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Article

Time, Entropy and Shannon Information: Toward the Evolution of Autonomous Human-Machine Teams

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Abstract: We review our theory of interdependence applied to autonomous human-machine teams, with which we have made several generalizations based on theory that have led to new discoveries, compared to social science which is struggling to break free of its validation crisis, but also has no generalizations to new discoveries with human teams, let alone to human-machine teams. In this invited article, based around the stability of a team, of our discoveries, we review the uncertainty between a team's structure and its performance, our first finding. We generalize that finding to deception, vulnerability, innovation and fittedness. From there, our next generalization is to the quantum likeness of interdependence and quantum mechanics; we move on to Shannon holes, knowledge, and conclude with the value of debate and the need for boundaries to contain debate, to reduce interference, and to protect states of interdependence. After the introduction, we extend our model in Section 2 to energy and time, and we close with a brief review of innovation and future plans.

Keywords: stability; interdependence; tradeoffs; uncertainty; evolution; time; entropy; available energy; innovation

1. Introduction

We address two issues raised in the call for this Special Issue: "Entropy is considered to be a measure of irreversibility, directionality of a process, and it is similar to time in this respect. ... [but] To what extent are time and entropy related?"¹ Our interest is in the different rates of evolution of independent versus interdependent human-machine teams, and how is useful information affected by them? We hypothesize that the key ingredient linking our wide list of keywords is interdependence, characterizing the best teams, more widespread in democracy than authoritarian regimes; that more free energy for teams is available in democracies; that the best teams reduce their structural entropy production to reach maximum entropy production; and that republics generate more Shannon information in the open which allows successes and failures to be more widely reviewed and debated, providing an evolutionary disadvantage to authoritarian regimes.

Interdependence is a part of every interaction among humans [20]. Social Scientists have long been baffled by interdependence, especially its study in the laboratory, where Jones (p. 33, in [20]) described it as leading to "bewilderment." We describe interdependence as a state of mutual dependence [12] characterized by three effects: Bistability (e.g., at least two sides exist to every story or belief); a measurement problem (measuring a cognitive belief about reality affects the belief, impeding it from corresponding to what may actually happen in reality); and non-factorable elements (e.g., the conflict between beliefs held by opposing sides can lead to courtroom cases for torts, even based on bizarre claims,² that take years to resolve).

¹ Entropy Special Issue 5Z60803917

² Editorial Board (2024, 1/14), "California Invents a Crazy New Tort. Golden State judges rule that Gilead can be sued for taking too long to develop an HIV drug," Wall Street Journal, retrieved 1/14/2024 from <https://www.wsj.com/articles/california-gilead-hiv-drug-lawsuit-tort-law-2143597c>

Before we begin, we offer three examples to briefly justify human-machine teams.³ First, human-machine teams may save human lives. For example, in 2015, the co-pilot of a Germanwings commercial airliner committed suicide, killing all 150 aboard.⁴ In the Germanwings case, the plane could have taken over from the copilot and safed itself until ground control took over or assisted the airliner (a human-machine team) to land safely. Second, human-machine teams may recover expensive systems. For example, in 2023, the pilot of an F35 ejected, but his \$100 million dollar stealth fighter jet continued flying for about another 60 miles.⁵ In this second example, after the ejection, we have the technology so that the plane could have safed itself until assisted by ground control, or landed on its own while overseen by ground control (a human-machine team). Third, human-machine teams may protect lives in the future of space travel, either taking over when in an emergency, or replacing humans with cyborgs and intelligent machines in deep-space travel overseen by humans on earth (a human-machine team) [34].

In comparison, social science seems focused on the value of cooperation as one of the social goods among animal taxa, if not the highest good [39]. In contrast, we have proposed and found that the best, most competitive teams minimize role or task duplication (redundancy), implying that the best teams are composed of complementary roles, making orthogonality more relevant than cooperation (reviewed in [11,24]). We have found that no evolution occurs without a competitive advantage arising [24]. And while teams appear to be systems of cooperation, the cooperation that does exist is subordinate to a team's ability to synchronize its teamwork to best be able to compete against its opponents (e.g., Einstein strove to present his version of the theory of general relativity before Hilbert could make a similar claim; reviewed in [26]).

We began our program of research with this puzzle: Why do many if not all social cognitive concepts fail to be validated in reality (e.g., self-esteem, in [2]; implicit racism, in [5]; forecasting political outcomes, in [46]). What adds complexity to this puzzle is that these cognitive concepts, like self-esteem, are significantly correlated with other cognitive concepts (e.g., depression; suicidal ideation; well-being), but not with the actual behavior predicted in reality; viz., the concept of self-esteem neither correlates with actual academic performance nor actual work performance. In other words, for example, while self-esteem significantly predicts the academic performance that students themselves believe when they self-report, the failure, and the most important clue, is that self-esteem does not predict the actual performance of student academics. Restated: Cognitive beliefs correlate well with each other, but these same cognitive beliefs do not correlate well if at all with their predicted outcomes in physical reality; however, as we have argued, they may be interdependently complementary, and if true, complementary may serve to rescue social science [27].

To account for this failure of social science concepts, we theorized that in the process of becoming a concept, a targeted concept becomes separated (disembodied cognition) from the underlying physical behavior it purports to track, especially when the presence of another human creates a state of interdependence (embodied cognition). States of interdependence reduce the degrees of freedom (*dof*) between interactants, but the cognitive conceptual process depends on data stripped of social effects, maximizing the *dof* to become independent and identically distributed (i.i.d.) data, which by definition cannot recreate whatever social event that has been observed no matter how simple [40], contradicting Shannon's information theory, but agreeing with Shannon's own finding in experiments with human subjects [43], with Shannon leaving an important clue for us to discover for what we have called Shannon holes in honor of Shannon (see more below).

