Cover sheet for the 14th ICCRTS
"C2 and Agility" 15-17 June 2009, Washington, D.C.

Paper No. 016

Title:

Information-Velocity Metric for the Flow of Information through an Organization: Application to Decision Support

Track 8 topic: C2 Assessment Tools and Metrics

Authors: Jeff Waters, J.D., Ritesh Patel, B.S, James Eitelberg, M.S., and Marion Ceruti, Ph.D.

Organization: Space and Naval Warfare Systems Center Pacific (SSC Pacific)

Address: 53560 Hull Street, San Diego, CA 92152-5001, USA, (619) 553-4068

Email: jeff.waters@navy.mil, , ritesh.patel@jpmis.mil, james.eitelberg@navy.mil, marion.ceruti@navy.mil

Marion Ceruti, Ph.D., Point of Contact
(619) 553 4068

Filename: Waters.etal.PaperID_016_InfoVelMet_ver38.CR.doc

Information-Velocity Metric for the Flow of Information through an Organization: Application to Decision Support

Jeff Waters, J.D., Ritesh Patel, B.S, James Eitelberg, M.S.,
and Marion Ceruti, Ph.D.

Space and Naval Warfare Systems Center Pacific (SSC Pacific)
53560 Hull Street, San Diego, CA 92152-5001, USA, (619) 553-4068
jeff.waters@navy.mil, ritesh.patel@jpmis.mil, james.eitelberg@navy.mil,
marion.ceruti@navy.mil

Abstract: - The rapid flow of information through a command-and-control organization strengthens the agility of the command and increases the efficiency of the organization. Therefore, a metric is proposed for the speed of useful information as it flows in an organization, enterprise or command structure. Information is assumed to be useful if a member of the organization considers it to have the potential to reduce uncertainty, and thus become an important contribution to a decision process. Information velocity depends on information flow and time, which is sometimes described as "getting the right information to the right person at the right time." Efficient information flow is the goal of net-centric warfare and is needed for making faster, better decisions. Everyone is a decision maker on some level. Modern organizations demand optimal agility, creativity, and innovation. Various factors, techniques, and tools can help improve information velocity. Given the state of technology at the time of this writing, a direct measure of information flow in command centers does not appear to be possible in the near future. Therefore, the present study focuses on the timing aspect of information velocity, which deals with time management in organizations in general, and in command centers in particular. This paper describes an individual decision-making model that attempts to fill this gap. It proposes formulas for measures, suggests a small, simplified set of questions to obtain a quick metric, and describes future research. The authors welcome comments and suggestions and would like to collaborate with others on this effort. This work supports the GIS3T interoperability test bed, which you are welcome to join.

Keywords: - Agility, assessment tools and metrics, C^2 concepts, C^2 theory, decision model, decision support, employee empowerment, entropy, industrial computer applications, infodynamics, information sharing, information theory, time management, uncertainty.

1. Introduction

Information Velocity (v(info)) is the first time derivative of the information flow. What is an Information Velocity Metric (IVM)? The definition for the word "metric" is "art, process, science or system of measurement." "Velocity" is the speed and direction of motion of a moving body. "Information" has been defined as "facts, data;" "knowledge obtained from investigation, study or instruction;" and "something, such as a message, experimental data or a picture, that justifies change in a construct, such as a plan or a theory, that represents physical or mental experience of another construct" [1]. The last definition is the one most relevant to the flow of information because it relates to how new information can change existing constructs by reducing uncertainty regarding some aspect of these constructs. IVM is an attempt to measure the speed and direction of information as it moves through an organization.

Information velocity has two significant aspects – information flow and time as illustrated in Figure 1. The study of information velocity is focused on factors that can reduce uncertainty in the fastest manner. These aspects are important in many different types of organizations but especially for command centers.

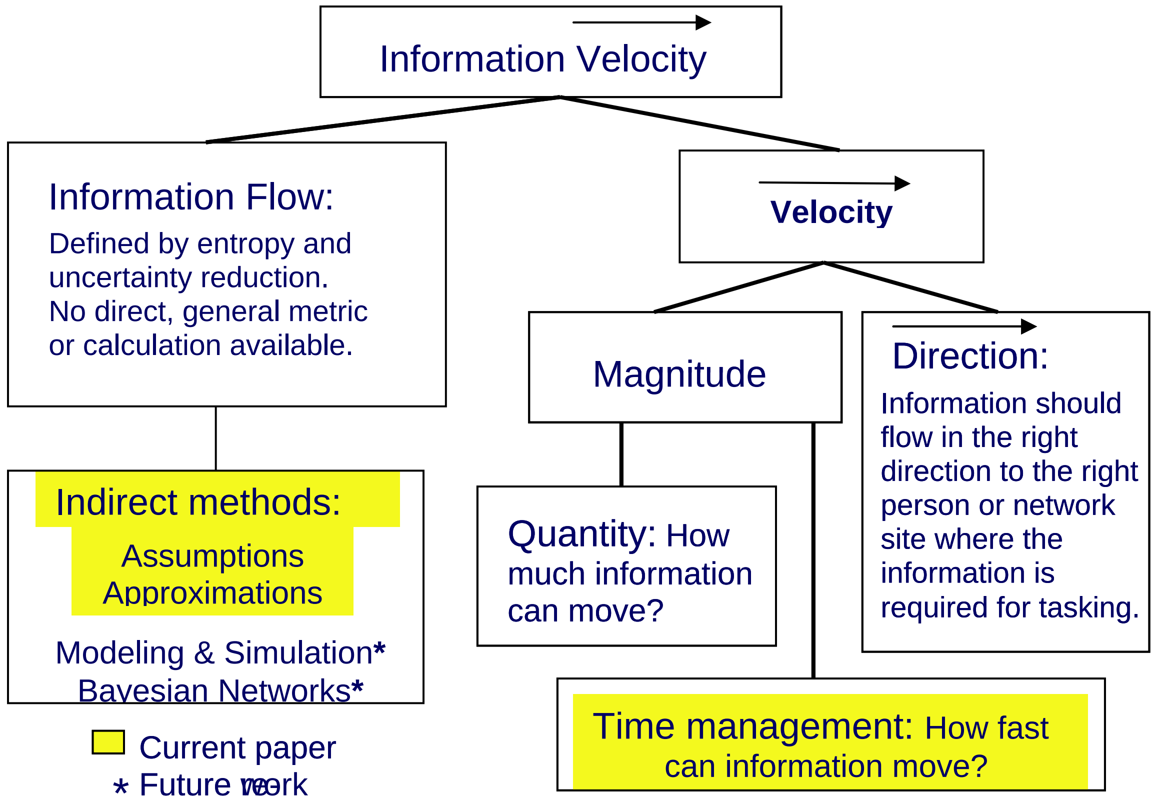

Figure 1. Taxonomy of Information Velocity

Ideally, information will move quickly and efficiently through the organization - not just up the organization's chain of command, but also down and across echelons in the organization. Today's organizations, especially those focused on information processing, demand a free flow of information. The global war on terror demands a focus on the need to share information across federal, state, county, city, local, tribal and non-governmental organizations and coalitions. The IVM is intended to measure the speed of information flow within an organization or enterprise with a view toward improving the speed and quality of making decisions thereby reducing uncertainty. As is often said in the Department of Defense (DoD), the IVM is intended to measure the speed with which the "right information is getting to the right person at the right time."

This paper covers the following topics:

- Information flow and uncertainty,
- A derived expression for v(info) that relates it to power and task tractability.
- Approximate, causal, and effects-based information metrics,,
- Advantages and disadvantages of the different metrics,
- Theory underlying the inclusion of the different metric components,
- Proposed metrics based on theory, a review of applicable literature, and an assessment of cumulative experience in development of situational-awareness tools in selected command centers.
- Future research to explore the efficacy of the measures in a modeling-and-simulation (M&S) environment, and explore the measures in an operational, organizational setting.

2. Developing a Good Metric

The study of information could benefit from an examination of the context in which a good metric would be used. The definition of a good and suitable metric is the first step in metric development. Ideally, a good and suitable metric is one that is:

- Measuring the right quantity,
- Important and significant,
- Relevant and useful,
- Well defined and understandable,
- Accessible and achievable,
- Reliable and predictive,
- Robust and comprehensive,
- Sensitive,
- Simple and easy to use,
- Timely and cost effective,
- Efficient to compute, and
- Helpful to improve processes.

In contrast, a bad metric is one that is:

- Measuring the wrong quantity,
- Ill defined and incomprehensible,
- Insignificant,
- Too complex and hard to use,
- Time consuming to compute,
- Subject to errors and misinterpretation,
- Ineffective and insensitive,
- Misleading, and useless.

A good metric should yield the same value for the same measurement data to within the tolerance or experimental error of the measuring device(s). Irrelevant modifications in the data should not perturb it significantly. A good metric is one that will help define and facilitate an understanding of the measured quantity. As expressed in quotations [2] attributed to Lord Kelvin, "To measure is to know."

