SWINBURNE UNIVERSITY OF TECHNOLOGY

Immunology as a Metaphor for Adaptive and Distributed Information Processing

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Complex Intelligent Systems, CITR

Overview

- Motivating the general and specific field of study
  - Artificial & Computational Intelligence
  - Artificial Immune Systems
- Some Methodology & Motivating Biology
- Abstraction and Hierarchical Framework
- Series of Algorithms (Mechanism, Model, Algorithm)
- Proposed Applications, Ongoing Work

Artificial Intelligence (AI)

- AI (A Modern Approach - Russell and Norvig)
  - Systems that think/act like humans
  - Systems that think/act rationally
  - Science Perspective: Understanding Intelligence
- AI (Complex Problem Solving - Luger)
  - Automation of Intelligence
  - A Computer Science with theory, application
  - Engineering Perspective: Solving Hard Problems

Stuart J. Russell and Peter Norvig. *Artificial Intelligence: A Modern Approach*, Prentice Hall, 1995.
George F. Luger and William A. Stubblefield. *Artificial Intelligence: Structures and Strategies for Complex Problem Solving*. USA: Addison Wesley Longman Inc, 1997.

AI: Neat vs. Scruffy

Neat

- Traditional (Good old fashioned AI)
- Problems: Well Defined, Complete, Tractable
- Symbolic
- Top-Down, Optimal
- Features: Propositional Logic, Predicate Calculus, LISP, Prolog, Formal

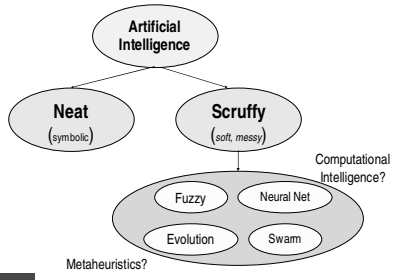
Scruffy

- New Wave (1980's +, fashionable AI)
- Problems: Ill Defined, Incomplete, Intractable
- Non- or Sub-Symbolic
- Bottom-Up, Approximate
- Features: Complex, Emergent, Trial-and-Error, Iterative, Empirical
- I fit in over here

Computational Intelligence (CI)

- Soft- Messy- Scruffy-
  - Computational Intelligence (CI) or *Metaheuristics*
- 'Computers only do what we tell them'
- Focuses on strategies and their outcomes for problem solving
- Typically patterned after biological and natural processes
- Popular subfields:
  - Fuzzy, Connectionist, Evolutionary, Swarm, etc.

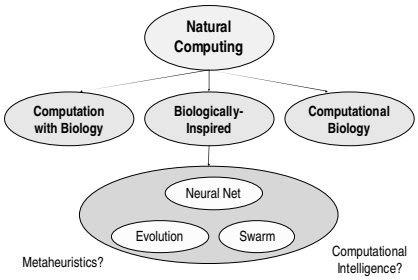
Computational Intelligence (CI)



Natural Computation

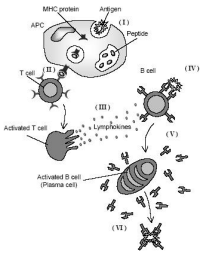
- Interested in CI approaches inspired by biology
- Natural Computation (*nature* ⇔ *computation*)
  - **Computation with Biology**
    - DNA, Quantum Computing, Soap Bubbles, etc
  - **Biologically-Inspired (Motivated) Computation**
    - Overlap with Computational Intelligence
  - **Computational Biology**
    - ALife, Simulations, Synthetic Biology

Biologically-Inspired Computation



The Immune System

- Focus on the mammalian (human) immune system
- The human body is under *constant* attack from pathogens (virus, bacteria, etc)
- Without an immune system, the host dies within days
- Acquired Immune System (vertebrates)
  - Immune cells (lymphocytes) produce proteins (antibodies) that identify and neutralise pathogen
  - Does so without harming the host (mostly)



Picture From: Leandro N. de Castro and Fernando José Von Zuben. Artificial Immune Systems - Part I Basic Theory and Applications [Technical Report]. Brazil, State University of Campinas; 1999 Dec; TR DCA 01/99.

