A WOVEN WEB OF GUESSES, CANTO THREE:
Network Centric Warfare and the Virtuous Revolution

Track: Information Age Transformation

Authors:

Dr Darryn J. Reid
Head, Land C4ISR Systems
Land Operations Division
Defence Science and Technology Organisation
PO Box 1500 Edinburgh South Australia 5111
Australia
darryn.reid@dsto.defence.gov.au

and

Lieutenant Colonel Ralph E. Giffin
Director Information Management Strategic Planning 5
National Defence Headquarters
101 Colonel By Avenue
Ottawa, ON
K1A 0K2
giffin.re@forces.ca

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ABSTRACT

The field of epistemology, which considers knowledge and knowledge development, is a source of great insight for considering how to exploit information and communications technology in military operations. A discredited epistemological position known as naïve inductivism is manifest throughout the NCW thesis, and we seek to use an alternative outlook called critical rationalism instead.

Inductivism conflicts with profound mathematical results that actually underpin computer science and information technology. Critical rationalism, which describes knowledge development as a process of conjecture and attempted refutation, is corroborated by these insights. In this view, information is merely evidence, conjecture logically precedes observation, and theories are tested by attempted refutation. Uncertainty is fundamental in nature, rather than just a residual insufficiency of information. Truth is not buried in the data, information does not bring about knowledge, and the best answer is not normally within reach even in principle.

Human beings are susceptible to systematic errors in reasoning, so we reject the idea of relying on intuition alone for making decisions. Yet human creativity is essential in proposing novel solutions to problems of explanation and action, and this is a cornerstone of critical rationalism. Our conceptual framework considers a system of distributed interacting decision cells seeking to achieve a higher intent, unifies planning and operations, harnesses human creativity in a programme of rational thinking, and considers all levels of the organisation holistically. Transactions convey evidence used to test theories, the value of those transactions is their potential to refute theories weighted against the importance of doing so, and the value of a network is the sum of the value of its transactions.

At the end of the day, war is a clash of wills, and transformation is driven not by technological innovation but by our deliberate decisions. Our essential theme throughout this series is that the real revolution we require concerns how we think about thinking, and this is a revolution that is altogether overdue.

INTRODUCTION

Our critical review of the NCW thesis, detailed in two earlier papers, uncovered a damaging arrangement of simplifications and a methodological position that is extensively rejected in the literature. Here we employ these realizations to outline a proposal for establishing an alternative conceptual framework for considering networked military operations and information age military transformation. Our broader aim is to stimulate and contribute to open debate in the defence research community regarding the nature of knowledge and knowledge development, models of information technology utilization in the military setting, and force transformation.

In the second paper in the series, we argued that a discredited approach to knowledge and knowledge development known as naïve inductivism[1] is apparent in the NCW thesis. In this paper, we use an alternative outlook called critical rationalism, and we contend that this significantly clarifies the challenge of exploiting information and communications technology in the military domain. A central point is that critical rationalism is corroborated by deep insights of pure mathematics that deal with logic, reasoning, information, computation, complexity, and randomness, while inductivism conflicts with these important results. In contrast to inductivism, critical rationalism describes rational thinking as a process by which propositions are developed and tested by attempting to refute them against the evidence. Information merely conveys observational facts, which must always be regarded with suspicion[2]. Propositions are never fully tested, and in accord with the theorems of incompleteness, the single right answer **is not** inevitable given a sufficiently large volume of collected facts. The truth does not lie buried in the data, and information does not lead to knowledge.

Our proposal is not a straightforward replacement for the NCW thesis, it is not about technology as such, and we do not subscribe to the notion that technological advances are driving the emergence of a new theory of war. Rather, we propose that an improved epistemological position enables us to consider together the issues of command, control, decision-making, intent, intelligence, surveillance, reconnaissance, and the promise of technological innovation, in a holistic way. Our model describes a number of interacting decision-makers seeking to achieve a higher intent, and unifies transactions between decision-makers with those that provide evidence for testing propositions about the environment and the adversary. The notion of transactions also unifies the role of social exchange with those of voice and digital data networks, and we ascribe to each such transaction a value in accordance with the evidence it provides. This approach of considering transactions in which packages of information are exchanged between decision-makers demonstrates an area where our model leads us to a different emphasis to the loose concept of 'information sharing' evident in the NCW thesis. We explicitly

[1] Inductivism is the positivist view in which data collection logically precedes hypothesis formation, inductive inference to produce a general hypothesis, and further verification of the theory over time, by which it eventually turns into a law. Naïve inductivism is the crudest interpretation of this idea.
[2] Chalmers' book *What is this thing called science?* recounts the difficulties of obtaining experimental evidence. Chalmers attacks inductivism initially on the grounds that to obtain relevant observations, the investigator first needs to have a framework of theories.

consider the coordination of physically distributed decision-makers, in place of the NCW idea of 'shared situation awareness'. The perceived requirement for a common operating picture[3] is revealed to be a widely held yet unchallenged assumption, and hence our approach does not yield a common operating picture of the usual kind. We also find that the fog and friction of war are fundamental, rather than being just residual consequences of insufficiency of information[4]. The pivotal theme of this series and culminating here is that the revolution we seek, virtuous in the light of current understanding of knowledge and knowledge development, is a revolution in military thinking.

THE CRITICAL RATIONALIST ENRICHMENT.

> **Thus I reject the naturalistic view. It is uncritical. Its upholders fail to notice that whenever they believe themselves to have discovered a fact, they have only proposed a convention. Hence the convention is liable to turn into a dogma.**
>
> **- Karl Popper, *The Logic of Scientific Discovery*.**

Sir Karl Popper put forward the idea that we regard science as an institution constituted on a set of principles that furthers its aims. He recognised problems of knowledge development as methodological in nature and, in doing so, established critical rationalism as a set of principles outlining the social conventions by which we may claim that our investigations into phenomena are rational and scientific. We contend that this outlook satisfies pressing requirements in considering force transformation and the opportunities for information and communications technology to benefit military operations. Critical rationalism provides a solid basis for understanding how knowledge is generated and decisions are made. Importantly, it satisfies our demand for an outlook that is consistent with the deep and far reaching results of pure mathematics and theoretical computer science. In this section, we will briefly compare critical rationalism with inductivism, which is the epistemological outlook that has remained manifest in the NCW thesis throughout its evolution. The aim of this discussion is to establish our choice to adopt critical rationalism in considering the role of emerging technology in military operations and in considering the phenomenon of force transformation.

We hope dispel at the outset the common misinterpretation that critical rationalism provides a fixed and ruthless procedure compelling refutation, wherein a single counter-example forces rejection of a theory. Instead, critical rationalism is about adherence to principle rather than to a fixed procedure, and correspondingly it emphasizes the crucial responsibility of the individual investigator and the community of investigators to make decisions regarding the acceptance of evidence apparently in conflict with a theory. In this way, critical rationalism goes beyond the individualistic quest for the absolute truth,

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[3] By common operating picture we also mean other constructions in which a consistent logical pool of data underpins the displays. This includes commonly informed operating pictures, for the issue is not resolved by the concession of applying filters to tailor displays to different operators.

[4] The NCW proponents offer, "Despite all of the advances that have and will likely be made, significant residual fog and friction will persist. The nature of this residual uncertainty is, as yet, unclear and its implications are not fully understood", in *Understanding Information Age Warfare*, page 37. As we will discuss later in this paper, the nature of the uncertainty that remains even after we have collected all the possible information concerning an event is actually well understood, and 'residual' is a completely insufficient way to describe it. This persistent uncertainty is actually fundamental in nature.

and embraces dependence on particular problem context[5] as well as the dual personal and social nature of knowledge development. In fact, it is not really the theory itself that is rational or otherwise, instead it is the property whereby the process of knowledge development is auditable.

The two problems to which critical rationalism is addressed are those of generalization[6] and demarcation. Generalization is the problem of gaining widely applicable knowledge from the school of experiential evidence, while demarcation is the question of how to distinguish empirical science from metaphysics[7]. Popper resolved the issue of generalization with the realization that the relationship between universal scientific statements and the experiences of observation and experimentation is deductive, rather than inductive, in nature. Historically, this position represents a revision of human expectations about what constitutes rational knowledge development, with the central message that we cannot expect science to ultimately consist of proven statements of certain truth.

The Critical Rationalist Outlook in Brief	
The Problem of Generalization	The question of the validity of inferring universal statements from singular statements.
Elimination of Psychologism	Removing reliance on intuition as the explanation of knowledge development, by delineating between the creative conception of a new idea and the examination of its internal structure and consequences.
Deductive Testing of Theories	Retrieving the consequences of a theory by logical deduction, and comparing those consequences with experimental or observational evidence.
The Problem of Demarcation	The way in which empirical statements are distinguished from those that are not empirical in nature.
Falisfiability	The logical property of a theory by which it may in principle be refuted by singular statements. Falsifiability is the criterion of demarcation between empirical and non-empirical theories.
Falsification	The methodological decision to admit singular statements in apparent breach of a theory, thereby falsifying the theory. The community in which our investigation is conducted defines guidelines for when we may consider a theory to be falsified.
Objectivity	The objectivity of theories lies in their testability in a reproducible way. In principle, the theory can be tested by anyone.

Popper found that the problem of demarcation between empirical statements and metaphysical statements is simply that the former are falsifiable, testable in a court of experience, while statements of the second variety are not. This logical property of falsifiability is central in the critical rationalist philosophy[8]. Conjecture and refutation always occur in the context of judgment decisions concerning problem situations, expectations of what will work and what will not, and other considerations. Critical rationalism clearly assigns responsibility to the investigator and his broader community to make decisions about whether facts apparently in conflict with a theory are accepted in refutation of it. Popper emphasized that he intends not be prescriptive about how a

[5] We shall come back to this point regarding the dependence of knowledge on context several times later in the paper. It is a central concept that reappears throughout pure mathematics and theoretical computer science when dealing with the limits of knowledge and reasoning.
[6] Other authors, including Popper, describe this problem as that of ‘induction’, which should not be confused with the ideal of ‘inductivism’ that alleges to resolve this problem in a particular manner. We use the term ‘generalization’ instead to avoid misunderstanding.
[7] Popper distinguishes empirical science from mathematics and metaphysics. We offer that the issue of not regarding mathematics as empirical science is actually subtler than perhaps it first appears, with insights in the field of Algorithmic Information Theory showing that much of mathematics is highly empirical. While we may sometimes find absolute truth in the world of pure concepts, we can never achieve this in the empirical sciences. Perhaps a better picture would have mathematics straddling the boundary.
[8] In *What is this Thing Called Science?*, Chalmers raises the question of how to define degrees of falsifiability, and suggests that only a relative measure of falsifiability is obtainable. In separate research, we are proposing a mathematically rigorous absolute definition of falsifiability in terms of the density of statements that can falsify a theory against the infinite fabric of all possible logical statements.

rational thinker should proceed in developing his knowledge. In contrast with the naïve depictions of critical rationalism that are frequently encountered, a single apparent counter-example only refutes a theory if the investigator decides that it is meaningful. Thus critical rationalism recognises the uncertain nature of information documenting observational facts, and, in recognition of the complexity of the world, asks an investigator to adhere to principle rather than to fixed procedure. In short, Popper is no more naïvely refutationist[9] than he is naïvely inductivist.

