An Introduction to the Artificial Immune Systems

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Presentation Topics

- **Part I**
  - Introduction to the Immune System
- **Part II**
  - Artificial Immune Systems (AIS)
- **Part III**
  - Examples of AIS and Applications
  - Discussion and Future Trends

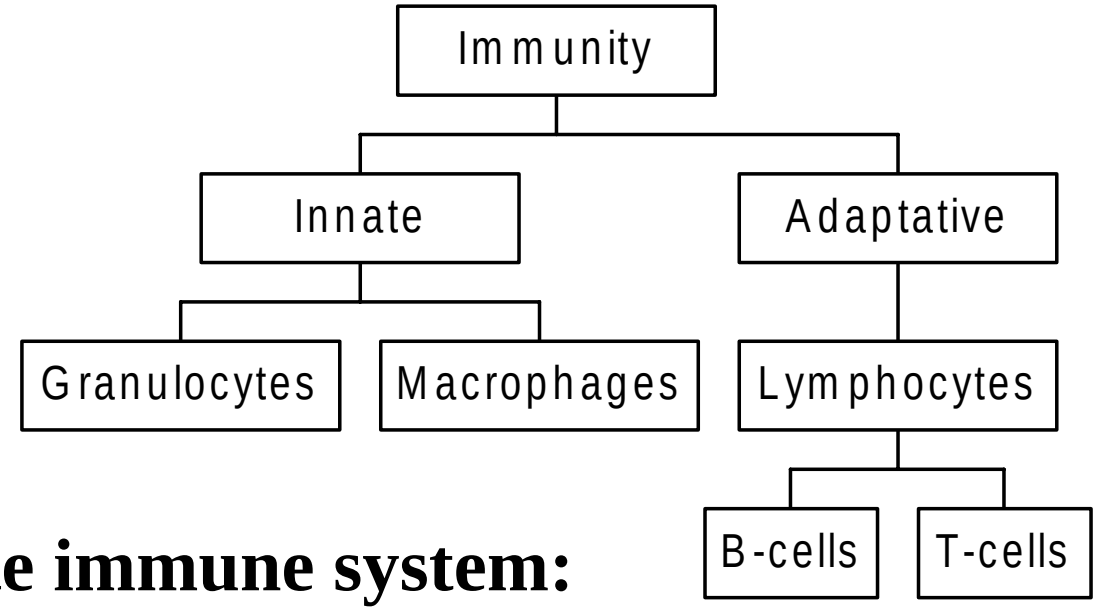
— Part I —

- **Introduction to the Immune System**
  - Fundamentals and Main Components
  - Anatomy
  - Innate Immune System
  - Adaptive Immune System
  - Pattern Recognition in the Immune System
  - A General Overview of the Immune Defenses
  - Clonal Selection and Affinity Maturation
  - Self/Nonself Discrimination
  - Immune Network Theory

The Immune System (I)

- **Fundamentals:**
  - *Immunology* is the study of the defense mechanisms that confer resistance against diseases (Klein, 1990)
  - The *immune system* (IS) is the one responsible to protect us against the attack from external microorganisms (Tizard, 1995)
  - Several defense mechanisms in different levels; some are redundant
  - The IS presents *learning* and *memory*
  - Microorganisms that might cause diseases (pathogen): viruses, funguses, bacteria and parasites
  - Antigen: any molecule that can stimulate the IS

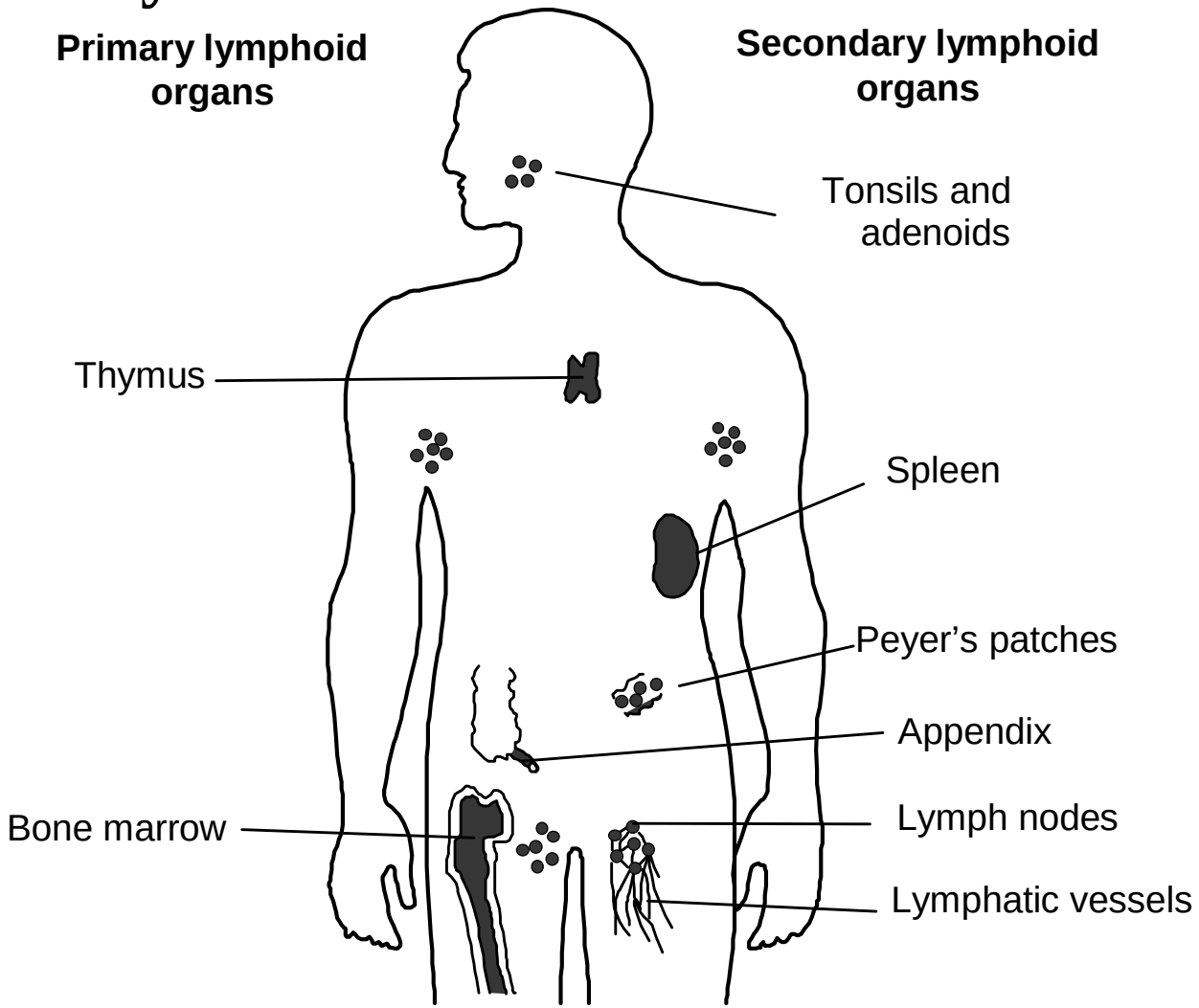
The Immune System (II)



- **Innate immune system:**
  - immediately available for combat
- **Adaptive immune system:**
  - antibody (Ab) production specific to a determined infectious agent

The Immune System (III)

- **Anatomy**



The Immune System (IV)

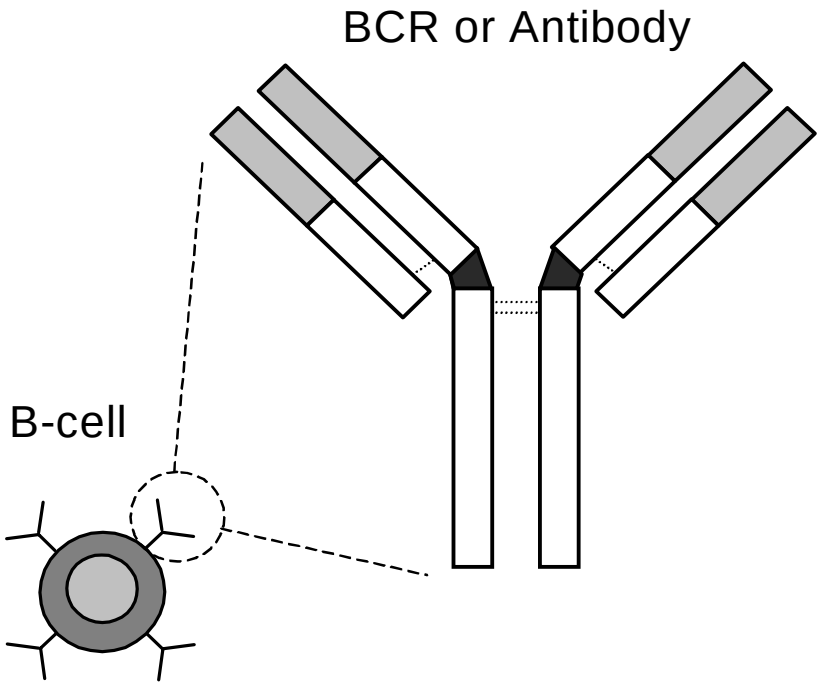
- **All living beings present a type of defense mechanism**
- **Innate Immune System**
  - first line of defense
  - controls bacterial infections
  - regulates the adaptive immunity
  - important for self/nonself discrimination
  - composed mainly of phagocytes and the complement system

