An Adaptive Systems Formalism

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Abstract - **Adaptive systems are difficult to describe, difficult to investigate, and extremely difficult to compare. In his seminal investigation of adaptive systems, Holland proposed an adaptive systems formalism specifically to address these concerns. This straightforward formalism may be used as a general framework for describing and investigating adaptive systems, and examples of both of these cases are discussed. This work promotes the adoption of the formalism in the field of artificial immune systems, and provides the immunological example of the clonal selection theory 'adaptive plan'.**

Keywords- Adaptive Systems, Formalism, Clonal Selection Theory, Artificial Immune Systems

I. INTRODUCTION

What is Holland's adaptive systems formalism, and how may this formalism be applied to the investigation adaptive systems?

Adaptive systems are difficult to define, compare, and evaluate and formal tools are necessary for the investigation of these systems. Holland proposed a formalism in his seminal work on adaptive systems [5] which provides (1) a general manner in which to define an adaptive system. Phrasing systems in this way provides a framework under which: (2) adaptive systems may be evaluated and compared relative to each other, (3) the difficulties and obstacles of investigating specific adaptive systems are exposed, (4) abstracted principles may be distilled. Ultimately, the formalism may provide a research methodology for the investigation of adaptive systems. This work provides a summary of the Holland's seminal adaptive systems theory including a number of examples phrasing adaptive systems within the formalism and using it as a framework for investigating adaptive plans. Finally the immunological clonal selection theory if phrased as an adaptive plan, highlighting the clear benefits and untapped potential of adopting the formalism for the investigation of artificial immune systems.

II. ADAPTIVE SYSTEMS FORMALISM

This section presents a brief of Holland's adaptive systems formalism ([5], Chapter 2). This presentation focuses particularly on the terms and their description, and has been hybridised with the concise presentation of the formalism by De Jong [6] (page 6). The formalism is presented in two sections: (1) Primary Objects and (2) Secondary Objects.

Primary Objects: These are the obvious objects of an adaptive system: the environment (e), the strategy or adaptive plan that creates solutions in the environment (s), and the utility assigned to created solutions (U).

Term	Object	Description
e	Environment	The environment of the system undergoing adaptation
s	Strategy (Adaptive Plan)	The adaptive plan which determines successive structural modifications in response to the environment
U	Utility (payoff)	A measure of performance or payoff of different structures in the environment. Maps a given solution (A) to a real number.

Table 1 - Summary of primary objects in the adaptive systems formalism

Secondary Objects: These objects extend beyond the primary objects and flesh-out the formalism. They suggest a broader context than that of the instance-specific primary objects, permitting the evaluation and comparison of sets of objects such as plans (S), environments (E), search spaces (A), and operators (O).

Term	Object	Description
A	Search Space (Solutions or Structures)	The set of attainable structures and the domain of action for an adaptive plan. An instance of which is a single solution to the problem.
E	Environments	The range of different environments, where e is an instance. It may also represent the unknowns of the strategy about the environment.
O	Operators	Set of operators applied to an instance of A at time t to transform it into A(t+1)
S)	Strategies (Plans)	Set of strategies (where *s* is an instance) and plans applicable for a given environment, that use operators (from the set O). Such strategies may be compared. In particular this refers to the constraints that apply as to what strategies may be applicable
X	Criterion	Criteria used to compare strategies (in the set S), under the set of environments (E). Take into account the efficiency of a plan in different environments.
I	Feedback (Signals)	Set of possible inputs or feedbacks from the environment providing dynamic information to the adaptive system about the performance of a particular solution (A) in a particular environment (E)
M	Memory	The memory or retained parts of the input history (I) for a solution (A)

Table 2 - Summary of secondary objects in the adaptive systems formalism

A given adaptive plan acts in discrete time (t) which is a useful simplification for analysis and computer simulation. A framework for a given adaptive system requires the definition of a set of strategies (S), a set of environments (E), and criterion for ranking strategies

(X). A given adaptive plan is specified within this framework given the following set of objects; a search space (A), a set of operators (O), and feedback form the environment (I). Given the definition of these terms, Holland defines a number of general theorems (some of which are quite intuitive). They are not reproduced here for brevity (see [5] Chapter 2). Holland proposes a series of fundamental questions concerning adaptive systems, which he rephrases within the context of the formalism (see Table 3).