A metric can provide an absolute measurement or a relative measurement. For example, an automotive gas gauge could indicate an absolute measurement, e.g. 8.7 gallons, or could provide a relative measurement, e.g. half full. Either format may suffice, but one may be better depending on the convention, the expertise of the users or the purpose of the measure.

The second step in metric development is to determine how well a quantity is defined and how well its processes are understood. This is important because it can affect the type of metric that one can employ, e.g. relative or absolute measurements. Consider three types of metrics, e.g. those that employ:

- A direct measure,
- Causal measures,
- Effects measures.

In the first case, if a quantity is well defined and accessible to measurement, direct measures are appropriate. Direct measures are especially important when:

- They are not too costly,
- They are not too intrusive,
- The causes and effects of the measured process are well understood.

Indirect measures, such as causal measures, are useful and appropriate when:

- They can be correlated to the process,
- They help to define the process,
- Direct measures are not easily employed.

Causal measures are especially helpful for exploring our understanding of the underlying mechanisms of a process. Causal measures also help to explain how to improve the process. Effects measures offer the advantage of helping to achieve the desired effect. Yet the effects measures often assume a correlation between the process and the effect, which is an assumption that direct measures avoid. Considering the applicability of the three different types of measures (direct, causal, and effects) helps guide the metric-design process and helps ensure that a good metric will result

3. Characteristics of Agile, Creative and Sustainable Decision Making

Making agile, creative, and sustainable decisions in a command-and-control environment depends on conditions that differ significantly from making decisions in a standardized and relatively static environment where sub-optimal decisions do not lead to life-and-death consequences.

For example, consider the stereotype of a traditional manufacturing assembly line in an environment where well-defined processes change slowly. Workers make decisions according to fixed rules that rarely change. Such an environment is characterized by the utmost standardization and optimization where no one expects the average worker to consider the big picture. Here, the goal is not for workers to "think outside the box," or worry about other people's tasks. The assembly-line worker must focus on limited, fixed, and standardized decisions that are important, but have a smaller scope. Here, the need for agility and creativity is partitioned and compartmentalized for each worker. In the DoD something equivalent to this environment occurred during the cold war. The enemy was static and the emphasis on symmetric warfare encouraged traditional thinking.

The stereotype described above stands in sharp contrast with the demands for agility and innovation in the current global business and military environment. For example, the DoD and other departments of the executive branch, such as the Department of Homeland Security (DHS), are focused on fighting the asymmetric, global war on terror. In this environment, the conditions are not as fixed and the processes not as standardized as they were during the cold war. Here, the need for honed optimization of narrow tasks is less possible and less desirable because everyone needs to be engaged in observing the environment. Agility and creativity on the part of all employees is essential because good ideas and innovation are not limited to a few experts. Successful, agile decisions are best accomplished by rallying all resources to the cause. (For additional insights into the decision-making process, see, for example, [3].)

The following observations pertain to an agile, dynamic decision-making environment.

- In the most successful modern organizations, people are empowered and encouraged to think independently, to develop new ideas, and to share information that sparks development. In this paradigm, employees assess and reduce uncertainty by passing useful information.
- At some level, every employee is a decision maker. Roles are broader and have more authority.
- People typically make decisions that are based on the decisions of others and often not on raw data especially in organizations that process information. Thus, optimizing the individual decision-making process also optimizes overall information flow. For example, decisions of people in support roles constitute the input information for most high-level decision makers.
- "Useful" information from an organizational perspective is any information that an employee considers important to reduce uncertainty. Thus, a general definition of information usefulness should be based on the employee's assessment of uncertainty before and after the information is received.

A proposed standard for representing decisions, a Common Decision Exchange Protocol, is defined and recommended for this purpose in [4].

4. Decision-Making Process Model

This section describes a model focused on the time-management component of information velocity (Figure 1.) Significant research has defined the basic decision-making process in the general form, commonly called the Observe–Orient–Decide–Act (OODA) loop. In this study, this decision-making model has been revised only slightly to capture the process from the perspective of information flow.

The decision-making process model is depicted in Figure 2, where states of information management are not the same as the states of information as described in [5], but rather, the states of information management parallel the states of information because information is aggregated at progressively higher levels from one state to the next. Data aggregation, data integration, and data fusion in support of command decisions are aimed at the rapid reduction of uncertainty by minimizing the alternative decisions. In Figure 2, this process of reducing the search domain (and the entropy) can occur anywhere, but mainly occurs in steps 1, 2, and 3 (See, for example, [6].)

The decision-making process depicted in Figure 2 assumes that some states can be skipped or that very little (or no) time is spent in a given state.

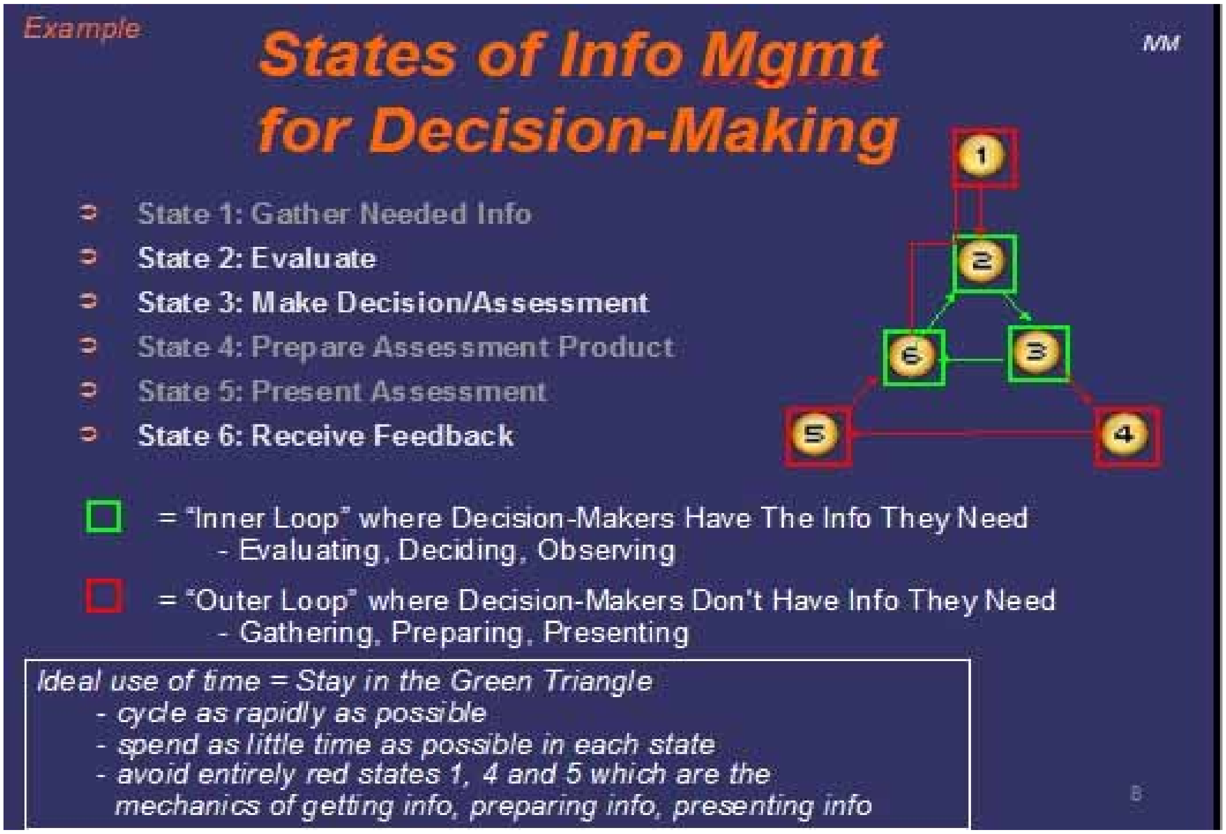

Figure 2. Information-Flow Model

The model assumes that decision makers use some variant of the following procedure.

- Gather information needed to make a decision.
- Group information according to the alternative courses of action it supports.
- Evaluates and prioritize alternatives.
- Make the decision.
- Prepare a decision product, which could be a PowerPoint slide, a report, an email, a meeting, a phone call, or some other means to communicate the decision.
- Communicate the decision to others in the organization,
- Receive feedback from others regarding the outcome of the decision.
- Either re-enter the evaluation state or finish the decisions process. (In Figure 2, the start and end states are not shown.)

With this model, one can consider the impact on a decision maker who gets the right information at the right time. The most immediate and obvious benefit of an improved time-management is that the decision maker can spend less time in State #1, gathering information. This is particularly true if one assumes that the decision maker has support personnel in State #1 who gather, process, and present information to the decision maker in an efficient manner. However, a person who is awaiting the decision also is a decision maker who needs the decision as input. From this perspective, time spent preparing a decision product (State #4) and communicating the decision (State #5) represents a delay in the information flow because the decision already has been made in State #3, and other decision makers downstream are still in a state of uncertainty.

