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ART AND SCIENCE OF JADC2 CONCEPTUALIZATION

FROM A NAVY PERSPECTIVE

by

Dr. Mark E. Nissen & Dr. Shelley P. Gallup

December 2022

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ABSTRACT

Joint All Domain Command and Control (JADC2) is the art and science to rapidly translate knowledge and information into decisions and actions. It seeks to integrate all services across all warfare domains and through all communication environments. The research described in this report works toward JADC2 conceptualization from a Navy perspective. A comparative case study is used to analyze command and control (C2) for a maritime focused joint task force (JTF) involving integrated fires and Grey Zone operations across services. Key results highlight the importance of satellite communications to enable JTF integration, and they elucidate a matrix of critical communication links that emerge in environments of denied, degraded, intermittent or limited (DDIL) communication. This DDIL communication matrix serves as a prioritized JADC2 requirements set. Recommendations center on prioritizing these requirements; articulating and disseminating clear command intent that can be understood and implemented in DDIL environments; practicing Mission Command, Battle Rhythm Dilation, and Edge C2; remembering that people remain the most important element in JADC2; and developing the new knowledge, education, training and practice necessary for JADC2 success.

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EXECUTIVE SUMMARY:
ART AND SCIENCE OF JADC2 FROM A NAVY PERSPECTIVE

Drs Mark E Nissen and Shelley P Gallup

Naval Postgraduate School

December 2022

Project Summary

Joint All Domain Command and Control (JADC2) is the art and science to rapidly translate knowledge and information into decisions and actions. It seeks to integrate all services across all warfare domains and through all communication environments. The research described in this report works toward JADC2 conceptualization from a Navy perspective. A comparative case study is used to analyze command and control (C2) for a maritime focused joint task force (JTF) involving integrated fires and grey zone operations across services. Key results highlight the importance of satellite communications to enable JTF integration, and they elucidate a matrix of critical communication links that emerge in environments of denied, degraded, intermittent or limited (DDIL) communication. This DDIL communication matrix serves as a prioritized JADC2 requirements set. Recommendations center on prioritizing these requirements; articulating and disseminating clear command intent that can be understood and implemented in DDIL environments; practicing Mission Command, Battle Rhythm Dilation, and Edge C2; remembering that people remain the most important element in JADC2; and developing the new knowledge, education, training, and practice necessary for JADC2 success.

Keywords: *agile C2, command and control, C2, rapid reconfiguration, knowledge flow, Joint All Domain Command and Control, JADC2, Mission Command, Battle Rhythm Dilation, Edge C2*

Background

JADC2 seeks to address the many challenges of C2 across all domains and services, but it requires thoughtful conceptualization, especially from a Navy perspective. A comparative case study is used to analyze C2 for a maritime focused JTF involving integrated fires and grey zone operations across services. The baseline case represents a geographically distributed carrier strike group (CSG), surface action group (SAG), Air Force (AF) wing, and Marine expeditionary force (MEF) operating jointly, through conventional C2, with full communication capabilities. The comparison case depicts this same JTF without satellite communications.

Comparative analysis across these cases exposes many C2 challenges and helps to conceptualize how JADC2 must support both operational and tactical levels of war, along a continuum of communications capabilities. This analysis also provides insight into elements of C2 that extend well beyond technology; particularly the people, processes, and organizations comprising the JTF; along with the knowledge, information, and data that must flow to interconnect them.

The analysis enables us to apply theory representing the state of the art and to draw from tools and techniques representing the state of the practice in knowledge management, organization, and C2 to JTF organizations and operations. This enables us also to induce new knowledge from analysis of JTF operations, which offers potential for translation into enhanced and refined Navy C2 organizations and approaches.

Findings and Conclusions

Key findings highlight the importance of satellite communications to enable JTF integration. This applies in particular to geographically dispersed services seeking to interoperate in an integrated manner. Further, a matrix of critical communication links emerges through analysis of DDIL environments. This DDIL communication matrix serves as a prioritized JADC2 requirements set.

Interestingly, respective Navy, Air Force, and Marine tactical operations within the CSG and SAG, AF wing, and MEF do not suffer as greatly in DDIL environments as their joint and operational counterparts seeking integrated fires and operations across services. Details remain beyond the classification level of this document.

Additionally, the prioritized JADC2 requirements set involves much more than technology. Indeed, commanders at all organization levels need to articulate and disseminate clear command intent that can be understood and implemented in DDIL environments, and subordinates at all levels must be able to understand and translate such intent into desired actions. This requires practice: Commanders at all organization levels and units at all levels need to practice operating under Mission Command and Battle Rhythm Dilation, for extended periods of time, much as the way that integrated submarine operations do. Moreover, these commanders and units need to practice integrated operations through very low bandwidth DDIL communication modes, which elucidates a compelling case for Edge C2.

Finally, people remain the most important element in JADC2. Geographically dispersed joint operations in DDIL environments can depart substantially from the kinds of education, training, and experience that most military personnel encounter. This provides a use case for additional education, training, and experience to develop and refine the necessary skills and competencies required to fight effectively.

Moreover, such operations can prompt the rethinking of standard operating procedures (SOPs); techniques, tactics, and procedures (TTPs); operational orders (OPORDs); and similar explicit knowledge. The key is to anticipate, develop and refine the kind of rich, experience based tacit knowledge that needs to permeate all organization levels from deckplate to command. Such tacit knowledge—once acquired and refined—can guide effective rethinking of SOPs, TTPs, OPORDs, and similar documents.

Navy educational institutions like the Naval Postgraduate School (NPS) represent one important locus for rethinking along these lines, as do tactical training groups: NPS can develop and teach the appropriate knowledge, which tactical training groups can translate into effective procedure and practice. **This may represent the most important finding for our study sponsor: new knowledge, education, training, and practice are necessary for JADC2 success**.

Five recommendations follow accordingly: 1) Use the Communication Matrix to prioritize JADC2 requirements that emerge from this study. 2) Teach and coach organization leaders to articulate and disseminate clear command intent that can be understood and implemented in DDIL environments over extended periods. 3) Learn and practice both Navy and joint operations through Mission Command, Battle Rhythm Dilation, and Edge C2. 4) Remember that people remain the most important element in JADC2. 5) Develop the new knowledge, education, training, and practice necessary for JADC2 success, both through continued study along these lines and through new education and training course development.

Recommendations for Further Research

We have five recommendations for further research.

1) The Communication Matrix indicates the key communication links required for effective joint task force (JTF) knowledge and information flows across service, unit, platform and geographic boundaries; and it shows which are affected most severely by denied, degraded, intermittent or limited (DDIL) communications. This provides an opportunity for each link to be studied more deeply—in terms of associated people, processes, organizations, and technologies.

2) Teaching and coaching leaders to articulate and disseminate clear command intent that can be understood and implemented in DDIL environments over extended periods should begin with dilation of the JTF battle rhythm. DDIL may require JTF commanders to receive knowledge and information inputs less frequently, with proportionately longer periods between opportunities to direct and guide subordinate commanders and units. Training and practice will be essential. This provides an opportunity to develop the corresponding courses and exercises.

3) Mission Command is likely to be understood relatively well, but it remains unclear how frequently and persistently it is practiced in the fleet and across services. With less frequent knowledge and information exchanges, the JTF—and most subordinate commands—will encounter Battle Rhythm Dilation, and commands at different hierarchic levels will likely follow different rhythms. For commands and forces accustomed only to a 24-hour rhythm, this may require considerable adjustment and practice. This provides an opportunity to develop the corresponding courses and exercises.

Alternatively, Edge C2 is less likely to be understood well, yet it is crucial for commanders and units to integrate operations through very low bandwidth DDIL communication modes. The C2 field has accumulated over two decades of research regarding Edge C2, but surprisingly little of the corresponding knowledge has found its way into Navy doctrine and training. This provides an opportunity to develop the corresponding courses and exercises.

4) It is both easy and routine for a project like JADC2 to degrade into a portfolio of technology efforts. However, JADC2 has a very long way to go before the Sense-Make Sense-Act cycle can be automated (if ever). This applies in particular to the latter two steps: decision makers and other people have to make sense of situations, while warriors and other people initiate and execute the associated actions. The faster that cycles become—speedy cycles represent an express JADC2 expectation—and the worse that DDIL restrictions become—severe

environments represent an express JADC2 expectation—the more challenging each step of the cycle becomes. This provides an opportunity for further study.

5) Each of these recommendations for further study points to knowledge gaps. Some gaps (e.g., 2 and 3) are relatively clear and can be filled through development of additional education and training courses, along with corresponding exercises and practice, whereas others (esp. 1 and 4) are less clear and require further study.

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I. INTRODUCTION

Joint All Domain Command and Control (JADC2) is the art and science to rapidly translate knowledge and information into decisions and actions. It seeks to integrate all services across all warfare domains and through all communication environments, including those in which they are denied, degraded, intermittent or limited (DDIL). This is the case in particular as the World and warfare continue to shift in monumental ways and as joint, multidomain operations—including Mission Command, long range fires and functional C2—continue to strain our current capabilities (Costello, 2020).

Previously, each of the services was moving ahead independently with C2 capability development in multi-domain operations. This suggested that interoperability would be at risk. Department of Defense (DoD) leaders recognized an opportunity to align, converge, synchronize and integrate a number of steps in the lifecycle of C2 capabilities. This led to establishment of the JADC2 cross functional team in 2020.

Despite the opportunity for joint C2, each Service has some unique operating environments and separate concepts (e.g., Air Force Multi-Domain C2, Army Multi-Domain Operations, Navy/Marine Corps Distributed Maritime Operations), each with a separate capability development approach (e.g., Advanced Battle Management family of Systems, Project Convergence), which must be accommodated by and yet integrated into JADC2. This calls for a Joint capability development approach that drives interoperability, encompasses and converges all domains, and offers a universal architecture to support them (Costello, 2020).

The Navy needs to play a vital role in JADC2 and to serve as a central pillar. This raises questions regarding how the Navy should prepare for this role, how naval fires and assets should cross geographical regions and services, how the Navy Tactical Grid should integrate into the Joint Grid, and how Service unique knowledge needs and capabilities should balance with important goals of convergence, commonality and interoperability (Joint Staff, 2021).

This leads to three primary research questions:

1) What issues can the Navy anticipate in terms of JADC2?

2) How can JADC2 be understood in terms of agility and rapid reconfiguration?

3) How can Mission Command and C2 knowledge flow integration be applied to support JADC2?

Leveraging prior research addressing agile C2 (Alberts & Hayes, 2003; Gateau et al., 2007; Nissen, 2007) and rapid organization reconfiguration (Alberts & Nissen, 2009; Nissen, 2017), along with experience with mission orders, distributed maritime operations and C2 knowledge flow integration (Nissen et al., 2019; Nissen & Gallup, 2019; Nissen & Gallup, 2020), this project seeks to address these needs.

For instance, our agile C2 work informs us regarding a range of C2 approaches—with varying allocations of decision rights (ADR), patterns of interaction (POI) and distribution of information (DOI)—that are suitable for different mission-environment conditions, and our rapid organization reconfiguration work outlines mechanisms for shifting smoothly and quickly between them.

As another instance, our research on mission orders and distributed maritime operations provides insight into different modes of maritime operations, and our C2 knowledge flow integration work supports powerful analysis and visualization methods for understanding how knowledge—which enables informed decision making and action—gets from when and where it is located to when and where it is needed.

This technical report is organized into four sections that follow this introduction. Key background information is summarized next and followed by a brief outline of the research method. Key findings and results are reported subsequently and followed in turn by conclusions and opportunities for continued research along these lines.

II. BACKGROUND

This section provides key background information necessary to understand JADC2 and the important elements of the study. We begin with a brief overview of Navy C2 in general and JADC2 in particular. We transition then to discussion of different approaches to C2 organization, with important implications in terms of agility and resilience. The section continues in turn with an overview of knowledge dynamics, which are very important for informed decision making and action. Each of these background sections stands alone and can be skipped by readers with the corresponding knowledge.

A. COMMAND AND CONTROL

Command and Control (C2) characterizes how military forces are organized and how they communicate to plan, synchronize and effect action in the battlespace. Drawing from Alberts and Nissen (2009), there is a substantial body of literature that addresses C2. Van Creveld (1985), for instance, uses only the term *command* but traces C2 from the Stone Age through the conflict in Viet Nam and beyond. Alberts and Hayes (2006), as another instance, describe how command is viewed widely as the authority vested in a commander as opposed to a set of activities centering on organization and leadership.

The US Department of Defense (DoD) describes C2 for joint operations in great detail via JP-6 – Joint Communications System (JCS, 2015). This characterizes five key elements:

1) The joint communication system, which is composed of the networks and services that enable operations of joint and multinational military capabilities and assist the joint force commander (JFC) in C2 of military operations. It involves the set of information capabilities and associated processes to collect, process, store, disseminate and manage information on demand to warfighters, policy makers and support personnel. Such personnel can be interconnected or stand-alone, and the system includes owned and leased communications and computing systems and services, software (including applications), data, security services, other associated services and national security systems.

2) The information environment, which is composed of the networks and services that enable operations of joint and multinational military capabilities and assist the JFC in C2 of military operations. It involves a set of mandatory standards, protocols and principles that provides a secure and reliable shared IT infrastructure, enterprise services and a single security architecture to achieve information superiority, improve mission effectiveness, increase security, and improve IT efficiency.

3) Communication planning and management, which enables planners to maintain an accurate and detailed status of the network, all networked assets and IT services. It combines centralized control with decentralized execution and provides effective and efficient communications system support for the JFC.

4) Information sharing and services, which involves the cultural, managerial and technical behaviors by which one participant leverages information held or created by another participant. Three core principles include: a) Information is a national asset. b) Information sharing and safeguarding requires shared risk management. and c) Information informs decision making, underlies all actions, and reinforces that better decision making is the purpose of sharing information in the first place.

5) The National Military Command System is a system of critical command centers, C2 nodes and underlying support systems designed to support the military leaders in the exercise of their responsibilities through the range of military operations.

The essence of C2 can be summarized simply and succinctly from a knowledge perspective: people in an organization must know what to do; how, when and with whom to do it well; and why it must be done. The first and last parts can be viewed in terms of command intent, which flows downward via communication channels from higher organization levels to lower ones. The second part involves education, training, experience, practice and communication that flows both hierarchical and horizontally through the organization.

In many cases—especially through history—C2 is accomplished within a single Service (e.g., Army, Navy, Air Force) and domain (e.g., Land, Sea, Air). As the nature of military operations has become increasingly complex, joint operations require coordination across services and domains (e.g., also integrating Surface, Subsurface, Space and Cyber). The majority of C2 systems and processes are designed for single service and single domain operations, and many such systems and processes cannot interoperate.

JADC2 as noted above is intended to address interoperability issues by integrating and enabling communication, command and control across all services and domains. JADC2 is not a new program per se, but it involves five lines of effort: 1) Establish the JADC2 Data Enterprise; 2) Establish the JADC2 Human Enterprise; 3) Establish the JADC2 Technical Enterprise; 4) Integrate NC2/NC3 with JADC2; and 5) Modernize Mission Partner Information Sharing. Much work on JADC2 is classified, so we provide only this brief summary here.

B. C2 ORGANIZATION AND APPROACHES

C2 can be organized and approached in a variety of different ways, and it may be very important for an organization to transition between one or more different C2 approaches. This section begins with an overview of the C2 Approach Space and the variety of C2 organizations available in the JADC2 context. It continues then with an overview of how an organization can transition between two or more approaches.

1. C2 Approach Space

This section provides an overview of the C2 Approach Space and the variety of C2 organizations available in the JADC2 context. Drawing from Alberts and Nissen (2009), Figure 1 depicts the C2 Approach Space in three interrelated dimensions, and it plots two dramatically different approaches to C2 organization.

The first dimension is Allocation of Decision Rights (ADR), which can be considered from either the perceptive of a single organization or a collection of entities. This dimension pertains to the degree of delegation of decision making to lower levels of the organization. The end points of ADR are “none,” indicating no delegation of authority, and “broad,” indicating that authorities are widely distributed.

For example, in the case of an organization with well-established and very limited delegations of authorities, the ADR (within the organization) can be thought of in terms of a centralized-decentralized continuum. An organization with no ADR forces all decisions to the apex (e.g., via the Commander), whereas its counterpart with broad ADR pushes decision making to low organization levels (e.g., to individual departments, divisions and branches).

In the case of a collective of disparate entities (e.g., joint or multinational operation), the ADR dimension has been labeled as the "allocation of decision rights to the collective" where "none" indicates that each individual entity maintains whatever decision rights it has, and "broad" indicates that entitles are willing to give up significant sovereignty. As with a single organization, a joint operation with no ADR forces all decisions to the apex (e.g., via the JFC), whereas its counterpart with broad ADR pushes decision making to the various services.