Artificial Immune Systems (AIS)

- Immune System + Scruffy AI = AIS
- Computation inspired by the structure and function of the immune system, directed toward problem solving
- About 15 years old
- Grew from computational (theoretical) immunology
- Computer Science: Natural Computational Metaphor
  - Computer Anti-virus (IBM Research) …autonomic computing
  - Intrusion & Anomaly Detection (UNM, Santa Fe Institute)
  - Classification & Other (HP Labs)

IBM: Antivirus Research, Kephart, et al., http://www.research.ibm.com/antivirus
UNM & SFI: Forrest, et al., http://www.cs.unm.edu/~forrest
HP Labs Bristol: Cayzer, et al., http://www-uk.hpl.hp.com/personal/Steve_Cayzer/ais.htm

AIS: *Why the Immune System?*

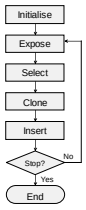
- **Defence** (*base-level*)
  - Pattern Recognition
  - Anomaly Detection
  - Diversity
- **Adaptive** (*AI things...*)
  - Learning
  - Memory
  - Intelligence?
- **Parallel & Distributed** (*interesting things…*)
  - Decentralised
  - Autonomous
  - Self-Organising

AIS: *Problems and Motivation*

- Maybe stuck?
  - Low-level Cell Based Algorithms
  - High-level Metaphor of Antivirus
  - No Quintessential Algorithm-Application
  - New perspective in AIS???
- Failed to exploit parallelism and distributed properties
  - Most popular feature of AIS, yet…
  - No algorithms that are distributed from the ground up
  - No frameworks that consider beyond cell interactions
  - Effectively exploit parallel & distributed qualities???

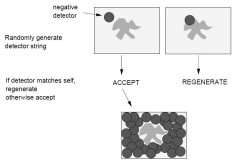
AIS: *Clonal Selection*

- **Theory** (*Burnet 1957*)
  - Initial pseudo-random population of lymphocyte cells
  - Lymphocyte cells are selected for proliferation by antigen
  - High rate of mutation (hypermutation), memory cells, plasma cells
- **Information Processing** (*general learning strategy*)
  - Selectionist (like Darwinian evolution), asexual
  - Make more of what is useful, with blind copying errors
- **Algorithms / Applications**
  - CLONALG (*optimization, pattern recognition, TSP*)
  - B-Cell Algorithm (*optimization*)
  - AIRS (*classification*)



AIS: *Negative Selection*

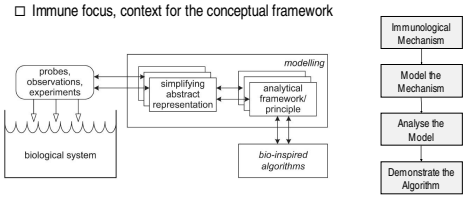
- **Theory** (*Burnet 1957+*)
  - Implication of clonal selection: Self/Nonself Paradigm
  - Preparation and generation of cells that do not match to self
  - Autoimmune cells are destroyed, 'negatively selected'
- **Information Processing** (*change detection strategy*)
  - Problem modelling in the complement space
  - Monitor information stream
- **Algorithms / Applications**
  - Negative Selection Algorithm (*intrusion detection, antivirus*)
  - Variants (*novelty detection, computer security*)



Picture From: Steven A. Hofmeyr and Stephanie Forrest. Architecture for an Artificial Immune System. Evolutionary Computation. 2000 Dec 1; 8(4):443-473.

Methodology: *Conceptual Framework*

- Biological Inspired Algorithms Conceptual Framework
  - Structured process (Stepney, et al.)
- Immunology as Information Processing (Forrest, et al.)
  - Immune focus, context for the conceptual framework



Conceptual Framework Figure From: Susan Stepney, Robert E. Smith, Jonathan Timmis, Andy M. Tyrrell, Mark J. Neal, and Andrew N. W. Hone, Conceptual Frameworks for Artificial Immune Systems *International Journal of Unconventional Computing*, vol. 1, pp. 315-338, Jul, 2005
Immunological Information Processing: Stephanie Forrest and S. A. Hofmeyr. Immunology as Information Processing. In: *Design Principles for the Immune System and Other Distributed Autonomous Systems*, ed. Lee A. Segel, I. R. C. New York: Oxford University Press, 2001.pp. 361-388

