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THE NON-LINEAR NATURE OF INFORMATION AND ITS IMPLICATIONS FOR ADVANCED TECHNOLOGY FORCES

By

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A paper submitted to the Faculty of the Naval War College in partial satisfaction of the requirements of the Department of Joint Military Operations.

The contents of this paper reflect my own personal views and are not necessarily endorsed by the Naval War College or the Department of the Navy.

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Abstract

A significant characteristic of information and information support technology is their non-linear nature. Non-linearities can be found in all elements of information support systems and is also inherent in the nature of information itself. These non-linearities represent vulnerabilities that can be exploited by adversaries. Examples of how to accommodate the non-linear nature of information are explored. Current U.S. military vision statements anticipated tremendous benefits from the growth of information based technology. It is now axiomatic that the ability to achieve information dominance against potential adversaries will become a significant comparative advantage for U.S. military forces. Yet, the results from this same strategy in the commercial world are mix. To achieve the information dominance anticipated through advances in technology, military decision-makers must understand and accommodate the non-linear nature of the information systems they employ.

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Introduction

The growing availability of information including the rapid expansion of means to collect, process, and disseminate it to the warfighter has persuaded some writers that the U.S. military is entering an information based revolution in military affairs.[1] The ability of U.S. forces to gain and maintain "***information dominance***" on the battlefield is a key tenant in the vision statement of the Joint Chief's of Staff.[2] In a larger context, others argue these same trends are evidence the world's developed nations are transitioning out of the industrial age and into an information based era.[3] While thinkers and writers are discussing the importance of information and information based technologies, limited analysis is available on the underlying nature of information itself. Clausewitz, for example, offers analysis about the nature of war, no such comprehensive analysis, however, has yet to be offered on information.

Gaining an understanding of the nature of information and its support systems is important. Tremendous benefits are anticipated through the growth of information based technology. It is now axiomatic that the ability to achieve information dominance against potential adversaries will become a significant comparative advantage for U.S. military forces. Yet, my experience indicates that, at the tactical and operational level of war, complex information systems present many challenges. Similar concerns are being raised in the corporate world. A recent survey of 360 companies indicated "42% of corporate information-technology projects were abandoned before completion."[4] In 1996, Fox-Meyer Drug Co. was forced into bankruptcy when its new $65 million computer project failed to keep up with the "huge daily volume of orders from pharmacies."[5] The front page of the April 30, 1998 *Wall Street Journal* declared that the "dark side of the corporate information revolution is coming into view," as "companies across the country are seeing their cutting-edge computer systems fail to live up to expectations - or fail altogether."[6]

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[1] James R. Blaker, "The American RMA Force: An Alternative to the QDR" Strategic Review, Summer 1997, p. 22

[2] Joint Chiefs of Staff, Joint Vision 2010,

[3] Alvin Toffler and Heidi Toffler, War and Anti-War, (New York: Warner Books, Inc. 1993), p.3

[4] Bernard Wysocki, Jr. "Pulling the Plug" The Wall Street Journal, 30 April 1998, p.1

[5] IBID, p.2

[6] IBID, p. 1

Thesis

One fundamental property of information and its support systems is non-linearity. Well-designed information systems exploit non-linearity to achieve desired results. Conversely, information systems that have not anticipated and planned for these non-linear properties can have their performance seriously diminished. To achieve the information dominance anticipated through advances in technology, military decision-makers must understand and accommodate the non-linear nature of the information systems they employ. If we are indeed entering an information era, understanding this aspect of information is critical. Increasingly, senior military decision-makers are being presented alternatives, which claim to achieve significant results based on the application of expanded and more sophisticated information technologies. Whether in system acquisition, force reorganization, or in joint warfighting, there is an implicit theme that by the sheer strength of technical advances alone the fog of war can be lifted.[7] In contrast, an analysis of the non-linear nature of information yields a more balanced understanding of the advantages and limitations inherent in modern information technology. It also provides a renewed appreciation for the older concept that human based wisdom is essential to dominate an adversary.

The New Military Force

During the Vietnam War U.S. pilots "flew 800 sorties and lost ten planes in an unsuccessful attempt to knock out the Thanh Hoa bridge. Later four F-4s armed with some of the earliest smart bombs did the job in a single pass."[8] In the first twelve hours of Desert Storm, 136 air and missile strikes by coalition forces "effectively blinded the Iraqi national command authority" and "paralyzed its command and control system."[9] These are examples of the dramatic results weapons and strategies based on information technology can achieve.

Writing about war in 2010, the Chairman of the Joint Chiefs of Staff argues:

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[7] Admiral William A.Owens, "US' Emerging Dominant Battlefield Awareness Promises to Dissipate the 'Fog of War'," Armed Forces Journal International, January 1996, p. 47

[8] Toffler, P. 84

[9] Major Elizabeth A. Hurst, "Introduction to Command and Control Warfare" Cyber Sword, Vol. I, No. 1, Spring 1997, published by the Joint Command and Control Warfare Center, p.10-11

"...what will differ is the increased access to information and improvements in the speed and accuracy of prioritizing and transferring data brought about by advances in technology. While the friction and fog of war can never be eliminated, new technology promises to mitigate their impacts."[10]

The Chairman's Joint Vision goes on to describe a new framework for military operations, based on the enormous increases in information to be achieved from technology. The "emerging operational concepts" call for:

- Dominant Maneuver
- Precision Engagement
- Focused Logistics
- Full-Dimensional Protection[11]

The former Vice Chairman of the Joint Chiefs of Staff argues that the United States is building a "system of systems" that will achieve a revolution in military affairs. This new "system of systems" consists of three sub-systems providing:

- Battlespace Awareness
- Precision Force Use
- Advanced Command, Control, Communications, Computers and Intelligence (C^4I)[12]

Admiral Owens maintains that by building these systems the United States will achieve "a qualitatively new military capability" which will offer "a new basis for deterrence and coalition leadership."[13]

Taking direction from the highest levels, the military services are collectively organizing, training, and equipping a new type of military force that is based on enhanced information technologies.