³ This is a part of the AAAI Symposium in Spring 2024 co-organized by the first author; see at <https://aaai.org/conference/spring-symposia/ss24/#ss01>

⁴ [https://bea.aero/uploads/tx\[underscore\]elydrappports/BEA2015-0125.en-LR.pdf](https://bea.aero/uploads/tx[underscore]elydrappports/BEA2015-0125.en-LR.pdf)

⁵ <https://www.marinecorpstimes.com/news/your-marine-corps/2023/09/19/pilot-of-downed-f-35-parachuted-into-residential-backyard/>

We review the discoveries and generalizations in this section that we have made with what we know about the mathematics of interdependence, reviewed in the next section and then followed by a generalization to time, entropy, and energy.

a. Our first discovery was that there exists an uncertainty relationship between the entropy produced by the structure of a team and the team's performance (reviewed in [24]). We resolved our struggles with Martyushev's [31] requirement for stability to be able to reach maximum entropy production in this way: As the entropy produced by a structure is reduced, freeing available energy to be applied by a team to its performance, the entropy produced in a team's performance is allowed to be increased, reflected by an increase to a maximum for a team's production of entropy (viz., MEP; reviewed in [31]). We confirmed this prediction in 2017 with the public data available for the largest oil firms in the world, and replicated our findings in 2017 with the available public data for the top militaries in the world. Specifically, we found that the more redundancy in the firms home-based in authoritarian countries rather than in democracies, the more redundancy that was likely to exist in those teams; that is, for those teams home-quartered in less free countries, the poorer a team performed.

b. We have since generalized our first discovery for human-machine teams to a theory of deception; a theory of vulnerability; a theory of innovation; and a theory of how to best replace team members (along with emotion, reviewed in [24]). For deception, we have reported that the best deceiver must act to minimize a team's structural entropy production caused by the deceiver's presence until after its deception is complete.⁶ Next, during a competition, both teams seek an advantage granted to a team by the discovery of a vulnerability in its opponent's structure, characterized by an increase in its opponent's structural entropy production, a decrease in its production of maximum entropy during its performance, or both; e.g., a nation's vulnerability can lead to change if it is a democracy, or to hide the information if it is an autocracy.⁷ To increase innovation in a nation, it should allow its overall production of Shannon entropy to be maximized (e.g., with news reports arising from checks and balances, a common occurrence in a republic; in [24]), maximize the opportunity for an education of all of its citizens, and maximize their freedom of choice; as an aside that we shall return to later, the nations that maximize Shannon information are democracies and republics [27].

In our next study, we used United Nations data for MENA (Middle Eastern North African) nations; led by Israel, we concluded that to best replace the members of a team depended on the "fittedness" of new members; indirectly supported by the National Academy Sciences report on AI and humans [15], and by the assembly theory of complexity for alien life [51], the replacement of a team member should occur by a random selection among the best candidates available, where a good fit is characterized by a reduction in a team's structural entropy production, hence, "fittedness"; as another aside, we found that the effects of complexity are reduced by fittedness, characterized by a reduction in entropy and a reorientation of a team's structure as each piece of a complex team fits together [27].

c. The second discovery was that a Quantum Likeness (QL) exists to establish a commonality with the state dependency [12] of Quantum Mechanics (QM): interdependence acts like the entanglement of QM; the invalidity of numerous social science concepts can be attributed in part to a measurement problem [24]; the need for random choices in the replacement of team members is characterized by "fittedness" which acts like the "no-copy rule" that occurs in QM (e.g., caused by the hidden and unseeable effects of dependence [41]); and the tradeoff between uncertainty in the structural production of entropy (SEP) by a team and its production of maximum entropy with its performance (MEP; in [31]), combining to act like the uncertainty principle of QM. However, despite our finding of the similarity between the QL nature of inter-dependence among teammates [15] and the effects of

⁶ For example, a deception uncovered after decades of undercover activity while working for Cuba, "This action exposes one of the highest-reaching and longest-lasting infiltrations of the U.S. government by a foreign agent," Attorney General Merrick B. Garland told reporters in Washington [48]

⁷ Back in June, 2023, when China's youth unemployment rate hit a record 21.3%, Western analysts saw it as a sign of a moribund recovery. China's ministry of statistics responded by announcing it would no longer publish the statistic [53].

QM among non-living atoms and subatomic particles, human teams display intelligence by adapting to, and by solving, the problems presented to them across different and uncertain contexts [29], an expectation we have for human-machine teams, leading to the next discovery.

d. For our third discovery, guided by a report of Shannon's experiment with human subjects, "Shannon holes" were used by us to identify a team as a nest of interdependence [43]. A Shannon hole allows us to characterize mathematically a state of maximum interdependence in which, as the National Academy of Sciences ([15], p. 12) reported, the "performance of a team is not decomposable to, or an aggregation of, individual performances." The Academy's claim is repeated by the assembly theory of complexity for alien life [51]. The Academy's finding is the first finding by an outside group in support of our research.

e. The fourth discovery is about knowledge: how human-machine teams may come to know that it exists, its limits, and the tensions created when the limits of knowledge are approached [26]. To discover knowledge requires tests, such as experiments, and also the debates which humans commonly perform in public whether in the practice of science, politics, or law. This discovery has led us to appreciate the special value of debate designed to test or uncover knowledge. For example, the U.S. Supreme Court has written [50] that for a courtroom to require a "witness to submit to cross-examination [it is] the 'greatest legal engine ever invented for the discovery of truth.'" Justice Ginsburg [17] amplified the value of finding truth based on cross examination by concluding that a review of appeals provided an "informed assessment of competing interests" (p. 3).

The law can be combined with anecdotes from the fields of art and music; e.g., Leonard Bernstein wrote [3]:

"A work of art does not answer questions, it provokes them; and its essential meaning is in the tension between the contradictory answers."

Generalizing to the university with another Supreme Court ruling [10]:

"In a university, knowledge is its own end, not merely a means to an end. A university ceases to be true to its own nature if it becomes the tool of Church or State or any sectional interest. A university is characterized by the spirit of free inquiry, its ideal being the ideal of Socrates – 'to follow the argument where it leads.' This implies the right to examine, question, modify or reject traditional ideas and beliefs. Dogma and hypothesis are incompatible, and the concept of an immutable doctrine is repugnant to the spirit of a university. The concern of its scholars is not merely to add and revise facts in relation to an accepted framework, but to be ever examining and modifying the framework itself. ... Freedom to reason and freedom for disputation on the basis of observation and experiment are the necessary conditions for the advancement of scientific knowledge. A sense of freedom is also necessary for creative work in the arts which, equally with scientific research, is the concern of the university."

