Complex Adaptive Systems of Systems: A Grounded Theory Approach

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Abstract

This paper details the classic grounded theory approach used in a research project to develop a conceptual theory for an engineering solution to address highly complex problems. Highly complex problem domains exist and are on the rise as we enter an Age of Interactions and Complexity. Our current world has been characterized by the plethora and ubiquity of information and global interconnections that link events and decisions to outcomes and effects that are often unpredictable and result in severe unforeseen and unintended consequences. Technological advances such as computers, the internet, Big Data, social media, artificial intelligence, and communication networks have expanded complex problem spaces. However, these same technologies present an opportunity to engineer a complex adaptive system of systems solution to address these challenging problems. This research project embarked on a classic grounded theory approach to study a number of knowledge domains and engineering processes, allowing a conceptual theory to emerge that offers an engineering solution to address highly complex problems. The project resulted in the emergence of a theory for a new class of engineered CASoS solutions. This paper details the classic grounded theory approach taken to conduct the research.

Keywords: complex adaptive systems of systems, grounded theory, systems engineering, complexity

Introduction

> Most people would agree that the world is becoming more complex. Much of this is driven by two phenomena that have started to dominate our lives in recent years. First, we face an unprecedented level of integration and are immersed in a *complex* web of interacting technologies and processes, dominated by the developments in information and communication technologies. Second, rapid change has become the norm with technologies, practices, and organizations being introduced continuously into this highly integrated web. (Calvano and John, 2004, p.29)

The rise of automation in many systems, and technological ubiquity in general, present complex problems that require a solution that can continually adapt to meet the changing demands of the operational environment. The interaction of heterogeneous and increased technologies introduces multi-faceted problems that are unlike any before seen. Alberts (2011) stated that we have entered the *Age of Interactions* in which events and decisions are linked to many outcomes that affect many other events. Bar-Yam (2004b) cited many examples of complex problem spaces including military conflict, health care, education, international development, large scale natural disasters, ethnic violence, and terrorism. National strategies often invoke the DIME (diplomatic, information, military, and economic) construct, as is the case when countries apply economic sanctions, or use diplomatic negotiations. Hillson (2009) explained that the DIME components constitute actions and consequential effects that can be highly interactive, complex, and unpredictable. As nations implement the DIME construct, the effects can be highly interrelated and can have unpredictable consequences. Technological advances in global information and communication infrastructures accelerate these complex interactions and the tempo of cause and effect. Complexity scientists are studying the causes and effects of seemingly unrelated events that have significant repercussions. Lagi, Bertrand, and Bar-Yam (2011) found that agricultural price increases in North America due to droughts were indirectly and inadvertently linked as a causal factor to violent protests in North Africa and the Middle East.

Technological advances in computers, Big Data, artificial intelligence, global information and communication networks have contributed to complex problem spaces. Big Data refers to the current paradigm of enormous amounts of data and information that exist because of commercial, government, and military enterprises, as well as individual communication and participation in social media (Zhao, MacKinnon, & Gallup, 2015). Big Data fosters the *Age of Interactions* through new technologies that enable rapid capture, processing, and storing of vast amounts of data, which result in heightened awareness, information overload, and unlimited access to information systems, individuals, and enterprises. Exacerbating the problem domain are vast global networks of interconnected information nodes that create increases in complex interactions.

Complexity is the state of having many different parts connected or related to each other in complicated, often non-linear interactions that are difficult to understand in a more complete manner. Highly complex problems are unpredictable and present dire consequences if not handled properly. They change over time, are unique from moment to moment, and often present shortened reaction times for involved decision-makers to address them (Johnson, 2012). Complex problems, resulting from numerous non-linear interactions, can overwhelm traditional systems that cannot adapt quickly enough; cannot address multiple missions occurring simultaneously; and cannot process information quickly enough to make effective decision-making possible. Calvano and John (2004) studied systems engineering methods aimed at handling complex problems. They called the current age, the "Age of Complexity" (Calvano & John, 2004, p. 29). They found that traditional methods of engineering systems to meet well-defined static requirements are not sufficient to meet the adaptable and complex behavior required of engineered solutions for highly complex problem spaces.

This research project studied complex adaptive systems of systems (CASoS) as a new class of systems with the potential to address highly complex problem spaces. These complex decision spaces require a new approach: one that enables intelligent adaptive systemic behavioral responses and courses of action to tackle the complexity. This approach includes a system of systems that can produce intentionally designed and desired emergent behavior through the self-organization of their intelligent and purposeful constituent systems. By developing a theory for engineering a CASoS, this research contributes to the bodies of knowledge regarding systems, systems of systems (SoS), and complex systems. The application of an approach based on CASoS theory to address certain complex problem spaces opens a new area of research within the domain of systems engineering.

