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Elements of a Framework for Studying Complex Systems

Track: C2 Concepts, Theory, and Policy

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Abstract

To complement the traditional linear and reductionism approaches, we are considering holism and the middle-out approach to better deal with the ever-growing complexity of modern command and control systems. In this article, four "complex conditions" (called modalities) are proposed for studying complex systems (CxS) and to characterize their evolution toward superior behaviors. Modalities address multiple notions such as features, properties, complex mechanisms that can be linked together into "interaction diagrams", which help understand complex cause-effect interrelationships in more holistic perspectives. The proposed modalities and approaches form the first version of a complexity framework (CxF). Its use is illustrated with an example involving the NATO C2 Network Centric Operation taxonomy.

Acknowledgements

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1 Introduction

Nowadays man-made systems used in our societies like the Internet are becoming more and more complex[1], hard to control and predict [Poussart, 2007]. They often involve intricate combinations of people that have different perceptions of reality and that are distributed in scattered organizations. In general, they are made of huge numbers of relatively autonomous sub-systems that are "willing" to work together in different modes[2] in order to achieve common goals using sets of communication means and protocols (herein called **components** of complex systems).

Internal rules, values, beliefs, cultures and models of understanding within each component drive or regulate their actions. Their ability to modify, adapt, and survive as a "whole system" in the face of unforeseen situations depends on specific internal conditions such as the decentralization of planning and control and the flexibility of components to spontaneously re-organize and innovate. Judicious sets of specifications and conditions give complex systems (CxS) higher robustness, responsiveness and resilience; making them more stable while operating

[1] The reader is invited to refer to Annex 1 for definitions of some key words related to complexity theory.
[2] Modes can be for instance: cooperation/collaboration, coalition, competition or conflict.

in highly unpredictable and variable environments and contexts. Intricate interrelationships between components of CxSs are at the source of the emergence of complex behaviors such as: self-adaptation, self-recovery, self-healing, and long-term evolution. The capability of the whole is greater than the sum of components' capabilities.

This ever-increasing "complexification" of our world is enabled by the tremendous evolution of communications. It has (and will continue to have) profound effects on the military C2 information systems [Alberts and Hayes, 2007], imposing new challenges to military organizations. For instance, officers in operations that are addressing complex problems shall have a good understanding of the critical "complexity aspects" related to the involved systems and (hostile or not) environments in which they evolve. Moreover, C2 systems operated in theatres of operations must reach levels of sophistication that are at least equal if not higher than those of their environment [Bar-Yam, 2005]. Military procurement must adjust accordingly in order to make systems more efficient and effective in any context[3] and environment. Typically, traditional (and relatively linear) reductionism top-down approaches are not enough to deal with this new complex problematic [CTW, 2006; Braha *et al.*, 2006].

This change of paradigm (imposed to military community) is truly challenging for at least three reasons. First, CxT is still evolving; it is the object of intensive R&D all around the world [Couture, 2006a]. Basic underlying principles and concepts are not necessarily interpreted the same way by different authors and some notions like "emergence" are still not completely understood. Second, theoretical concepts are often abstract and their subtleties are difficult to understand at first glance. This is particularly true for officers that are engaged in complex demanding tasks and in contexts and environments involving very high levels of stress. Moreover, human mental models of understanding that are based on traditional linear top-down reductionism approaches are not well suited to understand such highly interlinked and interdependent concepts. A global or holistic approach involving both the top-down and bottom-up approaches (i.e. the middle-out) appears to be preferable.

Third, there is not at this moment in the literature a complete complexity framework that could be used to study CxSs. As observed in a recent literature survey [Couture, 2006a-d], the definition of concepts[4] of CxT often varies from one author to another, making the formulation of a consolidated framework difficult at this time. For instance, the concept of "aggregation" is considered as a *fundamental element* in [Beech, 2004] while it is considered as *one of the basics of CAS* (i.e. Complex Adaptive Systems) in [Ilachinski, 1996a, 1996b] and [Axelrod and Cohen, 2001] and as a *basic complexity parameter* in [Holland, 1995]. Also, some of these concepts are sometimes used inconsistently with respect to their natural domain(s) of applicability. For instance, terms like "adaptation" or "resilience" of CxSs should normally be associated to the whole system, while terms like "diversity of roles" and "interdependence" should be intrinsic to components of CxSs. These lacks in the literature interfere constantly with the understanding and the use of concepts from the CxT.

The focus of this R&D work is placed on the formulation of a framework (the Complexity Framework; CxF), which helps structure these concepts and ease the building of an integrated picture of understanding. A high priority was put on the practical aspects of the framework, as shown in the next sections of this article. It is proposed to synthesize the intrinsic nature of CxSs with the help of interactions diagrams. A set of four modalities (i.e. descriptors to

[3] Context corresponds here to nowadays complex spectrum challenges which officers are facing on the battlefield: peacekeeping, humanitarian relief or full-scale military deployments.
[4] The word "concepts" includes here complex notions, properties, mechanisms and phenomena of CxS.

group or structure complex notions of CxT) supports the proposed process and helps the exploration of interactions between components of CxSs.

2 Elements of a Complexity Framework (CxF)

2.1 Objectives

The CxF is designed to address some key requirements:

1. the CxF shall be as generic as possible, it should allow to address a wide spectrum of complex problems in different fields or domains;
2. the CxF shall ease the understanding of underlying notions of complexity theory (CxT);
3. the CxF shall provide guidance on how to address complex problems;
4. the CxF shall facilitate the reutilization of any proven solution;
5. the CxF shall reflect and make use of the commonalities that can be found in the scientific literature dedicated to CxT.

In order to satisfy these requirements, it was decided to adopt the Santa Fe Institute approach [SFI, 2007; Holland, 1995]. Researchers at SFI focus on the emergence of a new order when components of CxSs are operating within a state called "Edge-of-chaos" [Langton, 1990, 1991]. Based on a multi-disciplinary approach, they postulate that this new order emerges at the level of the whole (i.e. CxS) when many of its interacting components are willing to improve the global fitness and find new solutions. Their approach involves the study of similarities between different CxSs. It aims at finding underlying principles or premises that would form the basics of a unified CxT. [Holland, 1995] describes the SFI approach in these terms: *The best way to compensate for this loss* ([5]) *is to make cross-disciplinary comparisons of CAS* (Complex Adaptive Systems[6]), *in hope of extracting common characteristics. With patience and insight we can shape those characteristics into building blocks for a general theory.*

2.2 Key Notions for Studying Complex Problems – The Four Modalities

There is not a common and shared way that exists for structuring concepts of CxT but a survey of the scientific literature dedicated to CxT [Couture, 2006a-d] has led to the identification of two **key perspectives**[7] for studying CxSs. The first key perspective is related to the well-recognized notion of **hierarchical level of aggregation**. It allows discriminating features related to interacting components of a CxS (i.e. at a lower level) from those belonging to the whole CxS (i.e. at a higher level)[8]. This key perspective is represented by a horizontal disposition of rectangles in Figure 1: **Level 1** represents components of CxT and **Level 2** represents the whole set of components of Level 1, considered as an entity (i.e. the CxT in this specific case). For instance, the description of "emergence" necessarily involves the notion of levels [Fromm, 2005b]; it is described as originating from interactions between components (Level 1) and it manifests at the immediate adjacent higher level (Level 2).

