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ABSTRACT

The concept of *C2-Entropy* is introduced, which seeks to build on heuristic principles such as Parkinson's Law, as well as approaches such as Perrow's Normal Accident Theory and Berniker's Organisational Cognitive Thermodynamics. This approach offers a quantitative framework for determining how entropy is distributed between the nodes *and links* of a C2 organisation. It describes how the complexity of a C2-system can lead to system failures while also giving the framework for understanding its capacity to deal with complex adversaries or environments. An intuitive explanation of "entropy" is given, with an explanation of the underlying formalism of non-equilibrium statistical mechanics. The concept itself is developed through the study of several characteristic historical military engagements – the Milvian Bridge battle, the withdrawal of ANZACs from Gallipoli and the Battle of Jutland. Initial steps in quantitative formulation are taken. The full development of this program of research is ambitious; nevertheless initial conclusions can be drawn about the role of C2 structure in the order/disorder properties of a military force, and the role of Military Command styles, such as Mission Command.

Introduction

Organisations consist of human beings interacting in structured relationships, expressed in a dynamic movement towards the fulfillment of specific objectives[1]. This triad, *humans-relationships-time*, is at the heart of military Command and Control (C2) systems irrespective of the level of technological enhancement of the myriad system functions. This paper contributes to the development of an effective quantitative theory of C2 wherein the impact of each three members of the triad must be effectively captured. An approach to this end will be proposed here and, for simplicity, called *C2-Entropy*.

Entropy originated in the study of heat engines in the 19th century, was developed further in analysing statistical and dynamical properties of systems of large numbers of particles, was applied to define "information" in the mid-20th century and finally underpins many of the definitions of "complexity" in the modern complex/dynamical systems literature. Loosely, entropy can be understood as the degree of "disorder" in a system, though this warrants clarification which will be provided later. The significance of entropy is captured in the Second Law of Thermodynamics which implies inevitability about entropy increase and therefore irreversibility of changes a system undergoes in time. In some cases, this increase of entropy implies system degradation.

Possible evidence for entropy in human organisations is implicit in the heuristic "Parkinson's Law" which states[2] that "Work expands so as to fill the available time for its completion". This captures the observation that organisations grow in size and complexity not necessarily because of an

increased external demand for their outputs but as a product of the relationships between organisational members. Counterbalancing this is the value put on increased network connectivity for information sharing by Network Centric Warfare (NCW). Weighing up the two requires a quantitative dynamical theory of C2.

At the intersection of Parkinson's Law and NCW lies the human participant in C2. The human is both the information generator, the decision maker who uses that information and the actor on these decisions. The human is also the greatest impediment to any "microscopic" theory of C2. Thus "stochasticity" is required for any model of C2, by which it is recognised that there are practical if not conceptual limits to completely modeling and tracking the detailed cognitive and physical state of a human centric C2-node. Therefore the absence of information about a node leads to behaviours *perceived* as random[3]. At the end of the day, through its role in non-equilibrium dynamics, channeled through the connections between organisational members, this stochasticity drives the entropy growth in an organisation.

This paper argues that, for a military organisation, entropy is *definable* and *useful* for C2 analysis. The main points of this paper are:

- A C2-system consists of human *nodes* and organisational *links*.
- C2-entropy limits a commander in exercising control of the system.
- C2-entropy increases with time and can be exchanged between nodes and links through non-equilibrium dynamics.
- In isolation, the C2-system approaches equilibrium with maximum C2-entropy. Equilibrium means the macroscopic system properties cease to change and therefore the system ceases to be able to exert change on other systems (for example Blue on Red forces).
- The exchange of C2-entropy from nodes to links creates opportunities for *relative* controllability over nodal properties. Not all entropy is "bad". Thus spatial "order" of C2-nodes can coexist with a state of high entropy[4], presenting opportunity in the battlespace.
- C2-links must be maintained in a state of "latency", namely being available but unexercised or used sparingly until the C2-system confronts crises, such as mortal combat.

Background concepts, namely Command and Control and the definition and role of entropy will be first discussed. Readers familiar with such technical material may overlook this section. Next, the characteristics of C2-Entropy will be derived through study of historical military scenarios: from Roman history and World War I. The mathematical setting for C2-Entropy will be Non-Equilibrium Statistical Mechanics (NESM), discussed in broad terms subsequently. This section, firstly, shows a (still formative) quantitative theory underlies the largely qualitative analysis of the majority of the paper. Secondly, it foreshadows some original work by this author in dynamical

network theory, to be reported elsewhere. The paper concludes with a discussion on the relevance of C2-Entropy to modern C2 concepts.

Background Concepts

Command and Control

The Pigeau and McCann definition of Command and Control will be adopted[5]:

> *Command is the creative expression of human will necessary to accomplish the mission; control is the structures and processes devised by command to enable it to manage risk. C2 is the establishment of common intent to achieve coordinated action.*

Implicit in this statement is that:

- the "structures and processes" apply principally to the human relationships embodied in the command and control system,
- the source of coordinated action is the presence of common intent.

In this paper, the underlying assumption is that the *seat* of the network of human relationships in a C2-system is the existence of common intent. Or alternately put: the establishment and sustainment of functioning Command and Control relationships is achieved by the expression of common intent. It follows that the outcome of "coordinated action", namely the constraining of otherwise unfettered individual behaviours, is a product of the viability of the Command and Control relationship. Certainly, technology plays a crucial role in facilitating C2-system functions. It enhances the processing and transfer of information and decisions relevant to common intent. But to miss the human element in this assemblage of sensors, wires and computers is to miss the wood for the trees.

This paper, then, will address the organisational aspects of C2-systems, which means it will be concerned with the overall strategic-operational-tactical compass of military command and possible substructures within them. It will not be focussed primarily on combat at the tactical level, though the historical examples to be considered will be drawn from combat situations.

Entropy: from Heat Engines to Organisations

Entropy in Thermodynamics and Statistical Mechanics

In the thermodynamics of heat systems, entropy formally is the rate of flow of heat per unit temperature. Its role in describing the diminishing capacity of converted heat to do useful work is encoded in the Second Law of Thermodynamics which can be stated as: for closed systems in *equilibrium* the entropy cannot decrease. Equilibrium is the property that a system, seen in

terms of its *aggregated* or macroscopic properties, does not change with time. In contrast, statistical mechanics relates the aggregate system properties to the temporally changing microscopic behaviour of the system constituents. At each level of aggregation quantification is assumed possible through the assignment of numerical values to the dynamical variables describing the properties of the relevant entities. The fact that such a description may not be complete is covered by stochasticity, to be discussed later. The types of such variables and their numerical ranges are the *degrees of freedom* of the system. Different variables may be relevant for each level of aggregation[6]. The collection of values of the variables describing a specific microscopic entity is called a microstate. A realisation of microstates is a particular collection of microstates over all system entities, while a macrostate is a specification of the values of the variables relevant at the aggregate level. Many *different* realisations of microstates may be *consistent* with a specific macrostate[7]. A state space is a multidimensional space whose axes are all the separate variables for each of the microscopic entities. The microstate of the system is then a point in state space. The evolution of the system by going from microstate to microstate with time is a one-dimensional *path* in state space. The different macrostates available to the system represent a particular type of partition of the state space into regions within each of which microstates are different but consistent with a given macrostate.