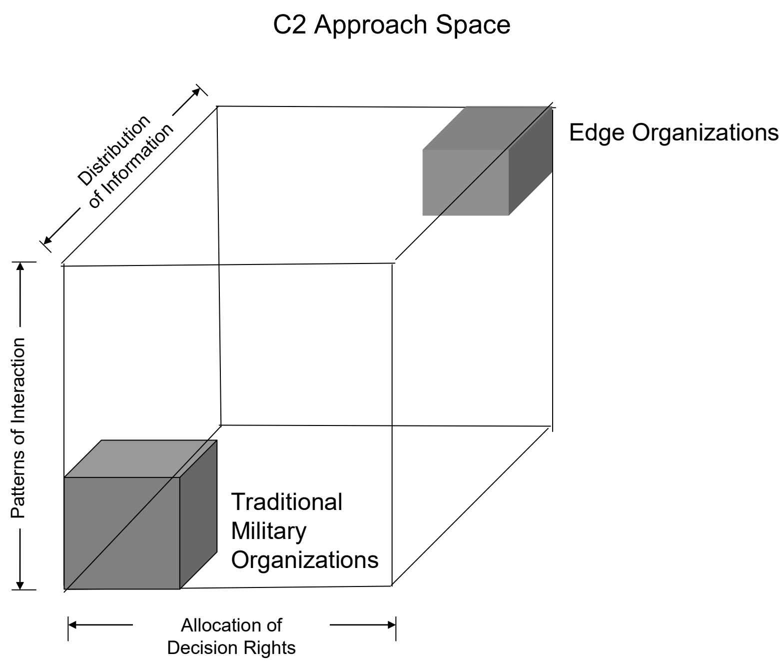

Figure 1 C2 Approach Space (adapted from Alberts & Nissen, 2009)

The second dimension is Patterns of Interaction (PoI), which can also be considered from either the perceptive of a single organization or a collection of entities. This dimension pertains to the degree of integration and interaction across different departments or functions in an organization, in addition to the degree of integration and interaction across different services in a joint operation or even militaries in a multinational venture. The endpoints of PoI are "constrained," indicating negligible cross-function, -Service or -national integration and interaction, and "unconstrained," indicating extensive integration and interaction.

For example, in the case of an organization with constrained PoI, the various functional departments would operate with relative independence and negligible interaction. This implies that integration is performed at the organization apex (e.g., via the Commander). Alternatively, the various functional departments of an organization with unconstrained PoI would integrate their operations tightly and interact closely.

The same applies to a joint or multinational operation: with constrained PoI, the various services or militaries would operate with relative independence and negligible interaction, whereas with unconstrained PoI, the various services or militaries would integrate their operations tightly and interact closely. For instance, say that a multinational operation divides a battlespace into geographic sectors, with each operating independently in a specific sector assigned to it. This reflects constrained PoI. The same could be said for dividing a battlespace into domains (e.g., land, surface, subsurface, air), with each operating independently in a specific domain assigned to it. Unconstrained PoI, alternatively, would reflect integrated operations across geographic sectors and/or domains.

The third dimension is Distribution of Information (DoI), which can be considered from either the perceptive of a single organization or a collection of entities as well. This dimension pertains to the degree to which information flows throughout the organization, both vertically and horizontally, or across different services or militaries in the case of joint or multinational operations, respectively. The endpoints of DoI are “none,” indicating that information does not flow through the organization or across services and militaries, and “broad,” indicating that information flows freely throughout.

For example, in the case of an organization with no DoI, all information would collect at the apex (e.g., the Commander). Alternatively, information in an organization with broad DoI would flow up and down the command chain as well as across functional departments.

The same applies to a joint or multinational operation: with no DoI, each of the various services or militaries would collect, process and act on its own information, whereas with broad DoI, the various services or militaries would share information freely. For instance, say that a multinational operation involves participating militaries that keep their key information classified and restricted to internal dissemination. This reflects no DoI. Broad DoI, alternatively, would reflect information shared across participating militaries.

Each of these dimensions is delineated as a continuum, which implies that myriad points in between each of the endpoints are both feasible and desirable, and each part of an organization (e.g., functional department) may reflect a different combination of ADR, PoI and DoI. Likewise with joint or multinational operations, each service or military may reflect a different combination. This implies that C2 across various organizations, services and militaries is fractal: the perspective of a JFC is similar to—albeit at a higher level—that of a joint service commander, ship captain, department head, division head, branch head or like person in charge of others.

The fractal nature of organizations at different levels is illustrated by Figure 2. On the right side of the diagram we show a team comprised of multiple people. Such team could then combine with one or more others to comprise an organization (e.g., division, department, ship), which could combine in turn with one or more others to comprise a collective (e.g., JTF, multinational coalition task force).

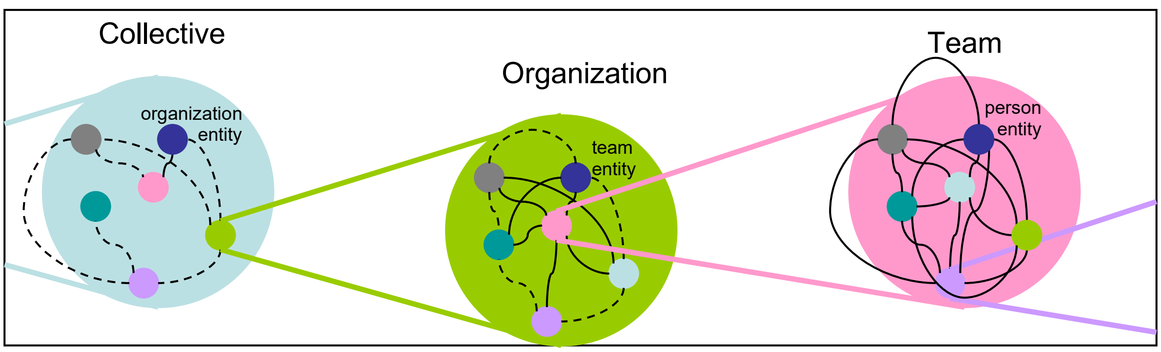

Figure 2 Fractal Nature of Organizations (adapted from NATO, 2010)

Further, each of these dimensions is delineated as independent, which implies that all combinations of ADR, PoI and DoI are possible. In practice, however, only certain combinations are organizationally feasible, and several noteworthy dimensional combinations can be examined in terms of C2 organization archetypes.

Referring back to the C2 Approach Space from above, for instance, we plot two such archetypes: 1) traditional military organizations and 2) Edge organizations. As reflected by their relative positions in the C2 Approach Space (i.e., the left-lower-front corner), the former archetype is characterized well by minimal ADR, constrained PoI and limited DoI. C2 in the traditional military organization is addressed primarily through deconfliction between different organizations and standardization within. This corresponds to the classic Machine Bureaucracy of Organization Theory (Mintzberg, 1979).

As a note, it does not make sense to describe "C2" at the extreme corner (i.e., *no* ADR or DoI). Such organization or C2 approach is referred to as "conflicted" and is ineffective. There is effectively no C2 at such point. Moving just a bit away, however, far enough to achieve deconfliction, one can characterize the traditional military organization and its approach to C2.

In great contrast, the latter archetype is characterized alternatively by broad ADR, unconstrained PoI and broad DoI (i.e., the right-upper-rear corner) with leadership emerging through meritocracy (Alberts & Hayes, 2003). C2 in the Edge organization is addressed primarily through mutual adjustment, both between different organizations and within each. This corresponds largely to the Adhocracy of Organization Theory (Mintzberg, 1979), but one finds aspects of both Simple Structure and Professional Bureaucracy as well (Gateau et al., 2007). The implications in terms of C2 organization, capability and performance are enormous.

Further, we understand well that no single organization design or C2 approach is "best" in every mission-environment (Alberts & Nissen, 2009). Indeed, fifty years of Contingency Theory and subsequent research (e.g., Burns & Stalker, 1961; Woodward, 1965; Lawrence & Lorsch, 1967) indicate that the classic Machine Bureaucracy, and hence traditional military organization, operates best in mission-environment circumstances that are relatively stable and predictable. As such, they tend to struggle in highly dynamic and uncertain contexts. Alternatively, the Edge organization struggles in circumstances that are relatively stable and predictable, but it excels in highly dynamic and uncertain contexts. These two C2 organizations and approaches are thus highly complementary (Gateau et al., 2007): whereas the traditional military organization is very efficient, reliable, predictable and effective, the Edge organization is flexible, adaptable, emergent and agile.

Additionally, as each of the three dimensions can take on intermediate values in between the endpoints, we can consider intermediate C2 organization archetypes and their corresponding C2 approaches in between the traditional military organization and its Edge counterpart (Alberts & Nissen, 2009). Figure 3 delineates a total of five: 1) Conflicted, 2) Deconflicted, 3) Coordinated, 4) Collaborative and 5) Edge.

As noted above, the extreme corner (Point A in the figure) represents a condition of conflicted C2 and is ineffective. By increasing ADR, PoI and DoI sufficiently to achieve deconfliction, we plot deconflicted C2 corresponding to the traditional military organization (near but apart from Point A in the figure). As noted above, this corresponds well with the classic Machine Bureaucracy. Deconfliction is characterized above and can be accomplished by separating geographic sectors, warfare domains or other aspects of the battlespace.

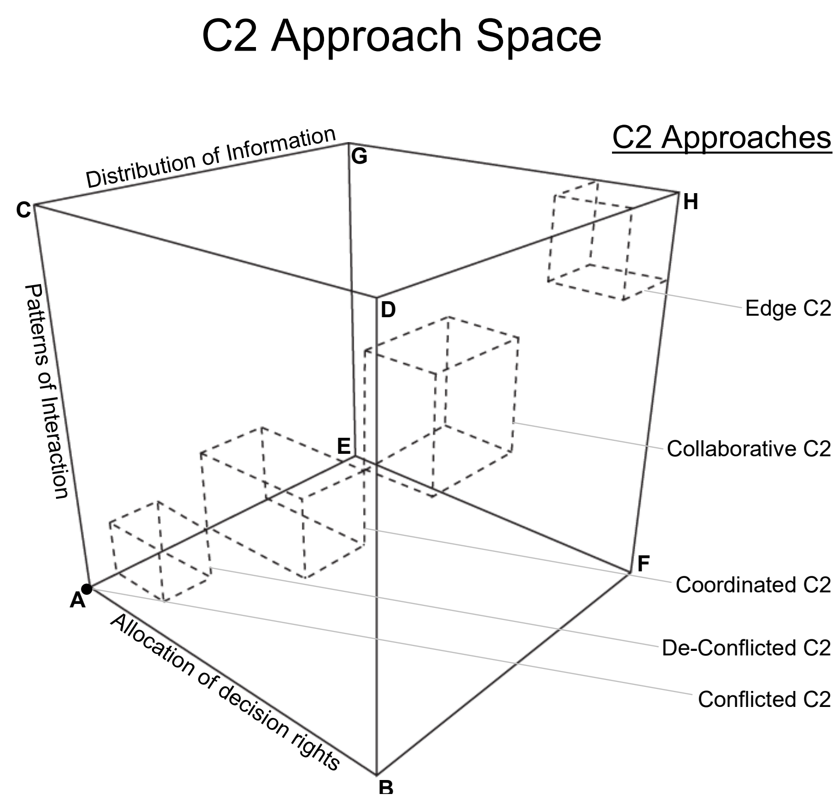

Figure 3 Intermediate C2 Organizations and Approaches (adapted from Alberts & Nissen, 2009)

Beyond deconfliction, one can increase ADR, PoI and DoI further, essentially moving diagonally through the C2 Approach Space to reach the point of coordinated C2. Instead of deconfliction by separating geographic sectors, warfare domains or other aspects of the battlespace, the various participants—which can be within a single organization such as a ship, across ships such as a strike group, across services such as a JTF, or across militaries such as a multinational coalition operation—would share their plans and communicate frequently with one another.

This corresponds more closely to the Simple Structure than the Machine, as multiple organizations are operating more as one entity than many separate ones. The corresponding coordinated C2 approach is notably less efficient than its deconfliction counterpart, due to the increased coordination and communication loads required for efficacy. However, it is also more agile, enabling quicker adjustments and responses to a dynamic mission-environment. Thus, as one moves diagonally through the C2 Approach Space, an important tradeoff appears between organization efficiency and agility.

Moving further along the diagonal, increasing ADR, PoI and DoI still further, we reach the point of collaborative C2. In addition to sharing plans and communicating frequently, the various participants would collaborate to develop common plans and communicate almost constantly. This corresponds more closely to the Professional Bureaucracy than the Simple Structure, as the various participants operate as specialists at what each does well (e.g., like different doctors in a medical office, different lawyers in a legal office, or different professors in a university) yet collaborate to ensure that mission objectives are met. As with coordinated C2 above, the corresponding collaborative C2 approach is notably less efficient than its counterparts further down the diagonal, due to the further increased coordination and communication loads required for efficacy. However, it is also more agile, enabling still quicker adjustments and responses to a dynamic mission-environment.

Finally, moving along the diagonal nearly to the opposite corner, increasing ADR, PoI and DoI to nearly their maxima, we reach the point of Edge C2. In addition to collaborating on common plans and communicating almost constantly, participants (e.g., teams, squadrons, divisions) break away from their home organizations and interact directly with counterparts from other organizations (e.g., Air Force and Navy planes fly together) and coordinate through mutual adjustment. This corresponds more closely to the Adhocracy or Edge Organization than the Professional Bureaucracy, as the various participants team with others as individuals and adjust without replanning to changing circumstances to ensure that mission objectives are met. As with collaborative C2 above, the corresponding Edge C2 approach is notably less efficient than its counterparts further down the diagonal, due to the further increased coordination and communication loads required for efficacy. However, it is also the most agile, enabling the quickest adjustments and responses to a dynamic mission-environment.

It is important to note that moving up the diagonal through this C2 Approach Space is challenging, expensive, risky and unstable. Such movement is challenging, because an organization must deviate considerably from many of its established policies, procedures and processes, and coordinating beyond deconfliction reduces each organization leader's autonomy and discretion. This is the case in particular as an organization seeks to progress to Collaborative or Edge C2. Moreover, such movement is expensive, because considerable time, energy and effort are required for coordination and collaboration, and the communication load can become intense, increasing exponentially with the number of organization participants. Further, such movement is risky, as the potential for errors increases with deviation from established policies, procedures and processes, many of which are designed to reduce risk and eliminate or mitigate errors. Finally, such movement is unstable, particularly as an organization progresses toward Edge C2, because of the huge coordination, collaboration and communication load. Like a sprinting runner, it can be very useful to run quickly, but sprinting cannot be sustained. An organization capable of moving across the diagonal exhibits greater *C2 maturity*, and higher maturity levels are required to move further across the C2 Approach Space (Alberts & Nissen, 2009).

2. C2 Organization Transitions

This section continues with an overview of how an organization can transition between two or more approaches. Following the discussion above, it is also important to note that some transitions are more challenging to achieve than others. Drawing from Nissen (2018), such C2 organization transitions can be divided into two classes: 1) conventional and 2) unconventional. As the class names imply, conventional transitions are much more common less challenging than their unconventional counterparts. We address them in turn.

a. Conventional Transitions

As outlined above, once an organization has established Deconflicted C2, then it can work to increase its maturity level and transition to higher C2 modes (e.g., Coordinated, Collaborative). The organization could then continue its transition to reach Edge C2, and then transition back through one or more of these other C2 organizations to reach Deconflicted again. Likewise, a mature C2 organization could (not that it would want to) transition down to Conflicted and back. In practice, however, as noted above, these last two transitions would be highly unconventional.

If we assign Roman numerals to the five C2 organizations and approaches (i.e., I – Conflicted, II – Deconflicted, III – Coordinated, IV – Collaborative, V – Edge), then we can depict the transition paths outlined above as follows:

(1) I → II → III → IV → V

(2) V → IV → III → II → I

Path (1) depicts the transition from Conflicted all the way to Edge, and Path (2) depicts the reverse transition from Edge all the way back to Conflicted. As noted above, however, both such complete paths are possible in theory but challenging in practice. Focusing instead on the conventional C2 designs and transitions, we shorten the paths by truncating both end points (i.e., I, V) to depict Paths (3) and (4).

(3) II → III → IV

(4) IV → III → II

Moreover, if both of these conventional paths are possible and feasible in total, then any of the constituent subpaths (i.e., II → III, III → IV, IV → III, III → II) are too. Hence we have outlined the set of four feasible, conventional transitions.

This suggests further that an organization cannot skip *higher maturity* transition steps along these paths, for the distance (e.g., consider the degree of organization change required and disruption experienced) is too great. For instance, the transitions II → III and III → IV are feasible, as are their reverse transitions, but II → IV and IV → II are not, because they skip a step. Thus, if an organization finds itself in a mode of Deconflicted C2, for instance, and it desires to transition to a considerably higher design (e.g., Collaborative), then its first transition must necessarily be to Coordinated (i.e., II → III).

Alternatively, when moving toward *lower maturity* C2 modes (esp. II – Deconflicted), an organization is able to skip steps, for it is simply reverting back to normal C2 organization and approach. By simile, this is like climbing a ladder one rung at a time yet being able to jump down several rungs with gravity: an organization must expend considerable time and effort to transition to higher maturity C2 modes, whereas reverting back to its normal C2 organization and approach is straightforward.

With this, we're able to plan dynamic C2 design in terms of three steps:

Step 1. Observe your current C2 design (C2c).

Step 2. Identify your desired C2 design (C2d).

Step 3. Transition incrementally from C2c <through C2n> to C2d.

Hence the first step is to fix an organization's current C2 design (e.g., Deconflicted). The second is to identify its desired design (e.g., Collaborative). The third is to transition through one or more incremental steps (e.g., II → III, III → IV) from the current to the desired design.

