



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SURFACE WARFARE PROFICIENCY KNOWLEDGE

MANAGEMENT ARCHITECTURE

by

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ABSTRACT

As a key tenet of readiness, it is important to know—tracking at the present time and forecasting through various future timeframes—measure, and understand unit level proficiency and individual career proficiency. As an example, this has been especially highlighted recently in trying to assess the proficiency of Surface Warfare Officer seamanship. This research works toward development of a knowledge management (KM) approach to such measurement and understanding, seeking to enable current tracking and future forecasting. The KM approach will be developed to enhance quality design characteristics such as intuitive operation, natural data entry, agility and global reach.

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I. INTRODUCTION

The Navy Surface Warfare Officer (SWO) Community provides a vital, sophisticated capability to address increasingly dynamic and unpredictable threats around the world. Effective performance in the SWO Community requires a somewhat unique set of skills and capabilities, which center on life and work aboard ships at sea. Such skills and capabilities are expected generally to grow in predictable ways (esp. via training and experience), and the Navy enforces established qualification procedures to help ensure that its people are proficient before taking responsibility for critical jobs aboard ship.

As with any human endeavor, however, different people possess varying levels of motivation, and each person learns new skills at an individual rate. Moreover, given the persistently high tempo of surface warfare operations around the world—coupled with shortened training times for SWOs—a huge part of SWO seamanship and like, critical skills are learned while underway (esp. via on the job training [OJT], mentoring under instruction [UI], personal qualification standards [PQS]). Hence it's difficult to know *ex-ante* how proficient each individual person aboard ship will be or, by extension, how ready a ship's company and crew are before getting underway. Further, not all ships (even of the same class) are configured or operated identically, so OJT and experience aboard one ship may not be 100% transferrable to another. As noted in the recent Comprehensive Review (Fleet Forces Command, 2017), factors such as these can contribute toward questionable seamanship, ineffective communication, and even avoidable collisions at sea.

As a key tenet of readiness, it is important to know—tracking at the present time and forecasting through various future timeframes—measure, and understand unit level proficiency and individual career proficiency. This research works toward development of a knowledge management (KM) approach to such measurement and understanding, seeking to enable current tracking and future forecasting. The KM approach will be developed to enhance quality design characteristics such as intuitive operation, natural data entry, agility and global reach.

It is important when approaching a project along these lines to maintain focus on the dynamic and human nature of knowledge (Nissen, 2014). Knowledge is in constant motion (e.g., as individual people learn and practice personal skills, as teams of people learn and practice working together, as ships' crews encounter and share experiences with others). This pertains in particular to the kinds of rich, experience based, tacit knowledge required for effective seamanship, bridge communication, tactical action and leadership aboard ship. Hence it is imperative to identify, measure, track and forecast the movement of knowledge (i.e., *knowledge flows*), in addition to maintaining a static understanding at each point in time.

Knowledge is also intangible, invisible and resistant to quantification, which makes measurement a continuing challenge. Indeed, it is principally through the action and performance of people (and groups, and whole organizations) that we gain insight into the underlying knowledge that enables such action and performance. Moreover, knowledge does not represent a single, monolithic concept: different kinds of knowledge (e.g., tacit, explicit, individual, group, created, applied) have qualitatively different properties and behaviors, and hence affect action and performance differently (Nissen, 2006).

In this study, we bring the state of the art in terms of Knowledge Flow Theory (KFT; e.g., see Nissen, 2014), analysis, visualization and measurement (e.g., see Nissen, 2017; Nissen, 2019)—in addition to recent research on the SWO Community (e.g., see Nissen & Tick, 2018)—to bear on measuring and tracking SWO proficiency and readiness. We also bring humility and understand the importance of working with SWO Community experts to tap the detailed and relevant insight and experience available. Hence this effort combines some of the best thinking about knowledge dynamics and measurement with some of the best understanding of surface warfare proficiency and readiness to create an integrated, practical, SWO focused endeavor.

This leads to four primary research questions:

RQ1: What are the key factors that contribute to individual and unit readiness?

RQ2: How can such key factors be measured, tracked and forecasted?

RQ3: What kinds of readiness knowledge and information are required for intuitive yet reliable assessment?

RQ4: What kind of architecture can support a KM approach to measurement and understanding, enable current tracking and future forecasting, and enhance quality design characteristics such as intuitive operation, natural data entry, agility and global reach?

These research questions are pursued through the four step method outlined below. The result increases our understanding and ability to identify, measure, track and forecast surface warfare proficiency and readiness. Clearly there is only so much that can be accomplished in a single study, however, and the present research is no exception. Nonetheless, we need to start somewhere and begin to lay out even a preliminary approach and set of concepts, constructs and results as a metaphoric foundation, upon which we and other researchers can build.

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II. BACKGROUND

In this section we summarize very briefly the nature and composition of the SWO Community. We then summarize some relevant prior research on knowledge flow theory, which we follow with an overview of our basic system for dynamic knowledge visualization and measurement.

A. SWO COMMUNITY

Drawing from Nissen and Tick (2018), the Surface Warfare Officer (SWO) profession is comparatively ancient, dating back to the beginning of naval warfare, and relatively homogeneous. Paradoxically, proficiency at surface warfare was such a fundamental of naval skill, that it was not recognized as a distinct warfare community until the early 1970s. Although the moniker applies to anyone who has earned the SWO Pin, by “SWO” we refer principally to Navy officers that lead and operate surface combatant vessels, especially those designed for surface warfare with their own weapons. This would exclude submarines, which operate submerged; aircraft carriers, which fight with airplanes; and other craft that do not use their own weapons in a surface warfare role. Hence in the current era, this points us principally toward cruisers, frigates and destroyers (CRUDES), littoral combat ships (LCS), and like vessels, as well as the various sub-types that constitute the Surface Navy’s Amphibious Force.

SWOs have traditionally followed a relatively rigid career path, with sea-shore assignments and rotations mapped out explicitly from junior officer (JO) to senior officer (SO; see SWO Community, 2016). The clear emphasis of initial assignments and rotations centers on gaining experience and proficiency at sea, typically with the first four years or so serving aboard ship. After completing the Basic Division Officer Course (BDOC), officers report to their first division officer (DivO) tour, during which time they would promote to Lieutenant Junior Grade (O2). The Advanced Division Officer Course (ADOC) would generally precede their second DivO tour, during which time they would likely face one or two Department Head screening boards and promote to the rank of Lieutenant (O3). Throughout these years at sea, they would also stand watches and earn their Officer of the Deck (OOD) and SWO qualifications. Exact career paths may differ a

bit, and some officers may earn additional qualifications (e.g., Tactical Action Officer [TAO], Engineering Officer of the Watch [EOOW]) as well.

A shore tour of roughly three years follows these two DivO tours, and those previously selected would then complete Department Head School before returning to sea for one or two Department Head tours (with a possibility of early command) as they are screened for Lieutenant Commander (O4). Signing up for the Department Head tour(s) generally involves a major commitment of additional service time in the Navy, and this has posed a retention challenge. Indeed, the Navy O3s selected to serve as Department Heads appear to comprise a particularly insightful population to study in terms of SWO talent and retention. Having been selected to become Department Heads, the Navy clearly views them as particularly valuable human capital, and facing a major commitment of additional service time, these officers have an important decision to make in terms of career and lifestyle.

B. KNOWLEDGE FLOW THEORY

It is important to summarize first the importance of knowledge in any organization: knowledge enables effective action; effective action drives superior performance; and superior performance supports mission success (Nissen, 2014). Any organization attempting to succeed at its missions must be able to achieve and maintain performance levels that meet or exceed those required for sustained efficacy. This requires performing all of the underlying actions effectively, which requires in turn timely and energetic knowledge that is sufficient to enable such effective actions. Hence knowledge is on the critical path of organization performance and mission success, rooting it through action in what people, teams and whole organizations know.

We begin with some brief but necessary background information on Knowledge Flow Theory (KFT). Nissen (2006a) 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. KFT (Nissen, 2006b; 2014) describes the dynamics of knowledge flows phenomenologically, and it includes multidimensional, analytic and graphic techniques for understanding, interpreting and comparing a diversity of flows. Drawing directly from Nissen (2014), we organize this

brief overview of KFT into discussion of two parts: 1) knowledge uniqueness and 2) knowledge flows.

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, behavioral 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).

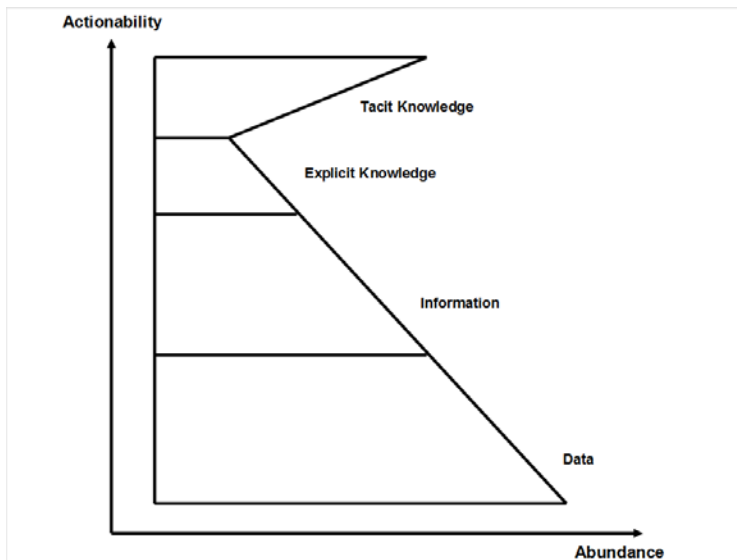


Figure 1 Knowledge Hierarchy (adapted from Nissen, 2014)

Many scholars (e.g., Davenport & Prusak, 1998; Nissen et al., 2000; von Krogh et al., 2000) conceptualize a hierarchy of data, information and knowledge. As illustrated in Figure 1, each level of the hierarchy builds upon the one below. 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.