Thus Popper is careful to distinguish falsifiability from falsification. While falsifiability is a logical property that a system we wish to regard as science should have, falsification concerns the deliberate decision of the investigator to accept an observation as contradicting a theory. However, this does not equate to a free hand to ignore evidence, in which case the investigator impoverishes his investigation by refusing to submit to the tribunal of observational and experimental experience. An empirical investigation shielded in this manner rapidly degenerates into a folklore of statements averse to evaluation. Popper asks the seeker of knowledge to adopt a supreme policy of not avoiding falsification[10], and this is in effect the essence of Popper's demarcation between empirical science and metaphysics. Accordingly, we propose that this principle of not avoiding falsification should be evident and explicit in our military command and control processes[11].

Critical Rationalism and Naïve Inductivism.

Our story of inductivism begins with the work of Sir Francis Bacon who, in his book *The Proficience and Advancement of Learning* published in 1605, solidified the view that the rational pursuit of knowledge is characterized by induction. Bacon proposed that the human mind is filled with prejudices that lead us to observe what we wish to observe rather than what is actually there, and therefore described rational thought in terms of first emptying the mind of preconceptions before viewing the facts. Thus we view in Bacon's philosophy the seeker of knowledge as an isolated figure who struggles to attain a particular state of mind[12].

Bacon's view of science has thus far remained popular for nearly four hundred years, although as early as 1748 David Hume had openly attacked it on logical grounds. Sir Karl Popper put forward the idea in 1934 in *The Logic of Scientific Discovery* that we should regard science as an institution constituted on a set of principles that furthers its aims. Thus he formulates problems of science as methodological and, in doing so, established critical rationalism as a set of principles outlining the social conventions by which we may claim that our investigations into phenomena are rational and scientific.

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[9] We again refer the interested reader to Chalmers' book *What is this Thing Called Science?*, where he discusses naïve and sophisticated falsificationism, as well as inductivism, at some length.

[10] See Popper's *Logic of Scientific Discovery*, page 53.

[11] In our little review of some incidents in military history later in the paper, we will revisit this principle of not avoiding falsification with some brief examples.

[12] While Bacon did bear in mind scientific institutions elsewhere in his work, he did not report such consideration in the context of his account of method of rational and scientific investigation.

While critical rationalism is often simply stated in terms of this rejection of induction in favour of deduction, Popper actually extends the repudiation of inductivism to the individualistic and psychologistic outlook. Instead, a rational thinker is freed of prejudices by a confrontation with experience that is guided by methodological principles, so that ideas are subjected to trial in the court[13] of observation and experimentation. There is a social aspect to this, for a process of review by peers governs the implementation of methodological principles. Theories are constructed in a manner that makes them publicly examinable in principle by anyone, within the framework of a set of methodological rules for how such an examination can be carried out.

The social context for rational thought is a central point in our proposition for a conceptual framework for considering force transformation. We offer that Inductivism is insufficient not only for its flawed method, but also because of its inability to provide us with adequate guidance regarding the distinctly social character of military operations. In contrast, critical rationalism offers a social as well as a personal view of the development of knowledge, which is crucial in considering force transformation and the promise of information and communications technology.

In the inductivist outlook, the "true conclusion" is inevitable given enough facts and an objective mental state, and therefore all the players in a distributed system thus prepared with appropriate training and sufficient quantities of information will come to the same understanding. The inductivist view of knowledge and knowledge acquisition does not properly equip us to consider the distinctly social nature of military organizations. We propose that this matter is resolved by replacing inductivism with critical rationalism to obtain a conceptual framework that properly admits a complex of interacting organizational elements having interrelated yet distinct goals. We shed the idea that conclusions are inevitable for different rational thinkers given sufficient information, instead recognizing the fundamental phenomenon of logical incompleteness that fully allows individuals to develop different points of view. A critical rationalist framework does not compel complete uniformity of information, and the high network capacity required to maintain it, nor does it demand that we seek absolute agreement from our different decision-makers despite being immersed in different local environments.

If we adopt a critical rationalist outlook, we are acknowledging that the role of distinct organizational elements is to perform different functions, to achieve different intents. Of course, distinct intents of different elements are interrelated and subordinate to an overall intent belonging to a superior organizational element, and ultimately to the intent of the organization as a whole. By replacing the inductivism of the NCW thesis with critical rationalism, we are compelled to face the problem of coordination between different organizational elements, of making decisions in an inherently uncertain situation. In contrast, an inductivist outlook demands uniformity of information, uniformity of

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[13] Popper compares rational thinking with trial by jury in *The Logic of Scientific Discovery*, pages 109-110. The question a jury is asked to decide depends upon the particular local laws in force, and within this framework it makes decisions on facts presented before it. The prosecutor puts forward a theory of the crime in which the defendant plays a leading role, while the defence counsel attempts to refute that theory.

understanding, and ultimately overlooks the fundamental uncertainty military decision-makers will always face[14].

THE LESSONS OF LOGIC AND REASONING.

> **Sometimes mathematical truth is completely random and has no structure or pattern we will ever understand. It is not the case that simple clear questions have simple clear answers, not even in the world of pure ideas, much less so in the messy world of everyday life.**
>
> **- Gregory Chaitin, *Paradoxes of Randomness*.**

Popper directly attacked the vision of science as eventually resulting in a final and complete body of verified truth. Such a belief happens to be entirely incompatible with the landmark incompleteness theorems of Kurt Gödel (1931), and Alan Turing's unsolvable halting problem (1937), whose work founded the entire field of theoretical computer science. This kind of position is further confronted by subsequent investigations by Andrei Kolmogorov, Ray Solomonoff and Gregory Chaitin in establishing the field of Algorithmic Information Theory, with important recent contributions by Ming Li and Paul Vitanyi, as well many other authors. Perhaps ironically, these results of pure mathematics actually underpin computer science in general and its application in information technology specifically, which is the very thing that the NCW thesis was constructed to take advantage of in the first place.

Here we briefly explore some of the relevant insights to be gained from a quick tour through some interrelated fields of pure mathematics and theoretical computer science. We submit that we cannot reasonably adopt any epistemological outlook that is not reconcilable with these mathematical results. As we will observe, this demand slams the door on inductivism, yet admits critical rationalism, as well as the various post-critical schools[15], to the party. We also draw from relevant work in psychology, where we relate theoretical limits to reasoning with the actual abilities of human beings.

The Lesson of Incompleteness

In his famous lecture of 1900, David Hilbert conjectured about developing a formal logic system that would encompass all of mathematics. This vision was really a culmination of over two thousand years of tradition, essentially beginning with Aristotle. Hilbert emphasized that such a system of logic should be consistent, meaning that it should not be possible within the axiomatic system to prove both a proposition and the negation of that proposition. The system should also be complete, meaning that it should be possible to either prove or refute any meaningful proposition that can be made.

Hilbert was wrong, but he had asked the right question. Kurt Gödel showed in 1931 that

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[14] As we will see, profound and highly influential results in mathematics compel us to reject the notion that perfect understanding is achievable even in theory. Thus we will always face uncertainties, regardless of how much information we can collect.

[15] Since Popper introduced critical rationalism, several post-critical schools have emerged in an effort to refine or develop critical rationalism further. They universally reject inductivism, and usually focus around particular issues such as the personal and social nature of knowledge, objectivism and subjectivism, bold or cautious conjectures.

Hilbert's vision of a formal axiomatic system in which every possible proposition can be proved or refuted is impossible. While it might be possible to prove every conceivable proposition within a formal system for doing reasoning by moving outside the system in order to consider new rules and axioms, this creates a larger system with its own set of irresolvable propositions. Godel's incompleteness theorems philosophically state that rational thought cannot find the total ultimate truth. The complete truth is inaccessible even in principle, no matter how large the brain, no matter how long one has to cogitate. The surprise to the mathematical community was that this is true even of the abstract and tidy field of pure mathematics, rather than being a phenomenon that is confined to the messy physical and biological sciences. Philosophers, given their wide rejection of inductivism anyhow, should be rather less surprised with the implications of Gödel's theorems, and it is no coincidence that Karl Popper produced his epistemological insights that outlined scientific method as we now understand it at around the same time. Popper's scientific method consisting of hypothesis generation and testing by attempted refutation methodologically unifies pure mathematics with other scientific pursuits.

Hilbert also stressed the importance of the decision problem for formal axiomatic systems, which requires a procedure for determining whether or not meaningful propositions are absolutely true. A decision procedure is any such solution to the decision problem. In essence, Hilbert sought a procedure, an algorithm, by which all mathematics could in principle be obtained[16]. It's worth emphasizing that Hilbert was concerned with the existence in principle of a decision procedure for all mathematics, and it is doubtful that anyone at the time could have believed that such an algorithm would be practical. Alan Turing completed the dismantling of Hilbert's conjecture in 1936 with his landmark paper proving that no such decision procedure can possibly exist. This is in fact a deeper result than Gödel's incompleteness theorems, since incompleteness is obtained as a corollary.

Turing's paper considers the computable real numbers, which are those that have algorithms that can be used to evaluate them to arbitrary precision. That is, an algorithm exists for each computable real number that successively generates its decimal digits. The computable real numbers are very much in the minority. Turing invented the first universal model of formal reasoning, now called the Turing Machine in his honour, and used an elegant diagonalization argument to prove the unsolvability of the halting problem, which asks for a logical reasoning process to determine whether or not an arbitrary reasoning procedure will eventually conclude. If Hilbert's vision of a formal axiomatic system from which all mathematics could be derived were plausible, then a solution would exist to the simple problem of whether an arbitrary reasoning procedure eventually finishes. Turing's proof that the halting problem has no solution dismisses the notion that a decision procedure exists for nontrivial consistent formal logic systems.

[16] This process assumes complete visibility of a given system of axioms, in other words perfect information, and from this yields every true conclusion that can be drawn from these axioms. Hilbert thought it would work by listing out every possible conjecture in turn and using the decision procedure to test each against the system axioms to see if it is true. Hilbert challenged the mathematical community to compose the decision procedure and to formulate the system of axioms for all of mathematics.

Gödel's incompleteness result does not itself rule out the existence of the decision procedure, so Turing's result is actually more powerful.

There is no safe haven to be had by adopting something other than Turing Machines. Alonzo Church developed an apparently very different formalization of formal reasoning called 'lambda-definability' in his 1936 paper *An unsolvable problem of elementary number theory*. These formalizations of effective computation are actually equivalent, in the sense that they define exactly the same set of mathematical functions. Numerous other systems are now in practical use and all are known to correspond precisely with the capabilities of the Turing Machine. The Church-Turing thesis states that no possible system of formal reasoning, no possible model of computation, can extend this set of what is solvable, and all methods of formal reasoning that satisfy the conditions for effectiveness are equivalent, and all suffer the same limitations.

Concepts in the Lessons of Incompleteness	
Hilbert's Conjecture	A consistent and complete formal system of logic for doing all of mathematics. The decision procedure is a solution to the problem of determining whether each meaningful proposition is true or false.
Incompleteness of Logic Systems	For every possible nontrivial consistent formal logic system, there are meaningful statements that can neither be proved nor refuted within that logic system.
Turing Machine	The first formal model of reasoning. The famous Church-Turing thesis states that no possible model of logical reasoning can exceed the capabilities of the Turing Machine.
Halting Problem	The problem of whether an arbitrary formal reasoning procedure eventually concludes; this is equivalent to the decision problem. The halting problem is unsolvable, so no decision procedure can possibly exist.
The Lesson of Incompleteness	*Numerous simple questions exist that cannot be answered, even given complete and perfect information.*

Even in the world of pure logic, simple questions do not always have straightforward answers. We cannot assume that it is possible to answer simple questions, let alone those more intricate, and thus we must normally regard even our best theories with eternal suspicion. These theories do not eventually turn into laws, nuggets of absolute truth, by experimental and observational verification. Incompleteness warns us that even if the truth is out there, we may not be able to find it.

