Engineering Applications of Artificial Immune Systems

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Bioinformatics and Bio-Inspired Computing Laboratory

Natural Computing Lab

Topics

- Engineering Problems and Their Challenges
- Examples of Engineering Problems
- Engineering Applications of AIS: Brief Survey from the Literature
- Examples of Engineering Applications of AIS from our Research Labs
- Discussion

Part I

Engineering Problems and Their Challenges

Engineering Problems

- Real-World Problems
- An imprecise and incomplete classification:
  - Pattern Recognition and Classification
  - Machine Learning
  - Data Mining
  - Search and Optimization
  - Robotics
  - Control
  - Industrial Applications

Engineering Problems

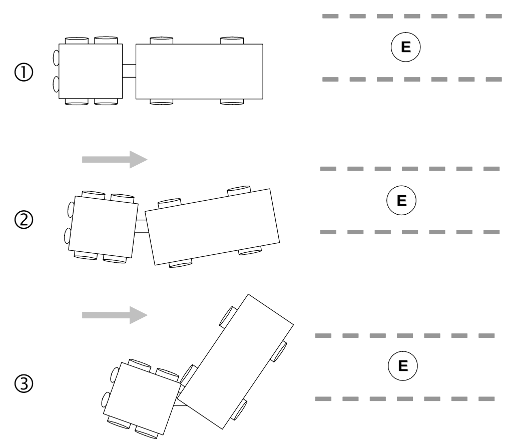
- Some Common Features:
  - Difficulty in modelling
  - Poorly defined
  - Dynamic environments
  - Large number of variables
  - Missing or noisy variables (attributes)
  - Highly nonlinear
  - Difficulty in finding derivatives
  - Combinatorial solutions (NP-Complete/NP-Hard)

Part II

Examples of Engineering Problems

Examples of Engineering Problems

- Non-Linear Control

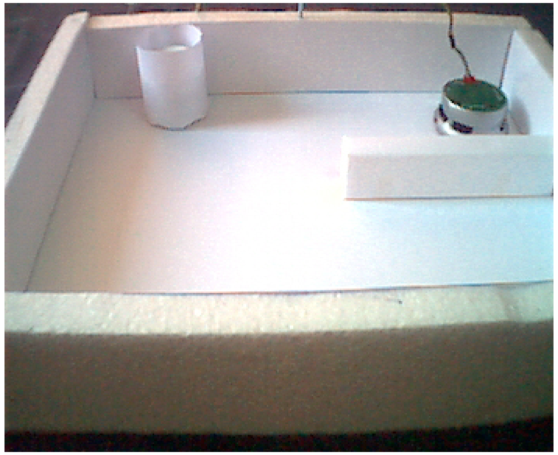


Examples of Engineering Problems

- Pattern Recognition

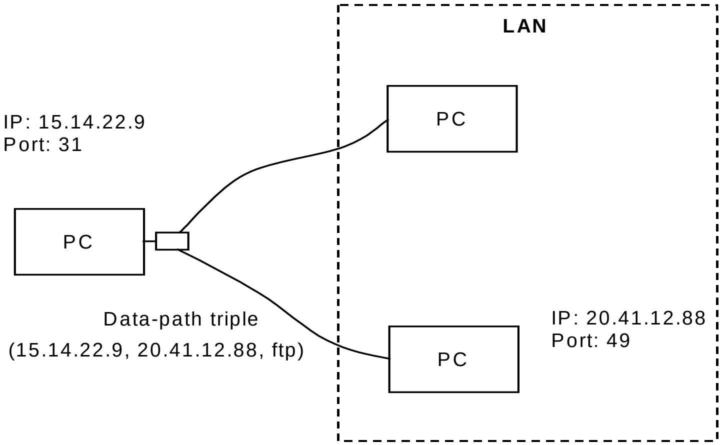
Examples of Engineering Problems

- Autonomous Navigation



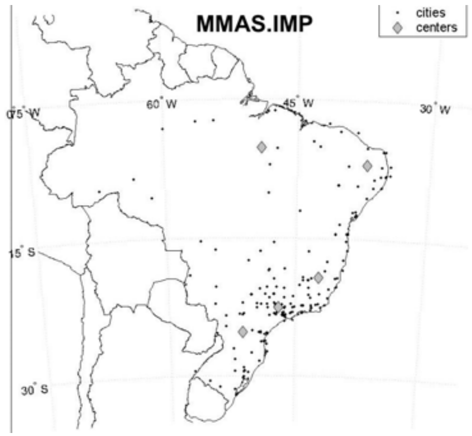
Examples of Engineering Problems

- Anomaly Detection



Examples of Engineering Problems

- Scheduling



Part III

Engineering Applications of AIS:
A Brief Survey from the Literature

Engineering Applications of AIS: Brief Survey from the Literature

- Pattern Recognition and Classification / Machine Learning / Data Mining:
  - Spectra Recognition
    - Dasgupta et al., 1999
  - Surveillanve of Infectious Diseases
    - Tarakanov et al., 2000
  - Medical Data Analysis
    - Carter, 2000
  - Virus Detection and Elimination
    - Kephart, 1994
    - Somayaji et al., 1997
    - Okamoto & Ishida, 1999
    - Lamont et al., 1999

Engineering Applications of AIS: Brief Survey from the Literature

- Pattern Recognition and Classification / Machine Learning / Data Mining:
  - Computer and Network Security
    - Kephart, 1994
    - Hedberg, 1996
    - Kim & Bentley, 1999
    - Dasgupta, 1999
    - Gu et al., 2000
    - Hofmeyr & Forrest, 2000
    - Skormin et al., 2001
    - Anchor et al., 2002
    - Dasgupta & González, 2002
    - Wang & Hirsbrunner, 2002
    - de Paula et al., 2004

Engineering Applications of AIS: Brief Survey from the Literature

- Pattern Recognition and Classification / Machine Learning / Data Mining:
  - Time Series Data
    - Dasgupta & Forrest, 1996
  - Image Processing and Inspection
    - Aisu & Mizutani, 1996
    - McCoy & Devarajan, 1997
    - Sathyanath & Sahin, 2001
    - Bendiab et al., 2003
  - Web Mining
    - Lee et al., 2003
    - Secker et al., 2003
    - Oda & White, 2003