The second key perspective allows the differentiation between **static descriptions of CxSs** (i.e. CxSs' architecture and properties at one given instant) and their **dynamical**

[5] We are missing the means for generalizing observations into a unified theory.
[6] A CAS is an "instance" of CxS. The acronym "CxS" is used all along this text.
[7] The terms "key perspectives" mean here: "a particular way of looking at CxSs and their components".
[8] Only two levels are used in this paper for clarity purposes, but additional levels can be used if the inherent structure of the studied CxS is multi-leveled.

manifestations (i.e. internal CxSs' movements and external manifestations). This perspective reflects two important focuses that can be found in the literature: some studies are dedicated to the description of CxSs in terms of their composition, inherent properties, structures, mechanisms, while others are dedicated to the study of more dynamical aspects such as interactions between components, reorganization, reconfiguration and the manifestation of emergence. This key perspective is represented by a vertical disposition of rectangles in Figure 1; **static descriptive aspects** are represented in the left column, while **dynamical manifestation aspects** are represented in the right column.

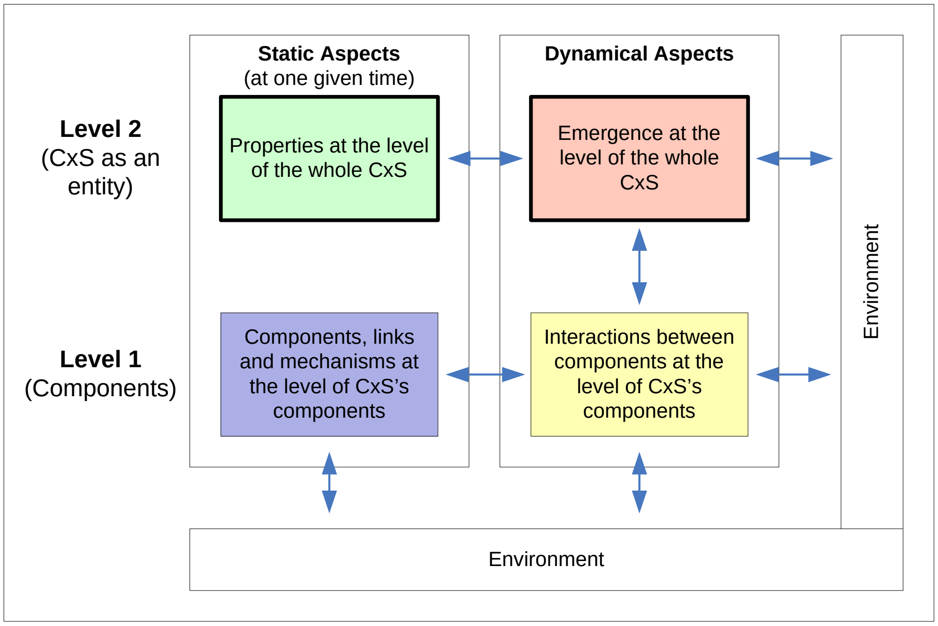

Figure 1. Commonalities of Scientific Literature Dedicated to CxT.

The two key perspectives are relatively orthogonal and they form a bi-dimensional structure that can be used to study CxSs [Couture, 2006d]; the Figure 1 shows, for instance, that static and dynamical aspect of a CxS can be studied at different levels. Put into another way, levels of CxSs can be studied in terms of static and dynamical aspects.

To illustrate this model with a more concrete example, one can think about the national economy (i.e. the CxS) and its different commercial businesses (i.e. components of this CxS). Businesses interact with each others in an environment that may impose some rules (governmental laws of commerce for instance). Interactions between these businesses (i.e. Level 1, right column) are factors that may favor the manifestation of many types of emergence like recessions and inflations (i.e. Level 2, right column), which in turn may give the global CxS some specific properties (i.e. Level 2, left column) and affect the environment (international commerce, for instance). Mechanisms can be put in place at the level of components (Level 1, left column) in order to regulate interactions between businesses in hope to better control the national economy. Finally, its performance can be described in terms of national indicators (i.e. Level 2, left column). The refining of this national economy model would show that this CxS is made of many adjacent aggregation levels (i.e. not only two). At some point in time, finer studies would also show the emergence of a quasi-monopoly in some markets (for instance, PC software), or the emergence of new leaders like in the car industry.

These two perspectives synthesize important commonalities of the scientific literature dedicated to CxT. They are used here as a basis for the identification of a set of four **modalities**[9], which are more adapted for the study of CxSs in general. The modalities are:

1- **Components (and comms links) of the CxS**; static aspects at Level 1 (Figure 1).
2- **Interactivities between components of the CxS**; dynamical aspects at Level 1.
3- **Global properties of interacting components**; static aspects at Level 2.
4- **Emergence occurring from interacting components;** dynamical aspects at Level 2.

Modalities are illustrated in Figures 2-5. The central horizontal arrow in these diagrams (i.e. the x-axis) symbolizes a scale that defines qualitatively the state of the studied CxS. It ranges from highly stable states on the left to unstable chaotic states on the extreme right. The region called **Zone of Rich Free-play** is located between these two extremes. It refers to complex states[10] within which systems will have greater chances of manifesting complex behaviors.

The state of a CxS at one given instant (i.e. static study) depends on the states of its components and the interrelationships between them at the same moment. Components, CxSs, interrelationships and their instantaneous states can be described and better understood by identifying and measuring critical descriptive elements that are associated with each modality at the same moment. These elements are called: **characteristics** and **outcomes**. The lower part of Figures 2-5 illustrates the characteristics used to describe each modality and the upper part depicts the enabled outcomes that are exhibited as a result "emerging" from these characteristics.

The chronological evolution of a CxS can be studied as well. The close examination of changes that are occurring within the CxS with respect to time may involve the addition of new characteristics and/or outcomes to the CxS's description, while others may have to be modified and/or deleted. Long-term self-adaptation is an example involving intrinsic modifications of CxS's composition and structure. These changes are better captured by modalities because their elements allow the capture of changes that are occurring for **critical complex aspects** of CxS. Modalities are thus well adapted for studying both static and dynamical complex aspects of CxS.

The distinction between the upper and lower parts in these diagrams is important. It allows one to discriminate what can be leveraged in a specific CxS to achieve a certain goal (or a desired behavior) from what can only be expected out of a given situation (or a set of conditions). Both parts of the diagram are, however, closely related and their descriptive elements may in some contexts be partly interchangeable. These figures only list a limited number of characteristics and outcomes for clarity purposes; they are related to the example of Section 3. A more refined study of a specific CxS and its components would yield a higher number of more precise characteristics, outcomes and cause-effect interrelationships between them.