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 chunks¹ 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 and energetic in terms of enabling action, whereas explicit knowledge represents often a diluted or attenuated formalization of its tacit counterpart, with many properties and behaviors that are similar to those of information (Nissen, 2006b). Further, unlike explicit knowledge, which by definition must 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 and times, from where and when it is located to where and when it is needed), the two connected knowledge hierarchies depicted in Figure 2 illustrate some key concepts. On the right side, we see a knowledge producer’s or source’s hierarchy,

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 have command of roughly 100,000 knowledge chunks in that domain and to require at least ten years to acquire such knowledge. We use *chunk* as a proxy for the volume or amount of knowledge possessed or moved.

and on the left side, we see a knowledge consumer's or receiver'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 an arrow pointed downward (i.e., from knowledge, through information, to data), and the consumer hierarchy includes an arrow pointed upward. This depicts the relative direction of knowledge as it flows from producer to consumer.

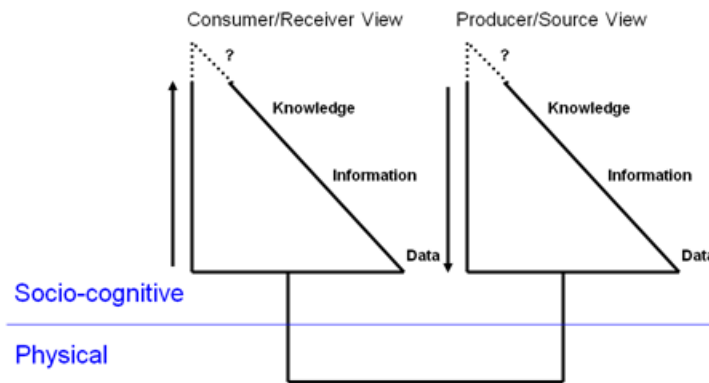


Figure 2 Knowledge Flows (adapted from Nissen, 2014)

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 medium. 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 phenomenologic 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.

C. BASIC KNOWLEDGE MEASUREMENT SYSTEM

This section continues with an overview of our basic system for dynamic knowledge visualization and measurement. Such basic system is described in detail by Nissen (2017) for the interested reader. The system 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 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 visualization and measurement techniques 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, or vice versa. 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.

1. 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*.

Table 1 Physical System Equations

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

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.

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 3. 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.

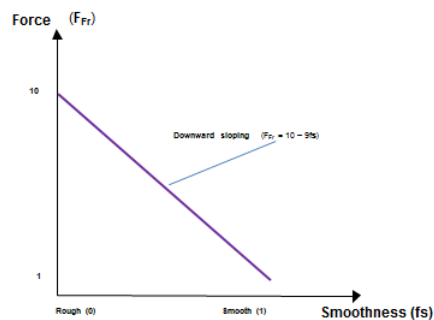


Figure 3 Force and Smoothness

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 4 delineates velocity (v), acceleration (a) and distance (d) over the first five seconds of movement down the aisle.

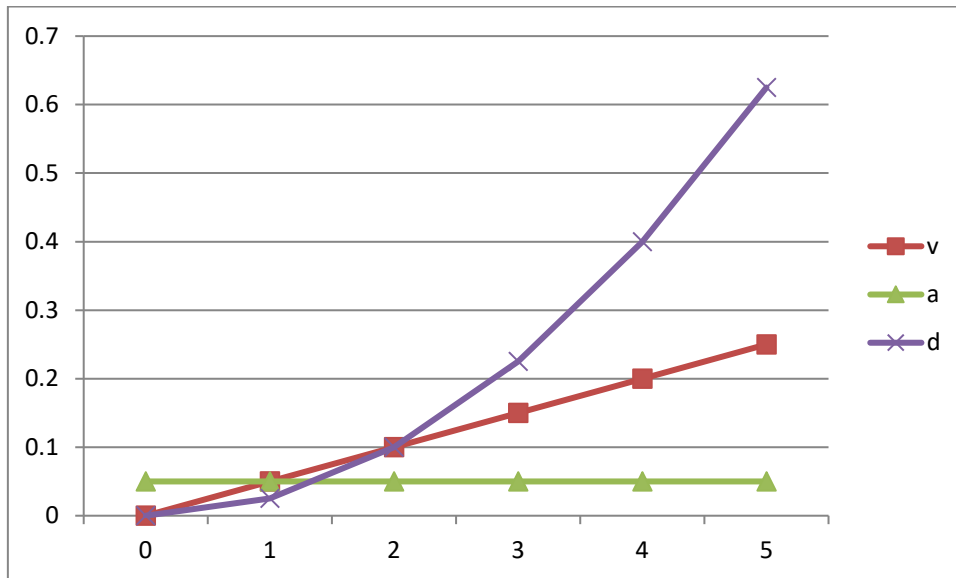


Figure 4 Physical System Dynamics

Moreover, now that this system of equations has been parameterized with measured and calculated values, one can understand and predict myriad changes and variations to the system 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 into the equations, and additional measurements in the field are not required.

2. 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* (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; the *explicitness* (E) of such knowledge; and 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.

Table 2 Analogic Knowledge System

Construct	Description	Analogy
K-Force (KF)	Effort required to accelerate knowledge	$f(C, E, \mathbf{o})$
K-Work (KW)	K-Force applied through reach	$KF \times R$
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 in the organization. *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.

Reach (R) derives from Nonaka's (1994) ontological dimension and represents the number of people able to utilize the knowledge chunks (analogous to physical distance). Reach combines with K-Force to specify *knowledge work* (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* (KE): K-Energy is required to perform K-Work, and K-Work performance involves the expenditure of K-Energy.

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) or time (e.g., night shift) to another. As a time measure, it combines with KW to specify *knowledge power* (KP), which represents the knowledge work accomplished (and knowledge energy expended) per unit time (analogous to physical power).

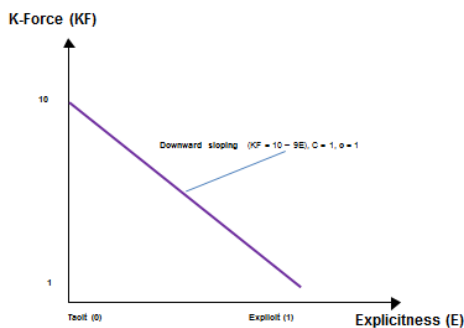


Figure 5 Knowledge Force and Explicitness

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 5.

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.

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. Consider, for example, flying an airplane: 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, and 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, information systems 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, 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	Units
K-Force	(5) $KF = C \times (10 - 9E) \times \mathbf{o}$	Nonaka
K-Work	(6) $KW = KF \times R (= KE)$	Polanyi
Flow Time	Measure	Second
K-Power	(7) $KP = KW / FT$	Bacon

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, and 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 measurement.

3. Knowledge Visualization

Here we illustrate the basic knowledge system from above through a multidimensional approach to the visualization of dynamic knowledge as it flows through the organization, after which we employ such system for knowledge measurement. Refer to Figure 6. The vertical axis represents *explicitness*, which is one of the knowledge measurement constructs from above and derives from Nonaka (1994). The horizontal axis represents *reach*, which is another of the knowledge measurement constructs from above and derives from Nonaka also. The third axis represents *life cycle*, which is helpful for visualization and used to extend Nonaka's model (Nissen, 2002). *Life cycle* pertains to what is being done with knowledge (e.g., *create*, *share*, *apply*).

Flow time is not delineated via separate axis, but it is another of the knowledge measurement constructs from above and used to extend Nonaka's model further (Nissen, 2002). Within the context of this multidimensional visualization scheme, *flow time* represents the time required for knowledge to flow between any two coordinate points in the space (e.g., Points A and B in the figure). When knowledge flows quickly through an organization (i.e., when flow time is short), for instance, we delineate the corresponding flow with a relatively thin vector arrow, whereas a comparatively thick one is used when knowledge flows slowly. Our expectations from KFT are that tacit knowledge, which is

notably “sticky” and difficult to move through the organization, will flow more slowly than its explicit counterpart, *ceteris paribus*. Hence tacit flows would be represented generally by relatively thick arrows, whereas comparatively thin ones reflect explicit flows better.

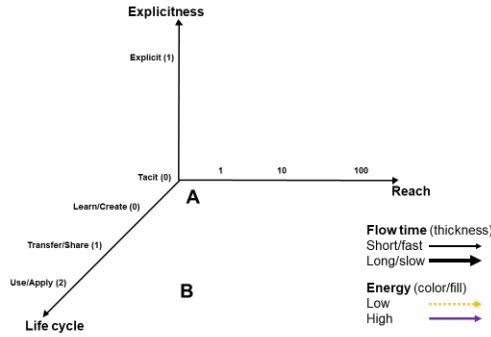


Figure 6 Knowledge Visualization Space

Finally, we also utilize different arrows to delineate *knowledge energy*, which is noted above with correspondence to the measurement construct *knowledge work*. A useful way to interpret K-Energy visually is through both the quantity and efficacy levels of K-Work that can be accomplished in the organization: high K-Energy flows enable high quantities of K-Work to be performed at high efficacy levels. We combine quantity and efficacy into the single term *performance* and indicate that high K-Energy enables K-Work at high performance levels.

Higher energy knowledge flows (i.e., which enable higher levels of knowledge work performance) are delineated with solid (purple) vector arrows, for instance, whereas dotted (orange) arrows are used for lower energy knowledge. Our expectations from KFT are that tacit knowledge, which can enable higher performance levels, will flow with more energy than its explicit counterpart, *ceteris paribus*. Hence tacit flows would be represented generally by solid (purple) arrows, whereas dotted (orange) ones reflect explicit flows better. In theory, *flow time* and *knowledge energy* represent orthogonal dimensions, but in practice, they may covary.