Given the assumption described above, the model suggests that the impact on a decision maker from increased information velocity is that the decision maker can spend less time in States #1, #4 and #5, the states colored red in the diagram, relative to States #2, #3, and #6 in the diagram.

Unless considerable data fusion has occurred in State #1, the decision maker will spend a greater proportion of the decision-making time in green states. The decision maker can move through the decision cycle faster and/or with a higher quality output. In this case, the decision maker and the organization overall can handle an increased number of decisions or workload.

Speed and quality are important in making decisions. High quality decisions that are based on subordinate decisions as input depend heavily on honest, unbiased, unfiltered assessments. Similarly, improvements in useful, high-quality information flow depend on a policy that fosters honest, unbiased, unfiltered assessments. The states that account for this part of the process need to be included in the decision-making state model to ensure that it is included in the metric. Figure 3 depicts an expansion of State #3 (Make Decision/Assessment) from Figure 2.

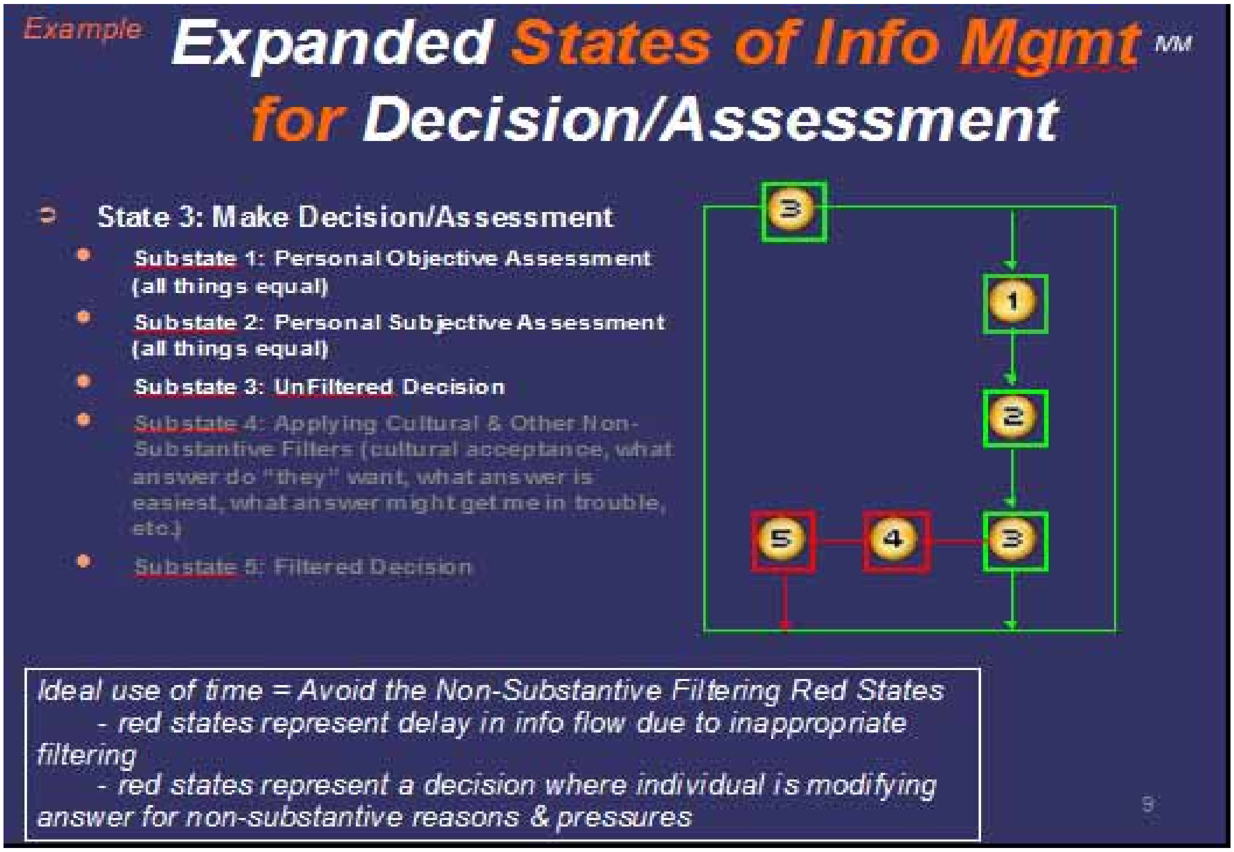

Figure 3. Information-flow model expanded decision substates

In Figure 3, the following subprocess is described in terms of substates of State #3 from Figure 2. The decision maker might use the following procedure (in this order).

1. Assess the alternatives according to one's own personal objective assessment based on education and training (Substate #1).
2. Perform subjective assessment based on personality and experience (Substate #2).
3. Make an internal, unfiltered, and externally unbiased decision (Substate #3). Ideally, the decision maker would exit these substates with a direct, honest, unbiased decision; however, most decision makers will continue to the next substate.
4. Weigh the above assessment against the possible acceptability of this decision with the decision-maker's supervisor, colleagues, and upper management. Consider the answer that they want, the easiest answer, and the answer that poses the least extra work or political risk (Substate #4).
5. Make an "external" decision filtered by external influences less honest, more biased,

and likely to reflect the desired and expected answer without any independent decision process. At this point, a decision-maker exits the substates with both the honest, direct internal assessment and the filtered external answer. Depending on the setting and the employee's organizational bravery, others will receive a recommendation that includes either one or both decisions.

What does improved time management mean in this context? In Figure 3, substates #1, #2, and #3 are colored green to represent states that are desired to derive useful information. Substates #4 and #5 are colored red because they reflect a “varnished” or influenced opinion that results in less “useful” information from an organizational perspective. As other decision makers downstream in the information flow await upstream decisions, time spent tailoring a decision for outside influences delays the process and results in an opinion less honest and more biased. Thus, improved time management enables decision makers to spend less time in Substates #4 and #5 as a proportion of the total time spent in State #3.

5. Elements of a Course of Action

More often than not, a decision will result in some type of Course of Action (COA). This section describes the components of a COA.. Generally, decisions pertain to future COAs based on current information, current options and projected trends. Components of a COA also are components of a decision process because to arrive at a decision requires a procedure, or COA. For the sake of argument, we consider the elements in a COA in general, but the same elements apply equally to a decision. Elements of a COA or a decision could include the following:

- What to do? Actions that must be performed as a result of the decision usually are conditioned on the receipt of data. COAs generally consist of many sub-tasks, some of which are sequential and some can or must be performed in parallel. Some COAs have critical actions that determine the outcome of the COA. If one or more critical actions cannot be performed, it may be necessary to select an alternate COA.
- Where to start? This could be a collection of geographic locations or it could be what document to examine to begin analysis.
- Where to end? The decision maker may not be able to specify exactly where to end because by the time the COA is complete, many modifications may have been made in the COA that could affect the end location.
- When to start taking action? This could be unconditional or conditioned on circumstances that may be unknown when the COA is formed. When to start could be a time, such as a date-time group. If the COA has many subtasks, when to start may be different for different subtasks. When to begin one subtask may depend on the outcome of an earlier subtask.
- When to end the COA? This could be a specified time, such as a date-time group, but usually includes exit criteria that depend on when each subtask is complete. The COA cannot end until each subtask is complete or not necessary to execute. When to end likely is conditioned on the success of the subtasks and how well they proceed.
- In what direction will information regarding the COA proceed? This relates to the part of information velocity that pertains to direction of information flow. Who should know about the outcome of tasks and subtasks in a COA will determine who gets these reports. The commander and subordinates alike will need to know this.
- Who will perform the COA? The larger the group involved, the more complex the estimation of the conditional entropy because each group member involved in the COA could have a different level of uncertainty associated with specific tasks that pertain to that individual.

6. Uncertainty and Information Flow

Previous work aimed ultimately at reducing uncertainty in command centers has focused on reducing search domains in database integration [6] and the delivery of available, relevant, timely, and needed (and therefore, useful,) information from the battle space to a user [7]. The reduction of a search domain in a database integration problem reduces uncertainty by limiting the search for the solution to the problem where it is most likely to be found [6]. Similarly, an improvement in the availability of information that can help solve a problem related to a user's tasking increases information flow to the extent that it reduces the user's uncertainty about the solution of the problem under consideration. In any case, users at all levels must make decisions. For example, an engineer recommends using a number that was the solution of an equation, or a commander orders a COA in battle.

In this section we derive an equation for v(info) to show how it is related to power and task tractability, T_Y, by invoking simple physics and infodynamics [5]. Specifically, information flow depends on the values of variable *h*, (which relates to the decision or solution) and variable *l*, (which relates to the available data) in a given process. Information flow, *p*, is defined in equation (1) as the difference between the uncertainty before the process started and the uncertainty after the process is finished [8].

$$(1) \qquad p = H(h|l_1) - H(h|l_2)$$

In equation (1), $H(h|l_1)$ is the conditional entropy of variable *h* before the process started given the variable l_1, also before the process started. In contrast, $H(h|l_2)$ is the conditional entropy of *h* before the process started given the variable l_2, which is the value of *l* after the process is finished. Conditional entropy can be conceptualized as the number of alternatives that are viable given the information at hand.

