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Complex Systems Engineering Applications for Future Battle Management and Command and Control

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Interesting for the aspects of physical approach to BMC2 systems.
- Needs some recognition worked into the paper to reflect that it addresses primarily this point
-- needs acknowledgement that the people of the organizations, with their social and societal factors are contributors to the BMC2 and the understanding of the complex changing environment which represents the real world and any smaller complex situation
- that the defense systems are only one small set of whole/all government engagement means which is a extensible part of any BMC2 of the military/DoD.
• see notes and questions + points in margins within following pages of paper.

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Complex Systems Engineering Applications for Future Battle Management and Command and Control

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INTRODUCTION

"...only complex systems can perform complex tasks." [3]

Engineered (man-made) systems become necessarily complex when they must perform and function in response to highly uncertain (complex) environments. Planning all the possible functions of such systems becomes very challenging when all of the possibilities that may be encountered cannot be predicted. When engineered systems become complex they start outgrowing the bounds of traditional (or classical) system engineering (TSE) methods. Traditional systems are expected to perform foreseeable tasks in a bounded environment, whereas complex systems are expected to function in complex, open environments with unforeseeable contingencies. Complex Systems Engineering (CSE) does not "...primarily seek to produce predictable, stable behavior within carefully constrained situations, but rather to obtain systems capable of adaptation, change, and novelty—even surprise!" [3]

Advances are being made in the science of complexity based on insights gained from the study of complexity found in natural and social systems. These are leading to novel approaches to designing and developing complex man-made systems. A central tenet of complex systems is the principle of emergence: that the whole is greater than the sum of its parts. This implies potential advantages for higher-level functionality emerging from engineered elements comprising a system. It also could imply possible emergent system behavior that is unpredictable. In other words, when the principle of emergence is applied to complex engineered systems, could these man-made systems perform or behave in unexpected ways? The newly forming field of CSE is attempting to address this question and explore methods to best engineer complex systems to take advantage of their complexity while also managing the unpredictability and large scope of such systems.

This paper explores future tactical battle management and command and control (BMC2) as a complex system of systems. The future tactical BMC2 of warfare assets quickly becomes a challenging endeavor as the number of collaborating warfare assets and the physical distance between them increases. Likewise, as the tactical threat environment grows more complex, the ability to command and control the warfare assets to effectively respond and operate becomes an increasingly complex mission. Therefore, complex BMC2 tasks are needed to address the complex mission; and a complex BMC2 system of systems is required to perform these tasks.

First the paper examines future BMC2 systems to determine whether and how they might embody complexity. Part 2 delves into a deeper examination of the complexity characteristics of BMC2 through comparisons with some principles of complexity. Finally, part 3 discusses some CSE methods that have potential for application in the development of future tactical BMC2 endeavors.

PART ZERO – OVERVIEW OF FUTURE BMC2 CONCEPTS

Before investigating definitions and characteristics of complex systems, an overview of future BMC2 concepts is provided. BMC2 is the command, control, and management of warfare assets. Depending on the operational need, BMC2 can range from a single unit (platform) using only local resources to many distributed units functioning collaboratively for the benefit of the group (or Force) (shown in Figure 1). Such collaboration requires system designs that are developed with a "big picture" or force-level perspective in which distributed warfare resources are all considered part of a system of systems. Shifting to a Force-level perspective is key to taking maximum advantage of the distributed warfare assets for the needs of the whole. For example, Force-level thinking is necessary for selecting the preferred shooter from a group of distributed firing units.

An emergent behavior resulting from this proposed future technology would be the added enhancements of the situational awareness or operational environment "picture" as a result of optimized sensor resource management. As sensors are better allocated (more timely, with greater accuracy, etc.), the information or "picture" will improve. So it becomes a self-improving cycle of capabilities.

The "effective engagement envelope" will greatly expand as the shift takes place from a single warfighting unit using only local sensor and weapon resources to a system of collaborating warfighting units. The shared sensor data will enhance situational awareness; thereby extending the detection envelope and improving the reaction time of weapons deployment—which will extend the effective range of engagements. The ability to select the optimum weapon to employ from across the force (rather than being limited to a single unit) will greatly improve the economy of weapons resources as well as improve the probability of effective engagements.

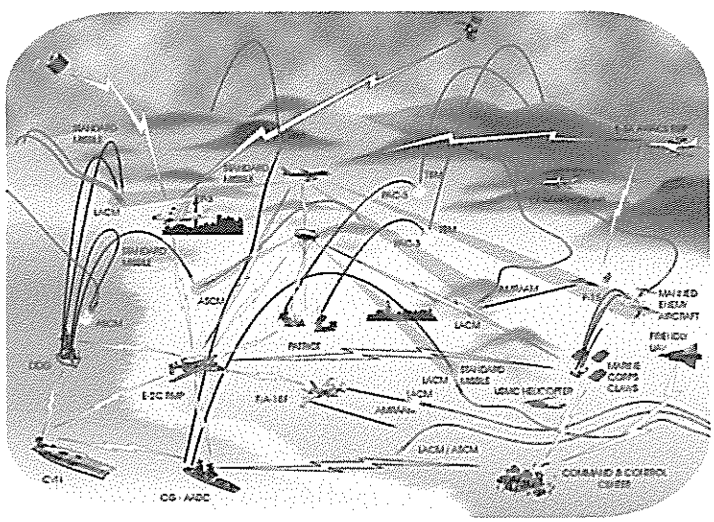

Figure 1 – Future BMC2 Operational Environment

A specific instance of force-level BMC2 is integrated fire control (IFC). IFC refers to the participation and coordination of multiple non-collocated warfare resources (sensors, weapons, C2 systems, and platforms (ships, aircraft, satellites, land-based units, etc.)) in tactical engagements of enemy targets. IFC is envisioned as the ability of a weapon system to develop fire control solutions from information provided by one or more non-organic sensor sources; conduct engagements based on these fire control solutions; and either provide mid-course guidance (in-flight target updates) to the interceptors based on this externally provided information or in certain cases, have them provided by a warfare unit other than the launching unit. Successful IFC would enable expansion of a weapon's battle space to the effective kinematic range of the missiles and can remove dependency on range limits of the organic/dedicated sensor. [16]

The attainment of IFC relies on the ability of participating sensors, weapons, and C2 systems to share target information in real-time and eliminate correlation errors so the engaging weapon system can utilize the information as if it was produced by its organic sensor(s). The ability to direct distributed warfare resources in a collaborative manner would enable major enhancements for tactical fire control. Here are some of the envisioned payoffs:

- Selection of the best shooter from a set of geographically distributed weapons
- Improved chance of interception (by selecting the optimal engagement geometry)
- Improved economy of weapon resources (by reducing redundant shots)
- Earlier launch decisions (by remote detection and precision tracking)
- Decoupling of local sensor/weapon pairing constraint
- Sharing engagement control – forward pass
- Off-board engagement support for guidance relay and target illumination
- Enhanced defense against complex threat environments (sophisticated or significant numbers of aerospace targets) – IFC may be a necessity for victory

Future BMC2 is envisioned as a decentralized architecture of intelligent common processors that share data and information to produce common operational pictures (shared situational awareness). Further, each common processor develops identical commands to task the warfare resources from a force-level perspective. Therefore, each element, equipped with its common processor, develops the same set of commands on a continuous basis to control the resources to respond to the operational environment in accordance with mission needs.

PART ONE: EXPLORING THE COMPLEXITY OF FUTURE BMC2

What makes a system complex? Experts in the field of complexity science have not agreed on an official definition of a complex system; but a number of definitions exist that contain similarities. Two definitions given in Melanie Mitchell's book on complexity capture two different aspects of complex systems. [8] The first definition captures the large size, collaborative behavior, and lack of central control: "...a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution."

An examination of future BMC2 concepts in light of this first definition indicates that future BMC2 constitutes a complex system. BMC2 can vary in its complexity based on the number of participating warfare assets that are collaborating. When the BMC2 "system" is comprised of a single platform with its resident weapons and sensors, it wouldn't be considered complex. However, in response to a complex operational mission, the "system" could contain a large number of varied platforms (based on the ground, sea, air, space, etc.) with many participating and diverse weapons and sensors. It would then fit the first definition of a complex system on the basis of "large networks of components", "complex collective behavior", and "sophisticated information processing." Additionally, if a decentralized architecture is adopted for future BMC2 endeavors, it would be possible to empower the elements of the system and avoid "central control." Future BMC2 capabilities to predict enemy courses of action and generate alternative plans and tactics, techniques, and procedures (TTPs) (rules of interaction) could be interpreted as "adaptation through learning or evolution."

The second definition focuses on emergence and self-organization: "...a system that exhibits nontrivial emergent and self-organizing behaviors." [8] Self-organization refers to the ability of the components of a complex system to create organized behavior without an internal or external controller.

Comparing future BMC2 to the second definition of complex systems requires additional analysis. Certainly nontrivial emergent behavior would be the central objective and payoff of creating a networked BMC2 system. This emergent "behavior" or functionality would include the ability to utilize warfare resources at the force-level or for the purposes of the system as a whole and not just for the purposes of the platforms to which individual resources are attached. Additional emergent capabilities would be the enhanced and shared situational awareness achieved through the sharing and common processing of data and information from the distributed sensors. The other part of the second definition for complex systems is the ability to have self-organizing behavior. On one hand, the TTPs and rules of engagement are internal controllers that constitute the rules by which the elements of the complex system are interacting or collaborating. So the BMC2 "system" itself is really the set of rules controlling the components. As long as each component is equipped with the common processing capabilities to determine how components should behave (sensors tasked, weapons engaged, platforms moved, etc.) is that considered "controlled" or "self-organized"? It depends on how it is viewed. In any case, the future BMC2 system of systems can certainly qualify as a complex system based on these definitions.

Just as there are a number of definitions of complex systems, a list can be compiled of properties and characteristics of complex systems. Table 1 lists some characteristics of complex systems compiled from a variety of sources. The following section evaluates to what extent future BMC2 has these properties.

Table 1 – Characteristics of Complex Systems

Characteristics of Complex Systems	
Complex Collective Behavior	Complex Operational Environment
Signaling and Information Processing	System Changes
Adaptation	Lateral Influences
Design Decisions	System Risk
Complex Objectives	Unforeseen Emergent Properties

Complex collective behavior: Complex systems are comprised of large networks of individual components, each typically following rules of interaction with no central control or leader. It is the collective action of these vast numbers of components that give rise to the complex, hard-to-predict, and changing patterns of behavior. In the potentially complex threat environment of BMC2, the system could consist of large numbers of warfare elements collaborating by following TTPs and rules of engagement in a decentralized architecture with no central control. The overall behavior would be changing in response to the operational environment and could be hard to predict with regard to which action might be taken by each individual element.

Signaling and information processing: Complex systems produce and use information and signals from both their internal and external environments. Information sharing to achieve information superiority is a key component of the future BMC2 system. The system will produce and use information generated by its internal components (elements comprising the system) and from external sources and the environment. Types of information will include: sensor data, environmental data, intelligence, health and status information concerning the warfare resources, resources tasking (commands), and much more.

Adaptation: Complex systems adapt – that is, they change their behavior to improve their chances of survival or success—through learning or evolutionary processes. Future BMC2 behavior is adaptive as it changes and responds to the threat environment and seeks to best utilize all of its warfare resource elements. The BMC2 system must adapt as its environment will constantly be changing. The common operational picture (situational awareness) generated by the BMC2 system will always be changing and adapting. Further, the set of resources participating will be changing in time; creating a unique set of resource tasking at any given moment in time. Additionally, the set of rules governing the tasking priorities and element interactions will adapt as more information is provided and plans are generated.

Design decisions: For complex systems a significantly large number of decisions have to be made regarding design, and typically the implications of design decisions are less predictable.

The future BMC2 system is based on a multitude of design decisions ranging from the micro-level (for each warfare resource) to the element level (integrating multiple warfare resources on platforms) to the macro-level (designing the system of systems architecture and force-level decision process). Design examples for the BMC2 system include: the common processing software, communications, and the decision process that governs resource allocation, interactions, and responses to the threat environment. The nature of future BMC2 including the complex threat environment and the large number and variance of the collaborative warfare elements results in a complex design whose implications are less predictable. The output of the future BMC2 system is the response of the warfare resources to the environment; which in the case of the weapons is a lethal or nonlethal engagement and in the case of sensors or platforms is the redirection of them to better optimize situational awareness or engagement geometries. This output is constantly changing and being updated as the environment and resources change in time. Therefore, the system output is necessarily unpredictable, unique, and changing in time.

Complex objectives: Complex systems have a large number of objectives and the objectives are generally inconsistent or changing. The future BMC2 system must operate under a large set of changing objectives that could contain inconsistent objectives at different points in time. Objectives include meeting the operational needs of different warfare areas based on threats present (i.e., air and missile defense, surface warfare, subsurface warfare, cruise missiles, asymmetric warfare, special operations, etc.). The system must also meet the operational objectives of individual platforms as well as those at the force-level. Conflicting objectives can arise from meeting both of these levels. Another challenge is the changing nature of the objectives of the system which change as the threat environment changes. Target priorities change as the combat environment unfolds.

Complex operational environment: Complex systems need to operate in complex operational environments. The complexity of the operational environment may be a result of adverse environments, widely varying environments, or environments that cause challenging missions. The operational environment for future BMC2 systems is envisioned to be highly complex and could include a combination of multiple and fast-moving air, missile, land, and space-based threats. These threats could be sequential or simultaneous and may come from various directions. Threats could also include unmanned vehicles, swarms of manned or unmanned vehicles, asymmetric attacks, and unconventional attacks disguised as a non-threat.

