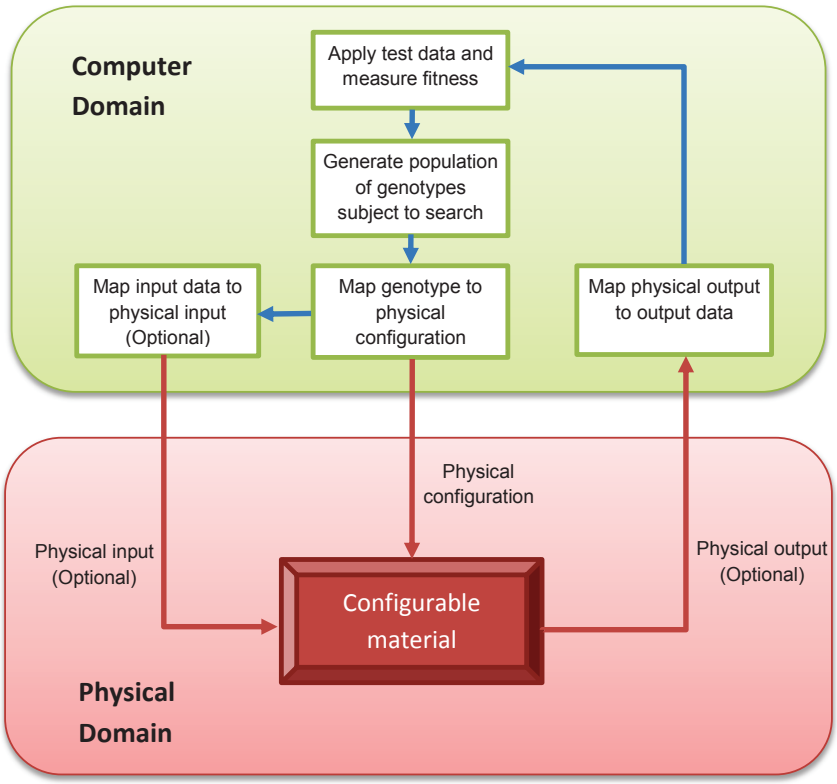

Fig. 12.2 Evolution *in materio* uses an evolutionary algorithm on conventional computer to search for configurations of materials that can carry out desired input-output mappings that solve computational problems.

Fig. 12.3 An electrode array interfaced to a material sample of carbon nanotubes embedded in PMMA (polymer).

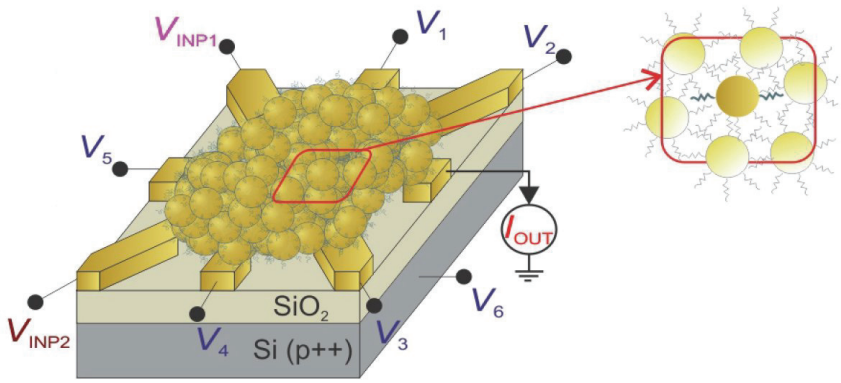

Fig. 12.4 An electrode array interfaced to gold nanoparticles with attached separating molecules (octanethiols)(Bose et al., 2015).

problem values: the main issues are scaling and precision. If the computation is not analogous, however, more thought must be put into how inputs and outputs are represented.