For illustration, say that a US Military organization (e.g., a CTG) reflects Deconflicted C2 in terms of (manned and unmanned) aircraft operations at sea. As noted in prior research (Nissen & Place, 2016), this implies that no two unmanned aircraft systems (UASs) can operate in the same airspace at the same time (i.e., the C2 deconflicts airspace-time). Likewise, as such, no UASs may operate in the same airspace-time as manned aircraft, although manned aircraft operate in common airspace-time routinely.

Say, however, that a new mission requires contemporaneous airspace operations (e.g., multiple unmanned and manned aircraft flying together), and the military organization can benefit by increasing its maturity and transitioning to a higher C2 maturity mode (e.g., Coordinated or Collaborative). We can follow the steps above, and utilize our transition map, to assist the Commander in expressing intent and to guide the Commander's staff and subordinate leaders in satisfying such intent.

The intent could read, for example, something like, "We need to transition our aircraft operations at sea from Deconflicted C2 to Collaborative C2 (within X time period) in order to complete Mission Y." The Commander's staff could then identify the required transition path (i.e., II → III, then III → IV), and they could in turn develop guidelines for subordinate commanders, for example, as something like, "We need to delegate authority (i.e., broaden ADR), loosen constraints across ships, aircraft and departments (i.e., increase PoI), and expand information sharing across units (i.e., broaden DoI)." It would then be up to subordinate leaders to determine exactly how to do so in a manner that makes the most sense in terms of the organization and its mission.

Through this example, clearly the C2 maturity level need not be ubiquitous, monolithic and permanent (e.g., one design for the whole organization, always). Rather, some aspects of C2 can reflect one mode (e.g., Coordinated C2 for the aircraft mission), whereas most if not all others can reflect a different one (e.g., Deconflicted for everything else). Likewise, an alternate C2 approach may be put into effect only during a specific mission, operation or period of time (e.g., while the various ships' aircraft operate in common airspace-time), reverting to status quo afterward. This is the key idea.

b. Unconventional Transitions

Now we address the unconventional C2 transition rules and guides. As noted above, such unconventional transitions involve the Conflicted and Edge C2 archetypical designs. It is difficult to understand, for instance, why any organization would ever wish to transition to a Conflicted design, and it is challenging for any organization to transition to an Edge. However, an organization or collective may find itself in a Conflicted design through default. This could happen, for instance, when established modes of C2 become unavailable or denied (e.g., if satellite communication fails).

The affected organization would need to increase maturity and transition a higher design (II – Deconflicted as a minimum, but likely higher toward Edge). Likewise, an organization may find itself in an Edge design through great effort, but it may wish to transition to a lower design to ease coordination efforts. As noted above, speaking generally, the higher the C2 design, the greater the coordination effort required. We examine both of these C2 organizations and approaches.

In the first, where a collective organization finds itself in Conflicted design, our transition rules point toward two alternate paths. Ironically, when established modes of C2 become unavailable or denied (e.g., if satellite communication fails), the most logical path I → II (i.e., Conflicted to Deconflicted) is possible theoretically but seemingly infeasible in practice. This is because the organization in charge must be able to communicate with all others before it can impose and achieve the deconfliction. Either that, or all participating organizations must agree to a common deconfliction approach, which would be very challenging in a degraded communication environment.

Alternatively, the organization could attempt the unconventional transition I → V (i.e., Conflicted to Edge). This may appear on the surface to violate the incremental rule set forth above (i.e., taking only one transition step at a time), for the Edge is depicted symbolically as four transition steps above Conflicted C2. However, we allow for transitions both up and down the path. Hence we can combine Paths (1) and (2) to delineate bidirectional transitions as shown in Path (5):

(5) I ↔ II ↔ III ↔ IV ↔ V

Moreover, if we view both ends of this bidirectional path as linked, as opposed to opposite endpoints along a line, then the I → V transition begins to look possible. We delineate such linked transitions in Figure 4. On the right side, we show the three conventional C2 designs and transitions (i.e., II ↔ III ↔ IV), and we illustrate their interrelationship as being relatively close to one another to indicate that transitions between them are comparatively easy for an organization. We also position these three points somewhat hierarchically to indicate that each represents a higher C2 design—and hence reflects greater maturity—than the one below (i.e., IV > III > II).

On the left side of the figure, we show the two unconventional C2 designs and transitions (i.e., I ↔ V), and we illustrate their interrelationship as being relatively far from one another to indicate that transitions between them are relatively difficult for an organization. We also position these two points hierarchically to indicate that one represents a higher C2 design—and hence reflects greater maturity—than the other (i.e., V > I).

Further, we position the conventional C2 archetypes comparatively far from both of their unconventional counterparts to show the difficulty associated with the corresponding transitions (i.e., I ↔ II, IV ↔ V) in the case of degraded communication environment. Although it may be difficult to discern in the figure, however, the transition distance between the two unconventional designs (i.e., I ↔ V) is less than that between either unconventional-conventional counterpart (i.e., I ↔ II, IV ↔ V). This indicates that the difficulty of transitioning between the two unconventional designs is less than transitioning between unconventional and conventional. Hence the transition I ↔ V may be less demanding than I ↔ II.

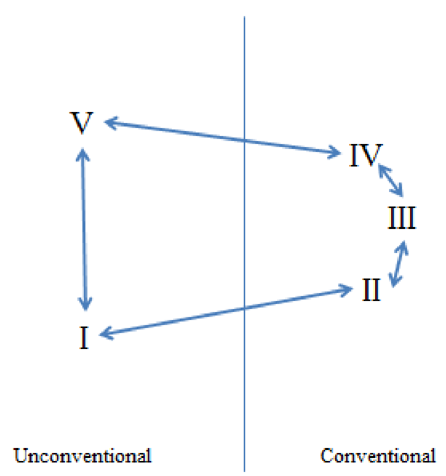

Figure 4 Linked Transitions (adapted from Nissen, 2018)

The availability of different C2 organizations and approaches is powerful, and a mature C2 organization's ability to transition between modes can be very useful when C2 conditions become challenged (e.g., by satellite disruption). We apply this in the analysis below to examine JADC2 across varying C2 environments.

C. KNOWLEDGE DYNAMICS

Nissen (2005) describes the concept *knowledge flow* in terms of dynamic knowledge and indicates that it subsumes similar concepts such as *knowledge conversion, transfer, sharing, integration, reuse* and others that depict changes, movements and applications of knowledge over time. Knowledge Flow Theory (Nissen, 2006; 2014) describes the dynamics of knowledge flows phenomenologically, and it includes multidimensional, analytic and graphic techniques for understanding, interpreting, measuring and comparing a diversity of flows. Drawing directly from Nissen (2007), we organize this brief overview of knowledge dynamics into five parts: 1) knowledge uniqueness, 2) knowledge flows, 3) knowledge visualization, 4) knowledge patterns, and 5) knowledge measurement. Interested readers are directed to Nissen (2014) for details.

1. Knowledge Uniqueness

In this characterization, *knowledge* is conceptually distinct from *information, data* and *signals*: knowledge enables effective action (e.g., decisions, behaviors, work); information provides meaning and context for action (e.g., decision criteria, behavior stimuli, work settings); data answer context-specific questions (e.g., How much profit is expected by selecting Alternative A? Who says that we should honor our commitments to the workers? How many industrial accidents have occurred so far this year?); and signals transmit detectable events across physical space (e.g., light patterns from pages in a book, sound waves from voices in a room, voltage differences across cables in a computer network).

Many scholars (e.g., Davenport and Prusak, 1998; Nissen et al., 2000; von Krogh et al., 2000) conceptualize a hierarchy of knowledge, information and data. As illustrated in Figure 5, each level of the hierarchy builds upon the one below. (Each is also fed from the one above.) For example, data are required to produce information, but information involves more than just data (e.g., need to have the data in context). Similarly, information is required to produce knowledge, but knowledge involves more than just information (e.g., it enables action). We operationalize the irregular shape of this hierarchy using two dimensions—*abundance* and *actionability*—to differentiate among the three constructs.

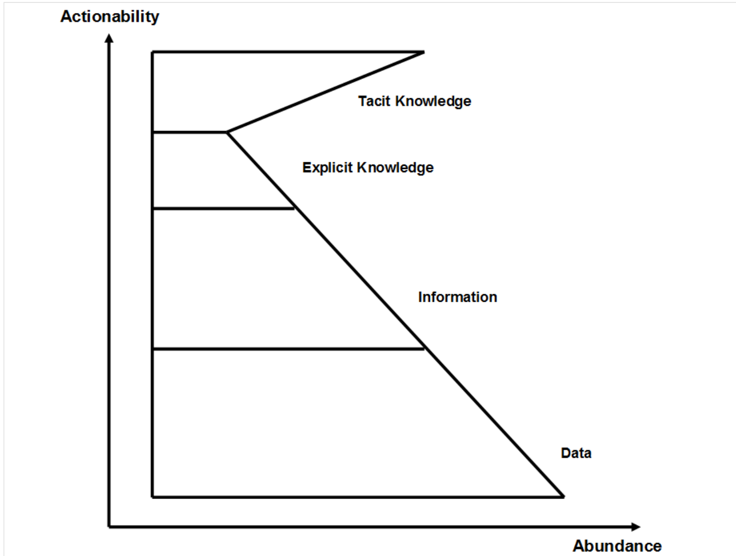

Figure 5 Knowledge Hierarchy (adapted from Nissen, 2014)

Briefly, data lie at the bottom level, with information in the middle and knowledge at the top. The broad base of the triangle reflects the abundance of data, with exponentially less information available than data and even fewer chunks[1] of knowledge in any particular domain. Thus, the width of the shape at each level reflects decreasing abundance in the progress from data to knowledge. The height of the shape at each level reflects actionability (i.e., the ability to take appropriate action, such as informed decisions, appropriate behaviors or productive work). Converse to their abundance, data are not particularly powerful for supporting action, and information is more powerful than data, but knowledge supports action directly, hence its position at the top of the shape.

Notice that we position tacit knowledge "above" its explicit counterpart in this figure. Tacit knowledge is characterized widely as being very rich in terms of enabling action, whereas explicit knowledge represents often a diluted formalization of its tacit

[1] *Chunk* (C) is a longstanding technical term, derived from psychology and used in the artificial intelligence literature, which describes a unit of knowledge that has become familiarized and can be recognized in one's field of expertise (Simon, 1996). A recognized expert in some domain is estimated to require roughly 10 years, 10,000 hours or 10,000 knowledge chunks in that domain and to require at least ten years to acquire such knowledge. We use chunk as a proxy for the mass or amount of knowledge possessed or moved.

counterpart, with many properties and behaviors that are similar to those of information (Nissen, 2005). Further, unlike explicit knowledge, which must by definition be formalized, articulated or otherwise made explicit (e.g., via books, graphs, charts, software), and hence is somewhat limited in abundance, tacit knowledge accumulates naturally (e.g., through direct experiences and observations of people) and is quite abundant. This is the basis for the irregular shape depicted in the figure.

2. Knowledge Flows

In terms of knowledge flows (e.g., movements of knowledge across people, organizations, places, forms and times; from where, when and how it is to where, when and how it needs to be), the two connected knowledge hierarchies depicted in Figure 6 illustrate some key concepts. On the left side, we see a knowledge producer's hierarchy, and on the right side, we see a knowledge consumer's hierarchy. Both of these knowledge hierarchies conform to the characterization above (e.g., abundance vs. actionability, layers building upon one another, distinct concepts, irregular shape). The producer hierarchy includes a vector arrow pointed downward (i.e., from knowledge, through information, to data; each level feeds the one below), and the consumer hierarchy includes an arrow pointed upward (e.g., each level builds upon the one below). This depicts the relative direction of knowledge as it flows from producer to consumer.

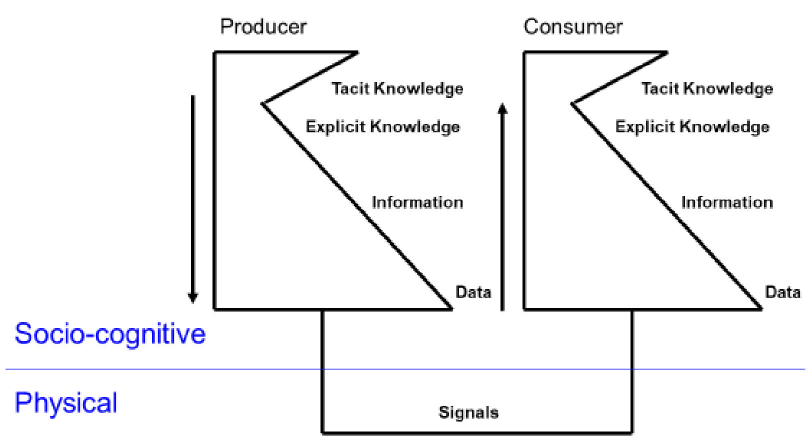

Figure 6 Knowledge Flows (adapted from Nissen, 2014)

Specifically, following Tuomi (1999), the producer utilizes existing knowledge to create information, which is used in turn to produce data, which are transmitted via signals across some physical space. Then, following von Krogh et al. (2000), the consumer interprets the data from signals, develops information through incorporation of meaning and context, and finally develops actionable knowledge through some learning mechanism. Of course, the directionality of arrows can reverse (i.e., a "producer" can become a "consumer," and vice versa), and multiple knowledge hierarchies can participate simultaneously, but this provides a phenomenological description of how knowledge flows. Notice that only signals are involved with flows across physical space; following Alberts and Hayes (2003), flows of data, information and knowledge take place in the socio-cognitive domain.

3. Knowledge Visualization

Figure 7 depicts a multidimensional space to visualize dynamic knowledge. Because knowledge is inherently intangible, invisible and resistant to quantification, understanding its dynamics through graphic representation remains a challenge. Alternatively, multidimensional representation and visualization is straightforward and commonplace in Physics, so we borrow some of its fundamental concepts and techniques, and we begin to adapt them for our purpose in the knowledge domain.

We are far from the first to borrow and adapt such concepts and techniques from other disciplines. Economics research, for instance, has borrowed concepts from Physics (e.g., *equilibrium, elasticity, differential*) for many years, and the Econophysics field (Gangopadhyay, 2013; Ghosh, 2013) employs both concepts and techniques from Physics (e.g., vectors, systems of dynamic equations, simulation) directly for use in addressing complex (esp. dynamic) economic problems. Hence our approach has abundant and relevant precedent, one that we continue to exploit for knowledge measurement below.

Briefly, the vertical axis represents the dimension *explicitness*, which characterizes the degree to which knowledge has been articulated in explicit form. This dimension draws from the Spiral Model (Nonaka, 1994) and includes a ratio scale between tacit and explicit endpoints. The horizontal axis represents the dimension *reach*, which characterizes the level of social aggregation associated with knowledge flows. This dimension draws from the Spiral Model also and is operationalized by the number of people associated with any particular chunk of knowledge. The third axis represents the dimension *life cycle*, which characterizes the kind of activity associated with knowledge flows. This dimension represents an extension to the Spiral Model (Nissen, 2002) and includes several ordinal categories of life cycle activity (e.g., create, share, apply). Together, these axes combine to form a three dimensional space.

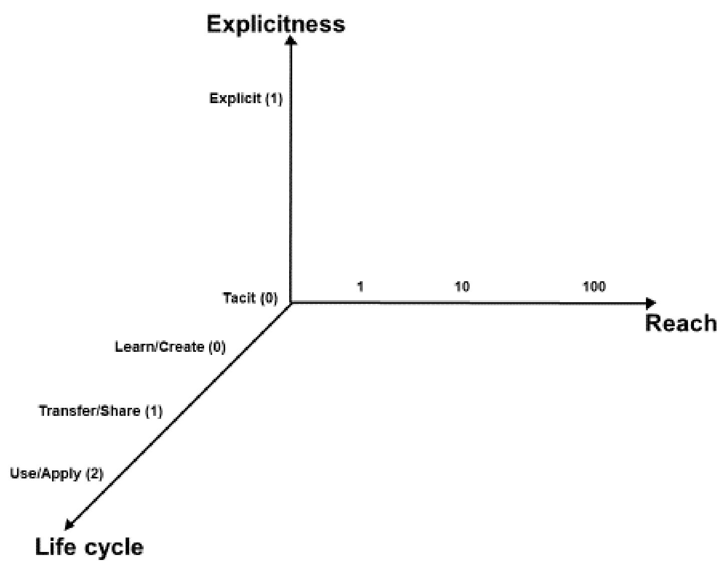

Figure 7 Basic Knowledge Flow Space (adapted from Nissen, 2014)

To represent important knowledge dynamics, through Figure 8 we continue to extend the Spiral Model by integrating the dimension *flow time,* which pertains to the length of time required for knowledge to move from one coordinate point in this three dimensional space to another, and *energy*, which depicts the performance level of action enabled by a particular knowledge chunk (Nissen, 2017). Because visualization in five dimensions does not come naturally to most people, we use arrows of different thickness (e.g., thick for slow flows, thin for fast flows) when delineating knowledge flowing at different speeds, and we use different color patterns (e.g., dotted-orange for low energy flows, solid-purple for high energy flows) to represent the energy dimension.