System changes: For complex systems, change at any level may have system-wide impacts and small causes may have large effects. This characteristic could occur for the envisioned BMC2 system occasionally; but might not occur in general. The types of inputs to the BMC2 system include data input concerning the environment (sensor data, intel, weather/maps data, weapon loads and status, heatlth and status of warfare resources, etc.), changes in the operating rules (TTPs, rules of engagement, decision rules, etc.), and operator input. So any individual input introduces a change in the system in terms of situational awareness, resources tasking, or longer-term planning. If individual inputs are considered small causes, then all system-wide impacts (identification of new threats, changes to tasking priorities, selection (or reselection) of best shooter, etc.) are results of individual small causes or small groups of small causes. But not all individual inputs (in fact the majority of them) will have system-level impacts or large effects.

Lateral influences: In complex systems, lateral influences are stronger and more dominant than hierarchical relationships. The future BMC2 system is primarily focused on lateral collaboration and interactions among the distributed warfare elements. The purpose of the BMC2 system is to ensure information is shared among the elements and that the warfare resources are tasked optimally to respond to the threat environment. The BMC2 enables the performance of the lateral collaboration. In the case of a single platform operating independently (which is no longer a complex system), the emphasis would be on the hierarchical relationship of the warfare assets resident on the single platform.

System risk: In complex systems, risk is dominated by system-level risks, rather than lower level risks in achieving the contributing parts. For the future BMC2 system, the risk shifts from the lower level to the system level as the system shifts from a single warfare platform operating independently to a collaborative system of multiple warfare platforms with many resources involved. Lower level risks, such as whether individual warfare resources (i.e., sensors and weapons) will function properly, become less of an issue as the number of participating elements increases. When multiple elements are involved, the risk shifts to system-level concerns such as whether information is being communicated properly and whether the force-level decision process of tasking resources is performing well and is synchronized across distributed elements.

Unforeseen emergent properties: Complex systems exhibit unforeseen or hard-to-predict emergent properties. It is difficult to predict if the future BMC2 system will exhibit unforeseen emergent properties. If such properties are truly unforeseen, then it remains to be seen whether the BMC2 will behave in unpredictable ways until it is operational or modeled. However, since weapon systems are involved, it is imperative to determine in system-level tests whether unforeseen emergent behavior occurs. Certainly, tragic results like fratricide and successful leakers need to be avoided. Human operator integration can prevent some unfavorable emergent properties. Humans can have override capabilities to have the ability to abort a weapons engagement, control a sensor, or verify intent prior to any weapons being fired.

PART 2 - APPLYING COMPLEXITY PRINCIPLES TO FUTURE BMC2

To gain further insight into the complexity of future BMC2, the system is compared to a set of general system laws and principles that apply to complex systems. [11-14] Table 2 provides a list of the system principles that are used in this analysis to study the complexity of future BMC2. The section that follows discusses how each principle applies to future BMC2.

Table 2 – Principles that Apply to Complex Systems

Principles that Apply to Complex Systems	
System Holism Principle	Redundancy of Resources Principle
Darkness Principle	Sub-optimization Principle
80-20 Principle	Relaxation Time Principle
Law of Requisite Variety	Redundancy of Potential Command Principle

System Holism Principle

The System Holism Principle states that a system has holistic properties not manifested by any of its parts and their interactions. [11] This principle can also be characterized as, "vertical emergence" and is widely understood as "the whole is greater than the sum of its parts." Holistic properties of future BMC2 systems are the force-level capabilities that are made possible through the collaborative interactions of the parts, or in this case distributed warfare elements. Force-level capabilities include enhanced situational awareness. A single fire control element (operating independently) that contains a sensor and processor will be able to generate a situational awareness that is limited to its own sensor data. A network of many distributed sensors will generate an enhanced situational awareness that benefits from an expanded field of view from many varied vantages and from a variety of different data collection devices. The ability to manage the sensors from a force-level perspective enhances the situational awareness further by redirecting sensors to collect data to enhance the force-level picture (increase the field of view, provide higher-fidelity data, or provide a different type of data); rather than just collecting data to enhance the more limited picture that would have been generated with a platform-level purpose if elements were not collaborating as a system of systems.

Another holistic property is IFC or the capability to engage threats using distributed (non-collocated) weapon, sensor, and guidance systems. Again, the engagements will be more effective (better selection of optimum weapon, more optimal engagement geometry, improved probability of engagement; improved economy of weapons resources; earlier launch decisions; etc.) as they are managed with a force-level perspective; rather than being limited to only considering the capabilities of resources from a single non-collaborative platform.

The Darkness Principle

The darkness principle in complexity thinking is the concept of incompressibility. The darkness principle says that "no system can be known completely." This suggests that the best representation of a complex system is the system itself and that any representation other than the system itself will necessarily misrepresent certain aspects of the original system. The darkness principle implies that there is no way a member of a complex system can ever know itself completely—they will always be in the shadow of the whole. "Each element in the system is ignorant of the behavior of the system as a whole, it responds only to information that is available to it locally. This point is vitally important. If each element "knew" what was happening to the system as a whole, all of the complexity would have to be present in that element." [11]

For future BMC2 with the existence of common processing resident in each warfare element and shared information, each element of the complex system gains a complete understanding of the whole system (or in this case, the force-level perspective for resource management and situational awareness). This implies that the system complexity is present in each element. Thus, the Darkness Principle of complexity doesn't apply in the decentralized command and control architecture proposed for future tactical BMC2 applications.

80-20 Principle

According to the 80-20 principle, in any large complex system, 80% of the output will be produced by only 20% of the system. Given a Boolean network as an example---it can be found that many "leaf" nodes do not contribute to the long-term behavior of the networks; and can be removed without affecting the emergent system-level performance; however, they do perform for small periods of time and support system stability. [11]

Without an analysis of the actual BMC2 system or the study of a system model, it cannot be presently known how closely the system follows the 80-20 Principle. However, a preliminary evaluation of system redundancy and an understanding of the system outputs reveal that a smaller percentage of the system will be responsible for generating a larger percentage of the output. The outputs of this system include situational awareness (continuously updated common operational picture), commands (tasks) for warfare resources (sensor, weapons, platforms), evaluations of decision alternatives, predictions of future threats, and plans for future responses to threats. These outputs are generated at each participating common "node" or processor; which exist at the distributed warfare element platforms. And the outputs depend on data and information from the sensors, external sources, warfare resources, commanders, and environment. So the question becomes, what percentage of the systems is actively producing this output at any given time? And, what percentage of the contributing sensor's data is really improving or adding value to the situational awareness? The answers to these questions will also depend on the complexity of the threat environment and the number of participating collaborative warfare elements at any given time. In any case, the percentages will be less than 100%. With identical processing occurring at each warfare element, the outputs are being generated as many times as there are elements; and they are being continually updated. So, a significant amount of redundancy is designed into the decentralized architecture that is envisioned.

Law of Requisite Variety
The Law of Requisite Variety states that "control can only be obtained if the variety of the controller is at least as great as the variety of the situation to be controlled." A variation on this is that "...every good regulator of a system must contain a complete representation of that system." [12] The future BMC2 system complies with this complexity principle. With common processors, each warfare element attains information superiority through the common operational picture which contains shared situational awareness, health and status information of the warfare resources, and identical rule sets. So, each warfare element is empowered with the variety of the situation and therefore has the ability to "control" (or arrive at the optimum resource tasking solution) warfare assets at the force-level.

Redundancy of Resources Principle
The Redundancy of Resources Principle states that maintenance of stability under conditions of disturbance requires redundancy of critical resources. [12] This is supported by the 80/20 principle – the redundant elements absorb external perturbations and prevent them from perforating through the network. Redundancy in feedback also provides a means for a system to maintain itself in the face of external forces.

System stability is a concern for the future BMC2 system. There are two types of conditions that could disturb the system. The first would be a threat to the warfare elements or platforms themselves. The second are disturbances to the BMC2 system itself. Having redundancy in the warfare resources (weapons, sensors, platforms, etc.) will support the defense of these systems against the first type of threat "disturbances" or enemy firepower. Disturbances to the BMC2 system could include an overload of information or data; false or corrupt data; outages/communication failures; a threat environment so complex that the number of resource taskings overloads the decision prioritization process; and delays that could slow the tasking process down to the point where the reaction time is not met. System redundancy that could address these types of disturbances include redundant links (communication paths), the redundancy of the common processors at each element; and the ability to synchronize information among elements.

i.e., extra capacity

Sub-optimization Principle
The Sub-optimization Principle states that if each subsystem, regarded separately, is made to operate with maximum efficiency, the system as a whole will not operate with utmost efficiency. [13] And the reverse is implied: if the whole is made to operate with maximum efficiency, the comprising subsystems will not operate with upmost efficiency. This can also be thought of as parts in isolation behave differently from parts that are connected to a system and/or an environment. The sub-optimization principle readily applies to the BMC2 system. If individual warfare platforms are considered subsystems, then it is easy to imagine that if the platforms are each operating as they would in isolation; then given threats in the environment, each would fire weapons to engage the targets. This would likely result in a waste of fire power with multiple weapons fired at targets. Each platform would also be functioning with a limited situational awareness based on only the data from its resident sensors. The result would be a platform-centric tactical paradigm rather than a force-level tactical paradigm. Examining the reverse implies that if the system is made to operate at maximum efficiency at the force-level, then the warfare platforms will not be operating at maximum efficiency. This situation would be the intent; since fewer weapons would have to be fired and sensors could share in the creation of the common operational picture.

- also come out of Goldratt - Constraints Analysis - the constraint keeps moving - along with value stream analysis.

consider: - including employing non-kinetic engagements at the best place + time + method for the outcome desired

Relaxation Time Principle
The Relaxation Time Principle states that system stability is possible only if the system's relaxation time is shorter than the mean time between disturbances. [13] Application of this

principle to the future BMC2 system is critical to the success and stability of the system. It is critical to understand the rhythm and tempo of the system events including the speed of communications, processing, decision-making, synchronizations, and generation of resource tasking. Additionally, the tempo of the "disturbances" on threats must be understood. This includes the speed, location, and numbers of threats and the resulting system reaction times necessary to address the threats. It is important to understand the system tempo and to ensure it correlates with the threat tempo and also includes built-in time for "relaxation" or processing necessary to stabilize in between actions (or recoveries from disturbances).

Redundancy of Potential Command Principle
The Redundancy of Potential Command Principle states that in any complex decision network, the potential to act effectively is conferred by an adequate concatenation of information. This means that to "control" a complex system we must at first have a sufficiently good representation of it. [13] The task of constructing such a "sufficiently good representation" is problematic when concerned with complex systems because any representation is incomplete. Such incompleteness always leaves open the possibility that the basis for taking action might be (sometimes wildly) inaccurate. So, for the future BMC2, how can the sufficiency of the representation be determined? For BMC2, the representation is the situational awareness (or common operational picture) shared among the warfare elements. In order for the BMC2 system to generate tasking (commands) that result in effective warfare actions, the situational awareness needs to have an acceptable level of accuracy and field of view (to effectively cover the operational area). Strategies such as requiring sufficient quality track data and target identification accuracy to support engagement decisions; supporting blue force tracking capabilities such as Interrogation Friend or Foe (IFF) that involve communication with targets to determine if they are friendly or not; and continually generating and refining plans to redirect resources as more information becomes available.

PART THREE – COMPLEX SYSTEM ENGINEERING APPLICATIONS FOR FUTURE BMC2

"As systems become increasingly large and must seamlessly interoperate with other systems in ways that were never envisioned, system engineers are bumping into the limits of the tenets, principles, and practices traditionally used in systems engineering." [15]

The purpose of this section is to introduce some concepts from CSE that have potential application in the design and development of the future BMC2 system. First an overview of some CSE methods is provided as well as a comparison of CSE with TSE. Next some take-aways from parts one and two of this paper are used to evaluate how the future BMC2 system may exceed the limits of TSE. Finally, some general CSE strategies are discussed that could have application to future BCM2.

Complex System Engineering
"Complexity Theory is found to have characterized naturally occurring systems and to potentially be the source of profitable application to the systems engineering challenge, namely, the creation of complex engineered systems." [4] The challenge for engineering complex systems is to design with a degree of confidence that is acceptable: to deal with the complexity in a predictable way. One proposed set of CSE steps to address this challenge is as follows:

1. Identify when a system and/or its solution complex
2. Determine the level of complexity (or relative complexity)
3. Determine when enough SE has been done; and when the level of confidence in the design (and the predictable behavior) is acceptable. [4]

Another CSE method is to engineer at the system level, or gain an understanding of the system as a whole and emphasize lateral interactions rather than hierarchical. "Highly integrated systems exhibit more complex interactions across the system than earlier, simpler systems. In the highly integrated system, the designer must consider effects on all parts of the system. We are therefore engineering at the systems level more fundamentally than ever; as opposed to introducing subsystems into an evolved, well-precedented system structure." [4]

Table 3 lists some differences between traditional systems (or systems that are good candidates for TSE) and complex systems. Highlighting these differences illustrates the necessity to engineer these two types of systems differently. In shifting from TSE to CSE, the design focus needs to shift away from hierarchical relationships and toward lateral relationships to support and enable collaboration among elements. Similarly the shift of risk dominance from local risks in traditional systems to system-level risks in complex system changes the focus from an engineering perspective. For complex systems, it emphasizes the greater need to engineer at the system-level. The decrease in certainty of design decisions, cause and effect relationships, and system boundaries for complex systems creates the need for a more fluid style of engineering with less stringent requirements satisfaction and more open-endedness.

