A quantum approach to multi-agent systems (MAS), organizations, and control

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Abstract

In some rapidly approaching future, on a battlefield, deep-space or planetary mission, teams of agents will be confronted with a problem beyond their computational capability, putting missions at risk. This risk arises from a lack of social theory based on first principles for decision-making in the face of ill-defined problems (*idp*'s*)*. Also, no first principles exist to address the downside of cooperation (e.g., terrorist cells; corruption; and, regarding agents, reductions in computational power from communication costs when an increasing number of agents cooperates interactively). These problems make traditional social models impractical for a multiple-agent system to solve *idp*'s. In contrast to logical positivist models, such as command or consensus decision models, quantizing the pro-con positions in decision-making may produce a robust model that increases in computational power with *N*. Previously, optimum solutions of *idp*'s were found to occur when incommensurable beliefs interacting before neutral decision makers generated sufficient emotion to process information, *I*, but insufficient to impair the interaction, producing more trust compared to cooperation. This model has been extended to the first quantum information density functional theory of groups, especially mergers between organizations; we begin now to integrate our model with Markovian models.

Introduction

To address how systems of computational agents, working alone, in teams, or with humans, can cooperate autonomously to solve problems better than the current generation of remotely controlled unmanned systems (Darpa, 2002), it is increasingly clear that a revolution in computing foundations is necessary to achieve multi-agent autonomy. For example, a staff of 20 humans is now required to operate a single Predator drone, yet the crash rate is 100 Predators to one piloted USAF aircraft (e.g., Pfister, 2002). To reverse this relationship will require the rational control and optimization of group processes, beginning with the major unsolved problem in Social Psychology of how individuals become a group (Allport, 1962). The related problem in game theory (Luce & Raiffa, 1967) is the mathematical inability to distinguish between an organization such as IBM and the aggregation of individuals who comprise IBM. While being able to determine the optimum structure for decision-making or the formation of organizations may offer the greatest opportunity for advancements in computational agent technology, the "groupness" problem remains not only unsolved, but also virtually unstudied simply because social scientists have until now been unable to study groups except from the perspective of the individual (Levine & Moreland, 1998), a critique applicable to game theory for different reasons. As the first attempt to analyze social interdependence, game theory only produces static information, *I* (Von Neumann & Morgenstern, 1953, p. 45), including repeated or "evolutionary" games. Luce & Raiffa (1967) concluded that logic based on the individual perspective, such as game theory, was unable to solve the "groupness" problem.

The "groupness" problem arises by recognizing that once members have been surveyed with questionnaires or polls, summing individual data does not reconstitute the group (adapted from Zeilinger, 1999). Nash (1950) avoided this issue in bargaining situations by assigning zero social value to groups with dissent, assuring that game theory only addressed the more stable groups where values might be summated. But even for stable, homogeneous, dissent-free groups, Lewin (1951) famously recognized that a group is different from the sum of its parts.

Disadvantages of the Traditional Approach

The idea that "cognitive systems might be best characterized as systems that know what they are doing" (Darpa, 2002) is a traditional rational vision of human behavior that sharply contrasts with vacillations between "rationality … [and] enormous irrational feelings" humans commonly experience as they anguish over difficult decisions (2002 interview of Fiona Shaw, the star of the acclaimed new interpretation of "Medea"; in www.washingtonpost.com). Besides not integrating emotion, there are three distinct disadvantages with traditional rational individual models of human behavior.

First, the knowledge, *K*, an organism holds about itself compared to observer *K* about the organism is replete with errors (Baumeister, 1995; e.g., alcoholic denial and hypochondria are common but opposite examples in the amount of extreme error possible with human self-*K*). Observer *K* is also error prone, such as eye-witness testimony (Loftus & Ketcham, 1992), captured in Umberto Eco's new novel by his character Bondolino: "The problem of my life is that I've always confused what I saw with what I wanted to see." Yet Simon (1992) speculated that an expert's *K* can predict the expert's behavior. Theoretically, however, if the *I* between an agent's actions and its perceptions of that action are conjugate (Lawless et al., 2000a), then the more perfect is either *I* or *I* flow the greater the divergence between them. Field evidence from a study with USAF combat fighter pilots of air combat maneuvering versus air combat *K*, and a replication of the combat pilot study in the laboratory with mathematics students of mathematics skills versus math skills perceptions, did not support Simon, but did support the conjugate or social quantum model (SQM) (Lawless et al., 2000b).