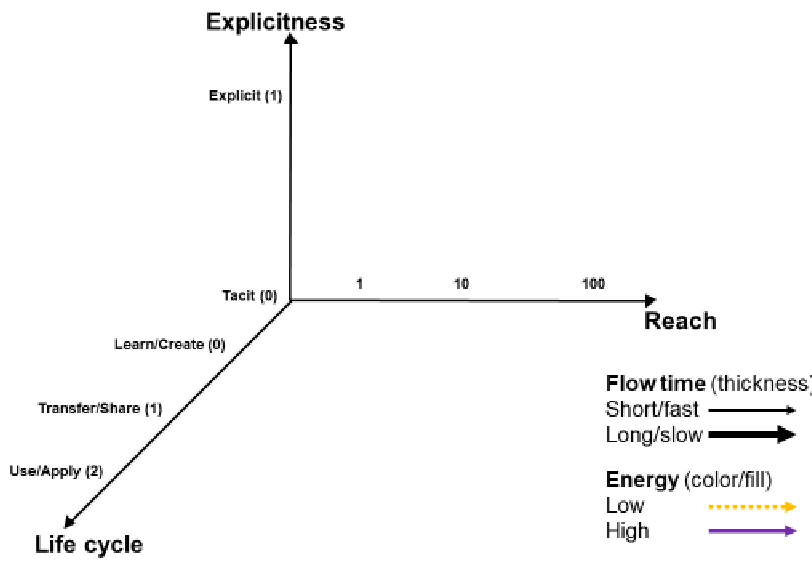

Figure 8 Extended Knowledge Flow Space (adapted from Nissen, 2014)

4. Knowledge Patterns

A wide variety of knowledge patterns emerge from the multidimensional visualization space from above. In Figure 9, for instance, we illustrate a basic knowledge sharing problem. Someone at Point A learns how to do something important. Notice that the corresponding knowledge is tacit (e.g., experience based): The person at Point A knows how to perform the knowledge enabled action, but he or she has not written it down or articulated it into explicit form otherwise. Nonetheless, we want this knowledge to flow team wide so that everyone is able to apply it *at the same efficacy level* (i.e., energy level) as the person at Point A.

The shortest distance between two points is a straight line, hence we would like for such knowledge to flow quickly and energetically from the one individual to all 10 of his or her teammates (Point B). Unfortunately, the organization does not possess a process for tacit knowledge to flow both quickly and energetically. (Few, if any, organizations do.) Indeed, much of the rich, experience based tacit knowledge in an organization can take weeks, months or even years to learn.

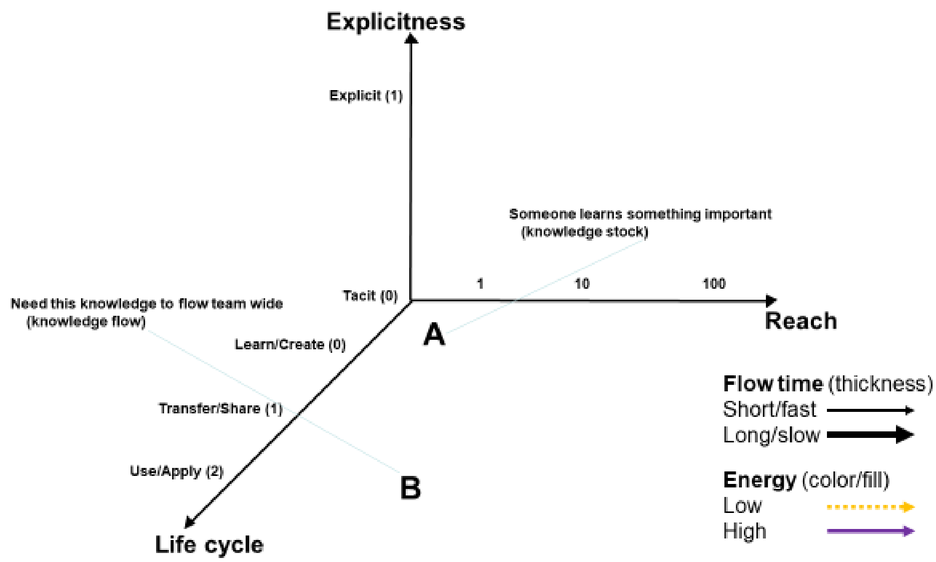

Figure 9 Basic Knowledge Sharing Problem

We illustrate this effect in Figure 10, which includes a thin, solid-purple vector extending from Point A toward B.

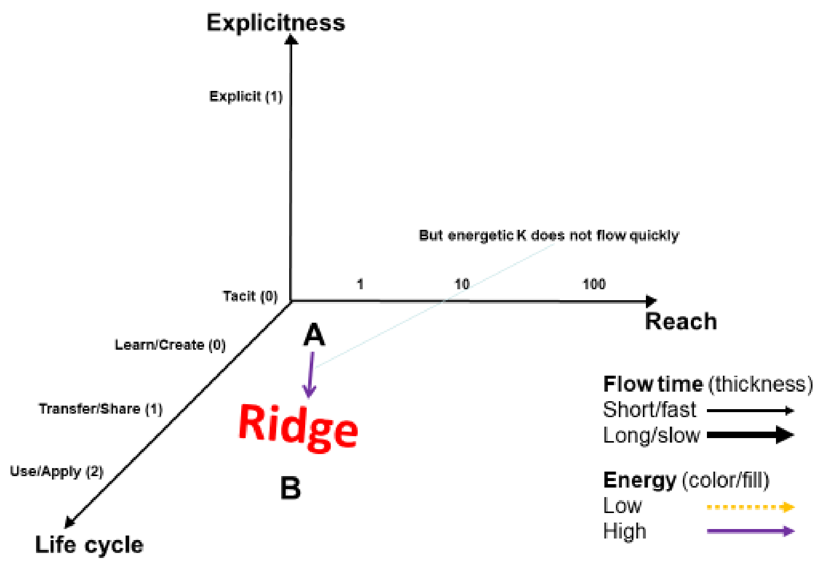

Figure 10 RIDGE Blocking Ideal Knowledge Flow

This delineates the kind of rapid, energetic flow that would be ideal. Because such ideal flow is infeasible, however, it cannot extend directly to Point B, so we annotate the figure with a RIDGE blocking the ideal flow. This indicates that the corresponding knowledge must flow either over or around the RIDGE in order to reach B.

These two flows are depicted in Figure 11. The organization possesses two, archetypical knowledge flow processes, to which we refer as 1) the Jump Shot, and 2) the River. The Jump Shot is delineated by a dotted line that rises up out of the tacit plane, whereas the River flow moves back and forth within this plane. With the former flow, the person at Point A expends both time and effort to articulate his or her knowledge in explicit form (e.g., written document, training material, SOP/TTP), who can then share it very quickly across the organization via network. Once shared as such, all 10 people on the team are able to access and apply the new knowledge. This explicit knowledge flow pattern is exceedingly common in the modern organization. The first and last knowledge flow vectors (i.e., A-M & N-B) represent knowledge conversions (i.e., tacit-explicit & explicit-tacit, respectively).

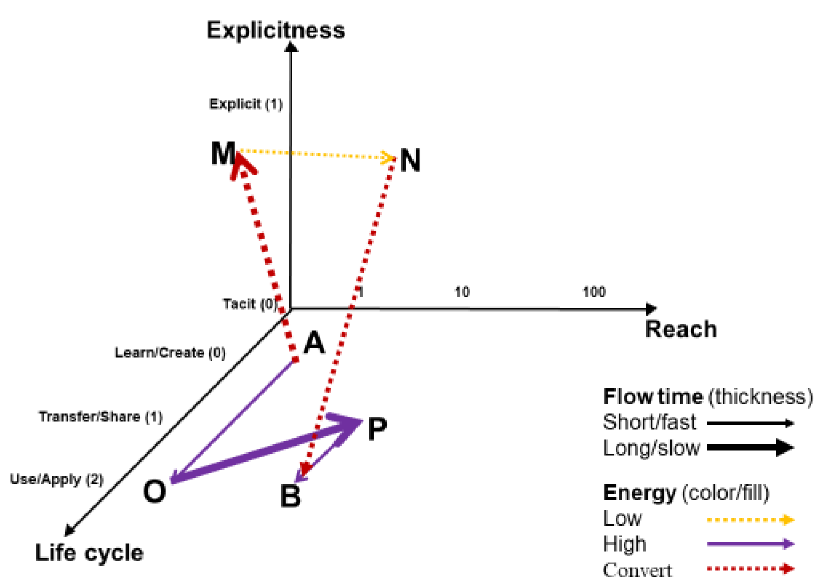

Figure 11 Archetypical Knowledge Flow Processes

The problem is, once articulated, explicit knowledge rarely flows at the same energy level as the corresponding tacit knowledge used to articulate it. Reading a book, for instance, about how to fly an airplane is not the same as direct experience flying airplanes. Simply reading a document, as another instance, about leading people rarely equips a leadership novice to be an effective leader without considerable experience and practice. Even the best training course on computer network defense, as a third instance, is rarely adequate for a novice computer security person to defend a complex network well without working defensively with that network. Thus, the Jump Shot archetype is known well for knowledge flowing very quickly and broadly through the organization, but it is known also for such knowledge to be comparatively attenuated in terms of energy.

Alternatively, with the latter flow, the person at Point A applies his or her knowledge directly and then shares it with (say ten) teammates using tacit knowledge flow techniques (e.g., demonstration, mentoring, coaching, observation, OJT). Once all ten people in this group are able to apply the knowledge *at roughly the same efficacy level* as the knowledge creator, each of them does so at roughly the same energy level. This latter energy level—and hence the efficacy level of performance—is generally much higher than that achieved through the Jump Shot.

Nonetheless, despite the high energy knowledge flow, the River has its own limitations. In particular, tacit knowledge flows comparatively very slowly and narrowly. It can take weeks, months or even years for someone to teach others to perform some knowledge enabled actions proficiently, and the kinds of tacit knowledge flow techniques noted above (e.g., demonstration, mentoring, coaching, observation, OJT) limit the number of people that knowledge can be shared with at any point in time. Effective mentoring, for instance, is limited to only one, two or perhaps a few people at a time. Thus, the River archetype is known well for knowledge flowing very slowly and narrowly through the organization, but it is known also for such knowledge to be comparatively very energetic.

This does not imply that one archetype is necessarily "better" than another. Rather, it explains that the two archetypes differ qualitatively and exhibit unique dynamic properties and behaviors. When circumstances necessitate rapid and broad knowledge flows (e.g., in an emergency), and when such flows do not require high energy, the Jump Shot represents the superior approach. Alternatively, when high energy flows are critical (e.g., when high performance is needed), and when the organization can wait for it to flow slowly from individuals through small groups, the River represents the better choice. With this as background, we have the ability to examine knowledge flows and needs within any operational organization and to determine—analytically—which approach to employ.

5. Knowledge Measurement

Finally, we summarize and extend recent information systems (IS) research (Nissen, 2017) that enables the visualization and measurement of dynamic knowledge. Such recent research builds upon our understanding of dynamic physical systems to outline a simple set of equations that characterize the dynamics of motion in physical space and time (e.g., including constructs *force, work, friction, energy, time, power*). This recent work then draws from Measurement Theory (Krantz, Luce, Suppes & Tversky, 1971) and leverages Knowledge Flow Theory (KFT) to develop an analogic set of equations to characterize the dynamics of knowledge as it flows through the organization (e.g., including constructs *knowledge force, knowledge work, knowledge friction, knowledge energy, flow time, knowledge power*). We link the dynamic knowledge measurement system that emerges with the visualization techniques from above to illustrate how such system is consistent with theoretic predictions.

This is done with full understanding and upfront admission regarding the limitations of analogic reasoning: In no way do we assert that the dynamics of knowledge follow or mirror the dynamics of physical systems precisely. Every analogy breaks down when stretched too far, and even some of the most basic physical concepts may have little meaning in terms of dynamic knowledge. Notwithstanding such limitations, however, we gain considerable insight from the deep understanding and mathematic representation of dynamic physical systems, which are adapted analogically to enable the measurement of dynamic knowledge.

a. Physical System

To recapitulate the approach, which is described in detail through research by Nissen (2017), a simple physical system is represented mathematically through the basic Newtonian equations summarized in Table 1. Such equations can be found in any introductory Physics textbook, yet they enable quantitative measurement, analysis, prediction and simulation of dynamic physical systems. Here we interrelate *force* (mass x acceleration; expressed in Newtons), *work* (force x distance; expressed in Joules) and *power* (work / time; expressed in Watts). We include three variations of Equation (3) to interrelate *time, distance* and *acceleration.*

We note also (beyond the table) how *work* and *energy* are exchangeable and expressed in the same units (Joules): energy is required to perform work, and work performance involves the expenditure of energy. We leverage such exchangeability below through analogic reasoning for knowledge systems.

We note further how friction affects many physical systems by opposing motion and acceleration. An ordinary shopping cart, for instance, requires greater effort (i.e., more force) to push along a store aisle with a rough floor than a smooth one: the greater friction associated with the rough floor opposes motion and acceleration of the cart, hence it requires more force to push.

Table 1 Physical System Equations (adapted from Nissen, 2017)

Construct	**Description**	**Equation**
Force (F)	Effort required to accelerate mass	(1) F = m x a
Work (W)	Force applied through distance	(2) W = F x d
Time (t)	Time for a mass to move its distance	(3a) $t = \sqrt{(2d/a)}$
Distance (d)	Distance that a mass moves	(3b) $d = ½ at^2$
Acceleration (a)	Change in velocity	(3c) $a = 2d/t^2$
Power (P)	Work done per unit time	(4) P = W / t

Considering friction in support of our analogic reasoning, a simple, linear, negative relationship between *force*—including that required to overcome friction (F_{Fr})—and floor *smoothness* (fs) is delineated in Figure 12. Here force can be measured in Newtons, and smoothness is expressed on a [0,1] continuum between rough (fs=0) and smooth (fs=1) endpoints.

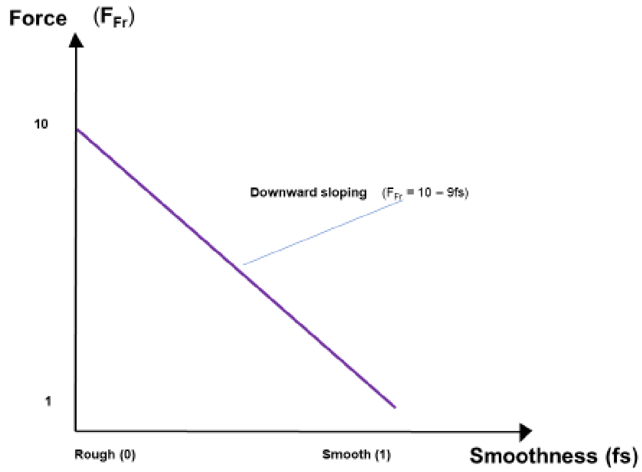

Figure 12 Force and Smoothness (adapted from Nissen, 2017)

Specifically as depicted in the figure, a rough floor is characterized here as requiring ten times the force to push a shopping cart as that needed on a smooth floor (F_{Fr} = 10 - 9fs). This downward sloping relationship between force and smoothness is representative, with specific slopes, intercepts and functions highly likely to differ across various carts, stores, aisles and floors. Nonetheless, the relationship makes intuitive sense and is consistent with many physical observations and measurements.

For illustration, say that some researchers go into a store and take three measurements: They observe a cart laden with 10 kg of groceries that takes 20 s to be pushed to the end of a 10 m aisle. The researchers use a scale to weigh the groceries, a stop watch to time the cart, and a tape measure to gauge the aisle length. This simple system of equations enables one to calculate all of the other parameters.

Using Equation (1) to find the force: The mass (10 kg) is known; and acceleration is calculated from Equation (3c), knowing distance (10 m) and time (20 s), at 0.05 m/s^2. Hence the corresponding force is 0.5 N. From Equation (2), work and energy are 5 J, and from Equation (4), the average power exhibited is 0.25 W. Thus, the researchers are able to discover much about this system from only three measurements. Figure 13 delineates velocity (v), acceleration (a) and distance (d) over the first five seconds of movement down the aisle.

