Designing Complex Adaptive Systems for Defence

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The complexity of defence systems has grown rapidly in recent years and has arguably already reached a level that challenges our human ability to understand, manage and steer the resulting highly interdependent and nonlinear defence enterprise. The next generation of defence systems must be more adaptive and agile, and must incorporate sufficient intelligence into their design to reduce the demands on human management. We can learn something about how to do this by examining naturally arising complex adaptive systems, and hence drawing insights into the research challenges defence has to address to bridge the gap between current system design practice and the evolution of future truly adaptive complex defence systems.

Introduction

Never has the design of defence systems been so complex. Systems design in a context where the demands and tasks, threats and opportunities are both unpredictable and in rapid flux is a serious challenge. Strategic planning is often conducted in the face of massive uncertainty across many dimensions (Davis, 2002). The increasing rate of technological change provides new opportunities equally to the defence force and to potential adversaries. Advances can erode the value of existing systems and force multipliers, sometimes even before they are introduced into service. Designers are unable to optimise systems in this environment. Traditional methods of developing, acquiring and operating systems are reaching their upper limit of effectiveness given the level of complexity of defence systems and operations.

To overcome these limits requires an approach capable of making and implementing adequate (as opposed to optimised) decisions rapidly to deliver quickly and accurately the desired outcomes while avoiding unwanted outcomes. Research into Complex Adaptive Systems (CAS) seems to offer ways of working with (or perhaps even exploiting) the complexity of a system rather than trying to contain or suppress it. New approaches in this interdisciplinary field have been applied to many naturally arising complex adaptive systems in order to identify fundamental properties of complexity. Molecules, brains, ecologies, economies, and even open source software development (Axelrod & Cohen, 2001) have been investigated as complex adaptive systems, with deep similarities being found in the meta-structures of these disparate problem domains, suggesting that a common CAS-based conceptual framework may underpin them all. Such a framework is likely to yield a rich harvest of insights and advances in each of the fields it applies to through exploring analogous features and phenomena.

CAS are characterised by many agents or elements interacting in many different ways, giving rise to a vast number of possible patterns of behaviour. Consequently a simple model of cause and effect cannot accurately model the networked causality of CAS. The behaviour of the system is described as emergent, not because it is necessarily unpredictable or unexpected, but because it requires concepts for its description which simply don't apply at the next level down of individual interactions between the system's elements. Particles of a molecule do not exhibit chemistry, neurons do not individually produce consciousness, nor can an individual in an economy demonstrate the pattern known as recession. A key emergent property of CAS is adaptation to their environment. Adaptation enables the system to be responsive to change and thrive in the face of uncertainty, even when the elements are brittle and cannot adapt. The classic illustration of this phenomenon is the "Ant Fugue" (Hofstadter, 1979) where individual ants, by following simple rules of behaviour, maintain a complex distribution of castes within the ant colony system.

Other domains have already benefited from the application of CAS thinking. Active research is applying the results to such diverse subjects as adaptive autonomous agent communication (Steels, 2000), and multilateral trade issues (Higgs, 2001). Within defence, Ilachinski's (1996) Land Warfare and Complexity reports provide an overview of how complex systems theory applies to understanding warfare, making policy decisions and modelling warfare.

In the area of management and public policy, Axelrod and Cohen (2001) argue that the inherent complexity of large organisations can be effectively harnessed by addressing three key concepts and questions:

- Variation: What is the right balance between variety and uniformity?
- Interaction: What should interact with what, and when?
- Selection: What agents or strategies should be copied or weeded out?

These concepts turn out to be fundamental in our analysis of adaptation in this study. By investigating how adaptation benefits naturally arising CAS we are not assuming these insights automatically apply in the defence context. Instead we seek inspiration for new hypotheses about force development, and critically examine old assumptions about how defence is organised, how command is exercised, and how resources are allocated. We are not looking for answers, yet; we are looking for better questions.

