The Mathematics of Aggregation, Interdependence, Organizations and Systems of Nash Equilibria: A Replacement for Game Theory

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Abstract

Traditional social science research has been unable to satisfactorily aggregate individual level data to group, organization and systems levels, making it one of social science's biggest challenges (Giles, 2011). For game and social theory, we believe that the fault can be attributed to the lack of valid distance measures (e.g., the arbitrary ordering of cooperation and competition precludes a Hilbert space distance metric for the ordering of and gradations between these social behaviors, making game theory normative). Alternatively, we offer a theory of social interdependence with countable mathematics based on bistable or multistable perspectives and linear algebra. The evidence that is available is supportive. It indicates that meaning is a one-sided, stable, classical interpretation, not only making the correspondence between beliefs and objective reality in social settings incomplete, raising questioning about static theories from earlier eras (i.e., Axelrod's evolution of cooperation; Simon's bounded rationality). The result indicates for open systems (democracies) that interpretations evolve naturally to become orthogonal (Nash equilibria), that orthogonal interpretations generate the information to drive social evolution, but that in closed systems (dictatorships), dependent on the enforcement of social cooperation and the suppression of opposing points of view, evolution slows or stops (e.g., China, Iran or Cuba), causing capital and energy to be wasted, misdirected or misallocated as leaders suppress the interpretations that they alone have the authority to label as unethical, immoral, or irreligious.[1] We conclude that a mathematics based on NE is feasible.

Introduction

Interdependence has long been regarded as the *a priori*, but elusive force at the center of social interaction (Jones, 1990). The first computational model of interdependence was in game theory, but it is static (Von Neumann & Morgenstern, 1955, p. 45). "Repeated games" were designed to make games dynamic (Luce & Raiffa, 1967). But their interdependent nature remained static, even when repeated rapidly over time, producing unsatisfactory results in social laboratory experiments (Jones, 1998). Other more fundamental criticisms of games exist. Traditionally, social theorists consider interdependence a hindrance to the independence between subjects that is necessary for experimental replication (Kenny et al., 1998), but this practice has kept the theory of social interdependence from advancing. Barabási (2009) and others (reviewed by Jasny et al., 2009) believe that a new theory of human behavior is needed to better understand "the systems we perceive as being complex ... [by understanding] the dynamics of the processes ... [to] form the foundation of a theory of complexity." (p. 413)

First, the values inherent in the choices selected by scientists and offered to "players" are arbitrary; second, these choices favor "cooperation" over "competition", which has been attributed to non-scientific influences, such as culture, religion and anti-free market ideology (Lawless et al., 2010a). Possibly accounting for the prevailing support among academics for collectivism over individualism, the source of anti-free market ideology, Klein and Stern (2007) found that Democrats typically outnumber Republicans at elite universities by at least six to one among the general faculty, with even higher ratios in the humanities and social sciences; this bias makes the approval of re-

[1] China has failed "… to provide evidence of increasing efforts to combat human trafficking, particularly in terms of punishment of trafficking crimes and the protection of Chinese and foreign victims of trafficking … the enormous size of its trafficking problem and the significant level of corruption and complicity in trafficking by some local government officials …" (CIA World Factbook, 2011).

search by Institutional Review Boards subjective (Ceci et al., 1985): "…the guise of objective scientific standards permits the rejection of proposals whose real offense might be their social and political distastefulness to IRB members." (p. 1001).[2,3]

Axelrod (1984, p. 7), for example, claimed without evidence external to toy games that competition (i.e., Nash equilibria) led to the worst of social welfare outcomes: "the pursuit of self-interest by each [participant] leads to a poor outcome for all" that can be avoided when sufficient punishment exists to discourage competition, a debate that continues in the journal *Science* today not over the validity of game theory (e.g., in support of games, see Rand et al., 2009; not supporting games, see Sanfey, 2007), but rather over whether cooperation is promoted more from punishment than reinforcement. Yet, the available physical evidence since Hayek (1944) contradicts Axelrod's claims; e.g., national competitiveness is associated with improved social welfare and lowered perceptions of corruption (Lawless et al., 2010b); in fact, the more consensus seeking is a society, the more likely it is governed by a dictatorship (viz., China's minority ruled government[4]). When the focus shifts to whether games are valid, games have been found to be unsatisfactory (Schweitzer et al., 2009).