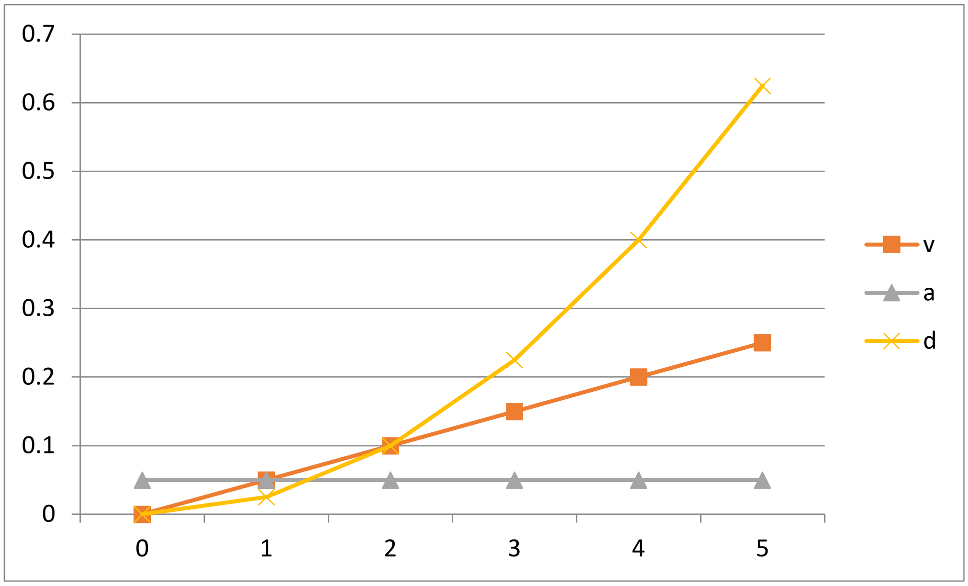

Figure 13 Physical System Dynamics (adapted from Nissen, 2017)

Moreover, now that this system of equations has been parameterized with measured and calculated values, one can understand and predict myriad changes and variations without having to observe and measure it again physically. Say, for several instances, that researchers want to know what would happen if someone were to double or halve the mass of groceries on the cart (i.e., 20 kg, 5 kg), if the aisle were to double or halve in length (i.e., 20 m, 5 m), or if the cart were pushed to the end in double or half the time (i.e., 40 s, 10 s). Calculating such changes is straightforward with our parameterized system of equations: different values are substituted simply, and additional measurements in the field are not required.

b. Basic Knowledge System

In this section we recapitulate development of a basic knowledge system via analogic reasoning with respect to the simple physical system summarized above. Details of such knowledge system are found in Nissen (2017). As summarized in Table 2, we outline an analogic knowledge system. Briefly, *knowledge force* (K-Force or KF) is analogous to physical force and represents the effort required to accelerate knowledge in an organization. From KFT, it is expressed as a function of the knowledge *chunks* (C) being accelerated and the *explicitness* (E) of such knowledge.

Table 2 Analogic Knowledge System

Construct	**Description**	**Analogy**
K-Force (KF)	Effort required to accelerate knowledge	f(C, E, **o**)
K-Work (KW)	K-Force applied through reach	KF x R
Flow Time (FT)	Time required for knowledge to flow	FT
K-Power (KP)	K-Work done per unit flow time	KW / FT

In this conceptualization, each chunk (see Simon, 1996) of knowledge can enable the performance of one atomic action (e.g., making one distinction) in the organization. As noted above in terms of knowledge visualization, *explicitness* derives from Nonaka's (1994) epistemological dimension and represents the degree to which a knowledge chunk has been articulated in explicit form. The greater the number of chunks being accelerated (analogous to physical mass), and the more tacit the corresponding knowledge (analogous to physical friction), the greater the K-Force required. Notice also the **o** vector representing a number of other, unspecified factors (e.g., experience, communication skill, motivation, stress, organization climate, IT support), which are likely to play a role, but which have yet to be integrated explicitly or analogically.

As noted above also, *reach* (R) derives from Nonaka's (1994) ontological dimension and represents the number of people associated with the knowledge chunks from above (analogous to physical distance). Reach combines with KF to specify *knowledge work* (K-Work or KW) accomplished in the organization (analogous to physical work). Analogous to the exchange between and common units of *work* and *energy* in physical systems, we also conceptualize a correspondence between *knowledge work* and *knowledge energy* (K-Energy or KE): KE is required to perform KW, and KW performance involves the expenditure of KE.

In turn, *flow time* (FT) represents the time required for such knowledge chunks to flow from one person (e.g., an expert), group (e.g., a sales team), place (e.g., West Coast office), form (e.g., tacit) or time (e.g., night shift) to another. As a time measure, it combines with KW to specify *knowledge power* (K-Power or KP), which represents the knowledge work accomplished (and knowledge energy expended) per unit time (analogous to physical power).

Continuing to draw analogically from the dynamics of physical systems; and considering friction, which opposes motion and acceleration; a simple, linear, negative relationship between *knowledge force* (KF) and *explicitness* (E) is delineated in Figure 14. Consistent with KFT, this relationship indicates that tacit knowledge, which is notably "sticky" (Szulanski, 2000) and difficult to move through the organization, requires more effort (i.e., greater KF) to accelerate than its explicit counterpart.

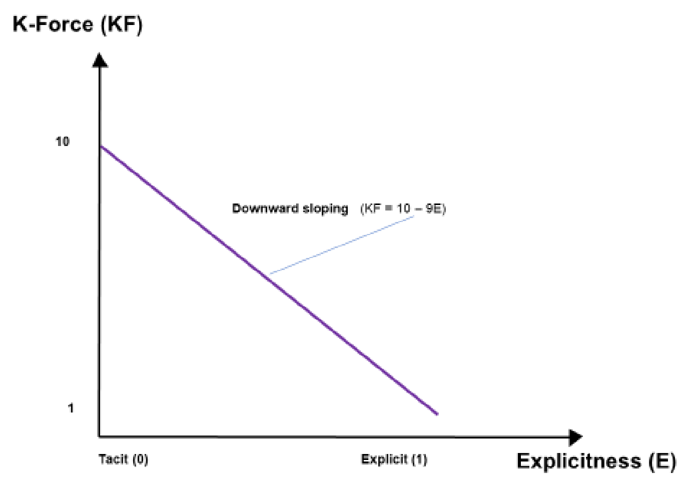

Figure 14 Knowledge Force and Explicitness (adapted from Nissen, 2017)

Alternatively, tacit knowledge, in the context of which Polanyi (1967) explains that we know more than we can say, can enable knowledge work at higher performance levels than explicit. As noted above, to recapitulate the instance, reading a book (i.e., explicit knowledge) about how to fly an airplane is not the same as direct experience (i.e., tacit knowledge) flying airplanes, hence it is unlikely to enable performance at the same level.

Specifically as depicted in the figure, a chunk of tacit knowledge is characterized here as requiring (analogously) ten times (10x) the K-Force needed to get a chunk of explicit knowledge flowing (KF = 10 - 9E). Space prohibits a long discussion of sensitivity analysis, but results are highly robust to differences in slope (e.g., 2x, 100x), linearity (e.g., x^2, $x^{1/2}$) and other factors. Indeed, this downward sloping relationship between K-force and explicitness is representative, with specific slopes, intercepts and functions highly likely to differ across various organizations, people, processes, technologies and kinds of knowledge. Nonetheless, the relationship makes intuitive sense and is analogous to physical friction.

Further, we can use this representative relationship to specify the set of dynamic knowledge equations summarized in Table 3. In Equation (5) we specify K-Force as a multiplicative function of knowledge chunks (C), explicitness (10 - 9E), and vector of unspecified other factors (**o**). We refer to units of K-Force as "Nonakas" (N), acknowledging the seminal knowledge flow research done by Nonaka (1994). K-Work (and K-Energy) then follows in Equation (6) as the product of K-Force and reach (R). We refer to units of K-Work as "Polanyis" (P), for the keen insight into tacit knowledge provided by Polanyi (1967). K-Power is specified in turn through Equation (7) by dividing K-Work (or K-Energy) by flow time, the latter of which must be measured (e.g., using a stopwatch or calendar, measured in seconds). We refer to units of K-Power as "Bacons" (B), acknowledging Sir Francis Bacon, to whom many scholars attribute the aphorism, "knowledge is power."

Table 3 Knowledge System Equations

Construct	Equation
K-Force	(5) KF = C x (10 - 9E) x **o**
K-Work	(6) KW = KF x R (= KE)
Flow Time	Measure
K-Power	(7) KP = KW / FT

To reiterate from above, this analogic reasoning is not strict, and we recognize its limitations. Nonetheless, we gain insight from the deep understanding and mathematic representation of dynamic physical systems, which are adapted here to address the measurement of dynamic knowledge. Even this simple set of equations enables us to begin measuring knowledge as it flows through the organization. This represents a substantial step forward in terms of knowledge management and measurement.

c. Measurement Example

Recall from Figure 11 above how the Explicit Path delineates knowledge flowing *over* the RIDGE via the Jump Shot pattern. As illustrated again here in Figure 15, one can visualize such flow via three vectors (i.e., A-M, M-N, N-B). This is the archetype associated most closely with technologic implementations, as it centers on making knowledge explicit and using technology for sharing. In contrast, the Tacit Path delineates knowledge flowing *around* the RIDGE via the River pattern. Through this same figure, one can visualize such flow via two vectors (i.e., A-O, O-P, P-B). This is the archetype associated least closely with technologic implementations, as it centers on sharing tacit knowledge through interpersonal interaction.

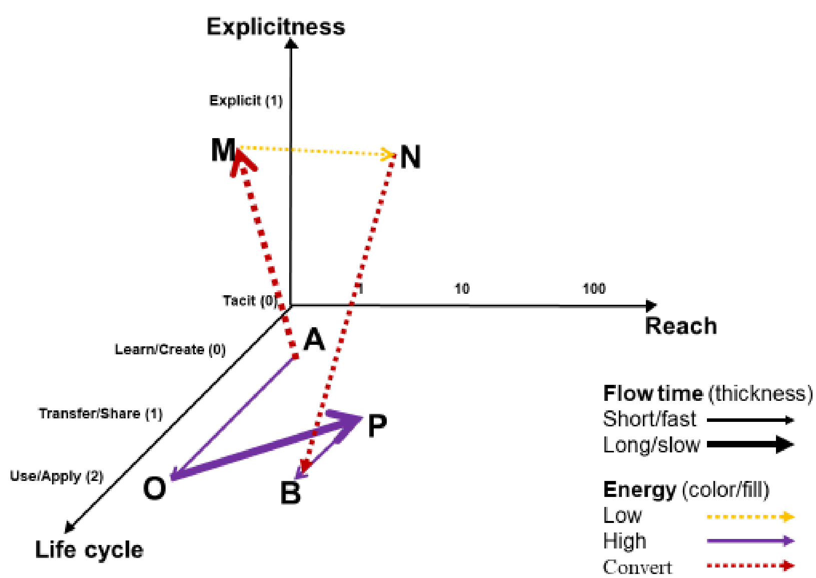

Figure 15 Archetypical Knowledge Flow Processes (adapted from Nissen, 2017)

Measurements corresponding to the Explicit Path for, say, 100 knowledge chunks are summarized in Table 4. Notice that we divide the measurements into three parts corresponding to each of the flow vectors. Walking across columns in the table, for the 100 chunks moving through the first flow vector (A-M), one can see explicitness is listed as a fractional value (0.5) in Column 2. This denotes that knowledge associated with the flow begins as tacit (E = 0) and ends as explicit (E = 1), as an individual worker articulates tacit knowledge into explicit form. Using Equation (5), this results in K-Force of 550 N (KF, KW and FT are expressed in thousands in the table), and with unitary reach (i.e., the individual), Equation (6) indicates K-Work (and K-Energy) of 550 P. The worker's time records indicate that just over four hours are invested in articulating the knowledge in explicit form and making it available on the computer network, which corresponds to 15,000 s flow time.

Table 4 Explicit Path Measurement

Flow	E	KF	R	KW	FT	KP
A-M	0.5	0.55	1	0.55	15.0	
M-N	1.0	0.10	10	1.00	0.1	
N-B	1.0	0.10	10	1.00	1.0	
Sum				2.55	16.1	0.16

Calculations for the other two flow vectors (M-N, N-B) involve the same 100 knowledge chunks and follow the same logic and procedure. Notice that knowledge is purely explicit (E = 1) for these latter flow segments and that both involve the same reach (10) across the team. In the first of these vectors (M-N), explicit knowledge flows very quickly (100 s) and simultaneously to all ten people via computer network. In the second (N-B), all ten coworkers apply such explicit knowledge directly and in parallel, through actions requiring nearly 17 minutes (1000 s) to complete. K-Work (and K-Energy) is nearly double (i.e., 1000 P) for these purely explicit flows because of the greater reach (10 vs. 1). Summing K-Work (2550 P) and flow time (16,100 s) for the process as a whole, (average) K-Power of 0.16 B obtains from Equation (7).

Measurements corresponding to the Tacit Path are summarized in Table 5. They involve the same 100 knowledge chunks and follow the same logic and procedure described above. Notice that knowledge for both flow vectors (i.e., A-O, O-P, P-B) comprising this latter process is purely tacit (E = 0). This reflects the kind of interpersonal, iterative, experiential interaction that is associated widely with tacit knowledge sharing. As such, and as above, the system of equations is used to obtain the measurement values in this table for the tacit knowledge flow path, and flow time from coworkers' time records is included.

Table 5 Tacit Path Measurement

Flow	E	KF	R	KW	FT	KP
A-O	0.0	1.0	1	1.0	0.1	
O-P	0.0	1.0	10	10.0	55.0	
P-B	0.0	1.0	10	10.0	0.1	
Sum				21.0	55.2	0.38

Notice further that a relatively long time (i.e., roughly 15 hours; FT = 55,000 s) is required for this tacit knowledge to be shared (O-P). This is consistent with the "sticky" nature of such knowledge. Alternatively, once learned, application of tacit knowledge is comparatively very quick (i.e., FT = 100 s) for the group of coworkers (P-B). Likewise for the individual demonstration to start the process (A-O).

Comparing measurements for the Explicit and Tacit Path archetypes, K-Work performance through the tacit flow is nearly eight times that of its explicit counterpart (20,000 vs. 2550 P), but flow time is more than three times as long (55,200 vs. 16,100 s). The K-Power metric reveals that the Tacit Path completes the knowledge flow at over double the power level (0.38 vs. 0.16 B) of its Explicit counterpart. Thus, the Explicit Path, leveraging technologic implementations for explicit knowledge sharing, accomplishes substantially less knowledge work—at lower energy levels—in the organization, but the corresponding knowledge flows much more quickly. The opposite applies to the Tacit Path, which relies more on interpersonal interaction than technology for knowledge sharing.

III. RESEARCH METHOD

A comparative case study is used to analyze C2 for a maritime focused JTF involving integrated fires and Grey Zone operations across services. The Baseline Case represents a geographically distributed carrier strike group (CSG), surface action group (SAG), Air force (AF) Wing, and Marine Expeditionary Force (MEF) operating jointly, through conventional C2, with full communication capabilities. The Comparison Case depicts this same JTF without satellite communications.

Comparative analysis across these cases exposes many C2 challenges and helps to conceptualize how JADC2 must support both operational and tactical levels of war, along a continuum of communications capabilities. This analysis also provides insight into elements of C2 that extend well beyond technology; particularly the people, processes and organizations comprising the JTF; along with the knowledge, information and data that must flow to interconnect them.

The analysis enables us to apply theory representing the state of the art and to draw from tools and techniques representing the state of the practice in Knowledge Management, Organization and C2 to JTF organizations and operations. This enables us also to induce new knowledge from analysis of JTF operations, which offers potential for translation into enhanced and refined Navy C2 organizations and approaches.

The cross case comparison is conducted in considerable detail, but the summary presented in this technical report remains at a relatively high level with representative platforms, technologies and processes discussed instead of their specific and detailed counterparts. This enables us to characterize how C2 can be approached across such a dramatic mission-environment contrast, without revealing too much information or risking the inclusion of any classified information in this document. The results elucidate a portfolio of techniques for C2, and they highlight important requirements for JADC2.

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IV. RESULTS

In this section we present results of the comparative case study noted above. We begin by summarizing the two scenarios used for comparison. We continue then with analysis of alternate C2 approaches and knowledge flows to support the cross case comparison. Emergent JADC2 requirements are summarized in turn, after which we summarize key findings.

A. SCENARIOS

In this section we summarize the baseline and comparison scenarios.

1. Baseline Scenario

As noted above, the baseline scenario centers on a JTF that has a maritime focus. A major Combatant Commander serves as the Joint Force Commander (JFC). A powerful nation with peer or near peer military capability is operating in international airspace and waters but in an increasingly aggressive manner. In response, the US President directs the JFC to maintain a more consistent and directed presence and show of force in the corresponding area of responsibility (AOR) to deter further aggression and provocation. In response, the JTF begins Operation Poseidon Buckler.

The JFC assumes control of Air Force, Navy and Marine Corps assets, which chop officially. The JFC then designates a numbered fleet commander as the Joint Force Maritime Component Commander (JFMCC). The JFMCC is currently allocated naval assets that include a Carrier Strike Group (CSG) and a Surface Action Group (SAG) that are operating in the general vicinity. The Strike Group is comprised of one aircraft carrier (CVN) with a carrier air wing, one Ticonderoga class guided missile cruiser (CG), two Arleigh Burke class guided missile destroyers (DDGs), one Los Angeles class submarine, and associated support vessels. The surface action group is comprised of one cruiser and two destroyers. The Joint Force converges on the JFC Battle Rhythm.

In addition to the carrier air wing, a US Airforce (USAF) wing joins the operation with a bomber and fighter squadron on land. The USAF Wing Commander has been designated as Joint Force Air Component Commander (JFACC). Marines join the operation also with land assets of a Marine Expeditionary Force (MEF). The MEF

Commander has been designated as Joint Force Land Component Commander (JFLCC). A Regimental Littoral Team (RLT) is detached from the MEF through its Expeditionary Advance Base Operation (EABO) Concept. An operational plan (OPLAN) is developed and shared with all participants via operational order (OPORD). This is considered Phase 0 Gray Zone operations. While the objective is deterrence, and hostile engagement is undesirable, tensions are very high, and the JFC is anticipating the possibility of escalation. A number of corresponding branch plans are developed and shared.