Properties of Complex Adaptive Systems

It is not trivial to tightly define a complex adaptive system. Nevertheless there is broad agreement as to necessary properties for a system to be considered complex adaptive. Holland's (1995) seven basics of complex adaptive systems provides a simple yet comprehensive set of characteristics: aggregation, building blocks, diversity, nonlinearity, tagging, flows and internal models. Each of these characteristics can be observed at many different levels of defence systems and operations. The obvious and naive approach is to perform a literal translation of the seven basics onto current force structures and systems perspectives. While this may provide limited insight, the full potential for better understanding and improving the way the defence force adapts will only be achieved through a critical examination of the assumptions and rationale behind the current systems and structures. Examples of Holland's seven CAS basics provided in this section are an illustrative rather than comprehensive account of their role in defence systems and operations.

Aggregation describes the way complex behaviours emerge from aggregate interactions of less complex system components. In Army, the capabilities of the individual soldier aggregate up to sections, platoons, and so on to form the more complex capabilities of the whole of force. Another common military perspective on aggregation considers the tactical, operational and strategic levels of warfare.

Aggregation is a system property which enables emergence of a coherent meta-agent from the interaction of agents at the system component level.

Building blocks are discrete components of a system that can be recombined to produce a great many distinct patterns of system behaviour. In defence operations different units can be combined into many different force packages. Planning is another good example of building blocks. A tactical plan can be decomposed into components that are reused in many different scenarios. The close air support, reconnaissance screen and armoured reserve are all building blocks that are added or recombined to produce a unique plan. At the lower level of individual building blocks, we can see these too are comprised of building blocks. An infantry advance has basic building blocks such as fire and movement drills and a range of techniques and procedures that are combined to produce the advance. This nesting of properties at multiple system levels is characteristic of CAS.

CAS exhibit diversity amongst system elements. Diversity occurs because the interactions between system elements provide niche opportunities for specialisation. Defence forces are comprised of a remarkable number of specialist units including air defence, amphibious landing platforms, stealth bombers, engineers and special forces. The diversity of a system is the source of its potential to adapt in the face of external change and conversely, systems with a high degree of uniformity are more likely to fail than to adapt successfully when the context changes significantly.

Nonlinearity is a property of CAS which is often discussed and frequently ends in confusion. In CAS nonlinearity simply means the behaviour of the system may be more complicated than a linear combination of the behaviour of its parts would suggest. Because the majority of analytical techniques assume linearity to make the process of aggregating system components tractable, this property implies that CAS are more difficult to model. Nonlinearity also contributes to two other phenomena of complex systems: deterministic chaos (sensitivity to small disturbances) and self-organisation (insensitivity to small disturbances), which are both discussed further in Richardson et al (2000). Nonlinearity can be seen in the effectiveness of a Combined Arms Team compared with the effectiveness of its components acting in isolation. Warfare is inherently nonlinear, which can be envisaged by the impact of providing an additional capability to one side involved in a conflict. The new capability may prove to be a watershed, may have little or no impact, but most often will not provide a linear increment in attrition ratios. The benefit of the capability depends not only on its strengths and weaknesses, but how they interact with the strengths and weaknesses of all other capabilities on both sides of the conflict.

Tagging refers to an attribute of system elements that enables them to distinguish each other on the basis of the tags and hence have selective or tailored interactions leading for example to the formation of highly-interacting clusters or cohesive aggregates. Tags are widely used in defence, eg Army, Air Force, and Navy have different uniforms that identify their different capabilities. Within Army, Corps have lanyards and Units have badges which identify the personnel who form these aggregates. Without a tagging mechanism to group specialists, aggregating system elements would only ‘average out’ different kinds of elements and hence diversity and specialisation at the aggregate level could not occur.

CAS can be thought of as networks of nodes (the elements), which are connected through their interactions, with resources (such as energy, information, authority, material goods) being processed and transformed at the nodes, and flowing through the network along the connections. As adaptation occurs, the connections between nodes change, creating new patterns of resource flow. In defence, morale, orders and intelligence are examples of resources that flow through networks of force elements connected by physical interaction, radio communication as well as electronic and paper based information dissemination.