The Lesson of Incompressibility

About three decades after Gödel and Turing established the foundations of computer science, Kolmogorov, Solomonoff and later Chaitin independently investigated the Theory of Computation to define a fundamental and absolute measure of complexity, and in doing so laid the foundations for the field of Algorithmic Information Theory. This measure is now widely known as 'Kolmogorov complexity', or sometimes as 'description complexity', and is a member of a family of closely related definitions collectively referred to as 'algorithmic complexity'. The Kolmogorov complexity of a structure described by a given binary string is simply the shortest possible program that generates that structure.

Algorithmic Information Theory formalizes the notion that the rational investigator seeks finite and compact theories to explain indeterminate volumes of data obtained from observations, both actual and potential. The broadly accepted definition of a theory is that of a rigid and precise system of rules, whereby its consequences remain constant over time and unaffected by who explores them. More formally, it is an effective procedure[17] for calculating predictions that are compared with actual data obtained by observation or experimentation, and by this comparison the value of the theory is understood. Occam's razor dictates that all things being equal in this comparison of prediction with observation of the phenomenon under study, the simpler theory should be preferred over the more complex. Thus comprehension is the codification of large or indeterminate amounts of information in the smallest possible theory[18]. In other words, comprehension is compression, the reduction of a large or even unbounded number of singular facts into a compact theory. The value of the theory then relates to its ability to reproduce the data obtained by observation or experimentation. Note that we intend compression in a technical rather than a vernacular sense, referring specifically the sizes of effective procedures that generate a structure compared with the size of the structure itself.

The Invariance Theorem states that all the absolute complexity measures are independent of the choice of which model of reasoning is used, up to a fixed additive constant. Structures for which the Kolmogorov complexity is close to the size of the structure itself are incompressible and have high information content, since there is no possible way to obtain a shorter description of such a structure than simply listing it in its entirety. The Incompressibility Theorem states that almost all possible structures are algorithmically random, and thus contain no discernible structure or pattern. To be slightly more technical, it is a proven fact that the difference between the number of structures that are compressible and those that are highly incompressible grows exponentially with respect to the structure size.

Mathematical truths can be demonstrated that are irreducible[19] in the sense that they cannot be fully explained by any theory smaller than they are. In fact, such truths are in the majority. The world of mathematics, of logic and reasoning, is proven to have infinite complexity, and is therefore not fully comprehensible. The current scientific outlook has

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[17] An effective procedure is a formal reasoning process, regardless of which particular model of reasoning might be employed. It is said to be 'effective' because it is internally complete and fully reproducible; it does not rely on magic or divine intervention to produce its outcome, for example. Although a rather loose interpretation of effective computation suffices here, the intention is to assert that the notion of a scientific theory can be approached mathematically.

[18] Kolmogorov complexity provides an absolute and objective definition for the notion of simplicity, and thereby formalizes Occam's razor. The theoretical underpinnings of Occam's razor constitute a deep mathematical insight first established by Solomonoff, one of the three principle founders of Algorithmic Information Theory. To state Occam's razor in a slightly different way, structures of low complexity have high probability, while structures of high absolute complexity have low probability. Pursuing this notion further yields the truly remarkable universal probability distribution, which can theoretically be used with complete accuracy in place of any actual a priori distribution in Bayes' rule.

[19] An example of an irreducible mathematical truth is Chaitin's Omega number for Turing machines. This is simply the probability that a Turing machine chosen at random eventually halts, and although this is a well defined fixed number, its infinite string of digits cannot be distinguished by any possible randomness test from sequential independent flips of a coin. Such numbers are algorithmically random, since they contain absolutely no recognizable pattern. The string of digits forming Omega is infinite in length and incompressible, so no effective procedure for determining Omega can exist. Even the approximation of Omega is problematic, since at no point in an unending estimation process can meaningful bounds on the error be asserted. No theory can ever determine more than a finite number of the infinite string of digits of Omega.

it that the real world contains randomness at fundamental levels, and therefore the real world is also infinitely complex and so contains many phenomena that cannot be fully elucidated by theories of finite size. In our military setting, the fog of war is not solely the product of insufficient information, but rather possesses a prevailing constituent that is a consequence of fundamental unpredictability inherent even in pure logic[20]. Regardless of how much information we collect on the battlefield, we cannot expect to know the adversary intent with complete certainty, for example.

Concepts in the Lesson of Incompressibility	
Absolute Complexity	Absolute measures of complexity consider the size of the smallest possible logic reasoning procedure for reproducing the given structure.
Fundamental Theorem	The absolute complexity measures are all independent of the particular choice of model of formal reasoning, up to an additive constant.
Ideal theories	A theory is ideally the smallest possible codification of the structure containing all possible evidence. Even given complete and perfect information, determining the best theory is an unsolvable problem.
Incompressible Phenomena	A structure is incompressible if it cannot be obtained by any possible procedure that is shorter than the structure itself.
Incompressibility Theorem	The overwhelming majority of structures contain no patterns discernable by any possible means, or in other words, they are incompressible.
Infinite Irreducible Truths	Omega numbers are examples of unknowable mathematical truths. Logic and mathematics have infinite complexity and are thus not fully comprehensible.
Theories are Simplifications	Almost all possible structures are incompressible, so theories must almost always be compressions that involve a loss of information.
The Lesson of Incompressibility	*Uncertainty is fundamental, not just the product of having limited information. In almost all possible cases, we cannot find the truth, even given complete and perfect information. We must simplify and approximate.*

We cannot expect to fully understand most phenomena, and instead most of the time we must be content with theories that simplify, approximate. A common way of building a useful theory in the face of such incomprehensibility is to use probabilistic methods. Such statistical descriptions describe phenomena in terms of broad arrangements of events or objects, simply because the approximate pattern suffices within the given problem context, and a precise and complete depiction is beyond our ability to achieve[21]. Quantum theory provides us with a statistical curve representing the expected amount of the original isotope remaining in a radioactive sample at any time, yet in reality this decay occurs in discrete steps marked by the disintegration of individual atoms.

Algorithmic information theory formalizes the concept of the best theory as the smallest possible procedure for recreating a given, possibly infinite, set of data. The problem of finding the most compact description is unsolvable, meaning that no general procedure can exist that allows us to find the best theory. And for the overwhelming majority of possible data sets, the best theory is not much smaller than the data itself anyhow. So we are left to contemplate our universe, and ourselves, with simplifications that suffice in a given context, approximating, compressing with a loss of information. Incompressibility

[20] The NCW thesis itself asserts that the fog and friction of war will never be dispelled. Nonetheless, our objection regards the assumed source and actual nature of the fog and friction, and thus we are led to a very different conclusion from the NCW prediction that networking will enable a fundamental and revolutionary shift to take us beyond the heavy burden of managing risk in military operations (see pages 38-40 of *Understanding Information Age Warfare 2nd Ed.*, for example).
[21] When we venture into Algorithmic Information Theory, we are dealing with randomness at fundamental levels, for probability theory itself has been constructed from Algorithmic Information Theory. This construction hides the incomprehensible details of infinite incompressible structures beneath a simplifying veneer, a process that sacrifices exactitude and deals only with broad trends. Further details are available in *An Introduction to Kolmogorov Complexity and its Applications*, by Li and Vitányi.

warns us that even if we accept that the truth is out there, we are almost always unable to completely comprehend it.

The Lesson of Simplification

Given that absolute truth is not achievable, and that our theories are merely approximations to the truth, we are naturally led to ask about how we might claim that one refuted theory is closer to the truth than another. This is the notion of verisimilitude, a measure of the likeness to truth of theories, which Popper introduced in his books *Conjectures and Refutations* and *Objective Knowledge*. Verisimilitude asks how theories can be ranked with respect to closeness to the truth. Popper proposed that the truth of one theory is greater than that of another if the true logical consequences of the first include the true logical consequences of the second, the false content of the first are included also in the second, and that at least one of these inclusions is strict. David Miller and Pvel Tichý independently showed that Popper's formulation only works for theories that are true, for in the case of false theories it is formally defective[22]. Popper withdrew his formulation of verisimilitude, and since then considerable effort has been directed towards achieving adequate definitions, at least within particular domains of application.

We conjecture that a general definition of verisimilitude may be unachievable[23]. Certainly, an absolute measure of the distance of a theory from the truth is not realizable[24]. We also suggest that even a general relative measure by which we compare competing theories may also be unachievable, although we are not at present aware of any formal proof of this conjecture[25]. No attempt to produce a completely generally applicable definition for verisimilitude has succeeded, and we believe that it would be unwise to rely in any way on a solution to the problem being discovered in the future. Finally, it is important to understand that unsolvability frequently gives way when we relax our demand for a general solution and instead seek answers within sufficiently

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[22] For some time Popper believed that verisimilitude corresponded neatly with his account of corroboration. He viewed an unlikely theory that had remained unfazed in the face of critical testing as having high truth content and low falsity content relative to rival theories. This idea was refuted when Miller and Tichý demonstrated that in the case of a false theory that possesses surplus content beyond that of a rival false theory, both the truth content and the falsity content of the first would exceed that of second. With respect to false theories, Popper's conditions for therefore cannot be met, in either quantitative or qualitative terms.

[23]The literature documents many efforts to construct completely objective experimental measures that are broadly applicable, and researchers frequently report encountering baffling impenetrability. The strong presumptions that such a measures exists and that it can actually be computed, if indeed it does exist, seems to be rarely challenged.

[24] This is another example of a simple question that cannot be answered. The Chaitin Omega numbers provide a compelling counter-example to the idea that a general measure of the absolute distance of a theory from truth is realizable. The Omega number for Turing Machines is an absolute truth, and any approximation to it is a theory. At no point in any possible approximation scheme is it possible to place meaningful bounds on the error, on the distance between the approximation and the truth.

[25] It is entirely conceivable that the verisimilitude question could lie at the start of an infinite chain of unknowable truths. Incompleteness and incompressibility tell us that we should expect to encounter simple questions that cannot be answered, despite the fact that the answer exists, but cannot necessarily tell us whether a particular instance is a case in point. We will examine in more detail later the question of whether P=NP, for example. The consensus is forming that the P=NP problem is at the start of an infinite chain of unknowable truths. We never really know, for by definition if this is true it cannot be proven.

specific domains. So our theories are actually useful explanations that work well enough in a particular context, and they almost always entail a loss of information, simplifying a phenomenon that has infinite complexity and consequently is not fully comprehensible.

Concepts in the Lesson of Simplification	
Ideal theories	Comprehension is compression, which means that a theory seeks to codify all possible evidence relating to phenomenon the theory seeks to explain.
Verisimilitude	Verisimilitude is a general measure by which we can rank our refuted theories according to their relative truth content.
Difficulty of Verisimilitude	Attempts to construct a general definition of verisimilitude have failed. We conjecture that verisimilitude is an unsolvable problem.
The Lesson of Simplification	*We must simplify, and simplifications are, of course, context-dependent. Furthermore, we may not be able to know, in a general sense, whether one of our refuted simplifications is closer to the truth than another.*

We receive no free rides, even in pure logic. Our theories are normally simplifications, compressions of incompressible data achieved only at the expense of a loss of information. Not all simplifications are born equal, and they differ not just in terms of their closeness to the truth but also in terms of their complexity, their internal consistency and elegance, and their congruity with other theories. Finding the balance between the straightforwardness of the theory and its ability to reproduce observation inescapably depends on the problem we intend the theory to solve. In short, we must content ourselves to seek theories that are fit for their intended purpose, and in doing so we even admit the possibility of employing theories that we nonetheless know to be refuted.