Definitions

Linearity. The linear world is a proportional one.[14] If a man, in good health, can walk a mile in fifteen minutes, he expects to walk two miles in thirty minutes. In classical

[10] Joint Vision 2010, p.16
[11] IBID, P. 19
[12] Admiral William A. Owens, "The Emerging System of Systems", Proceedings, May 1995, p. 37
[13] IBID, p. 39
[14] Alan Beyerchen, "Clausewitz, Nonlinearity, and the Unpredictability of War", International Security, Vol 17, No. 3, Winter 1992/93, p. 62, this article provides an excellent analysis of the linear and non-linear aspects of Clausewitz's thinking on the nature of war.

physics, acceleration of an object is proportional to the force that is acting on it. Apply a known level of force, expect a know and proportional level of results. In mathematics, an equation whose variables can be plotted against each other as a straight line is said to be linear. The *"X"* variable is proportional to the *"Y"* variable.

A second characteristic of linearity is superposition.[15] Things add up to an expected value: "the whole is equal to the sum of its parts." A linear problem may be reduced to its sub-parts, those parts may be solved in detail and then reconstructed to yield a solution for the problem as a whole. The success of the industrial revolution has its foundation in such useful mechanistic reduction.

Intuitively, people expect their world to behave in a simple linear fashion. When performing quick estimations, most people visualize and weigh the issues in a linear manner. For many situations this linear shorthand works well, but for most information related issues, assuming linear relationships will cause significant miscalculations.

Non-linearity. Non-linear systems do not exhibit the principles of proportionality or additivity.[16] A process with non-linear characteristics will yield outputs significantly out of proportion to its inputs. Additionally, non-linear systems can display "synergies." Their whole is not equal to the sum of their parts. The interactions among the parts of the system are significant but hidden; they require the unity of the entire system before they can take place.

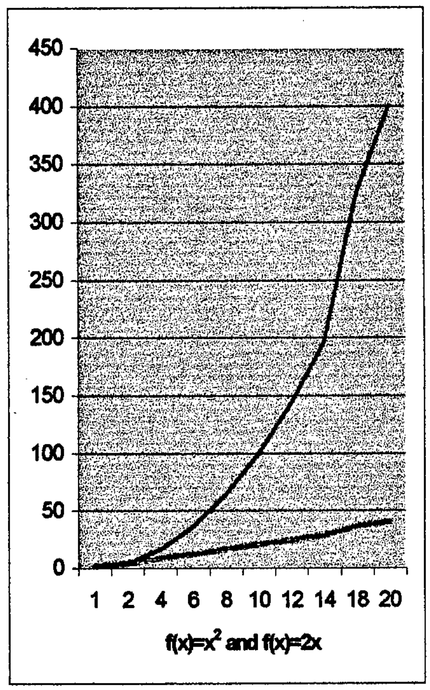

Figure 1. Linear and Non-linear Curves

Non-linear systems can often surprise and frustrate users who expect them to provide linear responses. Figure 1. displays two functions one linear and the other not. The exponential curve of the $f(x)=x^2$ function raises much more rapidly than the linear $f(x)=2x$

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[15] IBID, p. 62

[16] " A linear operation such as multiplying by a constant obeys both proportionality and additivity: let $f(u)=au$, then $f(u_1+u_2)= a(u_1+u_2) = au_{1+} au_2$. A nonlinear operation such as squaring, however, is different: let $f(u)=u^2$, then $f(u_1+u_2)= (u_1+u_2)^2$, which equals not just $u_1{}^2+u_2{}^2$ but also the interaction term $2u_1u_2$." IBID, p. 62

function. If these curves represented the benefit/cost relationship for two systems, users of these systems would see little difference in system response if they remained within the zero-to-four range on the X axis (e.g. a benefit of two X units, costs four Y units on either curve). As the user moves away from the range of similarity, say to six X units, the cost in Y units on the exponential curve begins to grows explosively relative to the linear curve. The exponential curve provides a non-linear response in costs. Users expecting linear responses would be very surprised by the increased costs required on the exponential curve.

An important aspect of exponential response curves is they act as operational thresholds for the systems which contain them. For the non-linear curve in Figure 1, the system user would quickly be unable to afford the Y units required for X benefits. He would have in effect hit a "wall" or a cost threshold he could not overcome. Often in information systems these rapidly increasing costs may not be apparent to the user until a significant threshold is reached. In the Figure 1.example, if the X units were number of users on an information system, the Y units could be the wait time each user experiences to use the system. If the wait time is in seconds, a user may not perceive a sharp cost increase between four seconds and 20 seconds (perhaps some annoyance). As the number of users increase, not only does the wait time increase, but the curve also grows steeper (the cost of the next user grows non-linearly). Often in such cases the difference between a functioning information system and a unusable one is two or three additional users. "Gee, I got 200 users on the LAN, what's the problem with a couple more?" This is linear thinking in a non-linear world!

Information and Information Systems. The Joint Pub 6-0 defines information as:

> "Information is data collected from the environment and processed into a usable form. Combining pieces of information with context produces ideas or provides knowledge. By applying judgement, knowledge is transformed into understanding."[17]

This definition of information will be the "working" definition for this paper, but the implied hierarchy of data, information, knowledge, and understanding will be revisited later.

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[17] U.S. Joint Chiefs of Staff, Doctrine for Command, Control, Communications, and Computers (C4) Systems Support to Joint Operations (Joint Publication 6-0), Washington, DC 30 May 1995, p. I-3

For this paper, an information system will be considered the organization of capabilities to collect, store, process, transmit, and present both data and information among users. An information system is more than technical devices, e.g. computers, telephones, radios, cable, software or space borne sensors. How a military staff is organized, and who talks to whom, is included in the definition offered above.

Non-linearities of Information and Information Systems.

Wherever one looks when studying information systems, non-linear functions appear. These non-linear functions may be individually separate but in the in aggregate they yield a non-linear environment that is ubiquitous in nature.

