A Spatial Clonal Selection Algorithm

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Technical Report 070531A
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***Abstract*-The clonal selection principle describes the selection and maturation of lymphocytes, accounting for the diversity of the antibodies they produce and the tolerance they have to self-antigens. The theory does not exist in isolation, the receptors, the host, and the antigens have a context that is commonly ignored when this principle is realised as a computational intelligence algorithm. This work attempts to provide context to the principle by introducing a spatial structure in which to house membrane bound receptors, and which simple clonal selection operations (as previously defined for the elaborated clonal selection algorithm) are applied.**

Keywords-Artificial Immune System, Clonal Selection Algorithm, Spatial

I. INTRODUCTION

The clonal selection algorithm accounts for the diversity of antibodies and the tolerance of the acquired immunity for self-antigens [2]. The processes of selection and maturation of lymphocytes described by the theory occur in the spatial distributed confines of the host organism lymphatic system [1]. In fact, the spatial organisation may be required to provide context to guide emergent specificity [3]. This work proposes a spatial repertoire as an extension to the elaborated clonal selection algorithm (ECSA) [4].

Section II introduces the spatial clonal selection algorithm with a focus on spatial competition, exposure partitioning, spatial replacement, and visualisation of the repertoire. Section III discusses some interesting implications of using a spatial-based repertoire in the context of the T-cell mediation algorithm and receptor movement.

II. SPATIAL CLONAL SELECTION

The elaborated clonal selection algorithm provides a top-end selective pressure (competition for activation based on affinity to antigen), and back-end replacement pressure (competition based on historic usefulness in terms of activations, and genetic similarity). In envisaging the repertoire as existing in a spatial environment an additional level of competition is introduced called spatial competition. This competition puts pressure on receptors in the same spatial neighbourhood to compete with each other. This pressure may be used for either the activation of receptors, the replacement of receptors, or both.

***Spatial Competition**: Competition between receptors that are in the same neighbourhood on an arbitrary spatial structure*

The spatial repertoire structure provides a manifestation of the space complexity limits imposed on repertoire size, and imposes relationships between arbitrary neighbouring receptors. A simple one or two-dimensional lattice spatial structure is used in which receptors occupy grid positions of the lattice, and the ends of the structure wrap around, removing edge effects and creating a torrid. The structure may be an equally arbitrary number of dimensions, although low dimensionality facilitates visualisation, an effect to be discussed later.

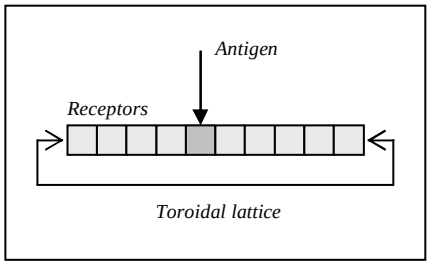

Figure 1 - Depiction of a one-dimensional toroidal lattice

A. *Spatial Selection*

The spatial structure may be exploited in the antigenic selection step (Step3) of the algorithm. This step is responsible for selecting those receptors from the repertoire, which compose the activated set, which is later subjected to cloning and maturation (in Step4). In an unchanged selection scheme, the repertoire is evaluated (a), scanned for the highest affinity receptor, which is returned to address the needs of the antigen (b), and an activated set is selected from high-affinity receptors (c). The activate set may be conceptualised as the selection of repertoire members from across the spatial structure.

***Antigen Partitioning**: Antigen signals may be partitioned such that regions of the spatial repertoire are assigned responsibility (activation set composition) for antigenic representational volumes (bit strings)*

One may partition antigenic signals and match them to regions of the spatial structure, such that regions are directed to be responsible for specific antigenic signals. Given that a bit string representation is used, a natural example would be the partitioning of the antigenic representation space into halves, quarters (or another suitable high level of division) and assign each partition

of the input space to a equal sized partition of the spatial structure. This partitioning scheme would be implemented such that activated sets of receptors may only be drawn from the allocated region of spatial structure, thus putting pressure on the region to produce and develop receptors suitable to the allocated portion of the input space. This process may be assisted by augmenting replacement such that clonal progeny of the activated set are replaced into the same spatial partitions. Some concerns with this approach is that effective receptors for representational volumes may be developed outside of allocated regions and not exploited. Further, without inter-region competition, the partitions may be considered isolated repertoires such that the partitioning prevents the take-over or resizing of spatial regions with proportion to signal frequency and complexity.