In this paper, the authors describe the method of inquiry used to explore CASoS as solutions to highly complex problems, with a general discussion of classic grounded theory—an approach resulting in the emergence of theory based on creativity, reflection, conceptualization, and a self-critical iteration of ideas. The majority of the paper discusses the detailed application of classic grounded theory to produce the CASoS Engineering theory.

Grounded Theory

> A theory is systematically organized knowledge applicable in a relatively wide variety of circumstances, using a system of assumptions, accepted principles, and rules of procedure devised to analyze, predict, or otherwise explain the nature of behavior of a specified set of phenomena. But it is also simply the best explanation which is available at the time. (Remenyi, 2014, p. 64-65)

Theory is a means of understanding and explaining observed phenomena. Adams, et.al. (2014) defined theory as “a unified system of propositions made with the aim of achieving some form of understanding that provides an explanatory power and predictive ability” (p. 115). They went on to write, “a theory does not have a single proposition that defines it, but is a population of propositions (i.e., arguments, hypotheses, predictions, explanations, and inferences) that provide a skeletal structure for explanation of real-world phenomena” (p. 115).

There are different research methods for developing theory. A common practice (deduction) follows the positivist scientific method of hypothesizing a theory and conducting experiments to test the theory, resulting in its adoption or rejection. The positivist approach is widely applied in the physical sciences. It relies on the scientific method, logic, and mathematics to develop theories that are predictive, reproducible, reliable, rigorous, and objective. Positivism assumes that the universe behaves according to inalterable, discoverable laws, and systems are merely the sum of their components (Stol et al., 2016).

Interpretivism, which is on the opposite side of the philosophical spectrum, is widely used in the social sciences and aims to understand and interpret human behavior. Interpretivism relies largely on qualitative data and assumes that no universal truth or reality exists (but rather reality is what people imagine it to be), and systems exhibit emergent behaviors not reducible to their component parts (Stol et al., 2016).

Another approach to developing theory is the classic grounded theory method, which is based on induction, and falls somewhere between positivism and interpretivism. Induction is a method used to determine possible correlations of the deficiencies between the desired and calculated. These correlations are accepted into the design knowledge as new knowledge. With the classic grounded theory method, a researcher studies observations and data in a structured and analytical way, thus enabling a theory that describes the phenomena to arise or emerge from the data. The results and findings are thus *grounded* in the empirical world. The classic grounded theory method *builds*, rather than *tests,* theory (Patton, 2015).

A recent review of software engineering research projects using grounded theory revealed a wide use of mixed methods based in positivism and interpretivism (Stol et al., 2016). However, this research project is neither positivist nor interpretivist. It does not develop a theory concerning observed physical phenomena or human behavior. Instead, its objective is to develop a theory for a new class of systems that shows potential as engineered solutions to highly complex problems. The research is rooted in pragmatism, and is largely theoretical or non-empirical, relying on examination of literature, reflection, and discourse with knowledgeable experts. This study focused on developing a critical theory that describes the class of CASoS solutions that can be applied to address highly complex problems. For these reasons, the classic grounded theory approach was chosen to provide a rigorous methodology for performing this theoretical engineering research. Grounded theory is an effective methodology for pragmatic research based on rationalism (a reason-based approach to understanding).

The classic grounded theory research method originated in the 1960s by Glaser and Strauss (1967) and was developed “due to a desire to build theories more rigorously and dispassionately by grounding them in objective reality” (Stol, 2016, p.3). The classic grounded theory process relies on theory-method linkage, a rigorous yet iterative research methodology, and creative synthesis. Theory-method linkage is the important connection between data analysis and the formulation of theory. This building of theory results from an iterative process of gathering and analyzing data, and articulating a theory to explain the phenomena (Creswell & Poth, 2018). The iterative process of data gathering, coding, and analyzing is illustrated in Figure 1. This figure shows how the classic grounded theory process begins with low-level substantive concepts and works toward high-level theoretical concepts using a series of analytic techniques. Coding is the process of categorizing and organizing data about phenomena, identifying properties and causal conditions that influence phenomena, specifying strategies or actions that result from phenomena, and characterizing the context and influencing conditions.