Information Transmission Systems' Non-linearities. If the transmission channel relies on Radio Frequency (RF) propagation, a number of non-linear functions immediately confront the system designer and user. A fundamental constraint to RF channels is path loss. Path loss determines how much transmission energy sent through the RF channel will be lost in the channel and not available at the receiver. The equation for free space path loss is given as:

$$\text{Free Space Path Loss} = \left| \frac{4 \Pi DF}{C} \right|^2$$

D = path length in meters
F = freq. in Hz
C = speed of light

Note the squaring exponent of the equation. As propagation path length increases, the path loss increases exponentially, i.e. a non-linear function. Even moderate distances can impose significant path losses. For a 50 MHz signal and a path length of 40 KM, the equation yields a free space path loss of 7×10^{109} or 98.5 dB.[18]

[18] Because the numbers become so large in information system design, engineers have adopted a mathematical shorthand to reduce the numbers to more manageable levels using a measure known as the decibel. Significantly, decibels provide a linear scale to a non-linear process. The equation for the decibel is given as: 10 log10 (ratio)= ratio in decibels or dB In the case of RF path loss the ratio in question would be the amount of transmission power put into the channel divided by the transmission power coming out of the channel. For the example cited above the path loss in dB is 10 log10 ($1/ 7 \times 10^{109}$) = -98.5 dB. A ratio of 2/1 or doubling yields 3 dB; a ratio of 8/1 is 9 dB; 32/1 is 15 dB; 100/1 is 20 dB; 1,000/1 is 30db; 10,000/1 is 40dB. Increasing something one million times or a 1,000,000/1 ratio is 60 dB. Note the relationship between the number of zeros

The insight to achieve when looking at path loss is how the function appears linear at its lower range but grows explosively beyond that point. Information system designers and users who do not achieve this non-linear insight will experience significant frustration when they push their system into the explosive growth portions of its operating curve.[19]

Another example of a non-linear process operating in information transmission systems is link availability. In the path loss example above, a transmitter's signal must be strong enough to overcome a 98.5 dB path loss to reach the receiver. But this was an average path loss, and many other factors affect RF signal propagation. The RF channel experiences

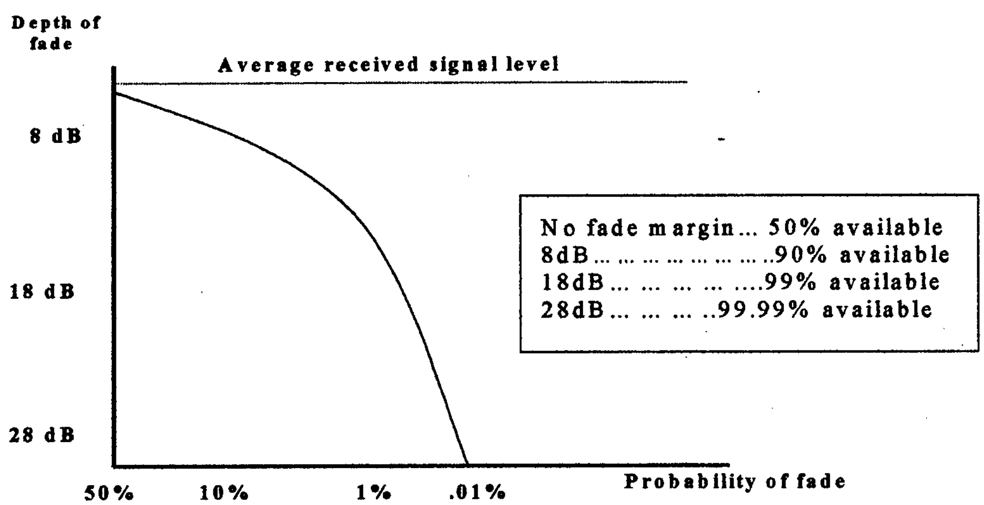

Figure 2. Fade Margin for Signal Availability

atmospheric fading phenomena, and link availability is a means of adjusting for these fades. A "fade margin" is used to determine how much extra power should be used to mitigate the fading phenomena. According to Figure 2, to provide 99.99% link availability, the sender must provide 28dB more power to his signal than the power required to just overcome the

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and the decibel equivalent.

[19] The exponential loss of RF signal with distance can also yield design advantages. Cellular telephones use this property to avoid frequency interference among cells. Without these tremendous path losses there would be insufficient channel frequencies available to make cellular phones feasible.

free space path loss. In other words, he would be required to amplify his output power by a factor of 631. (28dB= a power ratio of 630.95).[20]

The insight to gain from link availability is the "brute force" required to meet non-linear factors "head on." If an information system designer or user chooses to operate within the explosive growth portion of the system's non-linear process, tremendous force is required. In the example above, if the sender and receiver chose an information transaction process which requires 99.99% link availability, they must pay a cost 631 times as great as a choice requiring 50% link availability.[21]

The limitations, described above, are illustrative of the non-linearities associated with information transmission systems. Most of these non-linearities present limitations to how large the transmission system can be increased before significant expansion in effort is required, i.e. moving into the explosive growth portion of the non-linear curve.[22]

Information Processing Systems' Non-linearities Data must be processed at one end of the transmission channel or the other, often at both ends, in order to create information. A basic non-linear function operating in data processing is the factorial relation.

For three, data elements (a,b,and c) to correlate independently, six separate combinations must be considered: a to b; b to a; a to c; c to a; b to c; c to b. The decision space is considered to be six in this example, or 3! "factorial". (Note 3!=3x2x1=6) Add a fourth data element and the decision space increases to 4!=4x3x2x1=24. A fifth yields a decision space of 5!=5x4x3x2x1=120. Ten factorial yields 3.6 million and 20! expands the decision space to 2.4×10^{18}. The non-linear expansion is obvious. The more data that is

[20] National Bureau of Standards Note 110, for QPSK between 100-600Mhz, single diversity. Quoted in "AFCS Frequency Manager's Handbook" ECAC-pr-74-057, December 1974

[21] Currently many U.S. data information systems require very high levels of link availability. During Desert Storm, the TRI-TAC systems required fade margins above 30 dB in order to provide "data quality" circuits. In comparison, the USMC and Army's Position Location Reporting System (PLRS) can provide useful data transmission with less than 20% channel availability.