Engineering Applications of AIS: Brief Survey from the Literature

- Pattern Recognition and Classification / Machine Learning / Data Mining:
  - Fault (Anomaly) Detection
    - Ishida, 1990
    - Kayama et al., 1995
    - Xanthakis et al., 1996
    - D'haeseleer et al., 1996
    - Bradley & Tyrrell, 2000
    - Shulin et al., 2002
    - Taylor & Corne, 2003
    - González et al., 2003
    - Esponda et al., 2003
    - Kaers et al., 2003
    - Araujo et al., 2003
    - Branco et al., 2003

Engineering Applications of AIS: Brief Survey from the Literature

- Pattern Recognition and Classification / Machine Learning / Data Mining:
  - Learning
    - Watkins, 2001
    - Hunt & Cooke, 1996
    - Hightower et al., 1996
    - Potter & de Jong, 1998
    - Bersini, 1999
    - Nagano & Yonezawa, 1999
    - Timmis & Neal, 2000
    - de Castro & Von Zuben, 2000a
    - Watkins et al., 2004

Engineering Applications of AIS: Brief Survey from the Literature

- Pattern Recognition and Classification / Machine Learning / Data Mining:
  - Associative Memory
    - Gibert & Routen, 1994
    - Abbattista et al., 1996
  - Recommender System
    - Cayzer & Aickelin, 2004
  - Inductive Problem Solving
    - Slavov & Nikolaev, 1998
  - Bankruptcy Prediction
    - Cheh, 2002

Engineering Applications of AIS: Brief Survey from the Literature

- Pattern Recognition and Classification / Machine Learning / Data Mining:
  - Clustering/Classification
    - Nicosia et al., 2001
    - Timmis, 2001
    - de Castro & Timmis, 2002
    - Neal, 2002
    - Zhao & Huang, 2002
    - Greensmith & Cayzer, 2003
    - Ceong et al., 2003
    - Di & Xuefeng, 2003
    - Nasaroui et al., 2002, 2003

Engineering Applications of AIS: Brief Survey from the Literature

- Pattern Recognition and Classification / Machine Learning / Data Mining:
  - Bioinformatics
    - Recognition of promoter sequences: Cooke & Hunt, 1995
    - Protein structure prediction: Michaud et al., 2001
    - Spectra classification: Lamont et al., 2004
    - Gene expression data analysis: Bezerra & de Castro, 2003; Shin, 2003
    - Analysis of biological systems: Roy et al., 2002
    - Bioarrays: Tarakanov et al., 2002

Engineering Applications of AIS: Brief Survey from the Literature

- Search and Optimization:
  - Numerical Function Optimization
    - Mori et al., 1993
    - Bersini & Varela, 1990
    - Chun et al., 1998
    - Huang, 2000
    - Gaspar & Hirsbrunner, 2002
    - de Castro & Von Zuben, 2002
    - de Castro & Timmis, 2002
    - Hong & Zong-Yuan, 2002
    - Walker & Garrett, 2003

Engineering Applications of AIS: Brief Survey from the Literature

- Search and Optimization:
  - Constrained Optimization
    - Hajela & Yoo, 1999
  - Inventory Optimization
    - Joshi, 1995
  - Time Dependent Optimization
    - Gaspar & Collard, 2000
  - Others
    - Mori et al., 1997, 1998
    - Huang, 2000

Engineering Applications of AIS: Brief Survey from the Literature

- Search and Optimization:
  - Combinatorial Optimization
    - Mori et al., 1998
    - Endoh et al., 1998
    - Toma et al., 1999
    - Hart & Ross, 1999
    - King et al., 2001
    - Cui et al., 2001
    - Costa et al., 2002
    - Coello Coello et al., 2003
    - Cutello et al., 2003
    - Koko et al., 2003

Engineering Applications of AIS: Brief Survey from the Literature

- Robotics:
  - Autonomous Navigation
    - Watanabe et al., 1999
    - Michelan & Von Zuben, 2002
    - Hart et al., 2003
    - Vergas et al., 2003
    - Canham et al., 2003
  - Collective Behavior
    - Mitsumoto et al., 1996
    - Lee & Sim, 1997
  - Walking Robots
    - Ishiguro et al., 1998

Engineering Applications of AIS: Brief Survey from the Literature

- Control:
  - Identification, Synthesis and Adaptive Control
    - Bersini, 1991
    - Ishida & Adachi, 1996
    - Krishnakumar & Neidhoefer, 1999
    - Ding & Ren, 2000
    - Kim, 2001
    - Lau & Wong, 2003
  - Sequential Control
    - Ootsuki & Sekiguchi, 1999
  - Feedback Control
    - Takahashi & Yamada, 1997

Engineering Applications of AIS: Brief Survey from the Literature

- The references from this brief and incomplete survey can be found at:
  - www.dca.fee.unicamp.br/~lnunes/AIS.html
- An extensive and constantly updated bibliography on AIS can be found at:
  - http://ais.cs.memphis.edu/papers/ais_bibliography.pdf

Part IV

Examples of Engineering Applications of AIS from Our Labs

Examples of Engineering Applications of AIS from our Labs

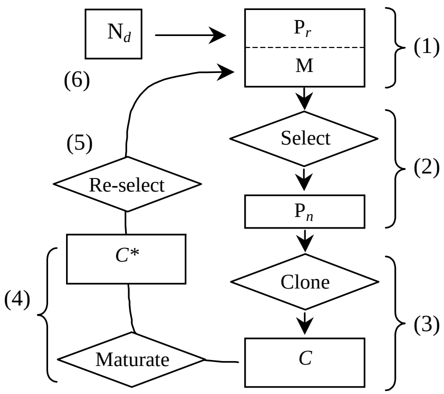
- Search and Optimization
  - Multimodal search
  - Dynamic environments*
  - Blind equalization
- Pattern Recognition and Classification
  - Classification and clustering
  - Detection of buffer overflow attacks

Examples of Engineering Applications of AIS from our Labs

- Machine Learning
  - Neural network initialization
  - Neural network training*
  - Hybrid neural networks
- Robotics
  - Autonomous navigation
- Bioinformatics
  - Gene expression data analysis