For example, consider using an EiM system to compute a solution to the classic Travelling Salesman Problem (TSP). The desired output is a permutation of 'city' indices, indicating the shortest route (see, eg, Lawler et al. (1985)). In classical computing, a permutation can be represented as a list of integers, and evolutionary operators defined to maintain the list as a valid permutation (no missing cities, no duplicated cities). But we have no such high level representations or operators available to us *in materio*; we have a list of output voltages. We need to use these to form a permutation. One method of doing so it to take the list of real-valued voltage outputs and sort them into increasing order: the sort permutation required to do this can be considered to be the desired output permutation (see fig. 12.5). We have many decades of using high level representations in classical computing; we will have to develop novel approaches to representation in unconventional devices.

In classical computing one considers the internal representation, occurring inside the computer during the computation, as well as the external representation of the input/output values. This is not possible with basic EiM, as there is no computational model of the internals of the material: evolution treats the material as a 'black box'. It is possible to apply a computational model onto such systems. For example, Reservoir Computing (RC) has been used as an 'unconventional virtual machine' for computation with carbon nanotubes (Dale et al., 2017a; Dale et al., 2016a; Dale et al., 2016b; Dale et al., 2017b). This could provide a potential route for analysing the internal computational representations in the material in terms of the underlying RC model.

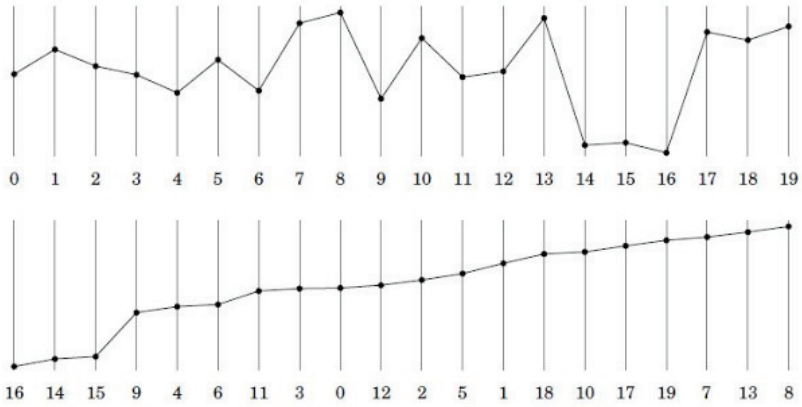

Fig. 12.5 (top) the output, a list of 20 real numbers, represented as a 20-D point drawn in parallel coordinates (Inselberg, 1985); (bottom) the same values, with the parallel axes ordered so that the components are in increasing order: the sorted axis indexes are the permutation represented by the 20-D point.

12.4 Biological information encoding and the evolution of a translation apparatus

Biological computational matter is encoded in DNA, allowing arbitrary changes in DNA sequences to have an impact on functionality. Additionally, the boot-block for the operating system, the code for constructing the map from sequence to function, is also materially encoded in DNA, in terms of the phase equilibria that underlie the "ecology" of interacting amino acid side chains inside folded proteins (Wolfenden et al., 2015), in particular, those proteins (aaRS enzymes) that operate the genetic code by simultaneously recognizing and matching specific amino acids and their cognate tRNAs. This provides a second level of abstraction of information from physical and chemical constraints, giving biological systems a remarkable ability to evolve new functionality. How could such a strongly evolvable and abstract system arise and what are its implications and potential for other forms of computational matter?

The clearest demonstration of the encoding of biological information in DNA is the efficacy of cloning with an artificially synthesized genome. Gibson et al. (2010) copied the DNA nucleotide base sequence information from the complete genome of *Mycoplasma mycoides* cells and then synthesized, from scratch, a very similar sequence which they then introduced into a system capable of interpreting the information – a DNA-voided cell of the closely related species *M. capricolum*. The interpreter system was able to maintain its integrity while transforming itself into the progenitor cell of a new species,

which corresponded to the engineered genome, was designated JVCI-syn1.0, and displayed a phenotype practically indistinguishable from the original native *M. mycoides*. Messages in the English language were encrypted into otherwise superfluous parts of the artificial genome, demonstrating the arbitrary character of DNA-encoded information. However, what distinguishes the biologically relevant information in the genome is the manner in which its semantic content relies on a process of interpretation that is executed by machinery that can only be maintained through its own operation. In chemical terms, the interpretation of biological information is obligatorially autocatalytic. The self-reinforcing effect of autocatalysis offers the only possible explanation for how an arbitrary system of (biological) semantics could, short of the intervention of some external intentionality, arise spontaneously from an initial state of apparently complete molecular disorder.

