Evolution *in materio*: Looking Beyond the Silicon Box

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Abstract

It is argued that natural evolution is, ***par excellence****, an algorithm that exploits the physical properties of materials. Such an exploitation of the physical characteristics has already been demonstrated in intrinsic evolution of electronic circuits. This paper is an attempt to point the way toward the exciting possibility of using artificial evolution to directly exploit the properties of materials, possibly at a molecular level. It is suggested that this may be best accomplished in materials not normally associated with electronic functions. Electronic components have been prefected by human designers to construct circuits using the traditional top-down methodology. Workers in artificial intrinsic hardware evolution have with the best of motives, been abusing such components. It is a tribute to the amazing resourcefulness of a blind evolutionary process that it has been possible to evolve new circuits in this way. Artificial evolution may be much more effective when the configurable medium has a rich and complicated physics. This idea is discussed and particular examples that look extremely promising are given. Ultimately it may be possible to evolve entirely new technologies and new sorts of computational systems may be devised that confer many advantages over conventional electronic technology.*

Indexing terms: Evolvable Matter, Molecular Circuits, Evolvable Hardware,Intrinsic evolution.

1 Introduction

The aim of this paper is to inspire and encourage other researchers in the field of Evolvable Hardware to consider a wider range of technologies and materials in which to conduct experiments in intrinsic evolution. Some of these ideas have been discussed in [15][32][33]. We begin with an examination of how complex "simple" organisms actually are, and how cells are not programmed by their genes. Instead a cell is an environment in which the genes conspire with real physics and chemistry to create a complex system. In section 1.2 we put forward the view that natural evolution is very effective at exploiting the physics and chemistry of the world. In section 1.3 we discuss aspects of open-ended evolution and the work of Gordon Pask. In section 1.4 we argue that there is great scope for artificial evolution to work outside the constraints of silicon based technology. In section 1.5 we dicuss how top-down design principles are inappropriate to nanoscale systems. Section 2 is concerned with the abstract description of a system that allows artificial evolution to exploit physical effects, we call this a configurable analog processor (CAP). In Section 3 we describe two seminal pieces of work that are fielded examples of a CAP. Section 4 describes some potentially exploitable materials. In section 5 we describe in detail some practical suggestions for building new forms of CAP. Conclusions follow in section 6. Finally we complete the paper with an unusually large set of references which we hope will assist researchers in following up some fruitful lines of enquiry.

1.1 The complexity of life and the unprogrammed nature of organisms

Natural evolution has produced the most subtle and complex bio-chemical information processing systems known (i.e. living things). The complexity of even the simplest forms of life dwarf anything than man has yet been capable of building. Consider the much studied Escherichia coli (E. coli). This is a single-celled bacterium. It doesn't have a nucleus (prokaryotic). It is about 2 micrometers long and 0.8 micrometers in diameter. Inside this living cell there are about 2,400,000 protein molecules (of 1,850 varieties), 1,400 mRNA molecules (600 varieties), 200,000 tRNA molecules (60 varieties), 20,000 ribosomes, and 2.1 DNA molecules [16]. This list continues. The recently decoded 4,639,221 base pair genome has 4,289 protein-coding genes [38].

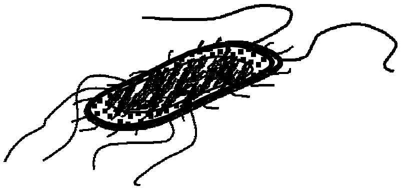

Figure 1: Diagram of E. coli bacterium

The numbers are less interesting than the number of different molecules and their arrangement. They allow an E. Coli cell to reproduce itself every 20 minutes. This is quite an acheivement since duplication of its genome takes about no less than 40 minutes [16]. How is it conceivable that a blind evolutionary process can have created a machine of such exquistite precision? How could the instructions in the genome tell the cell to divide every 20 minutes? The answer is that it doesn't. The cell isn't a machine in the clockword sense. The genome and the machinery that transcribes and translates it to proteins is responsible for creating a chemical factory. The many constituents of that factory are practically independent of the genome. These molecules obey the laws of physics, and the genome does not encode these laws. Lewontin stresses the inadequacy of the view that cells can be looked at as a manifestation of a program stored in a DNA base sequence [27]. Protein folding isn't even completely specified by the amino acid sequence. Coen sees biological development as akin to a creative process, in which each step interprets and elaborates what went before [7]. He argues that evolution is a kind of tinkering process that makes use, in an unplanned way, of the things produced in the past. There are lessons here for researchers in intrinsic evolution: we should not expect artificially intrinsically evolved circuits to be decomposable and understandable.