***Concern**: Arbitrary partitioning of the input space is likely to result in the over and under allocation of resources to input signals, which in turn will handicap system performance*

B. ***Spatial Replacement***

The spatial structure may be exploited in the integration of clonal progeny into the repertoire, specifically in the selection of receptors in the repertoire to replace (Step5 of the algorithm). Spatial-competition for replacement presupposes that receptors in spatial neighbourhoods have a similar genetic composition. This presumption may supplant the genetic similarity crowding-based competition of the elaborated clonal election algorithm. Thus, rather than clonal progeny competing with genetically similar receptors searched across the entire repertoire, the spatial replacement suggests that such competition may be restricted to the spatial neighbourhood the progenitor receptor. Thus, there is a gain in computational efficiency at the space complexity cost of maintaining receptor neighbourhoods.

***Spatial Replacement**: The integration of clonal progeny into the repertoire is achieved using a spatial-based competition. Thus, spatial regions of the structure become representative (facilitating clustering) of genetic composition*

Lattice: The spatial structure in which the repertoire of receptors is placed. Each receptor is associated with a position in the lattice. A lattice may be n-dimensional (lower dimensions facilitate visualisation), and toroidal (to remove edge effects for operations on the lattice)
Neighbourhood Function: A spatial-based (geometric) function for selecting those receptors in the spatial structure (lattice) in the repertoire that will compose the supplant set (neighbourhood set). An example function is those receptors adjacent to a clonal sets activated cell in the repertoire

Figure 2 - The principle components of the spatial clonal selection algorithm

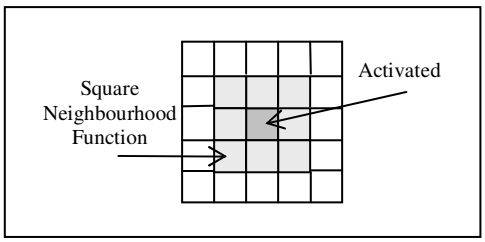

Figure 3 - Depiction of a 2D lattice with a square neighbourhood function around an activated receptor

In effect, cell lines are associated with regions of the spatial structure, which is defined by the early and continued dominance of receptors in regions for specific similar antigenic signals. The replacement strategy thus facilitates a mapping of the antigenic space onto the lower-order topology of the spatial repertoire. Thus the axiom of similar receptors taking responsibility for similar antigen is bonded to the lattice structure, facilitating the self-organisation of receptors to input signals (in a binary space), and the preservation of input signal topology (although in compressed form).

***Self-Organizing Receptors**: Cell lines take residence in regions of the structure, antigenic signals are associated with cell lines, and thus, regions of the structure automatically compete for responsibility for antigenic signals.*

The principle of a spatial replacement algorithm is that genetically similar receptors compete for a position in the repertoire. If a spatial repertoire is used without neighbourhood-based competition for replacement, then it is expected that clonal sets automatically compete for spatial regions. Further, it is expected that these regions will be spread across the structure, and that the clonal sets progenitor will be the genetically most similar region (region the size of a single receptor). Spatially restricted replacement may be implemented as clonal sets competing with the activated receptors spatial neighbourhood. This suggests that the clonal set the size or smaller than the selected neighbourhood.

***Principle**: Progeny compete with progenitor's spatial neighbourhood*

There is expected to be an evolution of spatial neighbourhoods as follows. Initially receptors for a given antigen compete from disparate regions of the spatial structure. Spatial-replacement results in the neighbourhood takeover by winning receptors, increasing the allocation of resources to a high-affinity cell line. Eventually, after a time of spatial organization, activation sets for known antigens will be contributed from specific regions of the structure that take responsibility for input signals.