Question	Formal
To what parts of its environment is the organism (system, organization) adapting?	What is E?
How does the environment act upon the adapting organism (system, organisation)?	What is I?
What structures are undergoing adaptation?	What is A?
What are the mechanisms of adaptation?	What is O?
What part of the history of its interaction with the environment does the organism (system, organisation) retain in addition to that summarised in the structure tested?	What is M?
What limits are there to the adaptive process?	What is S?
How are different (hypotheses about) adaptive processes to be compared?	What is X?

Table 3 – Fundamental questions regarding adaptive systems [5] (page 29)

III. EXAMPLES

This section provides a few examples of phrasing adaptive systems using the formalism and examples as to how the formalism may be used as a framework in the investigation of adaptive systems. Holland provides a series of illustrations rephrasing common adaptive systems in the context of the formalism ([5] (page 35-36). Examples include; genetics, economics, game playing, pattern recognition, control, function optimization and the central nervous system. Two examples taken from that work are provided (see Table 4 and Table 5).

Genetics (Biology) Adaptive System

Term	Domain Specific Meaning
Search Space (A)	Populations of chromosomes
Operators (O)	Genetic operations such as mutation, crossover, inversion, dominance modification, translocation and deletion
Strategies (S)	Plans that involve reproduction based on fitness with the application of genetic operators
Environments (E)	Set of possible fitness functions
Criterion (X)	Comparison of plans based on average fitness of populations produced

Table 4 - Summary of genetics adaptive system example

Function Optimization Adaptive System

Term	Domain Specific Meaning
Search Space (A)	Domain of the function to be optimized
Operators (O)	Procedures for generating a new point in the domain from a set of possible points
Strategies (S)	Plans for applying procedures from O to generate new points on the basis of observations
Environments (E)	An indexing set corresponding to the initial uncertainty about the function being optimized
Criterion (X)	Ranking strategies performance

Table 5 - Summary of function optimization adaptive system example

Holland goes on to apply the formalism to investigate his schemata theory, reproductive plans, and genetic plans. From working within the formalism, Holland makes six observations regarding obstacles that may be encountered whilst investigating adaptive systems ([5] page 159-160):

- The high cardinality of A – makes searches long and storage of relevant data difficult
- Appropriateness of credit – knowledge of the properties about 'successful' structures is incomplete, making it hard to predict good future structures from past structures
- High dimensionality of U on an e – performance is a function of a large number of variables, difficult for classical optimization methods
- Nonlinearity of U on an e – many false optima or false peaks, resulting in the potential for a lot of wasted computation
- Mutual interference of search and exploitation – the exploration (acquisition of new information), exploitation (application of known information) trade-off
- Relevant non-payoff information – the environment may provide a lot more information in addition to payoff, some of which may be relevant to improved performance

Cavicchio provides perhaps one of the first applications of the formalism (after Holland) in his doctoral work investigating Holland's reproductive plans [3] (and to a less extent in [2]). He summarises the formalism, presenting essentially the same framework, although he provides a specialisation of the search space (A). The search space is broken down into a representation (codes), devices (solutions), and a mapping function from codes to devices. The variation highlights the restriction the representation and mapping have on the designs available to the adaptive plan. Further, such mappings may not be one-to-one, thus there may be many instances in the representation space that map to the same solution (or the reverse).