With incompressibility comes the necessity of simplification, and with simplification comes dependence on context. Even if we found the exact truth, we could not normally recognise that we had done so. Incompleteness, incompressibility and verisimilitude warn us that we may not even be able to know whether one of our simplifications is closer to the truth than another.

The Lesson of Intractability

When John von Neumann began considering the execution time of computational procedures in around 1955, the now highly developed field of Algorithmic Complexity Theory was born. The basic charter of this field is to understand the resource requirements, principally in terms of time and memory space, of solving problems. Against this backdrop, Alan Cobham in 1964 and Jack Edmonds in 1965 discovered the class P of problems that are efficiently solvable. In 1971, Edmonds introduced the class NP, consisting of problems for which proposed solutions can be efficiently checked, along with the conjecture that P≠NP. This simple question of whether P=NP is one of the most perplexing and important problems of computer science, and it impacts directly on almost every aspect of information technology and even across science as a whole.

This subject concerns the efficiency of reasoning processes in terms of the growth of the required execution time with increasing problem size. Efficient methods are known for solving some problems, placing them in class P, which stands for 'Polynomial time'. An example of a problem in class P is that of sorting a list of words into alphabetical order. A harder problem is that of the travelling salesman, wherein a salesman has to travel to a number of towns, visiting each only once and returning to his starting point, while minimizing the distance travelled. No efficient method for solving this has been found, so it is not known for sure whether the travelling salesman problem resides in class P. A proposed solution can be checked quickly, and so the problem is in the class NP, which stands for 'Nondeterministic Polynomial time'. The class of problems P is a subset of NP, and most researchers believe that P≠NP, with problems like the travelling salesman residing in NP but not in P. Despite enormous effort, no proof has ever been found.

Concepts in the Lesson of Intractability	
Resource Complexity	The study of the bounds on the time and memory space required by a logic reasoning processes to produce an answer.
The Class P	The class of problems known to be efficiently solvable in the sense of requiring at most a polynomial number of logical operations.
The Class NP	The class of problems for which a procedure is known to exist for verifying postulated solutions efficiently in terms of the number of logical operations required.
P=NP?	The vexing question, currently believed to be unsolvable, of whether efficient algorithms exist for all problems in class NP. Most researchers believe the answer is false.
NP-complete Problems	The set of problems each of which encodes every other problem in the class NP. It is widely believed that NP-complete problems lie in NP but not in P.
NP-complete Phase Transitions	NP-complete problems have a phase-transition between a subset of problems for which efficient methods of solution are possible and a subset that are truly hard.
The Lesson of Intractability	*Solvable problems almost always cannot be completely unraveled within reasonable time and memory constraints. Thus we must usually approximate even when our problems are solvable in principle.*

The class of NP-complete problems is a subset of NP, and it is believed that they do not reside inside P. Many of the apparently different NP-complete problems are actually equivalent, in the sense that they can be quickly transformed into one another. Some NP-complete problems encode every other problem in class NP, so the discovery of an efficient method for the travelling salesman problem, say, amounts to the discovery of an efficient method for all of NP. That is, the discovery of an efficient method for solving the travelling salesman problem would prove that P=NP. Suddenly, practical tasks such as optimal data compression, optimally cutting parts out of sheets of raw material, and scheduling interrelated procedures would all become truly possible.

No algorithms for any NP-complete problems have ever been discovered. The literature testifies to an emerging belief that the question of whether P≠NP is unsolvable. However, nobody has successfully proven that the P=NP issue is unsolvable, which has resulted in researchers asking the question of whether P=NP is unsolvable is itself unsolvable[26]. An interesting hypothesis is that all NP-complete problems have an infinite subset of cases that are all technically easy (the problem restricted to this subset of cases belongs to the class P). The other infinite subset of instances contains cases that are truly hard, technically intractable[27], and beyond solution no matter how fast the processor or how large the memory. Attempts to refute this hypothesis have failed, and a large number of NP-complete problems are known to contain a phase transitions where the easy cases give way to hard the cases.

Even solvable problems are not straightforward, and again we must normally make do with approximate solutions. For each of the NP-complete problems, many different approximation schemes have been developed and applied with degrees of success that

[26] This line of thought leads to the conjecture that the question of whether P=NP might lie at the start of an infinite sequence of unknowable truths. The belief that NP contains problems not in P is based upon copious failed attempts to refute this proposition. Mathematics continues to progress with numerous results appearing in the literature each year that are based on the assumption that P=NP is false.

[27] Problems are intractable when they cannot be solved within a time that is at most a polynomial function of the problem size. In the travelling salesman problem, for example, the only exact methods known potentially require exponential time. It is easy to find small instances of such problems that are of practical use that require many times the age of the universe to solve even using all the computers in the world.

greatly vary depending on the situation. Intractability brings with it the need for approximation, and with approximation comes dependence on context. Intractability warns us that even if we are so fortunate to encounter only problems that are fully solvable, still the single best answer will almost always lie beyond our reach.

The Lesson of Perilous Intuition

We have explored the absolute limits on the ability of a hypothetical investigator who utilizes formal logical processes for solving problems. In doing so, we found that the mathematics of logic and computation set the absolute upper bound on reasoning, and even the most generous case this dissipates the inductivist dream. However, an increasing number of contemporary researchers in cognitive science strongly question the presumption that most humans reason logically most of the time, and instead propose that we use certain kinds of shortcuts to save effort. While humans are obviously capable of logical reasoning, this does not mean that they naturally do it well. According to this theory, these shortcuts are a consequence of our tightly restricted working memory, which leaves us to ignore information. This setting aside of crucial information may, in important circumstances, entail devastating consequences.

The first kind of information that is likely to fall victim to our limited reasoning memory are statements in the negative. Experiments conducted by Philip Johnson-Laird and others have observed this effect in practice, using simple questions that do indeed have simple answers but contain negative statements, with the outcome that the overwhelming majority of subjects tested obtain by intuition the incorrect answer. One of the logic puzzles used is reproduced below[28].

Exactly one of the following statements is true regarding a hand of cards.

- **There is a king in the hand, or an ace, or both.**
- **There is a queen in the hand, or an ace, or both.**
- **There is a jack in the hand, or a ten, or both.**

Is it possible that there is an ace in the hand?

Johnson-Laird reports that 99 per cent of students tested at Princeton University wrongly answered this question in the affirmative. The catch is the opening clause that demands that one and only one of the three statements is true, contradicting the conclusion that first two statements evaluate to true if the hand contains an ace. Very few people utilize in their deliberations the negative information requiring falsity of two of the three statements. Johnson-Laird *et al* have examined the responses of humans in dealing with the question of whether sets of assertions are mutually consistent[29]. This is the satisfiability problem of predicate logic, which is NP-complete and therefore computationally equivalent to the travelling salesman problem. Statements of falsehood are the first casualties of increasing problem size.

If humans normally reason by manipulating formal rules of logical inference, errors due

[28] The example reproduced here originally appeared in the article *Fooled Again* that appeared in *New Scientist,* 9 December 2000.
[29] This particular work by Johnson-Laird, Legrenzi, Girotto and Legrenzi was reported in *Illusions in Reasoning about Consistency*, in *Science* Volume 288, 21 April 2000.

Concepts in the Lesson of Perilous Intuition	
Positive information	Evidence in which a particular logical statement is asserted as being true.
Negative information	Evidence in which a particular logical statement is asserted as being false.
Illusion of consistency	Cases in which disregard of negative information leads to the systematic error of concluding that statements are consistent when in fact they are inconsistent.
Illusion of inconsistency	Cases in which disregard of negative information leads to the systematic error of concluding that statements are inconsistent when in fact they are consistent.
Systematic errors and creativity	Humans do not naturally perform logical reasoning well, and perhaps this is at the expense of creativity. This is consistent with critical rationalism, which distinguishes creative thought and the testing of ideas by attempted refutation.
The Lesson of Perilous Intuition	*Humans are highly unreliable in general at performing logical reasoning, so relying on intuition alone is to invite predictable systematic errors.*

to occasional misapplication of rules would be haphazard rather than systematic. This study provides compelling evidence that the theory that human reasoning usually operates by formal inference should be abandoned, for human subjects succumb regularly to the same kinds of errors. The nature of these errors, which fall into the dual categories of illusions of consistency and illusions of inconsistency, are consistent with the theory that negative statements are not well represented in working memory.

The systematic errors of human logical reasoning have a fascinating twist. Critical rationalism delineates between the creative process whereby tentative theories are proposed and the rational process of evaluating those theories against experimental or observational evidence. Ruth Byrne has proposed that the creative process involves deliberate and controlled counterfactual thought, wherein information is set aside, creating illusions of consistency and inconsistency. Accordingly, we suggest that tacit and explicit background knowledge is the crude substance fed into this creative process, including our refuted theories, other untested propositions, and theories not yet dismissed. These may be theories with which we have previously sought solution to our particular problem, or they may be theories associated with different contexts, different problems. For perhaps it is by setting information aside, particularly negative information, that we may draw the associations that allow us to interconnect these components to produce a new proposition. Returning to the example logic puzzle reproduced from Johnson-Laird's empirical studies of human reasoning, through critical rationalist eyes, human intuition almost always leads to the proposition that it is possible for the hand to contain an ace. The implication of this theory is that the first two of the three statements about the hand would be true. This consequence is in contradiction with the requirement for the falsity of two of the three statements regarding the contents of the hand, so the investigator is confronted with evidence demanding the falsification the theory.

We reject the notion, currently popular in some circles, of singular reliance on intuition for making rapid decisions[30], for this equates to a deliberate employment of untested propositions in making decisions with consequences of life or death. Studies of human reasoning advise us that human intuition does not operate by applying formal rules of logic, and is therefore prone to systematic logical errors. The most difficult kinds of evidence for humans to deal with intuitively appear to be statements of falsity. To compound the danger, the common operating picture offers no mechanism for conveying negative statements about what isn't observed, what's not known, that which is known or

[30] The NCW thesis advances the notion of "naturalistic decision-making based on self-synchronisation and shared awareness". A couple of the many examples of this position include *Information Age Transformation: Getting to a 21st Century Military* on page 33 and page 136.

believed to be false. The perils of intuition warn us that to rely on human intuition alone to make decisions quickly is to invite disaster.

AN ALTERNATIVE CONCEPTUAL FRAMEWORK.

> **Objectivity does not demand that we estimate man's significance in the universe by the minute size of his body, by the brevity of his past history of his probably future career. It does not require that we see ourselves as a mere grain of sand in a million Saharas. It inspires us, on the contrary, with the hope of overcoming the appalling disabilities of bodily existence, even to the point of conceiving a rational idea of the universe which can authoritatively speak for itself.**
> **- Michael Polanyi, *Personal Knowledge: Towards a Post-Critical Philosophy*.**

We have seen that critical rationalism provides significant advantages over inductivism in considering military affairs. We have also seen how simple questions rarely have simple answers, and that as a result uncertainty is ubiquitous and profound rather than just being a product of insufficient information. In response to these realizations, we propose a critical rationalist framework for considering military transformation and the opportunities for military operations to benefit from information and communications technologies.