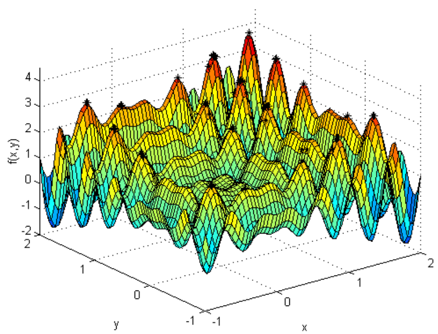
Search and Optimization

- Multimodal Search
  - CLONALG (de Castro & Von Zuben, 2002)

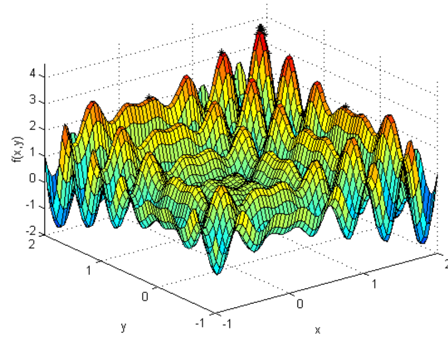


Search and Optimization

- Multimodal Search
  - CLONALG (de Castro & Von Zuben, 2002)



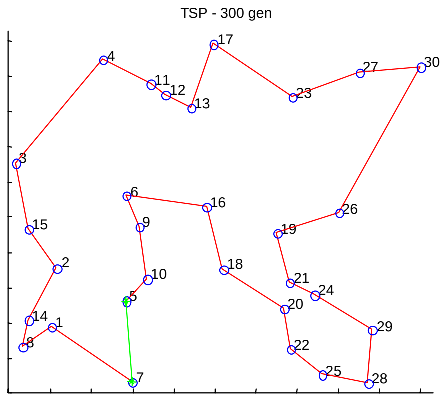
CLONALG



Standard GA

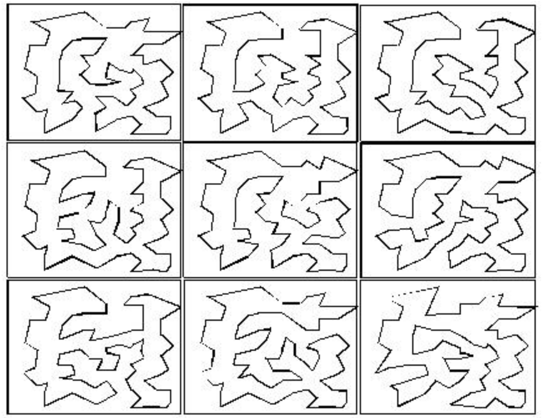
Search and Optimization

- Combinatorial Search
  - CLONALG (de Castro & Von Zuben, 2002)



Search and Optimization

- Combinatorial Search
  - Copt-aiNet (de Sousa et al., 2004)



Search and Optimization

- CLONALG (de Castro & Von Zuben, 2002)

DEMO 1: CLONALG

Search and Optimization

- Multimodal Search
  - opt-aiNet (de Castro & Timmis, 2002)
  - The algorithm for opt-aiNet is an adaptation of a discrete artificial immune network usually applied in data analysis
  - Features of opt-aiNet:
    - population size dynamically adjustable
    - exploitation and exploration of the search-space
    - capability of locating multiple optima
    - automatic stopping criterion

Search and Optimization

- Multimodal Search
  - opt-aiNet (de Castro & Timmis, 2002)

1. Initialize population (initial number not relevant)
2. **While** not [constant memory population], **do**

2.1 Calculate fitness and generate clones for each network cell.

2.2 Mutate clones proportionally to fitness and determine the fitness again.

2.3 Calculate the average fitness.

2.4 If average fitness does not vary, then continue. **Else**, return to step 2.1

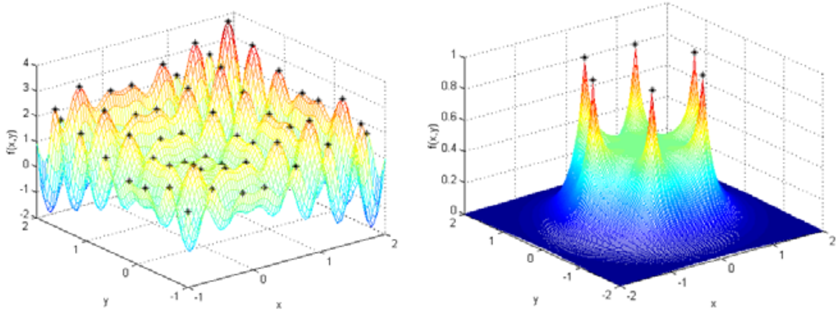
2.5 Calculate the affinity among cells and suppress all but one whose affinities are less than the suppression threshold σ_s and determine the number of network cells after suppression.

2.6 Introduce a percentage of randomly generated cells and return to step 2.

3. EndWhile

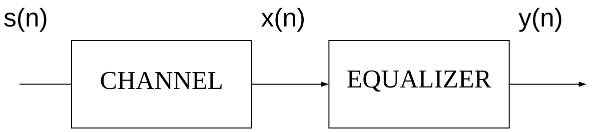
Search and Optimization

- Multimodal Search
  - opt-aiNet (de Castro & Timmis, 2002)



Search and Optimization

- Communications Engineering
  - Search for the optimal Wiener equalizer
  - opt-aiNet (Attux et al., 2003)
- Optimal Wiener Equalizer
  - y(n) = $\mathbf{w}^T.\mathbf{x}(n)$
  - $J_W = E\{[s(n-d) - y(n)]^2\}$



Search and Optimization

- Optimal Wiener Equalizer
  - The Constant Modulus (CM) criterion is used for blind equalization
  - To find the CM global optimum is equivalent to deterning the optimal Wiener solution (best equalizer)
  - CM results in a multi-modal problem
  - $J_{CM} = E\{[R_2 - |y(n)|^2]^2\}$

$$R_2 = \frac{E\left[\,|s(n)|^4\right]}{E\left[\,|s(n)|^2\right]}$$

Search and Optimization

- Optimal Wiener Equalizer via CM Search
- Sample performance
  - $H_{C1} = 1 + 0.4z^{-1} + 0.9z^{-2} + 1.4z^{-3}$