In evolutionary terms the advent of genetic coding represented an important transition, perhaps the definitive transition, in the origin of life. If there existed, prior to the evolution of the protein synthetic translation apparatus, an autocatalytic "RNA World", a system comprising a restricted self-sustaining set of ribozymes (RNA catalysts) that mutually catalysed their own formation, then the mapping from those molecules' sequences onto their catalytic properties would have been "given in advance" so to say, governed by the outcome of spontaneous folding processes and the like that were essentially unregulated by the system as a whole. On the other hand, all biological systems operate a genetic code that defines a geneotype-to-phenotype mapping from nucleic acid sequences to the catalytic properties of proteins. This mapping from information to chemical reaction enhancement is arbitrary with respect to the laws of physics and chemistry but is for all intents and purposes universal across the entire tree of life because it is the single surviving outcome of a process of stepwise self-organisation in which molecular biological operations progressively developed ever tighter, integrated, system-wide computational control of the chemical reaction processes involved in biochemical construction, maintenance and energy consumption.

There is a very interesting link between the computational control of physico-chemical processes afforded by genetically coded protein synthesis and the exquisitely detailed molecular composition and heterogeneous self-organized structure of systems in which translation of genetic information occurs. The genealogy of every living system can be traced back to a common origin through discrete generations involving the inheritance of both a library of genetic information and a material system existing in a privileged thermodynamic state and with a corresponding molecular composition that allows it to interpret the genetic information it contains as a blueprint for its own construction. Encoded protein synthesis is a cooperative process that cannot evolve in systems in which there is pure competition for survival among different replicating polymer sequences. Furthermore, the requisite evolutionary cooperation in the network of reactions needed for translation can neither spontaneously appear nor be sustained in a well-mixed (homo-

geneous) chemical system. Thus, some sort of spatially resolved structure, the result of either compartmentalization or Turing-type reaction-diffusion coupling, is required at the very first stage of genetic coding, when the first bits of truly "genetic" information were autocatalytically coupled to their interpretation through a nascent system of primitive computation: apparently a one-bit code sustained by two enzymes with distinct coding assignment functions, mutually encoded in the complementary sequences of the separate strands of the same DNA double helix (Wills, 2016).

12.5 Information encoding and translation in electronic-chemical systems

We propose that the facilely mutable information of electronics be coupled with the synthetically and functionally diverse and powerful information processing in chemical computational matter to enable humanly engineered computational matter to expand its potential.

Electronics is the dominant form of human-synthesized information processing, and hence largely defines our technical interfaces to the material world, residing in the machines and systems that we employ in our homes, factories, transportation, sensors, tools, and communication. It has enabled a remarkable transition in our society's ability to program material world processes and events. Electronic processing is also fundamental to chemical matter, in as much as the chemical bond is electronic in nature and chemical reactions reflect intricate quantum rearrangements of electronic states. In both contexts, electronic programming can operate extremely fast, allowing long sequences of transitions, compounding information from many different sources, to control processes on human-relevant timescales. For these reasons, it is both interesting and important to understand (i) the potential for interfacing electronic systems with chemical information processing systems; and (ii) the limitations and potential in encoding chemical and higher order computational matter functionality in electronics. Following the insights of the previous section on biological information coding and translation, we are curious about the process of bootstrapping an encoded translation system between electronic and chemical information.

Key concept: electronic genomes

A close analogy can be drawn between the processing of genetic information to construct enzyme catalysts and the use of electronic information interfaced with microscopic chemical processors (Fig. 3 of McCaskill et al., 2012). Because it is so easily and densely stored in a form that is essentially decoupled from the immediate effects of other processes, as well as being used to

control events at the molecular level, electronically accessible information is eminently suitable as a mode of "genetic book-keeping" in systems that employ chemical computation. As in DNA, information stored in electronic bits can be copied and edited facilely, in contrast with the complex processes of fabrication required to copy the most material structures including molecules. The encoding of hard to copy structures and processes in generically copyable forms of information is the key digital abstraction enabling both biology and the current information age.