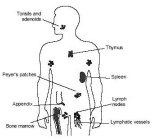
Some Immune Biology…

Biology: *Additional Cell Interactions*

- **Differentiated Cells**
  - Selected cells proliferate and differentiate
  - Different cell casts (naïve cell, effector cell, memory cell)
  - Cell cast influences behaviour (longevity, interaction)
- **Germinal Centres**
  - Three-dimensional pocket of tissue that houses lymphocytes
  - Spatial location where clonal selection takes place
- **Helper T-Cells**
  - B cells are selected by antigen and activated
  - B cells cannot proliferate (and differentiate) without a secondary signal
  - A class of T cells (helpers) mediate B cell response (two signal theory)

Biology: *Lymphatic System*

- Responsible for the cells of the immune system
- **Primary Organs** (*central*)
  - Bone Marrow (B and T cells), Thymus (T cells)
  - Creation of naïve lymphocytes
- **Secondary Organs** (*periphery*)
  - Spleen, lymph nodes, gut-associated tissues, tonsils, appendix
  - Filtering (blood, lymph, food, air), presentation of collected antigen
- **Tertiary Organs**
  - All other non-lymphoid tissues
  - Entry points for pathogen



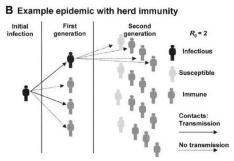
Picture 1 From: C. C. Goodnow. Chance encounters and organized rendezvous. . Immunological Reviews. 1997; 1565-10.
Picture 2 From: Leandro N. de Castro and Fernando José Von Zuben. Artificial Immune Systems - Part I Basic Theory and Applications [Technical Report]. Brazil State University of Campinas; 1999 Dec.TR DCA 01/99.

Biology: *Cell Mobility*

- **Migration**
  - Trafficking of cells from primary to secondary tissues
- **Recirculation**
  - Trafficking of cells around the host via the vascular system
  - Between secondary lymphoid tissues (e.g. lymph nodes)
- **Homing**
  - Return of cells to the tissues where they were generated
  - Imprinting by other cells (dendritic cells) as to the location of infection
- **Recruitment**
  - Sequestration of recirculating cells by infected and inflamed tissues

Biology: *Immunization*

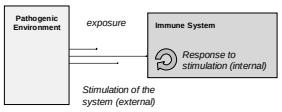
- Immune: acquired resistance to infection
- **Active Immunity** (*slow, long lived*)
  - *Natural*: Infections eliciting an immune response
  - *Artificial*: Inoculation, Vaccination
    - Herd Immunity
- **Passive Immunity** (*fast, short lived*)
  - *Natural*: Maternal Immunity, Mucosal Immunity
    - Protection early in life
  - *Artificial*: Transplant, Antivenom
    - Fast and effective



Picture From: Geoffrey P. Garnett. Role of Herd Immunity in Determining the Effect of Vaccines against Sexually Transmitted Disease. The Journal of Infectious Diseases, 2005; 191 S97-S106.

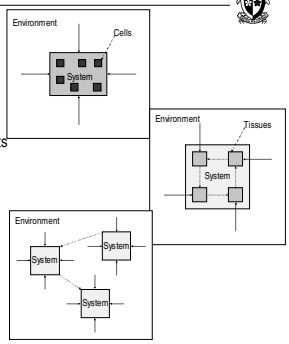
Abstraction: *System-Environment*

- **System**: *Immune Systems*
  - Internal activations (triggered)
  - Learning, Adaptive, Passive acquisition of information
  - Situated, Anticipatory
- **Environment**: *Pathogen Exposures*
  - External triggers, Unknown domain
  - Multiple exposures, Pathogen types, Exposure regimes



Framework: *Hierarchical Perspective*

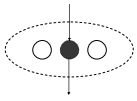
- **Cellular Level**
  - Cell interactions
  - Endogenous, exogenous
- **Tissue Level**
  - Tissues imposing constraints
  - Cell mobility
- **Host Level**
  - Population of systems
  - Immunization



Cellular Level...