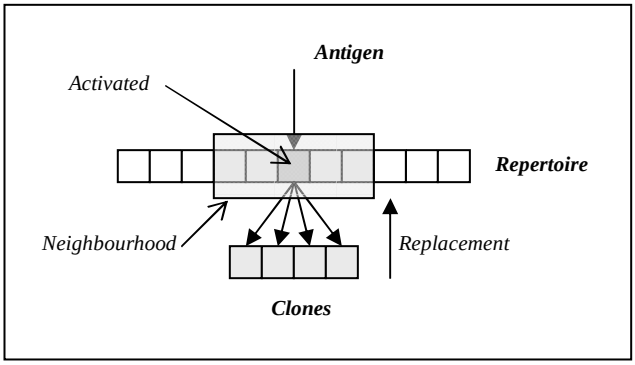

Figure 4 - Depiction of clones competing in the neighbourhood of their progenitor

Dominant receptors put pressure on their neighbourhood to conform to the antigenic signals to which they dominant. Dominance leads to neighbourhood takeover which results in the emergent effect of self-organized responsibility. The dominant

receptors become the memory cells, and their neighbourhood are the effector cells for a given antigen. Those regions of the structure that are neglected by activation (do not win), become regions that memory receptors may expand into, and which naïve cells may gain entrance into the structure, and attempt recruitment into the structure.

***Spatial Cell Types**: Dominant receptors become implicit memory cells, with a cluster of effector cells in the surrounding spatial neighbourhood, regions are separated by underutilised valleys, which provide an entry point for naïve receptors and takeover real estate for dominant receptors*

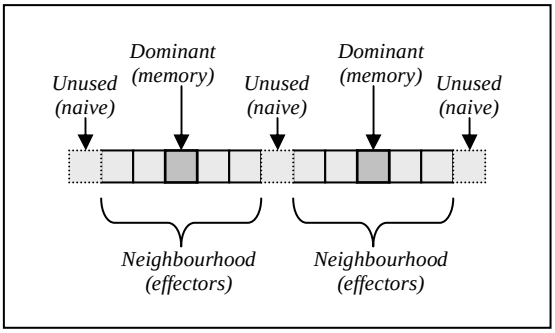

Figure 5 - Depiction on the expected self-organizing behaviour of the repertoire and related cell types

C. *Visualisation*

The use of a low-dimensional lattice (one, two, or three-dimensional) facilitates the visualisation of the repertoire. Spatial competition introduces spatial meaning between positions in the lattice, such that visualisation of the lattice can highlight relationships and facilitate the extraction of qualitative information from the repertoire. The following provides some examples of the qualitative information that extracted from a visualised repertoire.

Receptors: Average difference in receptor composition for each position in the lattice compared to positions in their neighbourhood
Antigen Signals: Average difference in received (activation) antigenic signals for each position in the lattice compared to the positions of their neighbours
Activation Frequencies: Histogram of relative activation frequencies for receptors across the lattice
All-Time Activations: Histogram of absolute activations across lattice positions
Replacements: Histogram of the absolute replacements across lattice positions
Real-Time Affinities: Map of relative receptor affinities for a given antigenic input signal, an aggregation of similar antigenic signals will highlight the *hotspots* (regions) of the lattice that have specialised for partitions of the antigenic signal space
Concepts: Concepts may be associated with receptors (such as classes via a feedback or labelling process), thus a map of receptor concept distributions across the lattice can be produced

Figure 6 - Example qualitative information that may be extracted from a visualised spatial repertoire

III. DISCUSSION

Exploitation of the spatial structure as an upfront pressure results in the partitioning of input signals to regions of the spatial structure, henceforth called the ***Upfront Method*** This has the benefit of limiting the 'scope of interest' of input signals space for regions of the lattice, with the problems associated with selecting meaningful ways of partitioning the signal space. All resources are employed for a specific task, although not all the allocated resources may be required for their allocations.

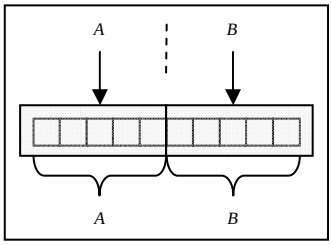

Figure 7 - Depiction of the explicit discrimination of input signals and the biasing of the adaptation that results

The exploitation of the spatial structure as a backend pressure results in the implicit partitioning of the input space and self-organization of receptor clones to take responsibility for the automatic partitions, henceforth called the ***Backend Method***. This has the benefit of proportionate allocation (specialisation) of resources for the automatically identified complexities of the input space with the computational and delay costs for the self-organising process. Resource allocation is determined automatically, although not all resources may be utilised effectively.