We submit that for a conceptual framework for considering information and communications technology utilization to be viable, it must not contravene basic insights into logic, problems, and knowledge. As we have discussed, the inductivist outlook that is apparent in the current NCW thesis does not pass the test. Critical rationalism survives to become the natural starting point for developing a new conceptual framework. We believe that great opportunity exists in the debate between the merits of critical rationalism and the different post-critical schools; however, such rich opportunities still lie deeply buried beneath an overburden of inductivist thinking. We are adopting critical rationalism as the first step.

The Art and Science of War.

We have observed an inescapable mathematical basis for our epistemological position that no theory can ever be really regarded as absolute truth. It is merely the most appropriate approximation for a particular purpose that has been developed so far. The acquisition of knowledge uses a creative process of theory proposition and a deductive process whereby the consequences of a theory are compared with observations of the phenomenon the theory intends to explain. Theories are developed and subsequently tested deductively by examining their consequences in the light of observational or experimental data. This is not a prescriptive procedure, but a principle in the implementation of which the investigator is compelled to make considered choices.

The primitives we offer here are motivated by a number of factors, including a need for precision where previously we have felt hampered by a lack of clarity, consistency with the fields of mathematics and computer science that underpin information technology, and consistency with the critical rationalism. Data refers to any sequence of symbols, where each symbol is a member of some alphabet. Information refers to statements of fact, which are expressions in a particular language over our alphabet of symbols.

Languages have a grammar that constrains the combinations of symbols that are admitted[31], and they have semantics, which relate those expressions admitted by the language to combinations of concepts[32]. These statements of fact, our information regarding our adversary, our environment, and indeed ourselves, are simply utilized as evidence against which we may test theories. Theories consist of a domain of applicability and logical procedures that generate sample information with which we compare our facts. Thereby we may make informed decisions about the value of our theories for solving a particular problem in a given context.

Some Important Primitives of a Critical Rationalist Conceptual Framework	
Knowledge development	Knowledge development is a deductive process of theory generation and testing by attempted refutation.
Falsifiability	The logical property of a theory whereby it can, at least in principle, be refuted by evidence.
Falsification	Falsification is a deliberate decision to accept that evidence is in conflict with the theory, thereby refuting the theory.
Knowledge	Knowledge of a phenomenon is simply any body of theories that attempt to explain that phenomenon.
Current Knowledge	Current knowledge about a phenomenon is any set of theories that have not been refuted.
Theory	A theory is an attempt to solve a problem of explanation, and consists of a set of rules. Equivalently, a theory is a logical reasoning process, for generating test information.
Information	Information refers to statements of fact expressed using particular languages. Languages have both grammatical and semantic structure.
Data	Data is simply sequences of symbols all of which belong to some particular alphabet.

We picture the military enterprise as a spatially distributed organization of decision cells, each of which seeks to achieve a local intent in a local context. Decision cells do not exist in isolation of one another, because their separate intents must integrate to achieve the higher intent of the overall organization. Local intents have global implications, and vice versa. In short, each decision cell exists because it performs a particular function, and thus it will express requirements for information commensurate with its particular intent and context. The problem of maintaining coherence across the organization amounts to that of managing different interpretations of different local contexts as well as coordination of subsequent decisions.

The raw material of decision cells is not information. The raw material is propositions, tentative theories about what the adversary might be doing, and possible solutions to problems of what the organization itself might do. Information, consisting of our collected statements of fact, is simply evidence against which a decision cell tests its theories concerning phenomena outside of itself. Untested propositions are just conjectures of possibility until they are evaluated using such evidence, and those theories that survive the test are capsules of knowledge about the adversary, about own force disposition, and about possible courses of action.

We consider theories of two broad kinds, the first of which being theories of explanation, and the second being theories of action. From the point of view of a particular force element, theories of explanation include theories of the adversary intent and possible courses of action, theories of the environment, and theories of intent and courses of action

[31] Formal Language Theory is the field that studies the grammars of languages. This field closely aligns with and borrows from Theory of Computation and Algorithmic Information Theory to study the logical properties of such constructions.
[32] We refer the reader to texts regarding Model Theory and Formal Ontology for a detailed discussion of the mapping of concepts to language elements. The implications of incompleteness are also felt strongly here, where the solvability of problems of reasoning and knowledge manipulation is the subject of much research attention.

of other elements of the same force[33]. In our classification, theories of action are possible solutions to the problems of decisions to act, meaning possible intents and subsequent courses of action that the force element itself may pursue in order to meet these intents. Theories of explanation are tested against evidence gathered from sensors, while theories of action are tested against models developed from theories of explanation. These models are really just effective procedures that instantiate any number of theories for the behaviour of the adversary, the environment, and other force elements, and generate information that may be compared with the consequences of theories of action.

In our vision, models should be constructed using various competing theories under consideration, for the presence of undifferentiated alternatives embodies the uncertainties the decision cell is facing. In this way, the decision cell can construct possible courses of action that are evaluated for robustness in the face of varying levels of uncertainty. Of course, the ultimate test of a theory of action is in its execution, and thus we enclose both planning and execution within an integrated methodological journey. Vertically, we might distinguish theories of intent at the top of a hierarchy, from theories of courses of action regarding how those possible intents might be achieved below.

We have argued here that a sophisticated methodology would greatly clarify and simplify the process of making decisions in what is a fundamentally uncertain setting. The knowledge of a decision cell exists in the form of a set of theories, some refuted, some tested but not yet refuted, and others newly proposed. Theories fall into two broad classes, namely theories that seek to explain phenomena external to a particular decision cell, which are tested against evidence collected from outside, and proposed options for how the decision cell might act. Models that embody alternative theories of explanation connect them in a further dance of attempted refutation. The art of war is the proposition of novel theories as well as finding clever ways to test them, and the science of war is the act of testing those theories. The science of war, the process of testing our theories, extends from the domain of initial planning through to execution and beyond, thus unifying the previously isolated stages of warfare into one methodological whole.

The New Clarity Over Value.

Decision cells coordinate with one another by engaging in transactions that convey information from those who have it to those who need it to test their theories. In our conception, a transaction is the fundamental unit of information exchange, occurring between two force elements because one possesses a statement that the other requires. Notice that we may build larger constructions from this basic notion, for example a conversation might consist of a sequence of transactions, each one initiated after a phase of theorizing or attempted refutation. Publishing information for use by many other force elements logically consists of single transactions between the provider of that information and each of its beneficiaries.

[33] This taxonomy is a simplification we find useful, but other classifications of theories may be worth considering. An alternative might be to distinguish knowledge of other elements of the force from that of the environment and the adversary on the basis that these are developed and tested differently.

We propose to measure the quality of information, its value to the military enterprise, by both its utility in testing theories and the importance of distinguishing between competing theories. Thus we describe the relevance of information specifically as its potential to enable falsification of theories, and its relevance together with the importance of differentiation to achieving intent provide us with a measure of potential value. In this approach, the value of information is directly dependent on the context of individual intents of the many different decision cells that make up the overall organization and what theories those decision cells are entertaining at the moment.

This concept of the potential value of information does not depend directly on how close theories are to the truth, only on their potential to refute theories and the significance of doing so. The significance of this distinction becomes clear when we consider verisimilitude, in which we rank refuted theories according to the relative distances their consequences are from the observed facts. Recall that we conjecture the unsolvability of this problem in a general sense[34], and our understanding of the value of facts accords with this. We distinguish between ranking refuted theories with respect to their relative distances from the truth, and the usefulness of those theories as capsules of understanding within a given context. Our model of the value of information relates to the second.

The utility of distinguishing between alternative theories will vary, sometimes the choice will have profound repercussions for the achievement of intent, while at others the distinction will be less vital. Understanding the importance of distinguishing between competing theories, and the potential of different facts to clarify the distinction by refuting one or another of those theories, provides us with a clear definition for the potential value of information. This potential becomes concrete when facts are utilized to test theories. When the source of the information and its beneficiary are not coincident, a transaction of some kind must occur to deliver it to where it is needed. The potential value of the transaction to the recipient is just the potential value to that recipient of the information it conveys, and therefore we might describe the potential value of a fact to the organization as a whole at any moment as an accumulation of its potential value to each decision cell. We consider the value of the network as a whole in any interval of time to be the total value of all the transactions it supports during that period.

So network transactions provide evidence against which theories, which are attempts to construct useful approximations, are evaluated. Many different approaches to approximation exist, and each performs in its particular domain of applicability. The consequence of our methodological framework is therefore a notion of value that is context-dependent, meaning that the specific choice of an appropriate outlook for examining the likeness to truth of theories is dependent on the particular problem area the theory is intended to address. We may attempt to understand the verisimilitude of theories, but this does not, in itself, capture their value to our organization. Our military enterprise is primarily interested in developing theories that suffice to solve problems of explanation in particular contexts. Hence we propose that the notion of the value of facts

[34] In fact, we would be surprised by a general formulation of verisimilitude also for other reasons. A tour through the literature reveals a wide range of particular approaches to approximation, and surely such a general formulation of verisimilitude would have to unify them all.

should be tied to this concept of fitness for purpose, through the measure of relevance whereby we capture their ability to differentiate between alternative theories, rather than to a concept of verisimilitude directly.

The Information Needs are Asymmetric.

A rational investigation of a phenomenon, whether it seeks knowledge of the adversary's intent on the battlefield or explanations for gamma ray bursts, is limited to developing theories about which we are perpetually and professionally sceptical. It is this very scepticism that provides us with the basis for workable methods for finding better theories, although we may not even be able to know in a general sense whether one of our refuted simplifications is closer to the truth than another. Critical rationalism proposes that theories solve problems of explanation, and that we can develop compact and comprehensible explanations even for phenomena that are incomprehensible in their fullness through a deductive curriculum of proposition and attempted refutation.

The understanding that a decision cell has of a given phenomenon comprises the total web of interrelated theories pertaining to that phenomenon, both current and those it has chosen to set aside. In this way, our definition of understanding captures not only current explanations, but also the history of refuted theories and by implication the reasons for eliminating the those options, at least within the particular context of the problem at hand. We distinguish the set of viable theories about a problem, meaning those theories that have been evaluated but not yet rejected, as a sound definition roughly corresponding to the NCW notion of 'situation awareness'. The total knowledge that the decision cell represents at any moment is simply its entire body of theories, whether they are newly proposed and untested, evaluated but not yet rejected, or discredited in the face of available evidence. We might also wish to consider other constructions, such as the total set of viable theories across all problems in play at any moment.

Notice that the total understanding of a phenomenon is more than just one theory, although in the degenerate case an account of the relevant theories might sum to unity. In our view, an understanding consists of all the relevant theories, including those we have appraised and found wanting. Awareness of a situation includes all the tested yet undefeated theories, for this captures not only our best guess but also indicates something of the current level of uncertainty, and indeed how it might be improved. The level of uncertainty and the pressing need to distinguish between alternative theories drives the requirements for information, and the information needs are really expressions of the ways in which the flaws in those theories might be exposed.

We submit that this methodological framework for military decision-making greatly clarifies the goal of employing advancing information and communications technology to benefit the military enterprise. We utilize clear and precise definitions where there have previously been indistinct notions of 'understanding' and 'situation awareness'[35].