1.2 Natural Evolution and Physical Exploitation

We suggest the process of evolving the genome is an amazing physical exploitation machine. Nilsson and Pelger explain how this infinitesimal process can perfect the incidental light-sensitive properties of some proteins in early single-celled life and then create a series of tiny modifications to eventually become a fish's eye [36]. Light sensitivity is not encoded in the genotype, it is just a property of chemicals and ultimately, the laws of quantum mechanics. It is an incidental property that happened to confer a tiny advantage to some early life forms. This view has been eloquently expressed in the writings of Richard Dawkins [11]

In his classic work on growth and form D'Arcy Thompson emphasized the natural mathematics and physics of the real world that is exploited by natural evolution [10]. The theme is taken up in a more up to date manner in [43]

In recent decades researchers have implemented a large number of different sorts of evolutionary algorithms within computers. Some of the key difficulties of these approaches is the speed of evolution, the simplicity of the solutions (or lack of complexity) and the problems of scalability. Despite these drawbacks researchers are finding that, using sufficiently realistic simulations of physical processes, novel solutions can be found, for instance in drug design [13][14] and circuit design [22][31] and in material composite design [41]. However there are always considerable computational difficulties associated with evolving novel designs using simulators. Firstly, by their very sophistication, simulators take a long time to execute and secondly and most importantly, *they are limited by our own knowledge*. Interestingly in chemical synthesis and drug design a new field is emerging, called Combinatorial Chemistry [4] in which microlitre chemical reactions are created in arrays of test cells. The reactants are chosen very carefully from special chemical libraries. The reaction products are analysed automatically with mass spectrometers. Genetic algorithms are being used to find chemical reactants that produce new chemicals or drugs with useful properties [51]. Natural evolution has been engaged in intrinsic combinatorial protein search and is able, by virtue of this, to exploit the full physics or chemistry of real systems. It has been exploiting the complex physics of molecules without any understanding of that physics for billions of years.

Biomimetics is a new field that is concerned with examining naturally evolved solutions to problems and trying to implement similar solutions using current technology [50]. This has the advantage that natural evolution in matter has already found many igenious solutions to various problems. While this is a fascinating field it is severly limited in its application. The biggest drawback is that we cannot find natural solutions to problems that have never been faced by living systems. Many problems associated with modern technology are just such problems.

Recently the use of design algorithms that employ the principles of Darwinian evolution have been applied directly in hardware to design of electronic circuits. This is called intrinsic evolution [44][45][46][47][48]. Adrian Thompson [46], in a now classic demonstration, showed that a blind evolutionary process could harness formerly unknown physical properties of a electronic configurable device (FPGA[1]). Thompson found that unconstrained artificial evolution explored very unusual ways of solving problems *precisely* because it was able to exploit the subtle and incidental physical characteristics. It can be argued that evolution has produced such complex systems because it can make use of the full, *unmodellable* richness of the physical world.

Subsequently, presumably motivated by real-world applications, Thompson looked at generating robust evolved solutions that would be reliable in a wide range of environmental conditions [47][48]. Though this was a natural step, we argue in this paper that it was very premature. Thompson's work had been the first to show that *artificial evolution* could directly exploit the physical properties of a physical device. We argue in this paper that there is great merit in adopting his work as a *starting point* and continuing the investigation of the exploitation of physical properties using artificial evolution. How this might be done forms the dominant theme of this entire paper.