[22] Other examples of transmission system non-linearities could include the length of LAN cable versus data rate or the addition of users to a telephone/data switch versus number of blocked connections (busy signals).

retained and correlated with incoming data, the greater the decision space grows and the data processing effort increases non-linearly. Note the issue here is not how fast data comes in, but how much previously collected data is correlated to it. This explosive expansion of the decision space is a fundamental limit on the size of modern relational data bases. [23]

Luckily, increases in computational power, achieved by the ever growing capability of computers, have allowed data base designers and users to "brute force" their way through data processing. Yet the non-linear limit is always present, and when the computational power of the processor hits decision spaces beyond its capability the impact is like hitting a wall!

An extreme example of non-linear expansion in data processing is the distributed, relational database. In this case the database is replicated and distributed to several locations. If a criterion is set that all databases must be fully relational and data integrity between them be continuously maintained the decision space is both factorial and exponential. If there are N data elements in each database and X separate database locations, the decision space expands as a function of $N!^X$.

The factorial expansion inherent in data processing is becoming more critical as different military data bases are interconnected. All source fusion of intelligence requires data from separate intelligence sources, e.g. HUMINT, SIGINT, IMINT[24], to be compared and integrated. The more observations confirmed by different sources, the higher the probability of the intelligence.[25] As this intelligence fusion is automated, the integration and cross-correlation of multiple databases becomes possible. Yet, unless the non-linearity of the problem is understood, explosive increases in the computational power required to perform these correlation's will emerge.[26]

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[23] Alternatives to fully relational data bases abound. Federated data base techniques limit the factorial expansion by pre-designating which data elements will be correlated. The advantage is reduced computation, but the price is the data base will only yield information on pre-designated data relationships.
[24] That is Human Intelligence, Signal Intelligence, and Imagery Intelligence.
[25] U.S. Joint Chiefs of Staff, Joint Doctrine for Intelligence Support to Operations (Joint Publication 2-0), Washington, DC, 5 May 1995, p.IV-12.
[26] The same type of non-linear challenge is present as sensor-shooter systems become more automated. In platform-centric warfare each shooting platform tracked its own targets, but in network-centric warfare multiple trackers share data and provide targets for multiple shooters (see VADM Arthur K. Cebrowski and John J. Garstka, "Network-Centric Warfare Its Origin and Future", U.S. Naval Institute Proceedings, Vol.124, No.

Non-linearities in the nature of Information. Information itself exhibits several non-linear characteristics. But before they can be analyzed, a more detailed definition of information needs to be developed. The definition of information accepted at the start of this paper was taken from Joint Pub 6-0. The Joint Pub 6-0 defines a "cognitive hierarchy," which it illustrates in the following manner:

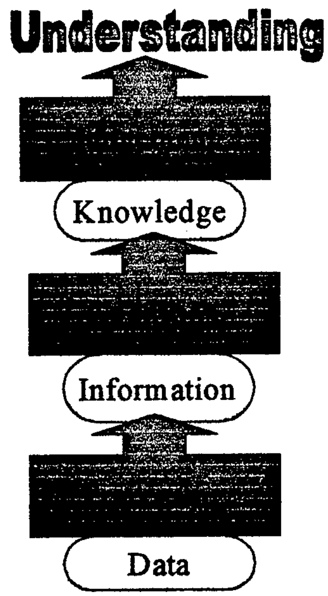

Figure 3. "Cognitive Hierarchy" From Joint Pub 6-0[27]

An implication to be drawn from this hierarchy concept is that data, information and knowledge are quantities[28] that are derived one from the other through a set of processes. The processes are ordered in terms of complexity with the most complex process, "judgement", yielding "understanding." An implication of Figure 3 is that "understanding" is the ultimate product of the cognitive hierarchy. It is unclear from the figure whether "understanding" is a quantity or a process.

The cognitive hierarchy offered in the Joint Publication is problematic for three reasons. First, it leaves unresolved the nature of "understanding." Second, it portrays "judgement" as the final process in the hierarchy. Finally, it offers no purpose for the

1/1,139, pp. 28-35) In order to check for duplicate tracks and ghost tracks in such interconnected systems, high levels of cross-correlation is required.

[27] Joint Pub 6-0, p.I-4

[28] Perhaps "quantum" or "commodity" should be substituted for the word "quantity."

quantities "data", "information" and "knowledge" but to serve as grist for the processes of "cognition" and "judgement." An alternative cognitive hierarchy is offered below:

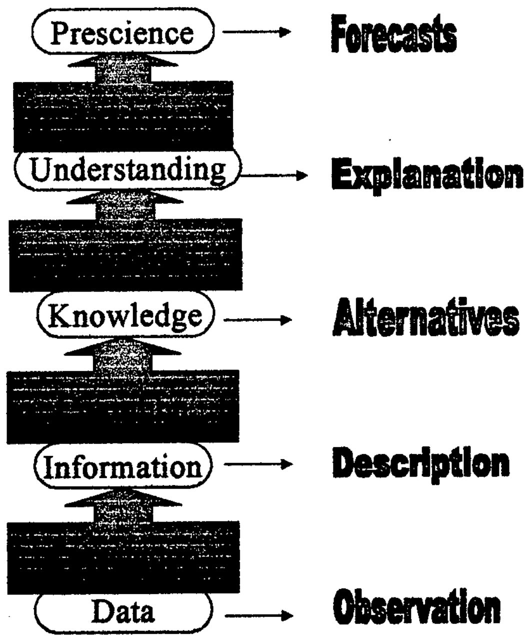

Figure 4. Cognitive Hierarchy "Proposed"

The hierarchy proposed in Figure 4 argues that wisdom, not judgement, is the most complex process in the cognition spectrum, and prescience, not understanding, is the ultimate quantity to be acquired. The proposed hierarchy also indicates the quantities "data," "information," etc, have other purposes than just grist for the next cognitive process.