Although not explicitly defines, Holland's specification of structures (A) is clear in pointing out that the structures are not bound to a level of abstraction – that his definition covers structures at all levels. Nevertheless, Cavicchio minor specialisation for representation-solution mapping is particularly useful in his exploration of reproductive plans (early genetic algorithms). Cavicchio proposes an adaptive system is 'first order' if the utility function (U) for structures on an environment encompasses feedback (I). He goes on to describe the potential independence (component wise) and linearity of the utility function with respect to the representation use.

De Jong also uses the formalism to investigate reproductive plans in his doctoral research [6]. He indicates that the formalism covers the essential characteristics of adaptation, where the performance of a solution is a function of its characteristics and its environment. Adaptation is defined as a strategy for generating better-performing solutions to a problem by reducing initial uncertainty about the environment via feedback from the evaluation of individual solutions. De

Jong uses the formalism to define a series of genetic reproductive plans, which he investigates in the context of function optimization.

IV. Discussion

Holland's work on adaptive systems, along with collaboration with colleagues at the Santa Fe Institute evolved into the field (and formalism) of Complex Adaptive Systems (CAS) [4]. Nevertheless, the adaptive systems formalism Holland proposed in 1975 is distinct and remains a useful tool, particularly in the phrasing and investigation of biologically inspired adaptive plans in computers.

One may consider the application of the formalism to the immune system, and to the inspired field of artificial immune systems. For example, the clonal selection theory may be considered an adaptive plan not too dissimilar to Holland's genetic reproductive plan, and is easily phrased in the formalism (see Table 6). The clonal selection theory in essence describes the diversity of antibodies of the acquired immune system. The strategy involves the selection of clones of lymphocytes by antigen based on affinity, and subsequent clonal expansion and hypermutation of cells, which results in an improved immune response to the triggering antigen (and related structures).

Term	**Clonal Selection Theory**
Search Space (A)	Lymphocyte receptors. This may be reduced to the genes, amino acids, and protein conformations. One may also wish to consider the 'shape space' formalism [1] for receptor placement and coverage in a detector space.
Operators (O)	The antigen-based selection of lymphocytes, clonal expansion of selection cells, and the hypermutation of progeny cells. Beyond rudimentary clonal selection theory, one may also consider additional operators such as lymphocyte migration, population homeostasis, and genetic-based generation of lymphocytes.
Strategies (S)	Combinations and varied implementations of the clonal operators: selection, expansion, and hypermutation.
Environments (E)	The range of different antigenic environments. There are clear additional constraints such as the genetic and biological limitations of receptor configuration and antigen presentation. One may also abstract antigenic environments to that of pattern recognition.
Criterion (X)	Rank plans based on the ability to detect and neutralise antigen. This may be reduced to general repertoire properties such as; responsiveness, plasticity, robustness, etc.
Utility (U)	Affinity (binding quality or complementarity of structure) is the utility measure of an individual structure given a single antigen-lymphocyte interaction.
Memory (M)	Memory is captured in the repertoire of lymphocytes. This occurs both explicitly in the memory cells that retain a long-term high-affinity impression of antigen exposures, and in the refined (small variations) repertoire of receptors that embody the bind accumulation of useful variation (reminiscent of neo-Darwinian evolution).
Feedback (I)	The environment embodies feedback in antigen. The repertoire exists to detect (be selected by) antigen. The detriment to the organism if harmful antigen (pathogens) are not neutralised or neutralised with a significant time lag is illness, and potentially death. Receptor affinity for antigen relates to responsiveness of the system.

Table 6 - The clonal selection theory rephrased in Holland's formalism

It is believed that the adoption of the reviewed formalism will provide an invaluable tool for investigating immunological-inspired adaptive systems. The formalism has clear and immediate benefits not only in elucidating the clonal selection theory as an adaptive plan, but also in facilitating the comparison of the (immunological) adaptive plan to the genetic (and other) adaptive plans. Further, the fundamental questions posed by Holland of an adaptive system (see Table 3) are broadly addressed given the terse phrasing of the theory.

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