Modality 1 (Figure 2): Components (and Comms Links) of the CxS. This modality aims at gathering a description of internal components, communication links and mechanisms that will contribute to make the system complex. The latter will be able to manifest the emergence of the needed capabilities in unforeseen situations through the creation of novelty.

This modality will, for instance, specify qualitatively and/or quantitatively the diversity and the redundancy of components' roles and expertise, the compatibility of components' values,

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[9] The word "modality" refers here to "descriptions", "composite conditions", or "meta-conditions" (from CxT) that characterize CxS and its evolution toward superior behavior.
[10] It includes what is referred to as "Edge-of-chaos" in the literature [Langton, 1990; 1991].

beliefs and rules, the degree of sharing of knowledge and understanding, and the components' independence and autonomy. Even if components are relatively autonomous and independent, their willingness to work together toward the achievement of a common mission or common goals will be exhibited if some specific characteristics and outcomes (such as: values, beliefs, culture) are shared among an agglomerate of components [Beech, 2004].

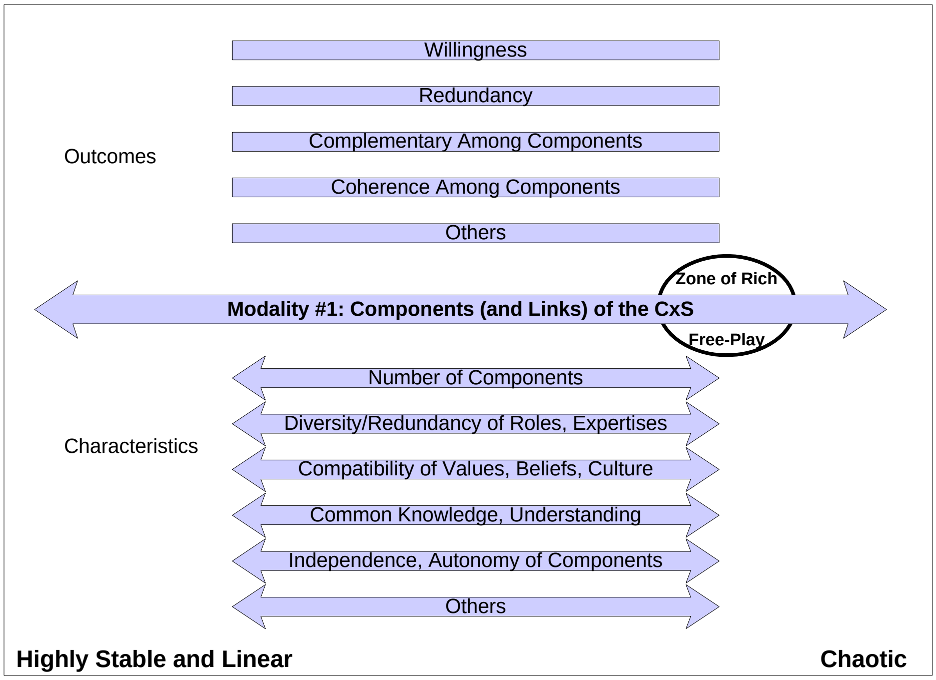

Figure 2- Modality 1: Components (and Comms Links) of the CxS. (Colors correspond to the ones of Figure 1)

Modality 2 (Figure 3): Interactivities between Components of the CxS. The degree of decoupling between components, the diversity and redundancy of communication links, the degree of interoperability, the effectiveness and efficiency of communications are all ingredients (i.e. characteristics) that will favor the ability and the willing of components to work together, to synchronize and to coordinate (i.e. outcomes). This is depicted in Figure 3 using the same horizontal scale as the one used in Figure 2.

Modality 3 (Figure 4): Global Properties of Interacting Components. This modality builds upon the results of the combination of characteristics and outcomes of modalities 1 and 2. For instance, the robustness and resilience of a CxS in face of unforeseen attacks are outcomes of modality 3, which are related to CxS's agility, which in turn is enabled by characteristics like decentralization of control (modality 1), loosely coupled components (modality 2), availability of critical understanding (modalities 1 and 2), etc. The quickness of availability of a second, third or even fourth solution in case of failure of the first one is an example of characteristics that will raise the global performance, resilience and fitness of a CxS.

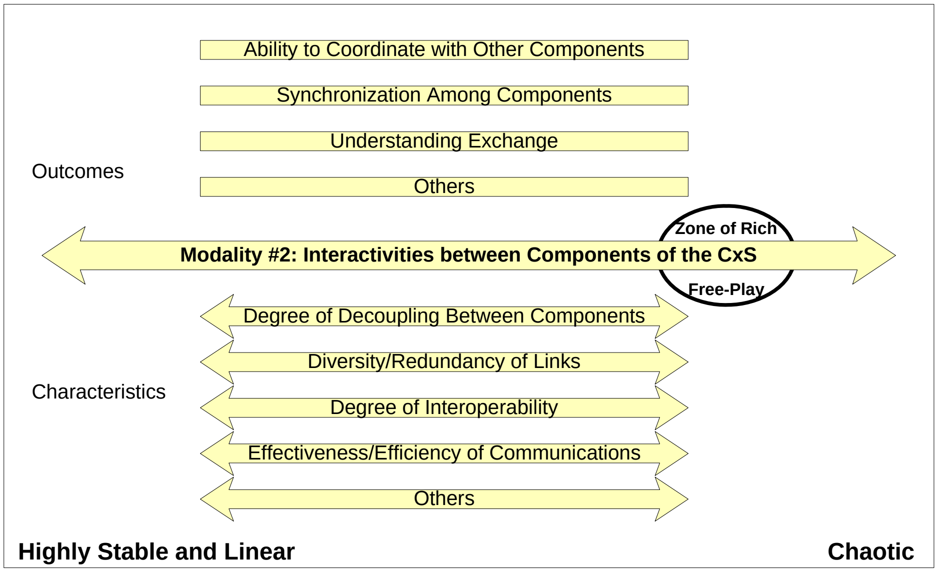

Figure 3- Modality 2: Interactivities between Components of the CxS. (Colors correspond to the ones of Figure 1)