1.3 Open-ended physical evolution

Natural evolution contrasts very strongly with human design primarily and most fundamentally because it is open-ended. Such open-ended evolution is probably the best mechanism for exploiting natural physics as small side effects are not necessarily rejected in the ruthless pursuit of a particular goal. This is a potentially important issue in intrinsic evolvable hardware. Trying to solve a specific problem with intrinsic evolution may impose a view of what is exploitable in the medium. This may not use the most naturally exploitable property of the material. A more open-ended intrinsic evolution (at least initially) may be a way of allowing the material to reveal its more exploitable properties.

The cyberneticist Gordon Pask was a pioneer of open-ended hardware design, and to some extent could be regarded as one of the founding fathers of evolvable hardware [5]. In the 1950's Pask carried out experiments with electrochemistry. He used arrays of platinum electrodes immersed in acidic metal-salt solutions (e.g. ferrous sulphate). He found that by passing a current through the electrodes allowed dendritic metallic threads to form. He could control the growth of these wires by applying specfic currents to the electrode array. Pask presented his work at a conference entitled "Mechanisation of Thought Processes Conference" [37]. He showed that by rewarding conductance changes associated with particular environmental disturbances allowed ferrous threads to be grown that were sensistive to sound or magnetic fields. "We have made an ear….The ear can discriminate between two frequencies, one of the order of fifty cycles per second and the other of the order of a hundred cycles per second". Interestingly very recently some researchers have been able to grow self-repairing, self-assembling wires by suspending gold particles between two electrodes [17].

We emphasize that natural evolution has been blindly exploiting the natural possibilities of the real world for millenia. It may be that only a truly open-ended evolutionary process can exploit the unknown physics and chemistry of the real world. This is one of the challenges of evolvable hardware. Human beings are always thinking within the framework of their own mental models of the world. To some extent we are running our own internal simulation of the world and only trying to do things that seem interesting and feasible within that confined model. Creativity and imagination and perhaps serendipity are the few ways we have of changing these models.

1.4 Beyond the silicon box

Much research in the field of Evolvable Hardware has been dominated by a transistor-centred view of hardware. This is not suprising. We live in a transistor dominated world. However we should guard against the temptations of such a world when we are using bio-inspired algorithms to design things. Evolutionary algorithms are abstract formalisations of natural processes. In a sense they have been removed from their natural context and transplanted into the artificial world of the computer. Evolution and silicon do not not necessarily go well together. Transistors were developed to help realise a top-down view of system design where components are stable, predictable, with almost mathematical properties. Natural evolution works with messy, unstable, complex, chemical systems. We have already argued that such systems with their rich array of embedded and exploitable physics are pre-eminently suitable for natural evolution. We argue here that artificial evolution of hardware might work much better if we can create ways of exploiting the rich resident physics of materials or complex systems. To some extent researchers in Evolvable Hardware are in a uniquely favourable position to do this. This is because we are already applying artificial evolution to exploit real physical systems. That is to say, that by definition intrinsic evolution is embodied or situated in the environment. Nehaniv points to the importance of embodiment in evolutionary robotics and suggests that there is a failure of a deeper sort of embodiment, to

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[1] Field Programmable Gate Array

quote, "the complexity of the automata was not realized via the interaction between the entities and the environment" [35]. In intrinsic hardware evolution this interaction is built in.

Thompson carried out his experiments in silicon on an FPGA. FPGAs are designed to implement digital circuits. It is not at all clear that such a physical environment is best suited to artificial intrinsic evolution. To some extent FPGAs were used simply because they allowed unconstrained intrinsic evolution not because they are particularly suited to it. This suggest that it would be very fruitful to search for other platforms to conduct artficial evolution. This is what we mean by "looking beyond the silicon box". One obvious possibility that we shall examine in more detail is to try to *enrich* the physics in the silicon. This might be accomplished by a sufficient level of ionising radiation. Silicon devices are built to human design with extremely stringent doping requirements. Perhaps we should be looking at enriching the doping!

We suggest that researchers in Evolvable Hardware should consider carefully the following question:

What kinds of physical systems are most easily exploited by an artificial intrinsic evolutionary process?

In this paper we try to suggest some alternatives to conventional intrinsic evolution in silicon. It may be possible for artificial evolution to construct complex information processing systems using components that are not thought of as being capable of such. Such systems may have many advantageous properties over conventional technology.