At equilibrium, *the probability of finding one microstate consistent with a given macrostate is equal for all such microstates*. The label E will be reserved for macrostates and the index i will label microstates. Thus if there are W realisations of microstates consistent with a single macrostate labelled by E (which may be a multidimensional vector), then the probability of finding i consistent with E is

$$p(i|E) = 1/W \ .$$

The quantity W corresponds then to the statistical *weight* of the macrostate E under equilibrium conditions where uniformity of the distribution is pivotal. A system *out of equilibrium* correspondingly is one where the spread of microstates within an available macrostate is not uniform: certain subsets of microstates may be more probable than others. Now disorder can be defined as the *degree of uniformity in the probability distribution of microstates*[8]. Disorder should not be confused with the term "stochastic". This will refer to the limitations in defining the influences on a microscopic entity.

Thermodynamic entropy is related to the probability distribution associated with microstates via Boltzmann's elegantly simple equation $S = k \ln W$. The natural logarithm is used and the constant k arises in the thermodynamic gas laws and will be set to one in the following. At a more fundamental level the entropy corresponding to the macrostate is computable from the probability distribution of microstates:

$$S(E) = -\ln p(i|E) \ .$$

As shown by Gibbs, the aggregate behaviour of system in equilibrium can be determined completely by the properties of the probability distribution and the maximisation of average[9] entropy

$$\bar{S} = -\sum_{E} p(i \mid E) \ln p(i|E) .$$

This is an overall system measure in taking into account all possible macrostates of the system and all ways of realising the various microstates for each macrostate. In terms of the geometric representation using a state space, the significance of the macrostates E now corresponds to finite measurement resolution available to an observer. Thus the size of gradations or "bins" into which an observer can arrange measurements limits the ability to discern the actual point in state space corresponding to the true system state. The average entropy can be seen as the average density of the probability cloud surrounding the system point. *At equilibrium, the observer has the least chance of randomly picking the precise system state.*

Entropy in Information and Dynamical Systems

The underlying probabilistic formalism implies broader generality of Boltzmann's formula for entropy. Shannon used it to give quantitative meaning to the term *information*[10]. The basic idea can be explained with reference to a bit-string, such as 0111000000110101…. Each symbol can have one of two values. The probability that any bit can be a one or zero is equal to one-half. For an *N*-bit sequence the probability that a particular sequence will be found by random selection is $p = 2^{-N}$. Shannon defined "the amount of information", *I*, in a string to be represented by the "surprise" at choosing a particular sequence correctly at random. Yet intuitively that surprise could be argued to be proportional[11] to the string length *N*. The definition which brings these into alignment is

$$I = -\log_2 p .$$

Thus, as long as a probabilistic description of denumerable entities can be given, the methods and dynamical implications of statistical mechanics can be used. This applies also to human organisations, as will be outlined below. At this point two implications can be stated. One is the role of *subjectivity* in the system description, through the choice and measurement precision of the variables E as determined by the observer[12]. For Command and Control, a Commander always has limited access to the microscopic behaviour of a subordinate organisation (not to mention the enemy's state). More specifically, this is important for *control*: one must be able first to determine the system state in order to influence it. The second implication refers to the irreversibility of certain changes in a system. Jaynes took this step in the insight that, for a general dynamical system in equilibrium, the *unique* probability distribution for realisations of microstates for fixed values of, or constraints on, macrostate variables is one which *maximises* the entropy[13]. The important consequence of this is that the processes which have led to "equilibrium" for any type of general system are *irreversible*. Applied to

organisational dynamics, this is a powerful implication: some organisational behaviours *cannot be internally reversed* once they have developed.
These ideas do apply for non-equilibrium conditions, through a "statistical mechanical version of the Second Law" related to Boltzmann's "H-theorem": *that entropy increases for systems seeking to approach equilibrium* as well as systems in equilibrium. The picture can be summarised as follows. The system is prepared in some initial constrained state whereby the observer/commander/controller has knowledge with high accuracy of the microstates, within a narrow probability cloud. As time evolves the system point moves along a trajectory in state space while the associated probability distribution distorts, expanding in some phase space dimensions and contracting in others as entropy is exchanged (or information is lost through interactions) between subsystems. If equilibrium is approached the average size of the cloud increases as the probability distribution spreads until at equilibrium the distribution becomes uniform in all the phase-space dimensions. For C2-Entropy this picture will be important for understanding how disorder can shift between organisational nodes and links as well as determining the final system fate.

Microscopically, "equilibration" or "thermalisation" takes place: under evolution available degrees of freedom are exercised, transitions between accessible values of variables occur so that in approaching equilibrium the probabilities for the microstates are equalised. Drawing on the earlier discussion, the onset of equilibrium hinders controllability of a subordinate organisation by its commander. The scope for correctly determining the precise system state and therefore foreseeing the consequences of applying influence to some part of it is diminished.

In contrast, some degrees of freedom can be "latent": *in principle* accessible but exercised sparingly. That some degrees of freedom may be latent longer than others is pivotal for the appearance of *structure* in a complex system[14]. For a military organisation this will be important as tactical success usually depends on structured application of force.

Entropy in Organisations

Organisations are dynamical systems. Numerous approaches have extracted the thermodynamic/statistical mechanical implications of this identification. Since entropy suggests degradation, one application is in "Normal Accident Theory" due to Perrow[15]. Here two system characteristics, *interactive complexity* and *coupling*, determine the susceptibility to systemic failure.

The term "interactive complexity" describes the impracticality of foreseeing unintended correlations in systems whose elements serve multiple functions, and are connected through multiple or even disconnected pathways. The "coupling" is a measure of the degree of slackness or responsiveness between system elements. Appropriate management styles for the various mixtures of

high/low interactive complexity and loose/tight coupling can be mapped out for some cases. The difficult and dangerous region is that of interactively complex, tightly coupled organisations which are inherently accident-prone. Lloyd *et al.* have translated Perrow's framework to military command[16].