Third, but more importantly, neither game theory nor social science has an adequate means of aggregating individual level data to group, organizational or system levels, [5] or, inversely, its disaggregation.

Aggregation

Aggregation remains unsolved almost 80 years after the formal mathematical study of interdependence in games not only because of the unknown mathematics that may be involved in constructing a formal mathematics of interdependence and its dynamics,[6] but also because of the conceptual difficulties in working with interdependence. To explain these conceptual difficulties from incomplete but natural rational convergence processes, Bohr claimed that humans could only interpret social interdependence with explanations that would always be insufficient (Bohr, 1955); his criticisms of games led Von Neumann and Morgenstern (1953, p. 148) to despair that if Bohr was correct, a rational model of the interaction would be "inconceivable" (also, Jones, 1990).

Hybrid group autonomy, organizations and teams composed of humans, machines and robots, are important to AI. Unlike the war in Iraq in 2002, the war in Afghanistan has hundreds of mobile robots aloft, on land, or under the sea. But when it comes to solving problems as part of a team, these agents are socially passive. Were the problem of aggregation and the autonomy of hybrids to be solved, robot teams could accompany humans to address and solve problems together on Mars, under the sea, or in dangerous locations on earth (e.g., firefighting; reactor meltdowns; and future wars). "Robot autonomy is required because one soldier cannot control several robots … [and] because no computational system can discriminate between combatants and innocents in a close-contact encounter." (Sharkey, 2008)

Yet, today, one of the fundamental unsolved problems in the social sciences is the aggregation of individual data (e.g., preferences) into group (team) data (Giles, 2011). The original motivation behind game theory was to study the interdependent effect of multiple agents on each other (Von Neumann & Morgenstern, 1953). What remains unsolved is what makes a group different from the collection of individuals who comprise the group. That the problem remains unsolved almost 70 years later is a remarkable comment on the state of the social sciences today, including game theory and economics. But solving this challenge is essential for the science and engineering of multi-agent, multi-robot and hybrid environments (i.e., humans, machines and robots working together).

Bonito and colleagues (2010) explain why aggregating individual information for human groups is unsolved: "What remains to be clearly elucidated, is how communication among members provides opportunities to make decisions that are not possible by examining only individual competencies, abilities, and motivations." We suspect that if aggregation cannot be solved for human groups, it will be more difficult to solve with AI for hybrid groups.

Aggregating data from teams is not direct: unlike an object in physical reality, each agent sees events in social

[2] From the *New York Times* (2011, 2/7), "Social scientist sees bias within", the social psychologist, J. Haidt, who studies morality and ideology, "argued that social psychologists are a "tribal-moral community" united by "sacred values" that hinder research and damage their credibility--and blind them to the hostile climate they've created for non-liberals."

[3] The approach to ethics may also increase subjectivity; e.g., from Resnick (2010), "… since research often involves a great deal of cooperation and coordination among many different people and different disciplines and institutions, ethical standards promote the values that are essential to collaborative work …"

[4] Minority rule underscores why autocracies prefer consensus, as in China; from White (1998, p. 472): "… hierarchy is relevant only if some enfranchised agent exercises a veto. If that member cannot be convinced by local colleagues to go along with a consensus, then the decision becomes subject to uncertainty from above. Various authors have called this procedure "management by exception", "delegation by consensus", or "the veto rule".

[5] The typical path from individuals to a group is the self-report using Likert scales, implying countable distances between, say, a preference affirming a belief or its disconfirmation, but these ordinal distances are entirely subjective, lacking in any arithmetic basis.

[6] Folk theory is the solution approach in repeated games that constructs a collective perspective by outsiders building a theory of mind with perspective taking of the collective as a tool for strategic thinking about the choices the collective will make; see Ely & Valimaki (2002); and Chwe (2010).

reality while embedded in different locations; agents are differentially collecting, sending or receiving information with other agents; and uncertainty is a factor in these different information flows.

For teams, we suspect that social uncertainty operates on two tracks. One is based on measurement, the other on probability distributions over allowed states. The first reflects physical characteristic of interdependence (bi-stability and multi-stability; e.g., two or more sides exist to every story), while the second reflects an incomplete knowledge about a system as its degrees of freedom increase.