Internal models are the last of Holland's seven basic properties and mechanisms of CAS. An internal model is a mechanism that enables anticipation of the outcome from interactions between a CAS and its context. Information about the state of the world is encoded in a model which can be used to sound out different interaction strategies before committing resources in the real world. In defence operations the battlemap provides a model of the current state of the environment. Both computer and seminar wargames provide models where strategies are tested before resources are committed. Training scenarios are another example of encoding information about the context to model plausible responses from different interactions with the context.

The examples above illustrate that defence systems and operations do indeed display the properties common across CAS. An awareness of how these properties and mechanisms manifest in defence systems and operations enables us to understand how the defence force adapts. The mechanisms also suggest leverage points where small parameter changes can influence system behaviour. For example, by changing resource flows, introducing new tags and encouraging diversity we may be able to improve the ability of defence to adapt to an uncertain and changing context.

In summary, a defence force is clearly a large complex organisation which exhibits many examples of the basic properties of CAS, and we argue that as a result there are many adaptive mechanisms already inherent in defence, operating over many different timescales from very short (at the tactical level of military operations) to very long (at the force planning and strategic end of decision making). We further postulate that many of these adaptive mechanisms are not formally designed to serve the endorsed objectives of the force, and that we need to study them in order to understand their operation, and to identify leverage points to improve the overall adaptivity of the force.

Our first step is to study adaptation in naturally arising CAS, and then we will attempt to extend the concepts to the case of deliberately-designed examples of adaptation.

Naturally Arising Complex Adaptive Systems

Adaptation occurs across all levels of a system. Understanding the mechanisms for adaptation in naturally arising complex adaptive systems can provide insight into how designed systems could adapt at different levels. The most important difference to observe when comparing natural CAS to designed CAS is that natural systems do not have any externally defined purpose or meaning. The explanation (see for example Dennett 1995) of biological evolution does not require any teleological driving force. It can be simply understood as a series of natural processes interacting with external pressures. In contrast defence systems and operations are designed for a specific purpose and the fitness measure for this purpose is artificially imposed upon the system. It is therefore imperative that the selection measures and feedback mechanisms contain strong links to the fitness function if adaptation is to drive system evolution in accordance with the system's intended purpose.

Table 1 contains an analysis of adaptation at three levels of complexity of living systems. At the organism level, individuals learn strategies that improve their chances of survival and reproduction. It is the set of strategies, and the propensity for using them, which adapts to a changing context. At the next level, species evolve in response to environmental change, noting that the environment that a species finds itself in includes the ecosystem of which it is a part, that is, all the other species with which it interacts through predation, competition and cooperation. In this case it is the composition and the frequency distribution of the set of genotypes belonging to the species that are dynamic. At the societal level, culture consists of the body of cultural objects (scientific theories, values, beliefs, practices, languages, art, technology) that is developed by and available to some or all of a community. These objects have varying degrees of proliferation within the culture. Over time new objects will be added to a cultural set and the extent of proliferation of individual objects will change in response to the total environment, now including the culture itself. Some, (but clearly not all, nor even most!) aspects of culture are clearly linked to the success of the community, so for the purpose of clarity we will restrict our attention in this analysis to those cultural objects that are directly relevant to the fitness of organisms (to survive and reproduce) and species (to perpetuate) within the society.

The comparison is insightful both in the similarities and differences. A generic model captures the process of adaptation occurring across all three levels of organism, species and society. Each level consists of a set of strategies, whether this is encoded chemically across a neural network, genetically, or extra-somatically within some media container. We can think of a strategy as an algorithm that transforms an input (which is encoded in the state of the system) into an output (react to the context, or invoke another strategy).