Traditional System	Complex System
Hierarchical Relationships dominate lateral influences	Lateral influences dominate hierarchical relationships
Cause and effect are relatively obvious and direct	Cause and effect are not obvious and direct; Small causes can have large effects
The implications of design decisions are relatively predictable	The implications of design decisions are much less predictable
Risks are dominated by the local risks in achieving the contributing parts	Risks are dominated by system risks, with unforeseen emergent properties
Influences on, and implications of, decisions tend to follow the local partitioning of the solution elements	Influences on, and implications of, decisions are much more difficult to bound and to establish

Table 3 – Traditional Systems vs. Complex Systems

Another proposed method is to adopt an evolutionary paradigm for CSE that involves rapid parallel exploration and a context designed to promote change through competition between design/implementation groups with field testing of multiple variants. [2] When the inherent nature of the complex system is too large to handle using TSE, an environment needs to be created in which continuous innovation can occur. This evolutionary strategy involves developing multiple designs in parallel; testing them in parallel; and combining them or combinations of them incrementally. This concept also promotes testing in the field to gain insight through direct system feedback from the environment.

Here is another set of proposed CSE steps:

1. Design the environment and processes by which the system is going to be created (without designing the system itself).
2. Design components of the system for the system as a whole.
3. Design a set of rules about how components engage with one another and the process of change. [15]

All of these CSE concepts provide alternative methods to address the challenges presented by engineering complex systems. The concepts are a starting point to stimulate thinking and promote the consideration of novel approaches beyond TSE. One final thought concerning the marriage of TSE with CSE is a good conclusion to this overview: "[Traditional] systems engineering and complex system engineering live together. Treating them separately doesn't make any sense. CSE builds on the capabilities of TSE but has its own unique perspective of focusing on the system environment." [15]

CSE Applications for BMC2

"Many engineering applications, such as real-time decision support, communications and control, are reaching the point where classical methods are no longer feasible for reasons of system interdependencies and complexity." [1]

The quote above embodies the questions posed in this section: having established that future BMC2 is a complex system; are classical systems engineering methods (or TSE) no longer appropriate? Should CSE methods be considered for future BMC2?

The complexity characteristics of future BMC2 pose serious challenges that may exceed the limits of TSE. Complexity in the objectives—including the number of objectives, the changing nature of the objectives, and the potential conflicting objectives results in a system that is difficult to define or bound. Generating a well-defined set of mission objectives and system requirements becomes very challenging. Complexity involved in design decisions – the large scope of design and number of decisions to be made, in addition to the unpredictability of design decision outcomes—is another major example of BMC2 exceeding TSE limits.

this depends on where the environment boundary is set/drawn.

Complexity in the operational environment coupled with complex collective system behavior, adaptation, and unforeseen emergent properties result in a system that will well exceed the limits of TSE. Ultimately, every moment in the operational life of the BMC2 system will be unique. The operational environment (including threat scenario) will be constantly changing and will never be static or repeatable. Additionally, the system itself will be changing in time as platforms "join" and "exit" the system and the status, location and capabilities of the warfare resources change. Thus, the BMC2 system will have to constantly adapt as the situation and its own comprising elements change from moment to moment. Additional consideration of the numbers of warfare element participants, decentralized collaboration, and hard-to-predict potential emergent properties further exceeds to boundaries of TSE. As an example, with an infinite number of operational scenarios, it would be impossible to follow traditional test and evaluation methods.

Given that future BMC2 requires some engineering methods beyond TSE, the next step is to examine some CSE methods that might apply. The first set of proposed CSE steps (in the previous part of this section) suggested (1) identifying when a system is complex, (2) determining the level of complexity, and (3) determining when enough SE had been accomplished. The first two sections of this paper have illustrated that the BMC2 system is complex and have examined complexity levels in various areas related to the system. The third step in this proposed method is actually a good starting place for designing the BMC2 system. In addition to capturing high level objectives and requirements, it would be beneficial to set some objectives for the SE effort itself so that a potentially open-ended, evolving design is complete enough for increments of the system to be developed and released for operations.

– or is it integrating the pieces which provide the capabilities of BMC2

Engineering at the system-level is another recommended CSE method. This is very applicable to the future BMC2 system. The emergent, force-level properties of this complex system are the pay-off for engineering this system. The ability to command and control the distributed warfare resources for the good of the force is the ultimate goal. Achieving shared situational awareness among the distributed warfare elements is necessary to gaining the force-level command of resources. Therefore, attaining as complete an understanding as possible of the properties of this complex system at the system-level is critical to the success of this system. Engineering activities at the system-level will include establishing high level objectives and requirements, managing high-level risk, understanding emergent properties, attempting to predict the hard-to-predict emergent properties, and attempting to predict adaptive behavior.

The evolutionary paradigm is another good candidate CSE method for developing the future BMC2 system. Since the BMC2 faces an ever-changing threat environment and will be comprised of an ever-changing set of warfare elements, a system engineering environment in which design adaptation is a central tenant needs to be the focus of development; perhaps more so than the system design itself. This environment can promote rapid parallel exploration, competition among design groups, parallel testing, process development, and a focus on designing the rules by which elements interact.

In addition to trying to cope with the scope and complexity of the future BMC2 system, engineering strategies must also strive to ensure designs take advantage of the benefits that complexity offers. Designs should not limit features such as redundancy, sub-optimization, and the 80-20 principle of output from producers. At first glance these may seem wasteful and inefficient and even costly design features; but they may be key to providing the stability and response times necessary to function in a complex environment and produce emergent functionality. The benefits are the abilities to adapt, self-organize, and provide agility and diversity.

CONCLUSION

An exploration of the complexity of future BMC2 reveals that the system has many characteristics of complexity and follows many principles of system complexity. Further examination shows that the design and development of future BMC2, with its inherent complexity, exceeds the limits of TSE. Thus, the proposed methods of CSE need to be explored for applicability to BMC2. Given the brief introduction to CSE in this paper, further investigation into appropriate CSE methods for BMC2 is warranted.

Several CSE methods show promise for applicability to the development of BMC2. One is gaining understanding at the system-level and maintaining a high-level vantage from which to engineer the system. Another is to focus on the development of an appropriate engineering environment in which the system can be developed within an evolutionary paradigm and parallel development and testing are possible. There should also be a focus on the rules that govern warfare element interaction. Methods from both TSE and CSE should be considered as a combination approach to engineering the future BMC2 system. Finally, the adopted and tailored approach needs to make sure that system designs don't limit or constrain the benefits and pay-offs of the complex nature of the future BMC2 system.

Further research in other aspects of the complexity of future BMC2 would provide a deeper understanding of the system and support the systems engineering approach. Listed is a set of future explorations:

- Understand and quantify the BMC2 system tempo, the threat environment tempo, and analyze and compare the tempos to identify disconnects
- Determine what a sufficient level of systems engineering completeness would be – develop a strategy to determine when the level of confidence in the design is acceptable
- Study the 80/20 principle as it applies to BMC2. What percentage of the system output will be produced by what percentage of the system?
- Predict and understand emergent properties
- Study the overall system stability against "disturbances" – is there enough redundancy and sub-optimization to compensate for disturbances?
- Study what sufficiency in representation (situational awareness) is required to support action (resource tasking).

In conclusion, the potential complex threat environment of the future and the mission need to provide defensive measures and tactical responses have created a need for a future BMC2 system that can perform complex tasks. And, only a complex BMC2 system can perform complex BMC2 tasks!

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Complex Systems Engineering Applications for Future BMC2

(Battle Management and Command and Control)

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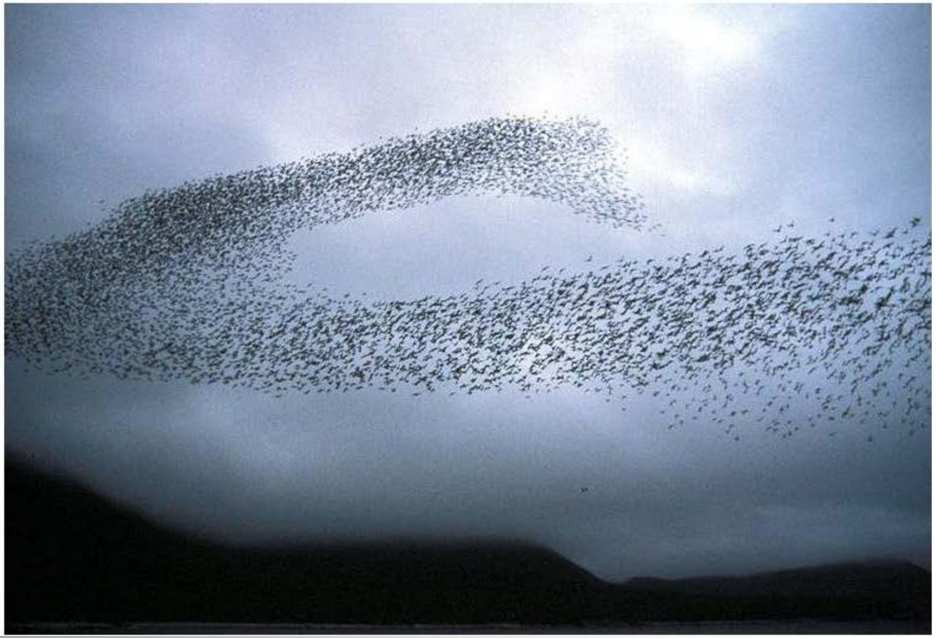
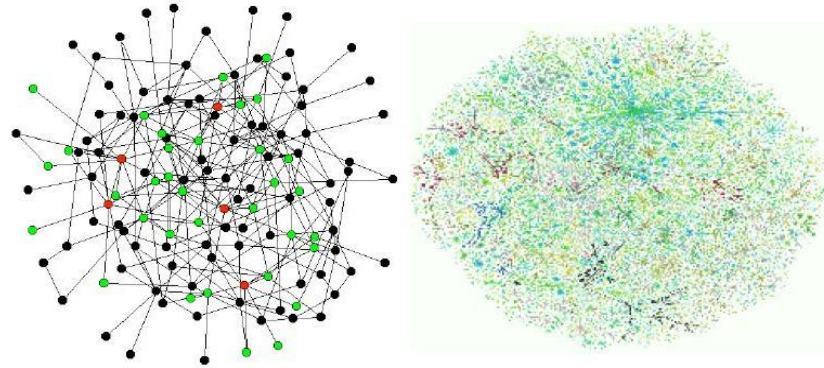
What makes a system complex?

- # of decisions that have to be made regarding design
- Complexity of operational environment
- Degree of control (Centralized, decentralized, etc.)
- Complexity of objectives (#, inconsistency, etc.)
- Implications of design decisions less predictable
- Change at any level may have system-wide impacts
- Lateral influences stronger and more dominant than hierarchical relationships
- Risk dominated by system-level risk (rather than local risk)
- Small causes can have large effects

SWARMS

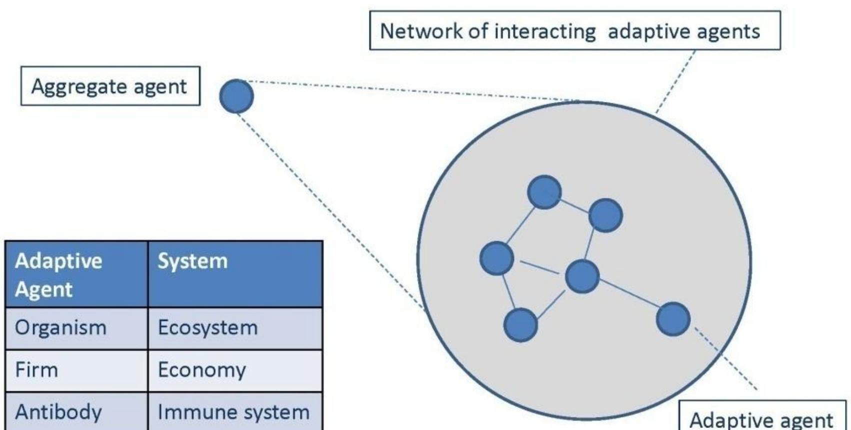


COMMS NETWORKS

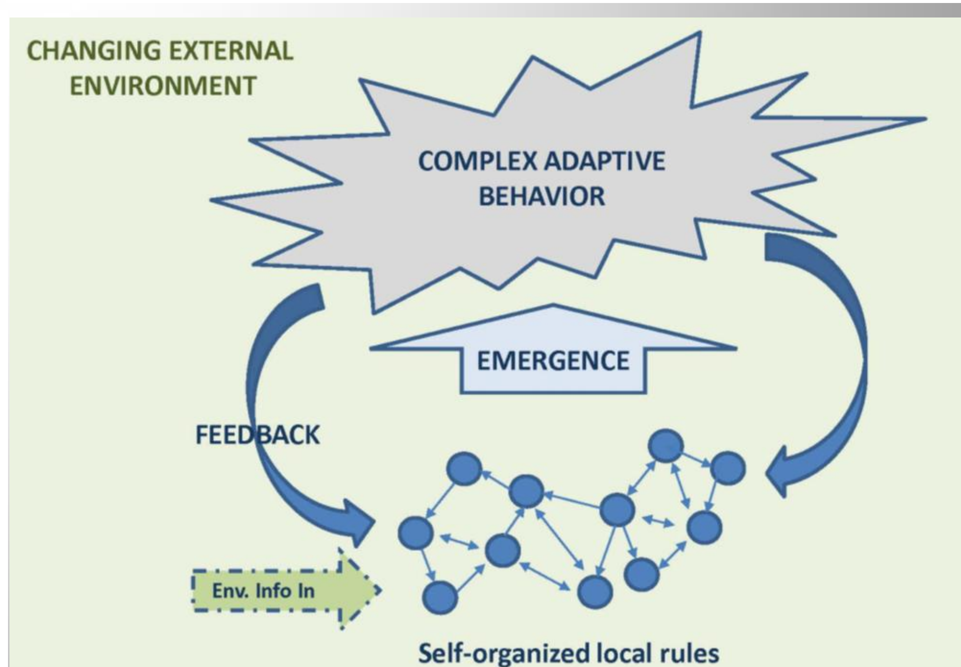


As yet, no one is studying how network interactions change over time...