Regardless of which hierarchy is considered, information in any of its higher forms, i.e. knowledge, understanding, or prescience, has non-linear characteristic based on its lack of superposition. If a quantity yields a greater (or lesser) value than the sum of its sub-components, then the quantity exhibits synergy. Synergy is non-proportional, i.e. an additional element of knowledge may or may not yield a greater amount of understanding. The significance of this non-linear characteristic is more information may or may not yield more knowledge; yet an implication of Joint Vision 2010 is the explosive growth of information will yield a proportional growth of knowledge.[29]

[29] This non-linear relationship between the subordinate quantities on the cognitive hierarchy and their superior quantities can be considered chaotic. A chaotic relationship is sensitive to initial conditions, as is the process "judgement", which is fed by the quantity "knowledge", and produces the quantity "understanding." In the case

Additional analysis of the cognitive hierarchy indicates all of the higher quantities, i.e. those above information, only exist inside the human mind. Knowledge and understanding do not exist in databases or on computer screens; rather the information derived from these sources produce knowledge and understanding in the minds of those who ponder them. In contrast, only information and data can be sent through communications channels. All other quantities, i.e. knowledge, understanding, and prescience, must be translated back into information and passed through a communications channel to be received and interpreted by the minds of humans.[30] The process of translating information is also known as coding and adds uncertainty to the information being translated.[31]

A more focused understanding of the quantity "information" can be gained from Information Theory. In Information Theory, information is measured by its level of uncertainty.[32] A message which tells you what you already know brings with it little information while one which is unexpected has a high level of information .[33] Claude Shannon, the founder of Information Theory, postulated a general formula for uncertainty.[34]

$$H = \mathrm{Log}_2 (N)$$

H = The average information associated with a message or its "entropy"
N = The number of possible events that could be contained by the message, i.e. its "information set"

As an example, the English language has a text (an information set) of 72 symbols.[35] If all the symbols were equally probable, the entropy would have a maximum value of: $H = \mathrm{Log}_2 (72) = 6.17$ bits/ symbol. The *New Webster's International Dictionary, 2nd Edition* advertises 600,000 word entries, which yields an information average (entropy) of $\mathrm{Log}_2 (600{,}000) = 19.2$ bits/ word.[36] As a reminder, entropy measures the average information content of the next message to be received, given a fixed set of possible messages that could

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of judgement, if the initial quantities of knowledge are pertinent to the topic, understanding will quickly follow. If not, as any researcher can testify, the process may take some time.

[30] Note a communications channel could be voice, print, or an electronic medium.

[31] In communication theory uncertainty can be considered noise.

[32] John Paul Froehlich, Information Transmittal and Communicating Systems, (New York: Holt, Rienhart, and Winston, Inc. 1969), p. 4.

[33] Consider the old journalism adage: "dog bites man is not news, but man bites dog sells papers!"

[34] Thomas Schneider, "Information Theory Primer", , ftp://ftp.ncifcrf.gov/pub/delila/primer.ps> 27 July 1995, p.4

[35] These symbols include upper and lower case letters, numbers, and punctuation. Froehlich, p.11

[36] IBID, p. 12

be sent. Entropy only applies to the quantity "information", not the higher cognitive quantities knowledge, understanding, or prediction.[37] A graph illustrating the growth of information entropy relative to the growth of the information set is offered in Figure 5.

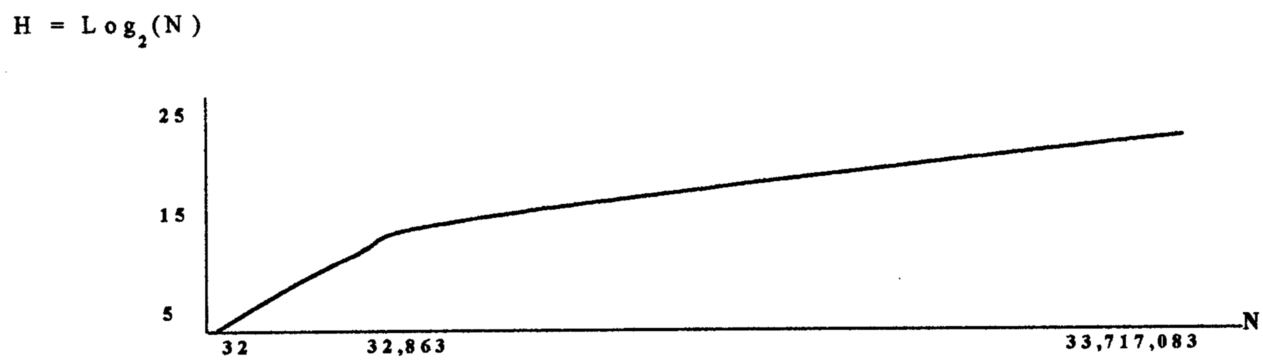

Figure 5. Information Entropy Relative to Growth of the Information Set

Note the horizontal scale in Figure 5 is extremely non-proportional to the vertical scale. While the curve in Figure 5 is non-linear, it is significantly different from the exponential curve in Figure 1. The exponential curve exhibited explosive growth, while the rate of growth on the logarithmic curve above continually diminishes. What the curve above reveals is the dramatic increases in an information set that is required to achieve limited growths in uncertainty. Remember the more uncertainty an information set contains, the more information (on average) each message received from it will bring. If it requires 600,000 entries in the *New Webster's International Dictionary* to achieve an average uncertainty of 19.2 bits/word, it would require 33.1 million additional words to gain an uncertainty level of 25 bits/word. In other words, greater levels of detail do not bring with them proportional increases in information.

An additional non-linearity of information involves the cognitive process and the computational intractability of continuous mathematical problems.[38] Continuous problems

[37] The chaotic nature of information's contribution to knowledge, understanding, etc. precludes applying this level of determination to those higher cognitive quantities.

can grow so complex that although the mathematical knowledge to solve them is available, the computational power required to crunch the numbers is not. Studies in computational complexity show that the cost in computational power necessary to solve a mathematical problem varies as:

$$\text{Computational Cost} = (1/\varepsilon)^d$$

ε = error threshold
d = the number of dimensions to the problem

As the number of dimensions increases, the computation complexity grows exponentially, i.e. non-linearly.[39] As an example, assume a missile targeting problem that we wish to solve through pure mathematics.[40] If we require four place accuracy and just missile and target tracks (four dimensions: missile time &distance; target time & distance), the computational complexity would be $(1/0.0001)^4 = 10^{16}$. If we had a computer capable of performing a billion functions per second (a very large machine!) it would take us 10^7 seconds (115 days) to solve this problem. Obviously, that is not how missiles find their targets. Instead missile guidance engineers use a combination of targeting computations, with greatly reduced accuracy, to get the missile close enough to the target and then switch to other targeting methods, e.g. heat sensors.[41] The important point is good engineers do not rely on brute force computational power to solve non-linear problems.