[35] Woolly notions have been favoured with the argument that they do not close down options for research. However, this provides a mechanism whereby to avoid falsification of the theory and therefore runs counter to principles of scientific method. Besides, it is inconsistent with the fact that mathematics is tightly

Decision cells develop theories regarding the adversary intent, how the adversary seeks to achieve its intent, the various options for achieving own intent, and the posture of other friendly force elements. We distinguish theories that capture understanding of the environment and the actions of the adversary from hypothetical choices regarding what might be done about it. The first are attempted explanations for observations of the adversary and environment, while the second are possible solutions to our problem of achieving our own intent, which presumably includes denying the adversary the success of realizing his intent. All these theories together, from all the decision cells in an organization, are the understanding of the organization as a whole. Different decision cells have different intents, different tasks to undertake, different local environments, different problems to solve and different minds working on them, and therefore they also exhibit different requirements for facts against which to test their theories.

An interesting consequence of our outlook is the fact that we do not reach the conclusion that that everyone across the military enterprise requires access the same set of facts regarding a particular problem[36]. We accept no presumption that so providing the same facts will enable separate force elements to come to the same conclusion, and thereby to self-organize. Although the truth might be out there, we are almost always unable to find it. There is usually no right or wrong answer, only better or worse within a particular context, so separate decision cells have every right to develop different theories of the same phenomena. We must confront our problems with the modest aim of finding reasonable simplifications, approximations that work well enough in our particular circumstances. Even within the same organization, the particular circumstances of individual decision cells vary, as do their specific intents. So they may rationally have dissimilar ideas, according to their individual circumstances, of even what constitutes a reasonable approximation. The problem of coordination simply does not dissipate with the provision of the same information to everyone, even if this information were perfect.

All in all, we reject the usual notion of a Common Operating Picture, with its underlying globally maintained pool of totally consistent data. Despite the apparent difficulty that our realizations represent, we do not perceive this with trepidation, for it compels a deeper examination of how we think about military decision-making and indeed highlights significant opportunities. Our investigations have emphasised the great value to be obtained by comparing the different understandings that different investigators develop concerning the same phenomenon. We submit that a critical rationalist outlook, in which different decision cells present different understandings, admits a far deeper

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defined, while it also achieves abstraction and generality. Our work in designing and constructing software and hardware systems has been frustrated by lack of clear meaning, rather than being assisted by it.

[36] Earlier works of the NCW proponents appear to state that all the same information be delivered to all the participants on the network. This attitude seems to have been clarified later, with the revised position that information relevant to a particular problem is made available to all interested parties. An example appears in *Code of Best Practice for Experimentation* on page 394. However, the presumption that the same information, or at least consistent information, is delivered to all concerned remains clear, and it is specifically this point with which we disagree.

understanding of the situation than the flat common body of consistent facts imposed artificially on all participants addressing a particular problem across the organization[37].

We see here the opportunity to make decisions with both statements of falsity and the uncertainty in our understanding as clearly set before the decision-makers[38]. Uncertainty is fundamental, so the problem of coordinating force elements is not solved by setting the same information, or wholly compatible information, before decision-makers with the expectation that they should, at least in theory, come to the same conclusion. Rather, we propose that the opportunities lie in the tension between different sets of information, and between alternative theories[39]. It is in this tension that the fundamental uncertainty in our knowledge is revealed, requirements for further evidence are specified, and an urgent decision to act can be justified even in the face of limited knowledge. And the evidence required depends upon the theories, while the theories depend upon the problem being tackled. Different decision cells exist because they solve different problems, albeit interrelated. Their information needs are asymmetric.

The Panoramic View.

Our critical rationalist outlook does not merely apply to deliberative planning[40]. Critical rationalism does not prescribe particular timeframes for its utilization, nor does it prescribe that the context and timeframes in which theories are developed be the same as those in which theories are exploited. The opposite is true: our epistemological perspective applies to all levels of knowledge acquisition and decision-making, regardless of the immediacy of the requirement. The critical rationalist perspective has great elegance in its ability to unite under a single framework the knowledge development activities across different levels of the overall military enterprise and operating along vastly different timelines.

Thus we submit that critical rationalism is a unifying outlook. We are able to frame our considerations of the information requirements of small units and even individual soldiers as clearly those of the needs of higher headquarters. We fuse the planning and execution

[37] One of our colleagues has coined a useful analogy, describing an enforcement of global consistency as a flat monochrome image of the situation and the place of the organization in it, while permitting differences in understanding between decision cells provides the organization with stereoscopic vision in full colour.
[38] It is not uncommon to encounter concerns that operators implicitly view the Common Operating Picture as representing ground truth. We reject the arguments to the effect that this is the fault of the operators themselves, for they only act in accordance with their training and the system at their disposal, and submit that the problem here is epistemological. We offer that adopting a defensible methodological position in the first place would see this put right as a natural consequence.
[39] Notice that this is in accordance with Shannon's Information Theory, which dictates that statistically the interesting information content of a stream of data lies in the exceptional events. But then we should expect such consistency, for Shannon's Information Theory may be constructed as a probabilistic counterpart and approximation to deeper notions in Algorithmic Information Theory.
[40] Current deliberative planning models are a strong indictment of the naïve inductivism that is still predominant in military thinking. Deliberative planning models attempt to formalize a rational process for decision-making in recognition of the need for alternative theories and planned collection of evidence. Yet inductivism muddles their design and permeates their implementation, so we should not be surprised at their apparent failure.

phases as a single methodological endeavour, for execution is merely the ultimate test of a theory. We can consider the necessities of rapid decision-making as clearly as those of deliberative planning. The key to exercising this potential lies in the observation that theory development can and does occur on vastly different timescales to that of its testing, which occurs in the employment of those theories to make decisions.

The critical rationalist outlook applies equally at all levels of command. Immediate decisions to act rapidly, particularly at the lower levels of the organization, are the result of intensive training. That training establishes theories for employment on the battlefield and teaches their rapid invocation in response to particular cues. In the broader sense, these theories are useful simplifications that have historically worked most of the time. The man in the foxhole is trained to put his face in the mud when his adversary starts shooting because military enterprises have maintained over many years of practical experience the theory that such action usually improves his chances of survival. Such theories are developed in a dissimilar setting having a dissimilar schedule from that in which they are used. Our critical rationalist outlook enables us to regard rapid action, deliberative planning and execution, capability development and even cultural change all within a single unified conceptual framework.

Rather than describe distinct deliberative and immediate planning phases, we find it meaningful to distinguish between decisions that are built on knowledge developed in place and those that are based on background knowledge developed outside the current situation. Higher levels of the military enterprise, and particularly enabling areas of responsibility such as capability development that function outside the envelope of actual engagement, define the doctrine by which lower levels undertake their knowledge acquisition and exploitation activities. Recall that critical rationalism defines a set of guiding principles concerning knowledge and knowledge development, which must be interpreted within the particular context of interest, rather than a prescriptive recipe of naïve refutation. Our broader view is that doctrine development should be specifically concerned with enshrining these principles in detailed procedures targeted specifically for the problem context that a given force element is intended to address.

The critical rationalist framework also subdues the cult of the commander, the habitual preoccupation with the quickening pace of decisions at the top level of the military enterprise and the associated relegation of the lower tactical elements to the stereotype of mere execution. Decisions occur at all levels, not only in the higher headquarters. We also must remember that even the individual soldier still makes the specific choice in his particular local circumstances to actually employ a theory he has been taught. Decisions to exploit knowledge by taking particular action are not the only decisions we must consider, for purposeful decisions are also imperative in the development of knowledge itself[41]. We have seen that creativity is integral to the acquisition of knowledge and

[41] This is an important difference between critical rationalism and the inductivist approach that it replaces. Critical rationalism emphasizes that decisions are actually fundamental part of knowledge generation itself. For example, decisions regarding evidence collection as well as decisions to accept evidence in contravention of a theory are crucial in knowledge generation. Inductivism, on the other hand, does not support the notion that deliberate decisions are integral to knowledge development.

thereby to the making of decisions, and every professional in the military organisation is there to do both. In the professional army, everyone collectively and individually faces complex problems in an environment of inherent uncertainty, so everyone must invent.

Our critical rationalist perspective also suppresses the natural but precarious preoccupation with our own force. This framework for understanding knowledge and the development of knowledge applies also to the activities of the opposition, whether they are a modern conventional force or an asymmetric issue motivated group with a willingness to visit violence upon civilian populations. Perhaps a terrorist only requires tonight's weather report before releasing a powdered biological agent tomorrow. We understand his information requirements simply in terms of the evidence needed to distinguish between alternative theories about the activities of security forces and about the effectiveness of his possible courses of action in achieving his intent. Ultimately, the critical rationalist outlook applies just as much to men with spears just as surely as it does to men with guided missiles and digital computers[42].

A robust conceptual framework does not apply only to a technologically developed force, and the lower levels of the organizations should not be typecast as simply executing orders from above, for they make decisions as surely as does the senior commander. Creative enterprise is indispensable in solving problems, at all levels. We have seen how critical rationalism applies to more than just deliberative planning, and unifies knowledge development and exploitation in across vastly different timescales. Planning and execution are no longer distinct, for the ultimate test of a theory is in its employment in execution. In short, the critical rationalist outlook offers us a panoramic view.

CRITICAL RATIONALIST REINTERPRETATIONS.

> **But there are other reasons for a continuance of military incompetence, which, paradoxically, came about with the transition from old-time to modern generalship. Far from diminishing the possibility of error, this transition opens up vistas of potential ineptitude hitherto denied to professionals in violence.**
>
> **- Norman Dixon, *On the Psychology of Military Incompetence*.**

Our critical rationalist framework does not begin with information and communications technology. Rather, it begins with an understanding of knowledge and the development of knowledge, and is cognizant of the fundamental limitations to knowledge and knowledge development within which any decision-maker, whether human or machine, must operate. In our outlook, the possibilities for technology utilization come as a consequence of this awareness of war as a clash of wills, of war as the generation of knowledge and the making of decisions in the face of pervasive uncertainty.

In this section, we begin with the suggestion that throughout military history, methodological errors, more than limitations of the available technology, are a dominant factor leading to disaster. Two brief examples from our broader review are offered in illustration. This adds an empirical aspect to our central argument for a revolution in

[42] We have contended in previous papers that this is a glaring issue in the NCW thesis. We have argued that as a theory of warfare, or even just as a theory of information and communications technology utilization, it is not applicable to a relatively low technology force or an asymmetric or criminal group.

methodology, and that such a revolution should drive our consideration of opportunities offered by advancing technology. The second issue concerns aspects of military culture that may continue to resist such a change. In particular, we suggest that aspects of military culture may favour the perpetuation of inductivism, despite its insolvency. This leads us to suggest that the current ideas for a common operating picture, for example, are as much a product of the military culture as they are a result of inductivism. The final part of this section contains a short description of some areas in which information and communications technology offers benefits to military operations, as seen through critical rationalist eyes. The opportunities are consequential to a sophisticated epistemological outlook rather than the driver for military transformation. While information and communications technology greatly expand our experimental capabilities, they can make no indentation in fundamental uncertainty.

A Litany of Methodological Error.

We suggest that the military has suffered disasters throughout human history that are accounted more to errors of methodology than to limitations of available technology. To put it another way, we submit that it is not so much the available technology but the manner in which we utilize it in our complex and uncertain military venture that wins the day. Of course, history is very malleable and can be made to serve any number of conflicting causes, and our purpose here is not to provide a rigorous account, but rather to briefly illustrate our thoughts. Other authors have studied military catastrophes in great detail from the psychological point of view[43], and in doing so correlate such errors with certain psychological traits. We submit that our epistemological focus allows us to distinguish the methodological nature of the errors that have led to tragedy[44].