This baseline scenario involves full technology and communication capabilities, with a traditional C2 approach. At 0600 local, the situation changes, as the other military begins an exercise to practice a maritime blockade of an island nation. JFC intelligence assets have been following their aircraft and ship movements. US forces have been operating in the area under clear command intent and rules of engagement (ROE): Command intent centers on being seen and noticed in the area; maintaining open sea lanes and airspace; and monitoring military activities, assets and tactics. The ROE stress the importance of not provoking hostility; maintaining planned maneuvers unless collision becomes apparent; and being prepared for self defense if necessary. US naval assets are in unrestricted emissions condition (EMCON Delta) for now.

One SAG DDG is tracking ships that have broken formation and appear to be readying a blockade. The SAG CG notices numerous new aircraft tracks as well, all of which are distributed via satellite communication (SATCOM). Air Defense Systems Integrator (ADSI) and Joint Range Extension Applications Protocol (JREAP) are involved here. A related but separate set of communications occurs in parallel via intelligence channels with indications and warnings.

Given the emergent nature of these aircraft and ship movements, the CSG Commander uses the Voice Tactical Network (SATCOM) and Chat to communicate with the JFC about this situation change. Such communication includes intent to pursue the most appropriate branch plan. JFC disagrees and issues a fragmentary order (FRAGORD) that alters command intent: JTF assets to maintain a show of force that could be used to defend the island nation. JFC directs all component commanders to do likewise. This communication is via voice call and FRAGORD. ROE remain unchanged.

At 1100, the CSG alters course and increases defensive counter air (DCA) via F/A-18s from the carrier, along with an E-2D to help coordinate battle management for the Navy, in accordance with the FRAGORD. The SAG is much closer to the other military ships. It alters course in accordance with the FRAGORD also and switches to EMCON Charlie: Ships may transmit from mission-essential equipment, but any sensor unique to the vessel must be turned off in order to prevent identification or classification by adversaries.

Following a Joint Targeting Board (JTB) meeting over secure video teleconference (SVTC), USAF personnel invoke a revised air tasking order (ATO) to reflect this FRAGORD. B-52s are launched at first opportunity for their long range anti-ship capabilities, along with a KC135 tanker and an AWACS, the latter of which will coordinate battle management for the Air Force. The various fourth generation (4GL) aircraft enjoy line of sight communication, generally via AWACS and E-2D. JFLCC directs the RLT to prepare.

All of these various forces must deconflict and synchronize their plans and operations. Doing so across services and geographic locations is challenging. SATCOM is essential. In terms of C2 organization and approach, this operation employs traditional military C2 and emphasizes deconfliction. Nonetheless, some aspects of the operation include plans that are shared across the various participants, so one can say that the JTF approaches Coordinated C2 to a limited extent, and certain events such as the JTB involve active collaboration, which approaches Collaborative C2. These aspects are limited, however, and the predominate approach remains Deconflicted C2.

Table 6 summarizes the communication requirements of the JTF. Every intersection marked with “X” denotes a necessary communication pair. Going down the left column, the JFC is required to communicate directly with the JFMCC (“MCC”), JFACC (“ACC”) and JFLCC (“LCC”). These communication requirements are shaded purple to denote their joint nature across services. Continuing, MCC is required to communicate with the other component commanders (i.e., ACC and LCC) in addition to the CSG and SAG. Likewise, ACC is required to communicate with the other component commanders also in addition to USAF wing assets (e.g., F35, B2 and AWACS [“ACS”]).

The same applies to LCC, but to simplify the presentation, we do not show land assets (e.g., MEF and RLT) in this matrix.

Table 6 JTF Communication Requirements

	JFC	MCC	ACC	LCC	CSG	SAG	CVN	CG2	F18	E2	F35	B52	ACS
JFC		X	X	X									
MCC	X		X	X	X	X							
ACC	X	X		X							X	X	X
LCC	X	X	X										
CSG		X				X	X						
SAG		X			X			X					
CVN					X			X	X	X	X		
CG2						X	X			X			
F18							X			X	X	X	
E2							X	X	X		X		X
F35							X		X	X		X	
B52			X						X		X		X
ACS			X							X	X	X	
Key	**Joint**	**Navy**	**AF**										

Moving now into Navy communications, CSG must communicate with MCC, SAG and the carrier (CVN), which hosts the CSG Commander. Likewise, SAG must communicate with MCC, CSG and the SAG cruiser (CG2), which hosts the SAG Commander. In addition to the communication requirements noted above, CVN must communicate with CG2 and aircraft from its wing (e.g., F18, F35, E2). CG2 must communicate reciprocally as well in addition to E2. Communication requirements for the Navy aircraft follow accordingly as noted in the matrix. These Navy communication requirements are shaded darker blue. USAF communications follow accordingly also and are shared lighter blue. This full matrix of requirements can be achieved only with all communication capabilities operational. This applies in particular to SATCOM (esp. for joint communications).

2. Comparison Scenario

As noted above, the comparative case centers on this same JTF in an environment of severely degraded and denied technologies and communications. Specifically, a Day without Space emerges, and the JTF participants are forced into a situation without SATCOM. Assume for this comparison that all ships go to EMCON Charlie.

The JFC, JFMCC, JFACC, JFLCC are dispersed geographically—well beyond line of sight (LOS)—as are the CSG and SAG. Even deconfliction becomes difficult, and synchronization is infeasible. This is exactly the kind of mission-environment that JADC2 is intended to address, but in this scenario assume that JADC2 remains too immature to address all of the JTF C2 issues. Without the ability to orchestrate the JTF centrally (i.e., JFC via component commanders), an alternate approach becomes necessary.

We separate this analysis into two conditions: 1) the JFC, along with all subordinate commanders, anticipates the likelihood of severely degraded and denied technologies and communications, and hence builds such likelihood into command intent, ROE and advance branch planning; and 2) the JFC, along with all subordinate commanders, does not anticipate the likelihood of severely degraded and denied technologies and communications, and hence is reliant upon all communications included in the matrix above.

a. Anticipated Communications Degradation

In this first case, all commanders and combatants are prepared to operate relatively independently and according to their own Battle Rhythms. Command intent is relatively clear, as are ROE, and all assets pursue their assigned missions. Communications are infrequent and short. All assets follow the manner in which submarines communicate infrequently. (To avoid classified discussion, we omit details here.) Because of the clear command intent, ROE and advance branch planning, all component and tactical commanders understand what needs to be accomplished and how to adjust to changing and unexpected conditions. JTF efficacy is clearly degraded due to its C2 challenges, and joint operations become much more difficult to plan and effect, but the joint force is able to fight relatively well overall.

b. Unanticipated Communications Degradation

In this second case, all commanders and combatants remain reliant upon the JFC and component commanders for direction, and they try to remain synchronized with the JFC Battle Rhythm. Although command intent is relatively clear, as are ROE, and all assets pursue their assigned missions, the component and tactical commanders lack clear understanding of what needs to be accomplished and how to adjust to changing and unexpected conditions. JTF efficacy is greatly degraded due to its C2 challenges, and joint operations become much more difficult to plan and effect. Individual assets are able to fight relatively well overall, but the joint force struggles with efficacy.

B. C2 AND KNOWLEDGE ANALYSIS

In this section we include C2 and knowledge analysis of the scenarios outlined above. Following the preceding format, we begin with the baseline scenario and then address its comparison counterpart. C2 analysis centers on the C2 Approach Space, whereas knowledge analysis focuses on the manners in which knowledge flows between commanders and units. For the most part, this analysis remains at the operational level. A subsequent study can delve into the myriad details associated with the tactical level.

1. Baseline Scenario

As noted above, and as depicted again in Figure 16 for reference, the baseline scenario represents a traditional military Deconfliction C2 organization and approach.

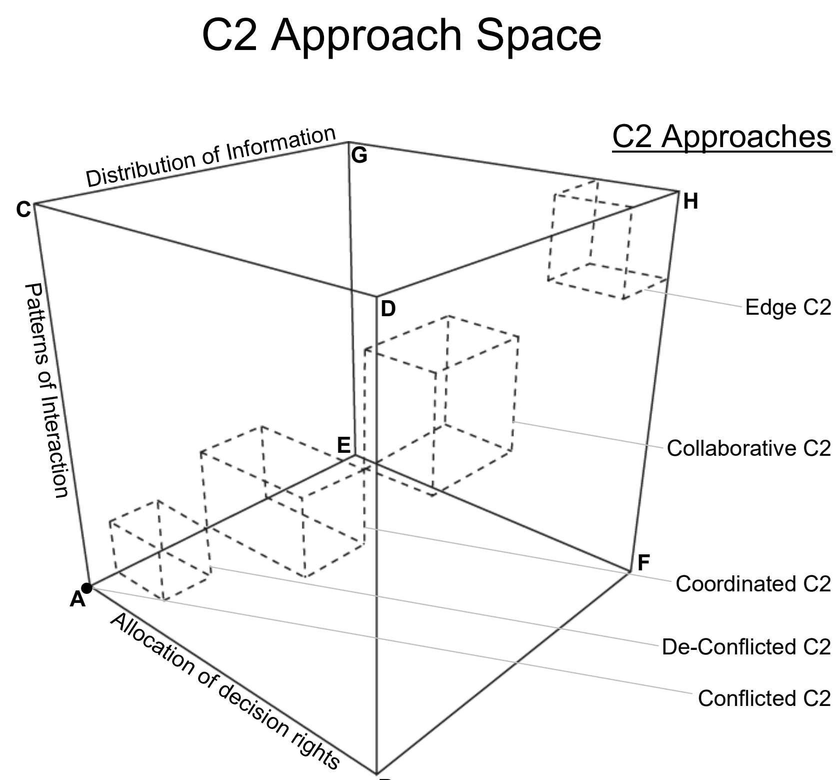

Figure 16 Baseline C2 Organization and Approach

More specifically, major JTF decision rights are retained very centrally with the JFC and component commanders. Although the Navy in particular practices command by negation, the tightly coupled JTF Battle Rhythm enforces frequent communication and centralized decision making. Further, assets associated with the various services and units interact principally through pooled and sequential interdependence, interoperating in the same airspace only infrequently and for limited periods of time. This approach is notably efficient and minimizes coordination costs, but it limits the extent of joint interaction. Also, information is distributed only to the extent necessary for component and tactical commanders to accomplish their missions. As above, this approach is notably efficient and minimizes coordination costs, but it limits the extent of joint information sharing. Deconflicted C2 organization and approach is highly appropriate for missions and environments that are stable and predictable, particularly where communications are unimpeded.

Indeed, as summarized in Table 7, the full matrix of communication capabilities is available, and the JFC—through component and tactical commanders—is able to direct the JTF with C2 that is more than adequate for the endeavor. Further, the Navy and USAF are able to share their plans (e.g., via the ATO), which suggests that joint air operations rise to reflect Coordinated C2; and some joint planning is accomplished through the JTB, which suggests that some operations rise to reflect Collaborative C2. Both of these C2 transitions are conventional in nature. The first reflects a transition from Deconflicted to Coordinated (i.e., II → III), whereas the second reflects an additional transition from Coordinated to Collaborative (i.e., II → III → IV). This C2 organization and approach are highly dependent upon unimpeded communication.

The Battle Rhythm is set regularly on a 24 hour cycle. This cycle can be adjusted to accommodate myriad different mission-environment conditions, but we assume 24 hours for the analysis here. The constituent activities can be adjusted also, but here we focus on the maritime organizations and assume that the CSG and SAG commanders are briefed at 0800. USAF and Marine counterparts may conduct briefings at the same time. Component commanders could participate in these morning briefings, or they could participate in the 0900 JTF briefing. It is possible also that component commanders could have separate briefings in between the others, or the CSG commander could also serve as JFMCC. In any case, the JFC briefing occurs at 0900 in this depiction.

Table 7 JTF Baseline Scenario Communication Capabilities

	JFC	MCC	ACC	LCC	CSG	SAG	CVN	CG2	F18	E2	F35	B52	ACS
JFC		X	X	X									
MCC	X		X	X	X	X							
ACC	X	X		X								X	X
LCC	X	X	X										
CSG		X				X	X						
SAG		X			X			X					
CVN					X			X	X	X	X		
CG2						X	X			X			
F18							X			X	X	X	
E2							X	X	X		X		X
F35							X		X	X		X	
B52			X						X		X		X
ACS			X							X		X	
Key	**Joint**	**Navy**	**AF**										

With a 24 hour cycle, the JFC and commanders at all levels have ample opportunity to adjust command intent, ROE and orders as necessary to anticipate, accommodate and react to changes in the mission environment. As such, the associated documents do not necessarily require extensive shelf life: if something is unclear or becomes inapplicable, it can be addressed through briefings in the next Battle Rhythm cycle, and revised intent, ROE and orders can be issued subsequently. Metaphorically, JTF subordinate commanders at all levels are kept on a relatively short leash, and the JFC enjoys great ability to monitor and fine tune the operation through (at least) daily interaction. Additionally, with full communication capability, the JFC—and commanders at all levels—enjoys also great ability to communicate with subordinates throughout the day.

Knowledge, information, data and signals (KIDS) flow incessantly throughout the JTF. As noted above, signal flows occur in the physical world, whereas data, information and knowledge flow in the socio-cognitive domain. It is the people—through the communication tools used—that translate signals into data, information and knowledge. This knowledge analysis begins with the JFC, who brings immense experiential knowledge to the organization as a very high ranking officer. Such knowledge accumulates generally over many decades through education, training, mentorship and experience, with experience representing the major contributor.

In terms of knowledge flow, the JFC needs for all JTF participants to understand what needs to be accomplished; how, when, where and with whom to accomplish it well; and how to keep him or her informed of both progress and difficulties. This is the essence of C2, and such knowledge flows primarily through five means: 1) command intent, 2) rules of engagement, 3) orders, 4) meetings, and 5) conversations. Notice that the first three means involve generally written documents, which represent explicit knowledge and information, and which flows principally unidirectionally (esp. top-down); whereas the latter two involve interpersonal interaction, which involves more tacit knowledge and information exchange, and which flows bidirectionally (e.g., bottom-up and top-down). The frequency of knowledge and information flows is driven largely by the Battle Rhythm.

The first three means require the JFC—via staff—to expend time and energy articulating C2 knowledge in terms that subordinates can understand and translate into desired action. Hence subordinates—throughout all services, organizations and units—must be able to understand JFC desires, conditions and orders, and they must be able to effect them via both coordinated and independent action until the next Battle Rhythm cycle is complete. (Clearly not all of these change with each Battle Rhythm cycle, but each cycle provides regular opportunities for knowledge and information exchange.)

These explicit knowledge flows are delineated via Figure 17, and such flows are comprised of three vectors. The flows begin with the JFC formulating knowledge regarding desires, conditions and strategies, which will become command intent, ROE and orders, respectively. This is represented by Point A in the figure. Notice that Point A is located near the origin: tacit knowledge, associated with one person (i.e., JFC), that is being created. The first vector (A-M) represents the JFC articulating such tacit knowledge into explicit form. This vector is relatively thick, indicating that tacit articulation can take some time to accomplish; and it reflects a dotted pattern, indicating that the energy level is attenuated, which is unavoidable when tacit knowledge is converted into explicit form.

The second vector (M-N) represents the JFC sharing such explicit knowledge with the JTF participants via the kinds of communication modes and media discussed above. This vector is relatively thin, indicating that such sharing can be accomplished very quickly when full communications are available; and it reflects a dotted pattern, continuing the attenuated energy level from the first vector.

The third vector (N-B) represents JTF participants receiving, reading, learning and effecting action based on the explicit knowledge. This vector is relatively thin also, reflecting the speed at which written documents can be read and absorbed. Such vector is thicker than its sharing counterpart, however, revealing that developing an understanding of what actions are necessary requires some time to accomplish. This third vector retains the dotted pattern corresponding to attenuated energy.

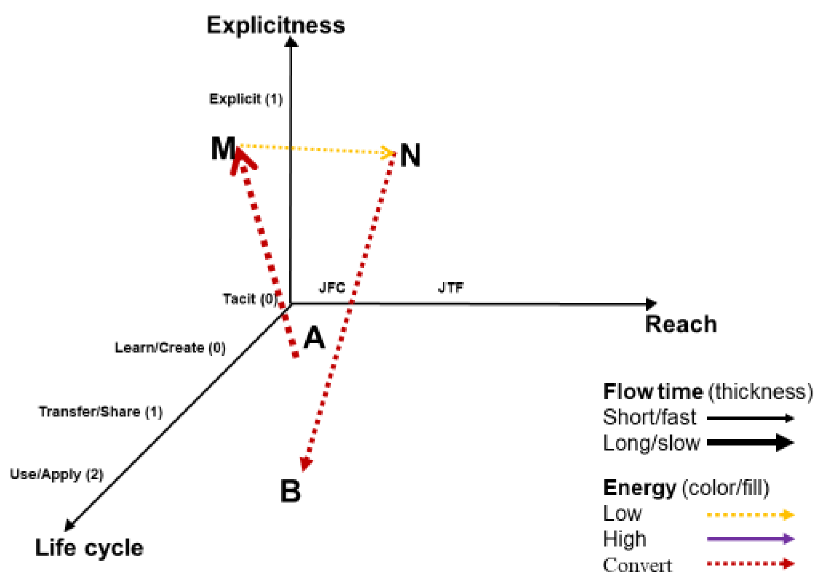

Figure 17 JFC Knowledge Flows – Explicit

To avoid cluttering this figure, we show the entire JTF as a single Point B, understanding that it is comprised of myriad participants that are distributed geographically, organizationally and hierarchically. Indeed, given the fractal nature of organization and leadership, explicit knowledge flows can be represented via similar figures for every echelon. Figure 18 depicts the corresponding explicit knowledge flow between JFMCC at Point A and maritime participants (e.g., CSG and SAG) at Point B, with comparable vectors (i.e., A-M, M-N, N-B) delineating the flow. A similar figure would depict the flow in turn from the CSG to its constituent ships, from the SAG to its constituent ships, from each ship CO to his or her constituent Department Heads, from the JFACC to its constituent squadrons, and so forth. It should be unnecessary to include them all here in this report.