In terms of measurement, *explicitness* can be represented as a continuous dimension, with tacit and explicit endpoints on a ratio scale (e.g., [0, 1]). This implies that various combinations of tacit and explicit streams may comprise some knowledge flows. Such conceptualization as a continuous dimension also serves to extend much prior research (e.g., Nonaka, 1994), which views tacit and explicit knowledge more as a categorical contrast than endpoints of a continuum. *Reach* can be measured along an integer scale (e.g., 1, 10, 100), enumerating the number of people who can utilize knowledge. *Life cycle* represents an iterative sequence of activities, with a somewhat arbitrary ordinal scale (e.g., 0, 1, 2) referring to what is being done with knowledge. *Flow time* can be measured along a ratio scale using a stopwatch, calendar, employee timecard, or like instrument. As noted above, *K-Energy* (and *K-Work*) is calculated as the product of K-Force and reach.

Together, this multidimensional framework enables the visualization of dynamic knowledge and is very general. Theoretically, any dynamic flow of knowledge can be characterized in terms of these dimensions and delineated in this space, and in theory, knowledge can flow via an infinite number of different paths between any two points.

Consider, for example, Points A and B in Figure 6. Say that an individual worker in the organization discovers some new and useful knowledge (Point A), and management is interested in having all ten people in a group learn and apply such knowledge (Point B). There are clearly many different organization sharing processes available to enable this new knowledge to flow between such individual and group members, hence equally many corresponding knowledge flow paths through the multidimensional space are possible too.

The thin, solid (purple) vector arrow connecting Points A and B in Figure 7, for instance, represents an ideal archetypical knowledge flow path: high energy tacit knowledge, which can enable knowledge work at high performance levels in the organization, is depicted as flowing quickly and directly, in a short, straight line, from A to B. A straight line delineates the shortest distance between two points in space, and this vector depicts the fastest, highest energy knowledge flow between Points A and B, hence its classification as “ideal.”

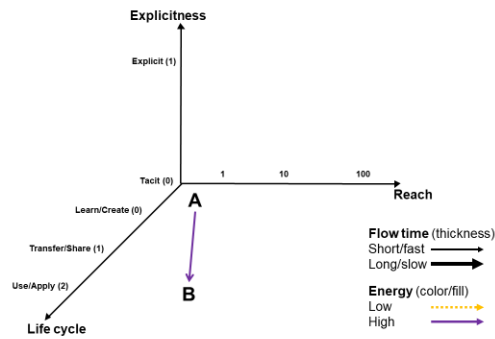


Figure 7 Ideal Knowledge Flow

In practice, however, the number of feasible knowledge flow paths is likely to be limited. The fast, direct, high energy flow vector delineated in Figure 7, for instance, may be ideal, but it’s doubtful that any organization is capable of accomplishing such flow. Indeed, as noted above, tacit knowledge is notably “sticky” and tends to flow slowly, hence the flow vector arrow should be thicker, and this arrow should also pass through an intermediate knowledge sharing step before it can be applied directly by the group members (e.g., members need to learn the knowledge via sharing before being able to apply it). Identifying feasible knowledge flow paths, and selecting the best ones for a given organization context and situation, represents an important leadership and management capability.

Consider, as a more feasible example, the archetypical knowledge flow labeled “Explicit Path” in Figure 8. This is the archetype associated most closely with information system (IS) implementations, as it centers on making knowledge explicit and using technology for sharing. Say that the individual worker (Point A) expends time and energy to articulate his or her knowledge in explicit form (e.g., written instructions, graphic depictions, mathematic relations, solved examples). This is represented by Point M in the figure. Then this individual could encode such explicit knowledge digitally within a computer network (e.g., via email attachment, website resource, document repository), which could be shared very quickly with all ten coworkers, wherever in the world they happen to be located. This is represented by Point N in the figure.

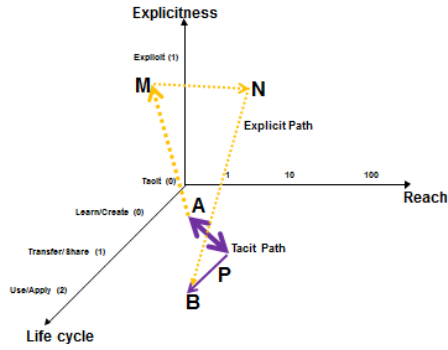


Figure 8 Knowledge Flow Archetypes

After sharing as such, each of the coworkers could apply the knowledge directly to his or her work activities (Point B²). This organization process and corresponding knowledge flow path are illustrated by light (orange) dotted vector arrows in the figure to represent the explicit nature of the dynamic knowledge. The first segment (i.e., A-M) is delineated with a relatively thick vector to indicate that the process of articulating tacit knowledge into explicit form can be time consuming, particularly when compared to the segment corresponding to explicit knowledge sharing (i.e., M-N). The explicit knowledge application vector (i.e., N-B) completes a loop as the explicit flow returns to the tacit plane at comparatively low energy. By using a stopwatch, calendar, employee timecard or like instrument, researchers or managers could measure the time required for this knowledge to flow from A to B, and hence obtain a measured value for flow time. Moreover, the equations from above could enable such researchers or managers to measure K-energy also.

Consider, as a contrasting example, the archetypical knowledge flow labeled “Tacit Path” in Figure 8. This is the archetype associated least closely with IS implementations, as it centers on sharing tacit knowledge through interpersonal interaction. Say that the individual worker interacts interpersonally with the group members, working closely with these people, soliciting and answering their questions, observing and correcting the coworkers as they practice, and both mentoring and

² Following Nonaka (1994), knowledge is presumed to be tacit when put into action (i.e., applied). However, absent another knowledge flow vector, we do not presume that such action necessarily involves learning.

coaching them until everyone in the group has learned the knowledge. This is represented by Point P in the figure.

With such learning accomplished effectively, all ten coworkers would be able to apply the knowledge directly to their work activities (Point B). This Tacit Path differs greatly from the Explicit Path above, and the corresponding knowledge flow is illustrated by dark (purple) solid vector arrows in the figure to represent the tacit nature of the dynamic knowledge.

The first segment (i.e., A-P) is delineated with a relatively thick arrow to indicate that the process of sharing tacit knowledge can be especially time consuming, particularly when compared to the other segment corresponding to tacit knowledge application (i.e., P-B). This first segment is delineated with a double headed arrow also to indicate that knowledge sharing goes both ways: the individual worker (Point A) is learning (e.g., group norms) from the other members as they interact interpersonally, and the coworkers are learning (esp. the new knowledge) from this individual.

As above, researchers or managers could use the same stopwatch, calendar, employee timecard or like instrument to measure the time required for knowledge to flow from A to B, and hence obtain a measured value for flow time along this alternate, tacit path. As above also, our system of equations could enable such researchers or managers to measure K-energy too. Since these two, contrasting, archetypical knowledge flow paths are very different—both in their paths through multidimensional space and their reliance upon IS implementations—one would expect for the corresponding flow times and energy levels to differ accordingly. We obtain the corresponding measurements next.

4. Knowledge Measurement

For any of the flow paths delineated above, let's say that the new knowledge involves 100 chunks. This would imply that such new knowledge enables approximately 100 novel actions to be performed. Let's say further that everyone in this organization is diligent about maintaining detailed records of how they spend their time at work, hence researchers or managers can obtain flow time measurements from the workers' timecards. Here we illustrate how to obtain measurements for the three knowledge flow archetypes delineated and described above. This begins with the Ideal Path, which, although

infeasible in practice, represents a noteworthy theoretic flow pattern for reference. Measurements are summarized in Table 4.

Table 4 Ideal Path Measurement

Flow	E	KF	R	KW	FT	KP
A-B	0.0	1.00	10	10.00	0.1	100.00

Walking across columns in the table, for the 100 chunks moving through this flow (A-B), one can see explicitness (0.0) in Column 2 denotes purely tacit knowledge. Using Equation (5), this results in K-Force (KF) of 1000 N (KF, KW and FT are expressed in thousands in the table), and with reach (10) for the whole group of coworkers, Equation (6) indicates K-Work (KW) and K-Energy (KE) of 10,000 P. The workers' time records indicate that only a couple minutes (100 seconds) of flow time (FT) are required for application. This results in K-Power (KP) of 100 B. We gain perspective below through comparison with the other knowledge flow archetypes.

Measurements corresponding to the Explicit Path are summarized in Table 5. Notice that we divide the measurements into three parts corresponding to each of the flow vectors noted above. For the same 100 chunks moving through the first flow (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 the individual worker articulates tacit knowledge into explicit form. Using the same equations noted above, this results in KF of 550 N, and with unitary reach (i.e., the individual), KW 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 FT.

Table 5 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 (1.0) for these latter flow segments and that both involve the same reach (10) across the group. In the first (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.

KW (and KE) is nearly double for these purely explicit flows because of the greater reach (10 vs. 1). Summing KW (2550 P) and FT (16,100 s) for the process as a whole, (average) KP of 0.16 B obtains, which provides a numeric measurement and basis for comparison with the Ideal Path from above. Clearly knowledge flowing through the Explicit Path takes considerably longer and accomplishes much less KW (at a miniscule relative KP level) than that moving through the Ideal Path, for instance.

Measurements corresponding to the Tacit Path are summarized in Table 6. They involve the same 100 knowledge chunks and follow the same logic and procedure described above. Notice that knowledge for both flow vectors comprising this latter process is purely tacit ($E = 0.0$). 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 6 Tacit Path Measurement

Flow	E	KF	R	KW	FT	KP
A-P	0.0	1.0	10	10.0	55.0	
P-B	0.0	1.0	10	10.0	0.1	
Sum				20.0	55.1	0.36

Notice further that a relatively long time (i.e., roughly 15 hours; $FT = 55,000$ s) is required for this tacit knowledge to flow (A-P). This is consistent with the “sticky” nature of tacit knowledge. Alternatively, once learned, application of such tacit knowledge is comparatively very quick (i.e., $FT = 100$ s) for the group of coworkers (P-B). As with the

Explicit Path above, knowledge flowing through the Tacit Path takes considerably longer than that moving through the Ideal Path, but it accomplishes double the KW (20,000 P). Nonetheless, the KP (0.36) is also miniscule relative to the Ideal Path (100.00 B).