The Non-linear Nature of Information and its Support Systems. In summary, wherever one explores in the analysis of information and its support systems, non-linear relationships appear. This section has presented several of these non-linearities in information transmission systems, information processing systems, and in the very nature of information itself. To say that the modern world is entering an information era, is to imply we are entering a non-linear world. To be successful in this world will require gaining and maintaining a solid perspective on the non-linear nature of information.

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[38] Joseph F. Traub and Henryk Wozniakowski, "Breaking Intractability" Scientific America, January 1994, p. 102.
[39] IBID, p. 104
[40] A very poor way to solve the problem!
[41] While such cascading guidance systems may work for single missile shooters, it will not work for a network-centric shooter solution that will add many more dimensions to the computational problem.

Vulnerabilities of Information Dependent Forces

Non-linearities can be found in all portions of the information system. These non-linearities represent vulnerabilities that could be targeted by an adversary. Such attacks could be devastating to a high-tech force that is unprepared, especially one that has lost the capability to continue the fight at lower levels of technology. Potential adversaries to the U.S. during the period 2010 to 2020 could range from an unsophisticated insurgent group to a sophisticated opponent, mirror imaging our own technology. During this timeframe, significant technology will be commercially available to both. The measure of sophistication will be how well this technology is integrated into the opponent's military structure.

The Information Transmission System. The Radio Frequency (RF) transmission systems used by U.S. forces can be both exploited and disrupted. Adversaries may decide the best place to hide their own radio transmissions is inside the RF channels used by U.S. forces. If an opponent chooses a data transaction process requiring low link availability, their signals could occupy the same frequencies used by U.S. forces. The enemy signals may be discovered, but could not be jammed without disrupting our own communications.[42]

A premise of the Joint Vision is that our forces will be able to "stand off " and project military power onto the battlefield through advance technology. As the distance between our reduced forces in the enemy's vicinity and our "stand off" controlling nodes grows, so do the D^2 transmission losses of our signals. Enemy RF jammers in the battle area would have the advantage of using lower power to disrupt our signals, while we would be required to "brute force" our radio output power to overcome these non-linear D^2 transmission losses.

All transmission systems are vulnerable to physical destruction, as Desert Storm's first night air strikes illustrate. As the U.S. military approaches the information intensive force described in the Joint Vision, our information transmission systems will be massive, dispersed and largely interdependent. The more interdependent the systems are, the more

[42] As the commercial telecommunications system becomes fully global, an adversary would not need to resort to using tactical U.S. frequencies. Several spaced-based cellular telephone services are coming on line which will be used by friend and foe alike. As an example, it would be very problematical for the U.S. to jam the Iridium System.

disrupting the loss of a single element will be to the system as a whole.[43] The dispersed elements of our information system will present excellent targets for enemy physical destruction efforts. They could be more vulnerable to the unsophisticated adversary using terrorist techniques, than a sophisticated opponent using conventional military weapons.

The Information Processing System. Information processing systems are vulnerable to factorial expansion. Adversaries could leverage this inherent non-linear characteristic to overload our data processing capabilities. Unsophisticated opponents do this by hiding in the general population. These insurgent "fish" swimming in the "sea" of peasants force data fusion systems to consider the entire population. More sophisticated opponents could flood our sensors with multiple targets, some real and some decoys. Instead of overtly jamming a sensor system, a sophisticated enemy may choose to induce duplicates and ghosts tracks into our data bases. The correlation necessary to overcome such tactics would have significant factorial costs.

Computer viruses can be very damaging to data processing systems. In highly interconnected systems, these viruses can quickly spread from one system to the other Amateur computer hackers have already demonstrated the vulnerabilities of our current data processing systems. More sophisticated adversaries could develop capabilities to insert viruses directly into our systems "over the air" through electromagnetic saturation techniques. Current technology offers protection against computer viruses through virus scanning software and "firewall" mechanisms guarding the interfaces between information systems. Future technology promises software programs that reside within the information system, detecting and destroying unwanted viruses.[44] The competition between virus and system protection is comparable to the traditional contest between projectiles and armor. During the periods when viruses have the advantage, information systems are vulnerable. Highly interconnected information systems are more vulnerable than those that are less interconnected.

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[43] The synergy derived from our interconnected information networks is part of their non-linear advantage.
[44] The these "cyber life forms" would be analogous to white blood cells that protect our systems from biological viruses.

Information and the Cognitive System. The vulnerabilities discussed above take place in the lower (data to information via correlation) portion of the hierarchy. In this section the higher portions of the hierarchy will be explored. It is important to remember the processes in this region have a more chaotic relationship to the quantities on which they work.[45]

With insurgents or terrorists, the value of high-tech information sensors will diminish. HUMINT is often more effective against these opponents, yet as the U.S. has invested in high-tech sensors, our HUMINT capabilities have been under funded. Also, the ability to collect information about enemy capabilities through high-tech means does not enhance our ability to understand or predict his intentions. Saddam's capabilities, as he massed his forces on the Kuwaiti border in August 1990, were clearly understood to our technical sensors, but his intentions were not. Good HUMINT would have helped.

The processes "judgement" and "wisdom" yield the quantities "understanding" and "prescience." These critical elements are the least affected by high-tech information systems and more dependent on education and experience. The non-linear targets in this region are more esoteric, but just as real.