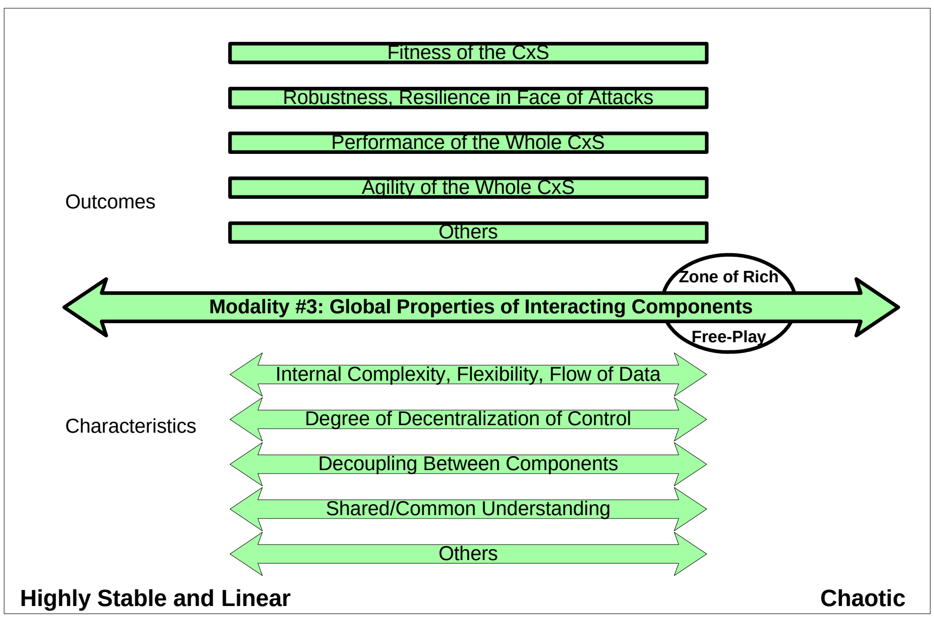

Figure 4- Modality 3: Global Properties of Interacting Components. (Colors correspond to the ones of Figure 1)

Modality 4 (Figure 5): Emergence Occurring from Interacting Components. This modality represents manifestations or emergence of ultimate behaviors like self-organization, self-adaptation, self-recovery, self-repair and self-replication. They are the result of intricate interactions (modality 2) between collaborating components (modality 1) that are guided by internal characteristics and by shared motivations (modality 3). For instance, a minimal number of components and communication links between them are needed for emergence to be possible. Supplementary conditions such as internal shared values, knowledge and understanding, the ability to aggregate (i.e. to reorganize, to reconfigure) and the decentralization of planning and control will give this emergence its coherence, efficiency and effectiveness (modality 3).

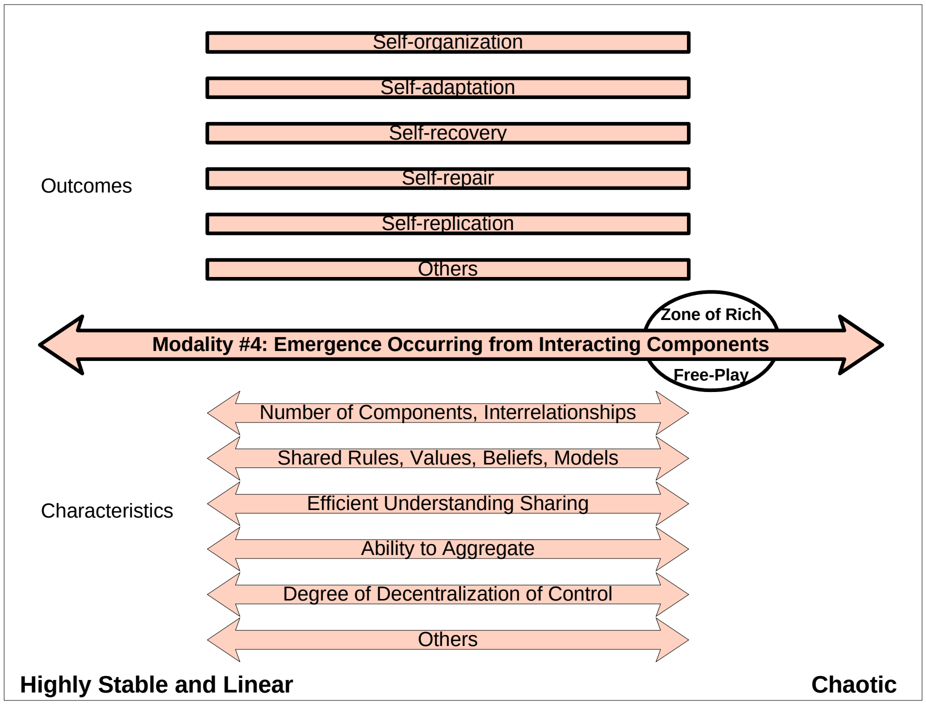

Figure 5- Modality 4: Emergence Occurring from Interacting Components. (Colors correspond to the ones of Figure 1)

Characteristics and outcomes of the four modalities are not orthogonal and they are highly interdependent; CxSs usually involve numerous components and mechanisms that are intricately interrelated in many different ways. The modification of one aspect of a CxS (i.e. one characteristic/outcome of one modality) might potentially have hard-to-predict global consequences on other modalities, particularly if the CxS evolves near the Zone of Rich Free-play. As an example, eliminating a shared rule within some components of a complex organization may trigger its evolution toward chaos states. Putting back the removed rule after some time will not necessarily restore the system in its original state. As it will be shown later in this paper, interaction diagrams help identify and understand the consequences of such changes that may concurrently happen in cascade.

Concrete applications of these modalities (and CxF) are currently done in different domains (including the example presented in Section 3 of this paper). They all suggest that this set is relatively complete and addresses most crucial aspects of CxSs in general. One of the advantages of using this set for the study of CxSs is that their characteristics are often simple to manipulate and they are adapted to complex studies. Modalities help focus on complex critical factors that affect the state of CxSs. It also helps the establishment of cause-effect interrelationships between them. More refined studies naturally lead to the identification of sets of **critical metrics** and **ranges of values** for each of them. The middle-out approach guides the use of modalities; it is briefly described in the next section.

2.3 The Middle-out Approach for Conceiving and Studying CxSs

Interactions between components of CxSs are non-linear. Their specifications must guaranty the necessary flexibility for being able to self-organize and self-adapt as a function of the received internal and external feedbacks. Traditional top-down and stovepipe approaches do not provide the development conditions that make such flexibility possible [CTW, 2006; Braha *et* *al.*, 2006]. Top-down approach often underestimates low-level components of a system at the price of very well-defined capabilities and stovepipe development projects have the tendency to be isolated from one another. The middle-out approach appears to be more adapted for the development of CxSs. It departs from the traditional reductionism by concurrently using both the top-down and bottom-up approaches, while constantly referring to a complete holistic view (and understanding) of the whole system and needed capabilities.

The design of a new CxS would, for instance, involve the study of both finding system's components from the needed capability (i.e. top-down) and, at the same time, finding how these components would interact to produce the emergence of the needed capability (i.e. bottom-up). The task of integrating the developed components is not only made at conception phase. It should also be possible to create a new CxS by reconfiguring and/or integrating components during operations (at "run-time"). **CxSs must be able to create novelty by elaborating new solutions in order to deliver the needed capabilities while facing unforeseen environmental situations or problems.** This requirement demands architects to keep in mind all the components' specifications and needed operational capabilities, while trying to provide the CxS the discovery strategies it will be able to use during operations in order to self-organize and self-adapt appropriately in the face of new situations or problems.