Other comparisons across the three archetypical knowledge flow paths are noteworthy, and some comparative measurements are summarized in Table 7. For one, the Ideal Path reflects enormous KP (100 B), illustrating the accomplishment of much KW (10,000 P) in very little FT (100 s).

Table 7 Knowledge Flow Path Comparison

Path	KW	FT	KP	Comment
Ideal	10.00	0.1	100.00	High power Infeasible
Explicit	2.55	16.1	0.16	Less work Less time
Tacit	20.00	55.1	0.36	More work More time
T:E Ratio	7.8	3.4	2.3	“Best”? K-Power

Looking now at the Explicit and Tacit Path archetypes, the tacit flow accomplishes nearly eight times the knowledge work (and flows with comparably greater KE) as its explicit counterpart (20,000 vs. 2550 P), but it takes more than three times as long to accomplish such work (55,100 vs. 16,100 s). Which of these two, feasible archetypes is “best”? The KP metric reveals that the tacit path completes the knowledge flow at over double the power level (0.36 vs. 0.16 B) of its explicit counterpart. This indicates that the additional knowledge work accomplished through the former process more than makes up for the greater amount of time required for the knowledge to flow. These measurements are highly consistent with KFT (Nissen, 2017). Theoretic consistency along these lines gives us considerable confidence in the measurement system.

III. RESEARCH METHOD

In this section we summarize the research method. As noted above, the research questions are pursued through a four step method, with each step representing a major task within the study:

Task 1: Research the academic, doctrinal and professional literatures to understand the key factors that contribute to individual and unit readiness. The key academic literatures are summarized above as background to this study, along with prior research to understand the SWO Community. We also review key articles and reports in the professional literature, including the Navy's Comprehensive Review of the 2017 accidents involving the cruiser *Antietam* and destroyers *Fitzgerald* and *McCain* (USFFC, 2017), approaches to measuring the talent of naval personnel (Corley, McAnallen & Palmer, 2015; Palmer, 2017; Parcell, Hodari & Shuford, 2003), and other sources of information, including several conversations with senior, active and retired SWOs (e.g., Strategic Contact, 2018).

Task 2: Understand how such key factors are or can be measured, tracked and forecasted today. This involves a combination of document review, survey, telephone conversation, personal interaction, and onsite observation. A key result of this task emerges in terms of the SWO Community seeking to build upon its Aviation counterpart through the implementation of the Mariners Log Book. Such log is intended to serve a purpose similar to that of the Aviation Log Book that has been used for many decades by aviators. Indeed, some of our best insight stems from analysis of the Aviation Community.

Task 3: Build upon our understanding of knowledge and information flows, and the results from Tasks 1 & 2, to identify the kinds of readiness knowledge and information required for intuitive yet reliable assessment. We report on this in the Results section.

Task 4: Work with experienced SWO personnel to draft the kind of architecture that can support a KM approach to measurement and understanding, enable current tracking and future forecasting, and enhance quality design characteristics such as

intuitive operation, natural data entry, agility and global reach. This remains for future research.

IV. RESULTS

In this section we present results of the study. We begin by summarizing the key problems facing the SWO Community in terms of surface warfare proficiency KM. We then summarize key information regarding the use of log books in aviation. The section concludes with key insights for the SWO Community.

A. KEY KM PROBLEMS FACING THE SWO COMMUNITY

In this section we outline key problems facing the SWO Community in terms of surface warfare proficiency KM. We begin with a relatively high level summary, which includes an excerpt from the 2018 Comprehensive Review for concrete context. We then complement and elaborate on this summary through application of the knowledge flow visualization and measurement approaches discussed above.

1. High Level Summary

When people are detailed to a particular ship, they are expected to have sufficient training and experience to perform the jobs assigned to them in a proficient and professional manner. They are expected to also learn and grow increasingly proficient while working, principally through “on the job training” (OJT), which is a euphemism for trial and error learning. Of course everyone on a ship has a supervisor (e.g., Chief) or superior officer (e.g., Department Head)—including the Commanding Officer (CO), who reports to a superior off ship (e.g., Commodore)—and such supervisor or officer is expected to explain job requirements to personnel and to assess how well each job is being performed. People also learn from peers aboard ship, with many sailors and officers willing to advise, guide and assist their shipmates.

The problem is that it’s not always completely clear what a person knows how to do or how well he or she knows how to do it. Many people may look qualified on paper and through perusal of his or her training jacket, but detailed skills and experiences from one ship or assignment may not translate completely to another. A sailor with experience, say on the Bridge, of a cruiser (CG) may not apply completely to the Bridge of a

destroyer (DDG), for instance. Even experience on one DDG—say built by a particular contractor, at a specific point in time, or reflecting a unique configuration—may not apply completely to another DDG—especially if built by a different contractor, at a different point in time, or reflecting a different configuration—of the same class. This complicates one’s ability to predict a given sailor’s knowledge and capability.

Further, with a high operating tempo, supervisors, superior officers and shipmates may not have (much, if any) spare time to teach, coach and train others. People are expected to do what needs to be done at the right time and in the right manner. If someone comes aboard and is assigned to a job for which they appear qualified, the whole ship and crew depend upon that person. Such dependence is exacerbated in team settings. A team of people standing watch, for instance, depends upon all of the watchstanders working together competently, and even one person can let down the whole team.

This situation is described well in the Comprehensive Review (2018: 11-13) of the fatal collision on the Bridge of the *McCain*.

On the morning of 21 August 2017 USS John S. McCain was preparing to enter the Singapore Strait for transit to Sembawang, Singapore. The ship completed a full Navigation Brief the day before that included the estimated time of 0500 to enter the Traffic Separation Scheme (TSS) and subsequent passage in close proximity to shoal water. Although the Executive Officer (XO) and Navigator recommended setting the Sea and Anchor Detail at 0500, the CO decided to delay stationing the detail until 0600 in order to give the crew more time to rest and to minimize the chance of a man overboard during hours of darkness. As mitigation, the CO planned to be on the Bridge for the entire transit and in fact arrived on the Bridge at 0115 and remained there until after the collision.

Of the Bridge watchstanders, the Junior Officer of the Deck (JOOD), the Boatswain’s Mate of the Watch (BMOW), and the eventual Lee Helmsman (Lee Helm) were on temporary duty from the USS Antietam (CG 54) to provide these Sailors underway time for qualifications while USS Antietam was under-going repairs. Although the watchbill listed the USS Antietam Sailors as qualified, the BMOW and JOOD qualification dates coincided with the day they reported to USS John S. McCain, and they conducted no requalification events. The Lee Helm qualified as Helm/Lee Helm within a few weeks of reporting to USS John S. McCain.

After entering the TSS, the CO noticed that the Helmsman was having difficulty

both steering the ship and adjusting the ship's speed due to prevailing environmental conditions. The CO ordered the OOD to separate the control of steering and thrust to two separate stations: the Helm and Lee Helm. While attempting to execute this order, the Bridge watchstanders unintentionally transferred steering control to the Lee Helm console and "un-ganged" the throttles (i.e., separated the port and starboard throttle controls from a coupled control to individual throttle control). Complicating the execution of the order was a series of watch reliefs for meals then in progress among the various watchstations and a lack of posted procedures for transfer of throttle and steering control. Recognizing that he no longer had control of steering, the Helmsman announced a loss of steering (system) casualty (malfunction). The After Steering station was manned in short order and attempted to take emergency control. Due to confusion on the Bridge about the nature of the casualty and the operation of the Ship's Control Console (SCC), steering control would be inadvertently transferred among various controlling stations four times within the two minutes leading up to the collision. As a result of this perceived lack of steering control, the ship began a slow turn to port.

After hearing the Loss of Steering casualty the CO directed the OOD to slow the ship. The OOD ordered 10 knots and the Conning Officer duly gave the order. The Lee Helm executed the order and slowed the port shaft, but did not recognize that the throttles were not linked and that he had control only of the port shaft. Unrecognized by the watchteam, control of the starboard shaft remained at the Helm station for more than 60 seconds after control of the port shaft was taken by the Lee Helm. The speed change to the port shaft slowed the ship but also increased USS John S. McCain's rate of turn to port as the starboard engines and shaft remained ordered to 20 knots. The CO then ordered a speed of 5 knots, but the Lee Helm's actions only reduced power to the port shaft due to the individual throttle control. The starboard shaft still remained at 20 knots, exaggerating the rate of turn even further. About three minutes after the reported Loss of Steering casualty began, USS John S. McCain regained positive steering control in After Steering and answered Right 15 degrees rudder. About this same time throttles were matched at the Lee Helm and the starboard engine and shaft slowed to 5 knots. These actions were too late to avoid collision with the ALNIC. At about 0524, and because of the port turn induced by the loss of steering control and thrust control actions, the USS John S. McCain crossed in front of ALNIC, whom the USS John S. McCain had just passed ahead of, and USS John S. McCain was struck on her port quarter. Despite what the watchstanders believed, there never was a loss of steering casualty.

Primary causes of the collision were leaderships' loss of situational awareness in a high traffic area and failure to follow safe navigational practices, coupled with watchstanders who were not proficient with steering control operations or engineering casualty response procedures. Contributing to the collision were failures in basic watchstanding and seamanship among the Bridge and Combat Information Center (CIC) teams; a failure by these same watchteams to take clear

and decisive action to avoid collision when in extremis; and the failure of the Commanding Officer in assigning and changing watchstanders, in ordering equipment configuration changes in the TSS, and in failing to take prudent measures to mitigate these risks. This critique of USS John S. McCain does not imply that ALNIC mistakes and deficiencies were not contributing causal factors in the collision.

