



#### Modelling as a way in design of novel algorithms in computational intelligence

#### Helena Szczerbicka

#### Modelling and Simulation Group Computer Science & Electrical Engineering Faculty Leibniz University of Hannover, Germany

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Contributors to the research

- Martin Drozda
- Sven Schaust
- Matthias Becker

<sup>ise</sup> SIM

Institut für Systems Engineering **Fachgebiet Simulation und Modellierung** Prof. Dr.-Ing. Helena Szczerbicka

11 Leibniz 102 Universität 1004 Hannover



Leibniz Universität Hannover



# Outline

- Motivation
- Methodology for design of bio- inspired algorithms
- Models of Functions of Biological Immune Systems
- Aritficial Immune Systems
- AIS inspired system for survivaliability of adhoc networks



### Motivation Computational intelligence

Computational intelligence is a group of **nature-inspired computational** methodologies and approaches that address complex real-world problems to which traditional approaches, are ineffective or infeasible.

Methods of computational intelligence frequently go beyond the standard models and model their computational algorithms based on non-standard paradigms.

Though the intelligence is usually attributed to humans , here the notion of intelligence is related to the reasoning and decision making



# Motivation

**Computer science** and **biology** have shared a long history together. For many years,

- computer scientists have designed algorithms to process and analyze biological data (e.g. microarrays), and likewise,
- biologists have discovered several operating principles that have inspired new optimization methods (e.g. neural networks).

Recently, these two directions have been converging based on the view that biological processes are inherently *algorithms* that nature has designed to solve computational problems.



#### Motivation Combining paradigms of biology and computer science

- Biologically inspired computing
  - Use of biological metaphors to influence the design of software and hardware in computer systems
  - It aims to capture problem solving strategies observed in nature for use in engineering systems
- Computational biology
  - Use of computing tools and methods to model and simulate biological systems
  - It aims to understand the biological system

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<u>Algorithms in nature: the convergence of systems biology and computational thinking.</u> S. Navlakha and Z. Bar-Joseph. Nature-EMBO Molecular Systems Biology, 7:546, 2011.



# Motivation

Traditional studies versus computational thinking.

(A)Traditionally,

- biologists leveraged computing power to analyze and process data (e.g., hierarchically clustering gene expression microarrays to predict protein function), and
- computer scientists used high-level design principles of biological systems to motivate new computational algorithms (e.g., neural networks).

Rarely these two directions were coupled and mutually beneficial.

(B) By thinking computationally about how biological systems process we can develop improved models and algorithms *and* provide a more coherent explanation of how and why the system operates as it does.



# **Motivation**

**Parallels** between computational and biological systems.

- (A) Biological and computational systems often coordinate and maintain functionality **without relying on a central controller**.
- (B)Networks are often the medium through which processes spread, either on the Web or in the cell.
- (C)Modularity is a common design principle in programming languages and also serves as the basis for increasing complexity and flexibility in evolving systems.
- (D)Stochastic processes in computational and biological settings help to remain robust in constrained, noisy environments.



#### Motivation : Examples of *biological systems* and their analog computational problems.



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# **Motivation**

Bidirectional studies have led to insights into

- how biological systems operate,
- while at the same time advancing computational methods.
- These studies have explored
- (A) coordination aspects
- (B) network design principles
- (C) vision problems



# Motivation

Example: Slime Mold (*Physarum polycephalum*)

What could engineers possibly learn from the slime mold?

Reliable, robust, cost-efficient computer and mobile communication network construction

Japanese and British researchers observed that the slime mold connected itself to scattered food sources in a design that was nearly identical to Tokyo's rail system. *Science* on Jan. 22, 2010

Inspired by this observation we have developed algorithms for design of reliable, fault tolerant networks

Becker, Matthias and Helena Szczerbicka; A Simulation Model of Dictyostelium Discoideum for the Study of Evolutionary Selection Mechanisms. In Intern. Journal 'Cybernetics and Systems', Volume 42, No 2, pp.68-81 (14), Taylor and Francis, February 2011





# network formation in Physarum polycephalum.



Food sources at each of the major cities in the region

Plasmodium of Physarum placed at the location of Tokyo (white border : the Pacific coastline )