1.5 Incompatability of self-assembly and exact specification

In nanotechnology there is considerable interest in so called molecular self-assembly [52][53]. Molecules have to self assemble, because they are so small that humans cannot place them in exact arrangements. Essentially self-assembly is nanotechnology's proposed solution to conventional circuit design at the molecular level. The idea is that we can get exactly specifiable circuits (billions of transistors) to self-assemble. How will we debug circuits assembled in this way? (even if it is possible). How many test patterns will we have to input to test the nanoscale circuits? Unfortunately nanotechnologists are imposing the exact same principles of top-down design to nanoscale systems. Living systems and more particularly *evolved* entities do not arrange themselves in this rigid manner. Computing at the nanoscale level is at best amorphous [1]. Precise functionality cannot be attained. There is also a 'price of programmability' [8] associated with an engineer excluding the possibility of unwanted interactions. This implies that the vast majority of interactions that could possibly contribute to problem are deliberately excluded [55]. This is where evolvable hardware can really make progress as artificially evolved systems do not require the exact regularity associated with top-down design. Evolved complex circuits and systems can make a fundamental contribution to the problems of molecular scale design.

Living systems self-assemble. They are "programmed" *from within* in a complex interaction with their environment. This is the miracle of biological development. Human design is *from without*. It is going to be extremely difficult to arrange molecules into exact patterns by passing information from the large to the small. Self-replication and differentiation may be the only practical ways this can be done. Ultimately, Evolvable Hardware will need to consider how to create an artificial embryogeny that is embedded in the physical world (i.e intrinsic embryogeny).

2 The Configurable Analog Processor

We envisage an evolutionary exploitable device as a kind of configurable analog processor (CAP). In its broadest sense, it is a physical device whose configuration is determined by discrete set of signals (voltages, fields). The idea is that a computer can supply the configuration data (which may be transformed into another physical data format).

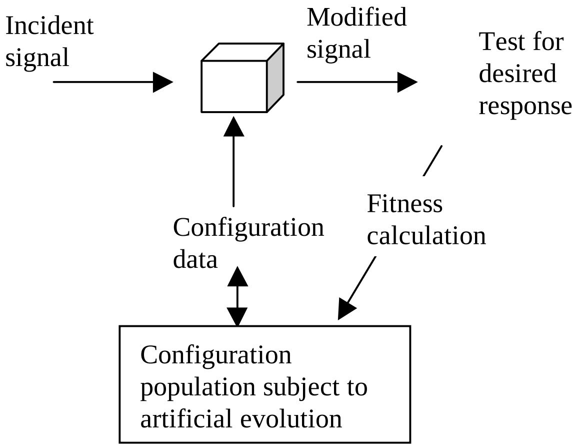

Figure 2: Configurable Analog Processor (CAP) in training process

Until now, the Evolvable Hardware research community has been pre-occupied largely with electronic devices that predominantly employ transistor technology. We argue that this is a very narrow view of potentially exploitable reconfigurable systems. A depiction of a CAP and how it might be trained is seen in Fig 2. It is anticipated that a large number of configurations will need to be tested to find one that transforms the incident signal in the desired way. We also anticipate the fitness landscape associated with the CAP to have many local optima, so an evolutionary algorithm may be an appropriate search algorithm. One potential advantage of the CAP might be that it could process the analog signal presented very quickly. It is necessary that the CAP can relax to its quiescent state quite quickly after configuration data has been removed. It is also necessary that the CAP maintains its state in a particular configuration while the output response is being tested. Every CAP would have to be individually trained, as it would undoubtedly have its own unique response to applied inputs. How can the behaviour of the CAP be characterised?