Figure 1 illustrates a common model of the adaptation process. The CAS contains a set $\{x_{11},x_{12},....x_{1n}\}$ (of strategies, genotypes or cultural objects respectively for the examples in Table 1) including associated metadata (propensities, or distribution frequencies). Variation by recombination, error, blind search or creative activity is the engine for adaptation and provides a new and larger set $\{x_{11},x_{12},....x_{1n},...x_{1(n+m)}\}$. These new strategies may come from within the CAS or externally from the context (for example imitation). From the enlarged set of possible strategies a subset of strategies must be selected to instantiate within the context. The down-selection mechansim can be a simple random selection, a filtering of strategies according to some metadata criteria, or a competitive bidding process between strategies. A CAS capable of parallel processing (such as species evolution) will instantiate a large number of strategies compared to systems where strategies are processed in serial. The short-listed strategies are then instantiated as interactions between the CAS and its context. The feedback mechanism provides a perception of the success of each strategy. Positive and negative feedback from the interaction must be incorporated in the selection mechanism for adaptation to occur. The selection mechanism results in a new set $\{x_{2j},x_{2k},....x_{2p}\}$ of strategies and adjusts strategy metadata according to the feedback. By incorporating metadata the selection mechanism can produce a richer weighted list of competing effective procedures rather than a binary accept / reject.

The adaptation cycle now operates on the new set of procedures held by the complex adaptive system. This model is highly simplified and in practice occurs more chaotically than the orderly, discrete depiction in Figure 1. Nevertheless it provides a workable simplification for a general model of adaptation in CAS and identifies the mechanisms for variation, interaction and selection.