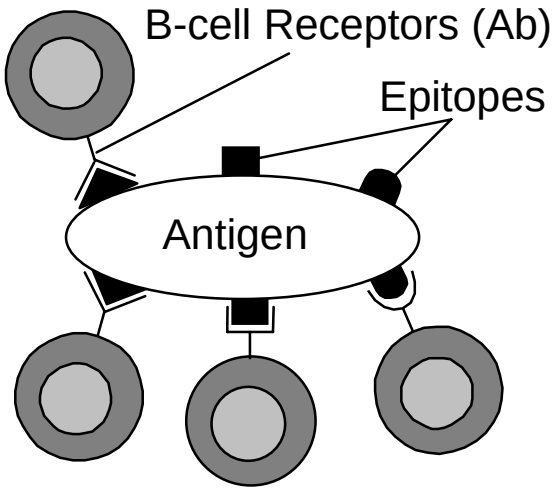
The Immune System (V)

- **The Adaptive Immune System**
  - the vertebrates have an anticipatory immune system
  - the lymphocytes carry antigen receptors on their surfaces. These receptors are specific to a given antigen
  - *Clonal selection*: B-cells that recognize antigens are stimulated, proliferate (clone) and differentiate into memory and plasma cells
  - confer resistance against future infections
  - is capable of fine-tuning the cell receptors of the selected cells to the selective antigens

The Immune System (VI)

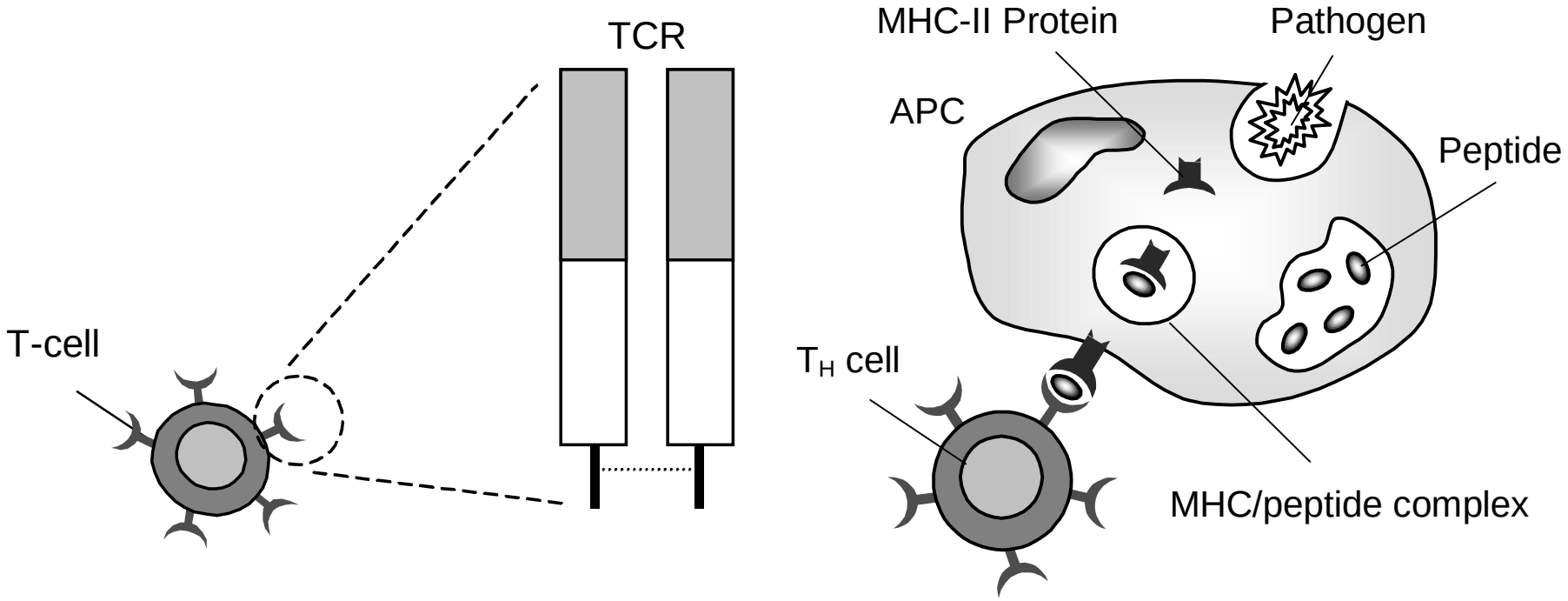
- **Pattern Recognition: B-cell**



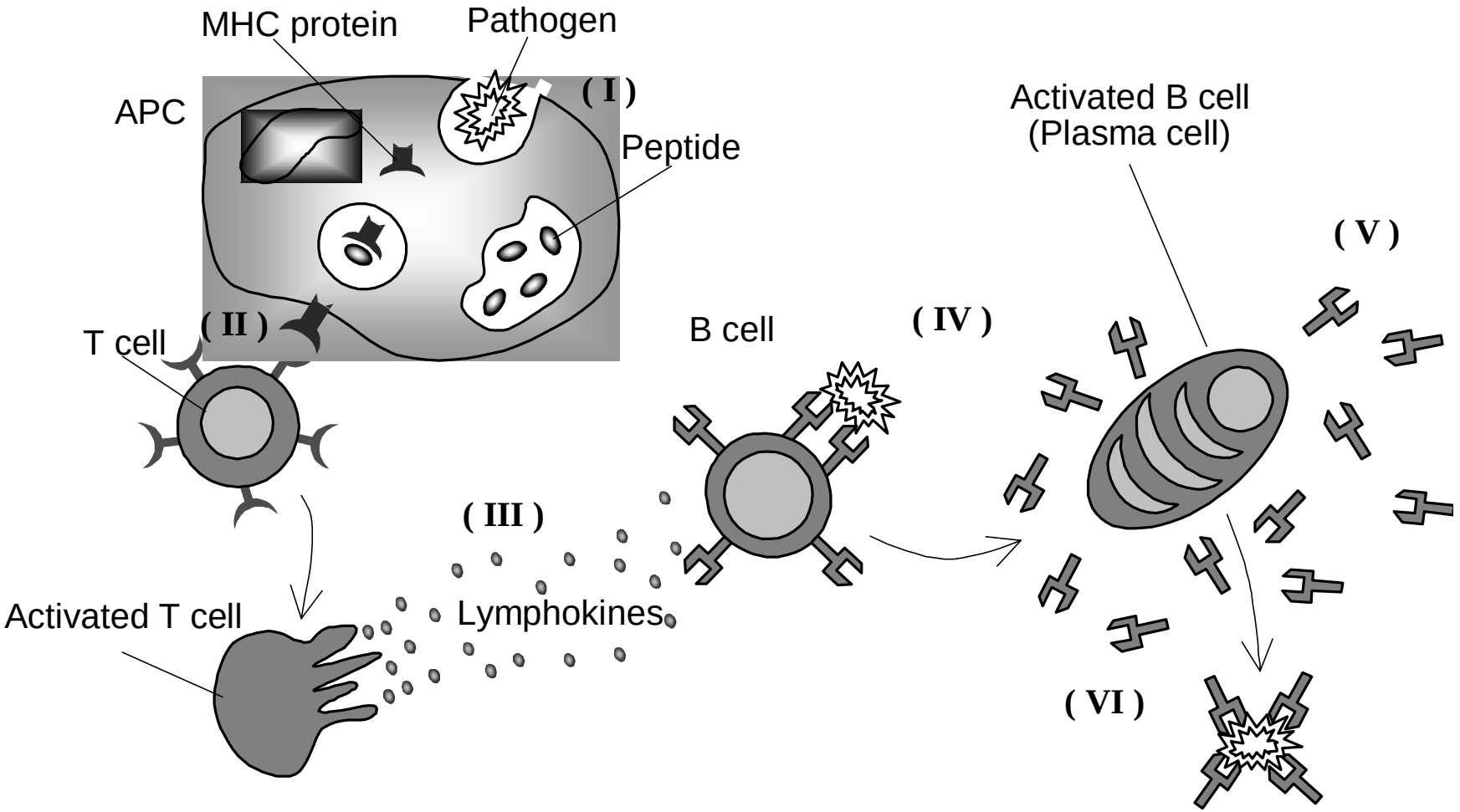


The Immune System (VII)

