Research Cluster in Brain-Inspired Novel Computation

An investigation of novel computational architectures, principles and mechanisms based on how the brain processes, manages and acts on complex, uncertain and dynamic information.

Case for Support

1. Background

The Challenge

The brain is one of the most complex systems known to mankind and understanding the principles and mechanisms governing its function is arguably the most fundamental and important scientific challenge facing mankind in the 21st century. The essential requirement is a quantitatively precise understanding of brain function at different levels of abstraction, including

- physiological properties of brain mechanisms, e.g. neurons and neural circuits;
- information representation, storage, processing and communication in and between interacting cortical and subcortical neuronal structures;
- higher level cognitive, control and affective functions;

and in particular an understanding of

- how the levels are linked to form an integrated functioning system
- the fundamental principles involved in providing the brain with high levels of resilience, and
- the mechanisms of self-organisation and adaption inherent in the brain for dealing with complex, uncertain and dynamically changing information.

Through this proposed Research Cluster we will seek to develop a small number of high quality, adventurous research proposals which will aim at a deep understanding of the computational principles of the brain, expressed in the form of new mathematical theories and computational models. The objective will be to provide the foundation for a radically new generation of machines that infer and act more like humans. Such machines should be simpler to interact with and to use. Achieving this understanding will require the collaborative efforts of neuroscientists, psychologists, computer scientists and mathematicians, as proposed for this Research Cluster.

The Scientific Basis

The neural circuits of the neocortex, together with their subcortical interactions, subserve sensory perception, attention, memory and a spectrum of other higher cognitive functions. They combine to provide animals with their outstanding powers in dealing with the complex information they receive from the external world and integrating this with internal states and models of the outcomes of behaviour. As several researchers have noted, a number of characteristics of the neocortex suggest that the brain achieves its powerful capabilities in a fundamentally different way from today's conventional computers, involving the use of highly parallel, asynchronous, nonlinear and continuously adaptive dynamical systems. Individual neurons can combine in flexible ways in order to make up these neural circuits, but are nevertheless precisely connected to each other and to their afferent inputs through synapses in specific cortical layers and on specific locations on their dendritic trees. Synapses act as adaptive filters for the transmission of data, changing their transmission characteristics dynamically and asynchronously, on a millisecond timescale. Both the synaptic connections and the transmission properties of the dendritic tree have the remarkable ability to continuously adapt and optimise themselves to allow the neural circuitry to meet the dynamically changing requirements of novel tasks and environments. This occurs both through unsupervised modification of their fundamental physiological properties, and through modulatory control of the synaptic and dendritic dynamics by specific neuromodulators which are used to inform and teach the neural circuitry about the drives, goals and rewards of the animal. Neural circuits appear to be able to maintain a virtual continuum of time scales of information processing, with time constants of activity ranging from a few milliseconds to years.

The Opportunity

Advances in all aspects of neuroscience, including neurobiology, computational and theoretical neuroscience, and neuropsychology have accelerated at a breathtaking rate over the last ten years. This recent explosion in neuroscience has been made possible by remarkable technical innovations in neurobiological experimental techniques at genetic, molecular and cellular levels, and also, with neuroimaging at more macroscopic levels. The availability of vastly greater computer power for data analysis and computational modelling has also played a key role.

The current level of knowledge and understanding of the workings of the nervous system at the neuronal level provides, perhaps for the first time, an remarkable opportunity for developing an understanding of how the brain operates as a complex integrated system, and, in particular, how it gives rise to high level cognitive capabilities. However, the major classes of brain functions such as perception, cognition, and control of movement depend on the *emergent functional properties* of vast systems of neural circuits and their interactions with the environment. It is not possible to understand this level of brain function fully at either molecular or macroscopic levels. A systems level approach is needed, in which neural circuits and their complex emergent properties can be studied. Key tools for research at this level are computational and mathematical models of neural circuits, which allow model functions to be compared against experimental data. Good models also make predictions that can be tested empirically. Thus, there is an essential interplay between the mathematical, computational and experimental neurosciences and the computer sciences. Unfortunately, the traditional boundaries between experimental neurobiology and the computational/mathematical sciences have not promoted this interplay. The Research Cluster offers the opportunity to create such a multidisciplinary collaboration, which will have the potential for making a major step forward in research into brain-inspired novel computation.