Additional support for debate comes from Nash's [33] computational theory applied to one agent countering another agent until they both arrive at an equilibrium; and from DoD's failure to use Nash's countering to challenge its own blue team's flawed decision to launch a drone attack on a car full of terrorists that turned out to be mostly full of innocent children, an unfortunate decision that led to tragedy [13].

Regarding debate, we have treated the value of beliefs as points in imaginary space, where $i = \sqrt{-1}$. From this has come the realization that debaters can easily talk past each other until an audience is present to add resistance that guides debate to reach a practical result; namely, in the absence of oppression (oppression more likely to occur under an authoritarian regime, but not always), agreement when reality is freely found, rejection when not. Oppressing debate or constraining its outcomes leads to a disadvantage reflected by a less than optimum decision; freely open debate can lead to a decision advantage (DA) if the outcome is successful.

Summing up this subsection, we have found that a *DA* is superior when practiced in regimes constrained by limited power, giving the advantage to republics with strong checks and balances versus majority-ruled democracies, and why both are superior to authoritarian regimes of all types, including gang leaders, military regimes, kings, etc. It is usually a surprise that centrally controlled governments remain convinced that controlling all of the available Shannon information gives them the advantage, when, instead, it places them at a significant disadvantage, at worst, putting a country at a possible de-evolutionary advantage (e.g., North Korea; Cuba; Venezuela⁸).

f. Lastly for now, our next discovery is a recognition of the value of boundaries that improve a space to allow for rational choice (e.g., [28]). Data dependency can be exploited to reduce uncertainty within bounded spaces where rational choice may be recovered [42], such as with game theory; e.g., Nash's countering; in [33]; Kissinger's balance of power between nations [22]; and Simon's bounded rationality [44]. For example, courtroom debates are usually held behind closed doors under the strict scrutiny of a judge;⁹ a military tries to control the air space over its operations during combat;¹⁰ and roundabouts significantly reduce traffic accidents and deaths.¹¹

2. Mathematical Approach

Bistability. There are numerous causes of conflict; e.g., beliefs, interests, mis-perceptions, information, structure, etc.¹² Assume the existence of two different beliefs about reality, *A* and *B*. Let one potential cause of different beliefs be based on a team's structure. If these two views of reality are held by two members of a team, conflict may arise by pitting self-interests against each other, but reduced or avoided by maintaining low redundancy across a team (e.g., high redundancy across a workforce leads to social loafing; reviewed in [24]). To avoid conflict, assume that low structural entropy arises when two views of reality are complementary (e.g., a cook and a waiter), precluding an overlap in their separate tasks that produces a difference in the information generated by agents and that feeds into their local perspectives of reality:

$$A * B = |A| * |B| * \cos\theta = AB \cos 90^\circ = 0. \quad (1)$$

Complementarity has long been theorized to exist in close-relationship pairs, but, based on the correlations derived from self-reports of close-relationships, not found to exist (e.g., for a review of the lack of an association between husbands and wives and other close relationships derived from self-reports, see [4]). However, Equation 1 justifies the lack of a correlation found among close relationships and those exhibit complementarity (e.g., a traditional husband might prefer yard work, a traditional wife house work, the information they both derive from their work being interdependently complementary).

Generalizing, if the views and task behaviors for multiple individuals who have been asked to self-report as single individuals, and if and only if these self-reported views and behaviors are also complementary, again, a zero correlation should arise, exactly what has been found for the concepts determined to be theoretically related, but with data from reality finding them to be invalid and

⁸ The USA is listed as the third most competitive country, Venezuela is number 63, but both Cuba and North Korea are not even listed; <https://www.imd.org/centers/wcc/world-competitiveness-center/rankings/world-competitiveness-ranking/>

⁹ https://www.americanbar.org/groups/criminal_justice/publications/criminal_justice_section_archive/crimjust_standards_trialjudge/; see Standard 6-3.2. Security in court facilities

¹⁰ <https://www.dctrine.af.mil/Portals/61/documents/AFDP3-52/3-52-AFDP-AIRSPACE-CONTROL.pdf>

¹¹ <https://highways.dot.gov/safety/intersection-safety/intersection-types/roundabouts>

¹² From the Vilendrer Law Firm's advertisement as a mediator to reduce conflict; see <https://www.vilendrerlaw.com/five-main-causes-conflict-mediation-can-resolve/>

unrelated ([20]; viz., also see for self-esteem [2]; implicit racism [5]; and ego-depletion [19]; for another failed attempt to validate ego-depletion, also known as "self-control," see [49]¹³).

Equation 1 suggests the need for a different approach to beliefs and behaviors. From a different approach to complementarity, we assume the existence of two operators, A and B . An operator is a means to extract information about the properties of a physical system to form an observable, viz., represented by a state vector. An observable can also be a physical property associated with the evolution of a state over time.

Measurement problem. If $A*B$ and $B*A$ have the same eigenfunctions, then $AB - BA = 0$, and no measurement problem exists; for example, in classical physics, observables of independent factors commute. However, if the eigenfunctions are not equal, occurring when there is interdependence between two non-factorables, as occurs in quantum mechanics ([41]; also true for any theory requiring state dependency; in [12]), then a measurement problem exists, and

$$[AB - BA] = iC. \quad (2)$$

We now know that imaginary numbers are central to the mathematics of QM, disputing Schrödinger's belief "that imaginary numbers were merely for convenience" [38]. Instead, we will use them to model unexpressed beliefs about reality, where two different beliefs are the inspiration and motivation for debates. Debates are characterized by an oscillation between the debaters.