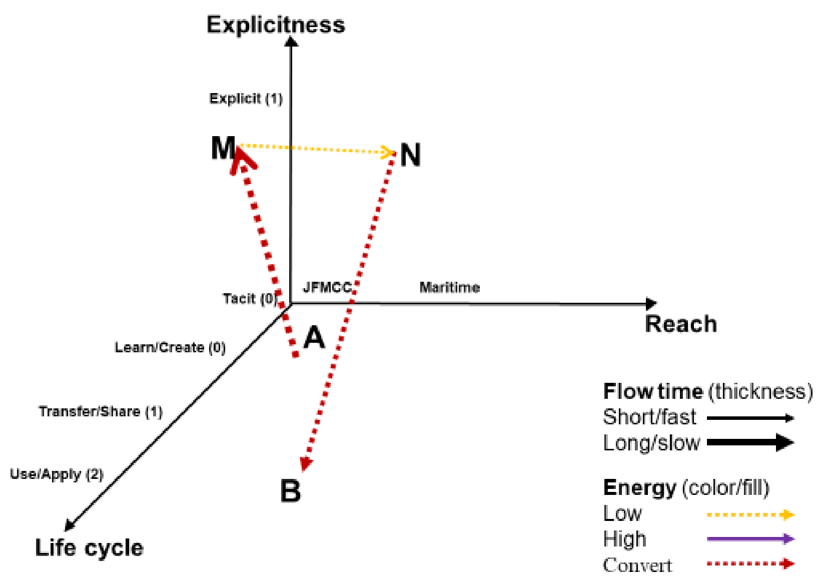

Figure 18 JFMCC Knowledge Flows – Explicit

One additional explicit flow is important to address: the Joint sharing of plans between Navy and USAF. As noted above, we can consider the manner in which the Navy and USAF share plans to reflect some aspects of Coordinated C2. Here the Navy and Air Force develop their individual air plans independently (e.g., USAF ATO) but then share them for coordination. Figure 19 depicts the explicit knowledge sharing through air plans and is similar in many respects to the explicit knowledge sharing depicted above.

In this figure, we show the Navy developing its air plan at Point A. This involves communication and planning within the CSG. This reflects tacit knowledge exchange and application, which we do not detail separately in the figure. When an acceptable plan emerges, it is formalized through articulation into explicit knowledge at Point M, which is share in turn with the Carrier Air Wing and the Air Force at Point N. The various commanders and squadrons then read, understand and effect the plans at Point B. A nearly identical figure would depict the Air Force undertaking its individual tacit air planning process, articulating it into explicit form, and sharing it with its commanders and squadrons as well as with its Navy counterparts. We do not show this latter figure due to high similarity with the figure below. Notice in either case that knowledge flows from one service to another so that both Navy and Air Force understand one another's air plans.

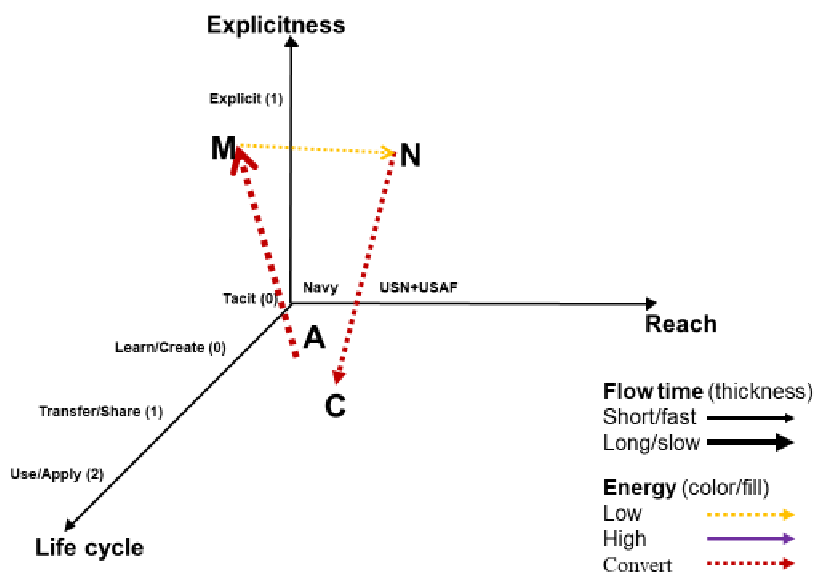

Figure 19 USN & USAF Knowledge Flows – Explicit

The tacit knowledge flows are delineated via Figure 20, and such flows are comprised of three vectors, which begin and end at the same Points A and B: A) The flows begin with the JFC formulating knowledge regarding desires, conditions and strategies. B) JTF participants effecting action based on the tacit knowledge. Notice the qualitatively different patterns corresponding to these tacit knowledge flows.

Beginning with the JFC, in addition to formulating knowledge regarding desires, conditions and strategies at Point A, this vector delineates a recurring pattern of action and learning (e.g., learning via experience or OJT), cycling repeatedly between learning and doing (i.e., knowledge creation and application). This pattern continues throughout the JTF operation, and the JFC knowledge level continues to increase through each iteration. To avoid cluttering the figure, we do not show the *level* of JFC knowledge: only the cyclic flow is depicted. (In an alternate representation, we could delineate how knowledge increases through the doing-learning iterations, but this is unnecessary here.) This vector is represented with a relatively thick line to depict the slow nature of experiential learning, but such solid purple line reflects high energy knowledge flow corresponding with comparatively high performance levels.

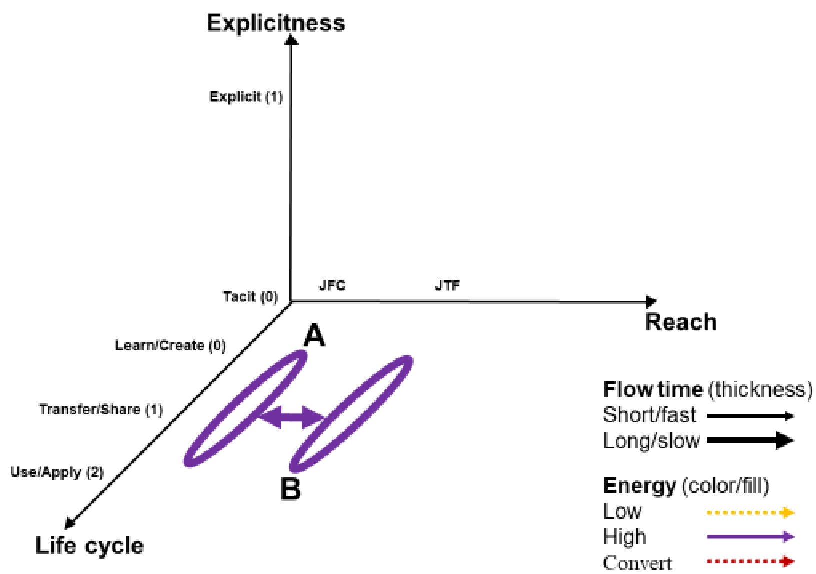

Figure 20 JFC Knowledge Flows – Tacit

Continuing with the JTF, in addition to the participants effecting action based on the tacit knowledge at Point B, this vector delineates a similar recurring pattern of action and learning (e.g., learning via experience or OJT), cycling repeatedly between learning and doing (i.e., knowledge creation and application). This pattern continues throughout the JTF operation also, and the JTF knowledge level continues to increase through each iteration. As above, this vector is represented with a relatively thick line also to depict the slow nature of experiential learning, and such solid purple line reflects high energy knowledge flow corresponding with comparatively high performance levels too.

The third vector connects these two recurring patterns. This vector represents the meetings and conversations between the JFC and JTF participants (esp. component commanders). It is delineated with a two headed arrow to indicate that knowledge and information flow bidirectionally: the JFC learns from JTF participants, but especially vice versa. It is drawn as a thick, solid purple vector in correspondence with the rich, tacit nature of such meetings and conversations and to acknowledge that knowledge continues to flow bidirectionally through this link throughout the JTF operation. Combining these three vectors, knowledge flows from Point A to B as with the explicit flows delineated and discussed above, but it flows from Point B to A also, and both the JFC and JTF participants benefit from steadily increasing knowledge through experience.

As above, to avoid cluttering this figure, we show the entire JTF as a single experiential doing-learning cycle, understanding that it is comprised of myriad participants that are distributed geographically, organizationally and hierarchically. Indeed, given the fractal nature of organization and leadership, tacit knowledge flows can be represented via similar figures for every echelon.

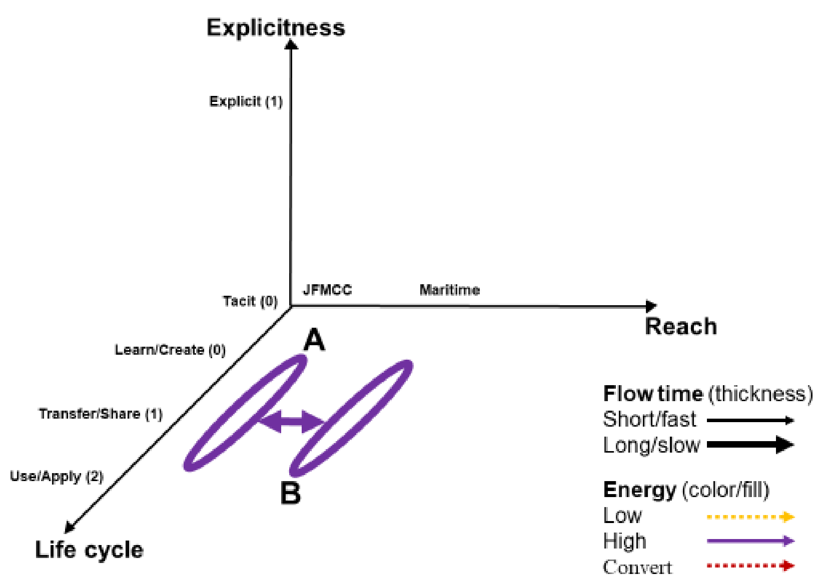

Figure 21 JFMCC Knowledge Flows – Tacit

Figure 21 depicts the corresponding tacit knowledge flows between the JFMCC and maritime participants (e.g., CSG and SAG), with comparable cyclic vectors delineating the flow. A similar figure would depict the flow in turn from the CSG to its constituent ships, from the SAG to its constituent ships, from each ship CO to his or her constituent Department Heads, from the JFACC to its constituent squadrons, and so forth. It should be unnecessary to include them all here in this report.

As noted above regarding the daily Battle Rhythm, the JFC enjoys great ability to monitor and fine tune the operation through (at least) daily interaction, and with full communication capability, the JFC—and commanders at all levels—enjoys also great ability to communicate with subordinates throughout the day.

One additional tacit flow is important to address: the Joint Targeting Board, through which the Navy and USAF work together. As noted above, we can consider the manner in which the Navy and USAF work together to reflect some aspects of Collaborative C2. Here the Navy and Air Force identify and prioritize targets jointly. In this figure, we show a single learning-doing cycle for the Navy and Air Force working together. This involves communication and planning between the CSG and USAF Wings, and it reflects tacit knowledge exchange and application, which continues throughout the operation and leads to monotonically increasing knowledge.

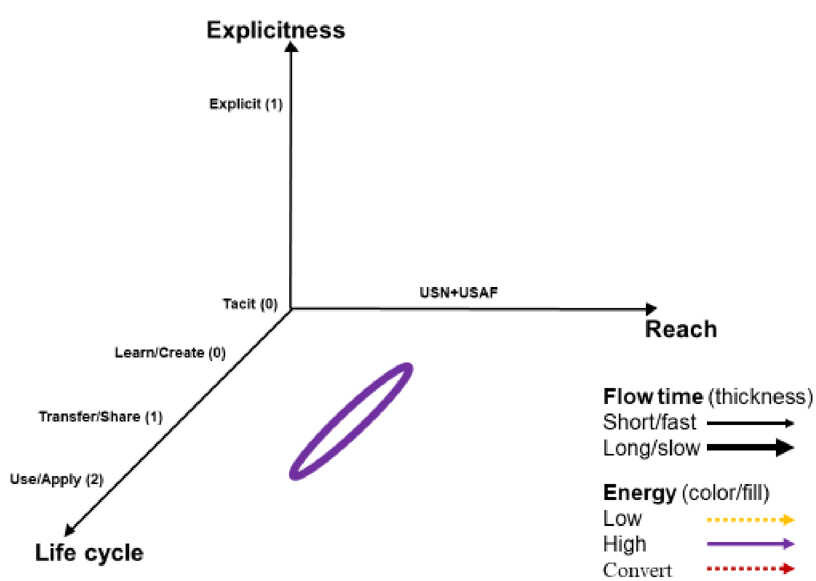

Figure 22 USN & USAF Knowledge Flows – Tacit

As explained in the background section above, each of these knowledge flow patterns can be measured. We omit such measurements for classification purposes.

2. Comparison Scenario

As noted above, the comparative case centers on this same JTF in an environment of severely degraded and denied technologies and communications. Specifically, a Day without Space emerges, and the JTF participants are forced into a situation without SATCOM. Further from above, we separate this analysis into two conditions: 1) the JFC, along with all subordinate commanders, anticipates the likelihood of severely degraded and denied technologies and communications, and hence builds such likelihood into command intent, ROE and advance branch planning; and 2) the JFC, along with all subordinate commanders, does not anticipate the likelihood of severely degraded and denied technologies and communications, and hence is reliant upon all communications included in the matrix above.

a. Anticipated Communications Degradation

In this first case, all commanders and combatants are prepared to operate relatively independently and according to their own Battle Rhythms. Command intent is relatively clear, as are ROE, and all assets pursue their assigned missions. Communications are infrequent and short. All assets follow the manner in which submarines communicate infrequently. (To avoid classified discussion, we omit details here.) Because of the clear command intent, ROE and advance branch planning, all component and tactical commanders understand what needs to be accomplished and how to adjust to changing and unexpected conditions. JTF efficacy is clearly degraded due to its C2 challenges, and joint operations become much more difficult to plan and effect, but the joint force is able to fight relatively well overall.

The JTF communication capabilities without SATCOM are summarized in Table 8. Notice that the JFC is unable to communicate with component commanders, and the JFMCC is unable to communicate with the CSG or SAG. Alternatively, due to their collocation on land, the JFACC is able to communicate with the USAF Wing. Moreover, the CSG is unable to communicate with the SAG. Nonetheless, the CSG retains communications with its ships and aircraft, as does the SAG, and aircraft are able to communicate with one another when within LOS, even across services.

Table 8 JTF Communication Capabilities – No SATCOM

	JFC	MCC	ACC	LCC	CSG	SAG	CVN	CG2	F18	E2	F35	B52	ACS
JFC													
MCC													
ACC												X	X
LCC													
CSG							X						
SAG								X					
CVN					X				X	X	X		
CG2										X			
F18							X			X	X	X	
E2							X	X	X		X		X
F35							X		X	X		X	
B52			X						X		X		X
ACS			X							X	X	X	
Key	Joint	Navy	AF										

The Navy in particular is accustomed to decision making and operating via command by negation. Even with infrequent and short communications, the CSG and SAG continue their missions without input from the JFC or JFMCC. The CSG and SAG commanders presume that their intentions would not be negated (i.e., approved) were full communications restored, and they are able to operate effectively through direct communications between their ships and aircraft, albeit with EMCON Charlie restrictions.

The Air Force is similarly able to operate effectively, particularly because the Wing is based on land and collocated with the JFACC. It continues to produce and follow its ATOs without interruption, and like the Navy, without JFC input, the JFACC adheres to the command intent, ROE and orders that were in place prior to losing SATCOM.

The JTF as a whole has fallen from Deconflicted C2 to Conflicted, because the Battle Rhythm cannot function without full communications. However, the CSG, SAG and USAF Wing have their own Battle Rhythms and continue to operate through Deconflicted C2. The major problem centers on joint operations: the ships at sea are unable to communicate with the Wing on land. This means that air plans cannot be shared, nor can joint targeting be accomplished between services. Hence these respective aspects of Coordinated and Collaborative C2 degrade to Conflicted.

Nonetheless, the Navy and Air Force continue their missions, some of which involve operating in common airspace-time. With E2s and AWACS aloft, the services are able to communicate via LOS; the E2s are able to communicate with Navy aircraft; and the AWACS is able to communicate with USAF planes. Once the airspace is occupied by aircraft from both services, they are able to share their plans and interoperate via mutual adjustment. This enables them to deconflict their operations and even collaborate to identify and prosecute targets—again, while they are within LOS and in common airspace. Even beyond Coordinated and Collaborative C2, the aircraft are operating via Edge C2: they are pursuing their respective missions, coordinating via mutual adjustment, and operating independently of the JFC and component commanders. Indeed, pilots are communicating directly with pilots and executing missions based upon their best understanding of command intent, ROE and most recent orders.