- **Pattern Recognition: T-cell**



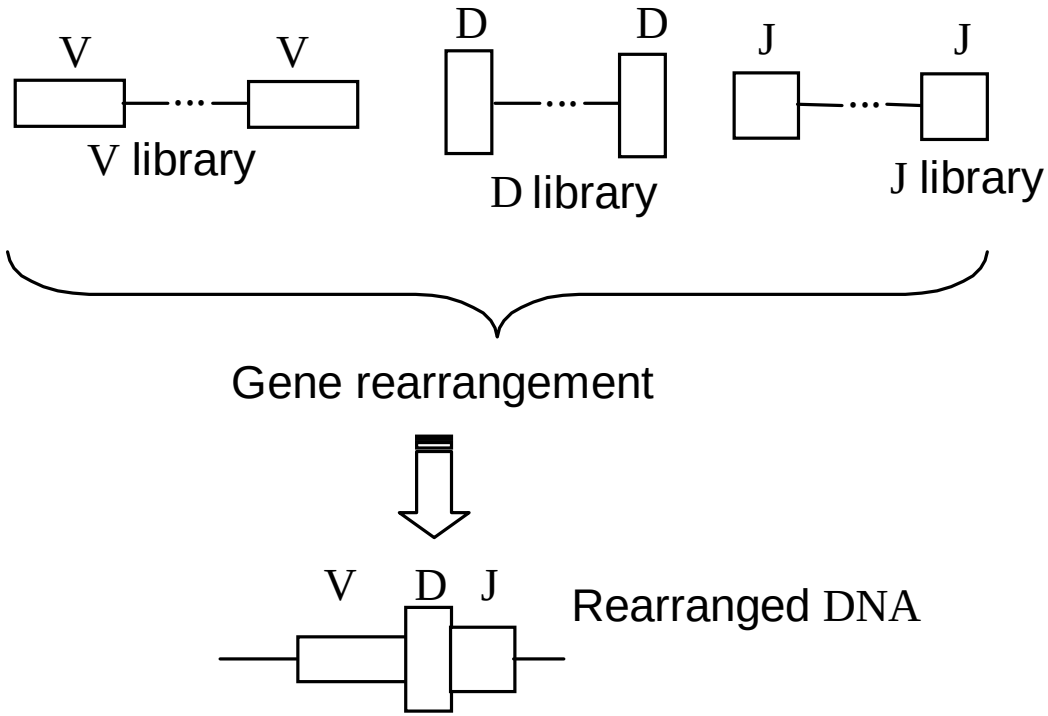
The Immune System (VIII)



after Nosssal, 1993

The Immune System (IX)

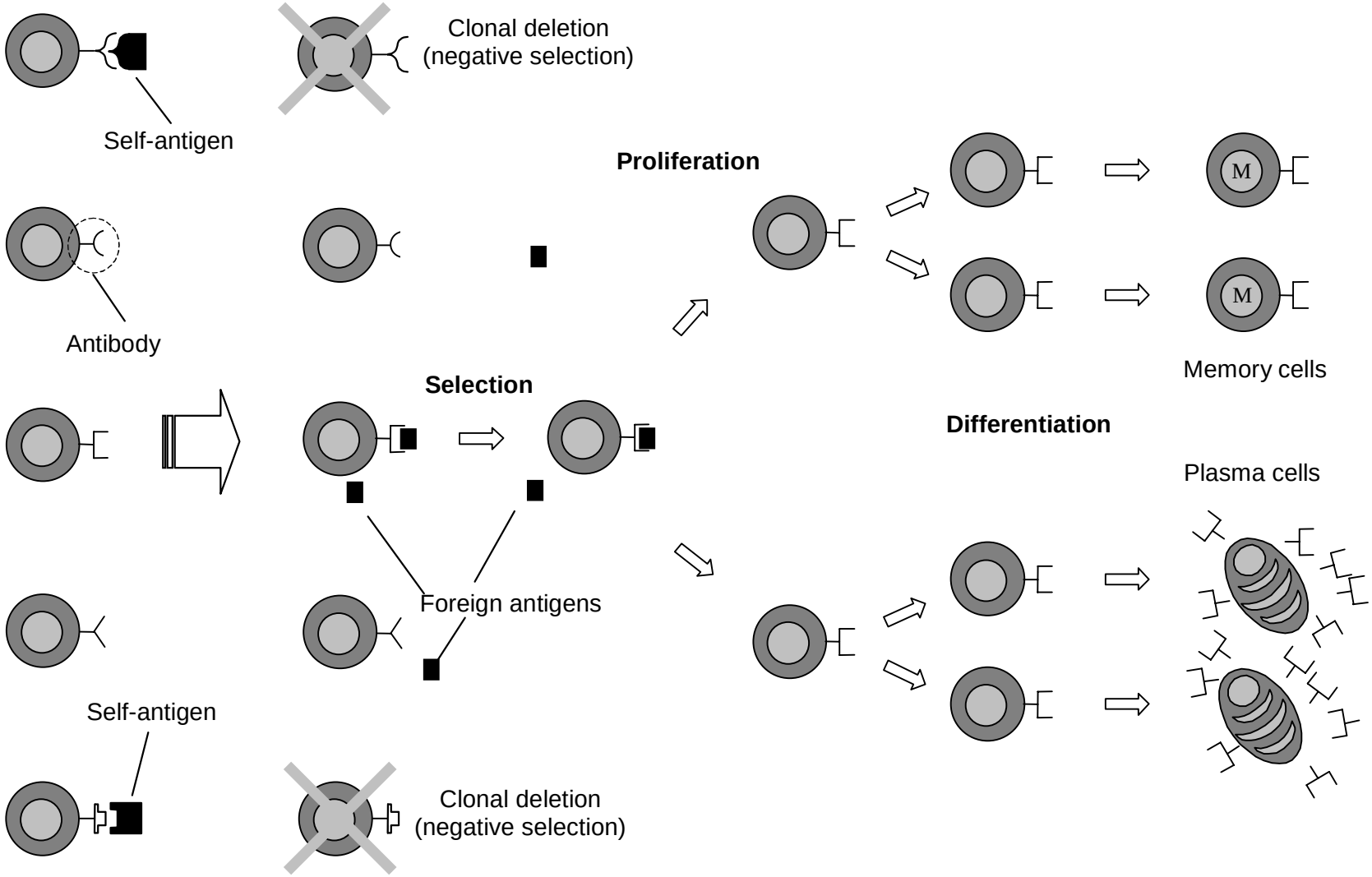
- **Antibody Synthesis:**



after Oprea & Forrest, 1998

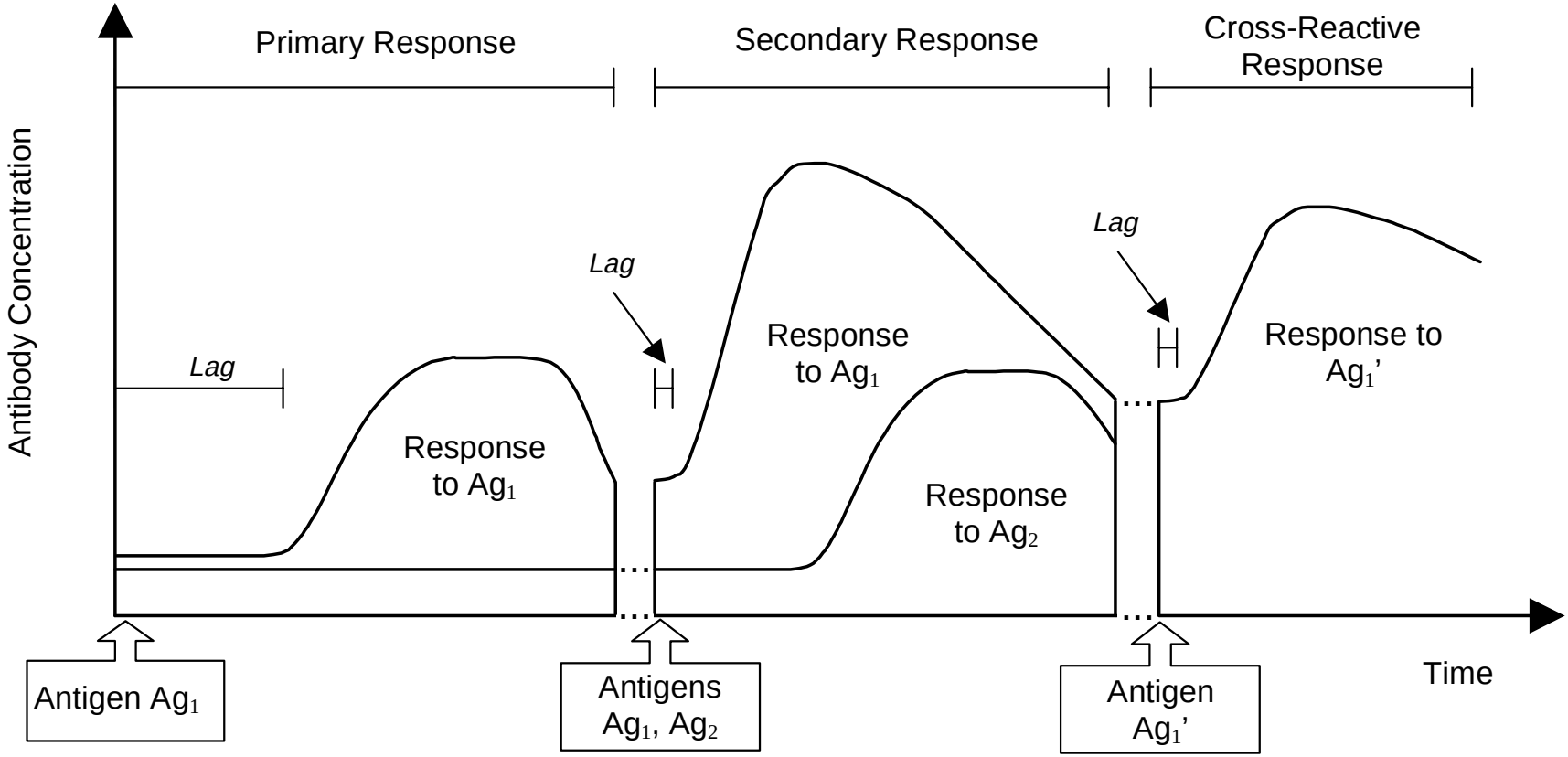
The Immune System (X)