Solution	MSE	Freq. (GA+niching)	Freq. (opt-aiNet)
$\mathbf{W}_{opt}$	0.1293	48 %	82%
$\mathbf{W}_2$	0.1397	22 %	17%
$\mathbf{W}_3$	0.1445	12 %	1 %
$\mathbf{W}_4$	0.1533	10 %	-
$\mathbf{W}_5$	0.1890	4 %	-
$\mathbf{W}_6$	0.1951	4 %	-

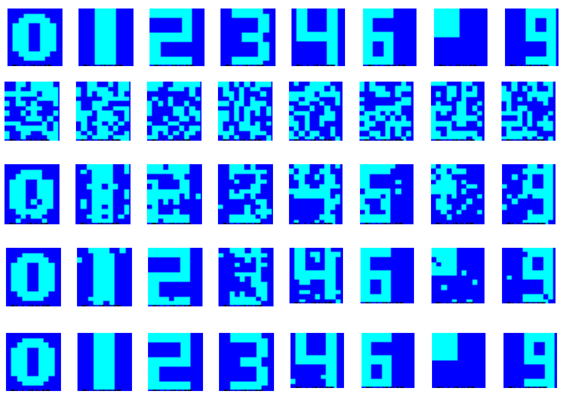
Search and Optimization

- opt-aiNet (de Castro & Timmis, 2002)

DEMO 2: opt-aiNet

Pattern Recognition

- Classification and Clustering
  - CLONALG (de Castro & Von Zuben, 2002)



(a) Input patterns
(b) 0 generations
(c) 50 generations
(d) 100 generations
(e) 200 generations

Pattern Recognition

- Classification and Clustering
  - aiNet (de Castro & Von Zuben, 2000)
  - Definition:
    - aiNet is an *edge-weighted graph*, not necessarily fully connected, composed of a set of nodes and sets of node pairs with a weight assigned specified to each connected edge.
  - Features:
    - knowledge distributed among cells
    - competitive learning (unsupervised)
    - constructive model with pruning phases
    - generation and maintenance of diversity

Pattern Recognition

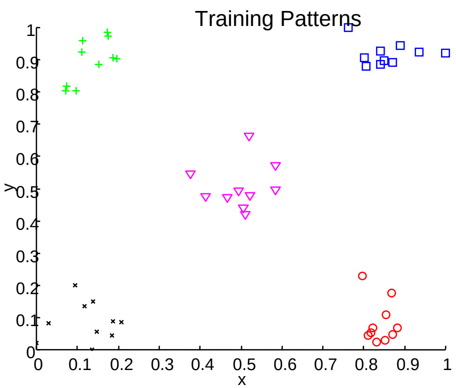
- aiNet:
  - Growing:
    - clonal selection principle
  - Learning:
    - directed affinity maturation
  - Pruning:
    - immune network theory

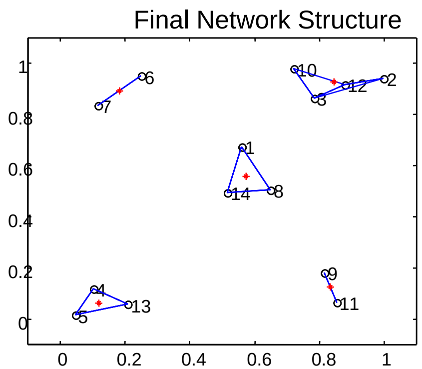
Pattern Recognition

- aiNet at each generation:
  - For each Ag
    - ① Affinity with the antigen (A_i) Ag_i-**Ab**
    - ② Clonal selection (n cells) $\propto A_i$
    - ③ Cloning $\propto A_i$
    - ④ Directed maturation (mutation) $\propto 1/A_i$
    - ⑤ Re-selection (ζ%) $\propto A_i$
    - ⑥ Natural death (σ_d) $\propto 1/A_i$
    - ⑦ Affinity between the network cells (D_{ii}) **Ab-Ab**
    - ⑧ Clonal suppression (σ_s) $\propto D_{ii}$: (m - memory)
    - ⑨ $M_t \leftarrow [M_t; m]$
  - Network suppression (σ_s) $\propto D_{ii}$: ($M \subseteq M_t$)
  - $M \leftarrow [M;meta]$

Pattern Recognition

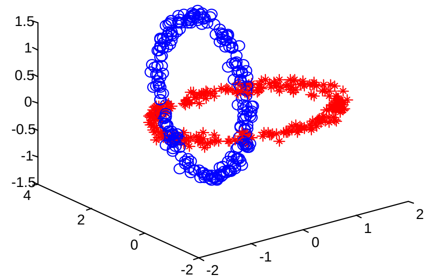
- Clustering

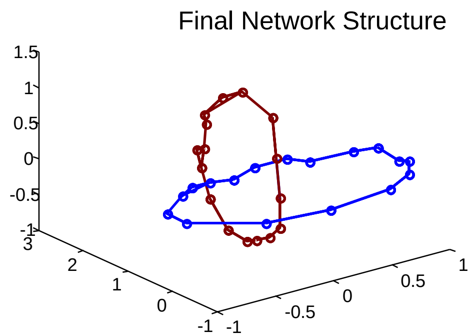




Pattern Recognition

- Clustering





Pattern Recognition

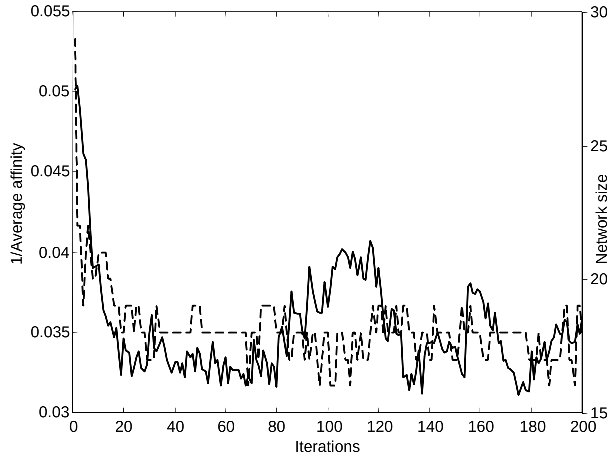
- The Immune Response of aiNet
- Network Hypotheses Used in aiNet
  - Clonal selection, expansion and maturation to foreign stimulation
  - Network interactions (suppression)
  - Network metadynamics
- Dynamics: Mix between learning and evolution