Hybrid agent teams must be able to report on their situation. Reports by humans are often reduced to ordinal data (e.g., with Likert scales, say, from 1 to 6). But "[t]he notion that modern economic theory can be founded on ordinal utility theory is an error." (Barzilai, 2010, p. 2) The problem was illustrated well for human agents when (Bloom et al., 2007) no correlation was found between the productivity of organizations and the assessments by managers. Whether computational hybrid systems will be afflicted by the same problem is an open question. Below, we will propose a mathematics that we hypothesize is feasible.

In summary, the main problem with social science in general and game theory in particular is the use of static or repeated static situations (e.g., game configurations) at the individual level with arbitrary values offered as the choices available to participants, producing results that are unsatisfactory probably due more to a cultural bias from moral and religious confounds than from scientific proofs (Lawless et al., 2010a). A successful replacement theory must be independent of social values, mores and religion (i.e., not normative). It must be mathematically tractable and provable. And it must withstand empirical challenges. It must also be able to predict the value of competition used in social and scientific practices, principally independent scientific peer review (ISPR), which social science cannot, an indictment of traditional social science and economics. ISPR is highly regarded in social science (Shatz, 2004), but its use is based on empirical practices, not on theoretical grounds (e.g., Stern & Lee, 1992).[7] Hamilton (2009), for example, concluded "A reasonable hypothesis is that a robust social contract fostering academic freedom, peer review, and shared governance contributes significantly to the academic excellence of [American] universities."

Our theory is based on the fundamentals of interdependence. It presently meets most of the criteria above that we have established to test it, including with ISPR. What is incomplete at this time is the mathematical structure, which we sketch here, as well as its limitations. While incomplete, nonetheless, it demonstrates that aggregation and the countability of distance metrics prove Axelrod's theory to be wrong, but, in addition, Simon's (1992) theory of bounded rationality, social network analysis, and data mining (e.g., the failure to list Egypt as a fragile state by the World Bank[8], or CIA, may be attributed to the data mining of written texts and reports with conceptual distances that are not countable, such as Hamming distances[9]). In contrast, a functioning and valid theory of interdependence will not only improve social science, it will make a science of autonomy available to build autonomous teams of robots, machines and humans working and evolving together cooperatively, and competitively (Lawless et al., 2010a).

Mathematics

We begin with an information (entropy) theory approach. Assuming that an agent acts as a source of information, no information is generated when outcomes are certain. The mutual information between two agents is the amount that can be obtained by observing one and the other agents acting alone or together, and describes the amount of information shared between sent and received signals. Given $H(x)$ as the entropy generated by agent x and $H(x,y)$ as the joint entropy for agents (x,y), the conditional entropy is $H(x/y) = H(x,y) - H(y)$, and the shared or mutual information becomes

$$I(x;y) = H(x) - H(x/y) = H(x) + H(y) - H(x,y) \quad (1)$$

[7] Stern & Lee (1992) recommend peer review in post-Soviet states as a way to save essential human and data resources; use free inquiry for policy analyses; employ practices that have been demonstrated internationally in a variety of settings; reduce bureaucracy in decision-making; evaluate alternative interpretations of data; encourage critical thinking; and motivate a competition of ideas with open access to information. These justifications for peer review are based on practices that become more succinct in recent National Academy of Sciences publications; e.g., NRC (2006): "All reports undergo a rigorous, independent peer review to assure that the statement of task has been addressed, that conclusions are adequately supported, and that all important issues raised by the reviewers are addressed."

[8] World Bank (2007, 4/13) Global Monitoring Report on the Millennium Development Goals (MDGs). Confronting the Challenges of Gender Equality and Fragile States": assesses the contributions of developing countries, developed countries, and international financial institutions toward meeting universally agreed development commitments. It publishes an index of fragile states; however, Egypt was not listed as fragile. This oversight was repeated at the Fund for Peace's "failed state index", with Egypt listed as 43rd (www.fundforpeace.org); and with the CIA's World Fact Book, which concludes only that "A rapidly growing population (the largest in the Arab world), limited arable land, and dependence on the Nile all continue to overtax resources and stress society. The government has struggled to meet the demands of Egypt's growing population through economic reform and massive investment in communications and physical infrastructure. … [but] living conditions for the average Egyptian remain poor." (www.cia.gov/library/publications /the-world-factbook/geos/eg.html)

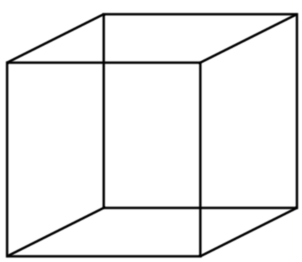
[9] van Rijsbergen (1979) uses cosine angles in vector spaces to determine the congruency between words, but with angles constructed by estimating the degree of congruence, not countable numbers, making it difficult to replicate (Song et al., 2010).

where $I(x;y)$ = {0 when x and y are independent; and $H(x)$, when x and y are mutually dependent}.