AGENTS



Adaptive Agent	System
Organism	Ecosystem
Firm	Economy
Antibody	Immune system
Trader	Market
Department	Organization



Complexity vs. Complication

Degree of Independence

- In a **complicated system**, various elements that make up the system maintain a degree of independence from one another. Removing one element does not fundamentally alter the system's behavior apart from that which directly resulted from the piece that was removed.
- **Complexity** arises when the dependencies among the elements become important. Removing an element destroys system behavior to an extent that goes well beyond what is embodied in that element.

Inherent Nature

- Complexity is a deep property of a system, whereas complication is not.

Reducibility

- Complicated systems are reducible, whereas complex ones are not.

Complex Systems Engineering

- Why is there a need for Complex Systems Engineering?
- TSE = Traditional Systems Engineering
- CSE = Complex Systems Engineering

Traditional System	Complex System
Hierarchical Relationships dominate lateral influences	Lateral influences dominate hierarchical relationships
Cause and effect are relatively obvious and direct	Cause and effect are not obvious and direct; Small causes can have large effects
The implications of design decisions are relatively predictable	The implications of design decisions are much less predictable
Risks are dominated by the local risks in achieving the contributing parts	Risks are dominated by system risks, with unforeseen emergent properties
Influences on, and implications of, decisions tend to follow the local partitioning of the solution elements	Influences on, and implications of, decisions are much more difficult to bound and to establish

Emergence

- A classical systems principle
- Emergence holds that patterns and properties in a complex system will come about (emerge) through operation of the system
- These patterns and properties cannot be anticipated beforehand and are not capable of being deduced from understanding of system constituents or their individual properties

…also known as the "law of unintended consequences"

- Potential advantage: higher-level functionality emerging from engineered elements comprising a complex system
- Potential risk: possible emerging behavior that is unpredictable and unexpected

Emergent Properties

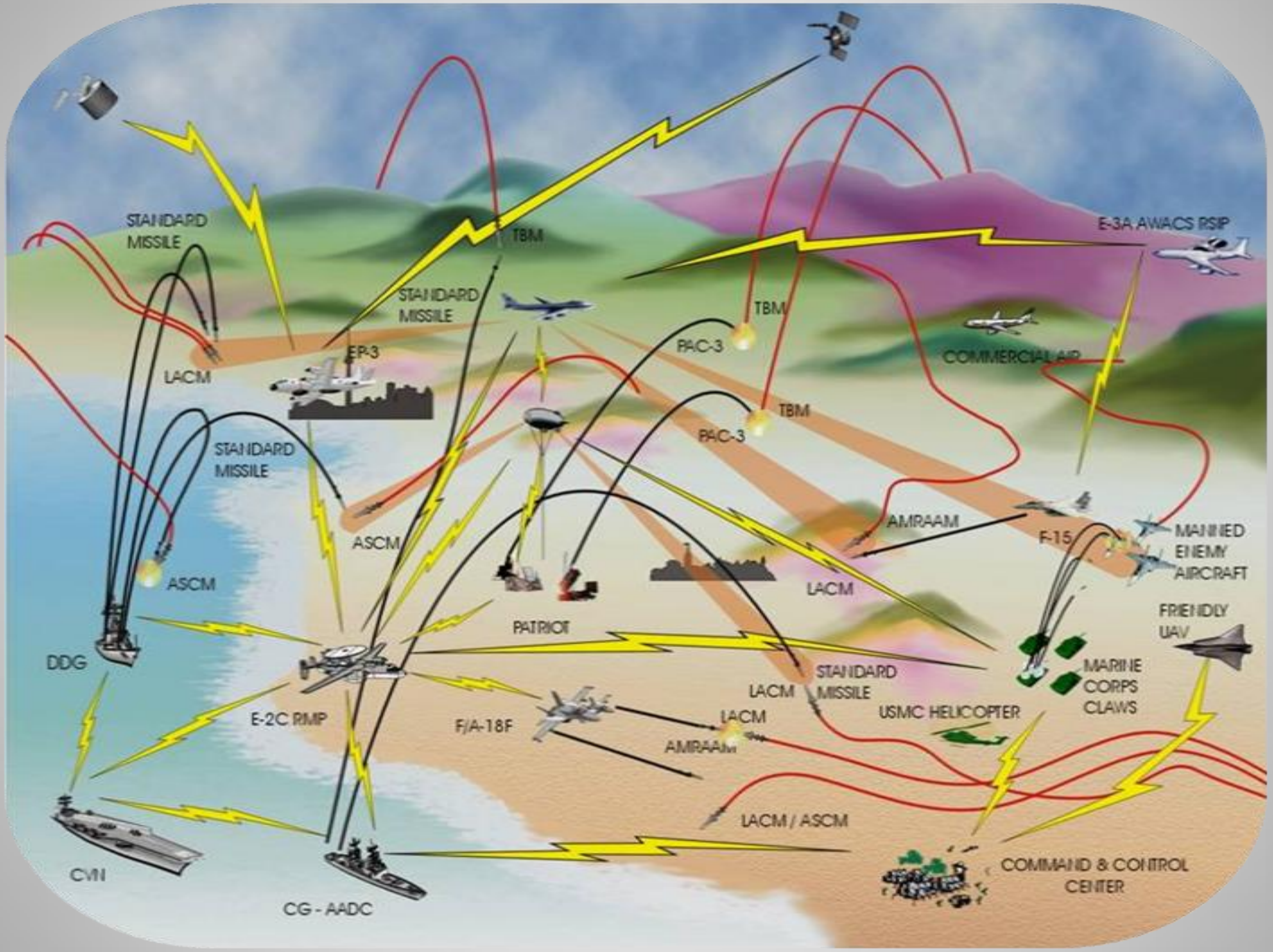
Emergent Properties in General:

- System-level properties exist only at the system level as it functions, being different from and existing beyond the constituent element properties
- System-level properties are not held by any of the isolated elements
- System-level properties are irreducible. They simply cannot be understood, explained, or inferred from the structure or behavior of constituent elements or their local properties
- Understanding the cause-effect relationships can only be established through retrospective interpretation. This renders traditional reduction-based analytic techniques incapable of useful predictions of emergent system-level behavior
- Emergent patterns are not adequately understood without the appreciation of the context within which the patterns exist

Emergent Properties for Future BMC2:

- Enhanced situational awareness (due to optimized sensor resource management) is an emergent property. As sensors are better allocated, the "picture" or information will improve. So it becomes a self-improving cycle of capabilities.
- Force-level capabilities, such as Integrated Fire Control (IFC)

Example: BMC2 as a Complex System of Systems



"…only complex systems can perform complex tasks" [Braha, Minai, & Bar-Yam, 2006]

Future BMC2

BMC2 is the command, control, and management of warfare assets.

Depending on the operational need, BMC2 can range from a single unit (platform) using only local resources to many distributed units functioning collaboratively for the benefit of the group (or Force).

The success of Joint combat operations depends on the individual capabilities of warfare resources (sensors, weapons, communications)

However…

A significant leap in operational capability (force multiplier) will result from achieving a <u>force-level warfighting paradigm</u> that optimizes the use of the resources for the needs of the force.

Future Collaborative BMC2

Shifting to a collaborative "big picture" system of systems arrangement for the BMC2 of the future

- This shift takes maximum advantage of the distributed warfare assets for the needs of the whole

- Example: collaborative BMC2 can select the best shooter (weapon system) from the Force of distributed firing units

Future BMC2 Vision

[1] Implement a System of Systems (SoS) architecture that distributes the "intelligence" among the warfare units

[2] Each warfare unit is a "system" within the SoS

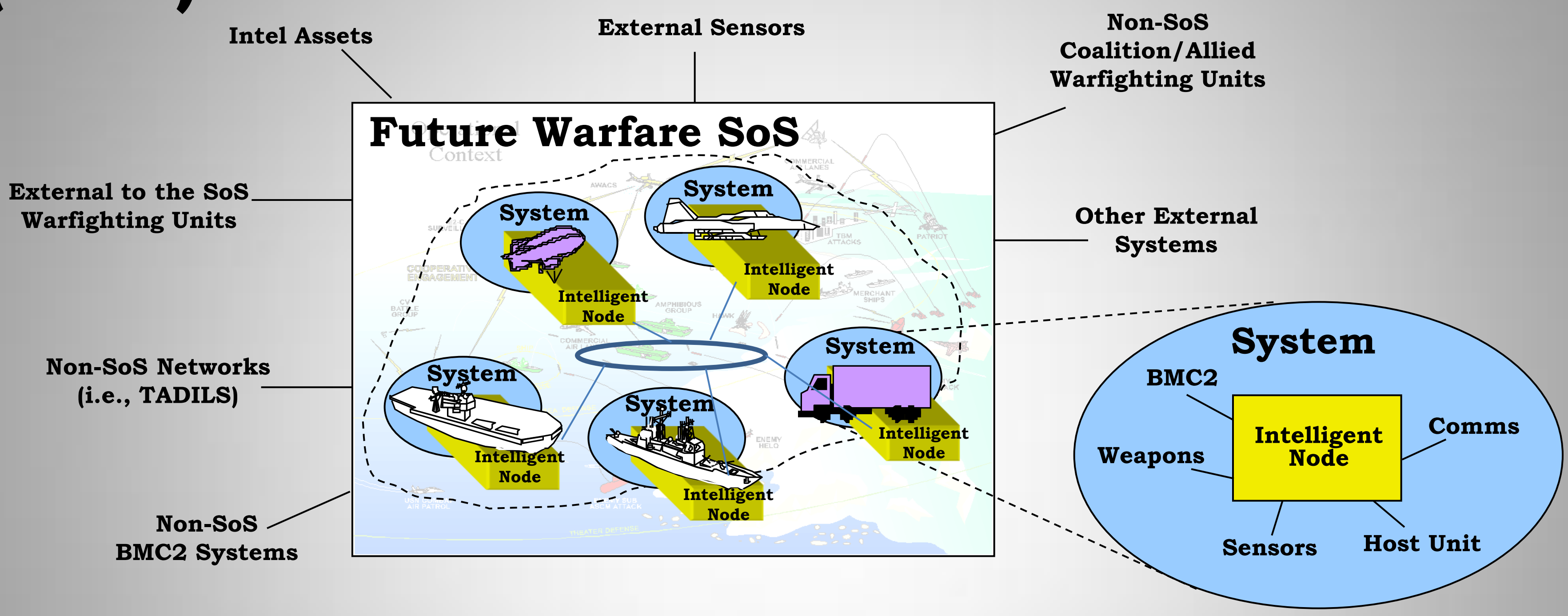
[3] Each system contains a common set of intelligent algorithms and processors

[4] All data and information is shared among the systems

[5] Each system within the SoS is empowered and equipped to operate as an intelligent agent—to make warfare decisions from a force-level perspective

