Foundations of Autonomy and Its (Cyber) Threats: From Individuals to Interdependence: Papers from the 2015 AAAI Spring Symposium

A Thermodynamics of Teams: Towards a Robust Computational Model of Autonomous Teams

W.F. Lawless[1]; Ira S. Moskowitz[2]; Ranjeev Mittu[2]; and Donald A. Sofge[2]
[1]Paine College, 1235 15th Street, Augusta, GA, wlawless@paine.edu
[2]Naval Research Laboratory, 4555 Overlook Avenue SW, Washington, DC;
{ira.moskowitz; ranjeev.mittu; donald.sofge}@nrl.navy.mil

Abstract

One of the great puzzles in social science is the failure of rational models of teamwork, a rising concern for Artificial Intelligence researchers. Social learning theory (i.e., rewards and punishments; associations; modelling) works partially with individuals, but not with teams. These theories of methodological individualism, including, but not limited to, game theory, have also failed to advance the field of economics. To address interdependence, the phenomenon central to teamwork, we explain why game theory, the first to study interdependence mathematically, has failed. As an alternative, we offer a non-rational theory composed at this time of three parts: quantum mathematics for interdependence (e.g., interference); biology for population effects; and min-max entropy production as a metric of good and unsatisfactory team performance for humans or artificial agents (with min entropy production as LEP, and maximum entropy production as MEP). We report on three mathematical breakthroughs: First, that the interdependence between an individual's observations and actions, once measured, breaks the link known as intuition, leading to the measurement problem of incompleteness, accounting for the failure of survey instruments to predict human action; second, that at the team and larger levels of analyses, the ill-effects on min-max entropy production of consensus-seeking rules and authoritarian leadership serve to suppress the search for solutions to the problems that teams work to solve; and third, as a speculation to integrate group decision-making and a team's emotions: with LEP as a team's ground state versus a team with internal conflict at an elevated LEP state.

Introduction

Based on last Spring's presentation at AAAI (Lawless & Sofge, 2014), that to achieve robust intelligence, we believed that two teams competing against each other are required to best determine the reality of a situation (i.e., situational awareness). Countering the prevailing assumptions about observation and action, until recently, we concluded that individual behavior was a curiosity for the theory of teams because what is learned about individuals transforms unpredictably during states of interdependence. We now believe that individual mobility determines the decisions, power and outcomes of teams, firms and organizations (see Fig. 2 and our revised conclusion in this paper).

In its simplest terms, teams and firms operate thermodynamically far from equilibrium, requiring sufficient free energy to offset the entropy produced as a byproduct of their activities (Nicolis & Prigogine, 1989); we add that teamwork can husband or squander scarce resources, but when successful, can multiply them. If social reality was rational, a model of team thermodynamics would have been discovered and validated decades ago. However, teams are interdependent systems (Conant, 1976), interdependence creates observational uncertainty (Lawless et al., 2013), and the measurement of interdependence collapses it to create situational incompleteness, manifestly irrational effects.

Multitasking (MT) is an unsolved but key theoretical problem for organizing teams, organizations and systems, including computational teams of multi-autonomous agents. Because MT involves interdependence between the members of a team, until now it has been treated as a hindrance or too difficult to conceptualize and adequately address. Exceptional and talented humans intuit most of the organizational decisions necessary to self-organize a business or organization, except possibly when faced with the challenge of decision-making in the context of big data. Even for big data where interdependence can increase uncertainty and measurement can generate incompleteness, unless scientists can construct valid mathematical models of teams and firms that produce predictable results or constrain them, computational teams of multi-agents will always be ineffective, inefficient, conceptually incomplete, or all three. Llinas (2014, pp. 1, 6) warned about interdependence:

> for action among the fusion, cognitive, decision-making, and computer-science communities to muster

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> a cooperative initiative to examine and develop [the] … metrics involved in measuring and evaluating process interdependencies … [otherwise, the design of] modern decision support systems … will remain disconnected and suboptimal going forward.