Information theory indicates that it is feasible for an organization to operate as a perfect algorithm, generating minimum entropy (Conant & Ashby, 1970), but not if the organization's control is based on feedback[10] (i.e., interdependently reactive). Based on Equation 1, competition generates more information from independence than cooperation; in contrast, an organization guided by a perfect algorithm controlling agents cooperating fully with management's dictates generates the minimum amount of information—the implication is that a perfectly run organization, based on information theory, becomes "dark" to observations of the background, including to itself (Lawless et al., 2011). Some organizations are dark on purpose (e.g., gangs, terrorists, undercover teams); however, their purposeful darkness "leaks" information from enforced cooperation (e.g., North Korea).

Research indicates that the social world is bistable (Figure 1), producing non-commutative effects between two interpretations of a single database, a common source of conflict, but one where its resolution produces knowledge (Von Neumann, 1961); e.g., politics, scientific peer review, courtroom arguments.

Figure 1. Necker cube illusion. It has two mutually exclusive interpretations, a cube pointing downward and to the left, or a cube pointing upward and to the right. One image of the Necker cube could represent, for example, belief in the value of Apple products, the other Google products; different religions; or different political positions. Viewing both interpretations simultaneously is not possible (Cacioppo et al., 1996).



Assume a vector operator, A, exists in Hilbert space (where distances between states can be measured exactly) that can fully describe an agent's state. The commutator of two operators vanishes for two agents with the same eigenvalue: $[A,B] = AB-BA = 0$. In this event, when a single worldview governs interpretations of reality, a common example is a dictatorship, a military operation, or a close-knit business firm.

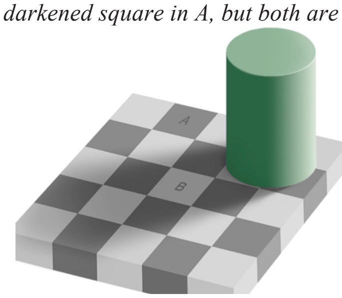
In contrast, for situations where different eigenvalues represent A and B, the commutator C is non-commutative:

$$[A,B] = iC \qquad (2)$$

We borrow the label of "Nash equilibria" (NE) to identify non-commutative situations. NE are found whenever and wherever social disagreements occur.

Based on the finding by Adelson (2000) using his checkerboard and other illusions, higher brain organizational processes were found to prevent the brain from performing as well as a photometer (see Figure 2), which easily discriminates among varying light intensities according to signal detection theory (SDT). We conclude that the individual brain does no better than SDT, a floor effect.

Figure 2. The Checkerboard illusion (Adelson, 2000). The brain construes the shadowed area in checker square B to be lighter than the darkened square in A, but both are equally dark.



This floor effect is foundational. With more uncertain decisions existing above the floor effect, humans operate in illusions caused by confirmation biases that establish the belief in their truth of a single worldview, and the intergroup bias that out-group beliefs are inferior; these two illusions drive social dynamics. Moreover, the floor effect allows us to shift from equation 2 to paired standard deviations of Gaussian distributions in SDT, where ρ_A is from a chosen Gaussian distribution and ρ_B its Fourier transformation (Cohen, 1995; Rieffel, 2007):

$$\rho_A \rho_B \geq ½ \qquad (3)$$

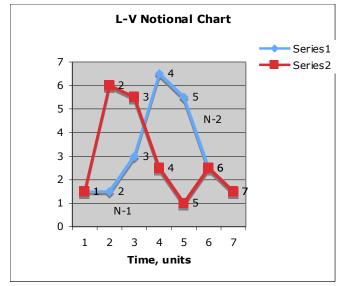
Equation 3 indicates that the variance in one factor is inversely orthogonal to the variance in the other factor. Evidence from multiple regressions using market data collected from across the stock market was supportive (Lawless et al., 2009). In a subsequent paper, we plan to develop the transformations between four sets of mathematically equivalent solutions: for planning and execution; organizational center of gravity and spatial frequency; size and volatility; and power and time.

