A Grand Challenge for Computing Research

Journeys in Non-Classical Computation

GC7 web site: http://www.cs.york.ac.uk/nature/gc7/

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Challenging paradigms

Today's computing, *classical* computing, is a remarkable success story. However, there is a growing appreciation that it encompasses only a small subset of all computational possibilities. There are several paradigms that seem to define classical computing, but these may not be true for *all* of computation. As these paradigms are systematically challenged, the subject area is widened and enriched. The Grand Challenge of Non-Classical Computation is nothing less than a reconceptulisation of computation.

Physical embodiment

Classically, computation is viewed mathematically, in terms of algorithms, complexity, and such like, based on the underlying essentially mathematical model of the Turing Machine. The fact that computation is *physical,* is necessarily embodied in a device whose behaviour is guided by the laws of physics, whose behaviour cannot be completely captured by a closed mathematical model, is becoming more apparent as we push the bounds of those physical laws. The mathematical model of the Turing Machine is not an adequate model of reality for all notions of computation.

For example, one of the most exciting, and seemingly weird, recent developments is the non-classical paradigm of ***quantum computing***. This has emphasised the fundamental link between computation and its physical embodiment in the real world, in that *quantum superposition* and *quantum entanglement* can lead to results simply not possible classically. Still in relative infancy, it holds out the promise of massive increases in computation power, of untappable communication channels, and of spooky effects such as quantum teleportation.

To emphasise the critical importance of the underlying physical laws on computation, it has been shown that the deep unsolved conundrum of whether **P = NP** is in fact answerable, in the affirmative, *if the laws of quantum mechanics are non-linear*. The fact that the precise form of the laws of physics can have an impact on what is classically thought to be a purely *mathematical* question is considerable food for thought.

At the opposite extreme, back in the everyday classical physical world, the importance of embodiment can turn up in strange places. For example, a computation, being embodied, takes time to execute, and consumes power as it executes, usually in a data-dependent manner. These time and power consumption *side-channels* can be measured and analysed, and such analyses have been used to attack the security mechanisms of certain smart cards. Side channels are ones outside the mathematical model of the computational system. Even if these channels are then explicitly added to the model, the world is open, and further side channels always exist: *no mathematical model of the world is complete*.

Bio-inspiration

Classical computations tend to be very *fragile* to unexpected changes. We have to carefully manage their inputs and interactions, keeping them locked in a safe, controlled environment. As our ambitions grow, and our computational devices interact more with the open, noisy, uncontrolled real world, it seems we need a radically new way of designing and implementing programs. So, how can we build complex computational systems – systems that are autonomous, adaptable, and robust – from millions of less reliable and simpler components? How can we build them to perform correctly and safely in an unpredictable, changing and hostile environment, and over long periods of time? Such tasks are currently well beyond the state of our computational art, and as our technology moves towards ever smaller and ever more numerous nano-scale and quantum devices, these tasks will get only more difficult.

And yet *biological* processes manage to do such things routinely. Living creatures are remarkably robust and adaptable. They can survive injury, damage, wear and tear, continual attack from other creatures, and can adapt to their environment. Biology manages to take huge amounts of potentially unreliable matter and use self-checking, self-repair, self-reconfiguration, multiple levels of redundancy, multiple levels of defence, to develop adaptable complex biological organisms that continue to work for long periods of time in an extremely hostile changing environment.

So, in an attempt to cope with complexity, researchers are drawing inspiration from biology, which seems to have already discovered the answers, to develop a host of ***bio-inspired algorithms*** from evolution (genetic algorithms, genetic programming), neurology (artificial neural networks), immunology (artificial immune systems), plant growth (L-systems), social networks (ant colony optimisation), and much more.