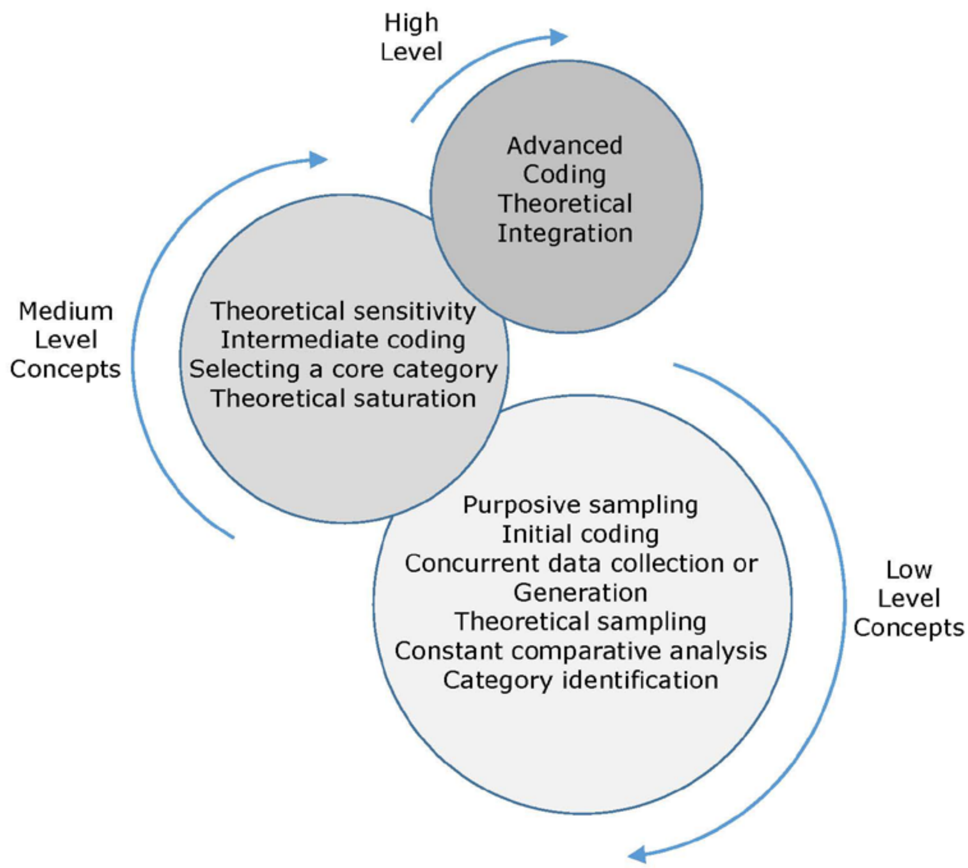

Figure 1. Conceptual Ordering of General Grounded Theory Methods (Birks & Mills, 2015)

Theoretical sensitivity, coding, sampling, constant comparison, saturation, selective coding, and integration are additional analytical steps in the research process (Glaser & Holton, 2004; Holton, 2007). With theoretical sensitivity, a researcher can recognize and extract relevant information about the theory from the data. The process of theoretical sensitivity involves conceptualizing and organizing theoretical insights and making abstract connections from the data. The researcher performs theoretical sampling to identify and pursue clues that arise as data are gathered, studied, and coded. The sampling process of data collection is controlled by the emerging theory, rather than being planned ahead of time. Codes are discovered, and the researcher tries to saturate them by constant comparison with new data. Saturation occurs when no new codes are identified and data categories have been clearly articulated. Selective coding occurs once a core variable (or central theoretical theme) emerges. The selective coding focuses and delimits the process to only analyzing data related to the emerging theory and related concepts. Integration pulls together the abstract theoretical scheme into a final grounded theory.

This study relied primarily on a literature review as the primary source of data. Remenyi (2014) equated this theoretical grounded theory approach, relying solely on non-empirical data, to thought experiments performed by Einstein, which involved the application of imagination and creative thinking to a hypothetical situation. With the theoretical grounded theory approach, a researcher studies established ideas and theories through the literature review process. With the theoretical grounded theory approach, a researcher studies established ideas and theories through the literature review process and extends these ideas to create new theories and insights with the goal of providing better or fuller explanations. This process is based on rationalism, which is the philosophical view that regards reason as the primary source of understanding. Remenyi (2014) explained, "Rationalism holds reason to be a faculty that can access truths beyond the reach of sense perception both in certainty and generality" (p. 71). Remenyi (2014) described eight distinct steps in the theoretical grounded theory approach:

1. Research question formulation,
2. Literature review,
3. Explanation of why a theoretical approach is being taken,
4. Concept identification and reflection,
5. Theoretical conjecture and formulation,
6. Discourse with peers and experts,
7. Theoretical conjecture, refinement, and acceptance, and
8. Discussion on the impact and implications of the theory.

This study incorporated Remenyi's eight theoretical research steps as part of the classic grounded theory method as it provided insight into performing grounded theory using literature review as the primary data source. Table 1 shows how the eight steps were mapped into the three levels of data coding. Steps one through four occur during the low level concept phase; step five occurs during the medium level concept phase; and steps seven and eight occur during the third phase of advanced level concepts. Step 6, discourse with peers and experts, occurs during all three phases of the classic grounded theory method.