Doubt has a significant impact on the higher cognitive processes. If an adversary can cause us to doubt the information we are receiving from our systems, our judgement and wisdom could be impacted non-linearly. If bombs could be surreptitiously planted on U.S. warships or airplanes, a crafty opponent may not detonate the bombs until he could launch an attack by alternative means against those platforms. If such a deception were successful, we would have doubts about the strength of our defenses or tactics and dis-information about an enemy's capability.[46] Conversely, if an adversary can discourage our doubts, he can persuade us to follow a course of his choosing. The "law of small numbers" operates here. Human judgement tends to be more persuaded by a small sample of information that specifically confirms a scenario, than a vast, but vague, sample of information that does not support it. Strategic and operational surprise can be generated from such techniques.[47] High-tech

[45] As noted previously, because of the sensitivity to initial conditions, the amount of quantity "knowledge" required by judgement to produce "understanding" is chaotic.
[46] There is an unsubstantiated rumor that the Soviets performed this trick when Gary Power's U-2 was allegedly shot down in the 1950's.
[47] Michael I. Handel ed., Strategic and Operational Deception in the Second World War, Lecture Handout, U.S. Naval War College, Newport, RI, March 1998, p. 37

militaries appear to be no less vulnerable to strategic surprise than low-tech forces. Witness the U.S. and Israel in October 1973 or in Kuwait in 1990.

A high-tech, information based force presents non-linear vulnerabilities to a crafty adversary.

Ways to Exploit the Non-linear nature of Information

An understanding of the non-linearities inherent in information systems can help overcome these vulnerabilities and improve the effectiveness of these modern forces. To achieve the information dominance anticipated through advances in technology, military decision-makers must understand and accommodate the fundamentally non-linear nature of information and its support systems. The definition for information support systems includes not only information technology, but also organizational and inter-personal considerations. Several examples of how to exploit these non-linearities are offered below.

Technology. A primary consideration when dealing with functions that exhibit non-linear characteristics is to stay in the relatively non-linear portions of their operation curves. This is known as operating below the "knee" of the curve. Computer cache is an example of this principle. Instead of forcing the computer's processor up a non-linear curve with "brute force" computational power, computer engineers chose to remain in the flatter portion of the curve by ensuring the processor has data immediately available in a fast memory cache. This principle could be better applied to military information technology.

A possible extension of cache memory is the physical propositioning of information at the operational or tactical staff level instead of transmitting all required information through communications channels. Our current information systems are not designed to facilitate such techniques, but if they were, a significant portion of the information sent down communication channels could be reduced. As an example, a JCS Warning Order to start crisis planning could be accompanied by a ten Gigabyte computer hard drive containing information about the crisis, to include options and forces available. Even a non-dramatic delivery method such U.S. Postal Overnight Express would yield an equivalent data channel of 18 Mbps[48], a significant savings in expensive communications bandwidth and perhaps a

[48] This is equivalent to over eleven "T1" lease lines.

corresponding increase in operational security.[49] The resulting Operational Order could include a similar hard drive with Commanders Intent as a video clip, a graphically animated Concept of Operations, and all considered "branches and sequels" outlined and animated. An even more sophisticated technique would be to send such orders with all conceivable enemy courses of action played out for say a five-day period. If both senior and subordinate commanders had such information available, then the one who first detected a forecasted enemy action would only be required to transmit a pointer to the memory address where the pre-analyzed occurrence was stored.

In some instances, moving beyond the knee of a non-linear curve is unavoidable and the "brute force" required to operate in this region must be employed. Traditionally, military brute force is achieved by massing forces against an opponent's center of gravity. No military concept for massing information has yet evolved, nor have we equipped our organizations to accept such massed information. Marine Corps infantry battalions can accept and control far more supporting arms fires (artillery, air, naval gunfire) then they would normally receive. They have been designed to accommodate massed fires.[50] However, these same organizations do not have the information technology or organizational structures required to receive, store, process and display an equivalent massing of information.

Traditionally, the military achieves mass through the concentration of forces. The Joint Vision 2010 force, however, will achieve mass through force agility, i.e. dominate maneuver. The same concept needs to be applied to the 2010 forces' information resources. In order to mass information, a Joint Task Force Commander must have agilely assignable bandwidth and individual units must have transmission technology capable of accepting large amounts of bandwidth. Current military communications architectures do not provide this capability, but the technology is certainly available to deliver it.[51] The issue is not having the capable technology, but not yet having the non-linear mindset to perceive the requirement.

The information processing capabilities of units receiving massed information is a critical consideration. Such information processing would include not only computers but

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[49] This assumes 12 hour delivery: ($8\text{x } 10^{10}$ bits)/ (43,200 seconds)= $18 \text{ x}10^{6}$ bits per sec for the 12 hour period. Ironically, there is some "techno-macho" bias to be overcome here..."real professionals" employ high bandwidth data circuits, not "air gapped" file transfers.

[50] The Marine infantry battalion example is used because of the author's familiarity with that organization. It is believed the argument will hold true for other Services and larger organizations.

also humans. The entire cognitive hierarchy needs to be considered. The following sections will explore these aspects of the non-linear challenge.

Organizational. A critical concern of the information massing concept offered above would be who would request the expanded information capacity. The Joint Chief of Staff's ***C4I for the Warrior*** program uses the term "smart push - warrior pull" to illustrate how information should flow down an organizational hierarchy. Under this concept senior organizations should be very "smart" about the amount of information "pushed" to subordinates. Too much information can overwhelm subordinates. The initiative to "pull" information is given to the subordinate. In the examples given above, smart push could be the pre-staged hard drive, while warrior pull could be a request for information massing to augment data not on the hard drive or to send the entire contents of the hard drive if time constraints prohibit its delivery by physical means.

Warrior pull illustrates other issues worth considering. Warrior pull allows subordinates to be more entrepreneurial, to retain more discretion. Pushing discretion down an organization can eliminate intermediate levels of supervision and flatten the organizational hierarchy. Flattened hierarchies are currently in vogue, but can be counter productive if the non-linear characteristics of information are not considered. Flattened hierarchies obtained by increasing supervisor's span of control can increase the supervisor's information requirements factorially. A three subordinate span of control requires the supervisor to consider six interrelationships; six subordinates expands those considerations to 6!=144. In combat, increased organizational spans of control have an additional disadvantage of making the senior command post a more important target, i.e. cut the head and the entire forces is without coordination. In contrast, flattened hierarchies, achieved by "powering down" discretion to subordinates, do not require this factorial growth in supervision complexity and provide more flexibility.[52]

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[51] To a limited extent Demand Assigned Multiple-access (DMA) techniques provide bandwidth agility, but not to the level of information massing considered here.

