What can biology teach us about pervasive adaptive systems?
(With a focus on the immune system)

Jon Timmis
Department of Electronics and Department of Computer Science
University of York, UK.
jtimmis@cs.york.ac.uk
http://www-users.cs.york.ac.uk/jtimmis
What are some of the requirements for pervasive adaptive systems?

- Evolvable
- Adjust, self-manage, self-organise
- Be able to respond dynamically to a changing environment
- Need structural plasticity
- Large numbers of components that need to interact / co-operate
  - Complex systems!
- Hardware and software based
What is the Immune System?

A complex system of cellular and molecular components having the primary function of distinguishing self from not self and defense against foreign organisms or substances (Dorland's Illustrated Medical Dictionary)

The immune system is a cognitive system whose primary role is to provide body maintenance (Cohen)

Immune system was evolutionary selected as a consequence of its first and primordial function to provide an ideal inter-cellular communication pathway (Stewart)
An analogy to biology: the immune system

<table>
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<th>Pervasive Adaptive Systems</th>
<th>Immune System</th>
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<tbody>
<tr>
<td>Evolvable</td>
<td>Evolution on two time scales</td>
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<tr>
<td>Adjust, self-manage, self-organise</td>
<td>Can be seen as a maintenance system [Cohen, 2000]</td>
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<tr>
<td>Be able to respond dynamically to a changing environment</td>
<td>Always under attack and always responding</td>
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<td>Structural plasticity</td>
<td>Immune networks constantly adapting - highly plastic</td>
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<td>Large numbers of cooperating components</td>
<td>Vast scale, vast number of interacting agents</td>
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<tr>
<td>Hardware and software based</td>
<td>Wet-ware!</td>
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Immune Learning

- **Antigen Ag₁**
- **Antigen Ag₂**
- **Antigen Ag₁ + Ag₃**

**Time**

**Primary Response**

**Secondary Response**

**Cross-Reactive Response**

**Antibody Concentration**

- **Lag**
- **Response to Ag₁**
- **Response to Ag₂**
- **Response to Ag₁ + Ag₃**

**Lag**

Graph showing the immune system's response to different antigens over time.
Immune Networks

- Maintenance of memory
- Idiotypic network (Jerne, 1974)
- B cells co-stimulate each other
  - Treat each other a bit like antigens
- Creates an immunological memory
- Recent work by Hart and Bersini on the affinity ‘metric’ and the topology of the network show the importance of these in the context of evolving, adaptive networks [Hart et al, 2006]
From Natural to Artificial
Some History

- Developed from the field of theoretical immunology in the mid 1980’s.
  - Suggested we ‘might look’ at the IS
- 1990 – Bersini first to use immune algorithms to solve problems
- Forrest et al – Computer Security mid 1990’s
- Hunt et al, mid 1990’s – Machine learning
- Gained a great deal of pace these past few years
- Started quite immunologically grounded
  - Kind of moved away from that, and abstracted more
- Now there seems to be a move to go back to the roots of immunology
  - Work by Hart and Bersini on immune network modelling starting to give insight into how immune networks evolve [Hart et al, 2006, Hart 2006].
A Quick Example of an Artificial Immune System

Adaptable error detection as a means to improved availability

- Error detection
  - Improved error detection enhances availability
  - Error detection techniques usually exploit known systems profile for detecting error states and behaviour
  - These error detection techniques are limited to the detection of errors known at design-time of systems
  - *Adaptable error detection* is aimed at detecting errors that were not known during the design-time of systems
Challenges then for Immune Inspired Fault Tolerance

- Data representation
  - We settled on M-status
- Minimal number of detectors
  - Have notion of generalised detectors
- Coping with change in the system
  - Require a system that can learn new failures and adapt to create a specific immune system for each ATM
  - Then immunise other machines!
Architecture for Adaptable error detection (AED) in ATMs
Extensible Architectures

- Current EPSRC funded work, developing an extensible architecture for homeostasis for electronic devices
- Based on evolvable hardware
  - A fundamental technology [Tyrrell et al, 2007]
So, what has the immune system taught us?

- There is a natural and simple metaphor between the immune system and pervasive adaptive systems.
- The immune system is a highly adaptive system, scalable, has the ability to cope with multiple data sources, fuses information together, makes decisions, has multiple interacting agents, is totally distributed, operates over multiple time scales, has a memory structure and can learn ...
However, there are some problems
(1) Methodology

realistic biological models

(necessary) extreme simplifications

“Ladybird book” biology

original bio-inspired algorithms

“observe-implement”, + ad hoc parameter tweaking

un-inspired algorithms
Methodology: A Framework for Developing AIS

- Probes, Observations, experiments
- Biological system
- DC activation, T-cell clonality

Simplifying abstract representation
- Analytical framework/principle
- Bio-inspired algorithms
- Analysable, validated systems that fully exploit the underlying biology

Abstract into algorithms suitable for an application

[Stepney et al, 2005]
(2) Multiple interacting systems

- Homeostasis:
  - Ability of an organism to achieve a steady state of operation
- Everywhere in nature
  - Immune system, neural systems, bodies, populations of cells etc etc
- Interactions of immune, neural and endocrine systems: supersystem
Multiple interacting systems

- Artificial immune, neural and endocrine systems
- Have started to bring these together in a computational framework
  [Neal and Timmis, 2003/5]
- Artificial hormones are a powerful metaphor
- Different timescales of responses
Future for immune inspired?

- They will be *embodied*
- They will exhibit *homeostasis*
- They will benefit from interactions between *innate* and *adaptive immune models*
- They will consist of *multiple, heterogeneous interacting communicating components*
- Components can be easily and naturally *distributed*
- They will be required to perform *life-long learning* [Hart and Timmis, 2007]
So …?

- Immune system affords us many ideas for pervasive adaptive systems
- Notion of homeostasis is crucial: Interacting systems
- Each of these systems is a complex system and has their own homeostatic operation
- When they interact, different level of homeostasis
- Different biological metaphors for different aspects of pervasive adaptive systems
- Combination of hardware and software
- There is no *magic bullet* and we need to look at the right biology for the right engineering solution, using a sensible methodology
Acknowledgments/References

- ATM work: NCR plc, Rogerio de Lemos, Modupe Ayara, Adam Knowles, Simon Forrest
- Homeostasis: Mark Neal (Neuro-endocrine), Andy Tyrrell, Andy Greensted
- Applications of AIS: Emma Hart
- EPSRC funded ARTIST network
  - [Tyrrell et al 2007] Evolvable Hardware, a Fundamental Technology for Homeostasis. IEEE Workshop on Evolvable Hardware