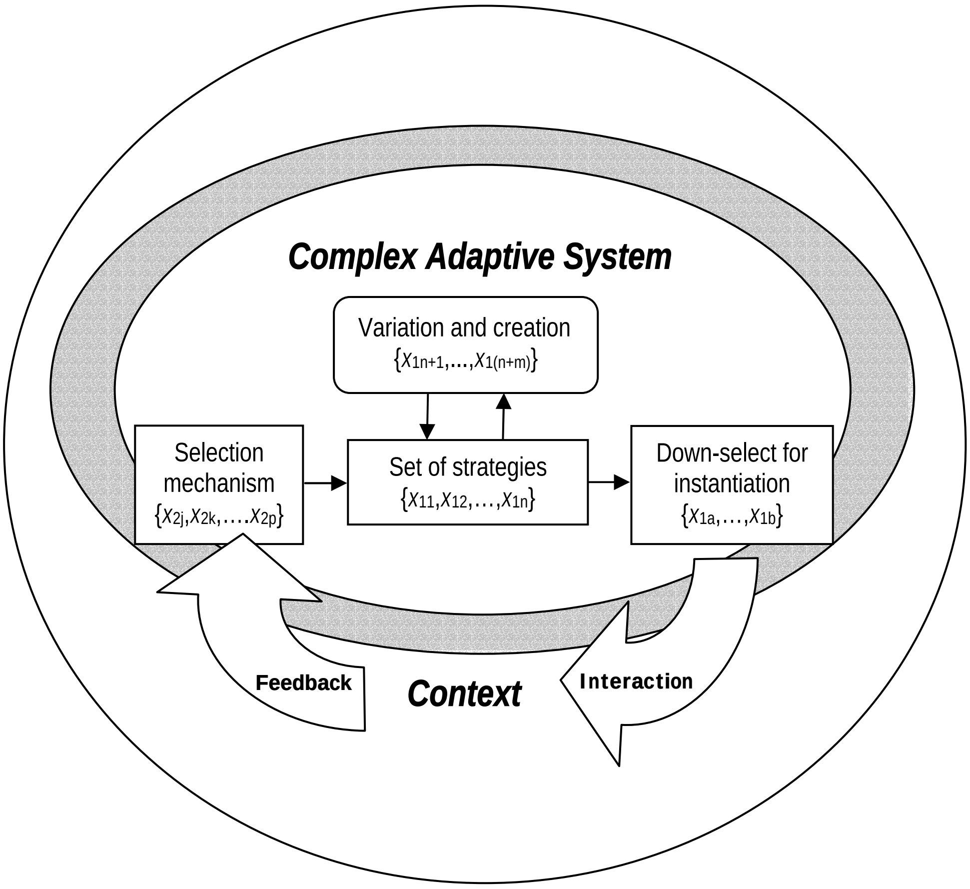

Figure 1. *Model of adaptation for complex adaptive systems.*

Example System **Adaptation**	**ORGANISM** **Learning**	**SPECIES** **Evolution**	**SOCIETY** **Development of Culture**
What is adapting and to what?	Individual's set of strategies for dealing with situations, and associated (possibly context-dependent) propensities for using them adapt. Each strategy in a given situation is expressed as a set of actions or behaviours which mediate the individual's interactions with others and with environment in the tasks of survival and reproduction.	Species' set of genotypes, and the associated distribution frequencies are the parameters which adapt. Each genotype (in a given environment) is expressed in a phenotype with an inherent set of functionalities, which mediate the corresponding individuals' interactions with context and with other individuals of the same species.	A society's set of cultural objects and an associated 'frequency' of objects within the culture adapt over time. There are an indeterminate number of variants of any culture (depending on resolution). Defining a taxonomy is problematic, since there is no hard boundary analogue to the ability to crossbreed Cultural objects are 'published', and mediate asynchronous interaction and communication of ideas between members of society across space and time.
Outcome of adaptation	Learning allows individual to: • Improve effectiveness of existing strategies • Improve ability to choose the most appropriate strategy, and • Develop new strategies to maintain or increase effectiveness in new or changed situations.	Evolution allows species to: • Improve the fitness of existing genotypes in a relatively fixed environment • Improve the fitness of the species by increasing the frequencies of the more successful genotypes at the expense of the less successful, and • Develop new genotypes that produce new phenotype functionalities that can maintain or increase fitness in a changed environment.	Culture allows society to: • Pass on and refine successful strategies • Cooperate to achieve greater utility than is possible through individual action • Through the accumulation of cultural objects, improve the long-term survival of members over time, and • Develop new cultural objects which are more effective in aiding survival in a changed environment.
Degree of parallelism	Strategies are tried essentially one at a time in the real world. However the selection of the 'best' strategy to use in a given situation may involve parallel processing.	Highly parallel processing since each genotype present in the species is simultaneously being evaluated by the reproductive success of the subpopulation bearing that genotype.	Highly parallel since each cultural object is potentially being evaluated by a very large number of proliferators.
Interaction mechanism	• Individual senses situation (threat or opportunity) • Sensing causes neural activation pattern (NAP) • NAP results in choosing a response strategy • Individual experiences consequence. Same process whether context is	• A species 'senses' its context through many interactions - its various subpopulations of genotypes utilising their functionalities to perform tasks required for survival and reproduction. • Species 'experiences' different consequent success rates in those tasks for different genotypes.	• Cultural objects are created and 'published' in some form. • Entities (either individuals or groups) in the society can utilise, modify, re-publish in another form, distribute, create related objects etc. • Such actions can result in various kinds of positive, neutral or negative outcomes for society members. When the context changes, the same information may provide a different outcome, and the metadata for a cultural object must be