- **Clonal Selection**



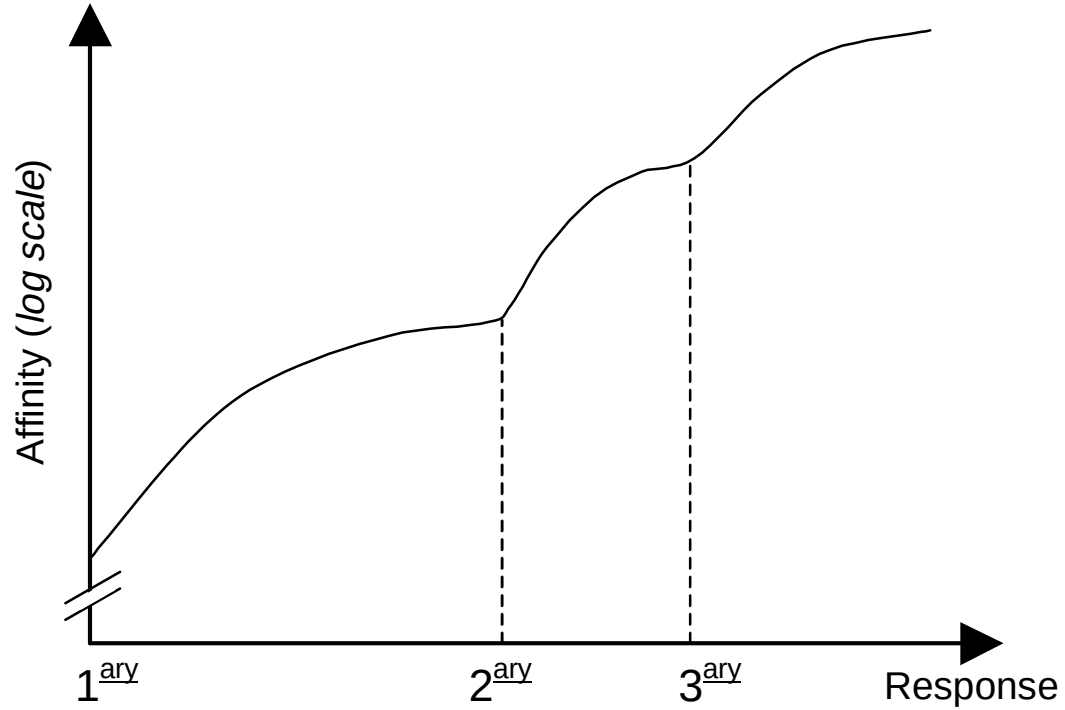
The Immune System (XI)

- **Reinforcement Learning and Immune Memory**



The Immune System (XII)

- **Affinity Maturation**
  - somatic hypermutation
  - receptor editing

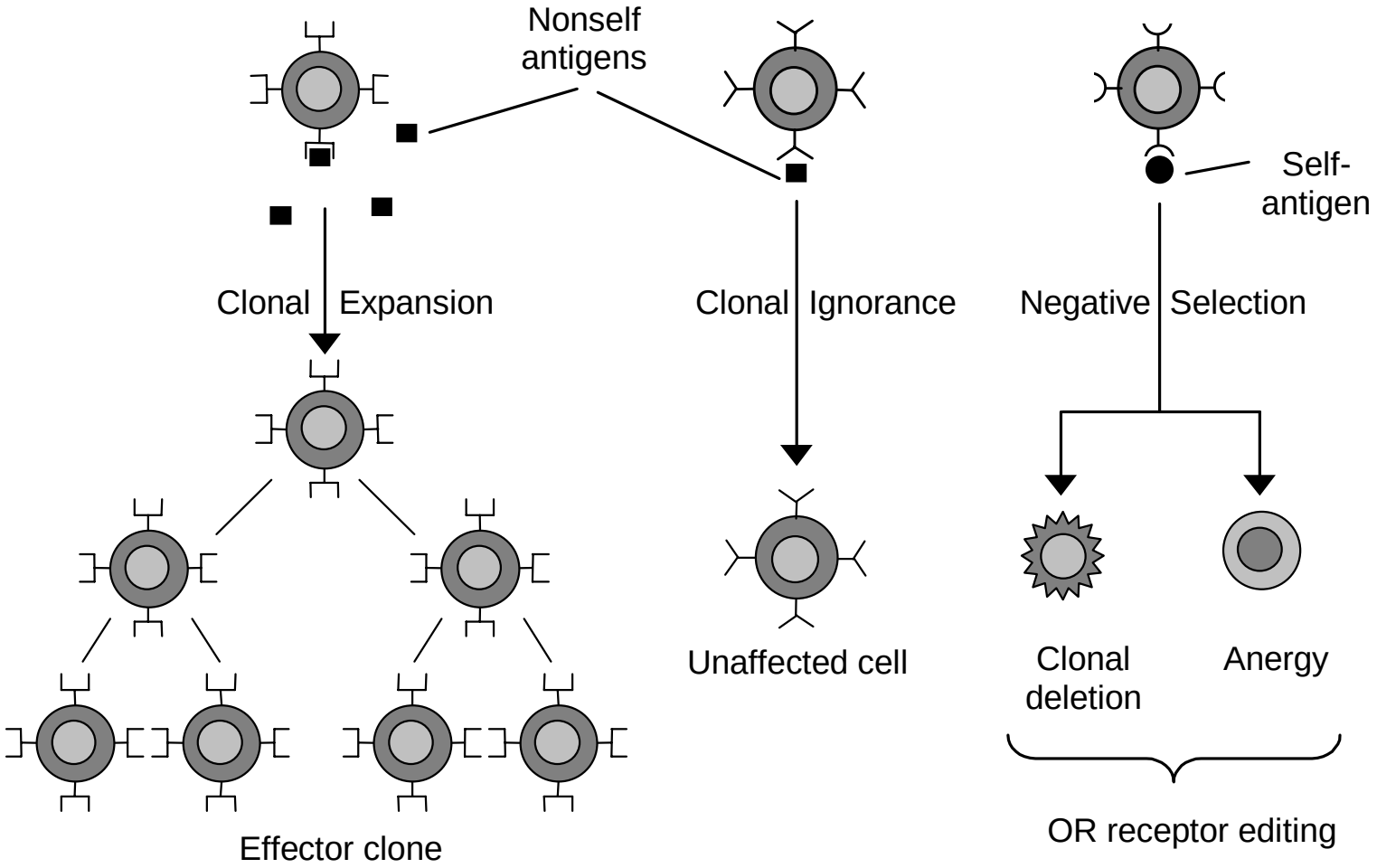


The Immune System (XIII)

- **Self/Nonself Discrimination**
  - repertoire completeness
  - co-stimulation
  - tolerance
- **Positive selection**
  - B- and T-cells are selected as immunocompetent cells
  - Recognition of self-MHC molecules
- **Negative selection**
  - Tolerance of self: those cells that recognize the self are eliminated from the repertoire

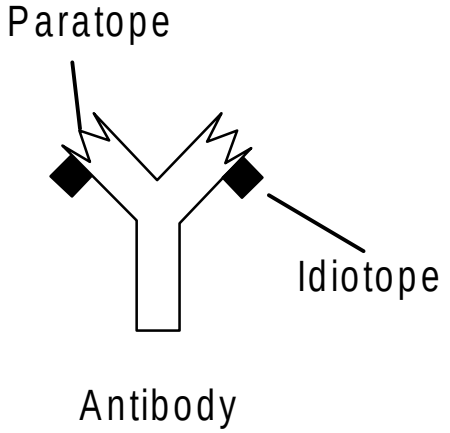
The Immune System (XIV)

- **Self/Nonself Discrimination**



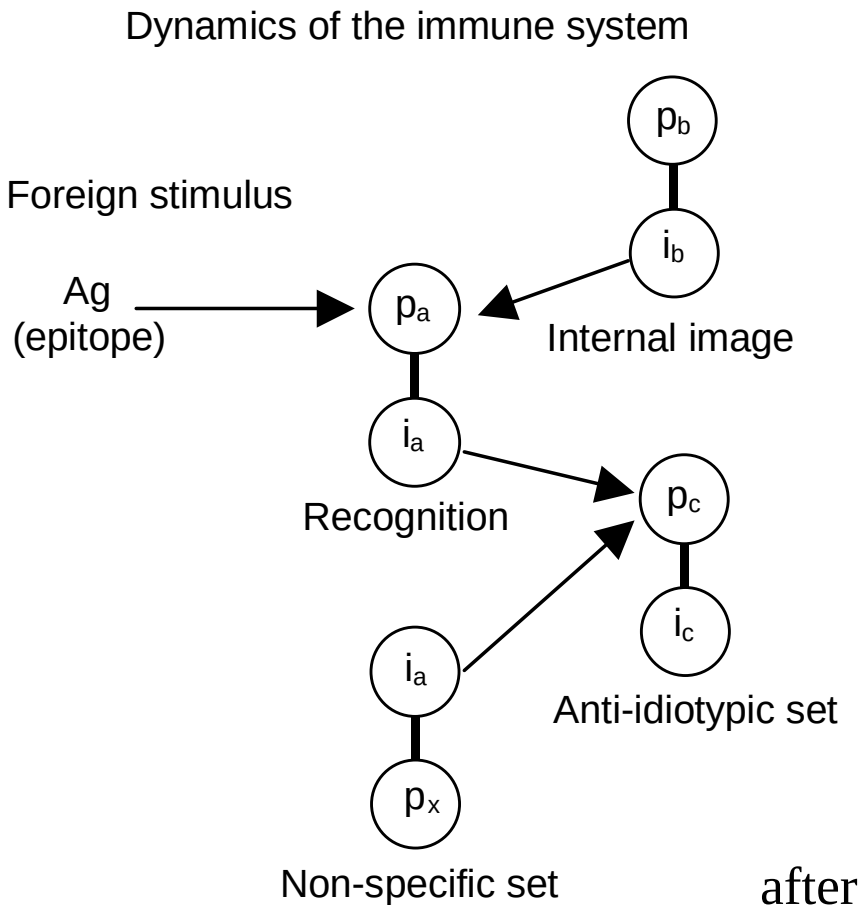
The Immune System (XV)