Behind the growing margin, the spreading mycelium resolved into a network of tubes interconnecting the food sources. Image courtesy of Science/AAAS



#### Methodology for developement of natureinspired systems

Basic rules:

- Avoid the "reasoning by metaphor" approach often seen in bio-inspired computing, whereby algorithms are just a weak analogy of the process on which they are based, being developed directly from (often naive) biological models and observations.
- Decide which aspects of the biology are
  - necessary to generate the required behavior
  - Surplus to requirements
- Develop models of the behavior reflecting that characteristics
- Map these models to computational framework



# Methodology

Interdisciplinary approach involves:

- Observations
- Modelling

of the biological process in order to

- Identify the key characteristics for the bio-inspired Algoritm
- Engineering a computational algorithm



## Example

Key characteristics specific to some computational intelligence methodologies :

- Artificial Neuronal Networks : system identification, learning, generalization, local search, adaptation
- Evolutionary Algorithms : systematized search, tuning, optimization
- Probabilistic Reasoning : decision analysis, management of uncertainty





## Conceptual framework for a methodology of developing bio-inspired systems



Stepney, S., Smith, R., Timmis, J., Tyrrell, A., Neal, M., Hone, A.: Conceptual frameworks for artificial immune systems. Int. J. Unconventional Computing, 1(3), 315–338 (2006)



# Methodology

Approach to a framework for **engineering** of natureinspired Algorithms:

- **Representation** of the components of the system
- Set of mechanisms to evaluate the interaction of individuals: each other and with the environment
- Procedures of adaptation for the generation of the behavior of the system over time.

de Castro, L.N., Timmis, J.: Artificial Immune Systems: A New Computational Intelligence Approach. Springer (2002)



### **Biological Immune Systems**

The **immune system** is a defense system that has

evolved to **protect its host** from pathogens (harmful micro-organisms such as bacteria and viruses)

The immune system is able to rapidly

- detect, recognize and respond to variety of invading organisms.
- It contains elements that are immediately effective against commonly seen patterns (innate immunity) and elements that are capable of responding to novel invaders (adaptive immunity).

Characteristics

- rapid recognition of a pathogen,
- amplification of the response, and
- subsequent mitigation of the infection.



#### Biological Immune System classical view

The discriminating agent is an individual cell, not the system of cells.



# Biological Immune Systems a non classical view

Cohen makes an analogy of biological immue systems to a Turing machine that transfers a sequence of information (input) to output according to set of rules. On that way the immune system *computes a state* of the organism. He also extends the role of immune systems to *maintaing the health* of the body.

- *Body maintenance* is achieved by selection and regulation of inflammatory responses according to the current *conditions*.
- *Condition* is assessed by innate and adaptive immune cells
- Specificity of response is result of a complex diagnosis of the situations and the *evocation of a suitable response* is not just the discrimination of danger, or the distinction of self-non-self.



# **Biological Immune System**

Computationally inspiring properties of biological immune systems

- pattern recognition
- Learning
- memory
- self-organisation

How do immune systems achieve the protection of the host organism?





### Models of Functions of Biological Immune Systems

BIS comprises a variety of specialized cells and molecules along with immune organs that provide a place for the immune cells to mature and function

#### Immune Vocabulary

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- Pathogens (harmful micro-organisms such as bacteria and viruses) & their antigens
  - Antigen Presenting Cells
  - Inflammatory signals, messenger proteins (cytokines & chemokines)
  - Immune agents (macrophages, dendritic cells, T-/B-cells...)
  - **R**eceptors
  - Ligands
  - Epitopes



Components of the immune system. Image sourced from http://nobelprize.org/medicine/ laureates/1996/illpres/introduction.html



# **Elements of Innate Immunity**

It incorporates general pathogen defence mechanisms that remain unchanged during the lifetime of an individual . These mechanisms include the inflammatory response, phagocytosis (ingestion of pathogens by specialised immune cells), and physiologic barriers such as temperature

Macrophages: First contact with pathogens. Encloses the foreign cell and mobilizes additional immune cells. Dendritic cells: Upon contact with pathogen activation and differentiation into APC or mature DC -> stimulates adaptive system.