Figure 6 shows how the middle-out approach can be used in the context of the proposed CxF. It depicts the description of a hypothetical CxS that would be made of three hierarchical levels. This description would involve a huge number of linked outcomes and characteristics for all modalities.

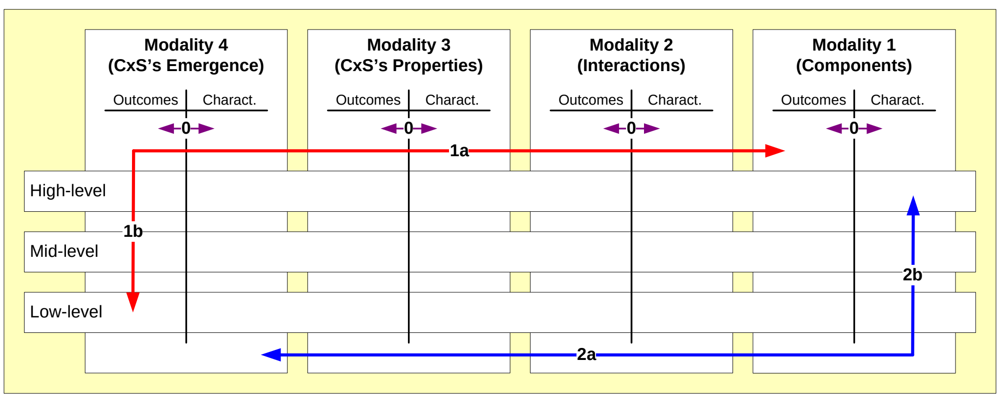

Figure 6. The Integration of the Middle-out Approach within the CxF.
(Colors do not correspond to the ones of Figure 1)

This figure shows that characteristics and outcomes of the four modalities are revisited in both "directions" at the same time: top-down (i.e. red arrows) and bottom-up (i.e. blue arrows). Top-down considerations consist in studying aspects of the CxS from modality 4 to modality 1 (i.e. arrow 1a) and from high-level to low level (i.e. arrow 1b), while bottom-up considerations go exactly in the opposite directions (i.e. arrows 2a and 2b). The process of finding elements of modalities would probably be iterative and incremental because the complexity level of the system makes it impossible to capture the whole description in one shot; many successive refinements and validations are necessary. It would involve the concurrent use of many specialized tools such as M&S and interaction diagrams[11].

[11] This linked information (i.e. linked elements of modalities) should be managed by a specialized tool with an adapted data model. Some of these tools are currently under study at DRDC Val (Section 3).

The next section introduces interaction diagrams; a representation that eases the identification and linkage of the characteristics and outcomes of the four modalities of the CxF. Using these diagrams, one can visualize among other things multiple influences and mechanisms that are occurring within CxSs.

2.4 The Study of CxSs through the Use of Interaction Diagrams

In order to successfully face external unforeseen, variable and complex environments, CxSs must evolve in the Zone of Rich Free-play (i.e. the identified circle in Figures 2-5). This region is far from the linear, predictable, rigid and non-creative states and at the same time, away from chaotic states. Life in the Zone Rich Free-play involves a high degree of flexibility to create new solutions to unforeseen problems (i.e. modality 4; emergence of new solutions). CxSs must show optimum efficiency and effectiveness (i.e. modality 3) in the face of high variability. CxSs evolving in this region continuously re-adjust their components and communication links (i.e. modalities 1 and 2) as a function of internal and external conditions.

The state of a CxS thus varies constantly with respect to time. The characteristics and outcomes of the modalities describing a CxS can be used to study these changes. They can also be used to identify critical factors that will help keep its state in the Zone of Rich free-play and optimize the emergence of the desired capabilities. The **Interaction diagram** is a simple tool that helps find such critical factors and cause-effect interrelationships between them.

Figure 7 depicts an example of the use of interaction diagrams. It shows the differences between loosely and tightly coupled components of a hypothetical CxS. The color code used in this diagram corresponds to the one used in Figures 1-5; yellow rectangles are related to modality 2, green rectangle to modality 3 and orange rectangles to modality 4. Arrows with the positive/negative (+/-) signs represent positive/negative *contributions* of the originating rectangle to the destination rectangle (i.e. cause-effect interrelationships).

This figure shows that **emergence** is a core principle for self-organization [Fromm, 2005; De Wolf and Holvoet, 2005], which in turn favor self-adaptation. Loosely coupled components within a CxS contribute to increase the number of choices the latter has to find new solutions to unforeseen problems and raise its resilience. The reason for this is that the components of a loosely coupled CxS form building blocks (i.e. in the sense of [Holland, 1995]) that can be re-combined in many ways, enhancing the probability of finding appropriate solutions. Through the process of aggregation and correlation [Holland, 1995] the network develops "redundant multi-way chains of causality" to accomplish its **collective interests** and contribute to the network's resilience; [Beech, 2004] provides a concrete example. This increased number of choices also contributes to raise the fitness of the whole in its environment because the number of available configurations is increased. This higher level of flexibility is often made at the expense of global performance; chances are that loosely coupled components will encounter interoperability or communication limitations, for instance, lowering performances of the whole.

On the opposite side, Figure 7 shows that tightly coupled components often involve rigid structures (i.e. linear and highly hierarchical systems that correspond to highly stable, linear states of Figures 2 to 5). Their performance is increased because their components are working the ways they were made to (they can hardly deviate); interoperability problems, for instance, were solved (i.e. fixed) at design phase. This rigidness contributes to lower the degree of resilience and the flexibility of the whole CxS; it has limited "redundant multi-way chains of causality". Linear systems are then “less able” to recombine in new and more adapted configurations when unforeseen problems or situations happen.

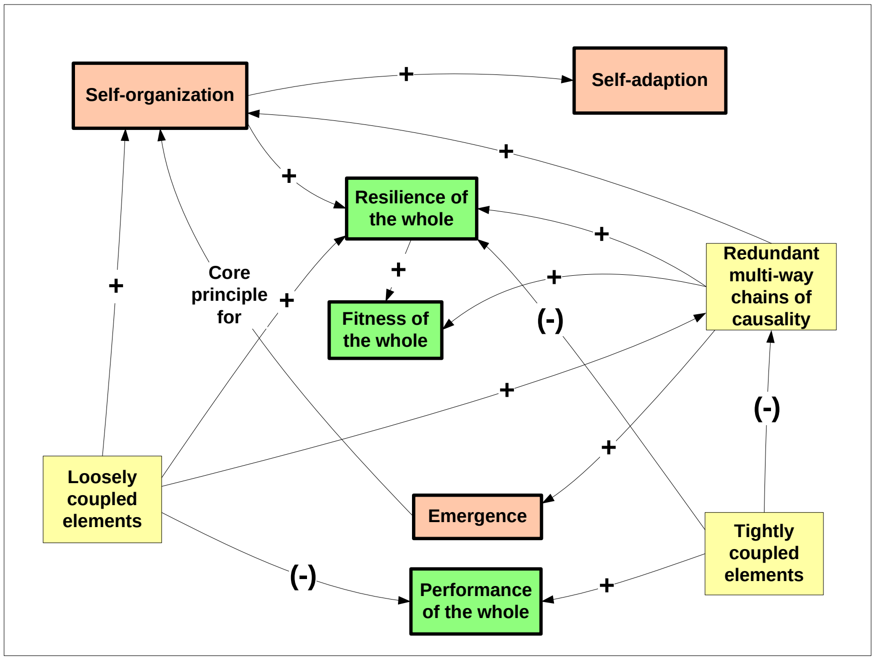

Figure 7- Interrelationships between Elements of Modalities
(Generic example not specific to any domain)
(Colors correspond to the ones of Figure 1)