While individuals multitask (MT) poorly (Wickens, 1992), multitasking is the function of groups pooling skills to accomplish goals they are unable to accomplish as individuals (e.g., Ambrose, 2001). But MT creates a state of interdependence that has been conceptually intractable (Ahdieh, 2009). Worse, for rational models of teams, using information flow theory, Conant (1976) concluded that interdependence is a hindrance on organizational performance. Kenny et al. (1998) calculated that statistically including the effects of interdependence causes overly confident experimental results. And unable to resolve the persistent gap he had found between preferences before, and the choices made as, games were played, speculating that the gap could not be closed, Kelley (1992) abandoned game theory in experimental social psychology for the nebulous theory of close relationships. Never has anyone closed this gap, nor do we; instead, we see this gap as a social resource to be exploited. Assuming that interpretations of reality are generally stable and accessible (i.e., two tribes agree that a waterfall exists at coordinate *x,y*), we note that in Moskowitz et al. (2014), Conant's ideas on interdependence are modified and extended in an information theoretic approach and developed into the idea of "Team Efficiency". This is a normalization of certain key concepts from Shannon. Furthermore, Moskowitz and his co-authors develop a Second Law of Team Dynamics. Additionally, they modeled team knowledge flow via epidemiological models from Network Science.

But social reality is not stable. Many of the claims advanced by game theory have not been validated (e.g., those for cooperation and competition in the Prisoners Dilemma Game; in Schweitzer et al., 2009), likely because its models do not model social reality, conceded by two of its strongest supporters (e.g., Rand & Nowak, 2013). Despite this disconnect with reality, Rand and Nowak (p. 413) conclude that cooperation produces the superior social good, a conclusion widely accepted by social scientists, including Bell et al.'s (2012) review of human teamwork. Within the computational multi-robot community (e.g., Schaefer, 2014), no one appears to be close to addressing the problems caused by interdependence in self-reported questionnaires; e.g., in a 30-year meta-analysis, Baumeister et al. (2005) found only a negligible correlation between self-reported self-esteem and performance at college or work. We claim that observations and self-reports are <u>*insufficient*</u> to capture human behavior observed "in the wild", let alone the principles of organization of teams and firms. In stable reality, how a team forms mathematically, how structural perfection is recognized, and what happens after formation is indeterminate.

The conclusions drawn from rational models, especially game theory, have, by and large, overvalued, misunderstood and misapplied the notion of cooperation, contradicting Adam Smith's (1977) conclusions about the value of competition between, and cooperation within, teams. Axelrod (1984, p. 7-8), for example, concluded that competition reduced social welfare. This poor outcome can be avoided, Axelrod argued, only when sufficient punishment discourages competition. Taking his advice to its logical extreme, we should not be surprised to see brutality highlighted as a technique to govern non-free societies by forcing citizens therein to cooperate (e.g., Naji, 2004).

We disagree with Axelrod and game theorists. Interdependence creates alternate perspectives; free speech encourages adherents to compete for their beliefs (e.g., Justice Holmes, 1919) or policies; e.g., per Justice Ginsburg (2011), "… as with other questions of national or international policy, informed assessment of competing interests is require".

By comparing night-time satellite photos to see the social well-being in competitive South Korea compared to its lack (North Korea very dark at night) under the cooperation brutally enforced by the leaders of North Korea (Lawless, 2014, slide 10), our theory has led us to conclude that, rather than a hindrance, interdependence is a valuable resource that societies facing competitive pressures exploit with MT to self-organize teams able to solve intractable problems, to reduce corruption and to make better decisions. The key to exploiting interdependence is to construct centers of competition, which we have borrowed from Nash and relabeled as Nash equilibria (NE), like Google and Apple, Democrats and Republicans, or Einstein and Bohr. NE generate the information that societies exploit to better organize themselves, be it for competition among politicians, sports teams, businesses, or entertainment. As proof, the first action of illegitimate societies, those managed by authoritarians or gangs, is to suppress opposing conflict centers on the way towards enslaving its people (Lawless et al., 2013; e.g., China, from Wong, 2014; Russia, from R&O, 2014, 11/13; and Cuba's enslavement of its people, from O'Grady, 2014; but this may also apply to the Pope, from Yardley, 2014).

The belief in the ubiquitous value of cooperation has led to strange bedfellows. Consensus-rules (CR) govern many of the decision processes used by the ruling levels of the Communist Chinese party (White, 1998); gangs (Lawless et al., 2013); and the National Academy of Sciences (NAS; e.g., <u>dels.nas.edu/global/Consensus-Report</u>). CRs attempt to increase information by reducing the barriers to participation in a discussion among the parties to a decision (Fiore, 2014), but at the expense of failing to compete for the best available argument (Lawless et al., 2014). There are several weaknesses with CR decisions: first, it allows weaker arguments to be on an equal footing with stronger ones, making it impossible to test the strength of the ideas in play; another weakness is that CRs increase the likelihood of mistakes; and CRs empower minorities, such as autocrats.