Table 1. The Theoretical Grounded Theory Steps According to the Data Coding Levels of the Classic Grounded Theory Method

<table>
<tr><th>Low Level Coding</th><th>Medium Level Coding</th><th>High Level Coding</th></tr>
<tr><td>Steps 1-4</td><td>Step 5</td><td>Steps 7-8</td></tr>
<tr><td colspan="3">Step 6</td></tr>
</table>

Classic grounded theory was the appropriate research method for this research. As an intentionally-designed and engineered CASoS does not yet exist, it was necessary to gather and study data (theories, concepts, ideas, definitions, indicators, etc.) to better understand CASoS and its engineered application to real world problems. Classic grounded theory provided a rigorous qualitative approach necessary to allow a theory to emerge from the data. Classic grounded theory is consistent with a systems approach, which made it an effective approach for the researchers' goal of developing system theory. Researchers who use classic grounded theory view reality in terms of systems and their interactions and it offers a holistic perspective. The benefit of a classic grounded theory research approach was that it lent formalism and rigor to the development of a CASoS theory. By using this methodology, the intent was that the CASoS theory is plausible, transferable, and applicable to real world problems.

Theory validation was also a consideration in the choice of research methods. For classic grounded theory, the process of theory validation is based on the concept of research quality. Birks and Mills (2015) wrote that quality in the grounded theory research methodology leads to theory credibility. They equated *quality* with procedural *rigor*. A quality grounded theory approach is demonstrated through controlled research processes and methodological congruence. Remenyi (2014) wrote that credibility is based on two criteria: the quality of the scholarship employed and whether the research results have added something of value to the body of knowledge. These methods of theory validation were compatible with the researchers' goals of applying a rigorous methodology and solving real world problems by extending the systems body of knowledge.

Research Methodology

This section describes how the classic grounded theory approach enabled the authors to define the characteristics and principles of the CASoS as a new class of systems to facilitate the study of highly complex problems.

Initial Coding: Low Level Concepts

The first phase of the research was the development of initial or low level theoretical concepts. Initial coding, also referred to as open coding, is a process of fracturing or opening data: to compare incidents, identify phenomena and patterns, and begin the process of identifying conceptual possibilities (Holton, 2007). Figure 2 illustrates this phase and lists the types of activities that were performed (inside the circle), and shows steps 1-4 of the theoretical method, as well as step 6, which occurs throughout the process. The classic grounded theory activities (purposive sampling, initial coding, data collection, data generation, theoretical sampling, constant comparative analysis, and category identification) occurred during the four steps of this phase. The following subsections present the research activities conducted during these first four steps, with a discussion of how discourse with peers and experts (step 6), occurred in each step.

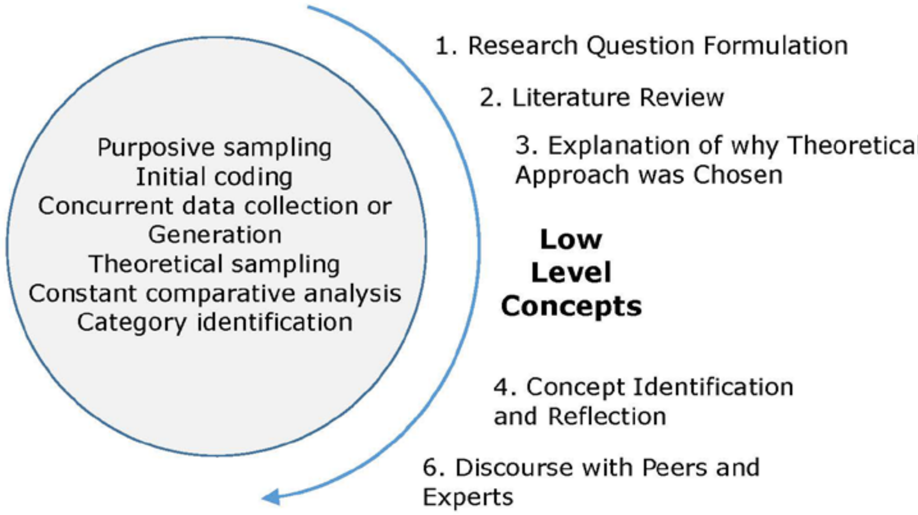

Figure 2. Initial Coding: Low Level Concepts (Adapted from Birks & Mills, 2015)