Perrow's approach captures well the problem of control of organisational systems. It uniquely identifies *system connectivity* (coupling, interactive complexity) in reducing or escalating the problems with control; this will be manifested in the role of links in C2-Entropy. Berniker[17] translates Perrow more carefully into an "Organisational Thermodynamics" by taking seriously the *irreversibility* implicit in the thermodynamical aspects of Perrow's model. By associating entropy, as above, with tendency of a system to failure, and then taking that entropy as a genuine physical quantity there is a link to the Second Law of Thermodynamics. Thus, such systems tend to ever greater "disorder" subject to an irrevocable arrow of time. Whereas Perrow speaks of how certain organisations or systems "are", Berniker speaks of how they "become":

> *… But the Second Law is ineluctable. Noise will increase and cognitive processes become ever more tenuous and fragile. A point will be reached when the organization cannot even hear itself, organizational cognition becomes problematic and organizing incoherent to its members. The combination of excess complexity of organization and too tight coupling leads to organizational "Normal Accidents", failures incomprehensible to actors when they occur.*

Berniker brings Perrow closer to a model for Command and Control. There is a duality in going from Perrow to Berniker. In the former the emphasis is on links. In the latter it is nodes which are[18], "points where control, intervention and monitoring are possible". High entropy thus is associated with limitations in the "cognitive capacity" of organisational units responsible for managing such points or subsystems.

Still, both Perrow and Berniker seem to describe equilibrium situations. Ingber[19] transcends this condition, utilising the full mathematical machinery of NESM for modelling tactical C2-systems. Here, noise terms, capturing the microscopically unmanageable contribution of human factors, are added to Lanchester-style attrition equations. What are missing here are the hierarchies of decision-makers characterising a complete strategic-operational-tactical C2 system. C2-Entropy seeks to complete this picture.

System Boundaries

A final cautionary comment is warranted. Khalil[20] argues for the disentanglement of the notion of system "dynamics" from that of system "development" in addressing socio-economic systems. The former, he argues, can be modelled by non-linear statistical/thermodynamics while the latter cannot. The former is the domain for cyclical, abrupt or intermittent dynamical phenomena while the latter is the domain of "purposeful

development" of a system, by which he means cultural or constitutional transformation of an institution. Effectively, Khalil's point here concerns the determination of "system" boundaries. Thermodynamics and statistical mechanics require careful distinction of the system and the environment. Few real world organisational systems are isolated. A system undergoing renewal or reconstitution is subject to fluxes from the environment. Therefore in seeking to elucidate C2-Entropy through historical military examples care will be taken to isolate initial and final times at which – at least crudely – an "isolated" C2-system can be said to exist. The evolution in time of such a system is then legitimately governed by "dynamics".

Deriving C2-Entropy from Military History

C2-Entropy and Spatial Order

It is useful to start at an extreme end of the spectrum, the fate of a military force in the absence of (or upon the destruction of) a Command and Control system. Given that the object of concern is a genuine military force in the first instance, the best place to look is an army in the face of defeat. This will be contrasted with a case study of an army suffering military defeat but managing a successful withdrawal. In both cases the absence or presence of a C2-system will be highlighted. In contrast to the previous discussions of precursors to C2-Entropy, the main thrust here will be to show how "disorder" in some C2-dimensions can enable spatial "order" and thus occasionally render entropy a beneficial characteristic.

The Battle of the Milvian Bridge

On October 28th, 312 AD, on the outskirts of Rome, two rival Roman armies met in open conflict. Defending Rome was the army of Emperor Maxentius (Emperor over Italy and North Africa). Attacking was the army of Constantine the Great (Emperor over Britain and Gaul). Estimates of troop numbers are vague though all sources insist on the numerical superiority of Rome's defenders: 80-100,000 men commanded by Maxentius against some 40,000 men commanded by Constantine who approached through northern Italy along the *Via Flaminia*. The types of forces were basically cavalry and infantry.

Significantly, Maxentius originally (and soundly) planned to retain his force inside Rome, or close to its defending walls but behind the defence of the narrow Tiber river forcing Constantine to cross the river across a single available bridge, the Milvian. Instead Maxentius absurdly transported his entire force across the river and arrayed the troops in a line of substantial depth (9 miles) parallel to the river behind him. Thus behind Maxentius lay only the Milvian and a makeshift pontoon bridge to fall back on. In front, his

army stood on broken hilly country spanning the space between the two northern roads into the City, the *Viae Cassia* and *Flaminia*. The historian John Holland Smith argues that Maxentius sent his left wing downwards along the *Via Cassia* to drive Constantine around on to the river[21]. This manoeuvre failed, and the armies met in full frontal combat at a hill called (to this day) *Saxa Rubra*. Zosimus[22], writing a century after the event, related that the cavalries fought intensely with Constantine's eventually overwhelming Maxentius'. And then,

> *… when his horsemen gave up he took to flight with the rest and made for the city via the bridge across the river.*

The pontoon bridge had been sabotaged leaving the Milvian as the only escape route. But then "the timbers could not sustain the pressure of the host, but broke". Another author, an anonymous panegyrist (addressing Constantine himself), wrote that

> *… all the rest went headlong into the river, so that there was at last some abridgement of the slaughter for the weary hands of your men. After the Tiber had swallowed the impious, the same Tiber also snatched up their leader himself in its whirlpool and devoured him …*

Indeed the turbulence that consumed Maxentius' body remains visible to this day downstream from the stone successor to the Milvian Bridge.

It is self-evident that general *disorder* was fundamental to the destruction of Maxentius' army. Can this loose use of the term "disorder" be refined into an application of entropy? First the system is identified as Maxentius' army. Its microscopic entities are the individual infantry men. The initial and final conditions will be chosen such that attrition plays a minimal role in determining how much entropy is in the system: the sustained attrition of an army will of course lower physical entropy, no matter what the remnant force elements are doing. Thus some period over which the system composition is *conserved* is required. In the absence of better historical data, it will be assumed that this is some interval between the collapse of Maxentius' cavalry and the army's arrival at the Milvian Bridge. The dynamical variables are the positions and velocities of the Maxentius' surviving soldiers over this time. During this flight, a large distribution of individual positions and, to a lesser extent, of velocities would have applied. This should be compared to both the narrow spatial and speed distribution required for a safe retreat across the Milvian Bridge. Evidently, during flight the system entropy was *high* compared to that required for a safe retreat. The requirement that entropy increase ensured that safe retreat was impossible. Moreover, no assumption of equilibrium is required for this conclusion: if spatial position and speed were the only degrees of freedom available to each soldier, the entropy could not be decreased. Of course telling here from a C2 perspective is the complete breakdown of any command structure, plan or strategy for escape. A lack of common intent led to unfettered behaviour by each soldier. The tempting conclusion is that Maxentius' force in its flight had a *high C2-Entropy*

thoroughly concentrated in its spatial behaviour of its nodes; the force had no C2 *link* degrees of freedom with which to exchange its spatial disorder.