Returning to the examples that we gave, in the case of gangs and China, the Communist rulers use gangs when it serves their needs: "Several times in October officers appeared to stand aside as triad gangsters attacked protest sites" (R&O, 2014). As an example for the NAS, many authors have addressed the benefit of its climate consensus (e.g., Oreskes, 2004). From the NAS report in 2001: "Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise" (NAS, 2001, p. 1). Yet this prediction turned out to be a mistake (see news accounts by Kintisch, 2014; Tollefson, 2014; to see another mistake regarding the climate consensus, such as the "Himalayan glaciers would vanish by 2035", see Victoriano, 2014).

As a final weakness for CRs, a minority governs by blocking progress on reaching a decision. Because of this pernicious nature of CR, the EU has expressly rejected them (WP, 2001, p. 29):

> 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."

Subsequently, we have relabeled CRs as "minority" rules (Lawless et al., 2014). Nonetheless, cooperation is vital to teamwork, especially when faced with well-defined problems (e.g., sports); and when faced with ill-defined problems, conflict can produce more creative solutions (Hackman, 2011).

We go much deeper to understand why game theorists, with their inferior models of reality, take strong exception to competition by rejecting its value to free societies. We believe the reason that most scientists are unable to readily "see" the root of the MT problem and its solution is that human behavior operates in a physical reality socially reconstructed as an illusion of a rational world (Adelson, 2000). That is, the brain has a sensorimotor system independent of vision (Rees et al., 1997; we use independent to mean a correlation of zero), the two working together interdependently to create what appears to be a "rational" world, but is actually bistable (Lawless et al., 2013), meaning that as an individual focuses on improving one aspect of itself, say action (e.g., skills), its observational uncertainty increases. Zell's (2013) meta-analysis supports our hypothesis: He found that the relationship between 22 self-reported scales of ability with actual ability to be moderate at best. Similarly, Bloom et al. (2007) found only a poor association between the views of the managers of businesses and the actual performance of their businesses. These poor associations, we argue, follow from measuring an interdependent state, thereby collapsing it and increasing uncertainty.

Next we review our mathematical model of a team. The interdependence between team members allows us to sketch conceptually and mathematically how the tools of entropy production may be deployed in a nonlinear model of teams and firms to construct metrics of performance.

Mathematical model

Briefly, from Ambrose (2001), teams form to solve the problems that an arbitrary collection of individuals performing the same actions are ineffective at solving, including through multi-tasking (MT) in competitive or hostile environments. Firms form to produce a profit (Coase, 1937); generalizing, teams or firms stabilize when they produce more benefits than costs (Coase, 1960).

But the mathematics that follow, while straightforward, are counterintuitive for individuals because we humans think rationally (i.e., linearly). We combine quantum mathematics (matrix algebra of two community operators that convert into Fourier pairs to account for the incompleteness of situational awareness; from Cohen, 1995); uncertainty relations (information flow in orthogonal models of teams; from Gershenfeld, 2000) and biology (the movement of individuals between different teams can be tracked with limit cycles in Lotka-Volterra type equations; from May, 1973). The results, unexpected breakthroughs, are metrics that, in the limit, represent Least Entropy Production (LEP; see Nicolis & Prigogine, 1989]) and Maximum Entropy Production (MEP; Martyushev, 2013).

Given that observation and motor activities are controlled in the brain by independent systems (i.e., zero correlations), assume that human behavior occurs in physical reality, while observations are reconstructed as interpretations (e.g., beliefs; situational awareness; illusions; from Ahdieh, 2009; or mistakes; from Graziano, 2013). Assume that the opposed beliefs of each human agent cause oscillations (Fig. 1).

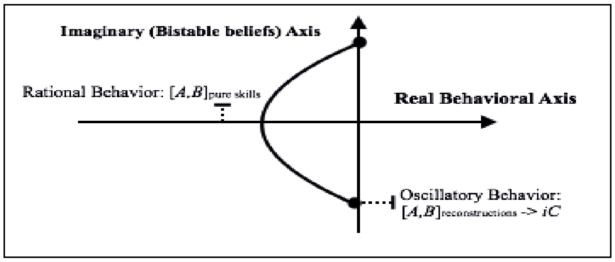

Figure 1. The real axis displays real behavior while the imaginary axis displays the social reconstruction of reality. The two end points for imaginary beliefs reflect oscillatory dynamics (e.g., rules in 2005 to govern the Nuclear Regulatory Commission's oversight of the Department of

Energy's High-Level radioactive Waste tank closures from about 2007-2011 led to endless debates between NRC and DOE until citizens recommended that the tanks be closed; in Lawless et al., 2014). Rational behavior produces no oscillations; the curve between the imaginary and rational axes reflects dynamics increasingly dampened as the real axis is approached (i.e., where rational means linear thinking; and where reaching the real axis happens when opposing teams are more likely to agree).