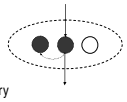
Cellular: *Minimal Clonal Selection*

- **Mechanism**: Clonal Selection Theory
- **Abstraction**:
  - Replication Strategy
  - Hill Climbing (*improvement*)
  - Essence of clonal selection: Winner-Take-All (*clonal dominance*)
- **Algorithm**: Minimal Clonal Selection Algorithm
- **Demonstration**: Optimization, Classification, Pattern Recognition



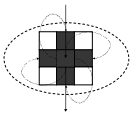
Cellular: *Elaborated Clonal Selection*

- **Mechanism**: Lymphocyte Differentiation
- **Abstraction**:
  - Cellular Densities (*take-over*)
  - Cell Casts as Functional Memory
    - Naïve guess, short term effectors, long term memory
  - Redundancy (*disposability*)
- **Algorithm**: Elaborated Clonal Selection Framework
- **Demonstration**: Proportional Resource Allocation, Improved Optimization & Classification



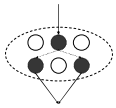
Cellular: *Spatial Clonal Selection*

- **Mechanism**: Spatial Germinal Centres
- **Abstraction**:
  - Spatial population structure (*lattice*)
  - Spatial competition/pressure
  - Spatial responsibility (*winner-take-all*)
  - Topology preservation (*similar info in similar locations*)
- **Algorithm**: Spatial Clonal Selection Algorithm
- **Demonstration**: Feature Extraction, Data Clustering



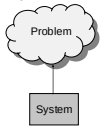
Cellular: *Mediated Response*

- **Mechanism**: Helper T Lymphocytes
- **Abstraction**:
  - Decoupled feature detection and concepts
  - Mediated proliferation (two signals)
  - Higher-order structures concepts
  - Bottom-up feedback (reinforcement of concepts)
- **Algorithm**: Mediated Clonal Selection Algorithm
- **Demonstration**: Supervised Classification, Feature Extraction, Reinforcement Learning (*supervised*)



Cellular Level: *Summary*

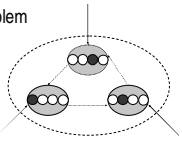
- **What do we have?**
  - A set of algorithms for traditional Machine Learning
    - Optimization, Design, Planning
    - Supervised Classification
    - Unsupervised Feature Extraction / Clustering
- **What is all of this useful for?**
  - Yet another perspective on such problems/methods
  - Foundation for more elaborate immune inspired algorithms



Tissue Level...

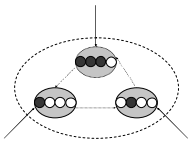
Tissue: *Cell Recirculation*

- **Mechanism**: Recirculation of lymphocytes
- **Abstraction**:
  - Directed graph of information processing centres
  - High frequency migration of small amplitude of information
  - Exploitation and integration of the environment
  - Information dissemination, spatial redundancy
- **Algorithm**: Cell Recirculation Algorithm
- **Demonstration**: Partitioned Problem, Problem Decomposition, Multiple Perspectives



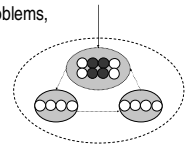
Tissue: *Cell Homing*

- **Mechanism**: Imprinting and Homing of lymphocytes
- **Abstraction**:
  - Recirculation model with preferential residence
  - Returning to the point of creation and/or application
  - Spatial self-organisation, spatial anticipation
- **Algorithm**: Cell Homing Algorithm
- **Demonstration**: Exploit Spatial Consistency in Partitioned Problems



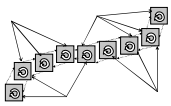
Tissue: *Cell Recruitment*

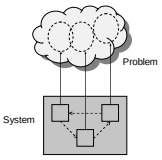
- **Mechanism**: Tissue inflammation and cell recruitment
- **Abstraction**:
  - Triggers as discrete random spatial-temporal events
  - Node inflammation, increased carrying capacity
  - Increase in-flow, decrease out-flow
  - Distributed recruitment, dynamic resource allocation
- **Algorithm**: Cell Recruitment Algorithm
- **Demonstration**: Dynamic Partitioned Problems, Resource Allocation