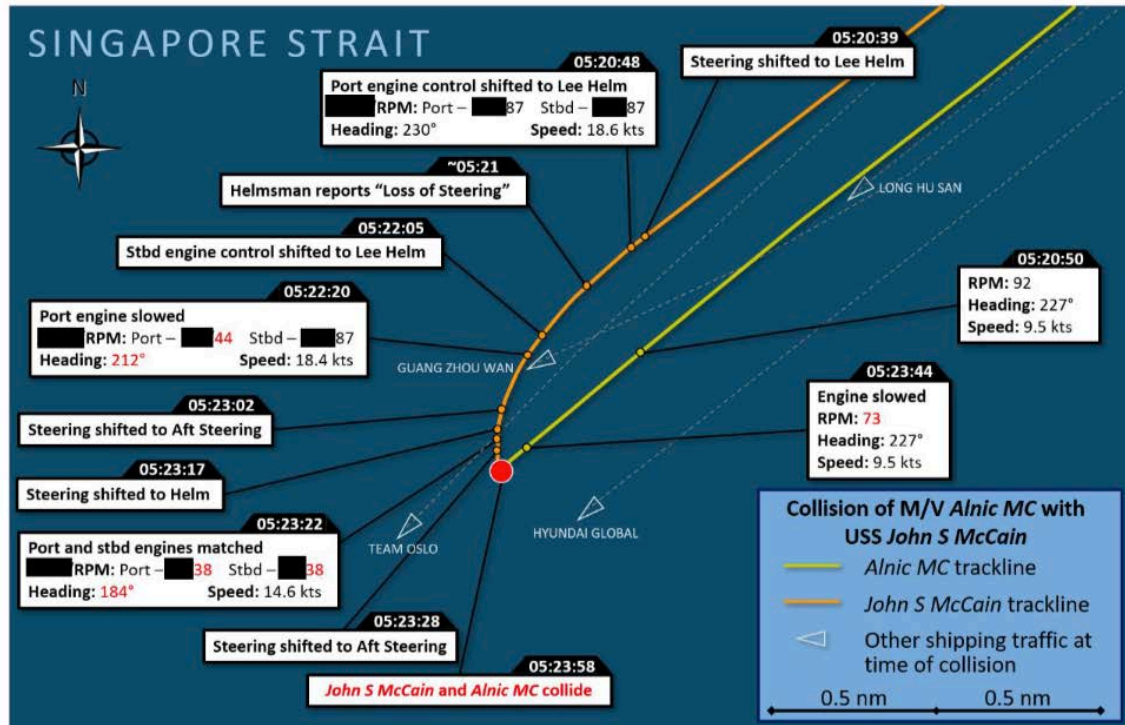


Figure 11. Vessel tracks and accident events.

NTSB Image with Navy redactions

In this image (from USNI News of 6 August 2019; “NTSB: Lack of Navy Oversight, Training Were Primary Causes of Fatal McCain Collision”) there were just over 3 minutes from the time steering was shifted to the Lee Helm to the collision. In addition to the analysis of knowledge flows and knowledge power that have already been described, another view emerges through Table 8, in which there are relationships between what could or should have been known, and what was not.

Table 8 Collision Knowledge and Timing

Event	Time	Actionable knowledge Actor(s)	What was known	What was not known	Alternate actions
Steering shifted to Lee Helm	05:20:39	CO, Helm, lee helm	How to shift steering	Helm unaware Lee helm had steering control, Lee Helm lack of understanding.	Acknowledgement by both Helm and Lee Helm of new state. CO/OOD verifying new state
Port engine control shifted to Lee Helm. Shafts “split” both at 87 RPM	05:20:48	Split shafts, CO/OOD/Helm /Lee Helm	An order was given, but not understood at the console	Steering was with the Lee helm, as well as the port shaft. Helm did not know that control of the port shaft also at the Lee Helm	Although standing at the same console, with ability to see what was happening, lack of coordination between Helm, Lee Helm and bridge watch
Helmsman reports loss of steering	05:21	Incorrect knowledge is also actionable. In this case the Helm thought steering was lost and reported that to the bridge team	Incorrect identification of the circumstances was amplified by procedures to shift steering to aft steering.	Steering had not been lost, only shifted between Helm and Lee helm. Both misunderstood the loss of situational awareness. Continued turn to port would result in a collision.	It is unclear what actions were being taken by the OOD/CO to help clarify the lapse in SA. In addition, little was heard from CIC with regard to closing on a constant bearing
Starboard engine shifted to Lee Helm	05:22:05	Lee helm brought both shafts under control.	Still a lack of knowledge about lack of steering control	Steering had not been lost. Proximity of contact on collision course.	CIC to CO and OOD of imminent danger if continuing on current port turn.
Port Engine slowed to 44 RPM (STBD 87)	05:22:20	Shafts under control of the Lee helm, however port engine slowed, with starboard shaft at 87 RPM. Continued to make an appearance of loss of steering control	Starboard shaft at 87 rpm, port at 44 should have helped in making a turn to starboard,	Mismatched shaft RPMS were contributing to port turn. Lack of SA by all on bridge team. Lack of knowledge that collision was approaching extremis.	CO orders to OOD to slow starboard shaft, flank on port with full right rudder. Order collision alarms. Bridge to bridge warnings to contact vessel for it to turn to port.
Steering shifted to After Steering	05:23:02	Continued actionable knowledge (incorrect) that	Rudder control established but having little effect on	Mismatched shaft RPM was the primary problem. Aft	Bring crew to general quarters and have damage control teams on alert

		the problem was with steering.	making a starboard turn.	steering not generally as responsive as normal steering.	
Steering shifted to Helm	05:23:17	Acknowledgement that steering needed to be on one console	Matching shafts was necessary	Ship had reached extremis	All hands out of their racks and brace for collision
Port and Starboard shafts matched at 38 RPM	05:23:22	Slow the ship to avoid collision	Full right rudder was needed, with all stop on starboard shaft, all ahead flank on port shaft	Rate of closure with target vessel	CIC advising bridge of actions to avert or mitigate collision
Steering shifted to After Steering	05:23:28	Continued action with after steering	Steering was available from the console and would have been much quicker in reaction	Actual distance to target vessel	All stop, full right rudder
Collision	05:23:58	Partial knowledge of crew about danger	Many crew asleep in berthing	Extent of damage	Bridge shift to damage control

This complex situation is typical of ships underway in busy waterways. Although there is ample fault to be distributed across the CO and Bridge teams, the issue centers on knowledge: not only did several individuals lack the requisite knowledge required to perform proficiently, but the Bridge teams as wholes—CO included—lacked the requisite *team* knowledge to perform as such. This implies that key surface warfare proficiency knowledge is not limited to individuals: it applies to teams as well. This is key in terms of a KM approach: it is insufficient to track individuals' knowledge, and it is necessary to assess the team knowledge of every person participating on a watch or like group assignment.

One very experienced SWO explains (Sponsor Contact, 2019) how he would review proposed watch bills and recommend (generally few and minor but important) reassignments to accommodate different combinations, experiences and personalities of personnel. He would team, for instance, a relatively experienced OOD with an inexperienced JOOD, or vice versa, in order to balance the experience levels and to promote knowledge flow between them. Likewise, even people with compatible experience levels could be separated onto different watch teams based on personality and

other factors. This former CO was focusing adroitly on *team knowledge* and its associated capability.

This is similar in many respects to how coaches of sports teams (e.g., football, basketball, soccer) consider the capabilities of the whole team playing together, in addition to those of the individual players. A group of terrific individual players may not play well together as a team without abundant practice—*together*—as a team. Consider, for instance, how the US and other nations assemble World Cup soccer teams every few years. These teams are comprised of many of the best individual soccer players in the world, nearly all of whom play professionally on *different teams*. Considerable time and effort are required for them to practice together and play at a high level as a coherent team.

This also suggests that our ability to leverage processes from Aviation Log Books may be limited in terms of application to surface warfare proficiency at the team level: although all pilots participate on teams (e.g., with maintenance, scheduling, weather, crew personnel), the log book captures principally individual information that is focused on the pilot. As explained below, individual pilot log book information can be useful to inform individual SWO log book organization, but team knowledge represents another and much more challenging step. One step at a time.

2. Knowledge Flow Visualization

Using the dynamic knowledge visualization techniques outlined above, we examine a relatively small portion of the *McCain* scenario above³: “Complicating the execution of the order was a series of watch reliefs for meals then in progress among the various watchstations and a lack of posted procedures for transfer of throttle and steering control.” We delineate the watch team relief knowledge flow in Figure 9.

³ Here we rely solely upon the report, and we make a number of assumptions to flesh out the apparent situation sufficiently well to apply our visualization and measurement techniques. Our interpretation is likely to differ from the events as they occurred, and we imply no difference of opinion. We are not trying to second guess the investigators and authors of the report.

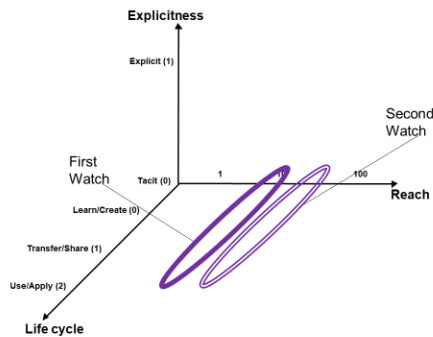


Figure 9 Watch Team Relief

The knowledge flow visualization space reflects the same three dimensional axes as illustrated above (i.e., *explicitness*, *reach*, *life cycle*), and knowledge flow vectors carry the same interpretation (e.g., thin vectors for fast flows, solid vectors for high energy flows). The thick, solid (purple) flow resembles an ellipse in the tacit plane, delineating the flow of knowledge *at the watch team level* as watch standers repeatedly apply their knowledge, learn from their experiences (e.g., ever improving situational awareness and Bridge teamwork), and share with one another. We depict this process with a relatively thick vector line to indicate that watch team knowledge accumulates over time as the people stand watch together. This represents dynamic knowledge of the original watch team that was in place when the *McCain* entered the Straight (labeled “First Watch” in the figure).