We suggest that it could be viewed either as some kind of amorphous cellular automaton whose local rules are determined by the configuration and whose cells may be connected to possibly large numbers of distant cells, or as some kind of non-linear coupled network. The coupling concept is very important here as we anticipate that a system of almost independent configurable cells will be less likely to have an interesting and exploitable behaviour. Cellular automata in which the state variables are continuous are known as Coupled map lattices (CML) have been receiving increasing attention in recent years [18] and have been used for modelling complex behaviour that arises in living systems [3]. It is stressed that the configuration data while originating inside a digital computer may be applied to the CAP as analog signals (voltages, magnetic fields, mechanical displacements, voltage pulses) or other appropriate means. In addition, the incident and modified signals may be voltages, radiation, sound, vibration, airflow or any other physical signal.

Another form of the CAP is depicted in Fig. 3. We call it the Field Programmable Matter Array. The idea behind the FPMA is that applied voltages may induce physical changes that interact in unexpected ways with other distant voltage-induced configurations in a rich physical substrate.

There are real practical difficulties associated with using an unconstrained design process. Firstly the evolved behaviour of the CAP may be extremely sensitive to the specific properties of the material sample, so each CAP would require individual training. Secondly, the evolutionary algorithm may utilise physical aspects of any part of the training set-up. Both of these difficulties have already been experienced [26][46]. A third problem can be thought of as "the wiring problem". How can we supply the huge amounts of configuration data to a tiny sample? This problem is a very fundamental one. It suggests that if we wish to exploit the full physical richness of materials we must allow the material to grow its own wires and be self-wiring. This has profound implications for intrinsic evolution as artificial hardware evolution requires complete reconfigurability, this implies that one would have to be able to "wipe-clean" the evolved wiring and start again with a new artificial genotype.

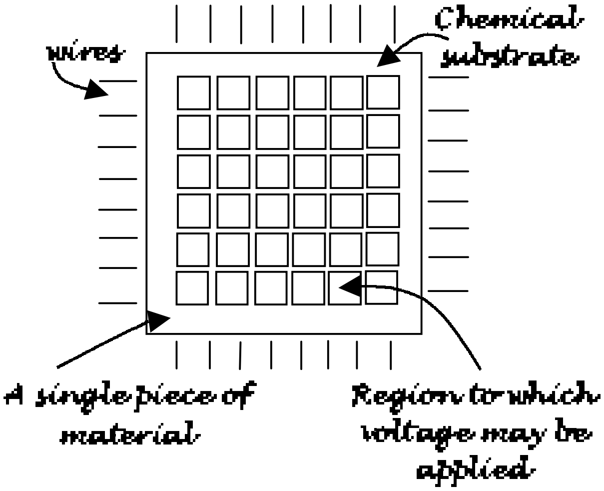

Figure 3: Concept of a Field Programmable Matter Array (FPMA)

This might be provided by the natural chaos in the medium. It seems clear from this that the CAP would have to be complex in the formal sense of the word [19]: it would be in a state on the 'edge of chaos' [24]. The applied configuration signal would provide the order and the natural chaos would provide the rapid removal of order when the configuration signal was removed. Finally, evolving *in materio* is more likely to contribute to Basic Science in the short term rather than lead to immediate real-world applications.

3 Fielded examples of the CAP

In this paper, we concentrate on two seminal examples of CAPs. Both are very well known in the field of Evolvable Hardware. The first is the CAP discovered by Adrian Thompson, namely the Xilinx 6216 FPGA [46]. Here the incident signals were low voltage, square wave pulses of 1kHz and 10KHz. The configuration data was the digital voltage data applied to the configurable logic blocks (CLB) (transistor logic circuits) inside the FPGA. Thompson picked up a signal on one of the output pins of the chip and examined it on a storage oscilloscope. He calculated the duration of the high state and low states of the output signal and determined a fitness to associate with the configuration data. A computer ran an evolutionary algorithm to reward configuration data that was associated with desired behaviour. Thompson found that analog circuits were formed on the FPGA that were utilising some of the underlying physical properties of the silicon. This was evident when he found that some CLB were not connected in the circuit according to the configuration data, yet when their output was clamped to a high or low voltage the entire circuits' behaviour was severely affected.