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	constant or changed. Consequences will change if context and/or selected strategy changes.	Same process whether context is constant or changed – consequent relative success of different genotypes will change if new genotypes appear and/or if context changes.	updated to reflect this.
Feedback mechanism	Individual senses consequence which generates NAP bringing immediate or delayed pleasure or pain. *Note that an intermediate consequence is required here to link direct consequence with a selection process mechanism(see below) for reinforcement or inhibition.*	Because of different resulting reproductive success rates the frequency distribution of genotypes will be changed. *Note that the direct consequences are directly linked to the mechanisms for reinforcement or inhibition so no intermediate consequence is needed.*	Like evolution, variation and the elimination of error will remove cultures which are self destructive by reducing the size of the society to zero. Feedback is also received at the object level as objects are used in parallel across a society, with mixed results. Positive and negative feedback about objects is passed through networks within the society, influencing the importance and level of use of the cultural objects.
Source of new set members (strategy / genotype / cultural object)	• Random: trial & error • From others: imitation • Creative: recombination • From culture: education	• Mutation • Recombination • Copying errors • Retroviruses	• Scientific research • Creativity • Analysis of recorded information • Misinterpretation
What initiates creation of new set members or affects rate of change	May be random (undirected) or deliberate (individual is searching for novelty or better strategy – requires memory)	The susceptibility of the species to mutations, copying errors etc will determine the rate at which variety is introduced and the range of variety continuously present in the population while the average frequency of reproduction will determine the rate at which the inherent variety is subjected to selection.	Vast number of ideas, practices, structures generated. May be triggered by perceived needs, opportunities, threats. May be triggered by seeking institutionalised rewards for it, or avoiding institutionalised punishments. May be individually motivated (internalised rewards/punishments). Rate affected by all the factors that affect these triggers – huge number of influences!
Selection process mechanism (note that selection here refers to which strategies get retained and reinforced and which get inhibited or discarded)	• Changed response leads to changed consequence • Pleasure or pain from sensed consequences reinforce or inhibit the neural activation pattern that corresponds to choosing that response in the presence of associated stimuli (which may make the choice context-sensitive) • Enhanced or decreased probability of choosing that response in the future in the presence of the same	Tautological since reproductive success is both the measure of fitness and the selection mechanism.	At least one member of society must perceive a benefit from perpetuating a cultural object, and the more entities that value an object, the more likely it is to be proliferated. It is often impossible to remove a cultural object. Alternatively, if sufficient ‘pain’ is experienced from a cultural object, a subset of society may produce a countering cultural object designed to cancel or dampen the effect of the offending object.

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	associated stimuli.		
Down-selection of which strategy gets invoked for a particular interaction	• Whichever has highest propensity given associated factors: preselection of likely ‘winners’ and avoidance of ‘killers’ by modelled interaction with context.	• Chance (whether germ cell with new information ends up in embryo) and then • Viability of total genotype (whether embryo develops) – i.e. there is a crude filtering-out here of totally unworkable genotypes.	• Try it in the world: A member of society publishes a new idea or object which has provided positive experiences in the real world • Try it in your head: A member of society publishes a new theory that has a perceived potential payoff.
What information consists of	• Characterising indicators of situation (associated stimuli = inputs) • Possible strategies (outputs) • A value associated with each strategy in the context of the sensed situation (associated strengths).	• Possible genotypes [i.e. instructions for building proteins (genotype) which determine functionality in the organism (phenotype)] • Frequencies of the various genotypes.	• The direct content (eg text, recipe for action, piece of music…) • Metadata including forms and media in which the information is encoded, importance, historical source and previous usage • Information about the ‘extent’ or ‘accessibility’ of the content.
Where information is encoded	In system between sensing & acting – eg stimulus-response circuits, brain, biochemistry.	In genome: set of genotypes and their frequencies.	Extra-somatic, in media.
What is ‘fitness’?	Likelihood that individual thrives.	Probability that individuals survive and their genes are passed on in viable offspring.	Increased chance of survival for the society.
OUTCOME	More responsive to local environment. Learning improves how a fixed design is used and the gain is local in time and only to the individual.	More responsive to large scale changes in environment. Explores design space neighbourhood and creates new design features.	Allows cumulative learning by retaining lessons from the past, while adapting this body of knowledge to changing circumstances. This ensures that cultural objects remain relevant to the current environment. The gain is distributed across society and across time towards future generations.

Table 1. Analysis of evolutionary adaptation at system levels of organism, species and society.

Examining the differences between adaptation at different system levels reveals how structural properties of a system influence the way in which it adapts, and its effectiveness in finding new and ‘fitter’ sets of strategies. Variation and creation of new information at the species level is mostly blind. This blind search technique is effective only because of hugely parallel operation over relatively vast time scales. In contrast, learning and cultural development are dominated by directed searches across the fitness landscape. While they too utilise an element of chance, creativity, research, analysis and education are all directed activities. Variation with the explicit purpose of increasing fitness will effectively hill climb to improved solutions similar to the current set of strategies, but becomes less effective further away from the current system state, since fitness functions cant be extrapolated very far into unkown territory in the presence of complex nonlinear interactions. In order to discover distant successful configurations or procedures, a series of viable intermediate stepping-stones must exist.