[52] Organizations composed of small entrepreneurial units act like complex adaptive systems which could be the best organizational response to chaotic complexity. Consider the chaotic nature of judgement and wisdom discussed previously. Current organizational trends in the commercial sector are well worth studying for their military applicability.

The Federal Aviation Agency's (FAA) ***Free Flight*** program illustrates some of the issues discussed above. In response to the growing intractability of centrally managing air traffic control, the FAA has initiated a program to pass many functions of flight control to the individual aircraft. The program will install navigation and air space awareness technology on commercial aircraft and then require the individual aircraft to stay on flight paths and avoid other aircraft in flight.[53] This program promises to reduce the number of air traffic control organizations and provide safer commercial air flight. By using technology and organizational redesign the FAA was able to reduce complexity and improve performance by accommodating the non-linear characteristics of its information system.

Interpersonal The cognitive "processes" above correlation, i.e. cognition, judgement and wisdom, occur in the human mind.[54] Additionally, linkages between the "processes" and the "quantities" are non-linear due to synergy. Finally, the linkages grow more chaotic as one moves up the hierarchy.[55] Considering the last three statements, one must expect advanced technology will have a more limited effect as one steps up the cognitive hierarchy. The improvements here are gained by enhancing the human "processes" and the "quantities" they produce.

In the lower portion of the hierarchy, the primary concern is how to present information to the cognitive viewer in order to derive knowledge. This is also known as the man-machine interface. Significant technological improvements have been made in this area employing Graphic User Interfaces (GUI) programs.[56] But generally, these GUI programs provide limited adjustment to individual preference. Military information technology presents its viewers with large quantities of complex information, yet the display of this information is rigidly standardized. Individual's preference for how information is displayed varies significantly. Some can capture information quickly by watching bar charts, others are

[53] U.S. Department of Transportation, Federal Aviation Agency, "Free Flight Phase I" JRC information brief, 17 April 1998

[54] While much work is being done in artificial intelligence, expert systems, and fuzzy logic / Bayesian uncertainty design, the results to date are more related to complex correlation than the higher cognitive processes. The human capacity to "design arguments" as well as solve them has not yet been emulated. Glenn Shafer, "Probability Judgement in Artificial Intelligence" in Uncertainty in Artificial Intelligence, ed. L.N. Kanal and J.F. Lemmer, (New York: Elsevier Science Publishers B.V. 1986), p. 135.

[55] i.e. they are chaotic because of their sensitivity to initial conditions.

[56] The adage "a picture is worth a thousand words" applies here. MS Windows provides a GUI, its predecessor MS DOS does not.

better with pie diagrams. Current technology can accommodate a multitude of display formats, but the synergy to be gained by providing each individual their preference is being lost through standardization. A better man-machine interface approach would be to allow individuals to determine their GUI preferences and archive them in computer recognized profiles.[57] People could then move from computer to computer (or ship to ship) with their personal GUI preferences loaded onto a small computer disk.[58] Designing this level of flexibility into military technology would reflect an understanding of the non-linear characteristics of this cognitive process.

Two people who collaborate on a common issue can pass information relating to that issue much faster than strangers. These collaborators share both a common information set and common knowledge about the issue. As the degree of complexity goes up, the advantage the two work mates share increases non-linearly.[59] If, when discussing their common issue, the two work mates can see, as well as, hear each other, even more information will be conveyed. The military trend of putting "actuals" instead of radio operators on a network or using video teleconferencing are two ways to exploit this non-linear phenomenon. As the level of collaboration moves up the cognitive hierarchy, e.g. both parties share a common understanding or even a common prescience, the non-linearity of the advantage continues to increase. An insight here is the costs currently being spent to build "virtual presence" environments between senior leaders is worth the expense.

A final interpersonal consideration concerns the capacity of the cognitive "processes." Not all humans possess the same levels of cognition, knowledge or wisdom. Training and experience can expand these capabilities, and the military makes large investments to ensure a highly trained force. Unfortunately, even with the best training, the distribution of cognitive talent will be uneven both within the military and society. In order to attract and retain talent the military must make large investments in its people. As demonstrated above, there is a significant non-linear advantage to be gained from operating as high as possible on the cognitive hierarchy. A technology based force must accommodate human non-linearities,

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[57] This preference setting could be done during skill training schools and aided by human matrix testing.
[58] On going research in Natural Decision Making (NDM) is making great strides in this area. See: U.S. Navy, Chief of Naval Operations Strategic Studies Group XVI, Command 21, Speed of Command for the 21st Century June 1997, p.10
[59] One reason for the non-linearity is the average uncertainty (information entropy) of each message passed between them is reduced. Also, the chaotic progression towards synergistic understand is reduced.

as well, or the information dominance anticipated will fail to be achieved.

Conclusion

Military decision-makers must understand and accommodate the non-linear nature of information and its support systems in order to achieve the information dominance anticipated through advances in technology. The United States is currently redesigning its military forces with the expressed intent to leverage rapid advances in technology to achieve information dominance over the battlefield and "revolutionary" increases in force effectiveness. Yet experience in the commercial sector gives this strategy mixed results. Military decision-makers need to ponder the lessons available from the civilian sector. I believe they will indicate, information solutions that over weight technology, while diminishing the importance of human judgement and wisdom, bring with them marginal value.

Non-linearities are pervasive throughout information technology and inherent in the very nature of information itself. When encountered, they can appear as abrupt limits or walls to those who do not anticipate them. Understanding the interactions of systems founded on information technology is often counter intuitive. To gain this understanding, military decision makers must acquire insights into the non-linearity of their high-tech systems. To master this new military force, decision makers must make accommodations to its non-linear nature.

As Clausewitz has noted, war is very difficult. In this new information age, technology may (or may not) reduce these difficulties, but it would be imprudent to expect the U.S. to enjoy its benefits unopposed. In the end, our high-tech advantage could be a fleeting one. Yet, equally as powerful, are the synergetic advantages inherent in human wisdom and prescience. These human processes exhibit the same non-linearities inherent to the nature of information and are more chaotic. But in the final analysis, they are the most essential and enduring ingredients required to achieve information dominance over an enemy. Any military solution that values technology over human capability is linear thinking in a non-linear world.

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