**Inflammatory signals**: Cytokines and chemokines activate and attract immune cells.





# **Elements of Adaptive Immunity**

Is able to recognise previously unseen pathogens (learning) and remember them for future encounters (memory).

Lymphatic system: Transport network of tissues and vessels. ->Lymph nodes B-cells: Recognize pathogens without APC. Able to produce antibodies T-cells: Recognize pathogens with APC help. Activation and proliferation into different function types -> killer-, helper-, regulatory-, memory- T-cells.





# **Elements of Adaptive Immunity**

- T-cells, along with B-cells: main actors of the adaptive immune system.
- Places of maturation : thymus and bone marrow,
- B and T-cells are called lymphocytes.
- Lymphocytes are the only cells that produce antigen receptors, with each lymphocyte producing an *antigen receptor that differs from all others.*
- receptors of B-cells are called antibodies,
- receptors of T-cells are called T-cell receptors (TCR).





# **Adaptive Immunity**

Adaptive immune responses rely on the continuous selection and amplification of specific *clones* from an enormous library of *immune receptors (antibodies and T cell receptors).* 

Stimulation of B-cell immunity results in the synthesis of antibodies that are secreted into the blood stream or into the mucosa as well as the programming of B memory cells that play a crucial role in n the generation of rapid protective responses upon reinfection.

The adaptive immune system confers protection by generating a diverse repertoire of antibody receptors that are rapidly expanded and contracted in response to specific targets.



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## Most popular theories explaining how BIS work

#### pattern recognition

- Receptors generation: via a stochastic process utilising gene libraries to provide a big repertoire of receptors
  - In order to bind with antigens receptors have to present a particular shape, that will be matched by the (complementary) shape of the antigen
  - Recognition is based on shape complementarity.
- Binding the receptor with an antigen triggers the immune response



ISE



## Most popular theories explaining how BIS work

#### **Basic mechanism: Negative selection**

Main mission of the immune system

The classification of antigens as either self or non-self Requirement: an **absence of any self reacting** lymphocytes

- negative selection: mechanism on lymphocytes during maturation. The immature T cells that strongly bind self antigens undergo a controlled death.
- Surviving T cells are unreactive to self antigens

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### Most popular theories explaining how BIS work Clonal selection

**Clonal selection** is central to **adaptive immunity as a** part of efficient Self-non-self discrimination .

- Once activated (successful binding it's antibody), a B cell clones expressing identical receptors to the original. Thus a clonal expansion occures.
- Lymphocytes bearing receptors specific to ubiquitous self molecules are deleted at an early stage in a cell development.( clonal deletion). It prevents randomly generated lymphocyte receptors from being equal to the body 's own molecules.

Burnet, F.M.: The Clonal Selection Theory of Acquired Immunity. Cambridge, University Press (1959)



### Most popular theories explaining how BIS work

## **Clonal Selection**

- **Affinity:** degree of binding of the cell receptor with an antigen. The higher affinity the better the immune recognition and immune response
- During the clonal expansion the average antibody **affinity** for the antigen that triggered the clonal expansion is **increasing**. (**affinity maturation**)
- Affinity maturation is a result of the hypermutation mechanism proportional to the affinity binding. The higher the affinity, the less mutation it suffers. After the mutation, B cells with higher affinity are selected to differentiate into memory cells

#### →the average population affinity of antibodies increases

*Burnet, F.M.: The Clonal Selection Theory of Acquired Immunity. Cambridge, University Press* (1959)



#### Most popular theories explaining how BIS work

#### **Clonal selection problem**

- T<sub>H</sub> cells control the decision whether or not initiate immune response
- This decision is achieved through the deletion of the selfreacting lymphocytes, so that responses will only be initiated *against non-self*.
- however, that T<sub>H</sub> cells themselves require a *co-stimulatory* signal from non-antigen specific APCs in order to initiate an effective adaptive immune response.
- →it could not be assured that immunity only be directed against non-self,