Bistable interdependence occurs between action and observation, and between competing claims. Socially reconstructed reality, as an illusion, is challenged by those with opposing interests, causing social dynamics (Lawless et al., 2013). An example (Buckley, 2014):

> The Chinese government rejected the Pentagon's claim that a People's Liberation Army fighter jet had buzzed dangerously close to an American surveillance plane in international airspace, and it warned that frequent surveillance flights were risking an accident near the Chinese coast.

We model bistability with signal detection theory (SDT) applied to two operators, *A* and *B*, to represent competing tribes. When two erstwhile competitors agree, their combined social system is stable, no oscillations or limit cycles exist (the goal of an autocracy), and their operators commute:

$$[A,B]=AB\text{-}BA=0 \tag{1}$$

But with disagreement between two competitors, the operators do not commute (i.e., their eigenvalues are not equal), indicating orthogonality, causing oscillations:

$$[A,B]=i\mathrm{C} \tag{2}$$

where *C* measures the "gap" with rotational distance in reality between *A* and *B*. However, for a team, as MT improves, the tradeoffs internal to each group's focus on tasks interferes with the bistable interpretation of how best to improve performance, motivating tradeoffs; converting equation (2) into (3) (from Cohen, 1995):

$$\sigma_{A\text{-}Skills}\sigma_{A\text{-}Interpretations} \geq \frac{1}{2} \tag{3}$$

where $\sigma_{A\text{-}Skills}$ is the standard deviation of variable *A* over time, $\sigma_{A\text{-}Interpretations}$ is the standard deviation of its Fourier transform, the two forming a Fourier pair that reflects tradeoffs between the physical reality of skills and the social interpretation of situations. For example, from equation (3), as uncertainty in a team's or firm's skills decrease (e.g., improved MT skills), uncertainty in its interpretations increase (i.e., poorer situational awareness), requiring that a team engage a relatively dispassionate observer as a coach to address a team's problems.

Before we proceed, let us compare our sketch with reality. Equation (2) captures disagreement in social processes, whether a process is political, judicial or scientific, but the result being insufficient for social dynamics. We assert that individuals committed to their beliefs more or less remain committed to them over time. If all individuals are committed to one side or the other, conflict ensues (Kirk, 2003). We further claim that neutrals can enter into a state of interdependence with both sides, somewhat like quantum entanglement, allowing them to process both sides of an issue. Neutrals not only moderate conflict, they usually decide elections (e.g., see the chart at NYT, 2010). If true, the competition for neutrals generates limit cycles modeled with Lotka-Volterra-type equations. We show as evidence the race to win the Senate and the House in 2014 (i.e., http://tippie.uiowa.edu/iem/).

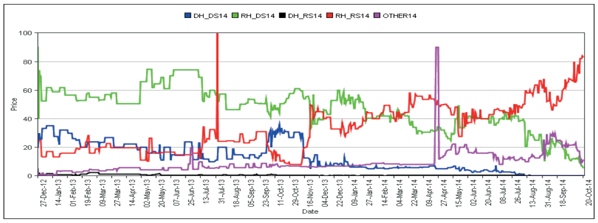

Figure 2. Results of the recently complete race to control both Houses of Congress. Notice the primary limit cycles (red and green curves) from about mid-November 2013 until about mid-July 2014. We claim that during this time when interdependence governed, predictions were often made, but were unrealistic. Once neutrals have made a decision, in this case, post mid-July 2014, predictions became increasingly credible (chart from https://iemweb.biz.uiowa.edu/graphs/graph_Congress14.cfm).

Equation (2) can be mathematically converted into Heisenberg's Uncertainty Principle at the atomic level, into another uncertainty relationship (Gernshenfeld, 2000), or into equation (3) as was done by Cohen (1995) for signal detection theory (SDT). Based on Adelson's (2000) work with illusions, we claim that humans cannot improve on SDT for their sensory perceptions; e.g., humans easily misjudge the checker-square illusion even as photometers do not. Cohen (1995, p. 45) concluded for SDT that a (see Fig. 3):

> 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.