$Ab_k^* = Ab_k + \alpha_k (Ag - Ab_k);\ \alpha_k \propto Aff_k;\ k = 1,...,Nc.$

$\Delta Ab = Nc - Ns + Nb - Nd$

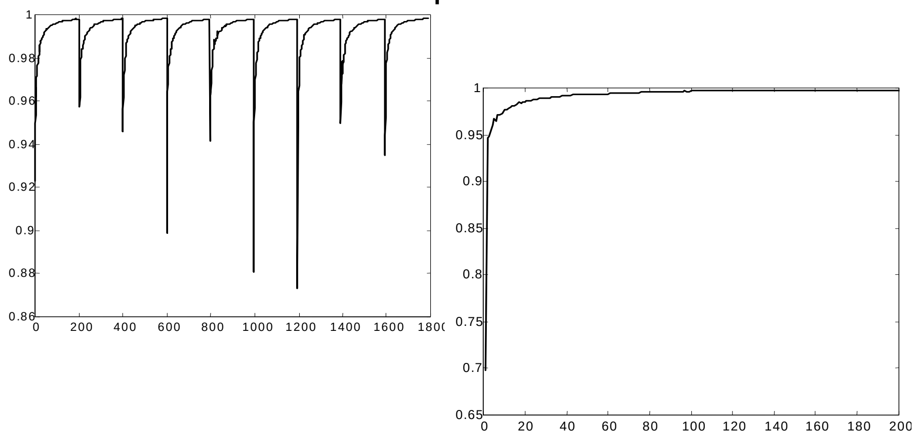
Pattern Recognition

- The Immune Response of aiNet



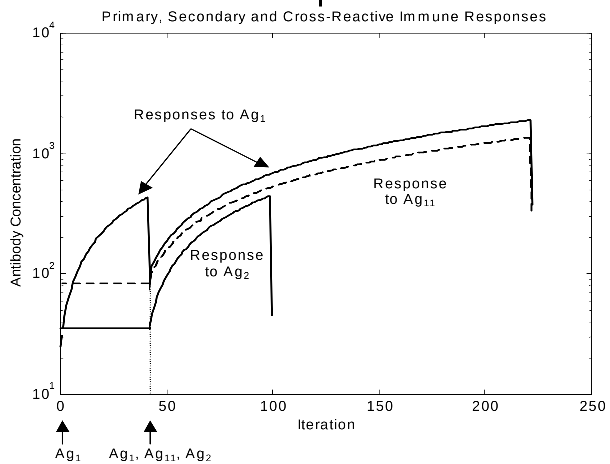
Pattern Recognition

- The Immune Response of aiNet



Pattern Recognition

- The Immune Response of aiNet



Pattern Recognition

- aiNet (de Castro & Von Zuben, 2000)

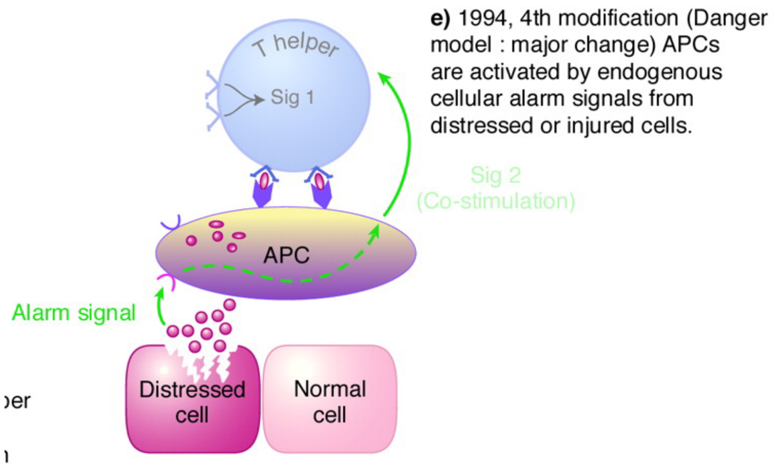
DEMO 3: aiNet

Pattern Recognition

- Detection of Buffer Overflow Attacks
  - ADENOIDS (de Paula et al., 2004)
  - An ID framework inspired by the architecture of the immune system
  - Prototype of an IDS based on the proposed framework
  - Elaborates on some ideas from Aickelin et al., 2002 about the Danger Theory as a missing link for AIS

Pattern Recognition

- Danger Theory (Matzinger, 2000)

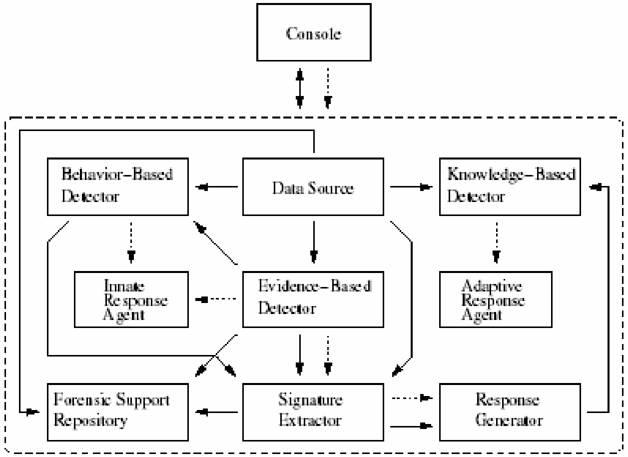


Pattern Recognition

- Detection of Buffer Overflow Attacks
  - Desirable features based on the immune system (danger theory)
    - Automated intrusion recovery
    - Attack signature extraction
    - Potential to improve behavior-based detection

Pattern Recognition

- Framework for Intrusion Detection



Machine Learning

- Neural Network Initialization
  - SAND (de Castro & Von Zuben, 2001)
- Initial neural network (NN) weights:
  - learning speed
  - generalization performance
- Correlation: initial set of weights and initial repertoire of immune cells and molecules
- SAND: a Simulated ANnealing model to increase population Diversity