Withdrawal of ANZACs from Gallipoli

An example of a successful military withdrawal comes from the ill-fated engagement of the Australian-New-Zealand Army Corps (ANZAC) at Gallipoli, Turkey, in 1915. Certainly the disasters that befell this engagement are solemnly remembered in Australia every April 25th. What is overlooked is the remarkable success of the withdrawal under harrowing conditions. One source[23] gives the figures of 130,000 men, 10 000 animals and large numbers of equipment and assets evacuated from hilly country sloping down to the sea with the Turks in possession of the high ground and line of sight view of nearly all the shoreline from which the Allied forces departed.

Comparison with the Milvian Bridge above is somewhat fraught, because the Roman battle took place within an extremely fluid sequence of events lasting little more than several hours. The ANZAC withdrawal took place after some eight months of stalemate, and the initial aspect of the withdrawal involved a month long conditioning of the Turkish forces "to silence" by cessation of sniping leading into winter. The Turks interpreted this as Australian preparations for bunkering down their positions for the oncoming severe winter. The actual withdrawal of the final 20,000 men took place over two nights, under the cloak of darkness. Therefore to make a detailed comparison some rescaling should be done but will be omitted from this broad stroke analysis. The main point is to discover the C2 degrees of freedom in operation and thereby come to grips with what "link variables" could mean for entropy.

As summarised by Bentley[24], the withdrawal took place using the following principles:

- maintenance of the frontline throughout, including the semblance of normal rates of fire on the enemy ,
- maintenance of morale through dissemination of a plan,
- a hollowing out of the existing command structure down to skeletal representation while keeping commanders in position,
- the transfer of command halfway through the withdrawal to a Rear-Guard Commander, who himself was present as the last subordinate embarked,
- and precise coordination of those withdrawing in stages and exploiting the cover of darkness.

Over the two nights transport ships arrived in three stages for each night, loaded thousands of men and departed within the hour. The last troops departed at 3.30 am on the 20th of December, 1915, with the enemy firing machine guns at empty trenches in the hills above, fooled by explosions of mines set to go off long after positions had been evacuated.

The initial state was one of low configurational entropy (high spatial order, little and coordinated movement). The picture is one of a crystalline structure (say, of salt) turned to the enemy while its rear dissolves into the sea. At the front the investment was in highly *active*, robust control relationships which could melt way into controlled movement. *Link-entropy was shifted into nodal spatial-entropy*. However there is a point at which the modelling should stop, where arguably the military force is no longer recognisable as the same initial system once it becomes confined to discrete and disparate ships sailing off into the Aegean Sea.

The control links moreover could hardly be characterised by "information exchanges" at the time of the operation. Most of the communication took place in advance of the actual withdrawal. The initial system state was being prepared during the information transfer phase, as messages and orders were input from the outside channelled on a daily basis through Brigadier General (General Staff) Brudenell White to the divisions. What controlled the change in spatial configuration was finally the shared intent or common picture carried by each soldier. The relationship between common intent and coordinated action *a la* the Pigeau-McCann definition of C2 is accentuated here *par excellence*. The common intent is expressed itself as an implicit constraint on arbitrary motion conveyed through an invisible bond between neighbouring soldiers. *C2-links were largely latent during the operation.*

The role of latency in link variables is underscored by reconsidering how Maxentius' disaster could have been averted at the Milvian Bridge. Either a pre-prepared contingency plan or some form of military doctrine could have been called upon[25] with little time for detailed message traffic in the execution. The exercising of C2-links would have to have taken place with little tangible physical or informational exchange taking place at execution.

Finally, the two systems considered involved relatively brief views on the system evolution so that equilibrium was not manifested. The greater the duration of the ANZAC's retreat (as for example Napoleon's army retreating from Russia) the greater the potential for equilibrium to overwhelm finally any benefit from shifting entropy between nodes and links. However, the nature of equilibrium in C2 will be considered next through the Battle of Jutland.

C2-Entropy and Equilibrium

The Battle of Jutland[26]

The battle involving the British Grand Fleet of the Royal Navy (RN), under Fleet Admiral Sir John Jellicoe, and the German High Seas Fleet (HSF), under Vice-Admiral Reinhard Scheer, took place in the North Sea off the coast of Denmark over roughly a fifteen hour period from 4 pm of May 31st to effectively dawn of June 1st, 1916.

Both sides utilised scouting formations. The British used a hybrid scouting "fleet", the Battle Cruiser Fleet (BCF), of lightly-armoured, fast battlecruisers led by David Beatty and a subordinate group of fast well-armoured battleships (the *Queen Elizabeth* (QE) Class), the 5th Battle Squadron (BS) under Hugh Evan-Thomas. The Germans had the First Scouting Group of Vice Admiral Franz Hipper. The main fleets of comparatively slow, heavily armoured battleships were respectively led by Jellicoe and Scheer.

The main German strategy was to try to lure and destroy parts of the British fleet while avoiding a full engagement with the Grand Fleet. The confident British on the other hand, sought to ensnare the entire German fleet in battle. Beatty's BCF was the lure: the fast and heavily armoured 5th BS was intended as the "sharp end" of the BCF whose aim was to tie down the HSF long enough that Jellicoe could reach the battle and give time for combat during daylight hours. In 1916 naval combat at night in open seas was problematic. From the Command and Control perspective it is also relevant that the RN employed an elaborate system of centrally controlled fleet manoeuvring via signalling (through flag, semaphore, Morse and wireless). Mission Command (MC) had been long absent as a doctrinal principle[27], despite its use under Nelson at the Battle of Trafalgar.

On the afternoon of May 31st the BCF made first contact with the German scouts. At a critical juncture orders were given from Beatty's ship using flag-signals to the 5th BS causing it to turn "in succession" in the face of heavy bombardment from Hipper's scouts. A delay in implementation of the order brought each of the *QE*s successively under direct fire with several being sunk. This delay was arguably caused by the responsible flags being left on the mast too long: *execution* of a flag order was meant to take place when flags were taken *down*. Despite its losses, the 5th BS fell into formation with the BCF, which collectively fired on the combined German fleet, inexorably drawing it in a "run to the north".

As Jellicoe's main fleet converged with Beatty's, orders were given at 18.10 for the BCF to configure into the main fleet with barely hours of daylight left. The full deployment of the entire Grand Fleet into a single line thus took place through masterful signalling, manoeuvring and not a little chaos. The completed process left Jellicoe having achieved the much desired "crossing the T" of the enemy[28]. But in the twenty minutes required for the deployment, the enemy had turned away. However, as if having a death-wish, Scheer subsequently turned back into the Grand Fleet and had his T crossed again now from the north-west. Turning away finally, night overtook the fleets.