Research question formulation (step one). Research began pragmatically with a goal of improving the U.S. naval warfighters' military advantage in complex tactical threat environments. Data collection consisted of studying maritime tactical threats, operational environments, and capability gaps in the Navy's ability to address or outmaneuver tactical threats in an effective manner. Comparative analysis of this data exposed the challenges and surfaced patterns of complexity in the tactical problem domain. This analysis was performed by identifying characteristics of the tactical maritime environment and comparing them to a set of characteristics of complex problem domains that are defined in current literature. Evidence pointed to the potential performance benefits of a SoS approach, in which distributed warfare systems would be networked for coordination using automated intelligence (Johnson, Green, & Canfield, 2001). Potential benefits included huge improvements in overall probability of kill and better usage of weapon resources through improved situational awareness (SA) and a layered defense. Another result was the observation of a pattern of complex behavior in the tactical problem domain. Additional literature review (Alberts, 2011; Ames, 2011; Bar-Yam et al., 2004a; Calvano & John, 2004; Levin, 2002) and discourse with experts, led to the concept that an engineered solution to the tactical domain would require the ability to adapt to dynamic situations and threats.

Continued data gathering through literature review revealed the concept of a CASoS (Glass, 2011) as a description of highly complex problems and an approach to addressing them. Through purposive sampling, the researchers identified additional problem domains that had similar characteristics as the naval tactical problem. These cases provided information-rich comparisons that resulted in the identification of patterns of similar complexity characteristics in the different problem domains. The researchers identified these patterns by studying the causes and effects of complexity in the problem domains. This discovery led to the decision to generalize the study of CASoS as a potential, engineered solution beyond a single focus on the naval tactical case. The result of this discovery was the formulation of the research question: what are the characteristics of the CASoS as a new class of systems, and how can they address *highly* complex problems?

Literature review (step two). Literature review was the primary method of data collection throughout the research process. The literature review informed all three phases of the classic grounded theory coding process: initial, intermediate, and advanced. The initial coding phase led to the study of the characteristics of complex problems and the potential of taking a systems approach as an engineered solution. After reviewing and comparing many types of systems and system characteristics, a set of initial codes to establish the categories of systems emerged. Additional forms of data collection resulted from coursework, targeted studies, and discourse with experts and peers.

The researchers relied on theoretical sampling, a process for generating theory by collecting and coding data, and deciding what data to collect next, in order to allow a theory to emerge (Glaser & Holton, 2004). Theoretical sampling was applied throughout the research process as new sources were recommended by experts, discussed in related academic courses, and cited in the literature. Theoretical sampling was applied to the three primary knowledge domains of systems theory, SoS theory, and complexity theory, as well as to the review of research methods and complex problem domains.

Why a theoretical approach was chosen (step three). An intent of the authors was to produce methodological congruence—a state of accordance among the research philosophy, stated aims, and methodological approach (Creswell & Poth, 2008). The overarching goals—to expand the body of knowledge of systems theory and identify an engineered solution approach to highly complex problems—provided a foundation for seeking an appropriate research philosophy and methodology. A review of inquiry methods and research philosophies ensued. This review included a review of books and journals that addressed research methods, as well as intellectual discourse. Giachetti (2015) provided a starting point for engineering studies. Works from Glaser and Holton (2004), Holton (2007), Remenyi (2014), Bryant and Charmaz (2007), Creswell and Poth (2018), and Patton (2015) informed the decision of the authors to use classic grounded theory approach. The major points of this research direction follow:

1. The types of data available (literature review and use-cases of observed phenomena, and information from discourse with experts) are suitable for the classic grounded theory method that can rely on qualitative data.
2. The need to develop theory for engineered CASoS solutions to complex problems (Glass et al., 2011) and the desire to allow it to emerge from the process of data collection, critical analysis, comparison, and creativity, supported the decision to use the classic grounded theory research method. Classic grounded theory enables a theory to emerge from constant comparative analysis and theoretical sampling of diverse qualitative data.
3. Classic grounded theory is consistent with a systems approach, which views reality in terms of systems and their interactions as well as has a holistic perspective. With the objective of adding to the body of systems theory knowledge, classic grounded theory was an appropriate choice.

4. The desire to provide validation and acceptance of the theory was a strong factor in selecting classic grounded theory which provides a formal and rigorous research method for enabling valid theory to emerge from data and analysis.
5. The decision to follow the classic grounded theory method was based on informed opinion, experience, and pragmatism.

Concept identification and reflection (step four). The process of data collection, initial coding, and theoretical sampling, led to a deeper understanding of complex problems and initial concepts for the CASoS solution. This initial level consisted of identifying and understanding the naval tactical use-case as an exemplary complex problem. A better understanding of this case provided a conceptual basis for developing a theory for CASoS solutions.

Viewing the problem domain using a systems approach enabled warfare assets to be organized conceptually as distributed resources. This observation resulted in identifying common command and control functionality across military platforms and patterns of similar system characteristics. This systems approach conceptually shifted the focus from a platform-centric paradigm to a network-centric paradigm and enabled the Naval engineering community to have a foundation for SoS concepts (Johnson, 2002). Through the research process, the authors identified solution concepts based on collaborations among distributed warfare assets, such as layered defense and interoperability within the Navy (Johnson & Green, 2002b). Research on distributed sensor resource management included an example of implementing a set of distributed systems as a SoS in a network-centric paradigm (Johnson & Green, 2002a).