Each system within the SoS is an intelligent agent

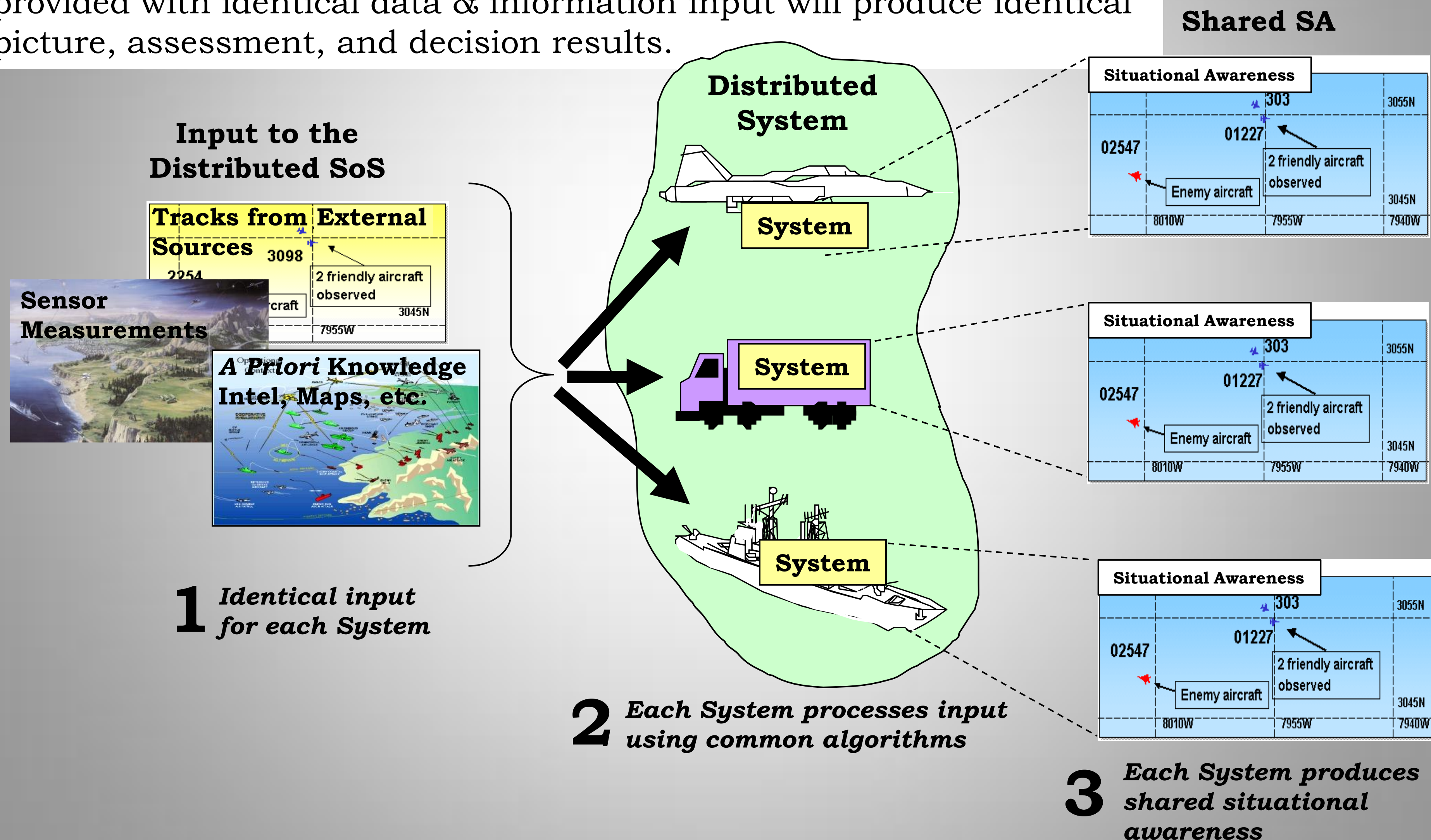
Future Warfare System of Systems (SoS)



- The warfare resources are considered the "systems"; the SoS will be the collaborative utilization and employment of them for the good of the whole.
- Each warfighting unit implements an "intelligent node" with identical/ common processing to perform BMC2 functionality.
- A "system" is defined as the intelligent node integrated with a unit's warfare resources.
- The distributed systems interact (collaborate/communicate) by sharing information with all other systems over a network.

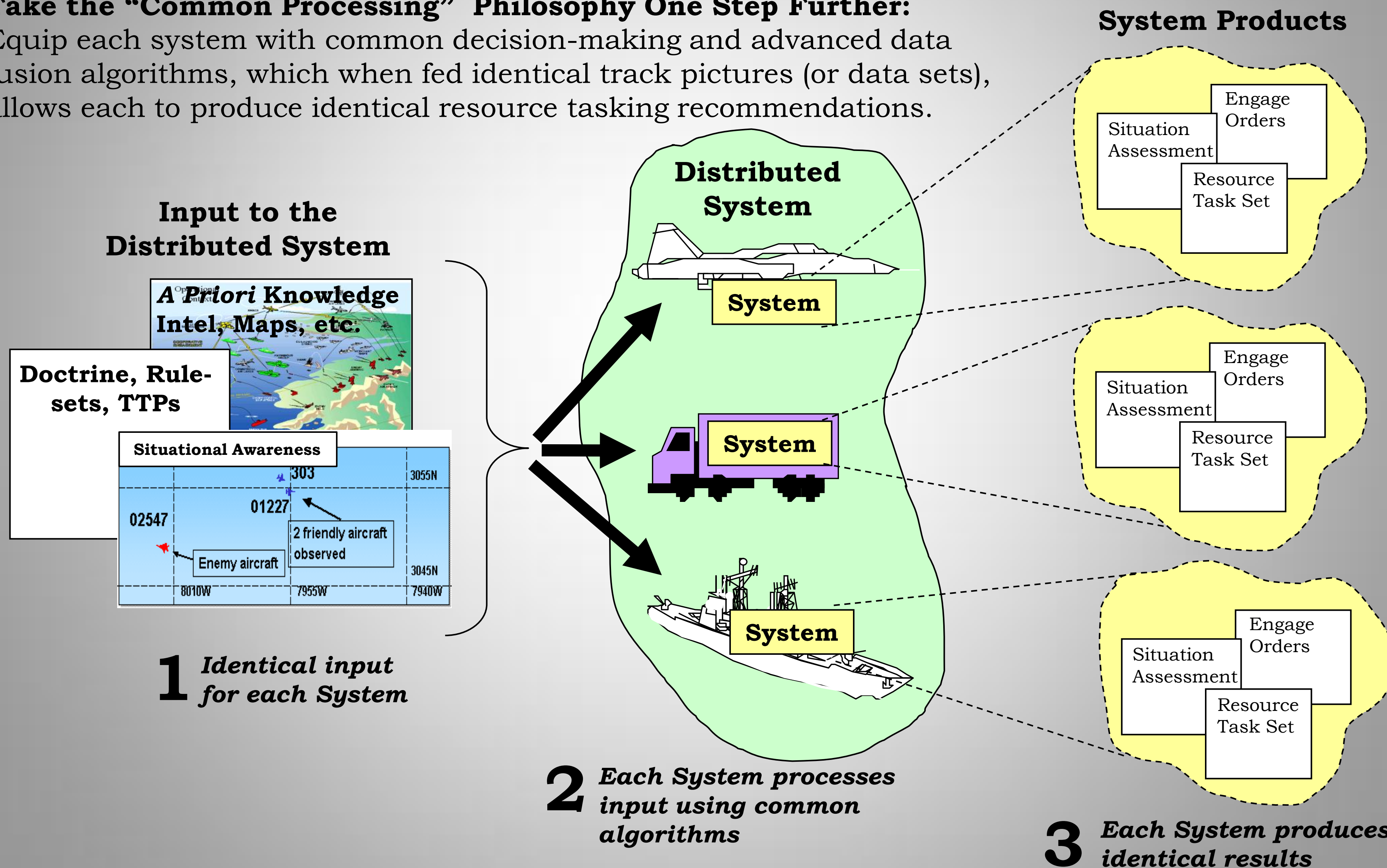
Common Processing Philosophy

The philosophy, simply stated, is that common processing algorithms provided with identical data & information input will produce identical picture, assessment, and decision results.



Common Processing for BMC2

Take the "Common Processing" Philosophy One Step Further:
Equip each system with common decision-making and advanced data fusion algorithms, which when fed identical track pictures (or data sets), allows each to produce identical resource tasking recommendations.



Emergent Capabilities (Payoffs)

Integrated Fire Control (IFC) refers to the participation and coordination of multiple non-collocated warfare assets in tactical engagements of enemy targets

- IFC is the ability to develop fire control solutions from information provided by remote sensors
- IFC expands the weapon's effective kinematic range by removing dependency on range limits of the local sensors
- Future advances in aerospace warfare depend largely on IFC – the collaborative use of distributed warfare assets for time-critical aerospace engagements.

Payoffs of Future BMC2 Collaboration:

- Improved chance of interception (by selecting the optimal engagement geometry)
- Selection of the best shooter from the distributed warfare assets
- Expansion of the battle space to the effective kinematic ranges of the weapons
- Removes dependency on range limits of the organic/dedicated sensors
- Improved economy of weapon resources (by reducing redundant shots)
- Faster reaction times (earlier launch decisions possible)
- Sharing engagement control – forward pass
- Off-board engagement support for guidance relay and target illumination
- Enhanced defense against complex threat environments (sophisticated or significant numbers of aerospace targets) – IFC may be a necessity for victory

Exploring the Complexity of Future BMC2

Definitions of Complexity

First Definition of Complexity: "…a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution."

- Complexity in future BMC2 systems dependent on:
  - # of participating warfare assets
  - complexity of operational environment
  - level of collaboration (& interoperability) achieved
  - Achievement of a decentralized architecture to empower elements and avoid central control
- Sophisticated information processing inherent in future BMC2
- Adaptation achieved through predictive capabilities—threat prediction, dynamic planning, etc.

Definitions of Complexity (cont.)

Second Definition: "…a system that exhibits nontrivial emergent and self-organizing behaviors."

- Nontrivial emergent behavior is the central objective and payoff of creating a networked collaborative BMC2 system of systems
- Emergent behavior would include: utilization of warfare resources at the force-level and shared situational awareness
- Self-organization refers to the ability of the components of a complex system to create organized behavior without an internal or external controller.
- Future warfare resources could self-organize given adaptable BMC2 rules/procedures and the ability to self-form collaborative systems of systems

Characteristics of Complex Systems

Common characteristics of complex systems. To what extent does the future BMC2 system of systems have these characteristics?

- Complex Collective Behavior
- Signaling & Information Processing
- Adaptation
- Design Decisions
- Complex Objectives
- Complex Operational Environment
- System Changes
- Lateral Influences
- System Risk
- Unforeseen Emergent Properties

Complex Collective Behavior

The collective action of the large numbers of components gives rise to the complex, hard-to-predict, changing patterns of behavior

The overall behavior of collaborative warfare resources would change in response to the complex operational environment and hard-to-predict in terms of which action might be taken by each individual element

Signaling & Information Processing

Complex systems produce and use information and signals from their internal and external environments

Information production, sharing, and usage is key for collaborative BMC2. Types of information include: sensor data, environmental data, intelligence, health & status information

Adaptation

Complex systems adapt—they change their behavior to improve their changes of survival or success through learning or evolutionary processes

Adapting to a constantly changing operational environment

- Future warfare threat environments will be complex and constantly changing.
- Additionally, the SoS itself will be constantly changing as its systems join and leave the SoS; as systems move; and as warfare resources change in time
- Therefore, the future BMC2 SoS will constantly find itself in unique and changing circumstances.
- Future BMC2 SoS behavior is adaptive as it responds to the threat environment and seeks to best utilize all of its warfare resource elements.

Characteristics of Future BMC2 Adaptation

- Adaptation can occur at system-level and force-level.
- Adaptation takes the form of changes to rules of operation/engagement, etc., doctrine, TTP's
- Adaptation can also take the form of the creation of new SoS's; acquiring additional systems into the SoS; dropping systems from a SoS

Design Decisions

For complex systems, a significantly large number of decisions have to be made regarding design, and typically the implications of design decisions are less predictable

Future BMC2 is based on a multitude of design decisions:

- micro-level (for each warfare resource)
- element level (integrating multiple warfare resources on platforms)
- the macro level (designing the system of systems architecture and force-level decision process)

Examples: common processing software, communications, decision process that governs resource allocation, interactions, and responses to the threat environment

The outcome of the future BMC2 system is the response of the warfare resources to the operational mission. Based on the design complexity and the complexity of the operational environment, this outcome is necessarily unpredictable, unique, and changing in time.

Complex Objectives

Complex systems have a large number of objectives and the objectives are generally inconsistent or changing.

Mission objectives include:

- Meeting the operational needs of different warfare areas based on threat present (i.e., air and missile defense, surface warfare, subsurface warfare, cruise missiles, asymmetric warfare, special operations, etc.)
- Addressing a set of objectives that are changing in time (priorities among threat change as combat environment unfolds)
- Meeting the operational objectives of individual platforms as well as those at the force-level

Conflicting objectives can arise from either of these types of mission objectives

Complex Operational Environment

Complex systems exist to operate in complex operational environments. The complexity of the operational environment may be a result of adverse environments, widely varying environments, or environments that cause challenging missions.

The operational environment for future BMC2 operations is envisioned to be highly complex and could include a combination of multiple and fast-moving air, missile, land, and space-based threats.

The threat may be sequential or simultaneous and may come from various directions

Threats may include unmanned vehicles, swarms of manned or unmanned vehicles, asymmetric attacks, or unconventional attacks disguised as a non-threat

Complexity in BMC2 Operations

Ultimately, every moment in the operational life of the BMC2 system will be unique.

All aspects are changing:

- Threats
- Participating warfare resources/units
- Status/health/capabilities of warfare resources
- Locations of units, threats, etc.
- Threat/mission priorities
- Rules governing resources and actions

System Changes

For complex systems, change at any level may have system-wide impacts and small causes may have large effects.

Changes include: inputs to the system; changes in the health or status of warfare resources, or the addition or deletion of participating warfare resources to a system of systems.

Inputs include: operational environment data (sensor data, intel, weather/maps, weapon loads and status, health and status of warfare resources, etc.), changes in operating rules (TTPs, rules of engagement, decision rules, etc.), and operator input

System-wide impacts; or force-level emergent capabilities include: identification of new threats, changes to tasking priorities, selection of best shooter, etc.)

Therefore, system changes and changes to inputs can impact the force-level emergent capabilities of the envisioned future BMC2 SoS

Lateral Influences

In complex systems, lateral influences are stronger and more dominant that hierarchical influences

- Empowering individual warfare units (systems) as intelligent agents with the force-level BMC2 capability (to arrive at force-optimized tasking for warfare resources) creates an emphasis on lateral influences over vertical

"In its highest state, shared context and understanding is implicit and intuitive between hierarchical and lateral echelons of command, enabling decentralized and distributed formations to perform as if they were centrally coordinated. When achieved, **these practices result in decentralized formal decision-making throughout the force**, leading implicitly to the opportunity to gain advantageous operational tempo over adversaries."