- **Immune Network Theory**
  - The *immune system* is composed of an enormous and complex network of paratopes that recognize sets of idiotopes, and of idiotopes that are recognized by sets of paratopes, thus each element can recognize as well as be recognized (Jerne, 1974)
- **Features (Varela et al., 1988)**
  - Structure
  - Dynamics
  - Metadynamics



The Immune System (XVI)

- **Immune Network Dynamics**



after Jerne, 1974

The Immune System
— Summary —

- **Pathogen, Antigen, Antibody**
- **Lymphocytes: B- and T-cells**
- **Affinity**
- **1ary, 2ary and cross-reactive response**
- **Learning and memory**
  - increase in clone size and affinity maturation
- **Self/Nonself Discrimination**
- **Immune Network Theory**

— Part II —

- **Artificial Immune Systems (AIS)**
  - Remarkable Immune Properties
  - Concepts, Scope and Applications
  - History of the AIS
  - The Shape-Space Formalism
  - Representations and Affinities
  - Algorithms and Processes
  - A Discrete Immune Network Model
  - Guidelines to Design an AIS

Artificial Immune Systems (I)

- **Remarkable Immune Properties**
  - uniqueness
  - diversity
  - robustness
  - autonomy
  - multilayered
  - self/nonself discrimination
  - distributivity
  - reinforcement learning and memory
  - predator-prey behavior
  - noise tolerance (imperfect recognition)

Artificial Immune Systems (II)

- **Concepts**
  - *Artificial immune systems* are data manipulation, classification, reasoning and representation methodologies, that follow a plausible biological paradigm: the human immune system (Starlab)
  - An *artificial immune system* is a computational system based upon metaphors of the natural immune system (Timmis, 2000)
  - The *artificial immune systems* are composed of intelligent methodologies, inspired by the natural immune system, for the solution of real-world problems (Dasgupta, 1998)

Artificial Immune Systems (III)

- **Scope (Dasgupta, 1998):**
  - Computational methods inspired by immune principles;
  - Multi-agent systems based on immunology;
  - Self-organized systems based on immunology;
  - Immunity-based systems for the development of collective behavior;
  - Search and optimization methods based on immunology;
  - Immune approaches for artificial life;
  - Immune approaches for the security of information systems;
  - Immune metaphors for machine-learning.

Artificial Immune Systems (IV)

- **Applications**
  - Pattern recognition;
  - Function approximation;
  - Optimization;
  - Data analysis and clustering;
  - Machine learning;
  - Associative memories;
  - Diversity generation and maintenance;
  - Evolutionary computation and programming;
  - Fault and anomaly detection;
  - Control and scheduling;
  - Computer and network security;
  - Generation of emergent behaviors.

Artificial Immune Systems (V)

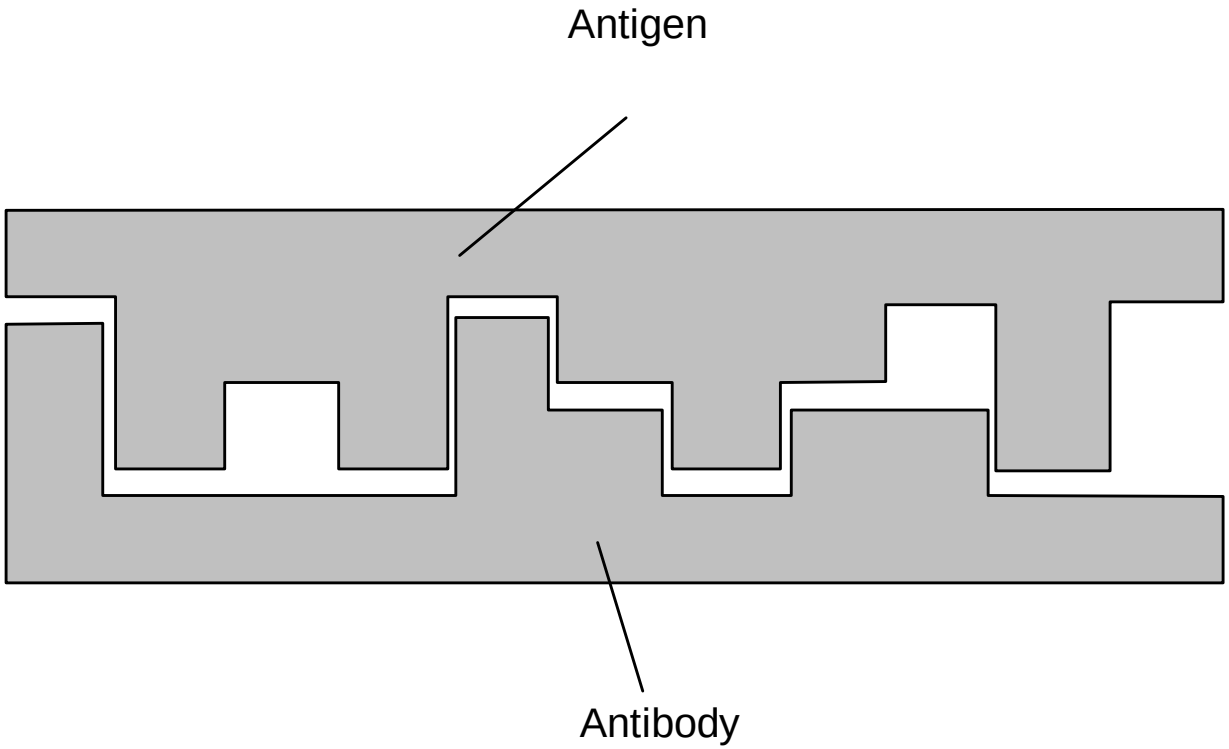
Year	Event	Activity	Organizer/Speaker
1996	IMBS	Workshop	Y. Ishida
1997	SMC	Special Track / Tutorial	D. Dasgupta
1998	SMC	Special Track	D. Dasgupta
	Book	First edited book	D. Dasgupta (ed.)
1999	SMC	Special Track	D. Dasgupta
2000	GECCO	Workshop	D. Dasgupta
		Talk: "Why Does a Computer Need an Immune System"	S. Forrest
	SMC	Tutorial: "Immunological Computation"	D. Dasgupta
		Special Track	
	SBRN	Tutorial: "Artificial Immune Systems and Their Applications"	L. N. de Castro
2001	ICANNGA	Tutorial: "An Introduction to the Artificial Immune Systems"	L. N. de Castro
	CEC	Tutorial: "Artificial Immune Systems: An Emerging Technology"	J. I. Timmis
	Journal (Special Issue)	IEEE-TEC: Special Issue on Artificial Immune Systems	D. Dasgupta (ed.)

Artificial Immune Systems (VI)

- **How do we mathematically represent immune cells and molecules?**
- **How do we quantify their interactions or recognition?**
- **Shape-Space Formalism (Perelson & Oster, 1979)**
  - Quantitative description of the interactions between cells and molecules
- **Shape-Space (*S*) Concepts**
  - generalized shape
  - recognition through regions of complementarity
  - recognition region
  - affinity threshold

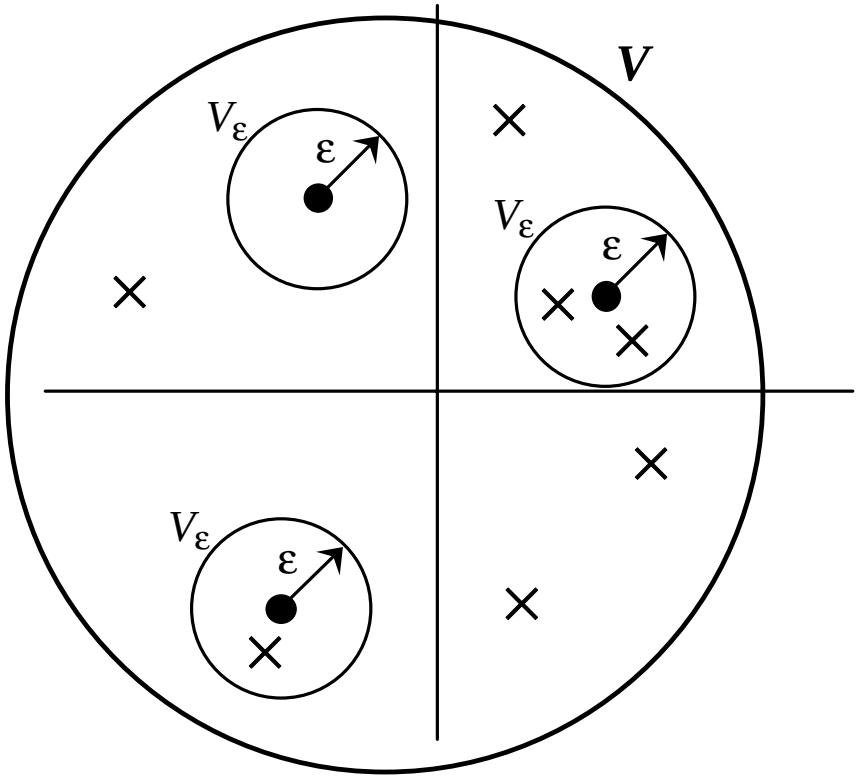
Artificial Immune Systems (VII)