For example, as depicted in Figure 2, information is gathered in state 1. Its transfer to a decision maker constitutes the transition to state 2. Here, $H(h|l_1)$ applies to the decision maker before new information is received. State #2 is where the transition from l_1 to l_2 takes place as information is evaluated for its content and ability to reduce uncertainty. $H(h|l_2)$, is related to the alternatives available to the decision maker after the gathered information is evaluated in State #2. Information flows to the decision maker to the extent that the uncertainty that previously existed becomes reduced as a result of receiving the new information. When State #3 is entered, the effect of the information flow already has taken place and the reduced uncertainty facilitates whatever decision is made.

To understand equation (1) in a command-and-control context, let the variable, *h*, be the COA, and variable *l*, the information from the battlespace that supports the selection of a particular COA. Conditional entropy, $H(h|l_1)$, which describes this state, could be the number of COAs consistent with the information initially available. Thus, variable *l* changes from l_1 to l_2 when useful information is received in the command center. The conditional entropy also changes to $H(h|l_2)$ after this information is instrumental in reducing the uncertainty. Thus, $H(h|l_2)$ will be smaller than $H(h|l_1)$ when the new information, l_2, reduces the number of alternative COAs because COAs that are inconsistent with the new information, l_2, will be ruled out.

Another way to conceptualize this process is as follows. Before the receipt of useful information, l_2, many COAs, *h*, are available. Entropy $H(h|l_1)$ is high and the uncertainty about what to do, therefore, is high. Information flow, *p*, increases in a command center when it results in a reduction of the number of viable COAs. This is because l_2 forces the elimination from consideration of COAs that will not work in light of the new information. This reduced selection in COAs is quantified by a reduction in the conditional entropy. Thus, what to do becomes clearer as a result of information flow.

The above example illustrates equation (1) using COA as variable *h*. However, other variables commonly measured in the battle space also could be selected to illustrate equation (1). One such example can be defined as, *h'*, the position of a particular hostile platform. In this case, any information, l_2 that sheds light on that position will reduce the uncertainty in variable *h'*. This is particularly easy to conceptualize and compute in terms of the ellipse of uncertainty typically drawn around a position measured by the triangulation of sensor lines of bearing. (See, for example, [7].) Initially, l_1 is the information available in the command center about the hostile platform, which could be anywhere in the battle space if no one knows anything about it.

Thus $H(h|l_1)$ is high. After the receipt of information, l_2, the hostile platform's position is confined to the ellipse of uncertainty associated with the measurement of its position. Now $H(h|l_2)$ is reduced considerably compared to $H(h|l_1)$. The value of p can be calculated in this case in a much more definitive way than in the case where h represents COA, which can depend on the integration and fusion of many different types of data, including but not limited to the positions of hostile forces.

Knowing the position of a hostile vessel may reduce the uncertainty of a COA because it may cause any COAs that are inconsistent with the vessel's position to be ruled out. The actual overall uncertainty in COA selection depends on the uncertainty in many variables and their interactions in the battle space, including but not limited to the positions, capabilities, and strengths of hostile and friendly forces; various sources of uncertainty associated with the measurement of data from sensor networks; weather observations and forecasts; sea states; time of day; the order in which messages are received and processed; the availability of logistical support; and the commander's interpretation of the culture to doctrine.

By definition, v(info) is the time derivative of the information flow, p. d stands for a small change.

$$\textbf{(2)} \qquad v\,(\text{info}) = dp\,/\,d\,t$$
$$= d\,H(h|l_1)\,/\,d\,t \;-\; d\,H(h|l_2)\,/\,dt$$

Note that v(info) is like acceleration because it involves a change in time derivatives of entropy. Thus, v(info) has the units of entropy, H, over time. In thermodynamics, entropy has the units of energy, heat (U), or work (W) over temperature (T). Equation (3) defines the thermodynamic entropy, dS, in terms of the change in the reversible heat, U_{rev} over T [9].

$$\textbf{(3)} \qquad dS \;=\; dU_{rev}\,/\,T$$

The infodynamic [5] analog of entropy, $H(h|l)$, also has the units of entropy over a temperature-like entity, T_Y, but in this case, the T_Y refers to the degree of tractability [5]. A task is highly tractable if the completion of a task requires simple, logical, straightforward combinations of independent data. The dependence of one data element on another tends to make tasks less tractable because more complex data-fusion algorithms are involved in task completion. A task will be highly tractable when entropy and uncertainty are low and the number of alternative decisions is relatively low. Another way to conceptualize T_Y is expressed in equation (4), where in most cases, T_Y will be proportional to the reciprocal of the sum over algorithms of the number of bits in each algorithm that is necessary to process and fuse raw data. (At least equation (4) should be a good estimate of the relative complexity of the data-fusion processes.)

$$\textbf{(4)} \qquad T_Y \;=\; C \;/\; \Sigma\, n_{bits}$$

C is a constant that depends on the type of task. T_Y also could be expressed as the reciprocal of the sum of the variables and their interactions in a manner analogous to the Virial expansion in gases. (See, for example, [9] and [5].) Here, we assume that T_Y does not depend directly on time.

The infodynamic analog of (3) is equation (5).

$$\textbf{(5)} \qquad d\,H(h|l) = d\,W\,/\;T_Y$$

In information management, especially as it applies to organizations, T_Y is like T because when $H(h|l)$ is high, T_Y is low. The tractability of a decision task decreases in inverse proportion to the number of possible alternative solutions i.e. the uncertainty. A high information flow, p, reduces the uncertainty and reduces the amount of work necessary to make a decision. Highly intractable tasks require a larger information flow to solve them. As p increases, the tractability, T_Y, of the decision task increases. T_Y, actually is not a constant and is conditioned on the data and their fusion algorithms

Newton's law defines physical force below.

$$\textbf{(6)} \qquad F \;=\; J \quad d^2X/\,dt^2$$

where J is mass, X is distance, and t is time. J represents only the useful information that is relevant to a particular task. Only this useful information will be instrumental in reducing uncertainty. The second time derivative of the distance, X, is d^2X/dt, acceleration. Work, W, is given by equation (7).

$$\textbf{(7)} \qquad W \;=\; F \;\; X$$

$$\textbf{(8)} \qquad d\,W \;=\; F \;\; dX$$

The concepts expressed in equations (6) through (8) can be adapted to apply to information flow. Combining equations (2) through (8) yields

$$\textbf{(9)} \qquad d\,H(h|l) \;=\; (J/T_Y)\;\;(d\,^2X/\,dt^2)\;\;dX$$

Dividing equation (9) by dt, as in equation (2), and proceeding to the limit yields equation (10).

$$(10)\quad dH(h|l)/dt = (J / T_Y)\,(d^2X/dt^2)\; dX/dt$$

Now set $X_d = dX/dt$ and substitute.

$$(11)\quad (d^2X/dt^2)\,(dX/dt) = \tfrac{1}{2}\, d/dt\, (dX/dt)^2$$
$$= \tfrac{1}{2}\, d/dX_d\, (X_d)^2\, (dX_d/dt)$$

Combining equations (2), (10), and (11) yields equation (12).

$$(12)\quad v(\text{info}) = d/dt\, \{ (\tfrac{1}{2} J X_d^2)_1 / T_{Y1} - (\tfrac{1}{2} J X_d^2)_2 / T_{Y2} \}$$

Where the ($\frac{1}{2}$ J X_d^2) terms are energies. As is evident from equation (12), v(info) has the units of power per degree of tractability. The power term, G , is given by equation (13).

$$(13)\quad G = d/dt\, (\tfrac{1}{2} J X_d^2)$$

Thus, an increase in either v(info) or T_Y, results in more power, G. Thus, the aphorism, "information is power" is almost accurate. Actually information velocity is proportional to the power, as is evident in equations (12) and (13). This is especially true in a command-and-control context, where the flow of information, or the lack thereof, influences power projection and could make the difference between victory and defeat. The velocity at which information flows in an organization will determine who and how many have power, how much power they have, when they have it, and for how long. This reflects the fact that information is important for individuals as well as for an organization as a whole. However, this power will be important and can be used only if the information is received in a timely manner.

Equation (12), suggests the analogy between information dynamics and fluid dynamics. X^2 is like the cross sectional area of the virtual "pipe" through which the information flows. J is the useful information moving through that "pipe."

Equations (12) and (13) are best tested in M&S experiments where variables are well defined and uncertainties can be calculated and controlled.