"Decentralization will occur beyond current comfort levels and habits of practice."

- Quotes from CJCS Paper on Joint Force 2020 (April 2012)

System Risk

In complex systems, risk is dominated by system-level risks, rather than lower level risks in achieving the contributing parts.

For the future BMC2, the risk shifts from individual warfare resources operating independently, to the collaborative system of systems.

Lower level risks, such as whether an individual warfare asset will function properly become less of an issue as the number of participating warfare resources participate

The risk shifts to system-level concerns, such as:

- whether information is being communicated properly
- whether situational awareness is shared and accurate
- whether the force-level decision process for tasking resources is behaving properly

Unforeseen Emergent Properties

Complex systems exhibit unforeseen or hard-to-predict emergent properties.

If such properties are truly unforeseen, then it remains to be seen whether the future BMC2 system of systems will behave in unpredictable ways

Since weapon systems are involved, it is imperative that modeling and testing occur to investigate unforeseen emergent properties

BMC2 Complexity Principles

Principles that Apply to Complex Systems

- System Holism Principle
- Darkness Principle
- 80-20 Principle
- Law of Requisite Variety
- Redundancy of Resources Principle
- Sub-optimization Principle
- Relaxation Time Principle
- Redundancy of Potential Command Principle

System Holism

A system has holistic properties not manifested by any of its parts and their interactions: vertical emergence. System holism widely known as "the whole is greater than the sum of its parts"

- Holistic properties of future BMC2 systems: force-level capabilities made possible through the collaborative interactions of their parts

- Examples: enhanced and shared situational awareness, distributed sensor and weapon management for force-level needs; integrated fire control

Darkness Principle

*The darkness principle in complexity is the concept of **incompressibility**: no system can be known completely. The darkness principle implies that members of a complex system do not have knowledge of the system as a whole: they will always be in the shadow of the whole.*

"Each element in the system is ignorant of the behavior of the system as a whole, it responds only to information that is available to it locally. This point is vitally important. If each element "knew" what was happening to the system as a whole, all of the complexity would have to be present in that element."

For future BMC2 with the existence of common processing resident in each warfare element and shared information, each element of the complex system gains a complete understanding of the whole system. This implies that the system complexity is present in each element. Thus, the darkness principle does not apply in the decentralized BMC2 architecture envisioned.

80-20 Principle

According to the 80-20 principle, in any large complex system, 80% of the output will be produced by only 20% of the system.

This principle can be evaluated in terms of future BMC2 in two different ways:

(1) The point of collaborative BMC2 is to best coordinate distributed warfare assets. So, the output of the system—the decisions or commands to task resources (or launch weapons) will reduce the number of tasked resources to a smaller fraction. As an example, the optimum weapon can be selected to engage a target; rather than each weapon system independently defending against a threat.

(2) On the other hand, for the envisioned BMC2 system, each node in the network is performing identical processing to develop the force-level tasking of the warfare resources. So, from this perspective, the decision outputs are being generated at each participating common node. So, from this perspective, 100% of the output is produced by 100% of the system. Thus, a significant amount of redundancy is designed into the decentralized architecture that is envisioned.

Law of Requisite Variety

- *"Control can only be obtained if the variety of the controller is at least as great as the variety of the situation to be controlled.*
- *A variation: "…every good regulator of a system must contain a complete representation of that system."*

The future BMC2 system complies with this complexity principle. With common processors, each warfare element attains information superiority through the common operational picture which contains shared situational awareness, health and status information of the warfare resources, and identical rule sets. So, each warfare element is empowered with the variety of the situation and therefore has the ability to "control" (or arrive at the optimum resource tasking solution) warfare assets at the force-level.

Redundancy of Resources Principle

Maintenance of stability under conditions of disturbance requires redundancy of critical resources

System stability is a concern for the future BMC2 system. Disturbances include:

- an overload of information or data
- false or corrupt data
- outages/communication failures
- a threat environment so complex that the number of resource tasks overloads the decision prioritization process
- delays that could slow the tasking process down to the point where the reaction time is not met

System redundancy that could address these types of disturbances include :

- redundant links (communication paths)
- the redundancy of the common processors at each element
- the ability to synchronize information among elements

Sub-optimization Principle

If each subsystem, regarded separately, is made to operate with maximum efficiency, the system as a whole will not operate with utmost efficiency. And the reverse: if the whole is made to operate with maximum efficiency, the comprising subsystems will not operate with upmost efficiency. Another way to think about this: parts in isolation behave differently from parts that are connected to a system and/or an environment

The sub-optimization principle readily applies to the BMC2 system. If individual warfare platforms are considered subsystems, then it is easy to imagine that if the platforms are each operating as they would in isolation; then given threats in the environment, each would fire weapons to engage the targets.

Examining the reverse implies that if the system is made to operate at maximum efficiency at the force-level, then the warfare platforms will not be operating at maximum efficiency. This situation would be the intent; since fewer weapons would have to be fired and sensors could share in the creation of the common operational picture.

Relaxation Time Principle

System stability is possible only if the system's relaxation time is shorter than the mean time between disturbances

Application of this principle to the future BMC2 system is critical to the success and stability of the system:

- the speed of communications, processing, decision-making, synchronizations, and generation of resource tasking.
- the tempo of the "disturbances" on threats must be understood: the speed, location, and numbers of threats and the resulting system reaction times necessary to address the threats.
- the correlation between the system tempo and the threat tempo—ensuring there is a built-in time for "relaxation" or processing necessary to stabilize in between

Redundancy of Potential Command

In any complex decision network, the potential to act effectively is conferred by an adequate concatenation of information. This means that to "control" a complex system we must at first have a sufficiently good representation of it.

The future BMC2 system of systems upholds this principle. One of the major outcomes is shared situational awareness among the distributed warfare nodes. This constitutes the adequate concatenation of information or self-knowledge of the operational environment and the system itself.

CSE Applications for BMC2

Designing Complex Man-Made Systems

"Many engineering applications, such as real-time decision support, communications and control, are reaching the point where classical methods are no longer feasible for reasons of system interdependencies and complexity." [Bar-Yam, 2004]

"As systems become increasingly large and must seamlessly interoperate with other systems in ways that were never envisioned, system engineers are bumping into the limits of the tenets, principles, and practices traditionally used in systems engineering." [Brian White, 2001]

CSE does not "…primarily seek to produce predictable, stable behavior within carefully constrained situations, but rather to obtain systems capable of adaptation, change, and novelty—even surprise!" [Braha, Minai, and Bar-Yam, 2006]

Complex Systems Engineering

- Why is there a need for Complex Systems Engineering?
- TSE = Traditional Systems Engineering
- CSE = Complex Systems Engineering

Traditional System	Complex System
Hierarchical Relationships dominate lateral influences	Lateral influences dominate hierarchical relationships
Cause and effect are relatively obvious and direct	Cause and effect are not obvious and direct; Small causes can have large effects
The implications of design decisions are relatively predictable	The implications of design decisions are much less predictable
Risks are dominated by the local risks in achieving the contributing parts	Risks are dominated by system risks, with unforeseen emergent properties
Influences on, and implications of, decisions tend to follow the local partitioning of the solution elements	Influences on, and implications of, decisions are much more difficult to bound and to establish

CSE Methods

How can we deal with complexity in a predictable way?

1. Identify when a system and/or its solution is complex
2. Determine level of complexity (or relative complexity)
3. Determine when enough SE has been done; and when level of confidence in design (and predictable behavior) is acceptable [Calvano, 2004]

Adopt an evolutionary paradigm for CSE that involves rapid parallel exploration and a context designed to promote change through competition between design/implementation groups with field testing of multiple variants. [Bar-Yam, 2003]

1. Design the environment and processes by which the system is going to be created (not designing the system itself).
2. Design components of the system for the system as a whole.
3. Design a set of rules about how components engage with one another and the process of change.

[White, 2001]

"Highly integrated systems exhibit more complex interactions across the system than earlier, simpler systems. In the highly integrated system, the designer must consider effects on all parts of the system. We are therefore engineering at the systems level more fundamentally than ever; as opposed to introducing subsystems into an evolved, well-precedented system structure." [Calvano, 2004]

CSE Considerations

- Design until an acceptable degree of confidence is met
- Attempt to deal with complexity in a predictable way
- Engineer at the system level—gain an understanding of the whole and emphasize lateral interactions rather than hierarchical
- Adopt an Evolutionary Paradigm with rapid parallel exploration and competition between design/implementation groups to test multiple variants
- Utilize best practices from TSE and CSE:

"[Traditional] systems engineering and complex system engineering live together. Treating them separately doesn't make any sense. CSE builds on the capabilities of TSE but has its own unique perspective of focusing on the system environment." [White, 2001]

Should CSE methods be considered for future BMC2?

- The complexity characteristics of future BMC2 pose serious challenges that may exceed the limits of TSE
- Complexity in the objectives results in a BMC2 system of systems that is hard to bound
- Generating a well-defined set of mission objectives and system requirements is very challenging
- There is much complexity involved in design decisions (large scope and unpredictability of design decision outcomes)

Taking Advantage of Complexity

In addition to trying to cope with the scope and complexity of the future BMC2 system, engineering strategies must also strive to ensure designs take advantage of the benefits that complexity offers.

- Designs should not limit features such as redundancy, sub-optimization, and the 80-20 principle
- These may seem wasteful, inefficient, and costly; but they may be the key to the stability and response times necessary to function in a complex environment
- Benefits also include adaptation, self-organization, and agility

Conclusions

- Future BMC2 has many characteristics of complexity and follows many principles of system complexity
- The system engineering of future BMC2 should adopt a mix of CSE and TSE methods
- SE approaches adopted should not limit or constrain the benefits of the complex nature of the future BMC2 system

Future Explorations

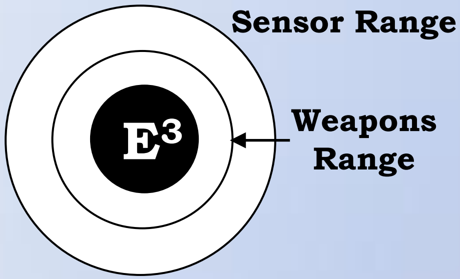
- Understand and quantify the BMC2 system tempo, the threat environment tempo, and analyze and compare the tempos to identify disconnects
- Determine what a sufficient level of systems engineering completeness would be – develop a strategy to determine when the level of confidence in the design is acceptable
- Study the 80/20 principle as it applies to BMC2. What percentage of the system output will be produced by what percentage of the system?
- Predict and understand emergent properties
- Study the overall system stability against "disturbances" – is there enough redundancy and sub-optimization to compensate for disturbances?
- Study what sufficiency in representation (situational awareness) is required to support action (resource tasking).

In conclusion, the potential complex threat environment of the future and the mission need to provide defensive measures and tactical responses have created a need for a future BMC2 system that can perform complex tasks. And, only a complex BMC2 system can perform complex BMC2 tasks!

Back-Ups

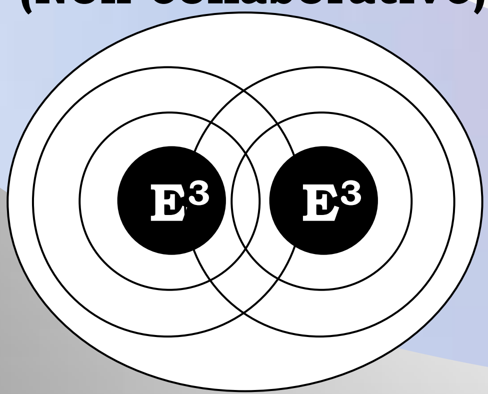
Improved Engagements

Single Unit

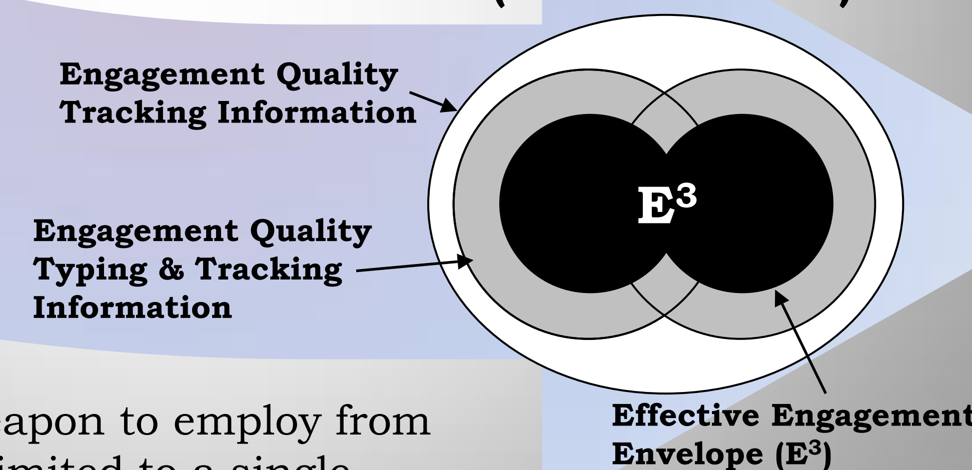


The "effective engagement envelope" will greatly expand as the shift takes place from a single warfighting unit using only local sensor and weapon resources to a system of collaborating warfighting units. The shared sensor data will enhance situational awareness; thereby extending the detection envelope and improving the reaction time of weapons deployment—which will extend the effective range of engagements.