The other ellipse in the tacit plane delineates another flow of knowledge *at the watch team level*, but this flow vector is not solid (purple), for here we represent the new people joining the watch and relieving the first set of watch standers (labeled “Second Watch” in the figure). Although we do not presume that the entire watch was replaced at one time, we do presume that multiple watch stations experienced reliefs during the period of time of the fatal maneuver. We presume also that these new people did not have the experiential benefit of the first group, which had been on the Bridge for some time, hence their watch team knowledge did not flow with the same energy level as that corresponding to the original watch team (e.g., considerably less situational awareness

and Bridge teamwork). Indeed, the new watch standers were unlikely to fathom fully the situation with steering, throttles and an unintentional turn to port.

Although we assume that each individual watch stander briefed his or her replacement before handing over responsibility and leaving the Bridge, there is no indication that the watch team as a whole conducted a thorough knowledge exchange. Had they done so, then we would delineate the knowledge flow with an additional, double headed vector (labeled “Knowledge Exchange” in the figure) between the two watch teams as depicted in Figure 10. This approach likely remains inferior to retaining the First Watch Team in its entirety until the maneuver was complete, but it is likely superior to relieving watch standers in the midst of it.

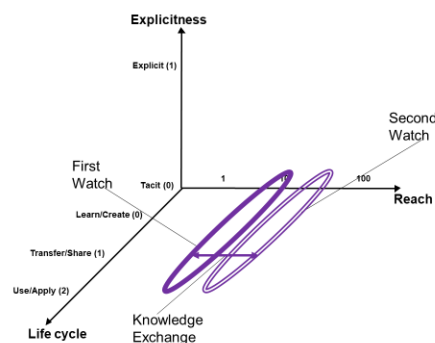


Figure 10 Watch Team Relief with Knowledge Exchange

Notice how informative this kind of knowledge flow visualization can be. Not only are we able to delineate knowledge differences across watch teams (e.g., the different ellipses in the tacit plane), we are also able to identify missing knowledge flow vectors (e.g., the knowledge exchange flow between ellipses). Imagine the ship CO examining knowledge flow diagrams such as these and using them to direct the OOD, for instance, to ensure sufficient knowledge flow exchange for a proficient watch team relief.

An alternate approach, mentioned in the report also, pertains to posted procedures for transferring steering and throttle control. We delineate this knowledge flow via Figure 11. Here we depict the first knowledge flow (i.e., before the knowledge exchange vector) shown in Figure 9 above, but we include a dotted (orange) vector series to illustrate the development, sharing and use of written procedures. The idea is that one or more

experienced people write the procedures in terms of explicit knowledge. This represents the vertical knowledge flow vector rising out of the tacit plane. Once written down in explicit form as such, the procedures can be posted (i.e., shared) and utilized by all members of both watch teams. We depict the sharing and utilization of this knowledge via relatively thin flow vectors, for it takes little time to read and follow written procedures. However, we depict them also via dotted (orange) flow vectors, for the energy level (i.e., performance level) associated with following written procedures is unlikely to match that of watch teams that have practiced the steps and learned them, tacitly, as a team.

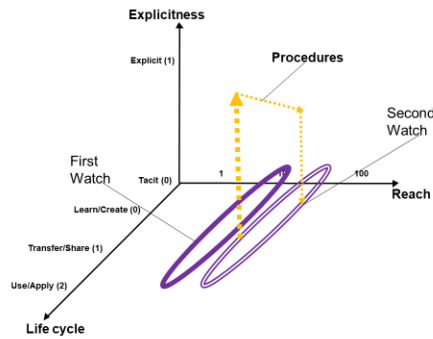


Figure 11 Watch Team Relief with Procedures

Neither of these alternate approaches appears to be ideal, for it remains difficult to conceive of a technique for watch relief that does not suffer some knowledge energy loss that translates into degraded watch team performance, at least until the relieving team attains the same level of situational awareness and Bridge teamwork as the original watch team. The only exception that comes to mind is if one or more of the relieving watch standers was sufficiently knowledgeable and experienced to recognize and remedy the steering and throttle issues upon arrival on the Bridge. Given that the CO was unable to do so, however, this appears unlikely as well.

3. Knowledge Flow Measurement

Using the dynamic knowledge measurement techniques outlined above, we examine this same, relatively small portion of the *McCain* scenario above⁴:

“Complicating the execution of the order was a series of watch reliefs for meals then in progress among the various watchstations and a lack of posted procedures for transfer of throttle and steering control.” We begin with the watch relief as it occurred and as delineated via Figure 9.

This is a bit more complicated than the archetypical example discussed in the background section above, for the original watch team knowledge flow had been accumulating and growing throughout the watch. Nonetheless, we can examine the *knowledge loss* associated with the watch team relief, which reduces to a comparison of the knowledge flow ellipses corresponding to the original and relieving watch teams.

Assume, for example, that the original watch team included 10 people and that it had accumulated a total of 10,000 knowledge chunks during the watch. It is important to note that these chunks accumulated *during the watch*. Hence they exclude all of the knowledge and experience acquired (e.g., via training and OJT) prior to setting foot on the Bridge to take the watch. Assume further that the replacement watch team included five new watch standers, who integrated in with five people from the original team. This implies that roughly half of the accumulated watch knowledge (i.e., 5,000 chunks) was lost through the relief process.

Table 9 summarizes the corresponding measurements. In the first column, “OW” refers to the original watch, “RW” refers to the relief watch, and “Delta” refers to the knowledge difference. For both watches, explicitness is listed at zero (i.e., tacit knowledge), as the knowledge flows are experiential. For the chunk counts noted above, the KF (in thousands) is shown in the third column (100 vs 50 kN). Both watches include the same number of people (i.e., Reach = 10), and the KE⁵ is shown in the fifth column (1000 vs. 500 kP). FT for the original watch (14.4 ks) reflects four hours that the original

⁴ Here we rely solely upon the report, and we make a number of assumptions to flesh out the apparent situation sufficiently well to apply our visualization and measurement techniques. Our interpretation is likely to differ from the events as they occurred, and we imply no difference of opinion.

⁵ We show knowledge energy (KE) here instead of knowledge work (KW) as shown in the archetypical example to highlight the energy—and associated performance—difference. Because KE and KW are equivalent here, there is no difference aside from emphasis.

team is assumed to have stood watch, whereas FT for the relief watch (0.6 ks) reflects ten minutes that the relieving watch standers are assumed to have been briefed by their relieved counterparts before taking responsibility. Thus, over the period of ten minutes (i.e., the 0.6 ks listed in the Delta row), the watch team lost 500 P of knowledge energy (i.e., corresponding to performance). This indicates knowledge loss at the rate of 833 B as shown in the KP column. We use this as a baseline case for comparison with the other approaches delineated above.

Table 9 Watch Relief Measurement

Flow	E	KF	R	KE	FT	KP
OW	0.0	100	10	1000	14.4	
RW	0.0	50	10	500	0.6	
Delta				-500	0.6	-833

We continue with the watch relief as it occurred but as delineated via Figure 10 to reflect the knowledge exchange inserted into the process. Table 10 summarizes the corresponding measurements and follows the same format as described above (e.g., “OW” refers to the original watch, “RW” refers to the relief watch, “Delta” refers to the knowledge difference). In this case, we assume that considerably more time and effort were invested in transitioning the new watch standers. Indeed, we assume that a full 30 minutes are spent with watch standers *from both teams* working together, and we assume that half of the knowledge lost in the original watch relief can be transferred to the relief watch team.

Table 10 Watch Relief Measurement – Knowledge Exchange

Flow	E	KF	R	KE	FT	KP
OW	0.0	100	10	1000	14.4	
RW	0.0	75	10	7500	1.8	
Delta				-250	1.8	-139

As above, explicitness is listed at zero (i.e., tacit knowledge) for both watches, and reach (10) remains the same. FT for the original watch (14.4 ks) remains the same as above, whereas FT for the relief watch (1.8 ks) reflects 30 minutes that the relieving

watch standers benefit from knowledge sharing before taking responsibility. Thus, over the period of 30 minutes (i.e., the 1.8 ks listed in the Delta row), the watch team lost 250 P of knowledge energy (i.e., corresponding to performance), which indicates knowledge loss at the rate of 139 B as shown in the KP column. Notice how knowledge power loss is reduced by over 80%.

We conclude with the watch relief as delineated via Figure 11 to reflect the use of posted procedures. Table 11 summarizes the corresponding measurements and follows a format similar to that described above (e.g., “Write” refers to developing the procedures, “Post” refers to posting them, “Use” refers to using them). In this case, we assume that considerable time and effort (15 ks = 4+ hours) were invested in writing the procedures, which can be posted within a couple of minutes (100 s) and then read and used by the new watch standers in about five minutes (300 s). All other factors remain the same as the original watch relief. The addition of these posted procedures adds some knowledge back after the watch standers change.

Table 11 Watch Relief Measurement – Posted Procedures

Flow	E	KF	R	KE	FT	KP
Write	0.5	1.38	1	1.38	15.0	
Post	1.0	0.25	10	2.50	0.1	
Use	1.0	0.25	10	2.50	0.3	
Sum				6.38	15.4	0.41

Writing down, posting and using procedures along these lines represents a process very similar to that delineated via the Explicit Path in Figure 8, and we break the knowledge flow into three similar segments in Table 11: 1) Write, 2) Post, and 3) Use. Because these posted procedures pertain only to transfer of throttle and steering control, we assume only 250 knowledge chunks for the corresponding knowledge. As with the Explicit Path flow delineated above, when writing the procedures, the knowledge flow begins as tacit (E = 0.0) but ends as explicit (E = 1.0), hence we note mixed explicitness (E = 0.5) for the flow overall along this first segment. Knowledge is purely explicit (E = 1.0) for the Post and Use segments. From the table, one can see that some knowledge energy (KE = 6.38 kP) is added back into the process with minimal knowledge power

(KP = 0.41 B). This does very little to counter the large knowledge losses reported above (i.e., -500 kP for the original watch relief, -250 kP with the knowledge exchange), but if these posted procedures provide exactly the right knowledge at exactly the right time, then they offer potential to obviate a collision nonetheless.