7. Assumptions and Approximations Regarding Information Flow

M&S not withstanding, exact, general, and direct metrics for overall information flow, *p*, and hence v(info) in a command center have yet to be developed and are not likely to be obtained in the foreseeable future using current technology. Therefore, additional assumptions are necessary. For example, to simplify equations (1) and (2), assume that $H(h|l_1)$ is large, unknown, intractably complex, and unknowable before the decision deadline. (N.B. It is not necessary to assume that $H(h|l_1)$ remains constant, just large compared to $H(h|l_2)$. In this case, the task reduces to minimizing $H(h|l_2)$).

Actually, l_1, and l_2 each represents the information associated with a data set or collection of n variables that consists of the potentially relevant data elements, l_i through l_{i+n} and, ideally, their pedigree metadata m_i [10]. Each metadata element, m_i, describes or summarizes the metadata associated with a particular data element. Each metadata element, m_i, which can be conceptualized as a weighting factor, expresses the uncertainty of l_i. Metadata element, m_i, also can include an estimate of the relevance of each l_i to the scenario associated with the decision task, as part of the metadata.

$H(h|l_2)$ is a multivariate function, the order of which is the number of data elements in l_2. To find the minimum of $H(h|l_2)$, the gradient, a vector of partial first derivatives, is set to zero as in equation (14). When minimizing $H(h|l_2)$, the m_i would be treated as constants.

$$(14)\quad \nabla\, H(h|l_i) = 0$$

Moreover, to preclude maxima or saddle points, the partial second derivatives of $H(h|l_2)$ must form a positive definite matrix [11], which reduces to inequality (15) in the case of a single variable, l_i.

$$(15)\quad \nabla^2\, H(h|l_i) > 0$$

Algorithms were developed to determine minima of multivariate functions [12], [13], but their application is beyond the scope of this paper.

Two- three- and…n-way data fusion contributes to data set, l_2, as is described in equation (16).

$$(16)\quad l_2 = \{ \{l_{i2}\, m_{i2}\}, \{ l_{a2}\, m_{a2}, l_{b2}\, m_{b2}\}, \{ l_{a2}\, m_{a2}, l_{b2}\, m_{b2}, l_{c2}\, m_{c2}\}, \ldots \{ l_{a2}\, m_{a2} \ldots l_{n2}\, m_{n2}\} \}$$

For example, the first set in equation (16), $\{l_{i2}\, m_{i2}\}$, represents the contribution of each single information source multiplied by its metadata-weighting factor, m_i. The metadata elements, m_i, which could be expressed a real number between 0 and 1, summarize the reliability and relevance of the information, l_{i2}, to the decision task. Thus, only the relevant data elements will contribute to $H(h|l_2)$ because any data element that is either irrelevant or unreliable will be ignored as $m_i \sim 0$.

The second and third data sets that are grouped in {brackets} in equation (16) represent the contributions to the relevant data set, l_2, that result from the data fusion of two and three data elements. Note that three-way data fusion generally will not yield the same result as a collection of results from pair-wise data fusion. However, the contribution to the information flow of data fusion involving multiple data elements could be very important and may be more significant than that of the single information sources and their respective pedigree metadata, $\{l_{i2}m_{i2}\}$.

A combined uncertainty also applies to the variables that are interdependent. The interdependence between two or more variables gives rise to and necessitates the multi-way data fusion in equation (16) for l_2. Fusion algorithms that combine data elements will have to account for this combined uncertainty in some way. The result of a complete fusion algorithm must include not only a combined data result, but a combined uncertainty derived from a consideration of the m_i. How to compute or estimate the combined uncertainty from data fusion of two or more data elements is context dependent and also is an ongoing research topic.

The fusion interactions in equation (16) are analogous to the two- three- and…n-way intermolecular interactions that contribute to the thermodynamic and spectroscopic properties of gases, as expressed in the Virial expansion. (See, for example, [9] and [5].)

A general evaluation of $H(h|l_2)$ is beyond the scope of this paper. The data set, $l_{2(\text{min})}$, that describes the minimum of multivariate function, $H(h|l_2)$, is not only unknown but is impossible to derive analytically in actual, non-trivial cases for the following reasons.

- The exact form of $H(h|l_2)$ itself is unknown and may not be analytic.
- The number of variables, $n(l_2)$, is generally unknown and is task dependent. Therefore, the exact order of the multivariate analogs of equation (14) and inequality (15) cannot be determined in general.
- The distribution of each variable, l_i, is unknown and one cannot assume it is a Gaussian distribution.
- The existence of some potentially important variables in l_2 may be unknown.
- Time constraints preclude discovery of the details of the items above before decision deadlines.

However, we can ignore inequality (15) if we assume that some information already is available in a command center and that this puts $H(h|l_2)$ close enough to a local minimum so that the risk of maximizing $H(h|l_2)$ would not be an issue. At best, quantities such as p and task workload can be determined only in very controlled modeling-and-simulations experiment [14] where the models and variables can be evaluated. Even with many assumptions, an exact calculation of information flow, p, and the final conditional entropy, $H(h|l_2)$, in actual field situations is not an option, for reasons listed above. Therefore, a different approach is needed to explore the various aspects of p.

8. Metrics for Factors that Influence Information Velocity

Because v(info) depends on both p and t, time management in organizations is considered here. Time is an important factor in decision making as most decisions have, either explicit or de facto deadlines. The visibility of information, the empowerment of people in the organization, and communications efficiency can affect v(info).

Thus, although equations, such as (1), (12), (14) and (16), have no exact and direct solutions, we can observe the effects of better v(info) if they lead to increases in decision speed and quality. This section describes each of these factors with suggested metrics. Unlike v(info), the metrics described below have no units. The metrics here depend on time estimates and arbitrary scales from 1 to 10 for individuals to use when estimating how information and the speed of its movement affect their tasking in the organization, or conversely, how their tasks affect the disposition of information.

These metrics will not track v(info) in all cases and the correlation between each of these metrics and v(info) will not always be 1.0. The metrics are assumed to be independent of each other but this will not always be the case in actual situations. However, the improvement over time of these metrics may be more significant in assessing the impact of improved v(info) in an organization than any single quantification of the metrics themselves in a given instance. Future research is necessary to shed light on this subject.

8.1 Direct Measures in Time Management

Information flow is only one aspect of information velocity. Other aspects include the delivery of the right information in a timely manner and to the right place or person. Timeliness in measures of performance and measures of effectiveness has been studied in the command and control context [15]. The following two aspects of timeliness were considered [15]:

- Time delay between the moment when the C^3 system receives a stimulus and the moment it can deliver a response (i.e. the phase delay in the system), and
- Tempo of operations – number of actions per unit of time that the system executes – a measure of how complex an environment the system can handle (i.e. bandwidth).

In contrast, this section describes direct measures of time segments in the decision process and refers to the model described in section 4.

Direct measures have the greatest simplicity, utility and appeal when designing a metric, as compared with causal or effects-based measures. The many advantages include accuracy, desirability, reliability, speed, and independence. First, a direct measure is more

- Accurate because it does not involve any intervening processing.
- Desirable because it does not necessitate any assumptions regarding causes or probable effects.
- Reliable because the measure correlates well with the process.
- Rapid and continuous since it tends to track as closely as possible the quantity being measured.
- Independent because applying the metric does not necessitate an understanding of the causes and effects.

However, direct measures cannot always be used because:

- They may be too costly or impractical.
- They may be too intrusive,
- They may interfere with the process being measured, especially when the human element is a significant factor.
- The measured quantity may be hidden or otherwise inaccessible.

A direct measure of time usage associated with information velocity based on the decision-making model is defined in equation (17).

(17) $$\mathbf{IVMDirect = Tg / (Tg + Tr)}$$

where Tg is the average time employees spend in green decision states (states 2, 3, and 6) and Tr is the average time spent in red decision states (states 1, 4, and 5). The assumption inherent in equation (17) is that Tg and Tr can be measured directly to yield a fraction of time spent in green states compared to the total time in the decision process (green and red states combined).

This metric has the advantages described above for direct measures. Equation (17) can be accurate to the extent that time spent in various states of the decision-making process can be estimated because the metric is tied directly to the states. The metric also is simple and can be computed quickly in real time, assuming the information is accessible. Application of the measure is independent of the causes and effects. If a decision-maker spends less time gathering, preparing and sharing information during the decision-making process, the decision can be communicated more quickly and the information velocity has improved by that relative amount.

Equation (17) can be separated from the harder problem of understanding cause and effect. Researchers pursuing this deeper understanding can use equation (17) whereas practitioners can use it to gain insight into practical situations.

8.2 Causal Measures

Causal measures are an option when direct measures are intractable, inaccurate, too intrusive, too costly, or otherwise unavailable. Yet, at the time of this writing, these instrumented tools for direct measures do not exist or are not widely employed. Moreover, standards [4] have not been adopted for representing decisions. Direct measures of information flow are not available. Therefore, causal measures that could influence information velocity are considered here. Equation (18) defines a metric that relates to v(info) based on causal components.

$$\text{(18)} \quad \text{IVMCausal} = \frac{\text{Min}(Vi, Vy, Ep)}{\text{Max}(Hh, Pcr, Bc)}$$

All component values in equation (18) are normalized to a 10-point scale. "1" is a low score; "10" is high score. The components are described below.