Machine Learning

- Neural Network Initialization
- Affinity measure: $ED = \sqrt{\sum_{i=1}^{L}(x_i - y_i)^2}$
- Proposed cost (energy) function:

$$\bar{\mathbf{I}} = \frac{1}{N}\sum_{i=1}^{N}\mathbf{I}_i$$

- Average unit vector

$$\bar{R} = \left(\bar{\mathbf{I}}^T \bar{\mathbf{I}}\right)^{1/2}$$

- Resultant vector (distance from the origin of the coordinate system)

$$E(\%) = 100 \times (1 - \bar{R})$$

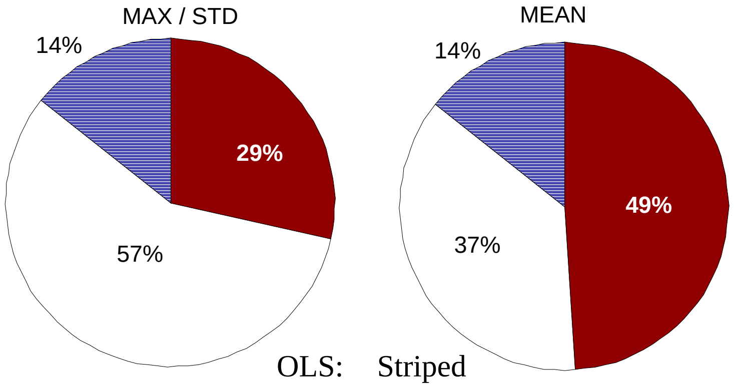
- Percentage energy

Machine Learning

- Neural Network Initialization
  - Ab $\rightarrow$ weight vector
  - Diverse antibodies in $\Re^L$ $\rightarrow$ neurons with well distributed weight vectors in $\Re^L$
  - SAND is applied separately to each network layer
  - The vectors (Ab) have unitary norms and can be normalized to avoid neuron saturation

Machine Learning

- Neural Network Initialization



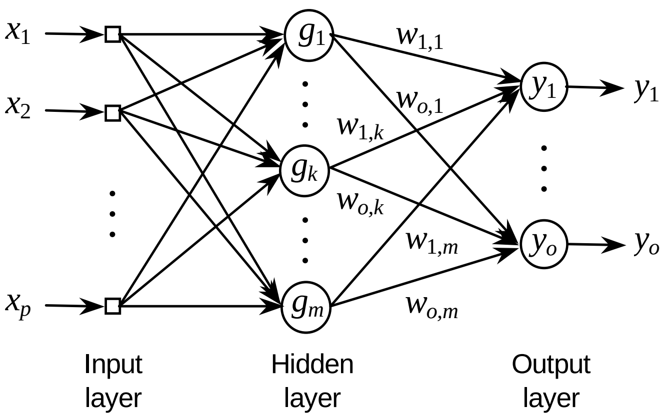
OLS: Striped
INIT: Red
SAND: Blank

Machine Learning

- RBF Neural Network Center Selection
  - de Castro & Von Zuben, 2001
- The performance of the RBF neural network depends on the number, positions and dispersions of the basis functions composing the network hidden layer
- Traditional methods:
  - randomly choose input vectors from the training data set;
  - vectors obtained from unsupervised clustering algorithms;
  - vectors obtained by supervised learning schemes.

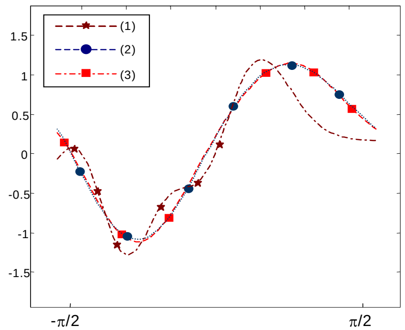
Machine Learning

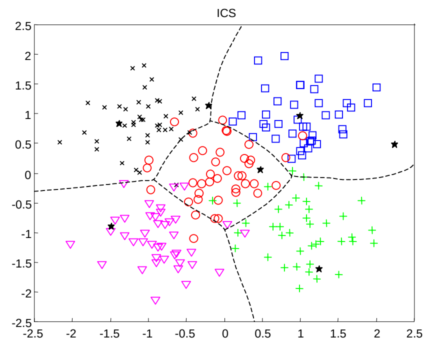
- RBF Neural Network Center Selection
  - Solution based on aiNet



Machine Learning

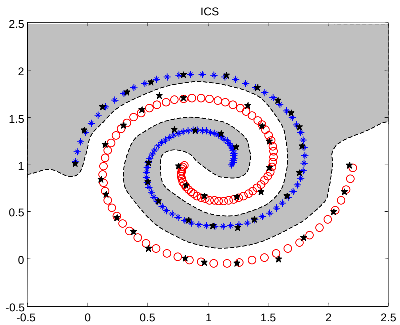
- RBF Neural Network Center Selection





Machine Learning

- RBF Neural Network Center Selection



Method	Etr (%)	Ete (%)	M_1
ICS	0.0	0.0	7
MSBFN	-----	2.9	5
ELEANNE 2	0.0	1.3	11
Gradient descent	1.3	1.3	7

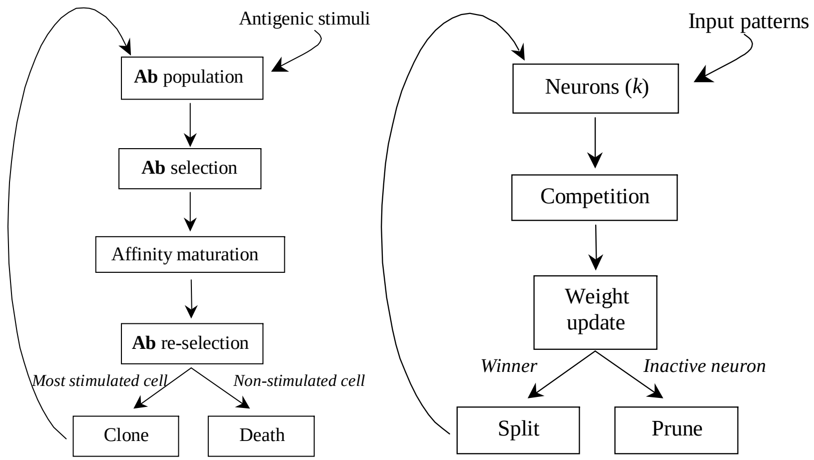
Iris data set
Best performance

Machine Learning

- Boolean Neural Network (ABNET)
  - de Castro et al., 2003
- Main Features:
  - clustering, or grouping of similar patterns
  - capability of solving binary tasks
  - growing learning with pruning phases
- Main loop of the algorithm
  - Choose randomly an antigen (pattern)
  - Determine the cell Ab_k with highest affinity
  - Update the weight vector of this cell
  - Increase the concentration level (τ_j) of this cell
  - Attribute $v_a = k$