Multiple Units (Non-collaborative)



Multiple Units (Collaborative)



The ability to select the optimum weapon to employ from across the force (rather than being limited to a single unit) will improve the economy of weapons resources and the probability of effective engagements.

Future BMC2 Information Architecture

Characteristics:

- High bandwidth, Secure, Reliable
- Timely sharing of data and information among units
- Adaptable to accept or drop units
- Employ authentication measures to ensure authoritative data sources

Information Architecture Capabilities

Objectives for Information Sharing:
Based on Force-centric de-centralized architecture
- Allows warfare resources to be managed according to Force-level needs (rather than unit-centric needs)
- Manages network to enable special data distribution needs during engagements. (higher data rate or throughput)

Information Dissemination Capabilities:
- Determines needs of information-recipient users or decision nodes (data advertisements/ subscriptions)
- Tracks data availability
- Establishes routing paths & maintains connectivity
- Optimizes bandwidth usage
- Determines feasibility of transmission/checks link status
- Sends and receives commands to/from remote link managers to control, manage, & synchronize transmission
- Transmits data/information according to local/remote synchronized commands

Information Exchange Required:
- Associated Measurement Reports
- Resource information: HSCC
- C2 Datasets (Doctrine, TTPs, plans, manual commands)
- Resource Tasking Requests
- Resource Commitment "Handshakes"

Data Exchange Characteristics:
- Supports real-time exchange of sensor measurement data
- Broadcast/Multicast/Point-to-Point
- Non-real-time traffic for operations control
- Link monitoring
- Quality of Service delivery
- Data integrity and confidentiality
- Bandwidth allocation/monitoring
- Data dissemination prioritization (for time-sensitive data or bandwidth constraints)
- Ad hoc nodal topology (nodes can easily join or leave network)
- Interfaces with Tactical Data Links (TDLs)

Shared SA Data Processing & Fusion

Shared SA relies on:
Data processing and data fusion algorithms to assess and develop a representation of the real situation

Situation Assessment Capabilities

Tracking & Combat ID
- Pixel/Signal-level association
- Object kinematics
- Object characterization
- Object kinematics prediction

C2 Situation Assessment
Assessment & Adoption of Blue Force BMC2 inputs
- Ensure peer promulgation of commands
- Translate BMC2 inputs into system operating rules, constraints, & parameters

SA Certification
- Assessment of track quality
- Assessment of track ID confidence
- Certification of fire control quality SA

Object Context Assessment
- Estimate object relations
- Refine object ID & typing based on group behavior
- Provide physical context for track picture
- Discrimination, kill assessment
- Maintain defended assets picture

Warfighting Resource Assessment
Assessment of sensors, weapons, & warfighting units
- Health & status assessment
- Configuration & capability maintenance

Environment Assessment
- Develop & maintain environmental picture (weather, mapping, jamming, etc.) for Area of Interest (AOI)

Processing Evaluation
- Assessment of processing performance
- Unit health & status assessment

Threat Evaluation
- Identify, evaluate, & prioritize threats

Force Readiness Assessment
Fusion of assessments
- Determination of overall readiness of warfighting forces

SoSE

A need exists for new approaches for engineering SoS's because of:

(1) An exponential rise in the demand, accessibility and proliferation of information
(2) Increasing requirements for interdependence between systems that have previously been conceived, developed, and deployed as independently functioning systems
(3) Demands for engineering solutions willing to trade completeness for accelerated deployment
(4) Holistic solutions that exist beyond technical resolution

Methodology vs. Process

There are 6 primary conditions that suggest a methodology may be preferable to traditional SE approaches (processes) for SoS's:

1. **Turbulent Environmental Conditions** (environment is highly dynamic, uncertain, rapidly changing)
2. **Ill-defined Problem Conditions** (in dispute, not readily accessible, or lack of consensus)
3. **Contextual Dominance** (the technical "hard" aspects are overshadowed by the contextual "soft" (circumstances, conditions, factors) aspects)
4. **Uncertain Approach** (path of how "best" to proceed is indeterminate)
5. **Ambiguous Expectations and Objectives** (inability to establish measure of success or system objectives)
6. **Excessive Complexity** (system boundaries are expansive such that the level of complexity is beyond the capabilities of traditional SE approaches)

Shared Situation Awareness

... is key because each unit needs identical, complete, accurate, & timely awareness (knowledge) of the operational situation.

Track Picture
Fundamental track & combat identification data representation of all objects in the environment

Defended Assets Picture
The location, status, & prioritization of all defended assets (ground, maritime, & aerospace; as well as Blue Force, Coalition, & Civilian)). Includes defended objects and zones as well as points or areas on the ground within an area of interest.

Object Context Picture
Estimates of the group behavior of threat objects.

C2 Situation Picture
Decision-maker commands, assigned missions of warfighting units, doctrine, Tactics Techniques and Procedures (TTPs), location and status of warfare units and network

Environmental Picture
Meteorological, electromagnetic jamming, & atmospheric information concerning the battle space area of interest.

Threat Picture
The identification, evaluation, and prioritization of threat objects

Warfare Resources Picture
The location, Health, Status, Configuration, and Capability (HSCC) information of each warfare resource (sensors, weapons, and warfighting units).

Shared Situation Awareness (SA) is the ability of distributed units (systems) to gain an understanding of the totality of the operational environment including the tactical situation, the threat, the defended assets, the readiness of warfighting resources, and command and control constraints within which the systems must operate.

Distributed Resource Management...

... is key to enabling and optimizing the use of distributed resources for collaborative BMC2 and integrated fire control

Distributed Resource Management

Engagement support strategy after launch
- Forward pass (preferred eng control option)
- Remote guidance relay (preferred sensor arrangement)
- Remote target illumination (preferred sensor support)

Selective engagement
- Selection of best option if multiple engagement options along the threat trajectory exist

Launch determination
- Receive threat determination
- Assess engageability of weapon options
- Determine intercept probability
- Decide to launch (or not)

Engagement support strategies
- Threat detection/cue
- Fire Control Quality data availability
- Sensor tasking/commitment
- Preferred sensor arrangement

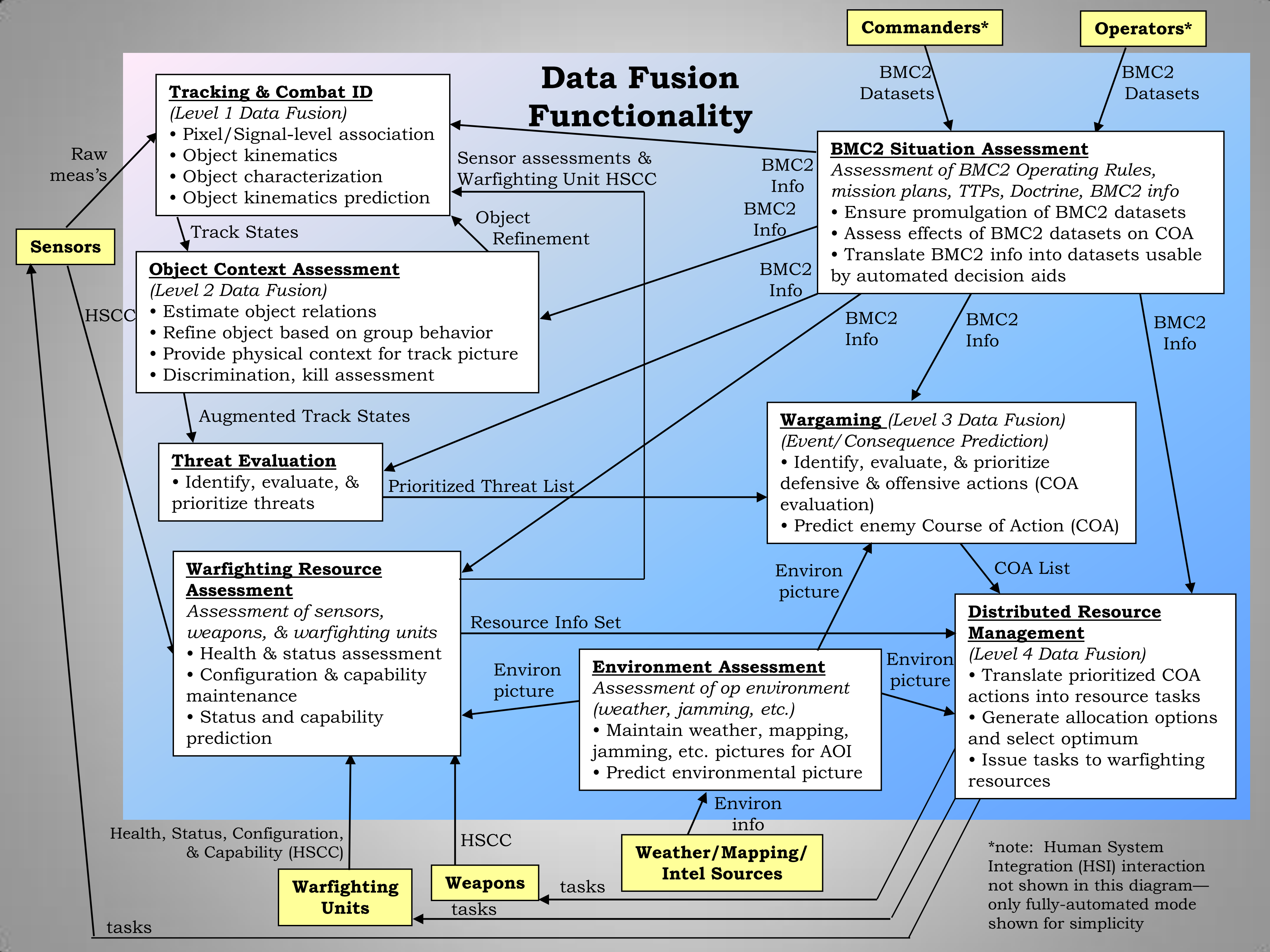
Weapon-target pairing
- Preferred shooter determination
- Engageability of weapon options

• Based on the use of automated decision aids to determine and recommend optimum uses of warfare resources

• Using identical automated decision aids on distributed units enables decisions to be made in a timely manner to support time-critical engagement operations.

• Each distributed unit uses distributed resource management (DRM) to determine tasks for all resources within the operational environment

• Resident operators can override resource tasking recommendations for local resources; thus command authority is upheld.


Data Fusion Functionality
Commanders*
Operators*
BMC2 Datasets
BMC2 Datasets
Tracking & Combat ID
(Level 1 Data Fusion)
• Pixel/Signal-level association
• Object kinematics
• Object characterization
• Object kinematics prediction
Raw meas's
Sensors
HSCC
Sensor assessments & Warfighting Unit HSCC
Track States
Object Refinement
BMC2 Info
BMC2 Info
BMC2 Info
BMC2 Situation Assessment
Assessment of BMC2 Operating Rules, mission plans, TTPs, Doctrine, BMC2 info
• Ensure promulgation of BMC2 datasets
• Assess effects of BMC2 datasets on COA
• Translate BMC2 info into datasets usable by automated decision aids
Object Context Assessment
(Level 2 Data Fusion)
• Estimate object relations
• Refine object based on group behavior
• Provide physical context for track picture
• Discrimination, kill assessment
BMC2 Info
BMC2 Info
BMC2 Info
Augmented Track States
Threat Evaluation
• Identify, evaluate, & prioritize threats
Prioritized Threat List
Wargaming (Level 3 Data Fusion)
(Event/Consequence Prediction)
• Identify, evaluate, & prioritize defensive & offensive actions (COA evaluation)
• Predict enemy Course of Action (COA)
Warfighting Resource Assessment
Assessment of sensors, weapons, & warfighting units
• Health & status assessment
• Configuration & capability maintenance
• Status and capability prediction
Environ picture
COA List
Resource Info Set
Distributed Resource Management
(Level 4 Data Fusion)
• Translate prioritized COA actions into resource tasks
• Generate allocation options and select optimum
• Issue tasks to warfighting resources
Environ picture
Environ picture
Environment Assessment
Assessment of op environment (weather, jamming, etc.)
• Maintain weather, mapping, jamming, etc. pictures for AOI
• Predict environmental picture
Environ info
Health, Status, Configuration, & Capability (HSCC)
HSCC
Weather/Mapping/ Intel Sources
Warfighting Units
Weapons
tasks
tasks
tasks
*note: Human System Integration (HSI) interaction not shown in this diagram—only fully-automated mode shown for simplicity

Knowledge & Decision Products

Example Products of Data Fusion Process:

- Preferred shooter determination
- Weapon-Target Pairing
- Sensor Support for Engagements
- Engagement Control Strategy (i.e., forward pass)
- Engagement Preferences (intercept geometry)
- Sensor tasking to support better situational awareness
- Unit tasking to reposition warfare units
- Identification of gaps in defense and recommendations to close gaps
- Threat identifications and prioritizations
- Awareness of SoS warfare resources: health, status, configuration, and configuration (HSCC)
- Situational awareness – object identification and characterization, map overlays, weather overlays, etc.

Example: each distributed unit uses "common" algorithms to produce identical Force-level engagement recommendations. Therefore, each unit arrives at the same conclusion that a particular weapon has the best shot and that a particular sensor (not necessarily collocated with the weapon) can best track and/or illuminate the target.