B. AVIATION LOG BOOK INFORMATION

As noted above, the Aviation Log Book offers potential to inform the SWO Community, and SWOs are beginning to utilize a mariner version of the log book as this report is being written. Here we summarize key aspects of the information collected and used in the Aviation Community, through a system of record keeping that has not changed appreciably in 40 years.

One key information source is the NATOPS Flight Personnel Training Jacket. For every aviator, this includes results of all tests, qualifications, physicals, courses and like events. The training jackets contain only paper documents, which are factual in nature.

Another key information source is the Aviator Log Book. It centers on aviator achievements. For several instances, it records each aviator's accomplishments, which are compared with training and qualification needs and plans of the squadron; it records takeoff and landing times, which are used to calculate flight hours; it records flight objectives, which are driven by the squadron training matrix (e.g., what missions, maneuvers, roles and activities are required).

Aviation shares a number of common factors with surface warfare along these lines. For instance, aviators must be qualified before being authorized or assigned to a given role on a mission. One aviator may be qualified to serve as Tactical Flight Lead, for example, whereas another may be limited to serving as Wingman. Through both training and operational missions, qualifications accumulate over time as aviators accomplish objectives and gain experience. SWOs aboard ship must become qualified similarly prior to serving in various roles (e.g., OOD, JOOD, TAO).

Every squadron has expectations—which flow down from the Wing—for how each of its aviators will progress over time, and aviators are evaluated in part on how they progress with respect to such expectations. An aviator's progress in terms of accomplishments must be confirmed by someone in the squadron. This can be the

Squadron Commander, a Flight Lead, or someone else with authority, who must sign off on every accomplishment before it becomes part of the official record. The process has a subjective aspect to it, as the aviator must satisfy criteria that may not be completely objective and that may vary across different evaluators, but once signed off, each accomplishment becomes an objective part of the record. Squadron leaders use accomplishments over time and expectations to evaluate aviators and to differentiate between excellent, average and poor performers. Most of this information stays within squadron, although it also travels with aircrew members as they transfer to other organizations.

The Aviation Community has a set of tools that are useful. For instance, SHARP tracks logbook information. This requires manual entry into a database, but it provides a useful record and summarizes information across the different aviators comprising a squadron. As another instance, the Scheduling Tool tracks training and is used to schedule people to perform the sorties required to accomplish various qualification tasks. As a third instance, the DRRS monthly readiness reporting system reports squadron training and readiness. It uses information recorded in SHARP, and after being endorsed by the Squadron Commander, its information is passed on to the Wing Commander. The Wing then drafts its training & readiness report, for each aircraft type, to pass along in turn to Higher Headquarters.

Training is clearly very important in the Aviation Community, and it is driven by NMETLS (Navy Mission Essential Task List) for each community. This extremely logical and methodical approach begins with a listing of tasks that are considered to be essential. Leaders then determine all of the training that is required for preparation to accomplish each of these essential tasks. Such determination feeds in turn the training matrix and sortie scheduling.

Additionally, aviators who are new to a squadron are evaluated and cleared (or not) by more experienced squadron members. Indeed, every aviator must be approved in this manner before being allowed to fly, regardless of prior flight experience. Although simulator time is important, time in the air is critical. The Aviation Community appears to be very good about sharing knowledge regarding problems and mishaps. Much of this knowledge accumulates via OJT, but many courses and specific objectives are in place as

well. Additionally, the Aviation Community generates and distributes mishap reports, hazard reports, updates to aircraft manuals, and other means of dissemination. This provides some useful fodder for considering the SWO Community, although with the caveat posed above: log book and like information can be useful to consider, evaluate and predict *individual* capabilities, but much more is required to do so for *teams* (e.g., watch teams aboard ship).

C. BRIEF COMPARISONS WITH SUBMARINE TRAINING DOCUMENTATION

In addition to the rigorous training and tracking of performance in the Aviation Community, the Submarine Community (including nuclear power) likewise is platform and performance centric. Knowledge of procedures and the specifics that apply to each boat (e.g., Forward, meaning the conning stations, and Aft, meaning the nuclear plant) are passed in face to face training that occurs each week. All hands are required to attend, and those that cannot have to be remediated.

Once a month a test is given the entire crew, which is all essay—there is no guessing about the right answer. Grading of exams is conducted by a central training office. The exam is purposely made difficult to reflect a 10 to 20 percent failure rate. Opportunities to retake the test are provided, but if failure continues, that individual will lose qualification in the area being tested. He or she then will have to requalify.

A training folder is maintained for each member of the crew, which is then reviewed by the ORSE (Operational Reactors Safeguard Examiners). It is interesting that the training folder does not follow the transfer of an individual from one boat to another, except for a performance technical rating that follows nuclear trained personnel. In general all transferees must requalify for each boat. This is true for both the forward and aft parts of the submarine. Performance in training and qualifications also does not follow the personnel to promotion boards. Rather the data from training records are used to make decisions regarding the balance of expertise and capability of each boat. Lessons learned are important in this community, and every collision or contact with an underwater feature is analyzed and briefed for contributing factors.

The Chief of the Boat develops a watch bill with input from officers at watch stations. One feature that assists with knowledge transfer is that watch relief starts with the most junior personnel and then progresses up through ever more senior personnel in the watch chain. This limits an *en masse* shift in personnel and helps maintain good knowledge transfer from one watch to the next. At each station there is a comprehensive pre-watch turnover briefing.

Another element to knowledge transfer is the requirement for incident reporting and lessons learned to be used by the submarine force, and frequent drills help further with knowledge flows.

For each of the communities discussed above there are training elements and sub-elements that need to be satisfied in order for each person to perform competently at a level that makes them useful. Acknowledging that there is a baseline for basic training in each professional path, records of training performance can and should be incorporated into a record that can be passed from command to command. Such record can be used to make decisions about how to create the right mix of personnel on a team.

D. SWO COMMUNITY APPLICATION

Given the discussion above pertaining to surface warfare proficiency KM needs, Aviation Community tools and techniques, and rigorous ongoing training and evaluation in the Submarine Force, here we apply what we've learned to the SWO Community. We begin by considering the log book, for this is being implemented in the SWO Community now. We progress then to examine expectations and progress over time, and continue to examine the tools available. This examination proceeds in turn as we inquire about NMETLS and personnel evaluation.

Preliminary to this examination, it is useful to consider some of the ways in which these communities are the same and different. In the Aviation Community, for instance, there are multiple paths a new aviator might take (e.g., F-18 and variants, turboprop E2-D, helicopters). At this level, aviators are learning the flight intricacies of their platforms. After airmanship, learning to use the mission electronics and weapon systems is required. It is not often that an E-2D pilot will end up flying a helicopter (unless that knowledge is transferred to him or her). The process is slow, and the learning is both explicit and tacit,

but a lack of knowledge becomes very obvious and can end an aviator's career. What is the significance of the platform? It moves through the medium (i.e., the atmosphere in this case) using power, is maneuverable through three dimensions, has rudder and other control surfaces for maneuvering, is greatly affected by weather, and in the case of multi-engine aircraft, an engine-out casualty has to be known instantly or power can be applied incorrectly leading to rolling the aircraft.

Consider the submarine, as another instance. It also moves through its medium (i.e., the sea in this case) using power, is maneuverable through three dimensions, has rudder and propeller for maneuvering, and is complicated by choices in buoyancy. In this way aircraft and submarines are similar, and training and the passing of knowledge reflect this similarity.

Finally there is the Surface Community. Ships move through a medium (i.e., the sea in this case) using power, are maneuverable through two dimensions, have rudder and propeller(s) for maneuvering, with different possibilities for power combinations, and handle very differently depending on weather conditions. Moreover, ships in general, even in the same class, are different, and those nuances are generally not part of a training program. One additional feature of ships: they are notoriously complex, with multiple mission areas and automated features are being added continuously, often with little training.

For decades the Surface Community has wrestled with the right combination of initial training and OJT aboard ship. It does not tend to be platform specific. A SWO pin can be earned on any warship, but with greatly different missions. Yet, realistically, when a SWO is transferred from an amphibious ship to a DDG, for instance, there is some expectation that this officer or senior enlisted person can attend to the needs of the ship with a remarkably limited amount of additional training. Some of this has changed with the LCS and Zumwalt classes, but in general it still holds true.

As noted above, the Aviator Community documents mishaps and hazards very well, and maintenance information is collected—often by the pilots, even referring to subtle issues and changes that can inform the next person flying—for every aircraft after every flight. In considering maintenance information along these lines—especially that collected by and transferred between pilots, who are users of the aircraft—we return to

our summary of the *McCain* accident above and the unbundled power yoke. This seems like the kind of information that would be useful on the Bridge, particularly as watchstanders are being relieved. Why wouldn't a relieving watchstander be informed about the unbundled yoke, for instance? We have no specific recommendations for how such information should be recorded and shared, but the kind of "Remove before Flight" tags that one finds on aircraft could provide some insight: whenever someone unyokes the throttles, some kind of signal (e.g., even a yellow sticky note) could be applied physically to the throttles.

In an aircraft, if an engine is lost or suffers a power reduction, the pilot only has moments to understand which engine is affected. There is a procedure for this ("dead foot") and for recovering the aircraft. Loss of physical connection with the ship's engine status does not give the OOD and helm the kind of physical feedback needed for quick understanding. Human systems could be added here (e.g., each shaft could have a tone on the bridge, and when synchronized is even sounding. When unsynchronized there could be a rolling sound).

We consider aviator achievements also, which are compared with training and qualification needs and plans of the squadron. We understand that ships have training officers (TrainOs), who are likely to capture and track much information along these lines. Perhaps TrainOs could compare their systems for recording and tracking SWO accomplishments with respect to ship needs and its training matrix. Returning again to the *McCain* incident, it appears that the two temporary duty crew members from the *Antietam* were "qualified" when they reported aboard the *McCain*, yet additional qualification (e.g., for Helm) was apparently required.