Continued emphasis on a SoS approach of using weapon and sensor systems from different ships and aircraft to operate collaboratively led the authors to identify categories and types of possible collaborations. The functions for combat engagement, or weapons-fire control, were identified and defined in general terms. Each function was studied to determine if it could be performed in a distributed manner. A number of distributed engagement concepts were developed, including precision cue, launch on remote, engage on remote, forward pass, remote fire, and preferred shooter determination (Johnson, 2005).

A course on complex systems prompted a study of the tactical domain as a complex problem. Several authors stated that complex problems can only be addressed by complex system solutions (Bar-Yam, 2003, 2004b; Calvano & John, 2004). Based on this concept, the tactical domain was studied to determine if it had the characteristics of complexity (Johnson, 2012b). First, the data was gathered to define the characteristics of complexity. Next, a comparative analysis related the problem domain to the characteristics of complexity. The analysis resulted in a determination that the tactical problem domain was, in fact, a complex problem space. In addition, the expected behavioral complexity of this domain was better understood and could be used to support an improved approach to the solution concepts. An additional result was a method by which future problem domains could be classified as complex or not.

The research process produced conceptualization of engineered approaches to battle-management that enable SoS collaboration among distributed warfare assets. One area of study was automated battle-management decision aids. Tactical decisions within the problem domain were identified and studied in terms of areas that could benefit from the support of automated decision aids (Johnson, 2001). A number of studies produced concepts for decision aid capability and functionality as well as a distributed architecture to support these concepts (Johnson, 2004, 2005, 2012a). One concept resulting from this area of research was the idea of a designer SoS—an approach in which the collaborations of warfare assets could be designed during operations to enable near-real-time adaptation to the tactical environment (Johnson, 2013). Another idea was to focus future tactical architectures and processes within a decision paradigm on warfare actions to be taken rather than on achieving situational awareness as the end goal (Johnson, 2014).

The first research phase resulted in the following initial concepts: (1) the military domain is a complex problem and therefore requires a complex solution; (2) an engineered solution for the tactical problem should take advantage of using distributed warfare systems as a SoS; and, (3) taking a systems approach to this problem enables a top-down holistic perspective as well as a means to address the complexity aspects. The process of initial coding identified three primary categories for additional research: systems theory, SoS theory, and complex systems theory. The constant comparison method showed that these bodies of knowledge form the basis for producing a theory for engineering a solution to certain highly complex problems. A generalized approach to the problem was adopted to describe the characteristics of complex problems; and by doing so, to understand and describe the set of solution systems that could address such a problem domain. This generalized approach became the focus of the next phase of the grounded theory research: the development of medium level concepts or intermediate coding.

Intermediate Coding: Medium Level Concepts

Intermediate level coding produced medium level concepts during the second phase of the research. The focus of this phase was the study of the theory and concepts that formed the foundation of the generalized treatment of CASoS as a solution approach to complex problems. Based on theoretical sampling, the decision following the first phase of initial coding was to generalize the problem domain and perform a rigorous study of the characteristics and principles of systems, SoS, and complex systems to provide the theoretical foundation to develop a theory of CASoS. Figure 3 illustrates the classic grounded theory approach followed during this phase of the research. This phase relied on intermediate coding to identify properties, dimensions, patterns, and relationships within the CASoS conceptualization. To accomplish intermediate-level coding, we applied theoretical sensitivity—the recognition and extraction of data elements that have relevance to the emerging theory–resulting in a focus on CASoS as a new class of system solutions. Theoretical saturation was the final state reached when the theoretical concepts were clearly articulated and any additional data reinforced the concepts rather than altering them (Glaser & Holton, 2004).

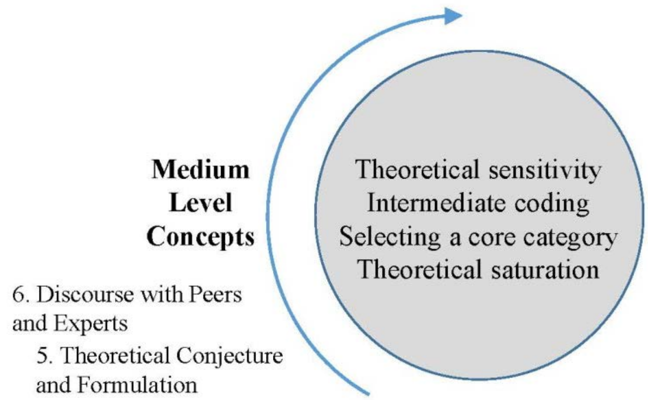

Figure 3. Intermediate Coding: Medium Level Concepts (Adapted from Birks & Mills, 2015)