Much progress is being made in the area of bio-inspiration, yet the resulting algorithms do not fit well into a classical computational framework. At the very least, they are inspired by highly parallel systems of multiple autonomous interacting agents, yet are often unnaturally sequentialised to fit the classical von Neumann execution paradigm. Additionally, the algorithms exhibit ***emergent properties*** – properties at one level that are not expressed in terms of, and not directly mappable to, the concepts available at a lower level. Emergence does not fit within the classical development process of stepwise refinement and correctness arguments. The most important divergence may be the fact that biological organisms are themselves embodied in a physical, chemical, biological world. For example, evolutionary algorithms model DNA as a string of ACGT bases, and from this build metaphorical chromosomes of bits or numbers. Yet DNA encodes for proteins, proteins fold into complex 3D shapes, and it is these physically embodied *shapes* that interact by chemical forces with other shapes to perform their functions.

Complex systems

Researchers are also beginning to explore ***open complex adaptive systems***, where new resources, and new *kinds* of resources, can be added at any time, either by external agency, or by the actions of the system itself. Such new resources can fundamentally alter the character of the system dynamics, and so allow new possibilities, new adaptations. Our current computational systems are beginning to open themselves, for example, through the continuing dialogue between user and machine, through continued new connections to networks such as the Internet, and through robotic systems controlling their own energy sources.

Open systems do not fit well into a classical framework, either. Turing Machine computations are defined in terms of *halting* computations, not ongoing ones with continual interactions with an open environment. Classical specification and refinement paradigms assume a pre-determined phase-space, with all the component types known beforehand. Yet a biological evolutionary system, or even a complex chemical catalytic network, is constantly creating new species, is constant surprising.

Enriching computation

Classical physics did not disappear when modern physics came along: rather its restrictions and domains of applicability were made explicit, and it was reconceptualised. Similarly, these various forms of *non-classical computation* – embodied computation, bio-inspired algorithms, open complex adaptive systems, and more – will not supersede classical computation: they will augment and enrich it. In the process, classical computation will inevitably be reconceptualised. This Grand Challenge seeks to explore, generalise, and unify all these many diverse non-classical computational paradigms, to produce **a fully mature and rich science of all forms of computation, that unifies the classical and non-classical computational paradigms**. It is clearly closely linked with sister Grand Challenges in Biological Modelling and Ubiquitous Computing.

Such a mature computational science will allow us to design and build robust, adaptable, powerful, safe, complex computational systems. It will help researchers to uncover deep biological truths: which features of biology are necessary for correct robust functioning (so true of any living organism)? Which are necessary only because of the particular physical realisation (carbon-based terrestrial life-forms)? Which are merely contingent evolutionary aspects (and so could be different if "the tape were played again")? And it will help researchers to uncover deep physical truths: what is the relationship between logical information (bits) and physical reality?

Journeying hopefully

Many Grand Challenges are cast in terms of *goals*, of end points: "achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to earth", mapping the human genome, proving whether **P** = **NP** or not. We believe that a goal is not the best metaphor to use for this particular Grand Challenge, however, and prefer to use that of a *journey*. The metaphor of a journey emphasises the importance of the entire process, rather than emphasising the end point. Indeed, we do not even know the end point; ours is an open journey of *exploration*. On such a journey, it is not possible to predict what will happen: the purpose of the journey is discovery, and the discoveries along the journey suggest new directions to take. One can suggest starting steps, and maybe some intermediate *way points*, but not the detailed progress, and certainly not the end result.

First steps

In this light, we have mapped out some initial journeys – first steps – of the Challenge. These more detailed statements are necessarily influenced by the specific interests of the researchers involved, but their purpose is to indicate the kind of research that we believe needs to be done to start the Challenge. (See the GC7 website for the full statements of these journeys.) Each of these journeys is already underway, to a greater or lesser extent, in the UK and worldwide.

Non-Classical Philosophy – Rethinking classifications

Recent philosophy, of Wittgenstein and Lakoff in particular, emphasises that people do not classify the world into sets defined by necessary and sufficient conditions. Yet this is one of the artificial constraints we impose on our programs, which may be why they are inflexible and lack "common sense". The challenge is to construct computing based upon family resemblance rather than sets, on paradigms rather than concepts, on metaphor rather than deduction, and to devise systems that make context-sensitive judgements rather than take algorithmic decisions.