The way each level of a natural CAS interacts with its context differs. A species ‘senses’ its environment by interactions between instantiations of each genotype and their local environment. Interactions modify the environment through the consumption of resources and the production of waste. The species ‘receives feedback’ as the frequency of genotypes in the next generation changes depending on each genotype’s success at survival and breeding. Organisms sense their situation, such as a threat or opportunity. This causes a neural activation pattern which ultimately results in selection of a response strategy. Feedback occurs when the organism experiences a consequence. Importantly, the learning process for an organism utilises an extra type of information than species evolution. By gathering information on the environment before selecting a strategy, the chosen strategy can be context dependent. By maintaining subsets of strategies for different situations, an organism can react much more effectively to a situation than by applying the same set of responses every time. At the third level, cultural development of a society interacts with its context as members of the society adopt ideas from the set of cultural objects and use them in their environment. Feedback is received second-hand as members of society pass their experiences back to the cultural object, altering its metadata. This looser coupling of the interaction and feedback loop can result in a less responsive and / or less sensitive adaptation process.

Selection pressures for the examples in Table 1 also differ. Selection for genotypes of a species occurs automatically through survival and reproduction. Organisms experimenting with new strategies receive a pleasure or pain consequence, which in turn stimulates or inhibits the neural activation pattern of that strategy. This adjusts the probability of using the strategy in the same situation in future. Holland (1995) provides an insightful example of credit attribution that can distribute the payoff of a good strategy across a chain of actions leading to a positive outcome. The credit attribution scheme is like an economy where messages are bought and sold. In this scheme strategies that set the necessary preconditions for the reward receive a share of the credit and become stronger, while ‘cheating’ or losing strategies become weaker. This credit attribution scheme illustrates how strategies with a short term cost but a long-term benefit to the CAS can still thrive. Selection pressures operating upon cultural objects in a society are more complicated. The frequency of cultural objects is a function of multiple decisions made by members of society. A cultural object that is not utilised by any members of the society will tend to die out, since culture needs to be actively maintained. The media in circulation is constantly renewed in a society, and the information in a cultural object must be copied to perpetuate. As well as fading away, a cultural object may be discredited (a metadata attribute) and while it may continue to remain in the cultural set as an idea, is not used by any of the society's members. An object may even be negated by the creation of an opposing idea or object if sufficient negative feedback occurs. For example, a society that adopted the idea "crop specialisation" may introduce an opposing idea, "crop diversity" if a bad experience, such as famine, affected the society and blame was attributed to this cultural object. The extent to which the new cultural object negates the old depends on a number of value judgements and their respective extents of proliferation in the society.

It is interesting to note that in the case of the species and organism of which a society consists, adaptation across the levels three levels are interdependent. As an organism learns new successful strategies, these are published in society resulting in cultural development. Learning of other organisms is then enhanced through access to this culture. This is an important mechanism which transcends the inherently local nature of learning mechanisms, and allows other members of the species to benefit from the accumulated strategies of many other preceding individuals.

Implications for Designing Defence Systems

The previous section identified variation, interaction and selection as the key mechanisms for adaptation and explored different implementations of these mechanisms in naturally arising CAS. Once the role of variation, interaction and selection in adaptation becomes clear it is necessary to re-examine defence policies that influence these mechanisms if we are to improve the defence force's ability to adapt. Some of the policy and design implications for each mechanism will now be discussed.

Once we understand the value of variation in generating new strategies and improving system diversity and robustness we can incorporate this understanding in finding a balance between exploration and exploitation of military capability. The concept of variety as healthy conflicts with military culture which traditionally values cohesion and conformity over diversity. The value and information content contained in multiple competing theories conflicts with the Network Centric Warfare push towards a commonly informed operating picture that suppresses diversity and uncertainty. CAS thinking suggests that a highly disciplined and doctrinally conforming force may be highly optimised to deal with particular types of situations, but in fact be catastrophically unable to respond to radically different situations. The cost of maintaining a high degree of diversity for robustness in the face of unexpected challenges is a reduced efficiency in the face of known ones.