Machine Learning

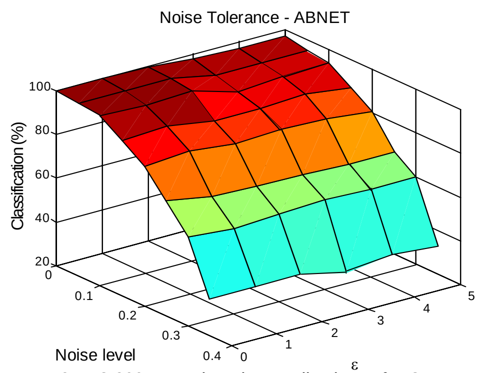
- ABNET



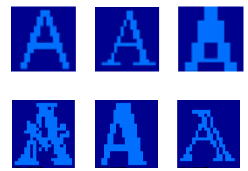
Machine Learning

- ABNET
  - Binary character recognition

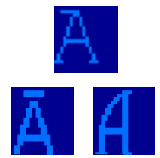
Noise tolerance:



2) Cross-reactivity
(generalization)



(a) ε ≥ 13.75%

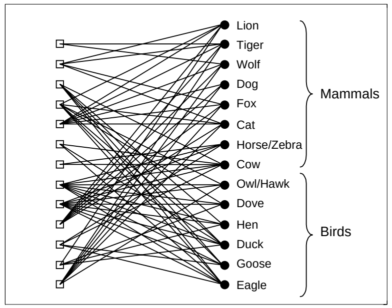


(b) ε ≥ 13.75%

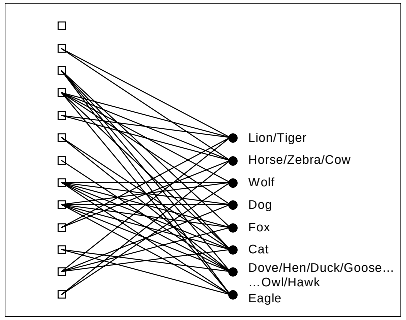
Machine Learning

- ABNET
  - Animals data set

ABNET (0-valued weights omitted)



ABNET (0-valued weights omitted)



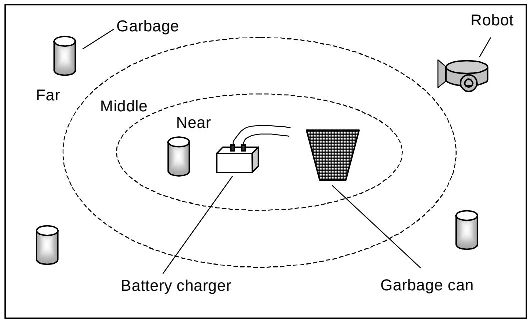
Machine Learning

- ABNET (de Castro et al., 2003)

DEMO 4: ABNET

Robotics

- Autonomous Navigation based on AIS
  - Michelan & Von Zuben, 2002
- Based on the works:
  - Ishiguro et al., 1996; Farmer et al., 1986

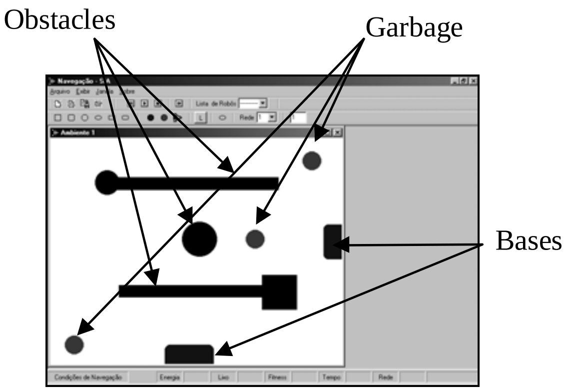


Robotics

- Autonomous Navigation based on AIS
  - Autonomous control system of a mobile robot based on the immune network theory
  - Each network node corresponds to a specific antibody and describes a particular control action for the robot
  - The antigens are the current state of the robot
  - The network dynamics corresponds to the variation of antibody concentration levels, which change according to both mutual interaction of antibody nodes and of antibodies and antigens
  - It is proposed an evolutionary mechanism to determine the network configuration

Robotics

- Autonomous Navigation based on AIS

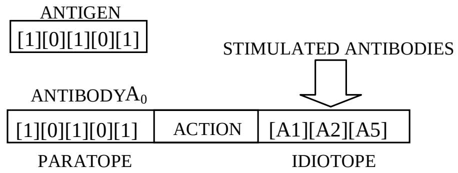


Robotics

- Autonomous Navigation based on AIS
  - Objectives of navigation

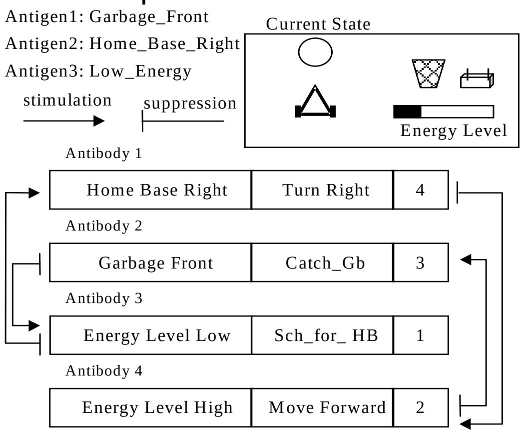
$$E(t) = E(t-1) - E_{step} - E_{collision} - E_{garbage}$$