Theoretical conjecture and formulation (step five). Data gathering for this phase consisted of a literature review of concepts, theorems, definitions, and axioms within the three core disciplines of systems theory, SoS theory, and complex systems theory. Information and feedback were obtained through coursework, discourse with peers and experts, and participation in conference presentations and publications. Data gathering was performed iteratively and concurrently with the intermediate coding of information into categories. The main categories of the intermediate coding that emerged were as follows: systems, purposeful systems, SoS, complex systems, complex adaptive systems (CAS) and CASoS. Figure 4 illustrates the relationships among these categories of systems. Data gathering, coding, and constant comparative analysis resulted in findings associated with the definitions, characteristics, and principles of each of these subclasses of system categories.

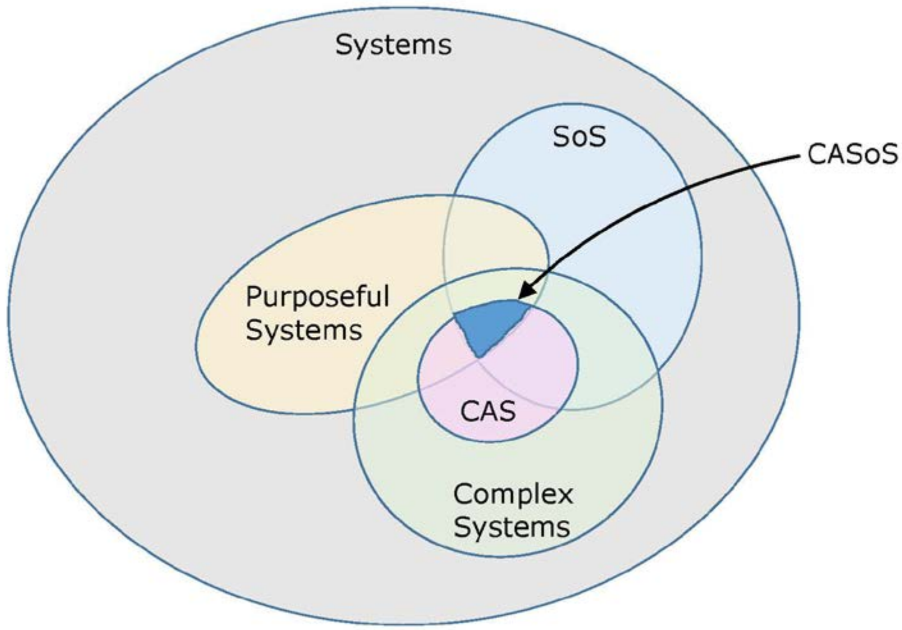

Figure 4. Intermediate Coding Categories

A study of highly complex problem domains produced a characterization of problem spaces based on intermediate coding. A comparative analysis of existing complex domains included problems identified by Bar-Yam (2004b), Glass, et al. (2011), Braha, Minai, and Bar-Yam (2006), Alberts (2001, 2003, 2011), and Harney (2012). This data was coded and compared with data that described characteristics of complex environments (Ames et al., 2011; Calvano & John, 2004; Miller & Page, 2007; Mitchell, 2009; Ottino, 2003; Page, 2011; Stevens, 2008). Data concerning these problems were gathered from the literature review, coursework, and discourse with experts at conferences, which was, in turn, coded and compared.

The process of intermediate coding produced the theory for the CASoS class of engineered system solutions. The theory for the characteristics and principles of CASoS resulted from the identification and comparison of characteristics of systems, SoS, and complex systems from the literature review and data gathered. The process of iterative discourse with advisors and experts produced feedback and refinement of the theory. The theory reached data saturation when additional data only reinforced the theory.

A process of concept synthesis, further discourse, and evaluation clarified the engineering implications of the CASoS theory and formed the basis for the development of the conceptual design of an engineered CASoS solution to highly complex problems. Further reflection and analysis of data led to a derived set of engineered capabilities required to design and build a CASoS. A number of papers were written describing these capabilities. The papers addressed distributed sensors to gain awareness of the environment, as well as an intelligent and adaptive architecture for sharing data and information among a set of distributed intelligent agents that make decisions for constituent system and collective SoS actions. Feedback from publishing and presenting the papers led to further refinement of required CASoS engineered capabilities.