Vi represents the visibility of information and decisions across the enterprise that has the potential to decrease uncertainty as it pertains to tasking and decision making. Vi is an estimate of how immediately accessible information is to everyone in the organization. To qualify for consideration in estimating Vi, the information needs to be delivered in a form that is useable, scalable and manageable. Usability includes conciseness, generic descriptions, tiered structure, and net-centric accessibility. For example, a tool has been developed to provide this type of visibility [16]. Vi can be estimated using an arbitrary scale from 1 to 10 as follows.

- 1-"no visibility or web presence;"
- 5-"Web-based visibility through search, blogs, wikis;"
- 10-Web-based 30-second situational awareness at any level of the organization.

Vy represents the visibility of the decision-maker across the enterprise that increases information flow. Vy is included in equation (18) because important information is tied closely to the author, emphasizing pedigree metadata where knowledge of the author affects the usability of the information. People in the organization can help each other because they can see the important concerns and needs of others. The use of Vy recognizes that the source of information is as important as the information itself. The fundamental issue is whether the concerns and needs of decision makers are visible to the organization in a clear and efficient format.

One option is to generalize Vy to any factor that affects the reliability of Vi, including but not limited to the visibility of the decision maker. For example, level and ease of web presence for Vy also can account for the visibility of pedigree metadata that supports the decision process by estimating the level of uncertainty, or conversely, the reliability of the information that contributes to the decision maker. Components of a pedigree metadata set can include uncertainty of sensor data, data-fusion algorithms, and visual observations as specified by the observer. The impact of these factors evaluated with respect to the visibility of the decision maker can be summarized using a scale of 1 to 10 that is similar to the one used to estimate Vi. More detailed formulae to estimate Vy can be determined in future work.

Ep represents empowerment of people in the enterprise to increase information velocity. Ep is an estimate of authority and responsibility sharing throughout the enterprise, that includes decentralized control, and how much people are allowed to share information. For example, one would expect to estimate an elevated Ep where the management philosophy reflects the goals and values of a "high-performance organization."

High scores for Ep imply that supervisors listen to and support employees and try to implement employee suggestions. Elevated Ep implies an inverted pyramid organizational structure and/or a flatter hierarchy. The best way to estimate Ep is through user assessments and employee surveys that probe the flexibility of the organization's policies. (See, for example, [17], [18], [19], [20].) A scale of 1- (low Ep) to 10- (high Ep) could be assigned as follows.

- 1- Traditional organization management attitude in which workers are not trusted;
- 5- Flexible policies with respect for employees;
- 10- Employee-led organization, inverted pyramid.

Hh represents the amount of human-to-human communication that limits v(info). Hh represents a traditional but inefficient, unscalable, and largely unmanageable form of information sharing, symbolized by meetings, telephone calls, chat, e-mail and conversations.

Using a computer to perform activities that Hh represents is not much of an improvement from non-computerized methods that contribute to the estimation of Hh because it means that new technology still is used in an old way that fails to take advantage of the opportunity for a paradigm shift. (This is like the idea of using the trucks to transport horses into the battlefield, or using e-commerce for the on-line purchase of slide rules.) The lack of significant increases in worker productivity despite the increase in computer technology is indicative of the problem.

The first step to improve Hh is to become aware of how each factor that contributes to Hh can be reduced without reducing communications efficiency. For example, the Top-Ten Best Practices [21] address effective meetings. To avoid wasting time, the moderator must strive to keep the meeting focused on the topic and to adjourn the meeting when the goal is accomplished. Hh will be smaller if everyone is not required to attend meetings that have little potential to improve v(info). This is a challenge in government organizations and corporations that may value the control of employees and the conformity of their behavior more than they value production efficiency. In this sense, Hh may be related to Ep because common factors may influence both. Clearly, top management must be committed to value time and efficiency to observe any substantial improvements in Hh.

Measures for Hh include objective measures of the number and length of e-mails, meetings, and phone calls, as well as the subjective estimates of user assessments. An arbitrary scale of 1 (low Hh) to 10 (high Hh) can be assigned as follows.

- 1- < 20 minutes/day spent on Hh;
- 5- < 2 hours/day;
- 10- > 4 hours/day.

Pcr represents the level of pressure and personal and cultural risk influencing the decision-maker. Although Pcr is an estimate based on an individual's personal reaction, when carefully collected statistically across an organization it becomes a more objective factor summarizing the level of pressure, etc. that people experience in specific organizational environments. Pcr is an estimate of organizational pressures to become "yes" people who are forced to dilute the truth to protect individuals from personal risk rather than to further the objectives for productivity of the organization as a whole.

An elevated Pcr is an estimate of the level of inhibitions that impede honest, direct opinions thereby reducing the usefulness of information provided. Elevated Pcr also indicates an organization with structures and policies that waste decision-making time while people strive to generate safe and acceptable answers. Examples of factors that contribute to elevated Pcr include risk and cost to the individual; risk and cost to the teams; the pressure to be a "team" player; the pressure to stay on schedule; the pressure for promotion or other rewards. Measures include objective analysis of the traditional organizational structures and policies as well as subjective user assessments. A scale for the evaluation of Pcr could be constructed as follows (1 low Pcr to 10 high Pcr).

- 1- External factors rarely affect decisions;
- 5- External factors often affect decisions;
- 10- External factors always affect decisions.

Bc represents the level of barriers to rapid, concise, honest communication. Bc is an estimate of factors that impose costs in time, discourage participation in decision-making processes, and create a climate of inefficiency, which can lead to inactivity. Often the requirements for formatting and submitting information such as proposals, ideas, patent applications, reports, and publications are based on the legitimate requirements of the receivers of the information to reduce errors and streamline the review process, rather than to encourage and promote widespread efficient participation.

Bc, therefore, is always estimated from the point of view of the organizations and individuals *providing* information rather than *receiving* it. A high-performance organization should promote the efficient and user-friendly submission and sharing of ideas by breaking down these barriers while simultaneously preserving the efficiency and accuracy of the review process. Efficient submission and review need not be totally mutually exclusive. For example, to reduce Bc, well-designed web-submission processes need to provide these advantages:

- Provide clear, simple, and intuitive instructions that explain what to do,
- Facilitate initial submission of abstracts and idea summaries rather than impose up-front requirements for large amounts of information that are time consuming to accumulate and useless to review for an idea that may be off topic or simply not needed at the time,
- Avoid undue delays and ambiguities in feedback regarding ideas.

Measures of Bc include objective measures of the length and subjective estimates of the formality of policies for submitting information. Other factors that should be taken into account when estimating Bc are the number of people participating in submission opportunities, as well as the total number of submissions because an efficient submission process may encourage productive employees to submit more than one idea. C can be estimated on a scale of 1 (low Bc) to 10 (high Bc) as follows.

- 1- The initial submission of an idea requires a very low investment in time and is not expected be more than a paragraph. Because of its brevity, any format is fine and the idea can be submitted at any time;
- 5- Fewer than 3 textual pages (e.g. using Microsoft Word), or 6 briefing slides (e.g. using Microsoft PowerPoint) with minimal formatting, specific due dates;
- 10- More than 10 pages expected initially, detailed formatting requirements that are ambiguous and hard to implement in a short period of time, several submission deadlines that occur in quick succession to impose a work schedule that is too compressed.

The philosophy of equation (18) is that the strength of an organization's v(info), which can be conceptualized as a chain, is only as strong as its weakest link. The numerator of equation (18) represents positive factors that can improve information velocity. The numerator of equation (18) is determined by selecting the *lowest* score among Vi, Vy, and Ep. This method is designed to ensure that only the weakest link in this three-member chain should be used to represent positive factors in IVMcausal. In contrast, the denominator of equation (18) represents a three-member chain of negative factors that tend to limit information velocity. In this case, the largest value from among Hh, Pcr, and Bc is selected as the weak link in the denominator of equation (18) to represent the limiting factor, which will overshadow the effects of the other two factors.

In short, previous research and personal experience in various projects suggest that increased visibility of decisions and more visible, empowered decision-makers improve information velocity, whereas increased human-to-human communication (meetings, teleconferences, etc.), increases in perceived risk, and barriers to communication tend to degrade information velocity. Of course, many other causal measures of a lesser degree may apply, but the measures captured in equation (18) are expected to correlate with the concept of information velocity illustrated in Figure 1. Future research described below will explore the performance of the components in equation (18) through modeling and simulation and a practical experiment to validate the causal metric.

8.3 Effects Measures

Another approach for measuring important factors that influence information velocity indirectly is to measure the effects of elevated information velocity. Improved information velocity by definition will reduce uncertainty in a timely manner for the specific decision maker who needs it to accomplish a current, time-critical task. Improved information velocity also will improve some state of the organization. Therefore, measures of the organization's state can reflect on the effects of information velocity.