Generalizing from biology (May, 1973), we assume that social power is a function of countable numbers of supporters, where power, P, and number, N, become:

$$P=f(N) \qquad (4)$$

[10] As an example of feedback after a social decision, the recall of Governor Gray Davis in California in 2003 led to the election of A. Schwarzenegger as his replacement (see *The New York Times*, 2003, Schwarzenegger Takes Oath And Vows End to Divisions, nytimes.com); similarly, "Mr. Alvarez easily won re-election in 2008 as mayor of Miami-Dade, the county of 2.5 million residents that includes the city of Miami. But a recall effort gained momentum last fall when he agreed to a budget that raised the county's property taxes while increasing pay to unionized public employees." (*The Wall Street Journal*, 2011, 3/15).

The problem becomes to link Equations 2 and 4. If $\rho_A \rho_B \geq \frac{1}{2}$ governs, applying it to decision-making indicates that as, for example, the variance in planning, ρ_A, increases, the variance in execution, ρ_B, decreases. For example, as uncertainty in road conditions on an expressway increase, as occurs when police stop a car ahead of others, approaching drivers slow to process the information. Similarly, when a fight occurs on a stage, passersby slow to observe, becoming an "audience" that will stop and watch the staged conflict for extended periods of time. Tying these ideas together, a political fight collects an audience of both ideologically pure "true believers" on one side offset by those on the other side, but it also includes neutrals. Both sides of a political conflict (Nash equilibrium) pitch their arguments to sway those neutral to both perspectives, not only giving neutrals the power to decide an election but also to moderate the conflict (Kirk, 2003). By counting those who are attracted to either one position or the other, then N_1 or N_2 form a limit cycle composed of countable elements (see Figure 3), where the oscillations are 90 degrees apart (Benincà et al., 2009).



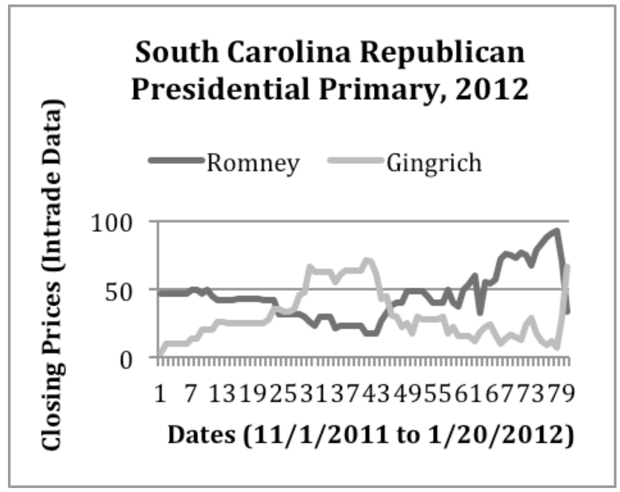


Figure 3 (from Lawless et al., 2010a). Instead displaying N_1 versus N_2 alone, the data are displayed with N over time, t. ***Above****: with arbitrary parameters, "frictionless" oscillations result (May, 1973). For an interpretation, at time 1 (and t = 3.5, 6 and 7), N_1 and N_2 are in direct competition. However, at time 2 (and t = 3, 4 and 5), the public has decided to act and social stability reigns.* ***Bottom****. Despite the notional nature of the data on the left, the campaign to become the Presidential nominee for the Republican Party models the public bets made on the Intrade Market (http://www.intrade.com) for Romney and Gingrich during two periods of intense competition (December 2011 and January 2012), indicating a collapse in Romney's support.*[11]

Finally, we represent the ideologues (operators) as being in either state *A* or *B*, but not both. In contrast, however, neutrals, can be in both states simultaneously as they engage the opposing arguments to process all of the available information. We represent neutrals in a superposition of states, reflecting interdependence, where

$$|\psi\rangle = a|0\rangle + b|1\rangle. \quad (5)$$

Equation 5 not only reflects an interdependent state where interference occurs in either constructive or destructive states, but also note that it is not a product state that can be factored. Interdependence represents a communication channel among agents in a state of superposition. Thus, any measurement of a neutral in a state of superposition generates an increase in uncertainty, meaning that any single "interpretation", such as the situational awareness of a military, business or political situation, is always misleading by being incomplete, accounting for the non-commutativity in Equation 2 and raises questions about Simon's theory of bounded rationality.