A knowledge of the complex critical aspects of a CxS (through the use of modalities and interaction diagrams) is important for its management or guidance; this is particularly true for organizations or groups of people [Shetler, 2002]. The next section applies the CxF to nowadays Network Centric type of command and control.

3 The Application of the CxF to the Network Centric Type of Military C2

The world of C2 is currently going through a significant complex revolution with the availability of Network Centric Operations (NCO). Therefore, NCO is an interesting case study that can be used as an example to illustrate the application of the CxF. The proposed example focuses on the “planning” and “control” aspects of C2 without delving into unnecessary details; the aim of this example is only to provide an overview of the application of the CxF. Figure 6 of [Alberts and Hayes, 2007] is used as a basis in this example. The following paragraph partly describes Alberts and Hayes’s figure where bolded words correspond to **outcomes** only and the triplet **M#/O** is used to designate outcomes of modalities. For instance, the triplet M3/O would represent “outcomes of modality number three”. Identified outcomes are then depicted in Figure 8/9 in the form of a tree-view/interaction diagram.

> The C2 that should be used in NCO is relatively different from the traditional C2. Information does not flow according to the traditional chain of command; it is rather free to move among components (**flexibility, creativity, responsiveness; M1/O, M2/O**) meaning that data is not pushed, but instead it is posted, pulled and smartly pushed (**smart communication; M2/O**) according to the need for expertise (**shared knowledge and understanding; M1/O**), which is distributed and available (**availability of data, information, knowledge and expertise; M1/O, M2/O**). The decision-making process is not anymore centralized into highly

rigid hierarchical structures. It is distributed among components of the CxS (**decentralization and distribution of decision making, heterarchy, independence, proactive; M1/O, M2/O**) and there exists a degree of flexibility (**flexibility; M1/O, M2/O**) at the level of components that allows responsibilities to be dynamically re-allocated (**ease of reallocation of responsibilities; M1/O, M2/O, M3/O**) on the basis of needs, efficiency and relevance, allowing parallel and continuous extensive collaborations (**collaboration; M1/O, M2/O, M3/O**). In this context, "planning" and "execution" of missions are interactive (**interactive planning, execution and control; M3/O**); they aim at enabling self-synchronization (**self-synchronization; M4/O**) and seeking synergies (**synergetic; M1/O, M3/O**) with focus on effects in multiple arenas (**able to deal with multiple arenas; M3/O**). Agility of CxS (**agility; M1/O, M2/O, M3/O**) becomes a common and shared goal among components. Alberts and Hayes recognize the dimensions of agility: robustness, resilience, responsiveness, flexibility, innovation and adaptation (**robustness, resilience, responsiveness, flexibility, creative; M3/O**), (**adaptation; M1/O, M2/O, M4/O**).

Other examples of outcomes of modality 4 that should normally be considered in our example are: **self-organization**, **self-orchestration**, **self-recovering**, **collective learning, self-heal,** and **collective innovation**.

The reader understands that, in this example, the chosen first step of the iterative and incremental process (Section 2.3) aimed at capturing and classifying all the available information from the Alberts and Hayes's figure; Figure 8 groups found outcomes.

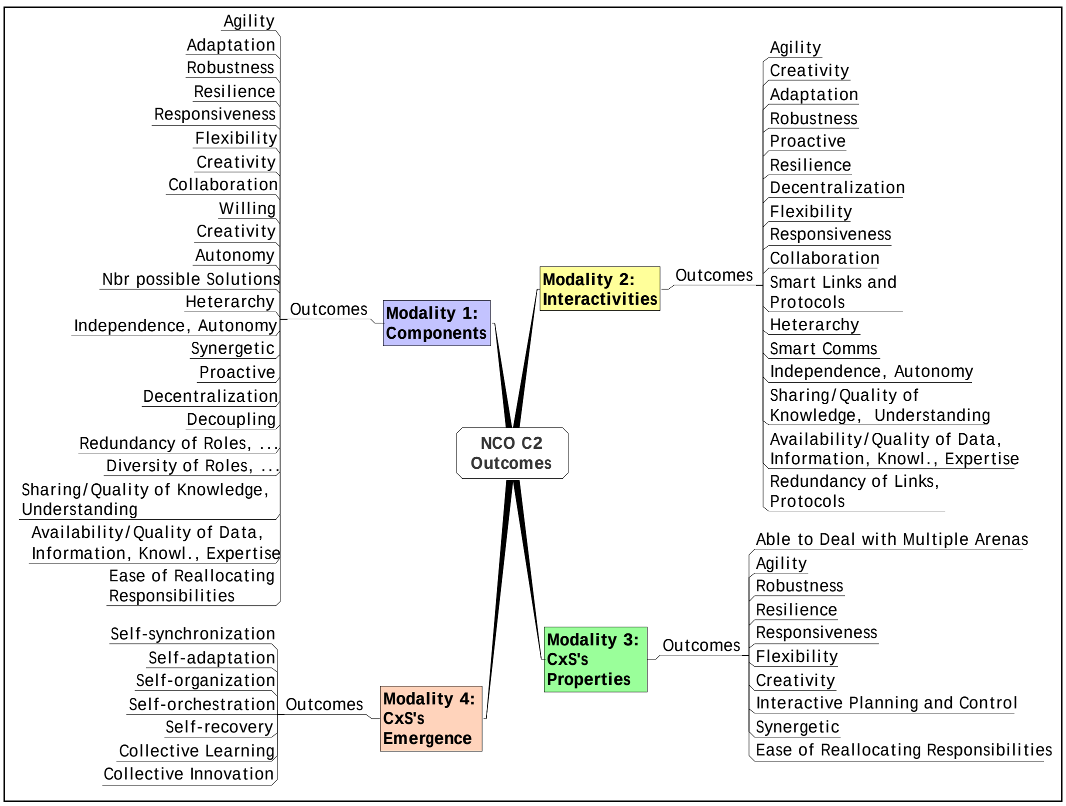

Figure 8- Selected NCO C2 Outcomes; Re-structured According to CxF.
(Colors correspond to the ones of Figure 1)

The second step of this process could aim at the identification of cause-effect interrelationships between these outcomes. The interaction diagram[12] (Figure 9) eases this discovery effort by providing the ability to generate visual recursive representations of outcomes[13]. In this example, agility/self-organization is the desired property/emergence (i.e. modality 3/modality 4) to be deployed in theatres of operations. Global qualities of CxSs such as robustness, resilience, responsiveness, flexibility, innovation or creation will contribute to improve agility of the CxS, which in turn will favor the emergence of complex behaviors such as self-organization.