The Research Community

In addition to the new opportunity presented by the recent explosion in neuroscientific research, there now exists a strong research community upon which the proposed Research Cluster can be based. In the UK, there are several research centres and individuals of international standing actively engaged in research in mathematical and computational neuroscience. These currently include:

Gatsby Computational Neuroscience Unit, University College London
Centre for Theoretical and Computational Neuroscience, University of Plymouth
Institute for Adaptive and Neural Computation, School of Informatics, Edinburgh University
Computational Neuroscience Group, Dept of Experimental Psychology, Oxford University
Roland Baddeley, School of Biological Sciences, Sussex University
Li Zhaoping, Laboratory for Natural Intelligence, University College London
Neil Burgess, Institute of Cognitive Neuroscience, University College London
Steve Coombes, Mathematical Biology Group, Dept of Mathematical Sciences, Loughborough University
Tom Coolen, Mathematics Dept, Kings College London
Jianfeng Feng, Si Wu, School of Cognitive and Computing Sciences, University of Sussex
Stefano Panzeri, Dept of Optometry and Neuroscience, UMIST
Tony Prescott, Jim Stone, Dept of Psychology, Sheffield University
Tibor Toth, School of Biosciences, Cardiff University
Marius Usher, Birkbeck College, London
Daniel Wolpert, Institute of Neurology, University College London

In addition there are internationally recognised research groups and individuals in the UK in the field of neuromorphic computational architectures, including:

Steve Furber, Advanced Processor Technologies Group, Dept of Computer Science, University of Manchester
Alan Murray, Institute for Integrated Micro and Nano Systems, School of Engineering and Electronics, University of Edinburgh

UK neurobiologists who are actively working with mathematical and computational modellers include:

Malcolm Brown, Dept of Anatomy, Bristol University
Vincenzo Crunelli, School of Biosciences, Cardiff University
Tony Dickinson, Dept of Experimental Psychology, Cambridge University
Karl Friston, Institute of Neurology, University College London
Michael Häusser, Dept of Physiology, University College London
John Jefferys, Division of Neuroscience, The Medical School, University of Birmingham
John O'Keefe, Dept of Anatomy, University College London
Andrew Parker, University Laboratory of Physiology, Cambridge
David Price, Centre for Neuroscience, University of Edinburgh
Peter Redgrave, Dept of Psychology, Sheffield University
Edmund Rolls, Dept of Experimental Psychology, Oxford University
Wolfram Schultz, Dept of Anatomy, University of Cambridge
Tim Shallice, Institute of Cognitive Neuroscience, University College London

Alex Thomson, Dept of Physiology, University College London
Miles Whittington, Biomedical Sciences, Leeds University

In Europe, there are many groups working on mathematical and computational neuroscience and neuromorphic computing architectures. Notable groups/individuals include the following:
France:
Nicolas Brunel, David Hansel, Carl van Vreeswijk, Neurophysics, CNRS, Université René Descartes, Paris
Alain Destexhe, Unité de Neurosciences Intégratives et Computationnelles, CNRS, Gif-sur-Yvette
Yves Burnod, INSERM U 483, CNRS, Université P. et M. Curie, Paris
Alain Berthoz, Institute of Biology, College de France, Paris
Jean-Arcady Meyer, AnimatLab, Labortatoire d'Informatique, Paris 6.
Belgium:
Erik De Schutter, Theoretical Neurobiology Unit, Born-Bunge Foundation, University of Antwerp
Germany:
Klaus Obermayer, Neural Information Processing Group, Dept of Electrical Engineering and Computer Science, Technical University of Berlin
Christian Eurich, Klaus Pawelzik, Institute of Theoretical Neurophysics, University of Bremen
Andreas Herz, Computational Neurobiology Group, Institute for Theoretical Biology, Humboldt University, Berlin
Rolf Kötter, Computational Neuroscience Group, C. &. O. Vogt Brain Research Institute, Düsseldorf
Spain:
Nestor Parga, Computational Neuroscience Group, Departamento de Física Teórica, Universidad Autónoma de Madrid
Gustavo Deco, University of Barcelona
Switzerland:
Wulfram Gerstner, Laboratory of Computational Neuroscience, EPFL, Lausanne
Rodney Douglas, Kevan Martin, Institute of Neuroinformatics, ETH, Zurich
Walter Senn, Computational Neuroscience Lab, Institute of Physiology, University of Berne
Israel:
Misha Tsodyks, Dept of Neurobiology, Weizmann Institute of Science, Rehovot
David Horn, Neural Computation Group, School of Physics, Tel-aviv University
Idan Segev, Interdisciplinary Center for Neural Computation, Dept. of Neurobiology, Hebrew University
Sweden:
Anders Lansner, Studies of Artificial Neural Systems, KTH, Stockholm