Non-factorable elements. As a first, simple model of debate over time, borrowed from an electrical circuit, assume that the oscillation in a debate can be modeled like an electrical circuit, where L is inductance, R resistance and C capacitance. Assume that two debaters act like a capacitor; the two debaters and the audience like a resistor; and the audience, two debaters and opposing views about a concept regarding a problem in reality combine to act like an inductor. To represent the oscillation, assume an exponential relationship, e^{st} , where s is the complex frequency of oscillation, x the amount of time consumed overall by the debate represented by distance on the real x axis, and ω is the angular frequency of oscillation, then $s = x + i\omega$. The orthogonal $i\omega$ axis reflects sinusoidal time functions, and the x axis represents the effects of the exponential time functions. Assume also that I is the motivational current, t the time, and that the potential driving the oscillations, E , is a constant, which we set to zero to study the circuit's characteristic responses. Then we have that:

$$Ld^2I/dt^2 + RdI/dt + I/C = E = 0. \quad (3)$$

Assume the existence of an exponential solution, $I = I_0e^{st}$ in Equation 3 to allow us to seek the natural or characteristic of our simple LRC-like debate-audience circuit:

$$Ls^2I_0e^{st} + RsI_0e^{st} + I_0e^{st}/(C) = 0. \quad (4)$$

Dividing by I_0e^{st} gives:

$$Ls^2 + Rs + 1/(C) = 0. \quad (5)$$

Setting the inductor, capacitor and resistor to 1 gives:

$$s^2 + s + 1 = 0. \quad (6)$$

In Equations 5 and 6, by letting $R = 0$, we get $s = \pm i$. This case is described in Figure 1.

¹³ Evans, T. (2024), Psychologists Were Wrong About the Science of Self Control; see Psychology Today, 1/1/2024 from <https://www.psychologytoday.com>

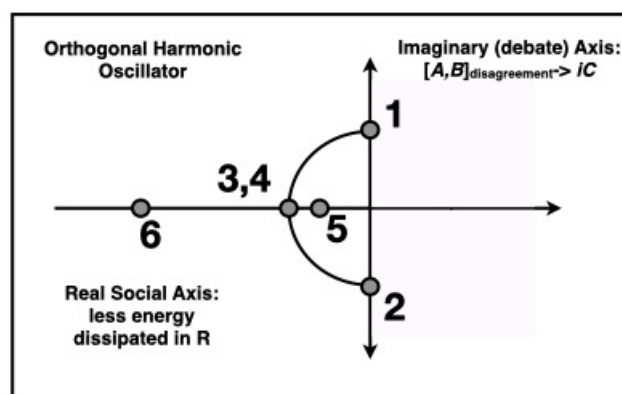


Figure 1. A model of a debate (from [24]). Two debaters ongoing without resistance provided by an audience is represented by points 1 and 2, where $s = \pm i$; this “war of words” [45] springs from beliefs held in imaginary space being displayed in a public space. As resistance is increased (e.g., by the presence of an audience), a compromise decision is represented by points 3 and 4 on the x axis. Motivated by time limits, and decided by observers (e.g., an audience, jury, judge), points 5 and 6 are possible decision solutions that have overcome resistance, time and energy (dissipation), both decreasing to the left

As an example of an oscillation and the dissipation of energy wasted over time, we review the monthly debates that occurred over a time period of several years at the Department of Energy’s (DOE) Savannah River Site (SRS) in Aiken, SC. DOE at SRS had successfully closed two of its highly radioactive high-level waste (HLW) tanks in 1997, the first two closures under a regulatory authority in the United States and possibly in the world [25].¹⁴

Before DOE could close its next two HLW tanks, DOE was sued and lost, leaving it unable to close additional tanks. The US Congress passed its National Defense Authorization Act in 2005 which in part allowed DOE’s HLW tank closures to resume.¹⁵ However, as a compromise, the new law authorized the U.S. Nuclear Regulatory Commission (NRC) to provide oversight of the technical decisions by DOE for its HLW tank closure program. Subsequently, DOE would propose a closure plan, and NRC would request changes. This back and forth between DOE and NRC went on for seven (7) years.

After those seven years, the Department of Health and Environmental Control¹⁶ became alarmed that DOE would not fulfil its commitment to DHEC to meet its legally and mutually agreed deadline to close its next two HLW tanks (viz., HLW tanks 18 and 19). At a public meeting held by DOE’s SRS Citizens Advisory Board (SRS-CAB) with DOE, NRC and DHEC present, the issue was raised and discussed; it was proposed that a recommendation would be drafted, debated and voted upon by the SRS-CAB to push DOE and NRC to resolve their technical differences.¹⁷ Subsequently, the recommendation was approved by the full SRS-CAB in which the citizens demanded of DOE and NRC, in public and with both agencies present, that the two agencies settle their differences and immediately restart tank closures, which happened.¹⁸ Paraphrasing one member of DOE’s staff at SRS, it was the fastest decision ever accepted, adopted and enacted by DOE-HQ that he had witnessed during his long career.

¹⁴ Drafted by the first author when he was a member of the SRS-CAB in 1997.

¹⁵ <https://www.govinfo.gov/content/pkg/PLAW-108publ375/pdf/PLAW-108publ375.pdf>

¹⁶ The South Carolina Department of Health and Environmental Control (DHEC) is the government agency responsible for public health and the environment in the U.S. State of South Carolina; see <https://scdhec.gov>

¹⁷ Requested by DHEC, the recommendation was drafted by the first author, who was previously a member of the SRS-CAB, but a former member at that time.

¹⁸ [https://cab.srs.gov/library/recommendations/recommendation \[underscore\] 284.pdf](https://cab.srs.gov/library/recommendations/recommendation%20284.pdf)

2.1. Debate, Negotiation and Nash Countering

Debate can be generalized by applying Nash countering [33] to negotiations and also to Kissinger's balancing among nations; to debate (cross examination), the best approach to truth in the courtroom; and to the form of government (viz., a republic) that best produces freedom and copious amounts of Shannon information, especially when constrained by checks and balances [30].

As well, we believe that aspects of debate generalize to negotiation. From the New York City Police Department's Hostage Negotiation Team ¹⁹

"A police negotiation technique that all skilled negotiators should possess in their negotiation skills repertoire is the ability to adapt to changing circumstances and to respond to those circumstances in a way that preserves the relationship they have built with their counterpart while also bringing them closer to their negotiation goals. ... Though not often fraught with the emotional complexity of a hostage negotiation, business negotiations still rely upon trust, rapport, and a mutual sense of respect in order to make the deal happen."

2.2. Interdependence and Entropy. A Mathematical Approach

In this section, we begin the shift from the world of separability between objects to the interdependence among intelligent agents. But first, to set the situation, earlier we reviewed our findings about the deception used, for example, in the spy business. When a spy gains access to the engineering drawings of a secret object, the device's drawing can be copied, stolen and recreated (viz., i.i.d. data).