The second example is that of the antenna design using evolutionary algorithms carried our by Linden [28]. Linden used an evolutionary algorithm to define the physical spatial geometry of straight wire segmented antennas. He tested the designs using a simulator and discovered that he could evolve extremely unusual antennas that performed very well. He then tried to do a similar experiment using actual physical hardware [29]. He created a network of reed switches whose state (open or closed) could be controlled via the digital voltage signals from a computer. He supplied a radio frequency electromagnetic signal to a source point within the reed network. The radiation field produced by the entire arrangement is a subtle function of the topology of the reed switch network. We emphasise here that the electromagnetic field *couples* the wire segments together in a very complex way. An evolutionary algorithm was able to exploit the subtle and nonlinear radiation effects to find very unusual structures that provided the desired characteristics. Similar effects have been observed in other work using intrinsic evolution [26].

4 Review of promising technology

In this section, we review some promising physical systems that might support an artificial evolutionary process and hence supply the basic material core of the CAP. Liquid crystal appears to be most promising in this regard as it digitally writeable, reconfigurable and works at a molecular level. Most interestingly, it is an example of *mesoscopic organisation*. It is within such systems that emergent, organised behaviour can occur [25]. Some biological structures such as the cell wall may even be liquid crystalline in nature [49] Liquid crystals also exhibit the phenomenon of self-assembly. They form a class of substances that are being designed and developed in a field of chemistry called Supramolecular Chemistry [30]. This is a new an exciting branch of chemistry that can be characterised as 'the designed chemistry of the intermolecular bond'. Supramolecular chemicals are in a permanent process of being assembled and disassembled. This gives rise to the type of natural fault tolerance so amply exhibited in living systems. Conceptually liquid crystals appear to sit on the 'edge of chaos' [24] in that they are fluids (chaotic) that can be ordered, under certain circumstances.

4.1 Liquid crystal

The liquid crystal (LC) is commonly defined as a substance that can exist in a mesomorphic state [12][20]. Mesomorphic states have a degree of molecular order that lies between that of a solid crystal (long-range positional and orientational) and a liquid, gas or amorphous solid (no long-range order). In LC there is long-range orientational order but no long-range positional order. The most commonly occuring LC molecules take the form

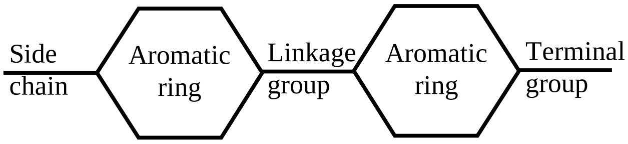

Figure 4: Aromatic LC molecule

Aromatic LC is often called a benzene derivative. There is also heterocyclic LC where one or more of the bezene rings are replaced with pyridine, pyrimidine or other similar group. LC can also have a metallic atoms (as a terminal group) in which case they are called organometallic compounds. Chemical stability is strongly influenced by the linkage group. Compounds where the aromatic rings are directly linked are extremely stable. LC tends to be transparent in the visible and near infrared and quite absorptive in UV. There are three distinct types of LC: lyotropic, polymeric and thermotropic. Lyotropic LC is obtained when an appropriate amount of material is dissolved in a solvent. Most commonly this is formed by water and amphiphilic molecules: molecules with a hydrophobic part (water insoluble) and a hydrophillic part (strongly interacting with water). Polymeric LC are basically polymer versions of the aromatic LC discussed. They are characterised by high viscosity and include vinyls and Kevlar. Thermotropic LC (TLC) is the most common form and is widely used. TLC exhibit various liquid crystalline phases as a function of temperature. They can be depicted as rod-like molecules and interact with each other in distinctive ordered structures. TLC exists in three main forms: nematic, cholesteric and smectic. In nematic LC the molecules are arranged positionally randomly but all share a common allignment axis. Cholesteric LC (or chiral nematic) is like nematic however they have a chiral orientation. In smectic LC there is typically a layered positionally disorderd structure. The three types are illustrated in Fig. 5. In type A the molecules are oriented in allignment with the natural physical axes (i.e normal to the glass container, depicted by the arrow), however in type C the common molecular axes of orientation is at an angle to the container. LC molecules typically are dipolar. Thus the organisation of the molecular dipoles give another order of symmetry to the LC. Normally the dipoles would be randomly oriented. However in some forms the natural molecular dipoles are aligned with one another. This gives rise to ferroelectric and ferrielectric forms. These are depicted in Fig. 6.