Finally, there are many research groups in the field of mathematical and computational neuroscience in the USA, too numerous to mention individually here. Notable individuals, most with substantial research groups, include: *Michael Arbib (USC), Paul Bressloff (Utah), Jack Cowan (Chicago), Christof Koch (Caltech), John Rinzel (New York University), Terry Sejnowski (Salk Institute).*

2. Research Cluster Aim, Core Membership, Activities and Timeliness

Aim

The aim of this research cluster proposal is to bring together the main groups in the UK in the areas of mathematical and computational neuroscience, and neuromorphic computational architectures, together with UK neurobiologists who are currently involved in mathematical and computational modelling research collaborations, in order to work together through the Research Cluster to:

- identify the key scientific research problems in the field of biologically-inspired novel computation and the key multidisciplinary approaches to their solution
- create a small number of multidisciplinary working groups to specifically address these problems
- develop and produce, through these working groups, a small number of high quality research proposals that will aim at solving the major scientific problems identified.

Core Members

The initial core members of the cluster will be (in alphabetical order):
Mathematical/Computational Neuroscience
Roland Baddeley, School of Biological Sciences, Sussex University

Neil Burgess, Institute of Cognitive Neuroscience, University College London
Steve Coombes, Mathematical Biology Group, Dept of Mathematical Sciences, Loughborough University
Peter Dayan, Gatsby Computational Neuroscience Unit, University College London
Mike Denham, Centre for Theoretical and Computational Neuroscience, University of Plymouth
Stefano Panzeri, Dept of Optometry and Neuroscience, UMIST
Mark Van Rossum, Institute for Adaptive and Neural Computation, Division of Informatics, Edinburgh University
David Willshaw, Institute for Adaptive and Neural Computation, Division of Informatics, Edinburgh University
Li Zhaoping, Laboratory for Natural Intelligence, University College London

Computer Architectures
Steve Furber, Advanced Processor Technologies Group, Dept of Computer Science, University of Manchester

Neurobiology
Malcolm Brown, Dept of Anatomy, Bristol University
Vincenzo Crunelli, School of Biosciences, Cardiff University
Tony Dickinson, Dept of Experimental Psychology, Cambridge University
Michael Häusser, Dept of Physiology, University College London
John Jefferys, Division of Neuroscience, The Medical School, University of Birmingham
John O'Keefe, Dept of Anatomy, University College London
Andrew Parker, University Laboratory of Physiology, Cambridge
Peter Redgrave, Dept of Psychology, Sheffield University
Wolfram Schultz, Dept of Anatomy, University of Cambridge
Alex Thomson, Dept of Physiology, University College London
Miles Whittington, Biomedical Sciences, Leeds University

All the above have given a firm acceptance of the invitation to participate as a core member of the Research Cluster (see Appendix for email confirmations where available).

Membership of the cluster will, of course, also extend to the members of the research groups of those individuals indicated above, since they will in many cases bring special expertise into the cluster. The cluster will also co-opt the assistance of key researchers in the field from Europe and the USA. Initially these will be selected from the individuals listed on page 3.