However, this ease of copying and the re-creation of an independent piece of technology is not true regarding social information. As warned by Schölkopf and colleagues [40], capturing social information with independent and identically distributed data (viz., i.i.d. data), by definition, cannot recreate whatever social event was being studied.

Based on his own experiments with humans, Shannon [43] was well aware of this problem. From information theory [7], the mutual information for two agents,

$$I(X;Y) = H(X) - H(X|Y) \quad (7)$$

That is, if measuring Y tells us everything about X , then, for example, $I(X;Y)=H(X)$, providing a minimum of only 1 bit of information (in log base 2). Alternatively, when both X and Y are independent, the minimum information is two bits of information for the two independent agents. Contrast that with Shannon's experiment with pairs of humans where he found a minimum of 0.61 bits to a maximum of 1.3 bits of information ([52]).

Interdependence acts similar to entanglement [27]. From Schrödinger [41]:

"the best possible knowledge of a whole does not necessarily include the best possible knowledge of all its parts, even though they may be entirely separate and therefore virtually capable of being 'best possibly known' ... even though we restrict the disentangling measurements to one system, the representative obtained for the other system is by no means independent of the particular choice of observations ..."

In the interpretation of Einstein's 1935 EPR paper by Fine and Ryckman [16], locally separated systems have their own reality, precluding a measurement of one object from having an effect on the other; moreover, a correlation on one object from a pair of objects before measurement is unaffected by the measurement. That is, separable objects require independence.

¹⁹ Police Negotiation Techniques from the NYPD Crisis Negotiations Team; 12/20/2023 from <https://www.pon.harvard.edu/daily/crisis-negotiations/crisis-negotiations-and-negotiation-skills-insights-from-the-new-york-city-police-department-hostage-negotiations-team/>

Separability is one of the key objections made by Einstein and his colleagues in their EPR paper, that the parts of a whole once separated were independent of each other [14]. However, in QM, we cannot know what happens inside of a state of dependency [12]; e.g., not only with entanglement, but also what occurs inside of a state of superposition [18]:

“But from the Einstein-Podolsky-Rosen viewpoint these perfect correlations are essential for the introduction of elements of reality. ... “Entanglement” is simply Schrodinger’s name for superposition in a multiparticle system. Schrodinger was so taken with the significance of multiparticle superposition that he said entanglement is “not one but rather the characteristic trait of quantum mechanics.” ”

To be more exact, in a review of the scientific background of entanglement posted for the three Nobel Physics Laureates in 2022,²⁰

“That a pure quantum state is entangled means that it is not separable; for the simplest case of two spinless particles, being separable means that the wave function can be written as

$$\psi(x, y) = \psi_1(x)\psi_2(y)...\text{”} \quad (8)$$

To model dependence among agents in a team, guided by the study of science teams in the National Science Foundation (NSF) awards’ data base, Cummings [11] found that the best teams of scientists were highly interdependent to the point that as one scientist in a team handed off a task to another scientist, it was immediately grasped by its teammate as part of a well-timed synchrony. To achieve synchrony, we use a model of the reduction in the degrees of freedom (*dof*) among the parts of a whole, in this case, a whole team. This leads us to model the effect of maximum interdependence on the structural entropy production (SEP) of a team by reducing its *dof* to a minimum to reach a point, at least theoretically, when the team acts like a unit:

$$\lim_{dof \rightarrow 1+} \ln(SEP) = 0 \quad (9)$$

When we first read Martyushev [31], we were concerned by his precondition of stability to achieve maximum entropy production (MEP) because a high-performing team is generating copious amounts of entropy. We found our answer in the stability of a team’s structure. That is, a poorly organized team over-produces entropy by consuming available energy in wasted, dysfunctional efforts (e.g., a divorcing couple has little available energy or time to manage a family (see [4]); a business undergoing a spinoff is also likely to have been struggling).²¹

In contrast, a well-functioning team, like a powerful hurricane, has a well-knit, stable structure (low SEP), allowing more of its available energy along with an increase in the *dof* of its output to produce maximum entropy (MEP), making it potentially highly productive [27]; e.g., for the benefits gained by the children of a stable two-parent family, see [21]; for the positive benefits of corporate mergers, see [1].

Using a state-dependency approach [12], modeling the mutual dependence between the uncertainty in a team’s structure (ΔSEP) and the uncertainty in its productivity (ΔMEP), provided a solution (for a review, see [24]; [27]):

$$\Delta(SEP) * \Delta(MEP) \geq C. \quad (10)$$

²⁰ <https://www.nobelprize.org/uploads/2023/10/advanced-physicsprize2022-4.pdf>

²¹ e.g., the company, Atos, is struggling, and has decided to spin-off its cybersecurity unit for cash; see Calatyud, A. (2024, 1/3), “Airbus In Talks to Buy Atos Cybersecurity Unit for Up to \$2 Billion,” Wall Street Journal, retrieved 1/4/2024 from <https://www.wsj.com/business/airlines/airbus-in-talks-to-buy-atos-cybersecurity-unit-for-up-to-2-bl-3fb034e0>

Here is a brief list of our findings based on Equation 10:

1. Businesses based in more democratic societies have less redundancy in their teams, characterized by more productivity with fewer workers [23]. Support was obtained in 2017 by studying the top oil firms in the world; e.g., Exxon's oil production with fewer employees compared to Sinopec's similar levels of production but with many more employees.
2. We replicated our finding in 2017 by comparing the top militaries in the world (reviewed in [24]).
3. We have found a similarity between Equation 10 and quantum mechanics (QM), where QM is a model of data dependency ([12]; reviewed in [27]).
4. We have generalized Equation 10 to a team's vulnerability, characterized by an opponent's finding that as its target's structural entropy production (SEP) increases above its baseline, its maximum entropy production (MEP) decreases, or both [27].
5. Deception, innovation and the complexity of team member replacements. For deception, the deceiver must keep a team's SEP minimized to deceive the others in a team to its presence as a spy until its deception has been enacted (e.g., in a recent case, see the footnote²²; for innovation, interdependence must best be maximized [37]; and for member replacements, team entropy must reduce to indicate that the right member has been found [27]. The last finding deserves more comment: If true, it means that a team, agency or government cannot simply copy, say, an army of the best agents without the trouble of fitting each new agent into a team to find which replacement agent reduces entropy to indicate its fittedness for that team.