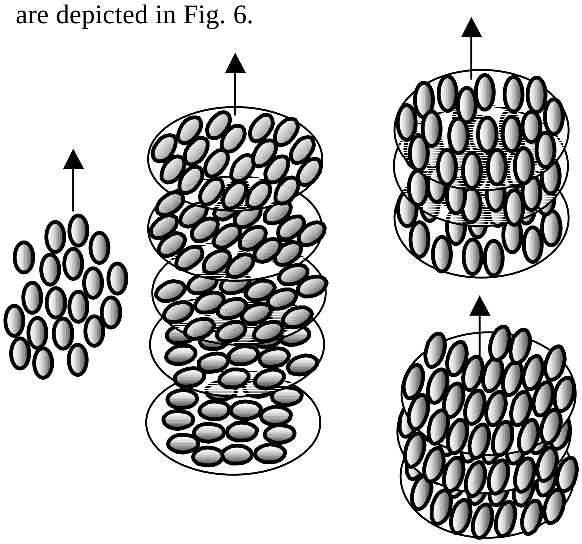

Figure 5: Nematic, cholesteric, smectic-A forms (top) and smectic-C of liquid crystal (from left)

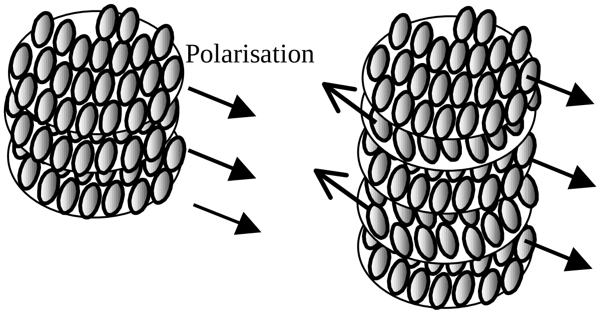

Figure 6: Ferroelectric smectic-C (left) and Ferrielectric smectic-C (right)

In this section we cannot hope to cover the vast range of different types of liquid crystal. LC of different types can be mixed. LC can be doped (as in Dye-Doped LC) to alter their light absorption characteristics. Dye-Doped LC film has been made that is optically adressable and can undergo very large changes in refractive index [21] There are Polymer-Dispersed Liquid Crystals these can have tailored electrically controlled light refractive properties. Another interesting form of LC being actively investigated is Discotic LC. These have the form of disordered stacks (1-dimensional fluids) of disc-shaped molecules on a two-dimensional lattice (Fig. 7). Although discotic LC is an electrical insulator, it can be made to conduct by doping with oxidants [6]. The oxidants are incorporated into the fluid hydrocarbon chain matrix (between disks).

LC is widely known as useful in electronic displays, however, there are in fact, many non-display applications too. There are many applications of LC (especially ferroelectric LC) to electrically controlled light modulation: phase modulation, optical correlation, optical interconnects and switches, wavelength filters, optical neural networks. In the latter case a ferroelectric LC is used to encode the weights in a neural network[9].

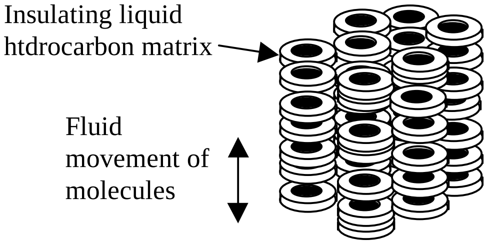

Figure 7: Schematic of discotic columnar liquid crystal.

4.2 Conducting and electroactive polymers

Conducting polymer composites have been made that rapidly change their microwave reflection coefficient when an electric field is applied. When the field is removed, the composite reverts to its original state. Experiments have shown that the composite can change from one state to the other in the order of 100ms [54].