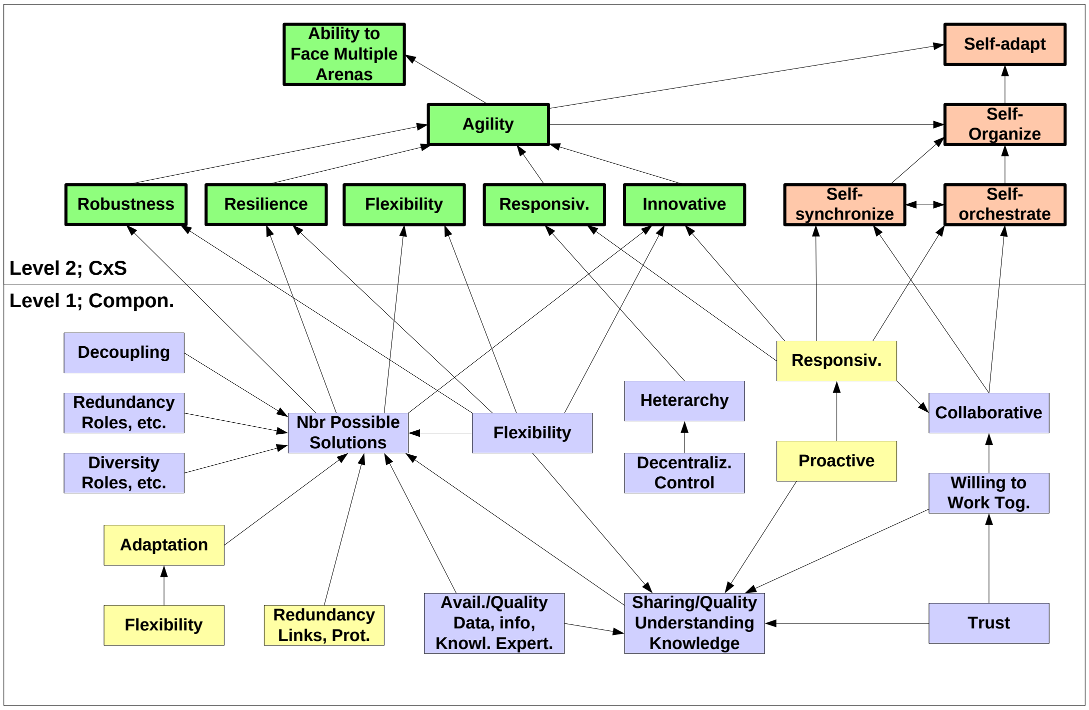

Figure 9- Integrated Set of Outcomes for NCO C2.
(Each arrow represents a positive contribution).
(Colors correspond to the ones of Figure 1)

A possible third step to this discovery process would be to identify and classify already owned physical and logical components of C2 systems (i.e. characteristics of modalities 1 and 2) and to establish cause-effect interrelationships between them. The process would then involve a refinement effort for revisiting each modality in order to identify/modify/delete/relate outcomes and characteristics. This iterative and incremental process would end when a “complete enough” integrated picture of the whole system would be attained. M&S and other specialized tools may be used for determining the completeness and usefulness of static and dynamical descriptions.

For this particular C2 example, finding characteristics, outcomes and cause-effect interrelationships between them would be made easier if one would make use of the NATO SAS-050 model [NATO, 2007]. This exhaustive model contains more than 350 variables related to

[12] Only a limited number of outcomes are shown for clarity purposes.
[13] Tools under study at DRDC Val are: an adapted data model, ontology, a repository that keep all the linked information (elements of modalities), a search engine and a tool to generate interaction diagrams. The full power of this set can be reached when the search engine is repeatedly used with different key words to regenerate multiple interaction diagrams, showing different aspects of this linked information.

NCO C2 and interrelationships between them that can be interpreted as characteristics and/or outcomes of modalities. The model includes not only favorable (or constructive) cause-effect interrelationships, but it also enumerates the negative ones that will interfere. The authors of this article truly believe that interaction diagrams must include positive and negative contributions to allow comprehensive analysis. Using this structured information, it would also be easier to categorize C2 CxSs in terms of the NATO NEC Maturity Model [NATO, 2006; Alberts and Hayes, 2007]. This will be further documented in a separate report.

In summary, it was shown in this section that the proposed elements of the CxF can help providing CxSs what they need for being able to manifest the desired emergence of capabilities. It departs from the traditional linear and reductionism approaches by concurrently using both top-down and bottom-up approaches, while constantly making references to the holistic view (and understanding) of the whole CxS.

4 Discussions and Conclusion

The analysis of complex C2 Information Systems comes with new challenges that are mostly related to the entangled coupling of sub-systems and to the predictability of behaviors emerging from the changes in the environment or in the internal organization. To ease the understanding of CxSs, we have proposed the "interaction diagram" that greatly facilitates the identification of the key complex features of CxSs, which helps visualize interactions between them and build holistic and integrated pictures of understanding.

Of course, to be meaningful, the interaction diagram has to be constructed in a rather rigorous manner that will guarantee some coherence in the representation of the reality. This is achieved in the CxF by the identification and definition of four "modalities", which are fundamental ingredients that are needed to achieve high-order emergence like self-organization, self-adaptation etc. Each modality can be expressed in two ways: first as "technical descriptors" (i.e. lower-level, parametrical and/or quantifiable; called "characteristics") and second as "observable manifestations" (i.e. higher-level, rather qualitative but more intuitive; called "outcomes"). This distinction appears to be critical to the coherence of interaction diagrams that must take into account entities that belong to different conceptual levels. Also, the ability to include "positive and negative contributors" in the same diagram makes the analysis much more revealing and much more comprehensive.

In order to illustrate its capabilities, the proposed CxF was applied to C2IS domain by bridging the description of the Command & Control in Network Centric Operation with the four modalities previously defined. Future R&D efforts proposed at DRDC Val will be directed toward the identification of metrics and mathematical relationships between the modality descriptors and their manifestation. This will provide some quantification capabilities to the CxF. An implementation of a set of specialized tools will also be made in order to ease the utilization of the framework in concrete applications.

5 References

Alberts S. David and Richard E. Hayes, 2007. Planning: Complex Endeavors. Document under review to be proposed to the DOD-CCRP for publication. The document is available (2007) at: http://www.dodccrp.org/. Number of pages: 122.