The First World War is rich with military misadventures, many of which resulted in destruction of human life on a staggering scale. The Battle of the Somme is a striking example, in which the British and French led by Field Marshall Sir Douglas Haig attacked German positions in the Somme valley. The initial artillery barrage had not destroyed razor wire obstacles, the Germans had sheltered safely in their deep bunkers, and the shelling shattered the ground over which the allied units subsequently marched towards their enemy. The result was 57 000 British casualties in the first morning of the battle, and this remains the highest loss sustained by any army on a single day.

The British battle plan was hopelessly inadequate for its total lack of flexibility. The attack continued despite reports of heavy German resistance and effective razor wire entanglements, because the plan stated that the opening artillery bombardment would neutralize these defences. No provision was made for encountering heavy German resistance because Haig's plan of frontal assault stated that there would be none. The

[43] Norman Dixon's highly acclaimed book *On the Psychology of Military Incompetence* is a stimulating examination of the individual psychological aspects of incompetent military commanders. Dixon also concludes that military culture overall can provide an environment to which such personalities may be attracted, and in which they subsequently experience significant opportunities for promotion to positions of great responsibility.

[44] The continued development of this historical perspective is an ongoing area of investigation. We have also found dominant methodological errors in recent military exercises.

infantry were to simply walk up and claim the undefended German positions. While the British knew of the limitations of their guns, they never thought to consider their theory regarding the effectiveness of the artillery bombardment against this evidence. This is interesting, for this is information about what was not available and what the guns could not do is an example of negative information. Worse still, reports filtering back regarding the failure of the bombardment were ignored, and the plan itself had been constructed completely without consideration for contingencies. Deteriorating weather brought the offensive to a halt and forced Haig to abandon the few significant gains that had been made. The total cost of the battle was 1 120 000 British, German and French casualties.

Our other example is Field Marshall Sir Bernard Montgomery's attempt to break into Germany through northern Holland in 1944, 'Operation Market Garden'. Montgomery's bold plan to secure five bridges using airborne troops and thereby establish a corridor through to and across the Rhine was born of a desire to shorten the war, and in doing so win the race for Berlin. This secondary objective apparently took precedence over the first, and the result was a devastating loss of life. The operation involved a massive drop of airborne troops to secure the bridges, coinciding with an invasion of land forces into southern Holland. Ground forces needed to cover long distances along vulnerable raised roads flanked by fields impassable to armoured vehicles. Strong German forces had escaped into northern Holland, while success for the allies was dependent upon the paratroopers experiencing only light resistance around Arnhem. And weather conditions can be notoriously difficult for airborne operations in that place at that time of year.

The plan relied on the absence of strong German forces in Arnhem and along the approach route to the south, yet the resistance in Holland reported the presence of two SS Panzer divisions in the area close to where the paratroops were to be delivered. Montgomery rejected this evidence as being ridiculous, and his subordinate commanders quickly followed suit. When presented with aerial reconnaissance photographs of the heavy German armour, General Browning dismissed this as well with the assertion that the vehicles pictured were probably not serviceable. Montgomery's intelligence staff surmised that any German forces near Arnhem or along its approach routes were of poor quality, demoralized and likely to capitulate in the face of the airborne assault. Far from being weak and demoralized, the elite panzer divisions decimated Urquhart's paratroops. Ground forces advancing into Holland experienced determined opposition in difficult terrain, and never reached Arnhem. Further air drops of reinforcements and supplies for the isolated paratroops were delayed by bad weather. Total allied losses exceeded 17 000, and civilian losses are estimated at anywhere up to 10 000.

Symptoms of inadequate planning are clear, and the problems were methodological. Facts were available that clearly compelled falsification of the theory: two independent reports of strong German forces were ignored, and together they must be construed as evidence in contravention of the plan. The commanders entertained a dubious reliance on weather suitable for conducting further airdrops to reinforce and re-supply otherwise isolated paratroops. This is a good case in point because Montgomery is widely acknowledged as a highly intelligent and resourceful commander, exemplifying that methodological errors and the disasters they contribute to are not dismissible as products of low intellect and inadequate intuition[45].

Our historical review also led us to consider the nature of the military culture that has and probably will continue to resist the kind of changes we are advocating. The problems of conducting war on a large scale include those of motivation and control, necessitating methods of ensuring group cohesion, inciting hostility towards an enemy largely in the absence of personal animosity, enforcing obedience and suppressing rebellion. Without such measures it would be impossible to translate the directives of the commander into coordinated action by those subordinate to him. In other words, military culture largely maintains an outlook that prizes conventionality and demands conformity of the individual and uniformity across the organisation as a whole. This drive towards conformity is in effect a mechanism to impose order over the immense uncertainty and personal danger in which military professionals must practise their trade[46].

We submit that military culture is very much in evidence in the perpetuation of naïve inductivism in military thinking. Inductivism has an implied conformity and uniformity among seekers of knowledge, for all individuals would ideally come to the same conclusion given the same information. While we have argued that the common operating picture as a natural consequence of naïve inductivism, this cultural aspect suggests that inductivism may be retained because it supports the values of standardization and orthodoxy apparent in military culture. Perhaps the common operating picture that presents the underlying pool of completely consistent information to everyone, albeit through tailored displays, is a reflection of this cultural desire for homogeny, as much as it is a product of the inductivist epistemology.

A Few Technology Opportunities.

Our critical rationalist conceptual framework defines knowledge as sets of theories, and knowledge acquisition as a process whereby theories are proposed and tested by attempting to refute them in the court of experience. This perspective provides us immediately with interesting opportunities for exploiting information technology in the management and testing of theories that have not, to the best of our knowledge, been previously identified in the military context. Information technology provides an ability to store and manipulate far more theories than can be accomplished by unassisted humans. Making real this possibility demands new approaches of visualisation to permit human operators to rapidly construct new theories, to compare alternative theories, to maintain their current status, and to record the history of previous attempts to refute them.

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[45] This raises a point of particular concern, namely the notion often put forward that commanders should make decisions intuitively, and therefore quickly. This suggests that a process of rational knowledge acquisition is only for the scientist, while the military commander must rely on nothing other than intuition to make major decisions. The disaster at Armhem should serve as a dire warning against this attitude. Note again our earlier observation that a rational process does not equate to slow deliberative planning.

[46] Norman Dixon, in his book *On the Psychology of Military Incompetence*, describes in detail these psychological aspects of military culture. In doing so, he asks whether modern military organisations achieve the right balance between the levels of conformity and discipline required for the military to function and the creativeness and independence of thought required to command effectively.

We intend knowledge management to mean automated assistance for storing, manipulating and displaying theories. Many of the potential benefits of information and communications technology we envisage rely on the formal representation of theories. The field of knowledge representation provides the ability to precisely represent theories, thereby facilitating their manipulation by machines. The basic concept in knowledge representation, regardless of the application, is the formal ontology, which may be described as an explicit representation of a conceptualisation. The ontology is formal because it is precisely defined and amenable to automatic processing, and is explicit because it defines the concepts that compose it. Conceptualisation refers to the fact that the ontology constitutes an abstract model of some real phenomenon or domain. Placing this in our critical rationalist outlook, a formal ontology is a way of representing a theory.

Ontologies can differ in specification despite having the same conceptualisation, and likewise may disagree in conceptualisation despite attempting to represent the same phenomenon. We propose that the problem of semantic interoperability, in which different ontologies are developed independently and the systems in which they are embodied are later required to exchange information[47], is important in epistemology. This importance is particularly noticeable when considering the activities of a group of investigators, tied together within an overall organisation through their interrelated intents. To coordinate between multiple decision cells, their theories must be compared and contrasted, the interrelationships mapped and managed. Other kinds of manipulations are also important, including the checking of theories for internal consistency and for consistency with other theories, logical deduction of the consequences of theories, specification of the requirements for evidence, the planning of evidence collection, dissemination of theories between decision cells, and appraisal of theories through comparison of the consequences with collected evidence.

We have seen that humans are vulnerable to certain regular kinds of logical errors, while computer systems operate by formal logical inference and are therefore not susceptible to such mistakes. On the other hand, humans are creative by nature, while machines are constrained to rigid logical progression. Our new conceptual framework naturally delineates between the creative thinking and the rational evaluation of ideas by deducing consequences and comparing them with the evidence. Johnson-Laird and others have made it blatantly apparent that in undertaking this deduction and comparison, humans are especially prone to errors in dealing with statements of falsity. We contend therefore that it is in handling such information that technology can provide great benefit. This is a shift from current models of information technology utilization, which do not consider assisting of humans in handling negative information and even fail to represent statements of falsity on their displays and in their underlying database structures.

There is an important subtlety of profound practical significance in all of this, which

[47] A typical example of the semantic interoperability problem is that of interconnecting independently developed database systems. Conceptual schemata languages of the database world are examples of a certain class of ontology language.

returns us to the lessons of incompleteness and tractability. The richness of the ontology language in terms of its ability to express complex ideas may be limited by the computational properties of associated reasoning processes. We see this directly in the description logics[48], with their emphasis on reasoning processes. To put it simply, highly expressive ontology languages have reasoning problems that are unsolvable in the general sense, moderate languages are technically intractable, and only rather insipid examples are truly computationally feasible. Yet again we are confronted with the necessity of considering particular problem context in making wise choices, and even in representing theories we cannot expect to find a truly universal solution.

Some Areas of Information and Communications Technology Utilization	
Knowledge Management	Managing multiple competing theories of adversary intent and possible courses of action.
	Managing multiple competing theories of adversary intent and possible courses of action.
	Knowledge bases of theories and their contexts that worked well in the past, for possible development in a future context.
	Visualization and manipulation of complex alternative theories by human operators.
	Visualization of the relationships between different theories, including those under continued test, those that are newly proposed, and those that have been refuted.
	Collaboration tools to assist in the management and comparison of different sets of theories relating to different local contexts, between physically separated decision-makers.
Hypothesis Testing	Deducing the consequences of theories, and deducing the differences in the consequences of competing theories.
	Developing requirements for evidence in attempting to distinguish between competing theories.
	Assessing theories of adversary and environment against collected evidence, and assessing theories for internal consistency and consistency with other related theories.
	Evaluating theories regarding own intent and possible courses of action against multiple competing theories of adversary intent and possible courses of action.
	Testing theories against statements of falsity, as well as against statements of truth.
Information Management	Assisted collection tasking and management of complementary and competing needs for evidence.
	Digital communication of collection tasking orders and delivery of the collected body of facts.
	Management and recording of collected facts, and their dissemination to those decision-makers who require them in evidence against their theories.
	Communication of alternative theories within different local contexts between physically separated decision-makers.

PICKING UP THE PIECES OF THE VIRTUOUS REVOLUTION.

> **I hope I have made clear the distinction between a scientific revolution and the ideological revolution which may sometimes be linked to it. The ideological revolution may serve rationality or it may undermine it. But it is often nothing but an intellectual fashion.**
>
> **- Karl Popper, *The Myth of the Framework*.**

Our critical review of the NCW thesis uncovered a range of problems that fall into two broad classes. Our first paper in this series revealed an assembly of oversimplifications in the business analogy on which the NCW thesis is founded. The second focussed on an epistemological outlook manifest in the NCW thesis that has been widely rejected in philosophy and refuted by mathematical logic and reasoning. In this the final paper of the series, we attempted to address these issues, and in doing so, have provided an initial description of a new conceptual framework for considering the opportunities for military operations to benefit from advances in information and communications technology.