During the night Jellicoe erroneously guessed the direction in which Scheer would seek to escape. Nevertheless, the German fleet drifted through the rear of the British with ships colliding or exchanging fire. Remarkably none of this

information was transmitted by wireless or Morse to the commander. By dawn, Jellicoe realised the HSF had escaped. Despite heavy mutual losses, the "new Trafalgar" had slipped from British grasp.

Many aspects of this engagement make it amenable to statistical mechanical analysis. The isolation in nearly every respect of the fleets from an "environment", at least during daylight hours, means the boundaries are quite clear. If one wished to focus purely on the British fleets, the High Seas Fleet can be regarded as the environment though a rapidly changing one. The system nodes can be treated as the ships themselves, though the humans commanding, signalling or firing may be different. There is a degree of heterogeneity in system nodes: the battleships, cruisers and "fast battleships" of the 5th BS. A key question is: was there some form of equilibrium? Certainly not in any configurational properties: for the impressiveness of numbers of British ships deploying at 18.10, by thermodynamic standards the distribution of ship positions and velocities was quite narrow.

The marked difference between this engagement and the previous ones is in the presence of communications. One can readily identify the C2-links: primarily from (as the name suggests) flagships to subordinates for the major transmission of manoeuvring orders. Gordon quotes a rate of a "flag-signal every sixty-seven seconds" during daylight hours at Jutland, yet major combat occupied only a short period within the overall affair; traffic along the links was tremendous. However the precise variables should be quantified, a sequence of random snapshot of their values in time would yield an equal probability that they could be in any of their available message "states". This is tantamount to equilibrium. C2-Entropy of the Grand Fleet can thus be argued to have been maximally distributed into C2-links.

This interpretation is supported by two of the prominent errors that occurred: the miscommunication that brought the 5th BS under fire from the German scouts and the sheer failure to communicate when ships in the rear of the Grand Fleet became aware that the Germans were drifting through. Gordon's point of emphasis is the chronic lack of initiative shown in both cases[29]. In Perrow's terms the system was both tightly coupled, with subordinates relying entirely on detailed orders from commanders, and high in interactive complexity, reflected in the complexity of messages, message media (flags, semaphores, etc…)[30] and signalling protocol. Indeed this analysis shows that the link variables are at the very least a vector of high dimensionality here, with the potential for noise to infect and spread through each of the components.

Summary: the Principles of C2-Entropy

From the three historical cases and the study of precursor concepts, the main result is:

A C2-System is a Statistical Mechanical system with two classes of dynamical entities, nodes and links.

And

C2-links can exist without actual communication taking place.

The input of information from the outside, through the dissemination of plans, through training or the teaching of military doctrine is tantamount to the preparation of the system with the result that

C2-links, through prior distribution of information, are created or reinforced but in a latent state.

Moreover

C2-links are exercised as degrees of freedom through communication about operational matters.

During this process disorder is absorbed in these degrees of freedom permitting order or coordination in the configuration or other properties of C2-nodes. The dangerous regime for a C2-organisation is when

C2-links, with the passage of time and the continued exercise of operational information exchange undergo thermalisation or equilibrate.

At a slightly more quantitative level

C2-link variables acquire a dimensionality commensurate with the communication modes actually available according to C2-nodes during the system preparation.

Technology can inflate this dimensionality.

This is as far as the present historical analysis can help. For the remainder of the paper, an attempt will be made to unveil the formalism of the Fokker-Planck equation and how this may guide the concretisation of the above, admittedly, qualitative description.

Towards a Framework for Quantifying C2-Entropy

Dynamical description of C2-node properties

To apply Non-Equilibrium Statistical Mechanics to C2-Systems, the "system" and the "observer" must be clearly defined. Here the observer is identified with the commander of a (subordinate) C2-system. That subordinate system is then quantified via the formalism of a state space. A node in a C2-network is represented by a vector of numbers[31]:

$$q_{\mu,i}(t)\,.$$

Here the Greek index μ represents the components of the state vector while the Latin index i indicates the node. A military C2 system will involve at least a set of nodes at the tactical level, where position, velocity and lethality are typical variables relevant to the projection of force in the battle-space. However, the manipulation of these variables is the scope of the nodes of intermediate C2-echelons – Task Force or Operational HQ Commanders - and their decision or planning cycles. The simplest model for this is Boyd's OODA loop consisting of discrete Observe, Orient, Decide and Act values. Thus for

such nodes cyclic variables are relevant. This can be generalised to a continuous OODA loop via variables whose values lie on the unit circle. More sophisticated variations on the OODA loop can in turn be mapped to more complex spaces for corresponding node variables. Most importantly, the OODA loops cascade up and down the nodes of the C2-hierarchy, in order that decisions are implemented as tactical effects.

The state vector changes as a function of (continuous) time. A fully deterministic equation describing the time evolution of the system can be written

$$\dot{q}_{\mu,i}(t) \equiv \tfrac{d}{dt} q_{\mu,i}(t) = F_{\mu,i}[q_{\nu,j}].$$

Here the function (actually, *functional*) F mixes both vectorial and nodal components. This can be broken down further in order to separate the behaviour of a nodal entity in isolation from the influence of other nodal entities:

$$\dot{q}_{\mu,i}(t) = f[q_{\mu,i}(t)] + \sum_{\nu,j} G^{ij}_{\mu\nu}(t) h[q_{\nu,j}(t)].$$

The matrix G represents the – possibly time-dependent - relationships between nodes in the network. The two functions f and h are respectively input and output functions indicating intrinsic and extrinsic macroscopic influences on property μ of node i. In particular, the function h can encode the manner in which the OODA loops of connected nodes influence each other, as well as the outcome of an OODA loop on tactically relevant variables. Though some link information is contained here, this remains essentially only a dynamical equation for the evolution of nodes. As an aside, it is worth mentioning that this equation is a generalisation of the Winfree-Kuramoto models which are used to study self-synchronisation[32].

The system is still deterministic. Stochasticity is introduced via the "noise" achieved by a set of functions $N_{\mu,i}(t)$. For any μ and i, $N_{\mu,i}(t)$ is not a single function of time but chosen from an ensemble of functions according to a distribution. Gaussian noise is typical, with average value of $N_{\mu,i}(t)$ zero and standard deviation given by some real number Ω, the diffusion constant. With the inclusion of noise the equation takes the form

$$\dot{q}_{\mu,i}(t) = f[q_{\mu,i}(t)] + \sum_{\nu,j} G^{ij}_{\mu\nu}(t) h[q_{\nu,j}(t)] + N_{\mu,i}(t).$$

The compact form for this will be given as

$$\dot{q}_{\mu,i}(t) = F_{\mu,i}[q_{\nu,j}(t)] + N_{\mu,i}(t).$$

This has the generic form of a *Langevin* equation of first order which are used to model macroscopic entities subject to identifiable macroscopic external driving forces, F, and unidentifiable, (hence, apparently random) microscopic forces (molecular collisions), N. In writing such an equation for C2 entities it is implicit that it is *not a high fidelity microscopic model*; the basic entities are *effective degrees of freedom.* In the same spirit, this approach identifies *internal*

structural influences as valid driving forces on the command and control entities.