#### Most popular theories explaining how BIS work

#### **Danger Theory**

- The danger theory explains the immune response mechanism and states that APCs (Antigen Presenting Cells e.g. dendritc cells, that can be recognized by T<sub>H</sub> killer cells) are themselves activated via an alarm: danger signals.
- Activated APCs are able to provide the necessary co-stimulatory signal to the TH cells that subsequently control the adaptive immune response
- The danger signals are emitted by ordinary cells of the body that have been injured due to attack by pathogen.
- Dendritic cells integrate the danger signal along with safe signals to make a decision about the safety and stimulating  $T_H$  cells ( in the process of costimulation), that control adaptive immune response

Matzinger, P.: The danger model: A renewed sense of self. Science 296, 301–305 (2002)



# **Danger Theory**

- Danger Theory blurs the distinction between the adaptive and innate arms of the immune system as the adaptive immune response is itself controlled by the action of innate immune cells
- The notion of self-non-self discrimination is replaced with a danger-non-danger metaphor, whereby foreign non-self no longer necessarily initiates an immune response





#### Most popular theories explaining how BIS work Immune response



The innate and adaptive immune systems are tightly interconnected. **Stimulation** and **co-stimulation** occur frequently



## **Immune Networks theory**

It provides a view on a immune system as a regulated network of mollecules and cells that recognize each other producing a self-organising behavior, even in absence of an antigen. The perturbation to the network causes an occurrence of the immune response.

• The biological evidence for immune networks is not strong

Jerne, N.K.: Towards a network theory of the immune system. Ann. Immunol. (Inst. Pasteur) 125C, 373–389 (1974)



# **Modelling Immune Systems**

Modelling plays an important role in the understanding how the immune system computes

- Agent Based Modelling (ABM) as a tool where cells are represented as individual agents, rather (as in the more traditional differential equations) than as a population of cell types. Agent that encoded with simple rules that govern its behaviors and interactions.
  - One difficult aspect of ABM is defining the right level of abstraction for each agent in the model, as this will affect how the simulation operates.
- state charts first proposed by Harel as a mechanism for representing computational processes by means of states and events that cause a transition between states.
- o-o modelling using simple UML class and state diagrams of a clonal selection model. This technique is capable to encapsulate certain design information easily, but also to isolate functionality within the model.

Forrest, S., Beauchemin, C.: Computer Immunology. Immunol. Rev. 216(1),176–197 (2007)



# **Modelling Immune Systems**

- Mathematical models based on differential equations( a selection)
  - Idiotypic networks: a simplistic model to simulate the

immune system which ignores the effect of T-cells and of macrophages in an attempt to capture the essential characteristics of the immune network. Central to the approach is the **calculation of the dynamics of B-cell population** related to a B-cell's stimulation level.

 Aritficial Cytokine Networks: dynamical model for the interaction of cytokines (small proteins in cell signalling)and immune cells.



# **Modelling Immune Systems**

#### Computational Modelling:

- $\pi$ -calculus, a formal stochastic language used to specify concurrent computational systems.
- Its more intuitive version , the  $\text{GS}\pi$  calcule graphical specification represents a model as a graph .

*Phillips, A., Cardelli, L.: Efficient, correct simulation of biological processes in the stochastic pi-calculus. In: Proceedings of Computational Methods in Systems Biology (CMSB'07), vol. 4695, pp. 184–199 (2007)* 



# **Artificial Immune Systems**

AIS has become an area of **computer science and engineering** that uses **immune system metaphors** for the creation of **novel solutions to problems.** 

AIS are more than engineered systems inspired by immunology.

They are an interdisciplinary result of immunology and engineering working together.

They are developed through the application of following techniques

- mathematical and computational modeling of immunology,
- abstraction from those models into algorithm /system design and
- implementation in the context of engineering.