Bell's inequality. An unknown for us in the laboratory is interference: Can we demonstrate constructive and destructive interference while subjects are in a state of social interdependence? How far apart physically and separated in time can subjects be positioned while still being able to interdependently influence decisions (i.e., violating Bell's

[11] To model the parameters in 3-D with Monte Carlo estimates and as a means to control ι (Lawless et al., 2009b), we use the interaction rate equation: $\Gamma = N_{1,2} * N_\eta * f_{1,2:\eta} * v_{1,2:\eta} \exp(-\Delta A/\langle A \rangle) \approx \Delta x/\Delta t$, where η is for neutrals, *f* measures the frequency of belief or behavior matching, *v* measures information exchange rate, *exp (•)* measures the probability that an interaction will occur, and ΔA is the resources or skills required for an interaction and $\langle A \rangle$ is the average resources or skills available to conduct the interaction. Applied to a gang (DSS), *f* reflects resonance from the agreement between a gang's capabilities and its market opportunities (Spulber, 2009, p. 231); $v_{1\text{-}2}$ is the velocity of information exchanged between the gang, its competitors and the customers; and *exp(•)* is the probability of the interaction taking place based on the barriers or requirements for the interaction to occur ($-\Delta A$; e.g., higher barriers to market entry from the use of violence leads to fewer entrants into the market by competitive gangs) and the average wealth of the users available to consume an illicit drug from a target organization ($\langle A \rangle$; the better the average level of wealth of the users in the pool of illegal drug consumers available to a gang, the greater the likelihood of its success; e.g., Hollywood starlets are more attractive targets than mid-America).

inequality for partitions among three independent states, such as

$$(A, \neg B) \cup (B \neg C) \geq (A, \neg C) \quad (6)$$

where *A* affirms “Do you support conservatives”; *B* affirms “Did you vote in the last election”; and *C* affirms “Did you switch parties in the last election (i.e., were you a neutral)”? (As an illustration of how interdependence violates independence in the last series of elections, see the chart in: www.nytimes.com/2010/10/28/us/politics/28poll.html) Our approach to solving this problem is to carefully construct a protocol to identify neutrals by teasing apart the effects of consensus-seeking rules, to increase cooperation, from majority rules, to increase conflict.

Discussion

Our theory of social interdependence is superposition in the information medium surrounding an interaction (i.e., the context of a business plan, a political debate, or social entertainment). It is similar to entanglement. Both social interdependence and entanglement are fragile, both replace independence with communication among interacting units, and both produce counterintuitive results, especially under measurement conditions. For both interdependence and entanglement, the measurement of their non-independent and conjugate properties precludes an exactness in evaluating two coupled properties simultaneously, producing an exactness in one property (e.g., a business plan or a quantum particle’s position, respectively) as a tradeoff with the conjugate coupled property (e.g., plan execution or particle velocity, respectively), reflecting bistable uncertainties (see Figure 1 above). As examples of a measurement problem between agent self-reports and action, first, Baumeister and colleagues (2005) found a negligible association in a 30-year meta-analysis between self-reported self-esteem and objective measures of academic or work achievement. Second, the traditional theory of organizational interdependence has failed (Pfeffer & Fong, 2005); Pfeffer speculated that interdependent illusions between members offer a possible way to incorporate dynamics into organizational theory; Nash equilibria offer a natural way to challenge illusions, beginning with Equation 2, especially with peer review, accounting for the evolution of democracies and why dictatorships do not. And third, the whole purpose of democracy is to challenge illusions, dampening their adverse consequences; in contrast, the goal of dictatorships is to suppress Nash equilibria with the illusion that a suppressed people are incapable of self-governance, that checks and balances are inefficient, and that it is better for a people to become domesticated by gangs and thugs under the guise of “kings” and benevolent leaders.

Future Research

We plan to continue to develop the mathematics. We are also running laboratory experiments using 3-person and 5-person groups making decisions under rules that promote competition (majority rule) or cooperation (consensus or minority rule). In addition, we address Quorum Sensing; Biology; and Gaussian-Power Law Distributions.