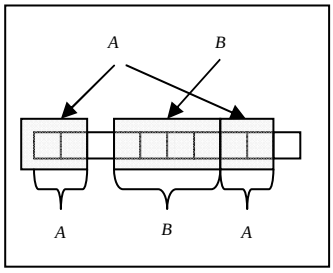

Figure 8 - Depiction of the unfettered response to input signals and the implicit adaptation that results

An interesting observation is that one method will lead the second, such that the explicit exploitation of the spatial competition of both ends is not required. The application of upfront spatial partitioning will force regions to adapt to input signals, thus result in replacements occurring in the same region, reinforcing the partitioning. The application of backend partitioning with self-organize the responsibility for antigenic signals via replacement, which will reinforce future input signals being directed to responsible areas of the spatial structure.

***Asymmetry Principle**: Spatial pressure need only be exploited at a single end (selection or replacement) of the system, and will be provided at the other end implicitly*

It is further proposed that such a symmetrical property (selection, replacement) also applies to affinity-based pressures, and genetic composition (similarity) based pressures.

A. *T-Cell Mediation*

T-cell mediation was introduced in a previous work [5] to provide a secondary (verification) signal to

activated receptors before they may be rewarded with proliferation and maturation. This was achieved through the introduction of a second repertoire of receptors with the purpose of detecting and responding to receptors in the activated set (B cells) of the first repertoire. The result is a system in which two repertoires of pattern recognition receptors co-adapt the first layer in response to input signals, and the second layer in response to a mapping of the input signals.

A spatial relationship may be introduced, firstly for the receptors in each repertoire, and then between the repertoires. A natural implementation would provide two repertoires of the same size aligned on the vertical axis, such that there is a one-to-one correspondence between the repertoires. Thus, if a backend (replacement spatial pressure) was employed, then the first repertoire would self-organize to the input signals, and the second repertoire would self-organize to the first repertoire. A spatial neighbourhood function may be used to match a single activated receptor of the first repertoire onto an activated set in the secondary repertoire. This simple configuration thus provides a self-organizing layer (back-end method), followed by a mapping layer (front-end method), exploiting the properties of both previously specified spatial configuration methods.

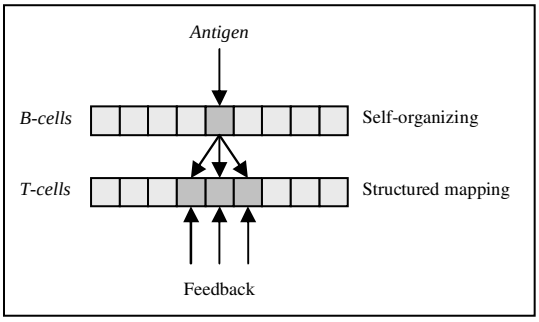

Figure 9 - Depiction of a natural application of the spatial repertoire to the T-cell mediated algorithm

The converse configuration may be employed (structured, unstructured), and combinations (see Table 1).

B-cells	T-cells	Summary
Upfront	*Upfront*	Structured (self-organizing) mapping end to end
Upfront	*Backend*	Structured organisation of input signals with an unstructured mapping onto concepts
Backend	*Upfront*	Unstructured organisation of input signals with a structured mapping into concepts
Backend	*Backend*	Unstructured (self-organizing) mapping end to end

Table 1 - Summary of the configurations spatial configurations for the T-cell mediated algorithm

The application of a spatial structure facilitates the use of spatial competition that may supplant genetic composition (similarity) based competition, providing both structure and unstructured (self-organizing) mappings between repertoires.

B. *Receptor Movement*

The spatial structures allocates positions to receptors, thus a natural extension is for those positions to change by allowing receptors to move between positions on the lattice. The movement of receptors facilitates spatial restrictions on the operations that are applied to receptors (such as selection).

***Information Sharing**: In a partitioned exposure regime, receptor movement may facilitate the sharing and exploitation of acquired knowledge between specialised reception regions*

Movement may be used with a partitioned exposure regime (upfront method) on the spatial structure such that receptors in one region of the structure that are specialised for a partitioned input signal may be shared and exploited by other regions. This information sharing would only be useful if (1) the shared receptors are meaningful and can be exploited by other input signals and (2) if the loss of a receptor from a region did not detrimentally degrade performance of the region for its antigenic signal.

The proposal of movement on a spatial lattice provides a natural bridge from the recent work on single repertoire clonal selection algorithms (elaborated, T-cell mediated, inter-receptor recognition, spatial) with multiple repertoire models and the concerns of recirculating and recruiting receptors between repertoires.

ACKNOWLEDGMENTS

Tim Hendtlass for his patience and for providing useful feedback on drafts of this paper

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