Managing interactions internally between system elements and externally with the context will influence the level of adaptation achieved in defence systems and operations. A surprising result for CAS is that tags, asymmetries and internal system boundaries that limit the extent of interactions can improve system performance and adaptation. With this in mind selecting between hierarchical and flat command and control architectures, the level of communication between organisational components, and internal boundaries between force components are all design decisions that affect adaptation. For example, a highly interconnected force such as discussed by proponents of Network Centric Warfare, is likely to exhibit 'groupthink' or 'premature convergence' to shared views or plans, which might be disastrously wrong in some situations. A CAS point of view would suggest that an optimal network configuration might be highly connected clusters that are more loosely coupled. Such topologies need to be explored in depth for their potential applicability to defence systems and operations.

Without an effective selection mechanism linked to fitness and feedback from interactions a system cannot adapt. The issue for defence is the identification of selection pressures and how they are connected to fitness. The attribution and distribution of credit, both positive and negative, should be as fair and consistent as possible if perpetual improvement is to be achieved. Operational experience captured in lessons learned databases must reinforce success and inhibit failed patterns of behaviour, incorporating appropriate knowledge of the context, but without fostering a risk-averse culture.

Another way to extract implications for the design of defence systems is to identify levels in defence systems and operations corresponding to the naturally arising CAS discussed in the previous section. The most obvious mapping is from organism, species, and society to system in the force, the force, and the world. Adaptive defence systems learn and store information about their local context, capability development evolves to provide improved materiel and effects, while defence as a whole maintains alignment with the needs of and roles required by society. Future research will detail the mechanisms of adaptation at each of these levels in a similar format to Table 1. As with any analogy it is important to explicitly address the differences between naturally arising CAS and human designed CAS. Most significantly, designed systems are developed to fulfil a purpose, which drives the definition of fitness. Because fitness is artificially imposed rather than an implicit result of the environment, system designers need to forge strong links between fitness and selection if adaptation is to provide increasing fitness over time.

Concluding Remarks

Adaptation occurs in defence systems and operations whether it is explicitly designed in or not, since we have shown defence is a CAS. The problem with implicit adaptation is it may work against design efforts and policies. By identifying the mechanisms for adaptation and understanding the nonlinear system dynamics it is possible to predict changes in system configurations that will generate desired outcomes as well as avoiding undesirable side effects.

Bibliography

Axelrod, Robert and Michael D. Cohen. 2001. *Harnessing Complexity – Organizational Implications of a Scientific Frontier*. New York: Basic Books.

Davis, Paul K. 2002. Strategic Planning Amidst Massive Uncertainty in Complex Adaptive Systems: the Case of Defense Planning. *InterJournal,* Complex Systems section. No. 375.

Dennett, Daniel C. 1995 *Darwin's Dangerous Idea*. New York: Simon and Schuster.

Higgs, Darby. 2001. APEC as a complex adaptive system: insights on the problem of multilateralism versus bilateralism from a new science. *APEC Study Center Consortium 2001 Conference.*

Holland, John. 1995 *Hidden Order: How adaptation builds complexity*. Cambridge: Perseus Books.

Ilachinski, Andrew. 1996. *Land Warfare and Complexity, Part I: Mathematical Backgorund and Technical Sourcebook*. Virginia: Center for Naval Analyses.

Ilachinski, Andrew. 1996. *Land Warfare and Complexity, Part II: An Assessment of the Applicability of Nonlinear Dynamics and Complex Systems Theory to the Study of Land Warfare*. Virginia: Center for Naval Analyses.

Richardson, K A, G Mathieson and P Cilliers. 2000. *The Theory and Practice of Complexity Science: Epistemological Considerations for Military Operational Analysis*.