- **Recognition Via Regions of Complementarity**



Artificial Immune Systems (VIII)

- **Shape-Space (*S*)**



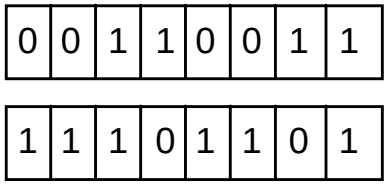
after Perelson, 1989

Artificial Immune Systems (IX)

- **Representations**
  - Set of coordinates: $m = \langle m_1, m_2, ..., m_L \rangle$, $m \in S^L \subseteq \Re^L$
  - **Ab** = $\langle Ab_1, Ab_2, ..., Ab_L \rangle$, **Ag** = $\langle Ag_1, Ag_2, ..., Ag_L \rangle$
- **Affinities: related to their distance**
  - Euclidean $D = \sqrt{\sum_{i=1}^{L} (Ab_i - Ag_i)^2}$
  - Manhattan $D = \sum_{i=1}^{L} |Ab_i - Ag_i|$
  - Hamming $D = \sum_{i=1}^{L} \delta, \text{where} \quad \delta = \begin{cases} 1 & \text{if } Ab_i \neq Ag_i \\ 0 & \text{otherwise} \end{cases}$

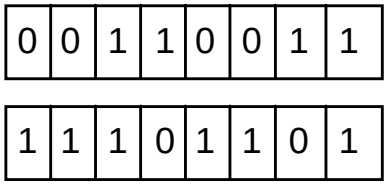
Artificial Immune Systems (X)

- **Affinities in Hamming Shape-Space**



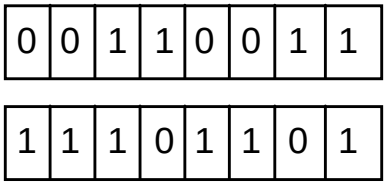
Affinity: 6

Hamming distance



Affinity: 4

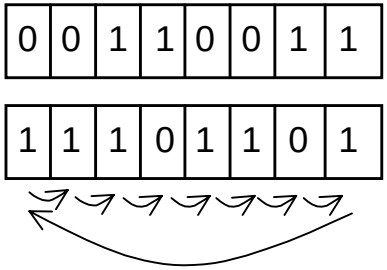
r-contiguous bit rule



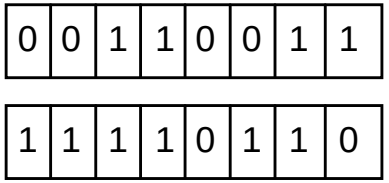
Affinity: $6+2^4=22$

Affinity measure of Hunt

$$D = D_H + \sum_i 2^{l_i}$$



Flipping one string



Affinity: 6 + 4 + ... + 4 = 32

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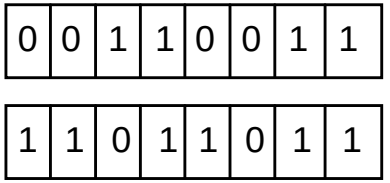
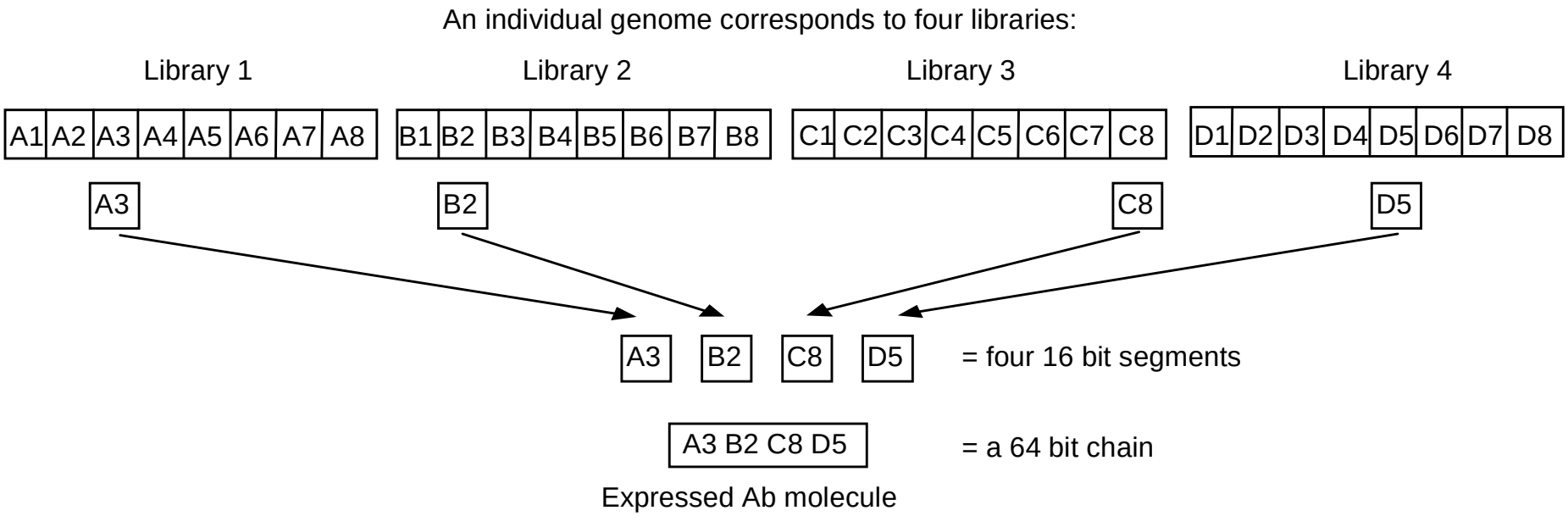


Artificial Immune Systems (XI)

- **Algorithms and Processes**
  - Main generic algorithms that model specific immune principles
- **Examples**
  - Generation of initial antibody repertoires (Bone Marrow)
  - A Negative selection algorithm
  - A Clonal selection algorithm
  - Affinity maturation
  - Immune network models

Artificial Immune Systems (XII)

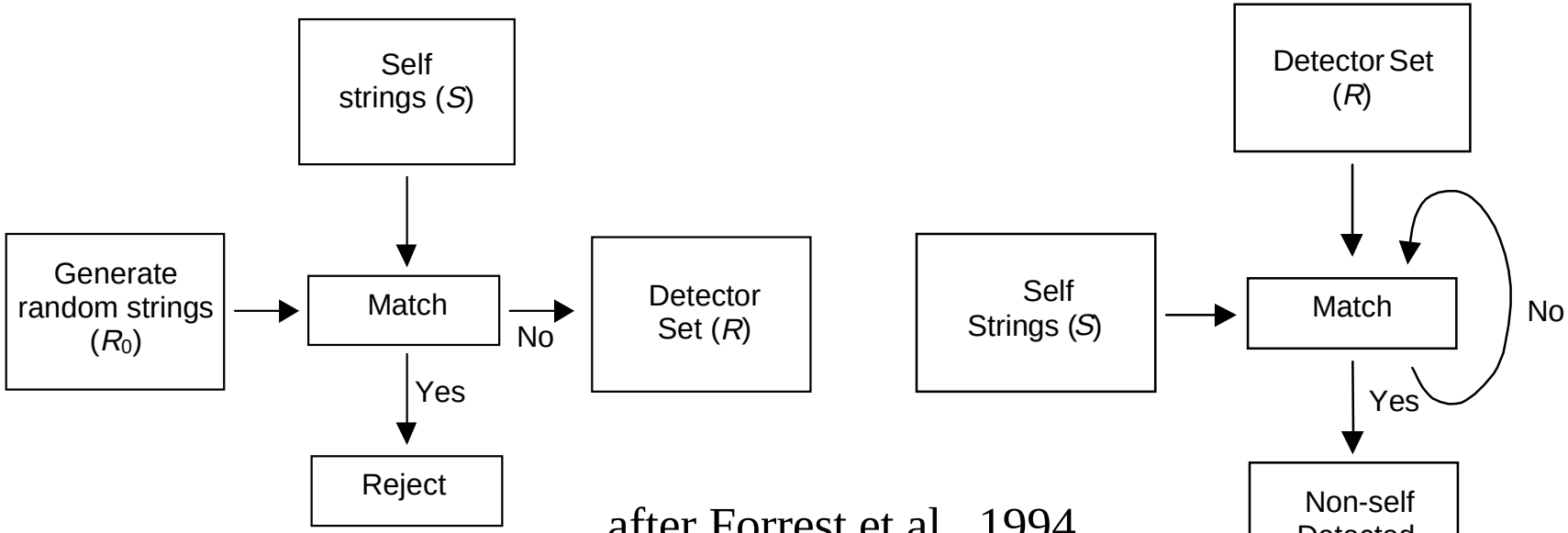
- **Generation of Initial Antibody Repertoires**



after Perelson et al., 1996

Artificial Immune Systems (XIII)

- **A Negative Selection Algorithm**
  - store information about the complement of the patterns to be recognized