At an appropriate point in the activities of the Research Cluster, in particular when the nature of the key 3-5 year challenges and the approaches to their solution have been identified (most likely after the first Cluster Meeting - see below), it is anticipated that a number of theoretical computer scientists will be invited to participate in the cluster and in the development of the research proposals.

Activities
1. Research Cluster Meetings
Within the first 4-6 months of the 12 month period of the cluster, it is intended to hold two key meetings:

Meeting 1: Understanding the brain: theoretical and computational principles and mechanisms
This meeting will aim at identifying a set of key scientific problems which it will be necessary to solve in order to further our understanding of the principles and mechanisms which underlie the way in which the brain represents, processes and acts on complex information. Most importantly, it will aim at not just identifying the problems but also drawing up a set of key approaches to addressing these problems that will exploit the combined power of the range of disciplines represented in the Research Cluster.

The meeting will involve the initial core members (approximately 20 participants including additional members from listed research groups) plus selected non-UK researchers. Other non-UK researchers will be invited to act as corresponding participants, and asked to provide written input to the meeting and comment on the meeting outputs via the website.

Each participant will be asked to prepare a short (two-page max) position paper prior to the meeting which will be circulated to all participants. Based on these the PI and Co-investigator and two/three members from the core group will identify a number of major themes within which key scientific problems can be identified. The meeting will then be organised in a manner which allows each theme to be focused on by the whole group initially and then by self-selecting subgroups.

The meeting will extend over two days in a location which will encourage continuing debate and discussion during the evening of the first day. A report will be prepared which will be posted on the cluster website (see below).

Meeting 2: "Setting out the research programme".
This meeting will focus on the key scientific problems and approaches to their solution identified in the Meeting 1, with the specific aim of setting out a draft research programme for each problem, together with a set of outcomes against which success can be measured. These draft programmes will be used by a set of working groups (see below) established at the meeting, to develop the specific set of research proposals in the next phase of cluster activities. Participants in the meeting are expected to be largely the same as those in Meeting 1, with additional experts invited as necessary. The meeting will be over two days as before, and the draft research programmes will be published on the cluster website.

2. Website
A website for the cluster will be established and the results from the initial meetings will be placed on the site, with a discussion forum to enable on-going debate. Access to the website will be through a registration process which will be set up to allow access by any bone-fide research group who wishes to participate in the cluster activities, in the spirit of an "open" cluster, as intended by EPSRC.

3. Working group meetings
A set of working group meetings will be held in various locations selected by the group leaders to assist in the development of the research proposals. This activity will be specifically targeted at producing a corresponding set of high quality, adventurous research proposals by the deadlines identified by EPSRC, ie for submission by 1 June 2004.

Timeliness of the Research Cluster
The establishment of a Research Cluster in Brain-Inspired Novel Computation is very timely in respect of two recent UK developments.

Firstly, the Foresight Cognitive Systems Project will be drawing to a conclusion in December 2003. The primary objective of this project is "*to examine recent progress in two major areas of research - computer science and neuroscience (and their related fields) - to understand whether progress in understanding cognition in living systems has new insights to offer those researching the construction of artificial cognitive systems*". Two workshops have been held, one for computer scientists and one for neuroscientists, with the aim of identifying the major issues which confront each community in the building of artificial cognitive systems and understanding of natural cognitive systems, respectively. A major "Interaction" conference is scheduled for September 2003 with the aim of scoping likely developments in these fields over the next decade, in particular the likely rate of progress in our capability to build artificial cognitive systems, and to articulate significant conclusions to a wider audience. Several of the initial core members of the proposed cluster are active in the Foresight project, as authors of the scientific reviews and workshop participants: Mike Denham, Peter Dayan, David Willshaw, Roland Baddeley and Steve Furber.

The work of the proposed research cluster will be able to draw on the outcomes of the Foresight project, which aim at defining the prospects for the field over the next ten to twenty years. However, most importantly the research proposals emanating from the Research Cluster will provide a timely mechanism for taking the first steps in Foresight's ambitious long-term research agenda, by establishing a set of high quality research programmes, aimed at achieving a set of well formulated and precisely defined objectives over the next three to five years.