When joint operations cease, and the USAF aircraft return to their land base, the airspace is occupied by Navy aircraft only, and the CSG maintains its routine C2. Likewise with the Air Force back on base, its routine C2 continues. When intermittent communication with the JFC can reengage, an abbreviated Battle Rhythm can be reestablished, with any updates communicated both upward (e.g., status) and downward (e.g., FRAGORDs).

While communications are interrupted, the JTF knowledge and information flows degrade. Figure 23 reflects this situation. This figure is identical to its counterpart delineated via Figure 17 above, except that the JFC is unable to share explicit knowledge with component commanders as before. The JFC and staff continue to articulate command intent, ROE, orders and like knowledge and information so that they will be ready and available if or when communications are restored.

Likewise with the component commanders. Their knowledge flows look identical to those of the JFC during interrupted communications. To preserve space, we do not show the JFMCC explicit knowledge flows without SATCOM.

Alternatively, as noted above, the combatants (esp. CSG, SAG, USAF Wing) continue their normal operations in the absence of ongoing guidance from above and without the benefit of the JTF Battle Rhythm. Hence their explicit knowledge flows continue to look just as they did in Figure 19 above.

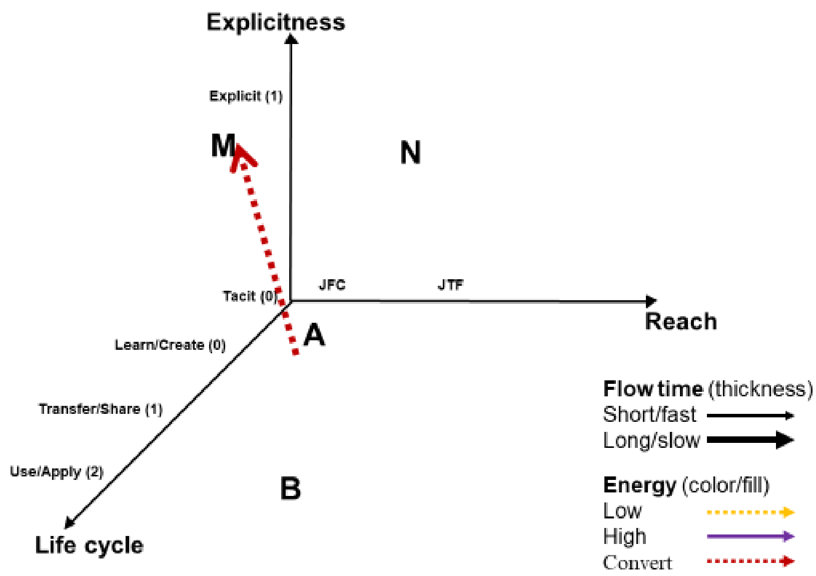

Figure 23 JFC Knowledge Flows – No SATCOM

The knowledge and information flows at the JTF level return to their previous patterns as delineated above, at least until communications are interrupted again. Although the combatants operated effectively without guidance from above, the JTF as a whole suffered from degraded capability. Such degradation was limited, however, by the clear command intent, ROE and orders provided in advance of the communication issue, as the JFC anticipated the issue.

As above, each of these knowledge flow patterns can be measured. We omit such measurements for classification purposes.

b. Unanticipated Communications Degradation

In this second case, all commanders and combatants remain reliant upon the JFC and component commanders for direction, and they try to remain synchronized with the JFC Battle Rhythm. Although command intent is relatively clear, as are ROE, and all assets pursue their assigned missions, the component and tactical commanders lack clear understanding of what needs to be accomplished and how to adjust to changing and unexpected conditions. JTF efficacy is greatly degraded due to its C2 challenges, and joint operations become much more difficult to plan and effect. Individual assets are able to fight relatively well overall, but the joint force struggles with efficacy.

As above, the JTF degrades to Conflicted C2, but as above also, the CSG, SAG and USAF Wing have their own Battle Rhythms and continue to operate through Deconflicted C2. The major problem centers on joint operations: the ships at sea are unable to communicate with the Wing on land. This means that air plans cannot be shared, nor can joint targeting be accomplished between services. Hence these respective aspects of Coordinated and Collaborative C2 degrade to Conflicted.

Without clear guidance, the Air Force is unable to coordinate effectively with Navy units, and vice versa. The USAF continues its separate missions, but it is unable to work through joint operations. Unlike the Navy and Air Force planes advancing to Edge C2 as in the scenario above, the services remain in Conflicted C2 and unable to interoperate jointly. Although the communication capabilities remain as summarized via Table 8 above—meaning that Navy and Air Force aircraft are *capable* of communicating with one another—their inability to interoperate because of Conflicted C2 makes it too risky for them to try once within common airspace. Until communications are restored, the JTF operates more simply and ineffectively as a force that cannot fight jointly.

Notice how much the efficacy depends upon how command intent, ROE and orders have been articulated, in addition to how interdependent the various JTF assets are and how synchronized the various Battle Rhythms become. Where command intent, ROE and orders are highly specific and short term in nature, for instance, units require detailed and frequent guidance and updates. This is even more the case where assets interoperate with high degrees of interdependence, and where Battle Rhythms become highly synchronized and rapid. This represents an efficient and effective C2 approach, one with high decision speed and the ability to cycle through decision loops (i.e., sense, make sense, act) more quickly than adversaries. This approach depends inextricably upon reliable, high-bandwidth, global communication, however.

Fortunately in the first scenario, the JFC—along with component commanders—communicates command intent, ROE and orders in two interrelated parts: 1) assuming that full communication capabilities remain operational, and 2) falling back in case of failed, denied or infeasible communication capabilities. The Navy in particular trains for the latter part, through both command by negation and Mission Command, so component commanders in general and combatants in particular are able to continue their missions, even at more restrictive EMCONs. Surface ships also learn from their submarine counterparts about infrequent, low probability of intercept or detection (LPID) communication and operation.

This works well for the CSG and SAG, which can continue their maritime missions based upon command intent, ROE and orders. The ships comprising the CSG can continue operating together as they have trained and practiced, as can those comprising the SAG. Assuming that the CSG and SAG are operating beyond LOS, however, their ability to interoperate becomes limited to a small number of comparatively low bandwidth technologies. (We avoid detailing their specifics in this report.)

This issue is exacerbated regarding USAF and USMC, both of which must also continue their respective air and ground missions based upon command intent, ROE and orders. As with ships comprising the CSG and SAG, USAF aircraft from the wing can continue operating together as they have trained and practiced, as can USMC units with their land missions.

To the extent that the missions and battlespace have been deconflicted sufficiently, each Service can continue what it was doing based upon its best interpretation of command intent, ROE and orders. However, to the extent that they must interoperate (e.g., USAF and CSG aircraft sorties in common airspace), communication and coordination become much more difficult, and the JTF is unable to fight jointly.

C. EMERGENT JADC2 REQUIREMENTS

The C2 and knowledge analyses above highlight a number of issues stemming from the lost of full communications capability, with the loss of SATCOM particularly challenging for a JTF distributed geographically, organizationally and hierarchically. Changes in the communication capabilities summarize the situation and elucidate emergent JADC2 requirements: in addition to supporting full communications capability across all services and warfighting domains, JADC2 must enable the joint force to interoperate at the level of Deconflicted C2 without SATCOM. This is summarized by the inverted matrix of communications capabilities shown in Table 9.

Table 9 JTF Emergent JADC2 Requirements

	JFC	MCC	ACC	LCC	CSG	SAG	CVN	CG2	F18	E2	F35	B52	ACS
JFC													
MCC													
ACC													
LCC													
CSG													
SAG													
CVN													
CG2													
F18													
E2													
F35													
B52													
ACS													

The orange shading illuminates all of the communication capabilities lost without SATCOM. Clearly most of these pertain to the highest levels of the JTF, at which C2 is conducted at the operational level. Moreover, communications between the highlighted organizations support the kinds of Coordinated and Collaborative C2 associated with shared air plans and joint targeting, respectively. Further, notice the requirement for the E2-AWACS communications: whether full communications capabilities are available or not, this link is essential for joint air operations. A number of technologies both exist today and are under development to address these emergent requirements. It is beyond the classification level of this document to discuss them, however. Nonetheless, this matrix elucidates the most critical communications capabilities for JADC2 to address first.

D. SUMMARY OF KEY FINDINGS

Here we summarize key findings of the study. Key findings highlight the importance of satellite communications to enable JTF integration. This applies in particular to geographically dispersed services seeking to interoperate in an integrated manner. Further, a matrix of critical communication links emerges through analysis of DDIL environments. This DDIL communication matrix serves as a prioritized JADC2 requirements set.

Interestingly, respective Navy, Air Force and Marine tactical operations within the CSG and SAG, AF Wing, and MEF do not suffer as greatly in DDIL environments as their joint and operational counterparts seeking integrated fires and operations across services. Details remain beyond the classification level of this document.

Additionally, the prioritized JADC2 requirements set involves much more than technology. Indeed, commanders at all organization levels need to articulate and disseminate clear command intent that can be understood and implemented in DDIL environments, and subordinates at all levels must be able to understand and translate such intent into desired actions. This requires practice: Commanders at all organization levels and units at all levels need to practice operating under Mission Command and Battle Rhythm Dilation, for extended periods of time, much as the way that submarines do. Moreover, these commanders and units need to practice integrated operations through very low bandwidth DDIL communication modes, which elucidates a compelling case for Edge C2.

Finally, people remain the most important element in JADC2. Geographically dispersed joint operations in DDIL environments can depart substantially from the kinds of education, training and experience that most military personnel encounter. This provides a use case for additional education, training and experience to develop and refine the necessary skills and competencies required to fight effectively.

Moreover, such operations can prompt the rethinking of standard operating procedures (SOPs); techniques, tactics and procedures (TTPs); operational orders (OPORDs); and like explicit knowledge. The key is to anticipate, develop and refine the kind of rich, experience based tacit knowledge that needs to permeate all organization levels from deckplate to JTF command. Such tacit knowledge—once acquired and refined—can guide effective rethinking of SOPs, TTPs, OPORDs and like documents.

Navy educational institutions like the Naval Postgraduate School (NPS) represent one important locus for rethinking along these lines, as do tactical training groups: NPS can develop and teach the appropriate knowledge, which tactical training groups can translate into effective procedure and practice. **This may represent the most important finding for our study sponsor: new knowledge, education, training and practice are necessary for JADC2 success**.

Five recommendations follow accordingly: 1) Use the Communication Matrix to prioritize JADC2 requirements that emerge from this study. 2) Teach and coach organization leaders to articulate and disseminate clear command intent that can be understood and implemented in DDIL environments over extended periods. 3) Learn and practice both Navy and joint operations through Mission Command, Battle Rhythm Dilation, and Edge C2. 4) Remember that people remain the most important element in JADC2. 5) Develop the new knowledge, education, training and practice necessary for JADC2 success, both through continued study along these lines and through new education and training course development.

V. CONCLUSION

Joint All Domain Command & Control (JADC2) is the art and science to rapidly translate knowledge and information into decisions and actions. JADC2 seeks to enable all services to interoperate jointly across all domains and in situations ranging from full communications capabilities to those in which they are denied, degraded, intermittent or limited (DDIL). JADC2 is not a program per se, but rather a collection of integrated organizations, processes and technologies to interconnect forces.

In addition to technical challenges, integral to JADC2 development is good understanding of how command and control (C2) can and should be conducted and how knowledge and information can and should flow. The research described in this technical report leverages prior research addressing agile C2 and rapid organization reconfiguration, along with experience with mission orders, distributed maritime operations and C2 knowledge flow integration to address these needs.

After summarizing key background information and outlining the research method, we present key findings and results. Such findings begin with two realistic yet fictitious scenarios: 1) a baseline JTF with a maritime focus and full communications, and 2) a comparison JTF without SATCOM. The baseline reveals how joint operations across domains can proceed smoothly through Deconflicted C2 and how both explicit and tacit knowledge flows rapidly, steadily and reliably across geographic, organization and hierarchic boundaries.

The comparison is separated into two parts: 1) where communications degradation is anticipated, and 2) where it is not. In the first case, the JFC loses control of the joint force, but the Navy and Air Force are able to continue joint operations through command by negation, mission orders and Edge C2. In the second case, the Navy and Air Force fall into Conflicted C2: each Service is able to continue its independent operations, but the joint fight becomes infeasible until communications are restored.

Clearly the efficacy depends upon how command intent, ROE and orders have been articulated, in addition to how interdependent the various JTF assets are and how synchronized the various Battle Rhythms become. Where command intent, ROE and orders are highly specific and short term in nature, for instance, units require detailed and frequent guidance and updates. This is even more the case where assets interoperate with high degrees of interdependence, and where Battle Rhythms become highly synchronized and rapid. This represents an efficient and effective C2 approach, one with high decision speed and the ability to cycle through decision loops (i.e., sense, make sense, act) more quickly than adversaries. This approach depends inextricably upon reliable, high-bandwidth, global communication, however.

Fortunately in the first scenario, the JFC—along with component commanders—communicates command intent, ROE and orders in two interrelated parts: 1) assuming that full communication capabilities remain operational, and 2) falling back in case of failed, denied or infeasible communication capabilities. The Navy in particular trains for the latter part, through both command by negation and Mission Command, so component commanders in general and combatants in particular are able to continue their missions, even at more restrictive EMCONs. Surface ships also learn from their submarine counterparts about infrequent, low probability of intercept or detection (LPID) communication and operation.

This works well for the CSG and SAG, which can continue their maritime missions based upon command intent, ROE and orders. The ships comprising the CSG can continue operating together as they have trained and practiced, as can those comprising the SAG. Assuming that the CSG and SAG are operating beyond LOS, however, their ability to interoperate becomes limited to a small number of comparatively low bandwidth technologies. (We avoid detailing their specifics in this report.)

This issue is exacerbated regarding USAF and USMC, both of which must also continue their respective air and ground missions based upon command intent, ROE and orders. As with ships comprising the CSG and SAG, USAF aircraft from the wing can continue operating together as they have trained and practiced, as can USMC units with their land missions.

To the extent that the missions and battlespace have been deconflicted sufficiently, each Service can continue what it was doing based upon its best interpretation of command intent, ROE and orders. However, to the extent that they must interoperate (e.g., USAF and CSG aircraft sorties in common airspace), communication and coordination become much more difficult, and the JTF is unable to fight jointly.

A summary of key findings leads to five recommendations: 1) Use the Communication Matrix to prioritize JADC2 requirements that emerge from this study. 2) Teach and coach organization leaders to articulate and disseminate clear command intent that can be understood and implemented in DDIL environments over extended periods. 3) Learn and practice both Navy and joint operations through Mission Command, Battle Rhythm Dilation and Edge C2. 4) Remember that people remain the most important element in JADC2. 5) Develop the new knowledge, education, training and practice necessary for JADC2 success, both through continued study along these lines and through new education and training course development.

These key findings lead also to five recommendations for further research to flesh out details and plan for implementation:

1) The Communication Matrix indicates the key communication links required for effective JTF knowledge and information flows across Service, unit, platform and geographic boundaries; and it shows which are affected most severely by DDIL conditions. This provides an opportunity for each link to be studied more deeply—in terms of associated people, processes, organizations and technologies.

2) Teaching and coaching organization leaders to articulate and disseminate clear command intent that can be understood and implemented in DDIL environments over extended periods may have to begin with dilation of the JTF Battle Rhythm. DDIL may require JTF commanders to receive knowledge and information inputs less frequently, with proportionately longer periods between opportunities to direct and guide subordinate commanders and units. Training and practice will likely be essential. This provides an opportunity for the corresponding courses and exercises to be developed.

3) Mission Command is likely to be understood relatively well, but it remains unclear how frequently and persistently it is practiced in the Fleet and across services. With less frequent knowledge and information exchanges, the JTF—and most subordinate commands—will encounter Battle Rhythm Dilation, and commands at different hierarchic levels will likely follow different rhythms. For commands and forces accustomed only to a 24 hour rhythm, this may require considerable adjustment and

practice. This provides an opportunity for the corresponding courses and exercises to be developed.

Additionally, Edge C2 is less likely to be understood relatively well, yet it is crucial for commanders and units to integrate operations through very low bandwidth DDIL communication modes. The C2 Field has accumulated over two decades of research regarding Edge C2, but surprisingly little of the corresponding knowledge has found its way into Navy doctrine and training. This provides an opportunity for the corresponding courses to be developed.

4) It is both easy and routine for a project like JADC2 to degrade into a portfolio of technology efforts. However, JADC2 has a very long way to go before the Sense-Make Sense-Act cycle can be automated (if ever). This applies in particular to the latter two steps: ultimately decision makers and other people have to make sense of situations, while warriors and other people initiate and execute the associated actions. The faster that cycles become—speedy cycles represent an express JADC2 expectation—and the worse that DDIL restrictions become—severe environments represent an express JADC2 expectation—the more challenging each step of the cycle becomes. This provides an opportunity for further study.

5) Each of the recommendations for further study from above points to knowledge gaps. Some gaps (e.g., 2 and 3) are relatively clear and can be filled through development of additional education and training courses, along with corresponding exercises and practice, whereas others (esp. 1 and 4) are less clear and require further study. Moreover, this executive summary is presented very deliberately at the unclassified level. A great many JADC2 details remain classified, and further research as suggested above will likely have to follow suit.

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