We sail on stormy and treacherous waters. Inductivism is a discredited epistemology, incompatible with fundamental theorems of pure mathematics and theoretical computer science. Interestingly, these landmark results, concerning the capabilities and limitations

[48] Description logics are the most powerful form of ontology, and are really restatements of mathematical logic, with model-theoretic semantics. Model theory is the study of languages and all their possible interpretations. In other work, we are examining reasoning in highly expressive description logics, where complete reasoning algorithms cannot exist. Most of the literature is concerned with description logics having solvable reasoning problems yet are sufficiently expressive to be useful in particular applications.

of formal reasoning and computation, actually underpin information technology itself. Simple questions do not always have simple answers, and in many cases the answer lies forever beyond our reach. Truths can be demonstrated that are infinite and individually random, and are therefore beyond full comprehension. Far from being an unusual, the overwhelming majority of phenomena forever reside beyond our ability to completely grasp them, and rather than being a mere legacy of a limited volume of information, fog and friction of war are fundamental realities. Here is the point of convergence for the mathematician and computer scientist, the empirical scientist, the engineer, and the military professional. Reasoning has severe limitations, and we have to simplify, and normally regard our theories with everlasting suspicion. Even problems that are solvable in principle are almost always intractable in the sense that they demand impossible resources to achieve full resolution. We almost always have to settle for approximate solutions, simplifications that are workable within a narrow problem context.

While humans are certainly capable of logical reasoning, we do not normally do it well, let alone when we are fatigued and under extreme stress. We make systematic errors, especially when it comes to handling negative information. Investigations into the actual abilities of human beings to carry out logical reasoning therefore confront the notion of intuitive decision-making. All this demolishes the notion that we may find absolute truth given a sufficiency of facts, and highlights the extreme peril of depending on intuition unaided. The idea that we may combine the intellects and knowledge of several people provides no harbour in the tempest. Dixon provides an astute summation:

> **Far from diminishing the chances of ineptitude, the group actually accentuates the effects of those very traits which may lead to incompetence in individual commanders. The symptoms of this process, which Janis terms 'group-think', include:**
>
> **1. An illusion of invulnerability that becomes shared by most members of the group.**
> **2. Collective attempts to ignore or rationalize away items of information which might otherwise lead the group to reconsider shaky but cherished assumptions.**
> **3. An unquestioned belief in the group's inherent morality, thus enabling members to overlook the ethical consequences of their decision.**
> **4. Stereotyping the enemy as either too evil for negotiation or too stupid and feebleminded to be a threat.**
> **5. A shared illusion of unanimity in a majority viewpoint, augmented by the false assumption that silence means consent.**
> **6. Self-appointed 'mind-guards' to protect the group from adverse information that might shatter complacency about the effectiveness and morality of their decisions.**
>
> **- Norman Dixon, *On the Psychology of Military Incompetence*, p399.**

We are warned that the limitations of human intuition and human nature combine to make a potentially deadly cocktail of self-delusion, and decision by committee alone can actually heighten the problem. At the end of the day, the problems of knowledge acquisition and decision-making are methodological in nature. So must the solution be methodological, and we alleviate our troubles by adopting a trustworthy epistemology. In the process, we greatly simplify and clarify the twin challenges of utilising information and communications technology and transforming the military enterprise.

The epistemology we adopt here is Popper's critical rationalism, which describes knowledge acquisition as a process of conjecture and testing by attempted refutation in the court of observational or experimental experience. With this approach, we have achieved concordance with our theoretical insights and provided overarching guidance whereby the process of knowledge development and the making of decisions, whether undertaken by an individual or by a group, is claimed to be rational. General theories can never be completely tested, so they never attain the status of conclusive laws. A best answer is not inevitable given enough facts. The truth is not buried in the data, and information does not lead to knowledge.

Verisimilitude is the formal notion of the ranking of refuted theories according to their respective distances from absolute truth. We conjecture that this problem may be unsolvable, with the implication that universal measures of effectiveness are unattainable. Accordingly, our notion of the value of information does not invoke the closeness of theories to absolute truth, relying instead on the ability of evidence to refute theories and the significance of so refuting them. The value of the network is a collective of the value of the individual transactions it supports, and the value of transactions according to the value of the information they convey. Ultimately, the lesson we draw from the concept of verisimilitude warns us that even the importance of distinguishing between alternative theories may be highly dependent on context.

The common operating picture, in any of its usual forms, is an inductivist inheritance, and reflects a goal of achieving the same outcome in what is actually a distributed system as would have been the case with centralised control. With our conceptual framework, we confront directly the need to coordinate between physically separated investigators whose knowledge consists of webs of interrelated theories that are developed by a process of conjecture and attempted refutation. This coordination, by exchanging evidence in the form of both theories and observational experience, does not yield a common operating picture of the usual description. Rather, we propose technology opportunities that regard knowledge as theories at various stages of their life cycles, and knowledge development by conjecture and refutation using collected evidence. We highlight the need to represent negative information, on our displays and in our systems. An important enabler to this vision is the field of formal ontology, whereby theories can be represented in a form in which they are amenable to manipulation by automated means.

Before we can really understand the opportunities offered by advances in information and communication technology we must first discard the epistemological legacy that has dominated military thought for hundreds of years, and replace it with an alternative outlook in line with the contemporary understanding. Warfare is not network centric, if we intend the network to mean communications and information technology. It is people centric, a manifestation of a clash of wills between human societies. Force transformation is not driven by technology, but by our decisions to act in particular ways. And herein lies the clincher, for the path forward is paved not with software, but with appreciation for how we may claim that the decisions made by commanders under circumstances of extreme stress and in the face of great uncertainty are truly rational. We hope that this viewpoint is natural and comforting, rather than threatening and foreign, for after all, our technology simply serves human needs and is not an end in itself. We submit that the revolution we seek is a transformation in how we think about thinking, and the change is motivated by important insights into the basic nature of logic, information, reasoning, complexity and randomness. It is a revolution that awaits us still.

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REFERENCES.

[1] Alberts, D.S., Garstka, J.J., Stein, F.P., "Network Centric Warfare: Developing and Leveraging Information Superiority", 2nd ed., *CCRP Publication Series*, 2000.

[2] Alberts, D.S., Garstka, J.J., Hayes, R.E., Signori, D.A., "Understanding Information Age Warfare", *CCRP Publication Series*, 2001.

[3] Alberts, D.S., "Information Age Transformation: Getting to a 21st Century Military", 2nd ed., *CCRP Publication Series*, 2002.

[4] Baader, F., Calvanese, D., McGuinness, D., Nardi, D., Patel-Schneider, P., (eds.) "The Description Logic Handbook: Theory, Implementation and Applications", *Cambridge University Press*, 2003.

[5] Balcázar, J. L., Gavaldá, R., and Hermo, M., "Compressibility of Infinite Binary Sequences", *Department de Llenguatges i Sistemes Informàtics, Universitat Politècnica de Catalunya,* technical report LSI-96-6-R, 1996.

[6] Brachman, R., "The Basics of Knowledge Representation and Reasoning", *AT&T Technical Journal* 67(1), pp7-24, 1988.

[7] Buchheit, M., Donini, F.M., and Schaerf, A., "Decidable Reasoning in Terminological Knowledge Representation Systems", *Journal of Artificial Intelligence Research* 1, pp109-138, 1993.

[8] Buhrman, H., Li, M., and Vitányi, P. M. B, "Kolmogorov Random Graphs and the Incompressibility Method", *SIAM Journal on Computing* 29(2), pp590-599, 1999.

[9] Chaitin, G.J., "Information-Theoretic Limitations of Formal Systems", *Journal of the ACM* 21, pp403-424, 1974.

[10] Chaitin, G.,J., "Randomness in arithmetic", *Scientific American* 259(1), pp80-85, 1988.

[11] Chaitin, G.J., "Algorithmic Information Theory", 3rd printing, *Cambridge University Press*, 1990.

[12] Chaitin G.J., "The Limits of Mathematics: A course on Information Theory and the Limits of Formal Reasoning", *Springer*, Singapore, 1998.

[13] Chaitin, G.J., "Computers, paradoxes and the foundations of mathematics", *American Scientist* 90, pp164-171, 2002.

[14] Chalmers, A.F., "What is this thing Called Science?", 3rd Ed., *University of Queensland Press*, St Lucia, 1999.

[15] Dixon, N., "On the Psychology of Military Incompetence", *Pimlico*, London, 1994.

[16] Buhrman, H., and Fortnow, L., "Time-bounded Kolmogorov Complexity Revisited", *Proceedings of the Symposium on Theoretical Aspects of Computer Science*, pp105-116, 1997.

[17] Cutland, N. J., "Computability: an Introduction to Recursive Function Theory", *Cambridge University Press,* Cambridge, 1980.

[18] Garey, M., and Johnson, D., "Computers and Intractability – A Guide to the Theory of NP-completeness", *Freeman*, San Fransisco, 1979.

[19] Hermo, M., "Compressibility and Uniform Complexity", *Information Processing Letters* 62, pp259-264, 1996.

[20] Horrocks, I., and Sattler, U., "A Description Logic with Transitive and Inverse Roles and Role Hierarchies", *Journal of Logic and Computation* 9(3), pp385-410, 1999.

[21] Jiang, T., Li, M., and Vitányi, P. M. B., "Average-case Analysis of Algorithms Using Kolmogorov Complexity", Journal of Computer Science and Technology 15(5), 402-408, 2000.

[22] Johnson-Laird, P.N., Legrenzi, P., Girotto, P., and Legrenzi, M.S., "Illusions in reasoning about consistency", *Science* 288, pp531-532, 2000.

[23] Johnson-Laird, P.N., "Mental models and deduction", *Trends in Cognitive Science* 5, pp434-442, 2001.

[24] Kobayashi, K., "On Compressibility of Infinite Binary Sequences", *Research Reports on Information Sciences, Tokyo Institute of Technology*, Technical Report C-34, 1981.

[25] Küsters, R., "Non-Standard Inferences in Description Logics", *Lecture Notes in Artificial Intelligence 21000*, *Springer-Verlag*, 2001.

[26] Ladner, R.E., "The Computaitonal Complexity of Provability in Systems of Modal Propositional Logic", *SIAM Journal of Computing* 6(3), pp467-480, 1977.

[27] Li, M., and Vitányi, P. M. B., "A New Approach to Formal Language Theory by Kolmogorov Complexity", *SIAM Journal on Computing* 24(2), pp398-410, 1995.

[28] Li, M., and Vitányi, P. M. B., "An Introduction to Kolmogorov Complexity and its Applications", 2nd Edition, *Springer-Verlag*, New York, 1997.

[29] Popper, K.R., "The Open Universe: An Argument for Indeterminism", *Routledge*, London and New York, 1988.

[30] Popper, K.R., "Conjectures and Refutations: The Growth of Scientific Knowledge", *Routledge,* London and New York, 1992.

[31] Popper, K.R., "All Life is Problem Solving", *Routledge*, London and New York, 2001

[32] Popper, K.R., "The Logic of Scientific Discovery", *Routledge*, London and New York, 2002.

[33] Polanyi, M., "Personal Knowledge: Towards a Post-Critical Philosophy", *Routledge*, London and New York, 1962.

[34] Sommerhalder, R., and van Westrhenen, S. C., "The Theory of Computability", *Addison-Wesley*, Reading, 1998.