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

Bar-Yam, Yaneer, 2003. Complexity of Military Conflict: Multiscale Complex Systems Analysis of Littoral Warfare. Report for Contract: F30602-02-C-0158, Multiscale Representations Phase II: Task 2: Multiscale Analysis of Littoral Warfare, number of pages: 27, could be found in 2007 at: http://necsi.org/projects/yaneer.

Bar-Yam, Yaneer, 2005. Making Things Work: Solving Complex Problems In A Complex World. Knowledge Press, ISBN: 0965632822, number of pages: 306.

Beech, F. Michael, 2004. Observing Al Qaeda through the Lens of Complexity Theory : Recommendations for the National Strategy to Defeat Terrorism. Center for Strategic Leadership, Student Issue Paper, Volume S04-01, can be found at: http://www.carlisle.army.mil/usacsl/Publications/.

Braha, Dan, Ali A. Minai and Yaneer Bar-Yam, 2006. Complex Engineered Systems: Science Meets Technology. Springer, 1st edition, ISBN: 3540328319, number of pages: 384.

Couture, Mario, 2006a. Complexity and Chaos – State-of-the-Art; List of Works, Experts, Organizations, Projects, Journals, Conferences and Tools. DRDC/RDDC Valcartier Technical Note TN 2006-450. Defence R&D Canada, Valcartier, Québec, Canada, number of pages: 347.

Couture, Mario, 2006b. Complexity and Chaos – State-of-the-Art; Formulations and Measures of Complexity. DRDC/RDDC Valcartier Technical Note TN 2006-451. Defence R&D Canada, Valcartier, Québec, Canada, number of pages: 62.

Couture, Mario, 2006c. Complexity and Chaos – State-of-the-Art; Glossary. DRDC/RDDC Valcartier Technical Note TN 2006-452. Defence R&D Canada, Valcartier, Québec, Canada, number of pages: 89.

Couture, Mario, 2006d. Complexity and chaos – State-of-the-art; Overview of Theoretical Concepts. DRDC/RDDC Valcartier Technical Memorandum TM 2006-453. Defence R&D Canada, Valcartier, Québec, Canada, number of pages: 115.

CTW, 2006. The Complexity Tutorial/Workshop 2006. Professor Yaneer Bar-Yam (NECSI) Tutorial that was held in December 2006 at DRDC-RDDC Valcartier. Valcartier, Quebec, Canada.

De Wolf, Tom and Tom Holvoet, 2005. Emergence Versus Self-Organization: Different Concepts but Promising When Combined. Engineering Self Organizing Systems: Methodologies and Applications, Lecture Notes in Computer Science, Volume 3464.

Flake, W. Gary, 1998. The Computational Beauty of Nature: Computer Explorations of Fractals, Chaos, Complex Systems, and Adaptation. The MIT Press, ISBN: 0262561271, number of pages: 514.

Fromm, Jochen, 2005b. Ten Questions about Emergence. This paper can be found at: http://arxiv.org/ftp/nlin/papers/0509/0509049.pdf.

Holland, H. John, 1995. Hidden Order: How Adaptation Builds Complexity. HarperCollins Canada, Perseus Books ISBN: 0201442302.

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

Ilachinski, Andrew, 1996b. 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.

Langton CG., 1990. Computation at the edge of chaos: phase transitions and emergent computation. Physica D 42:12–37.

Langton CG., 1991. Computation at the edge of chaos: phase transitions and emergent computation. PhD diss. University of Michigan.

NATO, 2006. Exploring New Command and Control Concepts and Capabilities. Final Report. NATO SAS-050 Working Group, can be downloaded from (2007): http://www.dodccrp.org/.

NATO, 2007. NATO SAS-050 Working Group. The model is accessible (2007) at: http://216.214.97.41/ebr/sas050/login;jsessionid=43154042C418000FF719F6DF48338368

Poussart, Denis, 2007. Complexity – An Overview of its Nature, Manifestations, and Links to Science & Technology Convergence, with Comments on its Relevance to Canadian Defence. Report submitted to DRDC-RDDC - Valcartier for publication, Defence R&D Canada, Valcartier, Québec, number of pages: 88.

Shetler C. Judith, 2002. Complex Adaptive Systems, Attractors, and Patching : a Complex Systems Science Analysis of Organizational Change. Dissertation Presented to the Faculty of the Graduate School of the University of Texas at Austin in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy, December, 2002, can be found at: http://www.lib.utexas.edu/etd/d/2002/shetlerjc029/shetlerjc029.pdf.

Williams, P. Garnett, 2001. Chaos Theory Tamed. National Academy Press (Trade): ISBN: 0309063515, number of pages: 499.

Annex 1 – Some Key Definitions

This annex proposes a short definition for a selected number of key words. The reader will find more details and additional relevant definitions in [Couture, 2006c].

Chaos: *a) Sustained and disorderly-looking long-term evolution that satisfies certain special mathematical criteria and that occurs in a deterministic non-linear system; b) largely unpredictable long-term evolution occurring in a deterministic, nonlinear dynamical system because of sensitivity to initial conditions* [Williams, 2001].

Complex Behavior: *A type of dynamical behaviour in which many independent agents continually interact in novel ways, spontaneously organizing and reorganizing themselves into larger and more complicated patterns over time* [Williams, 2001].

Complex System: *A collection of many simple nonlinear units that operate in parallel and interact locally with each other so as to produce emergent behaviour* [Flake, 1998].

Emergence: *A system exhibits emergence when there are coherent emergents at the macro-level that dynamically arise from the interactions between the parts at the micro-level. Such emergents are novel w.r.t. the individual parts of the system* [De Wolf and Holvoet, 2005].

Evolution: *A process operating on populations that involves variation among individuals, traits being inheritable, and a level of fitness for individuals that is a function of the possessed traits. Over relatively long periods of time, the distribution of inheritable traits will tend to reflect the fitness that the traits convey to the individuals; thus, evolution acts a filter that selects fitness-yielding traits over other traits* [Flake, 1998].

Heterarchy*: A heterarchy is a network of elements sharing common goals in which each element shares the same "horizontal" position of power and authority, each having an equal vote. A heterarchy may be independent or at some level in a hierarchy. Each level in a hierarchical system is composed of a heterarchy which contains its constituent elements* [Wikipedia, 2007].

Holism: *"The idea that the whole is greater that the parts". Holism is credible on the basis of emergence alone, since reductionism and bottom-up descriptions of nature often fail to predict complex high-level patterns* [Flake, 1998].

Middle-out Approach: Middle-out approach combines top-down and bottom-up approaches.

Reductionism: *The idea that nature can be understood by dissection. In other words, knowing the lowest level of details of how things work reveals how higher-level phenomena come about. This is a bottom-up way of looking at the universe, and is exact opposite of holism* [Flake, 1998].