Quorum Sensing (QS). Computational quorum sensing, a decentralized decision-making process used by bacteria and social insects to coordinate group behavior and to perform collective decision-making, provides a robust decentralized team coordination and collective decision-making paradigm for mobile autonomous teams performing complex tasks (Sofge and Lawless, 2011). Mobile autonomous systems capable of collaboration may provide significantly enhanced capabilities for recognizing targets, area searches, reconnaissance, and transforming enterprises with performance metrics. Future efforts will focus on refining QS-inspired approaches to interdependence such as collaborative tasks for multi-agent teams (like area searches and collective recognition), implementing these methods with autonomous system hardware, and testing autonomous teams under real-world conditions. Current implementations of artificial quorum sensing (outside of biology) are passive, like quorum sensing employed by bacterial colonies, in that the agents do not recruit to confirm their classifications. We will evaluate new recruitment strategies as identified in nature and tested in simulation, and potentially integrate these strategies into our agents’ QS policies. Key issues include the effect of disagreement in the collective decision-making process, and how the number of agents affects convergence times and accuracy in selecting the “best” policy. We plan to add social interference to increase uncertainty to generate bistable interpretations; to encourage teams to recruit new members; and to study mathematically the interference patterns in the limit cycles that result. In addition to metrics, we suspect that the key is to model communication, uncertainty, and interference among recruits and team members.

Biology provides many examples of interdependence in collaborative groups of individual agents. Swarm-based behavior control of autonomous teams focuses on understanding the techniques evolved and refined by nature for controlling flocks of birds, ant and bee colonies, and even schools of fish, and applying these techniques to coordinating control of a team of autonomous robots, or a team including both human and machine agents. A key issue is how much global knowledge is required, or whether the task can be performed efficiently using only local interactions (and only local knowledge) between neighboring agents. Another issue if what bandwidth (or quantity) of interagent communication is necessary, and what exactly needs to be communicated. For a multiagent team or enterprise performing an area search task, such as for surveillance or resource harvesting, we can improve upon the pure random walk strategy by utilizing biased walks, where two agents that meet can exchange information that influences the next walk taken by each agent. We plan to study whether refining the bias policy improves the overall effectiveness and efficiency of the team in performing the mission. We will investigate the integration of swarm-based behaviors with quorum sensing through stigmurgic communication combined with localized interagent communication.

Interdependent Walks. We are studying whether coupled random walks (e.g., Kempe, 2008; Peruzzo et al., 2010) are useful in "simulating" interdependent walks within and between organizations. In the field, we have found tradeoffs between Gaussian distributions, but other researchers have found power law distributions (Barabási, 2009); the difference between the two may be that shorter quantum walks break the social interference at each decision point to lead to Gaussian distributions, whereas a sequence of decisions under interference may lead to power law distributions. In the future, a starting point would be to compare a team of two random walkers against two interdependent walkers with one coin for consensus decisions and against another team of two walkers with an entangled coin.

Conclusions

Traditional social science research has been unable to satisfactorily aggregate individual level data to group, organization and systems levels, making it one of social science's biggest challenge, if not the most important (Giles, 2011). We believe that the fault can be attributed to the normative ordering of elements for the mathematics in game and social theory. As an alternative, we offer a theory with countable distances based on bistable or multi-stable perspectives patterned after quantum information theory. The available evidence is supportive. It indicates that meaning is a one-sided, stable, classical interpretation, making the situational awareness of a social situation incomplete, sweeping aside static theories from earlier eras (e.g., Axelrod's evolution of cooperation; Simon's bounded rationality; Kripke's theory of truth claims[12]). This indicates that in democracies, interpretations across a system evolve to become orthogonal (Nash equilibria), that orthogonal interpretations generate the information that uniquely promotes social evolution, but that in dictatorships, dependent as they are on enforced social cooperation along with the suppression of opposing points of view, social evolution stops or slows, such as in China, Iran or Cuba, misallocating capital and energy as government leaders suppress interpretations that they alone have the authority to label.

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[12] For a review of Kripke's modal logic and his theory of truth claims, see Menzel, C., "Actualism", *The Stanford Encyclopedia of Philosophy (Summer 2010 Edition)*, Edward N. Zalta (ed.), URL = <http://plato.stanford.edu/archives/sum2010/entries/actualism/>

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