  - Antibody structure



Robotics

- Autonomous Navigation based on AIS
  - Network example



Robotics

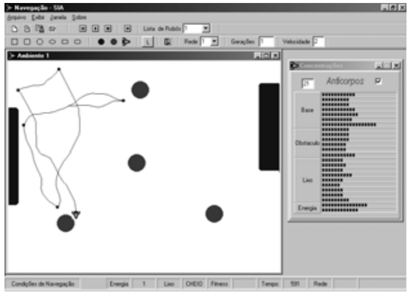
- Autonomous Navigation based on AIS
  - Dynamics

$$\frac{dA_i(t)}{dt} = \left(\sum_{j=1}^{N} m_{ji} a_j(t) - \sum_{k=1}^{N} m_{ik} a_k(t) + m_i - k_i \right) a_i(t)$$

$$a_i(t+1) = \frac{1}{1 + \exp(0.5 - A_i(t))}$$

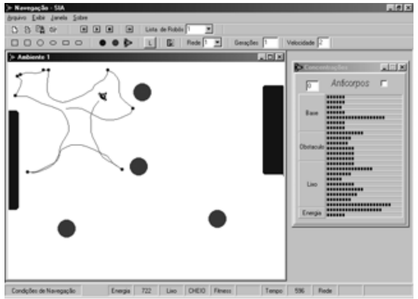
Robotics

- Autonomous Navigation based on AIS



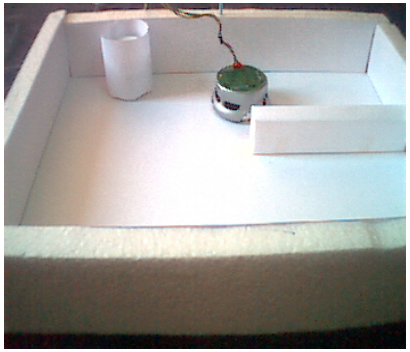
Immune network

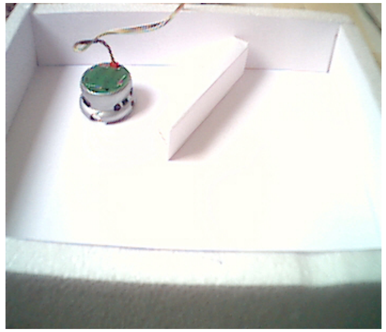
Evolved network



Robotics

- Autonomous Navigation based on AIS
  - Implementation on Khepera II®: Vargas et al., 2003





Robotics

- Autonomous Navigation (Vargas et al., 2003)

DEMO 5: Collision Avoidance

Bioinformatics

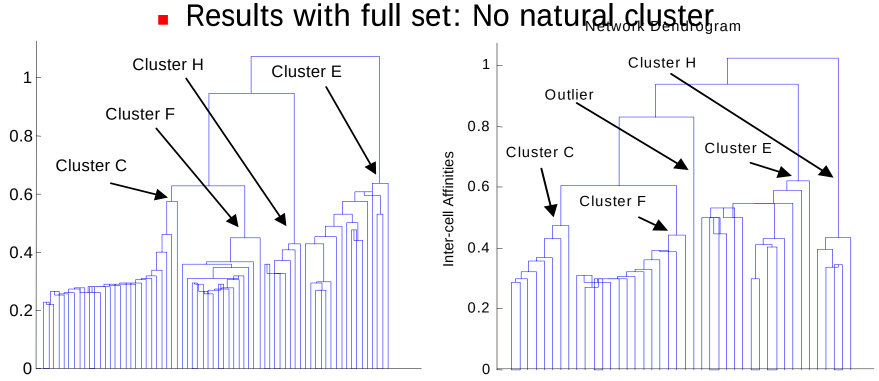
- Gene Expression Data Analysis
  - Bezerra & de Castro, 2003
  - de Sousa et al., 2004
- The Problem
  - Clustering gene expression data
  - Recent approach in bioinformatics that surged with the development of the DNA Microarrays
- DNA Microarrays
  - Experimental technique that measures the expression level of many genes simultaneously
  - A quantitative change in the scale of the experiments led to a qualitative change in the analyses, where the genes may be studied under a genome wide perspective

Bioinformatics

- Gene Expression Data Analysis
- Genes belonging to the same cluster may, among other things
  - Share the same regulatory system
  - Have similar properties or functions
  - Code products that interact physically
- Experimental Data
  - Gene expression data of the budding yeast *Saccharomyces cerevisiae,* obtained from Eisen et al. (1998)
  - Total of 2467 genes in 79 different conditions

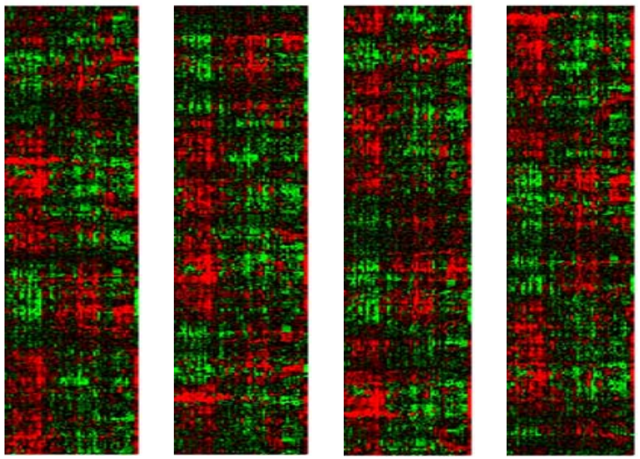
Bioinformatics

- Gene Expression Data Analysis
  - Clusters initially analyzed C, E, F and H (68 genes)
  - Results with full set: No natural cluster



Bioinformatics

- Multiple Simultaneous Views



Part V

Discussion

Discussion

- Vast number of applications available
- Great potential for further applications and developments
- Some issues that still deserve investigation:
  - Formal aspects
  - Comparison (theoretical and empirical) with other approaches
  - Loads of testing
  - Real benefits (Are they really useful?)
  - Danger theory
  - How far to stretch the metaphor?

Discussion

- Current trends in our labs
  - Improvements on the many versions of aiNet
  - Optimization on dynamic environments
  - Bioinformatics, mainly gene expression data analysis
  - Feedforward neural network training
  - Danger theory
  - Anomaly detection
- This Tutorial on the Web:
  - www.dca.fee.unicamp.br/~lnunes/AIS.html