2.3. Time and Entropy

Feeling gratified with our generalizations and discoveries afforded by Equation 10 and listed above briefly, reviewed in depth in our Introduction, we now further generalize our earlier research to time, t , and energy, H , where H is the Hamiltonian for potential and kinetic energy, and then later we return to innovation.

To address time and its effects on an organization like a team, if team and energy are independent, then $Ht - tH = 0$. However, assuming they are interdependent, we can convert the operators proposed for Equation 10 into time and energy:

$$[H, t] = Ht - tH = iC_2 \quad (11)$$

We find support for Equation 11 from the description of signal theory by Cohen (p. 45, in [9]) who concluded that, based on transformations between Fourier pairs, a

"narrow waveform yields a wide spectrum, and a wide waveform yields a narrow spectrum and that both the time waveform and frequency spectrum cannot be made arbitrarily small simultaneously."

The advantage of citing Cohen is that it applies the quantum micro-world directly to time and energy in the macro-world. Based on Cohen and Equation 10, we revise the latter to $\Delta(tEP)$ for uncertainty in the time needed to defeat an opponent, tradedoff with the uncertainty in the amount of energy available to execute that time requirement, $\Delta(HEP)$:

$$\Delta(tEP) * \Delta(HEP) \geq C. \quad (12)$$

Based on Equation 12, we propose that the faster a decision can be made compared to opponents, as in the case of the closure of the HLW tanks at DOE-SRS versus DOE-Hanford, and that the

²² Ives, M. (2024, 1/9), "U.S. Naval Officer Who Helped China Is Sentenced to 2 Years in Prison. Wenheng Zhao pleaded guilty to charges that he sent photos of American military installations and details of U.S. military exercises to an intelligence officer working for China," New York Times, <https://www.nytimes.com/2024/01/09/us/navy-officer-china-spy.html>

energy to make and execute the decision is available, that a decision advantage accrues to the faster decision-maker, all else being equal.

Hypothesis, H-1: Time is critical to the performance of the best teams, but its uncertainty is interdependently related to the uncertainty in the energy available to an organization (or team) to execute its decision.

Reviewing the lengthy, seven (7) year lapse before DOE's closure of HLW tanks by the CAB at DOE SRS allows us to pivot to a comparison of debates by the citizen's CAB at SRS, where its recommendations are decided among CAB members by majority rules (MR), versus the consensus-seeking rules (CR) that determine the recommendations made by DOE's Hanford CAB at the Hanford facility in the State of Washington. The speed of decision-making by the majority ruled SRS-CAB is significantly faster than the much slower consensus-seeking Hanford advisory Board [25], plus, MR recommendations are more concrete in the advice rendered (e.g., to close HLW tanks 18 and 19, cited above), and places more emphasis on accelerating the environmental cleanup of its site (see [6]; [25]). As of this date, SRS has closed eight (8) of its HLW tanks since 1997;²³ Hanford has closed none.²⁴

From a different source that supports our findings about consensus rules, a White Paper (2001, p. 29) written by the European Union [35] concluded that:

"The requirement for consensus in the European Council often holds policy-making hostage to national interests in areas which Council could and should decide by a qualified majority."

We concluded that majority ruled (MR) debates are faster than consensus-seeking ones (CR), providing a decision advantage, DA , where the torque from the back and forth during debate in MR, τ_{MR} divided by τ_{CR} is greater, giving:

$$DA = \tau_{MR} / \tau_{CR}. \quad (13)$$

If we apply DA to political contests, we should expect that in the give and take of a long, closely decided campaign between teams of intelligent agents, as one faction is attacked by the other, it adapts and counters each attack, leading to what crudely appears to look like a limit cycle. An example is the case of Moore versus Jones for Senator of the State of Alabama in 2016 and their runoff in 2017, see Figure 2.

Applying Figure 2 to companies in the stock market, we see consolidation mergers in a formerly competitive market as a reasonable decision among intelligent agents to address the weakness caused by the loss of revenue occurring across that market. For example, Exxon's purchase of Pioneer [47]:

"Exxon Mobile is closing in on a deal to buy Pioneer Natural Resources, a blockbuster takeover that could be worth roughly \$60 billion and reshape the U.S. oil industry."

In support of consolidation mergers occurring after a loss of revenue in a market, Lucas [29] concluded for traders in the stock market that humans, being intelligent, use logic to adapt to the opportunities, vulnerabilities and misfortunes that present themselves over time.

Influenced by time, the best location for the intelligent traders of investment firms occurs nearest to stock exchanges. There are two reasons why time influences the location of an intelligent trader. First, traders want to be able to process market data messages and generate an order wire-to-wire in under as few microseconds as possible. Second, the speed of light is a constant for all of the traders;

²³ <https://scdhec.gov/savannah-river-site/savannah-river-site-high-level-waste-tanks>

²⁴ <https://ecology.wa.gov/Waste-Toxics/Nuclear-waste/Hanford-cleanup/Tank-waste-management/Tank-monitoring-closure>

the further a trader is from the exchange’s trading system, the longer it takes to get the market data message and for an order to get back to the exchange. It is not the absolute time that matters, but rather that the market data message is received ahead of other traders (i.e., $DA = \tau_{Trader-1} / \tau_{Trader-2}$), and that the order confirmation has a correspondingly short time back [36].

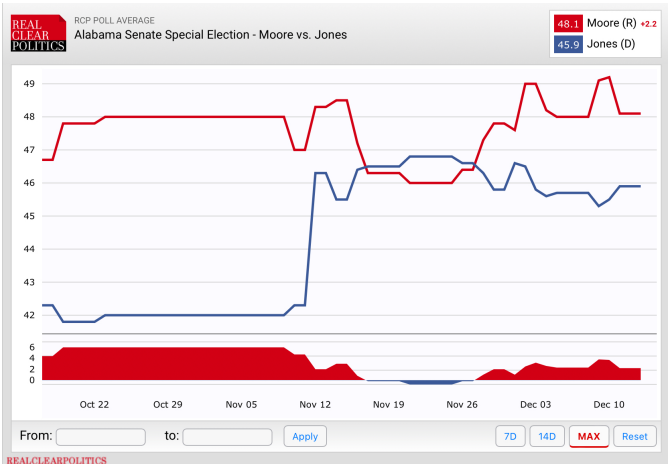


Figure 2. The run-off election for Senate in Alabama in 2017 gives a crude example of a limit cycle. Based on the RCP poll of averages, it appears that the red candidate won (i.e., the Republican). However, in the actual election, the blue candidate won, suggesting that the polls were inaccurate, likely caused by polls that under-reported the winner’s strength. A source of destructive interference among respondents to the polls may have been that unfavorable media existed for the red candidate.