With noise, it is useful to consider the probability that at time *t*, the variable $q_{\mu,i}(t)$ is in an infinitesimal neighbourhood of the value $Q_{\mu,i}$ given that initially at t_0 the variable took the value $Q^0_{\mu,i}$,

$$P[Q_{\mu,i},t;Q^0_{\mu,i},t_0].$$

For Gaussian noise, a corresponding evolution equation for the probability distribution can be derived[33] directly from the Langevin equation, and is the *Fokker-Planck equation*:

$$\dot{P} = \frac{1}{2}\sum_{\nu,j}\frac{\partial}{\partial q_{\nu,j}}\left[\Omega\frac{\partial}{\partial q_{\nu,j}}P + F[Q_{\mu,i}]P\right].$$

The constant Ω and the external function *F* are as described above. For the remainder of this discussion indices will be suppressed.

In the context of a C2-system the probability distribution encapsulates the difficulty of a commander to determine the state of subordinate entities at a given point in time after having initially set up the system in a definite state. In other words the distribution expresses the limited scope for control. The initial condition implicit in the Fokker-Planck equation is a pure "Dirac" delta function

$$P[Q,t;Q^0,t_0] = \delta[Q-Q^0].$$

This encodes the peaking of the initial distribution around the initial value: the state of all system elements (Order of Battle, C2 relationships, etc.) have been initialised by the commander establishing the system. As time evolves, the distribution broadens as noise propagates through the system according to the connectivity of the system entities built into *F*. An equilibrium (or more appropriately steady-state) distribution, if it exists, is given by the large time behaviour of the solution.

A convenient way to represent solutions to the Fokker-Planck equation is through the *path integral* for which some intuitive motivation can be given. Recalling that the system history is a path in state-space and that entropy limits the ability of the state determination to within finite region in this space, in the presence of entropy the system history becomes a *family* of paths connecting initial point to final region. A *weighted* integral over all paths summarises this family. The weight factor, incorporating effectively a cost function, encodes the distortion of the probability distribution with time under the influence of dynamics. A compact way of expressing this is:

$$P[Q,t;Q_0,t_0] = \int_{q(t_0)=Q_0}^{q(t)=Q}[dq]\exp\left(-S[q]/\Omega\right).$$

The reader is referred to the technical literature for more detail, in particular the expression for the exponential term, the so-called "action functional" which weights the paths contributing to this integral. For Ω=0, the

deterministic path is singled out. For non-zero Ω neighboring paths contribute. A two-dimensional illustration of these ideas is given in *Figure 1*. There is nothing *a priori* equilibrium in this formalism: the probability distribution is time-dependent because of the time-dependence of the end point of the state-space trajectory.

Towards a dynamical description of C2- links

Incorporating C2-links as dynamical variables must now be done self-consistently since dynamical properties on nodes and links cannot be cleanly decoupled. The state of a C2-link can be represented by

$$X_{\mu\nu,ij}(t).$$

The index structure reflects that *X* depends on the nodal components of state space as well the relationship between nodes *i* and *j* in the network. In the deterministic case (no noise) one might naively try to write down coupled deterministic differential equations for $q_{\mu,i}(t)$ and $X_{\mu\nu,ij}(t)$. Elevating these to stochastic equations is complicated by the dependence of the various noise contributions. The path integral formulation described above can lead to some insight into this problem. The action functional contains a number of nonlinear terms, involving the output function *h*. A trick often used in statistical physics, known as the Hubbard-Stratonovich transformation, to reduce nonlinear interactions is the introduction of auxiliary variables via the Gaussian integral

$$\exp\left[\sum_{a,b}\tfrac{1}{2}Z_i(A)_{ij}Z_j\right] = (2\pi)^{-n}(\det A)^{-1/2}\int\prod_i dX_i \exp\left[-\sum_{i,j}\tfrac{1}{2}X_i(A^{-1})_{ij}X_j + \sum_i Z_i X_i\right]$$

Formally, this changes none of the dynamical properties of the system but facilitates the interpretation by substituting nonlinear (here, quadratic on the left hand side) interactions between nodal degrees of freedom with linearised interactions with other new degrees of freedom (on the right hand side). By suitable identification of terms in the action functional for the left hand side, the variable X acquires the character of a "link" degree of freedom. The application of this method to the context of Fokker-Planck description of networks is, to the author's best knowledge, completely novel.

Studies of specific analytic forms for the structures discussed here are in progress and will be reported in the appropriate literature. The result of such calculations will be a probability distribution depending on both types of variables $P[Q, X, t; Q^0, X^0, t_0]$. The solutions – both short time and equilibrium – for varying network structure and noise models will yield scenarios whereby the growth of entropy can be exchanged between the two types of degrees of freedom. The distortions of the probability cloud at intermediate times, in Figure 1, are indicative of the type of behaviour one seeks to exploit in a C2-system: the narrowness of the distribution in one direction – for example, for C2-nodes - gives greater scope for control through the associated variables.

This approach has some connection with that of influence and Bayesian networks[34] in that a probability distribution is associated with the state of link variables. The difference is in the above approach this distribution is being derived from the dynamics of nodes. Nevertheless, a marriage of the two approaches may be beneficial.