Further, every squadron has expectations for how each of its aviators will progress over time, and aviators are evaluated in part on how they progress with respect to such expectations. SWOs aboard ship have similar expectations, and they perform many activities (e.g., personnel qualification standards [PQS]) to qualify for various jobs, roles and responsibilities. As above, perhaps TrainOs could compare their system of recording and tracking SWO accomplishments with respect to ship needs and its training matrix. It will be important to understand the nature of such accomplishments, however. Is an accomplishment simply a check in the block, for instance, meaning that a task has

been completed, or does the accomplishment have some kind of evaluation or grade assigned to it? Watch Bill information, for instance with CO capability ratings (e.g., Level 1-4), could help to inform this aspect of shipboard qualifications and capabilities further.

Regarding tools, SHARP and the Scheduling Tool represent promising places to start thinking about how to capture, record, summarize and distribute important SWO information. It appears as though the SWO Community has some existing tools that share some similarities with DRRS: TORIS tracks unit level certifications of ships, for instance.

We continue to be intrigued by how the Aviation Community can center its training on NMETLS, and we consider how the SWO Community may do likewise. If SWO shipboard NMETLS do not suffice or serve a similar function, for instance, then perhaps PQS line items could represent a suitable proxy. A thorough and orderly list of accomplishments that people onboard ship need to complete—along with the sequence and timing of completion—would appear to be very useful, and one can envision a colored dashboard (e.g., spreadsheet with red, yellow, green and blue cells) of accomplishments vs. plans and expectations would provide a ready summary of personnel status and qualifications.

Finally, we appreciate how aviators who are new to a squadron are evaluated and cleared (or not) by more experienced squadron members, and by how every aviator must be approved in this manner before being allowed to fly, regardless of prior flight experience. Thinking back to the *McCain* incident, we must surmise that this kind of evaluation and clearance was unlikely to have taken place before the original and relieving Bridge teams reported to their watch stations. Perhaps the SWO Community can learn from this practice as well.

We proffer these comments and suggestions with great humility and in the most constructive manner. We are not current SWOs. We were not on the *McCain*. We do not have in depth knowledge of and familiarity with the extant tools and techniques for collecting, recording, processing and sharing key surface warfare proficiency information. Nonetheless, there are many times when a new look through fresh eyes can be insightful. That is our intention.

V. CONCLUSION

As a key tenet of readiness, it is important to know—tracking at the present time and forecasting through various future timeframes—measure, and understand unit level proficiency and individual career proficiency. As an example, this has been especially highlighted recently in trying to assess the proficiency of Surface Warfare Officer seamanship. This research works toward development of a knowledge management (KM) approach to such measurement and understanding, seeking to enable current tracking and future forecasting. The KM approach will be developed to enhance quality design characteristics such as intuitive operation, natural data entry, agility and global reach.

In this study, we bring the state of the art in terms of Knowledge Flow Theory, analysis, visualization and measurement to bear on measuring and tracking SWO proficiency and readiness. After summarizing very briefly the nature and composition of the SWO Community, we summarize some relevant prior research on knowledge flow theory, which we follow with an overview of our basic system for dynamic knowledge visualization and measurement. This illustrates a novel and powerful approach to visualizing and measuring dynamic knowledge, which is inherently invisible, intangible and resistant to quantification.

We then summarize the research method, which centers of four tasks: Task 1: Research the academic, doctrinal and professional literatures to understand the key factors that contribute to individual and unit readiness. The key academic literatures are summarized above as background to this study, along with prior research to understand the SWO Community. We also review key articles and reports in the professional literature, including the Navy's Comprehensive Review of the 2017 accidents involving the cruiser *Antietam* and destroyers *Fitzgerald* and *McCain*, approaches to measuring the talent of naval personnel, and other sources of information, including several conversations with senior, active and retired SWOs.

Task 2: Understand how such key factors are or can be measured, tracked and forecasted today. This involves a combination of document review, survey, telephone conversation, personal interaction, and onsite observation. A key result of this task emerges in terms of the SWO Community seeking to build upon its Aviation counterpart

through the implementation of the Mariners Log Book. Such log is intended to serve a purpose similar to that of the Aviation Log Book that has been used for many decades by aviators. Indeed, some of our best insight stems from analysis of the Aviation Community.

Task 3: Build upon our understanding of knowledge and information flows, and the results from Tasks 1 & 2, to identify the kinds of readiness knowledge and information required for intuitive yet reliable assessment. We report on this in the results section. First, we outline key problems facing the SWO Community in terms of surface warfare proficiency KM. We begin with a relatively high level summary, which includes an excerpt from the 2018 Comprehensive Review for concrete context. An excerpt from the *McCain* incident turns out to be particularly informative in this regard. Specifically, we employ our multidimensional knowledge flow spaces to visualize some critical activities and processes on the *McCain* Bridge, along with a couple of suggestions for mitigating some of the knowledge flow issues that arose. The knowledge flow vectors provide keen and novel insight into the issues and processes.

We follow such visualization with measurement of the same knowledge flows. This enables one to compare, quantitatively, the knowledge flows—and knowledge losses—associated with some critical processes on the Bridge. It also enables one to understand better how simply posting procedures (e.g., for transfer of throttle and steering control) adds little additional knowledge to stem the huge losses that accompany watch changes. Because knowledge enables action, and action drives performance, one can see how knowledge lies at the root of all shipboard activity: where knowledge is sufficient, and where it flows reliably and responsively, the actions are sound, and the corresponding performance is good. Alternatively, where knowledge is lacking, or where it fails to flow with sufficient energy and speed, actions and performance suffer. Dynamic knowledge analysis along these lines represents a novel capability for the SWO Community.

Finally, we analyze the Aviation Log Book and Submarine Community in terms of potential to inform the SWO Community. Aviation and Submarines share a number of common factors with Surface Warfare, but they differ across myriad dimensions also, so one cannot expect a perfect or complete mapping. Nonetheless, insights and opportunities

appear, and we proffer a number of comments and suggestions for SWO Leadership to consider.

In particular, learning from the Maintenance Debrief in aviation could be useful on the Bridge and elsewhere aboard ship. Considering, for instance, the issue aboard the *McCain* with the unbundled power yoke, perhaps the kind of “Remove before Flight” tags that one finds on aircraft could provide some insight: whenever someone unyokes the throttles, some kind of signal (e.g., even a yellow sticky note) could be applied physically to the throttles.

As another instance, shipboard TrainOs may benefit through comparison of their systems for recording and tracking SWO accomplishments with respect to ship needs and its training matrix, as is done in aviation. As a third instance, regular exams could be given to all Bridge personnel to gauge proficiency, as is done on submarines. The *McCain* incident provides insight into these suggestions also. Likewise, Watch Bill information, for instance with CO capability ratings (e.g., Level 1-4), could help to inform this aspect of shipboard qualifications and capabilities further.

Regarding tools, SHARP and the Scheduling Tool represent promising places to start thinking about how to capture, record, summarize and distribute important SWO information. Further, we continue to be intrigued by how the Aviation Community can center its training on NMETLS, and we consider how the SWO Community may do likewise. If SWO shipboard NMETLS do not suffice or serve a similar function, for instance, then perhaps PQS line items could represent a suitable proxy.

Finally, we appreciate how aviators who are new to a squadron are evaluated and cleared (or not) by more experienced squadron members, and by how every aviator must be approved in this manner before being allowed to fly, regardless of prior flight experience. Thinking back to the *McCain* incident, we must surmise that this kind of evaluation and clearance was unlikely to have taken place before the original and relieving Bridge teams reported to their watch stations. Perhaps the SWO Community can learn from this practice as well.

Task 4 represents future research: Work with experienced SWO personnel to draft the kind of architecture that can support a KM approach to measurement and understanding, enable current tracking and future forecasting, and enhance quality design

characteristics such as intuitive operation, natural data entry, agility and global reach. We have many suggestions for approaching this future research, but there is much to be done now, with the problems we've identified here but have yet to solve.

Before closing, we must reiterate a very important insight that emerges from analysis of surface warfare proficiency. On the Bridge and elsewhere aboard ship, *team* knowledge and *team* performance are critical: It is insufficient for each individual officer and crew member to be knowledgeable, experienced and proficient. Rather, people must perform well on teams (e.g., watch standers on the Bridge), and to do so, as with sports teams, they must practice together, and team performance is important to track. This suggests that Watch Bill—and watch performance—information, for instance, may prove useful in this regard, but much work is required to outline an effective and consistent approach.

Team performance is important as noted, however a “watch team” can shift from an immediate need, an illness, departure for training by a core member or a re-mixing of the talent pool by the Senior Watch Officer. Other more radical approaches would separate the Bridge watch team into smaller groups (e.g., OOD/JOOD/CICO) that truly do represent a team, and the enlisted bridge crew (e.g., Helm, Lee Helm, Navigator) as examples. Traditionally the ship's work schedule is divided into watches, with rotations of watches moving with a regularity of 4 watches per day. (One is a “dog watch” to make sure the schedule progresses and the teams do not continually have a single time they are on watch.)

An alternative to this is to have the smaller teams organized in such a way that the Bridge watch (as an example) is staggered. In this way the burden of moving knowledge from one watch team to another in totality would be lessened. It would become a partial flow of knowledge and immediate situational awareness. Although more complex, the result would be a continuous flow of knowledge between watchstanders.

This also suggests that our ability to leverage processes from Aviation Log Books may be limited in terms of application to surface warfare proficiency at the team level: although all pilots participate on teams (e.g., with maintenance, scheduling, weather, crew personnel), the log book captures principally individual information that is focused on the pilot. As explained above, individual pilot log book information can be useful to

inform individual SWO log book organization, but team knowledge represents another and much more challenging step. One step at a time.

We proffer these comments and suggestions with great humility and in the most constructive manner. We are not current SWOs. We were not on the *McCain*. We do not have in depth knowledge of and familiarity with the extant tools and techniques for collecting, recording, processing and sharing key surface warfare proficiency information. Nonetheless, there are many times when a new look through fresh eyes can be insightful. That is our intention.

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