Situation Prediction Capability

… is key for determining that a threat requires defensive measures—taking into account possible ramifications (Effects Based Operations)

Situation Prediction Functionality

Environment Prediction
- Predict weather for AOI
- Predict possible jamming/clutter

Resource Projection
Prediction of sensors, weapons, & unit performance
- Availability & capability prediction

Wargaming – Event/Consequence Prediction
Prediction of sensors, weapons, & unit performance
- Predict threat
- Predict & evaluate enemy COA & intent
- Identify, evaluate & prioritize blue force COA
- Evaluate effects of C2 inputs on blue force COA
- Analyze historical trends

Force Projection
Prediction of Force Readiness
- Prediction of overall force readiness & capabilities

- Projects the current situation into the future to estimate the enemy Course of Action (COA) and potential impact of the blue force's planned actions.

- Develops and assesses alternative futures or hypotheses concerning the current situation and possible COAs.

- Assigns quantitative confidence values to potential COAs

- Enables collaborative planning, effective resource management, and dynamic replanning

Warfare Planning Capability

… is key to predicting operational situations that require defensive measures (such as collaborative fire control)

Built-in planning prior to operations is a key enabler of Distributed Resource Management:
• Establishing prioritization schemes for missions, threats, defended areas, weapons, tactics
• Establishing rule sets to guide resource behavior for tactical and strategic operations
• Establishing parameters to control engageability calculations, target-weapon pairing, target identification/threat evaluation, & sensor tasking
• Establishing decision logic

Deliberate Planning is the predetermination of resource utilization

Defense Planning - "Macro" Planning
• Assigning resources to missions
• Allocating areas/zones within theater
• CINC priorities
• Identifying critical assets

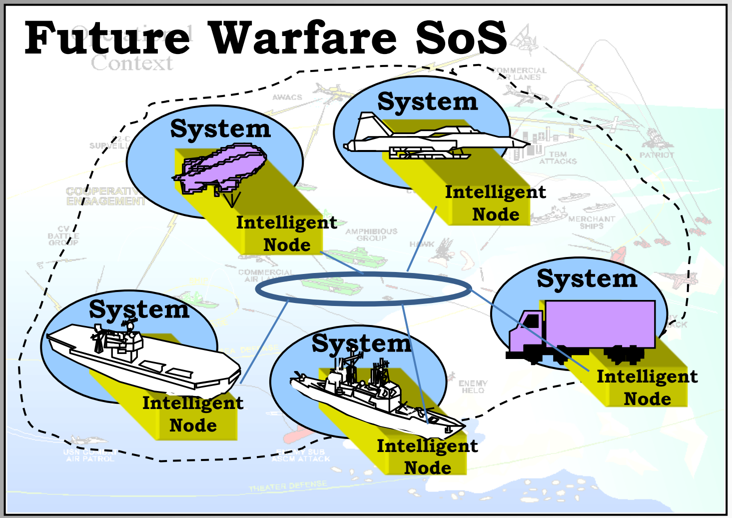
Defense Design – "Micro" Planning
• Specific TTPs
• Rule sets
• Initialization parameters
• Correlation Track Quality Values

Dynamic Planning is the modification of plans during operations

Dynamic Planning Functions:
• Replanning – dynamic creation of new plan
• Refinement of plan
• Reassignment of resources
• Ad hoc operations
• Alteration of rule sets
• Reset of parameters
• Reestablishing prioritization

Why Dynamic Planning is Useful:
• Plan implementation needs to reflect reality
• Resources change (things break, resources become unavailable)
• Enemy prediction never 100% accurate (unexpected events, enemy COAs, & threats)

SoS Design Characteristics



- Each constituent system can operate independently or as a collaborating member of an SoS
- Individual systems may enter and exit SoS's
- Multiple SoS's may exist
- Multiple warfare mission areas can be addressed by single or multiple SoS's
- Constituent systems have the ability to "self-organize"

- Each constituent system is "intelligent": has a replicated (identical or shared) situational awareness and arrives at replicated decisions for BMC2
- Lateral influences dominate vertical (hierarchical) influences
- SoS adaptation is possible, encouraged, and necessary
- SoS must be robust (resilient to external forces)
- Emergent capabilities are projected to include the force-level optimization of the use of the assets and enhanced situational awareness across the force
- SoS must maintain a strong self-identity

Independent Operation of Constituent Systems

- Each constituent system can operate independently or as a collaborating member of an SoS
  - ❖ Each system is empowered as an intelligent agent and is fully-equipped to operate independently as operationally necessary
- Individual systems may enter and exit a SoS
  - ❖ Examples: Mobile systems (aircraft, ships, etc.) may move into (or out of) the range of an SoS; system degradation or destruction may result in a system exiting an SoS
  - ❖ Systems need to get caught up to speed upon entering a SoS (data/information download and synchronization)
  - ❖ SoS must acknowledge systems that join – "handshake"
  - ❖ Systems must provide information concerning their warfare resources and SA knowledge to SoS upon entering
- Constituent systems have the ability to "self-organize"
  - ❖ Each system, empowered as an intelligent agent, can form a SoS with other systems as the operational mission/environment require

SoS Robustness

- Future warfare SoS's must be robust (resilient to external forces)
- Robustness refers to resilience to changes in understanding, interpretation, and context
- Perturbation for SoS is inevitable, may not be known beforehand, and emergent patterns/properties may develop in response

- Methods of achieving SoS robustness through design:
  - Knowledge of operational environment (SA)
  - Internal SoS monitoring
  - Design flexibility to respond to anticipated SoS deviations
  - Feedback to adjust over the mission performance of the SoS

SoS Communications

Communications, within and external to the SoS, are essential to ensure solution viability in the face of emergence.

"Channels" are proposed as a method for SoS communication:

Operations Channel – direct exchange between SoS subsystems
Coordination Channel – to monitor regulatory mechanisms for SoS standardization
Algedonic Channel – a direct link between subsystems and the SoS level for identification of high level threats
Command Channel – for high-level direction throughout the SoS
Audit or Operational Monitoring Channel – to examine SoS disturbances/health
Environmental Screening Channel – continuous monitoring of trends, patterns, and events in the environment
Resource Bargain-Accountability Channel – negotiation between the SoS and the constituent subsystems concerning resource distribution
Dialog Channel – to support the examination and interpretation of SoS decisions, actions, and events
Learning Channel – the detection and correction of SoS errors
Informing Channel – routine transmission of information throughout the SoS
Identity Channel – to support the exploration of the essence of the SoS – the purpose, mission and character

Context

Context – the circumstances, factors, conditions, and patterns that both enable and constrain a complex system solution; it's deployment; and it's interpretation

- For the future warfare SoS, the context can dominate the solution space (even more so than technical aspects)

- Context is a critical consideration for developing SoS's

- Context considerations for SoS's: technical, operational, human/social, managerial, organizational, policy, political

Multiple Objectives

Pluralism – the characteristic of having multiple purposes and objectives in play at the individual, entity, and enterprise levels.

- Differences in purposes may become sources of conflict at various points in the development of the SoS.
- The assumption that an SoS has a singular set of agreed-upon requirements and shared understandings may be questionable
- This is problematic for SE approaches based on rational-logical assumptions of objective/requirement alignment
- For SoS's, pluralism suggests that different objectives may be pursued in response to patterns and properties that manifest through SoS operation

SoS Requirements Specification

- Due to emergence and adaptation, the system design of an SoS can only be partially specified in advance of system operation

- Overspecification of system-level requirements is:
  - (1) wasteful of scarce resources necessary to monitor and control system level performance
  - (2) reduces subsystem autonomy, which in turn restricts the agility and responsiveness of the system to compensate for environmental shifts.
  - (3) fails to permit subsystem elements to self-organize based on their contextual knowledge, understanding, and proximity to the operating environment.

Boundaries

Boundaries in an SoS are ambiguous, fluid, and negotiable.

- They provide the criteria for what is included and excluded from an SoS
- Boundaries may form around geographic, time, spatial, or conceptual delineations
- SoS boundaries may shift radically; particularly in the early formation of the problem domain; and also during operations
- SoS boundary shifts should be expected and embraced

SoS Self-Identity

- Maintenance of a strong SoS identity is key to SoS viability, robustness, and continued existence
- There may be many decisions, actions, and interpretations necessary for an SoS to function in the face of changing objectives, operational missions, perturbations, etc.
- Thus, a stabilizing force is required that acts as a reference point for consistency in decisions, actions, and interpretations
- A strong SoS self-identity is the driving force that establishes the set of characteristics that is the essence of the SoS

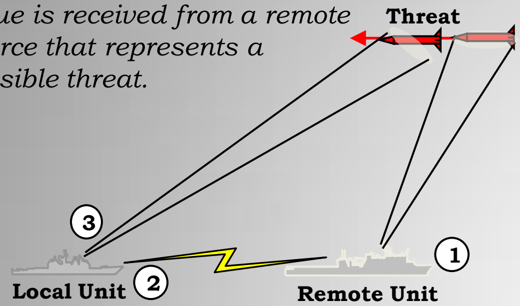
In conclusion, this presentation is intended to raise questions that will lead to further study. Here are some topics of interest:

- Study the application of SoS systems engineering (SoSE) & complex systems engineering (CSE) as methodologies
- Understand and quantify the BMC2 system tempo, the threat environment tempo, and analyze and compare the tempos to identify disconnects
- Determine what a sufficient level of SE completeness would be—develop a strategy to determine when the level of confidence in the design is acceptable
- Study the SoS against disturbances – is there enough redundancy and sub-optimization to compensate for disturbances?
- Understand the interplay between complex SoS's and their context/environments

IFC Variants

Precision Cue

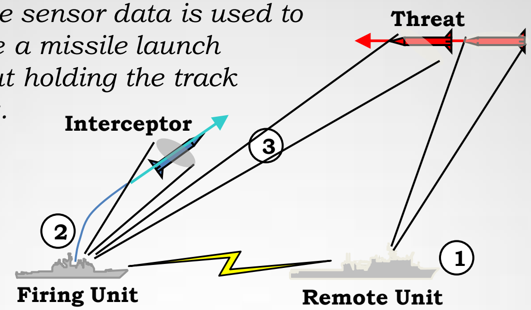
A cue is received from a remote source that represents a possible threat.



1 Remote sensor detects threat.
2 Local unit receives cue.
3 Local unit tasks local sensor to detect and track threat.

Launch on Remote

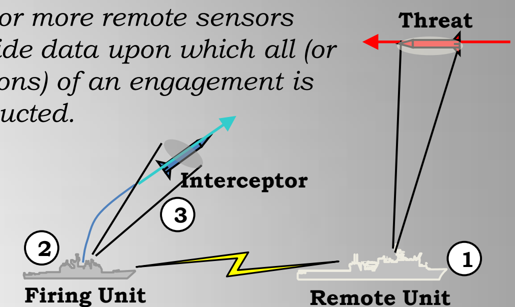
Remote sensor data is used to initiate a missile launch without holding the track locally.



1 Remote unit provides FCQ threat data.
2 Firing ship launches interceptor based on remote threat data.
3 Local unit tasks local sensor to provide FCQ threat data for remainder of post-launch engagement cycle.

Engage on Remote

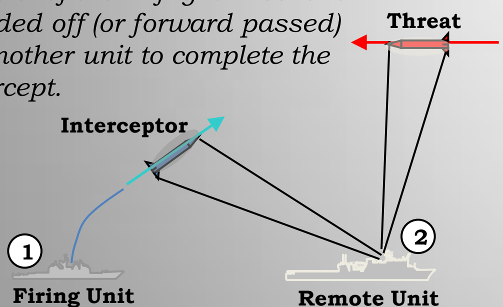
One or more remote sensors provide data upon which all (or portions) of an engagement is conducted.



1 Remote unit provides FCQ threat data.
2 Firing ship launches interceptor based on remote threat data.
3 Remote unit continues to control engagement (compute & provide interceptor guidance, etc.) based on remote data.

Forward Pass

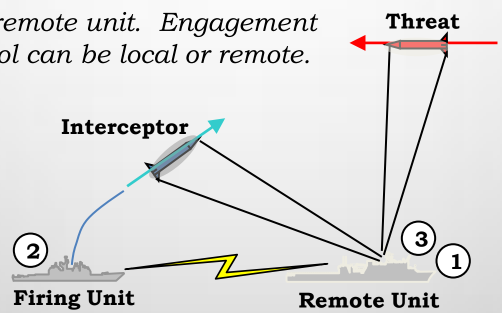
Control of the in-flight missile is handed off (or forward passed) to another unit to complete the intercept.



1 Firing Unit launches interceptor & passes engagement control to Remote Unit
2 Remote Unit takes over engagement control – tracks threat, passes guidance to interceptor, and illuminates threat when necessary

Remote Fire

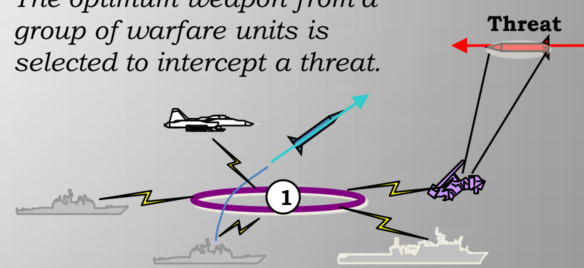
The decision to launch is made by a remote unit. Engagement Control can be local or remote.



1 Remote unit makes decision that firing ship should launch.
2 Firing ship launches interceptor.
3 Remote unit (in this example) controls engagement (threat tracking, interceptor guidance, etc.).

Preferred Shooter Determination

The optimum weapon from a group of warfare units is selected to intercept a threat.



1 The best shooter is selected based on optimum engagement geometry and engageability determination. PSD can be performed in conjunction with any of the other IFC variants. PSD is, in effect, Force-centric weapon-target pairing.