Several anecdotes exist that help us to appreciate the relative value of time.

“Pleasure and action make the hours seem short,” wrote Shakespeare.²⁵

Added Albert Einstein,

“When you sit with a nice girl for two hours you think it’s only a minute. But when you sit on a hot stove for a minute you think it’s two hours.”²⁶

3. Materials, Methods, and Results

In this section, we review the materials, methods, and results of our study. In that we cannot observe inside of whatever social interactions are occurring [15], we assume that the (MEP) products of these team interactions can be collected and analyzed, which we present in Table 1.

To obtain the results shown in Table 1, we focused on public sources of data available online. We considered primarily only the world’s top ten largest economies.²⁷ In Table 1, we contrasted Gross Domestic Product per capita (GDP/capita);²⁸ Innovation index;²⁹ Corruptions Perceptions Index (CPI);³⁰ Freedom;³¹ Energy used, in Million Tons Oil Equivalent (mtoe), divided by population from

²⁵ Othello, 1623, by William Shakespeare.

²⁶ *New York Times* (1955), "Scientist explained his theory with wit and homey parable," retrieved 11/26/2023 from <https://timesmachine.nytimes.com/timesmachine/1955/04/19/93803022.html>

²⁷ Russia, USA, China, UK, Japan, India, Brazil, Canada, Europe (estimated), and Mexico

²⁸ <https://www.forbesindia.com/article/explainers/top-10-largest-economies-in-the-world>

²⁹ <https://www.theglobaleconomy.com/rankings/gii/>

³⁰ <https://www.transparency.org/en/cpi/2022>

³¹ <https://freedomhouse.org/countries/freedom-world/scores>

CIA World Factbook;³² and Time, in days, to start a business, with the data provided by the World Bank.³³

Table 1. Column labels: GDP/capita; Innovation index; Low CPI; Freedom; Energy used per capita (E/mtoe/capita); Time, in days, to start a business)[2-way (N-2) Significance: $r \geq .632^*$, $p < .05$; $r \geq .765^{**}$, $p < .01$].

GDP/cap	Innov.	Low CPI	Freedom	E (mtoe/cap)	Bus. time
1					
.72*	1				
.03	.40	1			
.59	.15	.73*	1		
.81**	.70*	.39	.73*	1	
-.75*	-.66*	-.71*	-.23	-.53	1

From Table 1, we review the results from innovation, energy and time. To address our hypothesis, H-1, we included energy and the time in days on average that it takes to start up a new business, the World Bank’s former measure of competitiveness for businesses (the World Bank’s data collection was discontinued for its time report in 2021; see the link above).

Time. The average time it took to start a business in a nation was inversely related to that nation’s GDP/capita ($r = -.75$, $p < .05$); significantly related inversely to a nations ability to innovate ($r = -.66$, $p < .05$); significantly and inversely related to the low perception of corruption in a nation ($r = -.71$, $p < .05$); favorably and inversely but not significantly related to freedom in a country ($r = -.23$, $p > .05$); and strongly but not significantly related to the energy consumed per capita in a nation ($r = .53$, $p > .05$).

Energy. For energy, we found that it was significantly related to GDP/capita ($r = .81$, $p < .01$); significantly related to innovation ($r = .70$, $p < .05$); strongly but not significantly correlated to low Corruptions Perceptions Index ($r = .39$, $p > .05$); significantly related to freedom ($r = .73$, $p < .05$); and strongly related but not significantly to the time it takes on average for a business to start up in a country ($r = -.53$, $p > .05$).

Innovation. Innovation is significantly related to GDP/capita ($r = .72$, $p < .05$); related to low CPI but not significantly ($r = .40$, $p > .05$); positively but barely related to freedom ($r = .15$, $p > .05$); significantly related to energy/capita ($r = .70$, $p < .05$); and significantly related to the time it takes on average to start a new business in a nation, an indicator of competitiveness ($r = -.66$, $p < .05$).

4. Discussion

Our results are supported indirectly and directly in the literature. As an indirect example, from assembly theory for open systems, a theory of alien life published in the *Proceedings of the National Academy of Sciences* [51], evolving systems select preferentially based on function, an increase in the *dof* which we then liken to maximum entropy production (MEP), especially if the selected attribute is functional, stable, and reflects and increase in the *dof* of a team’s output (for MEP, see Martyushev, in [31]). As the complexity of an agent’s assembly increases, its functional information and *dof* in its

³² <https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html> and <https://www.cia.gov/the-world-factbook/>

³³ World Bank’s ranking for a nation’s competitiveness (<https://data.worldbank.org/indicator/IC.REG.DURS?most-recent-value-desc=true>); the Doing Business Report was discontinued in 2021; see <https://www.worldbank.org/en/news/statement/2021/09/16/world-bank-group-to-discontinue-doing-business-report>

output increase; i.e., in our words, its functional MEP increases. However, this complexity afforded by evolution is limited by the second law of thermodynamics, and the agent, stable as it is, must be "fed" energy to stay ordered. Then and only then do we agree with the authors of assembly theory that "natural selection preferentially retains configurations with effective function" (viz., p. 3, in Wong et al. [51]); however, we condition our agreement in this way: that life-forms must be able to sample extensively, softly rejecting the errors made along the way (e.g., about 50 percent of all mergers fail; in [8]). This allows us to agree only in part with Wong et al. (p. 4): "evolution is a process by which configurations with a greater degree of function are preferentially selected, while nonfunctional configurations are winnowed out." We disagree that the winnowing out is conclusive, especially when it comes to innovation.