#### Engineering AIS Systems according to the previously described Methodology

Approach to a framework for **engineering** of natureinspired Algorithms:

- **Representation** of the components of the system
- Set of mechanisms to evaluate the interaction of individuals: each other and with the environment
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#### Representation

- L dimensional Shape Space S containing cell receptors. Properties of a receptor molecule are described by a set of L parameters.
  - Representation of a cell receptor can be an attribute string or any other structure.
    - Real-Valued Shape Space: attributes of all the components are real numbers
    - Hamming Shape Space: attributes of all the components are from a finite alphabet
    - Symbolic Shape Space: attributes can be of any type, including symbols such as age and name.
  - frequently used representation is binary
- $V \subset S$  Represents a N dimensional set of antigens
- A Distance in the Space S represents the measure of affinity (degree of binding between an antigenic receptor and an antibody).
- $\mathcal{E}$  an afinity treshold,  $V_{\mathcal{E}}$  a recognition region



Set of Mechanisms evaluation interactions

- Affinity measures
  - For binary strings frequently used distance measures are Hamming distance and r-contiguous measuring the number of complementary bits



Immune algorithms Procedures for generating the behavior

• Bone Marrow Model: generation of the initial population

#### • Negative selection:

Negative selection algorithms are inspired by the main mechanism in the thymus that produces a set of mature T-cells capable of **binding only non-self antigens.** 

- The **starting point** of this algorithm is to produce a set of self strings, S, that define the **normal state** of the system.
- Next step is **to generate a set of detectors, D**, that only bind/recognise the complement of S.
- These detectors can then be applied to **new data in order to classify** them as being self or nonself,

Forrest, S., Perelson, A., Allen, L., Cherukuri, R.: Self–nonself discrimination in a computer. In: Proceedings of the IEEE Symposium on Research Security and Privacy, pp. 202–212 (1994)



# **Engineering AIS Systems**

#### **Negative Selection**

Input: set of **known self** elements Output: **D** set of generated **detectors** 



Forrest, S., Perelson, A., Allen, L., Cherukuri, R.: Self–nonself discrimination in a computer. In: Proceedings of the IEEE Symposium on Research Security and Privacy, pp. 202–212 (1994)



# **Engineering AIS Systems**

Positive selection





#### **Engineering AIS Systems** Clonal Selection

- Each B-cell is a n-dimensional bit vector.
- Characteristics:
  - Uses adaption, cloning, improved mutation.
  - the proliferation of B-cells is proportional to the affinity of the antigen that binds it, thus the higher the affinity, the more clones are produced.
  - the **mutations** of the antibody of a B-cell are **inversely** proportional to the affinity of the antigen it binds.
  - Each candidate solution has an independent mutation rate → contiguous somatic hypermutation
  - Randomly selects a start point of a contiguous region with random length for mutation
  - Evaluation of each clone by a fitness function



**Clonal Selection Algorithm** 

- input : S = set of patterns to be recognised, n the number of
  worst elements to select for removal
- **output:** M = **set of memory detectors** capable of classifying unseen patterns

begin

Create an initial random set of antibodies, A

for all patterns in S do

- Determine the affinity with each antibody in A
- Generate clones of a subset of the antibodies in A with the highest affinity. The number of clones for an antibody is proportional to its affinity
- Mutate attributes of these clones inversely proportional to its affinity.
- Add these clones to the set A,
- place a copy of the highest affinity antibodies in A into the memory set, M
- Replace the n lowest affinity antibodies in A with new randomly generated antibodies

end

end



#### Engineering AIS Systems Co-Stimulation Algorithm

#### Characteristics

- Based on the co-stimulation of immune agents.
- Focus on energy efficient detection with few false positives.
- 2-phase approach with decision tree classifiers
- Uses two disjunct network features sets  $\mathsf{F}_0$  and  $\mathsf{F}_2$ 
  - F<sub>0</sub> based on watchdogs
  - F<sub>2</sub> based on 2-hop observations
- high detection rate, low false alarm, low computational complexity

Martin Drozda, Sven Schaust, and Helena Szczerbicka.

AIS for Misbehavior Detection in Wireless Sensor Networks: Performance and Design Principles. Computing Research Repository (CoRR), 2009



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#### Engineering AIS Systems Co-Stimulation Algorithm





## Summary

- Some methodological considerations regarding engineering of Nature Inspired Algorithms in the frame of Computational Intelligence Paradigms have been presented
  - Especially we focused on a general framework for design of nature- inspired algorithms
- In particular we have discussed Artificial Immune Systems that constitute a novel computational intelligence paradigm inspired by the biological immune system, applied to solve to solve optimization and classification problems in different domains, due to their capability in identifying self and non self samples