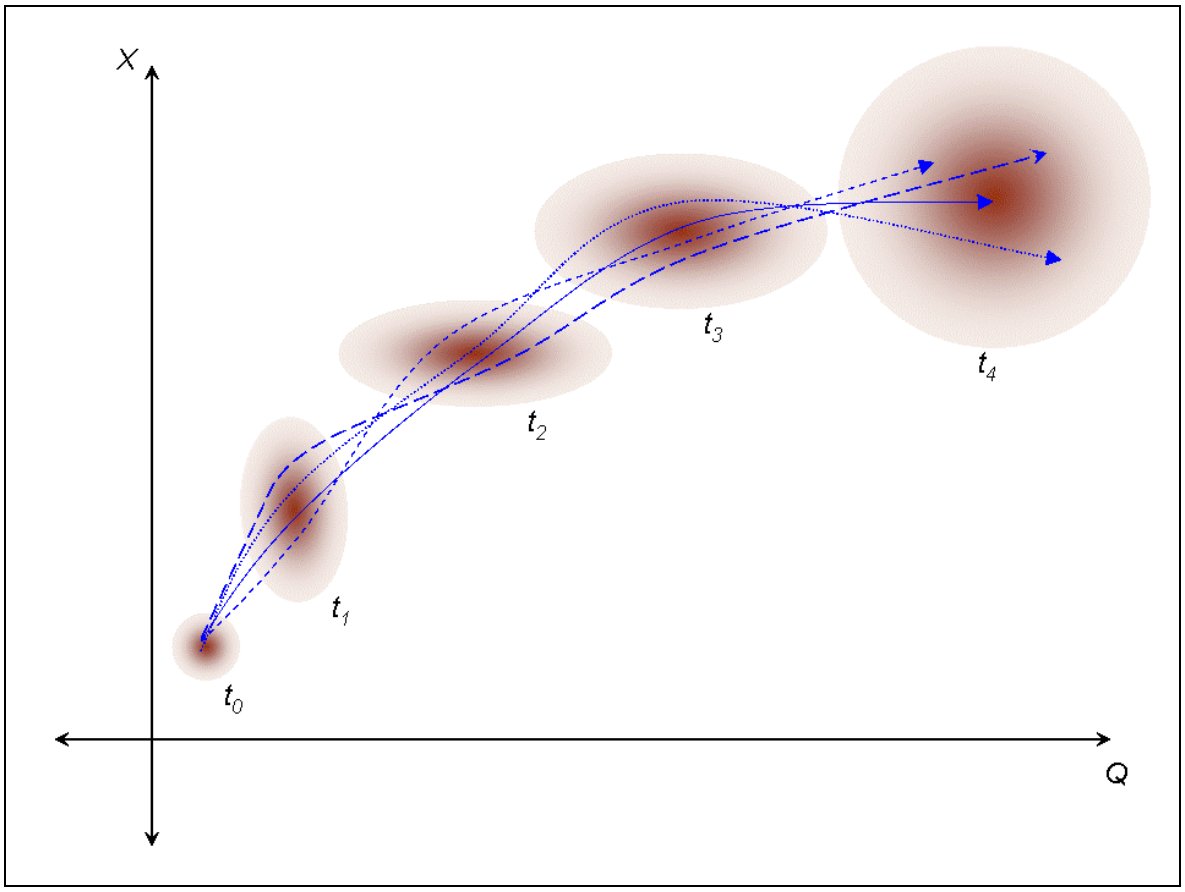

Figure 1 Illustration of the technical concepts discussed in the main text. The system state space is simplified down to two variables Q and X, (for example, node and link degrees of freedom, respectively). The system state, a point, is smeared by stochastic influences into a region limiting the precision with which an observer can identify the precise system state. The initial state is well-defined at time t_0. The probability distribution evolves out of equilibrium, distorting in shape, as determined by the Fokker-Planck equation, through times t_1, t_2 and t_3 until it reaches equilibrium at time t_4. No further change occurs at the macroscopic level. Equilibrium is manifest in the uniformity of the final distribution. The path integral solution to the Fokker-Planck equation is illustrated through the blue trajectories. Each trajectory represents a possible system history from t_0 to t_4. The paths dominating the path integral solution are those which pass through the densest part of the probability cloud. The solid line represents the deterministic path for the system in the absence of noise.

Final Discussion

Entropy and Mission Command

It is convenient here to draw out the implications of C2-Entropy for Mission Command. Quoting van Creveld[35],

> … the freedom granted junior commanders to select their own way to the objective in accordance with the situation on the spot, thus cutting down the amount of data processing required; and the willingness of superior headquarters to refrain from ordering about their subordinates' subordinates – all these are indispensable elements of what the Germans, following Scharnhorst and Moltke, call *Auftragstaktik*, or mission-oriented command system. Behind them all, there must be a realization that a certain amount of confusion and waste are, owing to the great uncertainty involved, inevitable in war; and that such confusion is not inconsistent with, and may indeed be a prerequisite for, results.

In this paper, disorder is recognised as inevitable in Command and Control. However, the multi-tiered nature of traditional C2 means that from the perspective of the highest commander, the lowest level will be least precisely determinable. Entropy will be high and will increase. This hinders the superior commander in exercising control, in managing risk, from such a distance. This drives the need for Mission Command. The closer the commander to the nodes over which control should be exercised the less stochasticity expressed in the subsystem units evolving under that commander's scope. The entropy invested in the subsystem under a junior commander is lower and will increase less rapidly. Anecdotal evidence for commanders adapting their command styles dynamically, from centralised control to mission command as an operation evolves, exists[36] and matches the phenomenology of non-equilibrium entropy evolution. There is also evidence that there is an asymmetry in this adaptability in team structures[37]: switching from "mechanistic" (centralised and functional) structure to "organic" (decentralised, divisional) is easier than the reverse. It would be interesting to explore whether this asymmetry also implies an irreversibility that would be the hallmark of increasing entropy.

Latency and modern signals

C2-Entropy implies that in the Information Age "redundancy" in a communications system is insufficient. Hard-wiring "latency" into the system is imperative: layers of a complex communication system need to be maintained in reserve (though exercised through training) for different phases of an operation. To some extent this is attempted in the classification of signals as "routine", "priority", "immediate" and "flash". However, as Gordon illustrates in his "perspective chapter"[38], at conflict escalation in the First Gulf War, messages were upgraded in classification by operators seeking to overcome the congestion. Using the message priority to give a discrete value to some associated C2-link variable one observes, in the conflict regime, there is an equal probability of finding a message labelled under any category: *equilibration*. Signalling discipline, often insisted upon by commanders[39], breaks down. Hard-wiring latency inhibits such thermalisation.

Implications for NCW

The dangers inherent in a complex network enabling information to be pushed to every node are evident. Perrow warns against this in a recent paper on NCW[40]. However the leading theoreticians of NCW specify that the key assumption making NCW feasible is that of "post-before-processing"[41]. This can be reinterpreted as a partial hard wiring in the network so that some information lines are uni-directional. In graph theoretical language, digraphs are avoided. Certain link degrees of freedom are forced to be more latent than others; the uni-directional flow of information slows thermalisation but does not stop it. For example, the internet search engines such as Google enable information to be pulled. Initially there is oversight (and even efficient use) of new sources of information. Eventually, the volume of downloaded material is so high the identification of useful local information becomes increasingly harder. Search engines for the individual drive, structured directories and other tools bring this disorder into some shape. The complexity of information on the network becomes reflected in the local drive and the "smartness" of search methods used globally requires application locally. Again, the word "equilibration" (between the local drive as system and the environment as the network) applies.

The crucial danger at the tactical level is the scope for thermalisation in the link degrees of freedom facilitating real-time, continuous observations, super-precision targeting in high-tempo, high-density combat. The information transfers between technology nodes will be tremendous even if there is only a single posting by a human operator. Moreover "post before process" directly conflicts with the next often stated goal, "improve sense making"[42] Automated "fusion" either at the push or post end creates a host of (non-human) subsystems where stochasticity may be suppressed but not eliminated. The potential for maintaining latency will be limited. Intuitively, one suspects that the longer such tempo and activity are sustained in any single military mission, the greater the approach to equilibrium and the greater the potential for the system to be "overwhelmed" and errors to cascade. The potential for C2-Entropy here is to make such statements more precise but requires development of C2-Entropy from concept to an actual "theory".