Tissue Level: *Summary*

- **What do we have?**
  - Parallel Machine Learning
  - Partitioned & Decomposed Problems
  - Consistent, Dynamic Sub-Problems
- **What is all of this useful for?**
  - Partitioned model, integrated solution
  - Larger & Harder Problems (classification, optimization, …)
  - Exploiting Parallel Hardware (cores, processes)

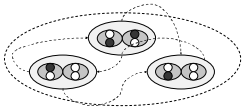




Host Level…

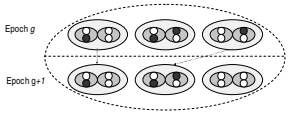
Host: *Vaccination Immunity*

- **Mechanism**: Vaccination and inoculation of hosts
- **Abstraction**:
  - Controlled exposure of systems to domain information
    - Information dissemination
  - Transplantation: small scale (point-to-point)
  - Vaccination: large scale (most systems)
- **Algorithm**: Host Vaccination Algorithm
- **Demonstration**: Parallel Models, Shared Domain/Acquired Information



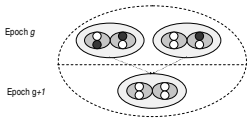
Host: *Maternal Immunity*

- **Mechanism**: Maternal and mucosal immunity
- **Abstraction**:
  - Inter-generational sharing of acquired information (*Lamarckism?*)
  - Seed naïve systems with knowledge fragments
    - Too little: may as well be naïve
    - Too much: may as well be a clone of mature system
- **Algorithm**: Maternal Immunity Algorithm
- **Demonstration**: Naïve Models with Information Seeding



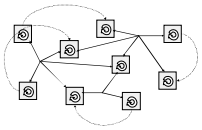
Host: *System Evolution*

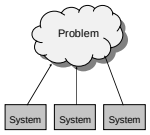
- **Mechanism**: Evolution of hosts by natural selection
- **Abstraction**:
  - Parameterised basis for system traits
    - Base repertoire, arrangement of interfaces, interaction with environment
  - Natural selection, sexual/asexual reproduction with variation
  - Accumulation of adaptive traits + lifetime learning (*Baldwin Effect?*)
- **Algorithm**: Host Evolutionary Algorithm
- **Demonstration**: Naïve Models With Tuning (adaptive model parameters)



Host Level: *Summary*

- **What do we have?**
  - Distributed Machine Learning
  - Multiple Systems
    - Share Domain/Acquired Information
  - Multiple Restarts
    - Seed/Adapt Naïve Models
- **What is all of this useful for?**
  - Exploiting Distributed Hardware (networks)
  - Really Hard Problems (not-decomposable)





Where Are We?

- **Inspiration** (*Acquired Immune System*)
  - Cell Interactions
  - Lymphatic System & Cell Mobility
  - Population Immunization
- **Abstraction** (*System-Environment*)
- **Hierarchical Framework** (*Cells, Tissues, Hosts*)
  - Adaptive, Parallel, Distributed Information Processing Algorithms
  - **Cellular** (machine learning, e.g. optimization and classification)
  - **Tissue** (decomposed problem in parallel)
  - **Host** (multiple distributed systems)

Framework: *Applications*

- Strategies for hard problem instances
  - Optimization, Data Mining, Planning, Scheduling
- **Robot Navigation** (*Autonomous Control?*)
  - Robots with sensors, Integration of signals, Cooperation between fleet
- **Fault Detection** (*Factory Machinery?*)
  - Machines with fault monitors, Integration of signals, cooperation
- **Anomaly Detection** (*Computer Security?*)
  - Network intrusion detection, Share patterns between hosts

Future

- **Ongoing Investigation of Algorithms**
  - Analytical (*economy of models*)
  - Demonstration (*benchmark problem instances*)
- **Application of Algorithms**
  - Domain Studies
  - Comparison to 'state-of-the-art'

The End: Questions?

- **More Information?**
  - My Research Page
  - http://www.ict.swin.edu.au/personal/jbrownlee
    - Or Google "*Jason Brownlee*"
- **Interested In Computational Intelligence?**
  - Free Software Package
  - http://optalgtoolkit.sourceforge.net
    - Or Google "*Optimization Algorithm Toolkit*"