Discourse with peers and experts (step six). Discourse with peers and experts was a crucial contribution to this study. The exchange of ideas in every step of the research process informed the decisions for how to proceed, provided a wealth of knowledge, and directly influenced the emergent CASoS theory. The following methods were used to gain this discourse: taking courses (Systems of Systems, Complex Systems, and Systemic Strategic Thinking), participating in conferences (Complex Adaptive Systems Symposium, National Fire Control Symposia, Complex Systems Conferences, IEEE Systems Conferences, Military Operations Research Symposium, and the Association of the Advancement of Artificial Intelligence Symposia), and conversing informally with many experts from these groups and with faculty members of the Naval Postgraduate School. In many cases, the discourse led to recommendations for further sources for the literature review. In some cases, the discourse led to decisions, such as the focus of the study, the choice of research method, the choice of the focused use-case application. Discourse also provided invaluable feedback for the CASoS theory and derived engineered capabilities and approach.

Advanced Coding: High-Level Concepts

The final, high-level concept phase consisted of advanced coding and theoretical integration. The research process focused on integrating the coded data and concepts from the intermediate phase into a coherent theory for the new class of CASoS. Figure 5 illustrates this final phase of the research approach. The steps during this phase were as follows: theoretical conjecture, refinement, and acceptance (step 7) and discussion on impact and implications (step 8). Discourse with peers and experts (step 6) occurred during steps 7 and 8.

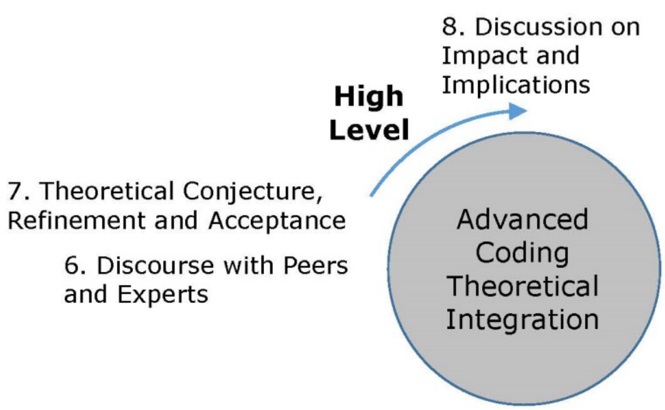

Figure 5. Advanced Coding: High Level Concepts (Adapted from Birks & Mills, 2015)

Theoretical conjecture and refinement and acceptance (step seven). The advanced coding and theoretical integration consolidated the abstract concepts into a final grounded theory for an engineered CASoS. This final coding process allowed the authors to refine the theory based on the process of studying the application of the CASoS solution to the naval tactical problem domain and further interactions with peers and experts. The grounded theory results from the advanced coding phase that consists of a theoretical conceptualization of CASoS and its interactions with the environment. Feedback from peers and experts was incorporated as amendments and refinements to the theory. This feedback provided greater clarity, completeness, and accuracy to the theoretical concepts. The final form of the theory establishes the characteristics and principles of CASoS as a new class of systems that address highly complex problem domains.

For this study, the process of theoretical conjecture provided an explanatory theory for an engineered CASoS based on the initial and intermediate levels of coding. The development of a conceptual CASoS design for the tactical domain provided a method for understanding how the CASoS approach becomes a workable solution. The solution depended on the derived set of engineered capabilities that must exist (or be required) for an intentionally-designed CASoS to be a viable solution. These capabilities must exist for the engineered solution to attain the needed CASoS characteristics. The naval tactical problem domain served as a use-case to understand how an engineered CASoS warfare solution would improve the Navy's ability to be successful in complex tactical situations.

Discussion on impact and implications (step eight). The final step in the research approach was a study of the theory's impact and implications. A set of capabilities required for an engineered CASoS solution were derived from the CASoS theory. This set of engineered capabilities was applied to the naval tactical use-case as an application of the CASoS theory. This application was accomplished by studying how a CASoS could provide a solution to many of the challenges faced by the Navy in the complex tactical domain. Using the CASoS theory, a conceptual design for an intelligent adaptive architecture for managing distributed warfare assets to address a complex tactical domain was based on the CASoS theory. This conceptual design was used to understand more clearly the potential benefits of this approach within this domain. The implications of this application were further studied by identifying other highly complex problem domains in which a CASoS approach could provide a solution.

Conclusion

A new class of system solutions—CASoS—has been defined and characterized as a theory for an engineering approach to highly complex problems. Such problem domains are on the rise as information and communication technologies continue to advance, causing greater global interaction among systems, entities, and events, which often lead to unpredictable and unintended consequences. The classic grounded theory approach provided a useful method of inquiry for researching several bodies of knowledge to produce a theory for the new class of system solutions. Applying classic grounded theory to systems engineering research allowed the authors to develop a systems theory and provided an engineering approach to addressing highly complex problems. The CASoS theory emerged from several knowledge domains through an iterative process of data gathering, coding, constant comparative method, pattern development and refinement, and discourse and feedback.

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