One difficulty with direct time and causal measures is that a task activity that demands that an employee's time or, alternately, a causal chain may not have a clear beginning or a clear end. One way around this difficulty is to measure a number of quantities along the causal chain. The long-term objective of this research area in general and this study in particular is improved decision making. Therefore, we identify factors in various categories to improve v(info) with the overall objective to increase the efficiency and quality of decisions. The effects of improved V(info) can be estimated using equation (19) as a metric.

$$\text{(19)} \quad IVMEffects = \langle N_D \rangle \langle Q_D \rangle \langle S_D \rangle$$

where $\langle N_D \rangle$ is the average number of decisions per unit time, $\langle Q_D \rangle$ is the average estimated quality of these decisions, and $\langle S_D \rangle$ is the average satisfaction of the individual with the rate of uncertainty reduction. In short, improved information velocity should increase the rate of decision making, raise the average quality of the decisions, and increase the flow process. These effects measures are difficult to quantify and certainly require either instrumentation of the decision-making process and/or subjective assessment by individual participants. The average number of decisions per time unit is best acquired through instrumentation of decision-making tools. Some assumptions to achieve this will be necessary. For example, it will be necessary to determine where one decision ends and another begins. This will not be trivial when decisions are interdependent.

The quantification of the quality of decisions is a difficult task. Previous research suggests various pitfalls, including the typical pitfall of tying assessments too tightly to results based on 20/20 hindsight. The satisfaction, S_D, of individuals with the uncertainty reduction in the decision-making process is important because, according to equation (1), it should correlate highly with information flow.

The individual Q_D and S_D that contribute to the averages in equation (19) can be estimated on the scale of 1 to 10, whereas N_D is really a measure of decision speed.

9. General Metric

Ideally, this initial work would lend itself to a simple metric or rough ad hoc measure, in addition to a full set of metric components for continued research. This general metric would provide a quick "back-of-the-envelope" calculation that anyone could perform to estimate the performance of the organization and to assess the value of certain policies or techniques. This metric could be a few questions to pose to an individual or subgroup of an organization to assess the state of information velocity quickly, regularly and efficiently. For this purpose, the following survey questions are offered [15], [22].

1) What percentage of your day do you spend in meetings, reading and writing e-mail, talking on the telephone, in teleconferences, and in other forms of conversation and communication with others?
2) What percentage of your day do you spend preparing products intended for sharing information? For example, what percentage of your day do you spend preparing briefing slides, reports, agendas, minutes, and completing forms and logs?
3) What percentage of what people are doing in your organization is important and relevant to you and your assigned tasks?
4) What percentage of what others across your organization decide is important throughout the day is visible and easily understandable to you?
5) What percentage of what you decide is important is visible and appreciated across your organization or enterprise on a daily basis?

The percentages derived from these questions could be combined as follows to give a score ranging from 0 to 100.

$$\text{(20)} \quad IVM\% = \{ (Q3\% + Q4\% + Q5\%) / 3 - Q1\% - Q2\% + 100 \} / 2.$$

How IVM% differs between one individual and the next, and how it changes for a single individual over time is more significant than any isolated value of IVM%. Rank orderings of IVM% are more important than absolute values of IVM%. However, "100" appears in equation (20) to ensure non-negative values for IVM%. Equation (20) weights evenly improved efficiency of sharing information (by moving away from traditional human-to-human communication methods and products) with visibility, awareness, and relevance of what people in the organization are doing. An assumption associated with equation (20) is that if the important work of the organization is visible, understandable, and relevant, the right information is getting to the right person at the right time. The second line of equation (20) implies that human-to-human communication methods are inefficient and unscalable.

For example, an overloaded, discouraged, un-empowered employee might provide input to equation (21) as follows: (1) 60%; (2) 20%; (3) 20%; (4) 10%; (5) 10%. In this case,

$$(21)\ \ IVM\% = \{ (20 + 10 + 10)*0.33 - 60 - 20 + 100\} / 2 = (13.2 - 80 + 100)/2 = 17\%.$$

This low score reflects the situation of an employee who cannot share important information and who is spending almost all the employee's time on inefficient communication mechanisms.

In contrast, consider a high-level executive who believes the organization is operating in concert with the executive's philosophy and instructions. However, the executive still spends most of the day using a portable e-mail device and attending meetings. Such an executive might provide the following input to equation (21): (1) 80% (2) 10% (3) 100% (4) 90% (5) 80%. In this case,

$$(22)\qquad IVM\% = 50\%.$$

This score suggests that the executive is sharing information at half strength. The executive gets useful information, but is still using inefficient and unscalable human-to-human communication and lacks organization-wide visibility.

Consider a third example of an employee at any level who benefits from a new organizational structure and tool that enables the employees, the employees' decisions, and the employees' decision-making processes to be visible and easily understood across the organization. Assume the organization is synchronized though the use of the new structure and tool, such that the employee's vision is shared and appreciated by the organization and vice versa. Such an employee might provide the following input to equation (21): (1) 10% (2) 5% (3) 90% (4) 80% (5) 80%

$$(23)\qquad IVM\% = 84\%.$$

This high score reflects good information flow, since the decisions of the organization and the employee are visible, concise, and relevant to both the organization and the employee, and both benefit from the use of improved, more scalable communication methods and structures. Questions 1 though 5 together with equation (20) provide somewhat arbitrary percentages based on rough estimates that may be difficult to measure. However, individual employees and organizations can use the general metric method described above as a point of departure for improvement. Here again, the trend of the organization as it changes over time, according to equation (20), may be more significant than any single assessment of an organization taken in isolation. The results can be averaged across a statistically significant sample of employees to assess information velocity. For organizations where information velocity is high, the right information goes to the right person at the right time.

10. Limitations of the Methodology

As with all approximate methods that rely on estimates and assumptions to make the process of assessment tractable, the metrics described in this paper will be more valid in some instances than in others. This section describes the conditions under which the method will be most useful and valid. IVMDirect, as defined in equation (17), is not a direct measure of *p* or v(info). It is a metric for time management in decision making the validity of which depends on the following assumptions.

- Better time management increases v(info).
- States and substates described in Figures 1 and 2 are independent of each other.
- Time spent in green states increases v(info).
- Time spent in red states does not increase v(info).
- Decision makers have the information they need in green states.
- Decision makers can define start and end times for entry and exit of various states.

Sometimes the states described in Figures 1 and 2 can be interdependent in which case, Tg and Tr might not be independent. Increased time spent in state 1 refining the data and presenting them in a form that decision makers can understand may reduce significantly the time spent in states 2 and 3. However, the model implies that the time spent in state 1 is inefficient whereas only states 1 and 2 will get credit for the efficiency.

Decision makers don’t always have the information they need in green states. They may have some of the information they need. They might not be able to wait until they have all the information they need because decision deadlines can occur before sufficient information is received. Decisions made under these conditions can reflect considerable uncertainty. Thus, the time that the decision maker spends on a particular task does not always correlate to preferences but may be regulated by the decision deadline. A decision maker may spend less time gathering, preparing and sharing information because less time is available before the decision deadline and not because the decision will be better if made before additional facts and alternatives emerge. Simulations and surveys to test and evaluate IVMDirect will need to be designed very carefully to consider the effects of decision deadlines.

The model described in Figures 1 and 2 does not explicitly account for the time that support personnel spend performing data fusion and data integration and preparing information for the decision maker. This would occur presumably somewhere between states 1 and 2. Time spent preparing the data for the decision maker is not time wasted and may be included in more detail in a future refinement of the model.

Another limitation of the time-measurement approach is that it may not address adequately the relationship between information quality and the timeliness-quality tradeoff. The time spent in certain states depends on the quality of information that enters these states. More time may be needed to refine, process, and understand the meaning of a noisy or incomplete data set. If more time is spent on a task the quality may increase. Quality, which is not (yet) part of the IVMDirect, can be the cause of spending more or less time with a data set, a report, etc.

However, IVMEffects depends on estimates of decision quality and user satisfaction with the quality of information, Q_D and S_D respectively, in equation (19). Thus an approach that combines the metrics of IVMDirect and IVMEffects may be more accurate than either metric used in isolation. The challenge with IVMEffects lies in the subjective nature of the estimates of N_D, Q_D, and S_D. N_D may be difficult to estimate because it depends on a value judgment of where one decision ends and another begins. It also depends on being able to select a time interval that reflects when one decision is finished and another begins. For example, if a decision is detailed with many steps, is each step considered a separate decision or are they counted as one?

IVMDirect also does not account for the uncertainty before and after the information was passed. It is possible to have a high measure of IVMDirect, i.e. low time in green states and high time in red states, and still not transmit any information that reduces uncertainty. This observation also underscores the need for a combined metric that includes the contributions of IVMDirect, IVMCausal, and IVMEffects in one equation or algorithm.