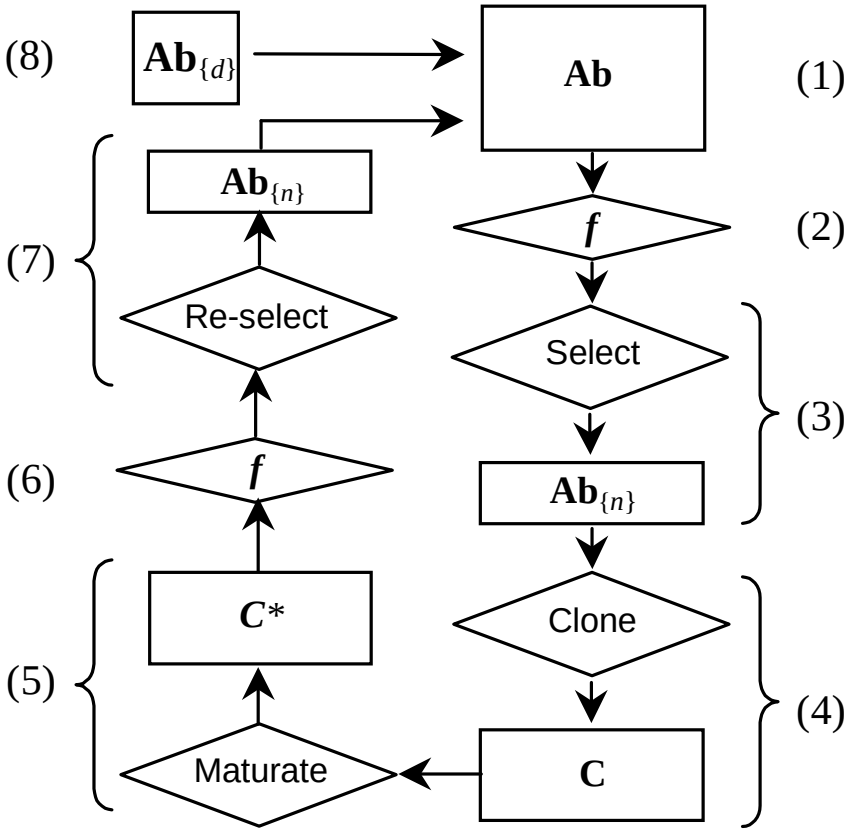
after Forrest et al., 1994

Censoring phase

Monitoring phase

Artificial Immune Systems (XIV)

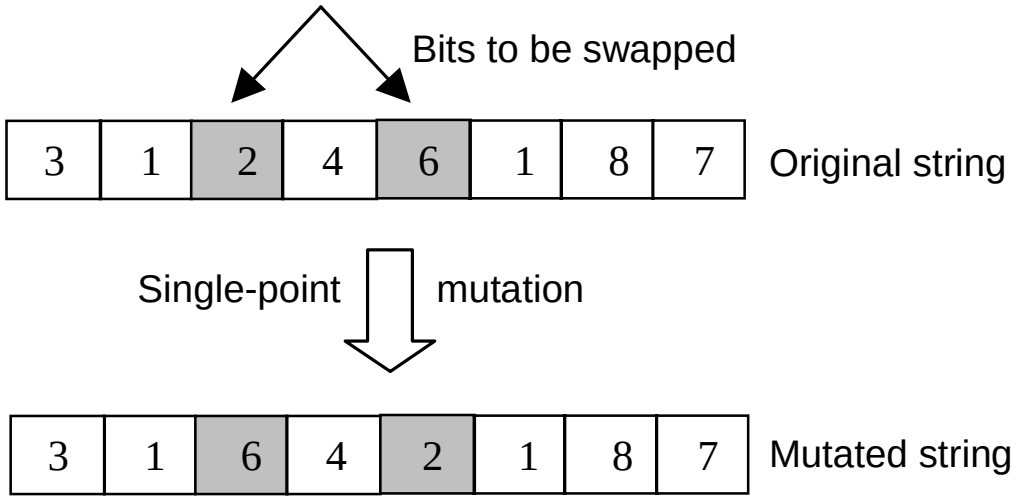
- **A Clonal Selection Algorithm**
  - the clonal selection principle with applications to machine-learning, pattern recognition and optimization



after
de Castro & Von Zuben, 2001a

Artificial Immune Systems (XV)

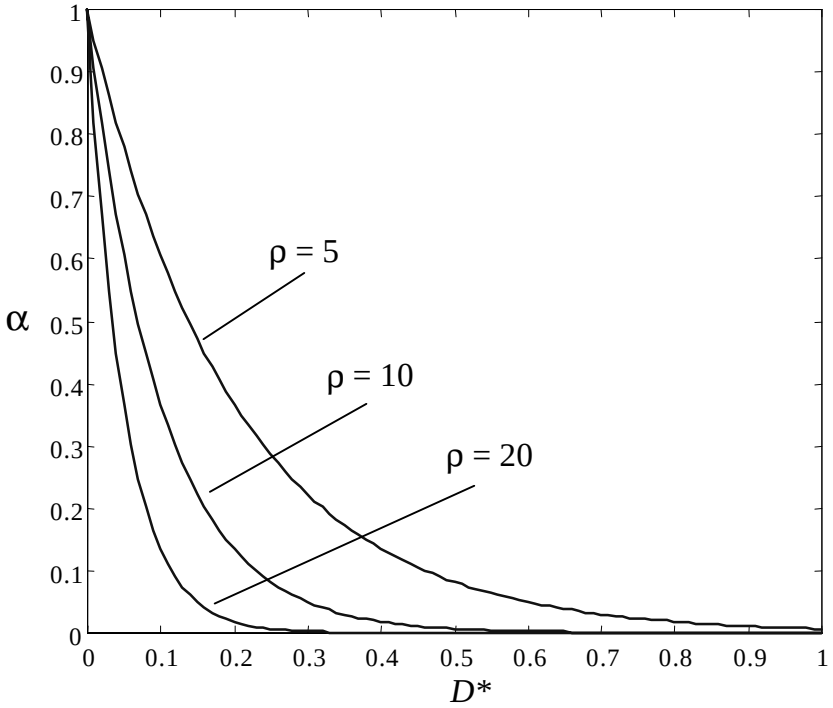
- **Somatic Hypermutation**
  - Hamming shape-space with an alphabet of length 8



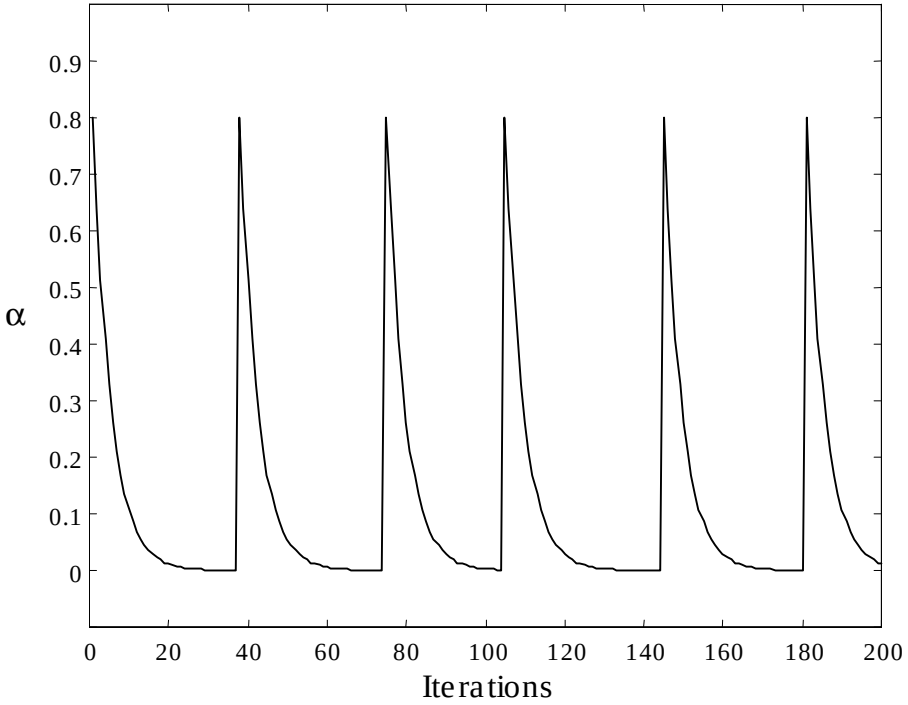
  - Real-valued vectors: inductive mutation

Artificial Immune Systems (XVI)

- **Affinity Proportionate Hypermutation**



after de Castro & Von Zuben, 2001a



after Kepler & Perelson, 1993

Artificial Immune Systems (XVII)

- **A Discrete Immune Network Model: aiNet**

1. For each antigenic pattern Ag_i,
   - 1.1 *Clonal selection*: Apply the pattern recognition version of CLONALG that will return a matrix of memory clones for Ag_i;
   - 1.2 *Apoptosis*: Eliminate all memory clones whose affinity with antigen are below a threshold;
   - 1.3 *Inter-cell affinity*: Determine the affinity between all clones generated for Ag_i;
   - 1.4 *Clonal Suppression*: Eliminate those clones whose affinities are inferior to a pre-specified threshold;
   - 1.5 *Total repertoire*: Concatenate the clone generated for antigen Ag_i with all network cells
2. *Inter-cell affinity*: Determine the affinity between all network cells;
3. *Network suppression*: Eliminate all aiNet cells whose affinities are inferior to a pre-specified threshold.