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1 See for example, E.L. Khalil, "Organisations vs Institutions", *Journal of Institutional and Theoretical Economics*, **151**, 445-466, 1995.

2 C. Northcote Parkinson, "Parkinson's Law: The Pursuit of Progress", London, John Murray (1958).

3 For example, as expressed by Poincaré in 1903: "A very small cause which escapes our notice determines a considerable effect that we cannot fail to see, and then we say that the effect is due to chance."

4 An analogy for the physics-literate reader is with black holes: these are objects of extreme spatial *order* of the matter trapped within though of the highest imaginable entropy (encoded in the "Bekenstein-Hawking Law"). The compensation comes from the extreme disorder in the quantum states of gravitons which are quantum particles corresponding to the gravitational attraction between the matter particles.

5 R. Pigeau, C. McCann, "Reconceptualising Command and Control", Canadian Military Journal, 53, 2002.

6 For example, for an ideal gas "temperature" makes sense at the macro-level but has no meaning for a gas molecule while "velocity" and "kinetic energy" are useful at the microscopic level but have no utility for the gas as a whole. However they are functionally related: the energy of the whole ideal gas is the sum of individual kinetic energies of the gas molecules.

7 For an ideal gas there is a variety of ways of assigning velocities or individual kinetic energies to the collection of gas molecules giving the same total system energy.

8 This is not the same as "chaos". Randomness is also inadequate as a synonym for disorder since non-uniform probability distributions are still random.

9 For a given probability distribution, the average of a quantity $f(E)$ is $\bar{f} = \sum_E p(i \mid E) f(E)$.

10 C.E. Shannon, "A Mathematical Theory of Communication", *The Bell System Technical Journal*, Vol. 27, pp. 379-423, 623-656, July, October, 1948

11 As Shannon puts it, "… we intuitively measure entities by linear comparison with common standards …" (Shannon, 1948).

12 Kolmogorov developed an "objective" measure of system complexity. However in practice his complexity is often incomputable.

13 See, for example, E.T. Jaynes, Probability Theory: The Logic of Science, Cambridge University Press, 2003. Jaynes' original papers in *Physical Review* date back to 1957.

14 For example, the role of gravity in the cosmic Big Bang was latent. As put elegantly by Penrose: "Rather than sharing in the thermalization that, in the early universe, applies to all other fields, gravity remains aloof, its degrees of freedom lying in wait, so that the second law would come into play as these degrees of freedom begin to become taken up.", R. Penrose, "The Road to Reality: A Complete Guide to the Laws of the Universe", Random House (UK), 2005. This played an important role in allowing *structure* to appear in the universe.

15 C. Perrow, "Normal Accidents: Living with High-Risk Technology", Basic Books Inc., New York, 1984.

16 M. Lloyd et al., "Use of Complexity-related ideas in understanding military operations and military capability", ICCRTS, 2006. Curiously, these authors locate the place for "Mission Command" in the relatively low interactive complexity and intermediate coupling.

17 E. Berniker, "The Thermodynamics of Organizing: Information and Noise in terms of the Second Law", 43rd Meeting of the International Society for Systems Science, 1999.

18 F. Wolf, et al., "Complexity and Tight Coupling: A test of Perrow's taxonomy in the Petroleum Industry", 43rd Meeting of the International Society for Systems Science, 1999.

19 In fact Ingber applied this approach to compare Janus(T) wargaming data to the US Army National training Center at Fort Irwin, California.

20 "Nonlinear Thermodynamics and Social Science Modelling", E.L. Khalil, American Journal of Economics and Sociology, 54, No.4 (October, 1995), p. 423.

21 J. Holland Smith, "Constantine the Great", Hamish Hamilton, London, 1971.
22 Zosimus, "*Historia Nova*", 5th century.
23 K.A. Lawless, "The Evacuation Phase of the Gallipoli Campaign of 1915", Masters Thesis, US Army Command and General Staff College, 1993.
24 John Bentley, "Champion of ANZAC: General Sir Brudenell White, the First Australian Imperial Force and the Emergence of Australian Military Culture, 1914-18.", PhD thesis, University of Wollongong, 2003.
25 Flavius Vegetius Renatus of *De Re Militari*, "The Military Institutions of the Romans", Book III. Republished in *The Roots of Strategy*, Stackpole Books, 1985.
26 A. Gordon, "The Rules of the Game: Jutland and British Naval Command", John Murray, London, 1996.
27 Mission Command or "Tactical Doctrine" made a brief come back and then fell out of favour with the tragic death in 1893 in a training exercise of its main proponent in the RN, Sir George Tryon.
28 Crossing the enemy's T enabled all ships to simultaneously fire on a single enemy ship one at a time while ensuring the other enemy ships, being in a single line themselves behind the lead, were unable to fire in return.
29 This is consistent with the absence of any Mission Command or Tactical Doctrinal principles.
30 In Perrow's terms: "indirect or inferential information sources" [Table 3.1].
31 Another example is provided by Thuve, looking at Effects Based Operations, H. Thuve, CCRTS, 2006. He divides the complete operational space into Political, Military, Economic, Social, Infrastructure and Information (PMESII) dimensions, however for the present focus on C2 not all these dimensions will necessarily be relevant.
32 S.H. Strogatz, "From Kuramoto to Crawford: exploring the onset of synchronization in populations of coupled oscillators." *Phys. D* 143, 1-4 (Sep. 2000), 1-20.
33 For example, see: J. Zinn-Justin, "Quantum Field Theory and Critical Phenomena", Oxford U.P., NY, 1989.
34 For example, L.W. Wagenhals, A.H. Levis, "Modelling Support of Effects-Based Operations in War Games", CCRTS, 2002.
35 M. van Creveld, "Command in War", Harvard U.P., Cambridge, Mass., 1985.
36 K.G. Stewart, "Mission Command in the Networked Era", 11th ICCRTS, 2006.
37 D.K. Jundt, et al., "The Impact of Hybrid Team Structures on Performance and Adaptation: Beyond Mechanistic and Organic Prototypes", 20th Annual Conference for the Society for Industrial and Organizational Psychology, Los Angeles, 2005.
38 Point 15, "Signals' prioritizing mechanisms become dislocated in times of overload", Ch. 25 of Gordon, "Rules of the Game", 2000.
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42 For example, S.B. Alterman, *Complexity of Network Centric Warfare*, Ch.9 in Gansler and Binnendijk cited above.