Some polymers exhibit electrochromism. These substances change their reflectance when a voltage is applied. This can be reversed by a change in voltage polarity [34]. Electroactive polymers [2] are polymers that change their volume with the application of an electric field. They are particularly interesting as voltage controlled artificial muscle. Organic semiconductors also look promising especially when some damage is introduced. Further details of electronic properties of polymers and organic crystals can be found in [39]

4.3 Voltage controlled colloids

Colloids are suspensions of particles of sub-micron sizes in a liquid. The phase behaviour of colloids is not fully understood. Simple colloids can self assemble into crystals, while multi-component suspensions can exhibit a rich variety of crystalline structures. Colloids can be made in which the particles are charged.

Dielectrophoresis refers to the phenomenon of the motion of polarized but electrically uncharged particles in nonuniform electric fields [23]. This was used to recently grow tiny gold wires [17]. Applying voltages to create special configuations of colloids looks promising for intrinsic evolution.

5 Specific suggestions

The first suggestion for a novel reconfigurable device is a Liquid Crystal Display (LCD). These have a number of virtues that make them an obvious candidate. They are already widely available in a form that they can be addressed by digital voltages. In its simplest form an LCD is a sandwich of crossed polarising filters, transparent electrodes and liquid crystal. The glass immediately surrounding the liquid crystal is scratched in a regular fashion. The liquid crystal molecules align themselves with local surface of the glass. Essentially the application of a local electric field causes the liquid crystal molecules to untwist. This means that the incident light will be blocked by the crossed polaroid filters and hence a dark spot will be visible at the electrode position. An evolutionary algorithm could be used with the LCD to evolve local molecular twists according to some fitness function. Since LCDs alter the local refractive index of light it would seem natural to try to evolve some useful function for modulating light in some way. Already researchers are investigating the usefulness of liquid crystal in adaptive optics and for the creation of specialist microlenses [40][42]. It may be possible to evolve a complex optical function using artificial evolution. However a more interesting possibility would be to somehow couple together the local molecular twists so that one local group of liquid crystal molecules caused a change in the behaviour of another (similar to the coupling of wire elements in Linden's work on antennas). It might even be possible to apply a radio signal to an electrode on a LCD and evolve some sort of antenna by applying voltages to the LCD! Liquid crystals now come in an amazing number of forms. It seems likely that at least one form will have exploitable properties. The semi-liquid nature of liquid crystal is a very attractive feature as it implies that the material is semi-ordered and can relax back to its quiescent state. This is an important requirement of all artificially evolvable systems. Another attractive feature is the applied voltage can alter the molecular comfiguration of the material. Conducting polymers or conducting liquid crystal look attractive as the applied voltages may create tiny molecular interactions that can be exploited by artificial evolution. One of the inherent difficulties in this kind of research is to identify the kind of properties that a material should have that could be exploited in an artificial evolutionary process.

Another possible CAP is irradiated silicon. Work is currently in progress to investigate whether it may be easier to evolve more complex functions in irradiated silicon rather than conventional silicon. The idea here is that ionising radiation will upset the silicon doping in an existing transistor device. Submitting transistors or even FPGAs to known amounts of radiation damage and then evolving them to perform some useful computation may reveal a correlation between damage and evolvability. It is interesting to reflect that the reason why silicon has proved so useful is that it is a semi-conductor whose conductivity can be controlled. The most interesting materials are likely to be on the edge of two boundaries (conductivity for silicon, crystallinity for liquid crystals etc.). These types of materials would seem to have the most exploitable properties.

6 Conclusions

In this paper, we have argued that the artificial intrinsic evolution may be best attempted in physical substrates that are rich and complex rather than conventional transistor-based technology. Exactly which sorts of materials would be best suited is an extremely difficult question. However, we have attempted to point in the direction of promising candidates. The materials must, of course, be reconfigurable as we expect to evolve very many configurations in our attempt to produce the desired response. Almost by definition, we are looking for physical platforms that can support emergent computation. Materials that exist in a mesophase where disorder and order coexist appear to be good candidates. Ideally, the physical configuration of these materials should be affected by small applied-voltages. Researchers in evolvable hardware are uniquely well situated to look for these materials and to evolve novel computational devices. It is hoped that this paper might stimulate further work in this direction.

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