Artificial Immune Systems (XVIII)

- **Guidelines to Design an AIS**

1. Problem definition
2. Mapping the real problem into the AIS domain
   - 2.1 Defining the types of immune cells and molecules to be used
   - 2.2 Deciding the immune principle(s) to be used in the solution
   - 2.3 Defining the mathematical representation for the elements of the AIS
   - 2.4 Evaluating the interactions among the elements of the AIS (dynamics)
   - 2.5 Controlling the metadynamics of the AIS
3. Reverse mapping from AIS to the real problem

— Part III —

- **Examples of Artificial Immune Systems**
  - Network Intrusion Detection by Hofmeyr & Forrest (2000)
  - aiNet: An Artificial Immune Network Model by de Castro & Von Zuben (2001)
- **A Tour on the Clonal Selection Algorithm (CLONALG) and aiNet**
- **Discussion and Future Trends**

Examples of AIS (I)

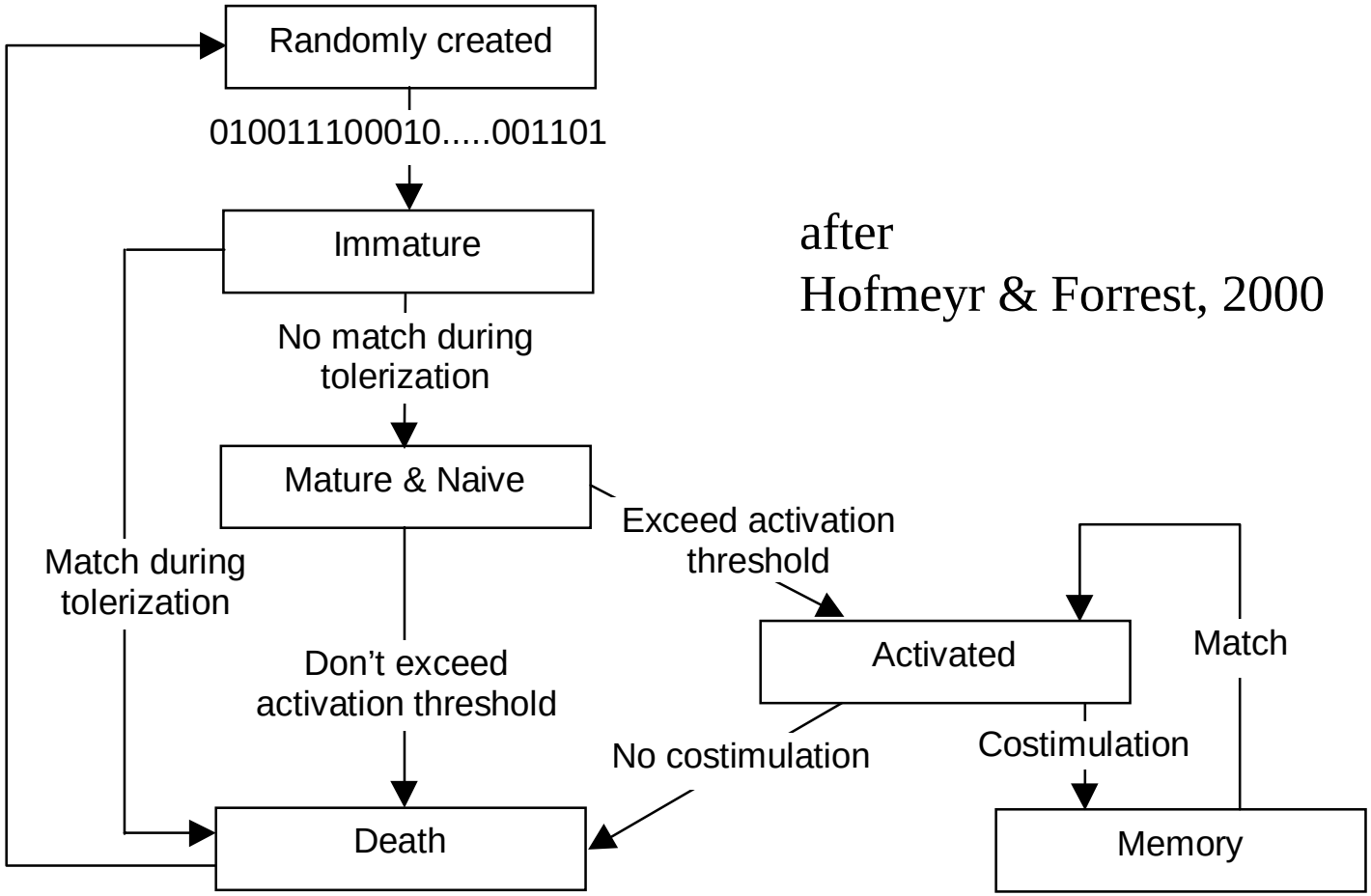
- **Computer Security**
  - direct metaphor
  - virus and network intrusion detection
- **Network Intrusion Detection by Hofmeyr & Forrest (2000)**
  - Rationale: protect a computer network against illegal users
  - Basic cell type: detector that can assume several states, such as thymocyte, naive B-cell, memory B-cell
  - Representation: Hamming shape-space and *r*-contiguous bits rule

Examples of AIS (II)

Immune System	Artificial Immune System
Receptor	Bitstring
Lymphocyte (B- and T-cell)	Detector
Memory cell	Memory detector
Pathogen	Non-self bitstring
Binding	Approximate string matching
Circulation	Mobile detectors
MHC	Representation parameters
Cytokines	Sensitivity level
Tolerization	Distributed negative selection
Co-stimulation: signal one	A match exceeding the activation threshold
Co-stimulation: signal two	Human operator
Lymphocyte cloning	Detector replication

Examples of AIS (III)

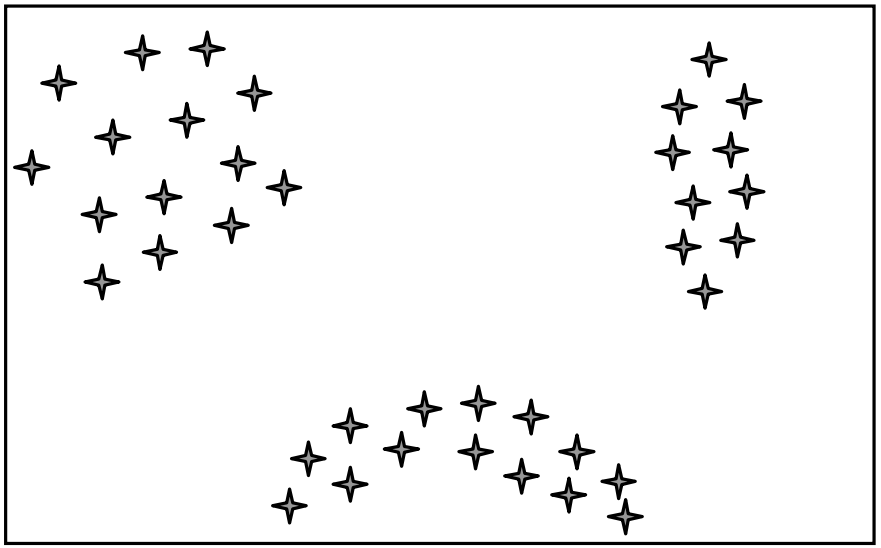
- **Life-cycle of a detector**

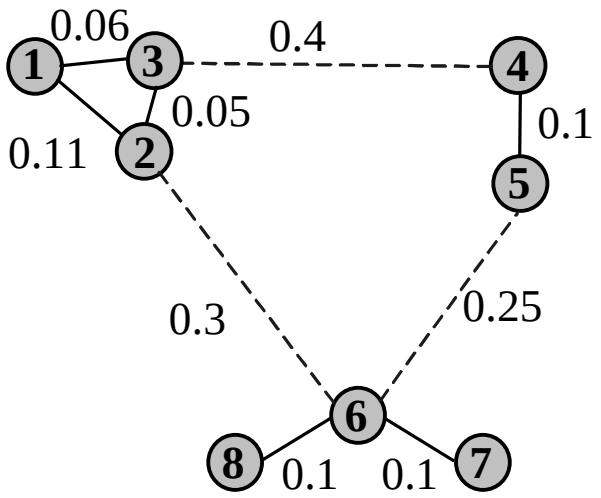


after
Hofmeyr & Forrest, 2000

Examples of AIS (IV)

- **aiNet: An Artificial Immune Network Model**
  - The aiNet is a *disconnected graph* composed of a set of nodes, called *cells* or *antibodies*, and sets of node pairs called *edges* with a number assigned called *weight*, or *connection strength*, specified to each connected edge (de Castro & Von Zuben, 2001)





Examples of AIS (V)

- **Rationale:**
  - To use the clonal selection principle together with the immune network theory to develop an artificial network model using a different paradigm from the ANN.
- **Applications:**
  - Data compression and analysis.
- **Properties:**
  - Knowledge distributed among the cells
  - Competitive learning (unsupervised)
  - Constructive model with pruning phases
  - Generation and maintenance of diversity

A TOUR ON CLONALG AND aiNet . . .

Discussion

- **Growing interest for the AIS**
- **Biologically Motivated Computing**
  - utility and extension of biology
  - improved comprehension of natural phenomena
- **Example-based learning, where different pattern categories are represented by adaptive memories of the system**
- **Strongly related to other intelligent approaches, like ANN, EC, FS, DNA Computing, etc.**

Future Trends

- **The proposal of a general framework in which to design AIS**
- **Relate AIS with ANN, EC, FS, etc.**
  - Similarities and differences
  - Equivalencies
- **Applications**
  - Optimization
  - Data Analysis
  - Machine-Learning
  - Pattern Recognition
- **Hybrid algorithms**

References (I)

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