Non-Classical Physics – Quantum Software Engineering

Quantum Computation and Quantum Information Processing are in their early days, yet the more we look at them, the weirder their consequences appear to be. The challenge is to rework and extend the whole of classical software engineering into the quantum domain, so that programmers can manipulate quantum programs with the same ease and confidence that they manipulate today's classical programs.

Non-Classical Refinement – Approximate Computation

In interacting with the continuous, noisy real world, a radical departure from discrete correct *v.* incorrect computation is required, a shift away from logics towards statistical foundations, such that meaningful estimates of confidence emerge with each approximate result.

Computing in non-linear media – reaction-diffusion and excitable processors

Chemical reactions can exhibit excitation waves. Such waves do not conserve energy, rather, they conserve waveform and amplitude, do not interfere, and generally do not reflect, properties that may be used to perform a novel form of embodied computation. The challenge is to develop a science of computation using spatio-temporal dynamics and propagating phenomena, in many-dimensional amorphous non-linear media.

Artificial Immune Systems (AIS)

AIS are an exciting new form of bio-inspired computation. There is a broad and rich set of models available for investigation, from population-based selection models, to dynamic network models. The challenge is to develop a corresponding computational theory of the variety of AIS-inspired algorithms, and to extend and unify these with other bio-inspired results.

Non-Classical Interactivity – Open Dynamical Networks

Dynamic reaction networks can have complex non-linear interactions, and feedback where reaction products may themselves catalyse other reactions in the network. They exhibit the emergent complexity, complex dynamics, and self-organising properties of many far-from-equilibrium systems. Computation can be viewed as a dynamical process. The challenge is to develop a pragmatic theory of dynamic, heterogeneous, unstructured, open networks, and thence to develop a computational paradigm in terms of dynamical attractors and trajectories.

Non-Classical Architectures – Evolving Hardware

Most bio-inspired algorithms are implemented in software, in disembodied simulations. But hardware can have bio-inspired properties to, and can exploit unexpected properties of embodiment, such as the analogue characteristics of devices. The challenge is to use such properties to develop (biologically-inspired) computing hardware that can adapt, evolve, grow, heal, replicate, and learn.

Non-Classical Architectures – Molecular Nanotechnology

Molecular nanotechnology envisages the use of hordes of molecular-scale robots to construct macroscopic artefacts, as guided by their programming. Centralised control is infeasible. The challenge is to find ways of designing and assembling artefacts in ways that can be described in terms of predominately local interactions, that is, in terms of the *emergent properties of vast numbers of cooperating nanites*. This requires analysis of emergent behaviour, of growth, and of complex adaptive systems.

Non-von Architectures – Through the Concurrency Gateway

The classical von Neumann sequential execution paradigm forces computation into a sequential straightjacket. Classical approaches to overlaying a concurrency framework are conceptually very difficult to program, and expensive in time and memory to implement. The challenge is to enable concurrency to be a fundamental modelling and programming concept, with a clean and simple conceptual model, that can be efficiently implemented.

The Grand Challenge Umbrella

These various first step challenges cover embodiment, bio-inspiration, and complex systems, sometimes within the same journey. Such wide-ranging and novel research necessarily requires multidisciplinarity, with computer scientists working alongside biologists, chemists, physicists, mathematicians, materials scientists, and hardware engineers.

The purpose of the overarching Grand Challenge is to coordinate such separate journeys, to cast their research hypotheses and view their results in terms of the overall vision, and to abstract out common results into new paradigms. These individual exploratory journeys, and others yet to be defined, form part of the process of mapping out the wide-ranging new discipline of Non-Classical Computation. The GC7 group is building a Network of interested researchers to this end. Please subscribe to the GC7 mailing list, or contact the GC7 moderator, if you would like to join us in our Journey.