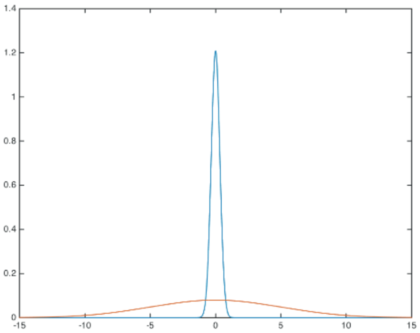

Figure 3. The smaller Gaussian at the bottom is Fourier transformed to the top one. While the Standard deviation for the smaller one is 0.33, that for the second one has increased to about 5.0; the two multiplied together roughly constitute a constant value greater than 1/2.

As an example of skills coupled to awareness that supports bistability, firms like Arthur Anderson, the auditor of Enron in 2000, missed the collapse of a business they were auditing; today, KPMG is accused of having repeated this mistake (Kowsmann et al., 2014): "KPMG Faces Criticism for Espírito Santo Audit Work. Bank's Collapse Raises Questions Whether KPMG Should Have Detected Problems Earlier." Thus, equation (3) accounts for the failure of intuition, our first breakthrough.

Entropy Production

Zipf (1949) concluded that "Frequent behaviors become quicker and easier to perform over time." How does Zipf's idea fit with teams? Interdependence represents a unique reduction in individualism (Kenny et al., 1998) that reduces the degrees of freedom (*dof*) in a social group. Given ρ, for interdependence (equation 4, below):

$$\varrho=\frac{\left(MS_{GT}\text{ -}MS_{SGT}\right)}{MS_{GT}+\left(N\ 1\right)MS_{SGT}} \tag{4}$$

MS_{GT} is the sum of the mean squares from the group on a measurement of an arbitrary, self-reported factor, T, such as a culture, an issue, or a problem that is a group's focus as it assigns roles to produce MT; MS_{SGT} is the aggregated contribution from the individuals on a measurement of factor T; and N represents the number of members in a group being measured (from Kenny et al., 1998, p. 235). At one extreme, ρ ranges to -1 as MT goes to zero when the group is replaced by a collection of independent individuals; or ρ can range to +1 as MT replaces the individuals with subservience to a group's efforts, like groupthink or authoritarianism.

If a team functions to reduce *dof*, setting Boltzman's constant k to 1 (independent of the logarithm's base):

$$\log(dof_{Teammates})<\log(dof_{\sum Individuals}) \tag{5}$$

Assuming that when a set of tasks performed by the least number of individuals forms a complete circuit (or complete network graph) to MT (for a restaurant, assume this means five individuals: a waiter, cook, dish washer, cashier and manager; similar arguments can be made for autonomous multi-UAVs), then a group is converted into a team with the least entropy. (Later, we discuss that a perfect team is in a ground state; i.e., when no task conflict or role conflict exists, a perfect team resides in the lowest emotional state possible as it performs its tasks).

Balch (2000) used low information entropy as a principle for multi-agent teams. But he overlooked the interdependence involved in MT. Guided by Balch that three slaves make a unit group, log 3/3 = 0; from him, three independent individuals give an entropy of 3*1/3 log 1/3 = 1.584. In contrast, using graph theory (Smith, 2014), we calculate that a team of independent individuals interdependently completing a circuit to allow the team to multitask, like the different roles played by the independent members of a baseball team, gives the minimum or least entropy production (LEP; Nicolis & Prigogine, 1989).

Returning to equation (3), we revise it to give us the standard deviation of LEP times the standard deviation of MEP (maximum entropy production; from Martyushev, 2013). Taking limits, as σ_{LEP}-> 0, we find in the limit that lim(σ_{MEP})=∞. This result means that as teamwork improves to a maximum, i.e., as entropy of teamwork goes to zero, MEP reaches a maximum. In other words, at MEP, the best teams are able to perform a maximum search of the environment for solutions to difficult problems, our second breakthrough.