Interfacing electronic and chemical systems: micro/nano electrodes and alternatives (e.g. light)

Electronic information is highly amenable to the control of molecular processes, down to the level of individual polymer chains being ratcheted through nanopores in steps of a single monomer unit. It can also be used for the ultra-precise control of electrode processes, including the runtime modification of the distinctive functional specifications of micro- or nano-electrodes and their immediate fluid, active-surface or quasi-membrane environments. Thus, the development of interfaces between chemical and electronic information offers a vast range of possibilities for computation, molecular construction and process control in nanotechnologies. Not only can different voltage levels electrochemically turn on different reactions, and these reactions provide the conditions e.g. as catalysts for further reactions, but different reaction products at spatially orchestrated electrodes can interact and react to form further products and structures. Furthermore, electrodes can interact electrokinetically with ionic solutions to direct the transport, concentration and separation of chemicals. The control of complex chemical processes through spatio-temporal electronic control of microelectrodes is an area that we are only beginning to unravel. Apart from acting in direct control, such electronic signals can also modulate and direct purely chemical pattern formation as in reaction-diffusion systems. Electrochemical sensors have demonstrated an impressive diversity of target molecules and sensitivities in recent years, underscoring the two-way nature of this interface to digital information, especially when analog electronic as well as chemical signal amplification are employed prior to analog digital conversion.

Optical and opto-electronic interfacing to chemical systems provides a wireless and surface-independent technique for interfacing to bulk chemical systems. Imaging systems for both structured illumination and imaging of chemical systems have been perfected at macroscopic scales and now support nanoscale super-resolution beneath the wavelength of the light employed. Parallel spatial structuring with spatial light modulators, digital mirror devices, masks are complemented by fast scanning serial techniques for directly writing spatial patterns in 2D or 3D to chemical systems, inducing for example polymerization and changes in phase in the media involved.

The advantage of autonomous particles

The siting of a variety of electronic-chemical interfaces on autonomously powered microscopic devices, rather than on a large cabled surface, adds dimensions of completely new possibilities to the type of molecular-level computation that can be constructively instantiated in electro-chemical devices, in the same way as the advents of both genetic coding and multicellularity each marked a transition to previously inconceivable opportunities for biological evolution. The analogies are striking. Just as the genetic code originated in the obligatory cooperation of two autonomous units with dual versions of the same general function with distinguishable specificities (the Class I and II amino acyl-tRNA synthetases – aaRSs), so too could a "gas" of initially identical devices suspended in a suitable fluid bifurcate into subpopulations of units that performed complementary, separately controllable chemical functions of a kind simultaneously demanded by some shared electronic program able to fulfill a defined goal. Likewise, the association of individual units to form diverse conglomerates offers further possibilities, not only for the efficient execution of multistep tasks but also for the selection of "morphogenic stages" in the development of systems with extraordinary levels of computational specificity.

Lablets: electrochemically functional autonomous microscopic reaction walls made of silicon electronic chiplets

Lablets (tiny labs) have been designed to be used for autonomous experimentation and share some of the essential features of both cells and chemical labs (McCaskill et al., 2017). Both chemical labs and cells need to have a restricted reaction vessel, separating the place where reactions may occur from the rest of the world/system. They both require a source of energy and a means of converting this into useful work and/or chemical synthesis. Most importantly they need an information platform to control the opening and closing of the reaction vessel, the selection, input and output of chemicals, including reagents and catalysts. In addition, they both require a chemical separation mechanism allowing only selective products to be enriched and maintained, while waste is removed, and mechanisms for sensing progress in chemical reactions. Of course, in standard chemical labs the information platform controlling chemical processing is either played directly by a chemist or indirectly with the help of computer controlled machines (such lab automats). In cells, the key functions are mostly played by membranes for compartmentation and selective transport, metabolism for energy and construction chemistry and information control by genes encoding proteins to direct the choice of processes and to allow sensing and separations. In lablets, a reaction vessel can be reversibly formed by one of them docking on a flat surface or two of them docking together, to provide restricted diffusional access to the con-

tents retained in the relief profile. Since diffusional interchange is typically on the timescale of 10s or more for such lablets, there is significant potential for advancing local chemical concentrations and processes. Energy stems from electric fields and is accumulated and stored as separated charge in an encapsulated supercapacitor (Sharma, McCaskill, et al., 2017), currently occupying about half the area of the lablet. Information is saved in the silicon substrate electronically and directs electrochemical and/or electrokinetic actuators and sensors.