Secondly, the UK Computing Research Committee, a specialist committee of both the IEE and the BCS, recently established an on-going activity to develop a set of "Grand Challenges" for computer science research. The set of grand challenges to be taken forward was established at a UKCRC Workshop in November 2002 and these have been developed into a set of web-published draft

proposals. The PI of this Research Cluster proposal is the author/moderator of the Grand Challenge proposal: "Architecture of Brain and Mind". The proposal sets out the basis of the following challenge: "*To create a computational architecture of the brain and mind which is inspired both by the neuronal architecture of the brain and high level cognitive functioning in humans; captures the information processing principles present in the brain; describes how low level neuronal processes are linked and integrated with high level cognitive capabilities, such as adaptability, self awareness and creativity; provides a major input into the worldwide scientific endeavour to control or eliminate a range of human mental disorders; and will allow the creation of intelligent artefacts which incorporate a significant subset of human cognitive functional capabilities.*" This is a proposal for a 10-15 year project, and the proposal clearly states that " *...whilst this Grand Challenge is guided by the long term scientific goal of understanding how the human brain functions in supporting the full range of human mental processes, it is not claimed here that this goal can be achieved in fifteen years: on the contrary a far longer time will be required. Nevertheless, within ten to fifteen years major progress is possible that will provide a solid foundation for further research in the decades that follow*". The aim of the proposed Research Cluster is fully consistent with achieving the long term objectives of the GC proposal, and will provide an ideal vehicle for taking the initial steps in pursuing this Grand Challenge, by developing a specific set of research proposals which contribute to the GC aim *"to use the developing understanding and models of brain function to design and build a succession of increasingly sophisticated architectures, demonstrable as working models of behaviour in either a physical or simulated/virtual environment, meeting carefully selected combinations of requirements. The intention would be that each step will be both achievable and, in itself, a major challenge, capable of pushing forward the frontiers of knowledge.*"

3. Relevance to Beneficiaries

The major benefit deriving from the establishment of the proposed Research Cluster will be the provision of a unique opportunity for a multidisciplinary group of mathematicians, computational neuroscientists, psychologists, computer scientists and neurobiologists to meet and formulate a set of key, three to five year scientific challenges and a set of high quality research proposals to address them.

Ultimately, the outcomes from the research proposals which will emanate from the Research Cluster will provide great benefit to the science, industry and the community generally, as identified, for example, in the Architecture of Mind and Brain Grand Challenge proposal: *new insights into how neuronal processes can mediate high-level cognitive functions, providing the basis for novel intelligent systems and human-computer interfaces; novel paradigms and processes for artificial learning and memory systems based on principles derived from how the brain carries out these functions; novel tools for computational modelling of complex cognitive systems; new insights into the principles underlying information processing in neuronal circuits and systems, leading to novel artificial sensory systems (vision, audition) and speech and language understanding systems, which approach human levels of performance and display similar properties of graceful degradation; the increased possibility of robot-like devices with the cognitive capabilities, to support mobility and care of the aged and the physically challenged.*

4. Justification of Resources

Meeting costs
It is estimated that the travel and subsistence costs of each of the two initial meetings will be, on average, of the order of £600 per participant, ie total of £12K per meeting. To cover the additional meeting costs, eg room hire, a total of £30K is requested for these meetings. The cost of the working group meetings is less easy to predict. Based on five people attending a total of three one-day meetings in each of three working groups, the required travel and subsistence funds are of the order of £12K.
Administrative Support
Support for a part-time (50%) administrator for a period of twelve months is requested, at a cost of £8.5K. Additional support is requested for consultancy costs for setting up and maintaining the cluster web site (£3K). The input of information to the web pages will be managed by the administrator, in close liaison with the PI.
Consumables - Contribution to cost of PC for administrator (£1000)and web server (£1000)

Total requested: £55.5K plus indirect costs.