Moreover, reversing the limits, as σ_{LEP}-> ∞, σ_{MEP}->0, an unexpected finding that reinforces our second breakthrough. It means that as teamwork becomes dysfunctional, possibly due to suppression, the zealous enforcement of consensus rules or authoritarianism, random exploration and stochastic resonance stop (i.e., RE&SR). This accounts for the Department of Energy's use of ordinary cardboard boxes as its primary disposal container of solid radioactive wastes until the whistle was blown on it in 1983 (Lawless, 1985); it accounts for the huge environmental problems in China today (Lawless et al., 2013); and it accounts for the inability of youth in gang-controlled areas to flourish in school. As a simple test, using patent applications over the last thirteen years (the data is from USTPO, 2013), we looked at Israel's applications filed in the US with whether or not it was experiencing an Intifada (-1), peace (0) or hostilities (+1), finding a significant correlation (r=0.53, p<.05, two-tailed test), suggesting that internal conflict like an Intifada reduces MEP (i.e., RE&SR).

Discussion

For future research, if the min state for an optimal team forming a circuit is LEP, controlling for the team's energy needs that we assume are satisfactory, LEP becomes the team's ground state, allowing it to generate MEP as a result (where we assume that MEP reflects the maximum searches across all solution spaces).

On the other hand, if, for example, in a divorce, both partners are placed into an elevated or “excited state", MEP reduces to zero. Working backwards from this answer means that the team's LEP goes to maximum as internal conflict forces a team to splinter. In business, the result is like the 300 stores that Sears plans to spinoff (Kapner & Dulaney, 2014); in city government, it’s a bankruptcy like Detroit (EB, 2014); or in Palestine, it's an internal battle for control; e.g., from the *New York Times* (Casey, 2014).

> ... signs in recent days indicate Hamas is having difficulty controlling hard-line militants in the territory. Last Friday, a rocket was launched at Israel, which Hamas officials blamed on outside extremists that they said were later arrested. ... Earlier this year, Hamas and Fatah, which dominates the Palestinian Authority-run West Bank, agreed to form an administration of technocrats to govern both Palestinian territories. Friday’s attacks dealt a blow to hopes of implementing that deal, which was delayed by Hamas’s 50-day war with Israel. ... Last month, the international community pledged $5.4 billion in aid to help rebuild the Gaza Strip after this summer’s war. Most of the donors, including the U.S. and the European Union … want the Palestinian Authority to control the enclave before writing their checks."

Thus, fragmentation is a common, but important link (Lawless et al., 2013). From the *Wall Street Journal* (Hope, 2014)

> At the same time, the Securities and Exchange Commission was pushing to increase competition among exchanges and encourage more electronic trading. As a result, stocks now can be traded on 11 exchanges and more than 50 privately run trading venues and dark pools in the U.S. The NYSE runs three stock exchanges and two options exchanges. "The biggest issue is to reduce the fragmentation and get more trading back on the exchange," Mr. Thain says. "How do you get more of the stock to trade on the NYSE again?”

Conclusion

Based on last Spring’s presentation on robust intelligence and this paper, we revise our conclusions to the following that robust intelligence is more or less likely if and only if bistable agents are allowed to work as follows (see slides by Lawless & Sofge, 2014, 3/25; presented at AAAI-Spring 2014; now revised):

1. For an individual bistable agent, computational robust intelligent MT is unlikely to occur (producing a higher than satisfactory LEP), precluding robust intelligence, autonomy, and thermodynamic effectiveness (e.g., productivity); these require the self-organized MT of a team;
2. For a team of bistable agents, bias reduces robust intelligence and autonomy; robustness requires a team of MT observing *Reality* against an opposing team (two teams of MTs best capture the reality of a problem; i.e., situational awareness), implying the value of competition to determine *Reality* and cooperation to reach a compromise, but insufficient for robust intelligence and autonomy;
3. With two equally balanced MT teams, thermodynamic effectiveness (productivity) and autonomy strengthen (decreased LEP, increased MEP); but robust intelligence requires three teams (two opposing MT teams to construct *Reality* and a neutral team of freely moving bistable independents attracted or repelled to one team or the other to determine the team outcomes (e.g., decisions); this interplay affects the thermodynamic forces resulting in the outcomes shown in Figure 2);
4. Given two teams, adding a third team to constitute a spectrum of neutrals who invest freely (properties, ideas, works), act freely (joining and rejecting teams), and observe freely make the greatest contribution to robust intelligence, to mitigating mistakes, and to maximizing effective and efficient autonomy (i.e., optimum LEP implies perfectly matched members to form a stable team, allowing MEP to imply optimum RE&SR -> maximum robust intelligence by a team to address and solve problems or to innovate).

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