Lablets were first proposed by McCaskill et al. (2012) and constructed in the MICREAgents project (www.micreagents.eu) at the scale of 100–140 μm. Partners in the project focused on the separate functions of lablets such as reversible association, internal logic, electronic control of chemical concentrations and supercapacitor power. They have been further developed in the EON Seed Grant Project (2016–2017); see also chapter 6.

Two-way interfacing electronic genomes on lablets with chemical control and sensing

Information in replicable and editable form is a vital resource to both biology and society. Functionally deployed information in biology is generally "folded" or "deployed" in a condensed or convoluted form, as in proteins, that precludes copying. Instead, the genes realized using DNA act like design blueprints or CAD programs that can be readily copied. Digital electronic information is also in a form that can readily be copied, in contrast with the material and chemical artefacts resulting from processes directed by this information. Electronic genomes have been proposed by McCaskill (Wagler et al., 2012) as a useful encoding of information for microscopic chemistry. McCaskill and Wills have developed the idea of an electronic to chemical translation code as analogous to the protein translation code in biology. The flow of information is in both directions in biology, with signal sensing changing protein concentrations which can change the RNA-mediated expression of other proteins from their genes. Independently of the many significant complications of this picture, unraveled by modern biochemistry and molecular biology, most information in the DNA remains constant during the lifetime of a cell while the RNA expression patterns may change significantly. Likewise, the electronic operation of lablets involves a program, the code for which is not being rewritten during normal operation, and various information state bits of information, which change in response to certain sensor, timer, or succession events. As with the genome, lablet programs can be communicated from a functional lablet to a new lablet in a process mirroring cellular reproduction (mitosis, but meiosis and sexual recombination of genomes may also be realized).

The range of phenomena induced by or sensed by microelectrode potentials in aqueous chemical solutions is extraordinarily diverse, context depen-

dent and linkable to both selected chemical reactions and overall mechanical events (such as docking). The modulation of ionic distributions is already richly nonlinear in the Nernst Planck level of description, especially when the geometric scale is commensurate with the Debye length (for low concentrations and/or nanoscale dimensions), so that there is firstly a non-trivial encoding between electronics and ionics. Certain ions, like H+, modulate a wealth of reactions and structural equilibria for instance through the biasing of protonation and hence the charge state of molecules. Other ions can be involved in specific reactions, redox or otherwise, electrochemical or in solution, and their concentration changes influence the rates of reactions. Specific threshold potentials on electrodes (compared with the solution potential) can switch on specific electrochemical reactions (following Butler–Volmer threshold kinetics which turn on like the diode current law). Furthermore, potentials can release specific ions reversibly from porous structures on electrodes that have been imprinted to hold them, and these electrodes can so act as reversible reservoirs for specific chemicals (Frasconi et al., 2010). Of course, encoding specificity of response is not straightforward, given the multitude of possible effects. However, hysteresis effects can be employed to bootstrap specificity: for example, electrode potentials can be first designed to perform specific coatings on electrodes and then the repertoire of specific signals further diversified by these coating. Here we can only hint at the range of the possibilities, noting that many other physical effects, including electrowetting and electroosmotic phenomena will play a role. As in the complexity of protein folding, it is not necessary for all these effects to be separable and modular for an effective encoding of functionality to be possible.