We also disagree with Wong and colleagues on assembly theory in a couple of other critical areas. First, they argue (p. 5) that those "processes ... [having] causal efficacy over the internal state of a system ... [are] functions." However, their causal efficacy implies the existence of an awareness, and we disagree with the requirement for that occurring, especially for internal systems that are complementary (viz., Equation 1); the authors seem to agree with us (p. 6) by concluding that this awareness becomes less possible the more interwoven and complex a system becomes. Under the same constraint, we agree that exaptations drive changes in functions over time, primarily because the phase space containing the interference between interacting agents in a team can be constructive or destructive.

Second, Wong et al. argue that humans and human-like agents have negative adaptive value that may lead to self-inflicted collapse (p. 6). We argue instead that weaknesses observed in the teams of humans are important sources of information that must be attacked with tools and ideas of increasing complexity for the discovery of weaknesses, driving innovation to occur more often in free and open environments. But then the authors seem unaware of the effects that complementarity can have on information losses (viz., Shannon holes), because they specify (p. 9) that "Evolving systems are ... interdependent." This leads us to the major flaws in assembly theory (p. 7): "the context-dependent features of the situation can be specified objectively"; and "a comprehensive understanding of the system's agents" is required. As we have argued, Equations 1 and 10 preclude such context and internal-team information from being easily available and instead require trials and errors to be able to successfully replace a teammate, or to find a vulnerability in an opponent's team, or one's own team. Moreover, to restate from earlier, the National Academy of Sciences (p. 12, in [15]) agreed with us regarding the lack of information available to distinguish cause and effect inside the internal interactions of teams by concluding that: The "performance of a team is not decomposable to, or an aggregation of, individual performances." That is a statement with which Wong and colleagues also seemingly agree (p. 6), yet maybe one that has not yet been fully incorporated into their assembly theory. Further, structure and function are not additive, but complementary. Otherwise, the information building up in a complex system would overwhelm the life form(s) directing it, as has been found with teams of highly sophisticated scientists [11]. Complementarity allows for tradeoffs to occur; but it also introduces a loss of information (Shannon holes) and uncertainty into every process even as it provides the (entropy) tools to manage both.

Innovation. Campaigns against corporations increased last year, reaching an "all-time record for activity in Europe and APAC" (APAC is the Asia-Pacific nations that encompass approximately 62 countries), indicating a search for vulnerabilities in 2023 by activist investors, the busiest year on record with 252 campaigns by activists worldwide. These activists were seeking to improve the performance of the firms they held investments in, but attacked their leadership because they felt that these firms were under-performing.³⁴

³⁴ Lazard's Annual Review of Shareholder Activism 2023; <https://www.lazard.com/research-insights/annual-review-of-shareholder-activism-2023/>

Campaigns occur against universities, too. After the attacks by Hamas against Israel on October 7, 2023, antisemitism eruptions occurred across many university campuses. Subsequently, recent attacks against the Congressional testimony provided by the Presidents of the University of Pennsylvania, Harvard and MIT led to the resignation of the President of the University of Pennsylvania and, eventually, the new President of Harvard. The center so far has held at MIT, but not at Harvard.^{35,36}

5. Conclusions

The results supported our hypothesis: entropy from the uncertainty in the time needed to execute a decision that fits within the uncertainty of the energy available are strongly correlated, indicating an interdependent relationship. That is, as the time needed to complete a process reduces, more available energy is required to operate a process successfully. This need for more and more available energy motivates organizations to combine in mergers that both increase size in a market but with the goal of having a net of fewer members,³⁷ especially when a market is consolidating.³⁸

To operate a team or business well, speed in making decisions is a critical factor [32]. In contrast, being unable to execute quickly possibly indicates an increase in an organization's administration bureaucracy, a sign of a poorly run business.³⁹

From de León and colleagues addressing evolution [37], interdependence between humans and their technology derived from innovation leads to their co-evolution.

But by suppressing interdependence, authoritarian regimes function at a technological disadvantage, motivating their need to steal ideas from freer, more competitive nations operating in open societies just to be able to keep pace with the ability of democracies to race ahead with innovations.

We again showed the value of a mathematical approach to interdependence for human-machine teams, which we have presented as occurring with three effects in reality: Bistability; a Measurement problem; and Non-factorable information. In the past, we have shown that the value of interdependence is in parsing the tradeoffs between structural entropy production (SEP) and maximum entropy production (MEP). Now we have generalized those earlier results to uncertainty in the time-entropy-energy tradeoffs for teams. However, we made one claim that we need to follow up in our next study:

H-2: The reduction in the *dof* to achieve least SEP should be accompanied by an increase in the *dof* in the output for teams achieving maximum entropy production in their output (MEP).

Hypothesis H-2 leads to a new one, H-3, that we also want to explore in the future:

H-3: As uncertainty in the speed of decision making is significantly reduced to a minimum for a team (or organization) to better compete, the size of the organization is increased (we speculate that this hypothesis may be backwards).

³⁵ "It's crucial that we bridge the fissures that have weakened our sense of community..." Harvard's Interim President Alan M. Garber, Harvard Crimson, <https://www.thecrimson.com/article/2024/1/9/garber-first-message/>

³⁶ W.B. Yeats (1923), line 3: The second coming: Things fall apart; the centre cannot hold

³⁷ E.g., In its new acquisition, Blackrock plans to lay off 600 people; in Pitcher, J. (2024, 1/12), "BlackRock to Buy Global Infrastructure Partners for \$12.5 Billion. The acquisition would be BlackRock's largest in 15 years," Wall Street Journal, retrieved 1/15/2024 from <https://www.wsj.com/business/deals/blackrock-to-buy-global-infrastructure-partners-for-12-5-billion-22f8e3d9>

³⁸ Cooper, L.; Thomas, L.; Morene, B. (2024, 1/5), "Southwestern, Chesapeake Near \$17 Billion Merger. Combination of natural-gas producers could come together as soon as next week," Wall Street Journal, retrieved 1/12/2024 from <https://www.wsj.com/business/energy-oil/southwestern-chesapeake-near-17-billion-merger-24d7372d>

³⁹ E.g., by taking "out layers of excess staff," Citigroup is restructuring to improve its competitiveness; see Baer, J. (2024, 1/12), "Citigroup Plans to Cut 20,000 Jobs. Reductions will amount to about 10% of bank's workforce, excluding a Mexico business," Wall Street Journal, retrieved 1/15/2024 from <https://www.wsj.com/finance/banking/citigroup-plans-to-cut-20-000-jobs-71619fd0>

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