11. Ongoing and Future Research

As is the case with any metric, the metrics described here need to be demonstrated and validated in studies, surveys, experiments, and observations. Although this preliminary research has suggested some metrics to estimate factors that affect v(info), unanswered questions remain. For example, how should the metric components be normalized, weighted, and combined for an optimal, single value? Do the causal measures actually measure factors that correlate well with v(info) in simulations and in practice? How do the various metrics interact and correlate with each other? Can we design and build tools to measure observable variables in the decision-making process? What emergent behavior may appear in simulations that model *p* and v(info) under expected conditions?

To address these questions, current and future research will explore the behavior and performance of the metrics in a modeling-and-simulation environment. The work described above lends itself to modeling with Markov processes, potentially hidden-Markov processes, Bayesian adaptation, and agent-based techniques. Preliminary work in the area of agent-based modeling suggests some interesting behavior [23]. The results of an agent-based model suggest that a traditional organizational hierarchy and promotion policy will suppress and even stagnate potentially useful information [23].

Future research will explore components that contribute to improved v(info) in a modeling and simulation environment to determine whether the theoretical analysis matches the expected performance in typical use cases. Then the metric will be used in a realistic organizational setting by developing a baseline, employing a v(info) improvement technique, and using the metric to estimate the resulting improvement in v(info). The directional component of the v(info) (See Figure 1.) will be addressed in future work. This relates to directing the flow of information to the right decision maker.

Future studies will include modifications to IVMDirect to include a quality factor and estimates of uncertainty, as well as time estimates. The relationship between IVMDirect, IVMCausal and IVMEffects needs to be explored to use the quality factors in IVMEffects to compensate for the lack of quality factors in IVMDirect. The resulting theory also is needed to relate IVMDirect, IVMCausal and IVMEffects to provide a more unified approach to factors that can affect v(info) and their interdependences. For example, section 10 above expresses the need for a metric that combines IVMDirect, IVMCausal, and IVMEffects in one equation or algorithm.

This future research also will be directed toward testing the assumptions that supported the development of the metrics described in this paper. Whereas experience suggests that the following assumptions are good in most cases, they still need to be tested.

- Improving organizational v(info) improves decisions by timely reducing uncertainty.
- Direct human communication, such as meetings, telephone calls, and e-mails, limits the velocity of useful information
- Reducing this and other inefficient forms of communication will increase v(info).
- Honest, efficient and visible decisions increase v(info) and are derived from empowered employees without much cultural bias or other undue pressures.
- Formality, deadlines, and format requirements can reduce information velocity from the sender’s perspective, even if they support efficient evaluation.
- Decision products need to be transformed from both the formal and time-consuming briefing slides and reports, and the informal unmanaged personal conversations, meetings, telephone calls, into a managed, concise, dynamic, lightly structured, generic format that is useful for sharing information rapidly across the organization.

12. Conclusion

This paper introduces the concept of information velocity, which combines the notion of information flow and direction with time dependence. A theoretical development is described to explain the relationship between entropy, uncertainty reduction, information flow, information velocity, and the time dependence that is so important in making agile decisions. The relationship of entropy in thermodynamics to entropy in infodynamics is discussed, as well as the analogy between information flow and the flow of a liquid or a gas through pipes. An equation was derived to show the relationship between information velocity and power.

A decision-making model focused on time management is described. This model breaks the decision process down into various states that a decision maker will experience in pursuit of useful information that supports uncertainty reduction.

Direct, causal and effects-based measures for estimating factors that affect information velocity in organizations in general were introduced. The advantages and limitations of the metrics are discussed. In these metrics, time management and information visibility are central, contributing themes due to their importance in decision making. These metrics can be applied to military command centers to assess information velocity and agility in the decision-making process. The goal of this research is to develop and refine a method for estimating factors that influence information velocity across an organization or enterprise to help determine whether the right information is getting to the right person at the right time. This will support creative, agile decision-making.

Acknowledgements

The authors thank the Office of Naval Research for their support of this work, and Drs. I. R. Goodman and J.R. Smith for helpful discussions. This paper is the work of U.S. Government employees performed in the course of their employment and no copyright subsists therein.

References

[1] N. Webster, *Webster's New Universal Unabridged Dictionary*, Deluxe Second Edition, (Webster's New Twentieth Century Dictionary), J. L.

McKechnie, editor, Simon and Schuster, New York, N.Y., p. 587, 1983.

[2] Sir William Thomson Lord Kelvin, http://www.zapatopi.net/kelvin/quotes/

[3] J.E. Russo and P.J.H. Schoemaker, *Winning Decisions*, New York: Doubleday, 2002.

[4] J. Waters, R. Patel, J. Eitelberg, and M. Ceruti, "A Proposed Common Decision-Exchange Protocol for Representing, Managing, and Sharing Organizational Decisions," *Proceedings of the Intl. Conference on Naturalistic Decision Making (NDM'09)*, London, UK, June 2009.

[5] M.G. Ceruti and S.H. Rubin, "Infodynamics: Analogical Analysis of States of Matter and Information," *Information Sciences*, **177**(4), pp. 969-987, 14 Feb. 2007.

[6] M.G. Ceruti, B.M. Thuraisingham, and M.N. Kamel, "Restricting Search Domains to Refine Data Analysis in Semantic-Conflict Identification," *Proc. of the 17th AFCEA Federal Database Colloquium and Exposition 2000*, pp. 211-218, San Diego CA, 6-8 Sep. 2000.

[7] D. Swanson, T.L. Wright, M.G. Ceruti, D.R. Wilcox, and S.C. McGirr, "Design, Development, and Reuse of Software Agents in the Knowledge Management for Distributed-Tracking (KMDT) Program," *Proc. of the 2nd Intl. Workshop on Ontology, Conceptualization, and Epistemology for Software & Systems Engineering (ONTOSE 2007)* 27-28 June 2007, Milan Italy.

[8] http://en.wikipedia.org/wiki/Information_flow_(information_theory), 29 Oct. 2008.

[9] G.W. Castellan, *Physical Chemistry*, Addison-Wesley Publishing Co., Reading MA, 1964.

[10] M.G. Ceruti A. Ashfelter, R.Brooks, G.Chen, S. Das, G. Raven, M. Sudit, and E. Wright, "Pedigree Information for Enhanced Situation and Threat Assessment," Paper 43, *Proc. of the 9th IEEE Intl. Conference on Information Fusion (FUSION 2006)*, Florence Italy, 10-13 July 2006.

[11] http://en.wikipedia.org/wiki/Positive-definite_matrix, 4 Dec. 2008.

[12] E.R. Lancaster, "A Method for Finding a Minimum of a Multivariate Function with Applications to the Reduction of Missile and Satellite Data," *Proc. of the 14th Annual National Conference Meeting of the ACM*, Cambridge, MA, pp. 70-1 - 70-4, 1959.

[13] D.F. Shanno and K.H. Phua, "ALGORITHM 500 Minimization of Unconstrained Multivariate Functions (E4), *ACM Trans. on Mathematical Software*, **3**(1), pp. 87-94, Mar. 1976.

[14] B.G. Knapp, "C3I Information Flow Models: Integrating and Interfaces," *Proc. of the Workshop on Engineering of Computer-Based Systems (ECBS'97)*, pp. 136, 1997. http://www2.computer.org/portal/web/cdsl/doi/10.1109/ECBS.1997.581838.

[15] P.H. Cothier and A.H. Levis, "Timeliness and Measures of Effectiveness in Command and Control," *Information Technology for Command and Control*, S.J. Andriole and S.M. Halpin, Eds., IEEE Press, New York N.Y., 1991.

[16] J. Waters, J. Eitelberg, D. Kellmeyer, and M. Stelmach, "Knowledge Web for the SOC: Interoperability through the Use of Open Standards," *Space and Naval Warfare Systems San Diego Biennial Review*, TD 3202, pp. 54-59, Sep. 2006.

[17] M. Biazi and J. Walinga, "Employee Empowerment Study," 20 May 2007.
http://axiommedialab.com/portfolio/employee_empowerment_Research_Methodology.pdf

[18] A. Mueller, "Employee Empowerment," St. Louis *Business Journal*, 15 Apr. 2005.

[19] Navran Associates, "Employee Empowerment Evaluation Kit," pp. 1-4, 2004
http://www.navran.com/downloads/Employee-Empowerment-Evaluation-Survey.pdf

[20] D. Seeley, "Industry Insights: Create Culture that Empowers Your Employees," *Business Courier of Cincinnat*i, 6 Jan. 2006.

[21] SSC, "About Continuous Process Improvement (CPI) and the SSC Pacific Balanced Scorecard," 16 Sep. 2008. http://sepo.spawar.navy.mil/Process_Improvement.html#TTBP

[22] J. Baron, *Thinking and Deciding*, New York: Cambridge University Press, 2000.

[23] J. Waters, R. Patel, J. Eitelberg, and M. Ceruti, "Investigation of Information Flow in Hierarchical Organizations Using Agent-Based Modeling," *Proceedings of the ACM/SCS Agent-Directed Simulation Symposium (ADS'09)*, San Diego, CA, Mar. 2009.