Stepwise evolution of a translation system between microelectrode signals and chemical functionalities

oblig We envisage the possibility of designing and building electronic-chemical systems in which constructive functionalities can spontaneously progress to more finely differentiated, information-rich states through a series of transitions analogous to what is seen in the development of the genetic code. A realistic mechanism for the stepwise self-organization of genetic coding has already been demonstrated in a system that was set up to have functionalities embedded in a hierarchical fashion, allowing an initial “easy” transition to a binary code and then a “harder” transition to a four-letter code (Wills, 2009). We first observe that the actual genetic code created its own quasi-hierarchical “design”, writing step by step into the space of nucleotide triplet codons an ever more detailed map of the diverse roles of amino acids in folded proteins. What facilitated this remarkable evolution of computational complexity in nature was autocatalytic feedback: the coded placement of amino acids at specified positions in protein sequences was dependent on the functional effects of amino acids being placed at certain positions in the sequences

of the enzymes (aaRSs) that defined the coding relationships. However, coding self-organization alone is not enough: it is also necessary for local success in coding to give selective advantage to the encoded information on which it relies. An extremely simple way of meeting this requirement has been implemented in studies of gene-replicase-translatase systems (Füchslin and McCaskill, 2001), demonstrating a plausible mechanism for the simultaneous corralling of a code and the rare information needed for its autocatalytic maintenance.

Bootstrapping up to cell-like functionality using smart particles carrying electronic genomes

We see no ultimate impediment to the recapitulation of this deep evolutionary process in electronic-chemical devices. The key features of the implementation environment are: (i) electronically stored "genomic" programs and local chemical environments should both exert influence over the functionality of electrodes in contact with the fluid milieu/interface; (ii) entities that have specific functional effects at and near electrodes should be constructed through parametrically controlled sequences of chemical events within near the fluid milieu/interface; (iii) a feedback mechanism for the local, selective preservation of electronic programs that sustain autocatalysis of functionalities in the chemical environment; and (iv) the embedding of functional effects in the space of sequence-wise constructible entities should be sufficiently diverse, differentiated and complex to cater for the emergence of autocatalytic sets of functional molecules/conglomerates. The third requirement captures the ubiquitous biological phenomenon of the genotype-phenotype mapping being defined by an operational physico-chemical system that is under the immediate influence of the local information that it interprets. The fourth requirement is rather abstract but can be understood by analogy with the rich variation of ribozymal or enzymatic functionality across nucleotide or amino acid sequence space. We envisage self-creating devices whose emergence in electronic-chemical systems is driven by the constrained channeling of dissipative processes for the achievement of materially defined goals, especially the directed synthesis of special organic compounds, polymers or nano-architectures.

Connection with reservoir computing

Unlike the digital electronic system, with its precisely programmed deterministic switching, both the electrical and the chemical system response to the temporal voltage control signals on sets of microelectrodes is complex, involving significant hysteresis and dependence on environmental factors (such as

the concentration of various chemicals in the medium). For systems involving NPs and CNTs it has been demonstrated that the electrical properties of various nanoscale structured media have the echo state property and hence (Jaeger, 2001) can be employed as a bulk learning medium (as a simpler and powerful substitute for neural networks) with only surface connections needing to be learnt. No doubt, certain aqueous chemical systems, coupling physical and chemical reaction effects will share this property and hence allow, from an electronic perspective, complex learning and memory. From the chemical perspective, long term memory responses will generally involve the synthesis of specific substances and structures in the aqueous coupled system. This coupling of interface controlled reservoir computing with chemical system self-organization should open a powerful approach to computational matter in the future.

12.6 Conclusions

Unconventional computing devices need new techniques for representing and encoding their inputs, outputs, and programs.

Most unconventional devices have non-existent, or still rather primitive, computational models; they are often treated as black boxes. This makes it difficult to think about and apply internal programming representations to them. As the discipline progresses, higher level models should become available, allowing more sophisticated representations to be employed. Reservoir Computing appears to be an interesting model applicable to many systems.

Currently, much of the focus on representation is on inputs and outputs. These can be digital or analogue. Analogue representations can have scaling and precision issues.

The construction of copyable technical information systems that must communicate with complex physical or chemical systems shares many of the encoding issues faced by biological systems in genetic encoding, and it is fruitful to understand how effective coupling between such systems can be established and encoded as a single problem.

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