Second, the wide-spread and traditional belief, noted by Benardete (2002), that there always exists a single rational decision superior to the same decision made in a democracy (a democracy promotes autonomy and, from self-organizational processes, factional diversity among agents), remains the premise of game and decision theory (Luce & Raiffa, 1967), even though neither theory has been validated in the laboratory or field (Jones, 1998; Kelley, 1992; Klein, 1997). Interestingly, both theories use processes similar to convergence theory in the social sciences, eventually rejected by its founder Campbell (1996), and also in machine learning (e.g., genetic algorithms, neural nets, fuzzy logic, etc.), the premise being that an optimum solution exists at a global minimum in rational space (e.g., minimum cost functions), rejected early on by Bohr (1955; see also Von Neumann & Morgenstern, 1953, pp. 147-8) when *I* is interdependent and conjugate, as always occurs during social interaction. The convergence process in machine learning fails to capture the social interaction for two subtle, other reasons: Convergence governs social learning theory (i.e., classical and operant conditioning and modeling), whereas in groups governed by democratic decision-making, convergence is delayed by *I* processing, captured by SQM (Lawless & Castelao, 2001); and social learning theory is predicated on a lack of cognitive awareness (Skinner, 1978), but awareness is the *sine qua non* of democratic decision-making and self-roganization, also captured by SQM (Lawless & Schwartz, 2002).

SQM is congruent with dissonance learning theory. Surprisingly, dissonance learning theory offers a link between machine learning and cognitive awareness processes. Assuming that first interactions before structure exists are approximately Markovian, then social (e.g., stable relationships, organizations, laws, cultures, business practices) and psychological structures (e.g., habits, stable beliefs, personal K) are social mechanisms that reduce randomness by increasing predictability (i.e., if $I = -\sum p(x) \log_2 p(x)$, and I flow *is* $\Delta I/\Delta t$, or a, K occurs as $\Delta I \rightarrow 0$). Management reduces to managing I to make rational decisions (e.g., Farber, 2002). According to Nicolis and Prigogine (1989, p. 255), by construing society as a dissipative system with chaotic attractors, predictability recovers along the direction of flow in contracting phase space (e.g., axes of I and I flow), while variety and choice generate along the expanding directions of flow. This leads us to postulate that outside of the range of social structure, randomness is more likely (e.g., the stock market as a random walk; in Malkiel, 2000). But with dissonance learning theory, randomness can be mindfully injected within structures. Examples are plans (e.g., in 2003, on the national stage the U.S. and N. Korea have lurched between plans for conciliation and confrontation; new recovery plans have recently been published by Ford, Gateway, United Airlines, and Fiat; new political plans have been announced for the 2004 Presidential race; and the Catholic Church struggles to plan past the issue of priest-child abuse); disagreements and arguments (e.g., Lawless & Schwartz, 2002); and a wide range of many others (war, art, entertainment, innovation, technology), including mergers (e.g., Lawless & Chandrasekara, 2002). Mergers occur in environments where uncertainty increases ($\Delta I \rightarrow \infty$), as when a sector loses pricing power (e.g., airlines in 2002), in an attempt to regain predictability by consolidation, just as slime molds and ants do (Nicolis & Prigogine, 1989, pp. 33 and 236, respectively). Randomness can be mindfully marginalized from structure (e.g., crime, dictatorship, consensus, bureaucracy), but by proportionately slowing its evolutionary rate. To generalize, increasing uncertainty among autonomous agents increases their emotional temperature (T, where $T = \partial E/\partial I$), producing more I and anxiety, thereby motivating efforts to reduce uncertainty by processing I to increase K (Lawless, 2001).

Returning to disadvantages, the third disadvantage is the belief that group decision-making is inferior (Darpa, 2002; see also Stroebe & Diehl, 1994, for lab support using toy problems). This overlooks the three greatest decision-making groups in the world today: the American stock markets (Insana, 2000), the U.S. Congress (Schlesinger, 1949), and the U.S. Courts (Freer & Perdue, 1996). In the Fall of 2002, The New York Times cited doubts by Hong Kong's Secretary of Security Regina Ip, a top aide to Tung Chee-Hwa, its Chief Executive, about the usefulness of democracy. But in contrast to command or consensus decision-making (CDM), we have found that democratic decision-making is significantly associated with scientific wealth, human health, economic freedom, increased trust, and reduced corruption (Lawless & Castelao, 2001). For example, unlike the experience of Soviet Russia, Communist China, or numerous countries in Africa during the 20th century, and despite a dogmatic belief in the value of communism and other command economies by Skinner (1978), the founder of operant conditioning, Sen (2000) concluded that no democracy has ever suffered from famine. Taken together, these findings illustrate the theory behind Western systems of justice, markets and science is that the same data can lead to multiple, incommensurable, or orthogonal interpretations that can be exploited with a social mechanism to power information processing in observers neutral to argument, evolving a social system (Lawless & Schwartz, 2002), crudely analogous to quantum computation (Lloyd, 2000).

Von Neumann (1961) admired that physicists signaled the limits of rational thought by conflict, they never avoided conflict, yet their resolution of conflict created the largest advances in rational thinking. Encouraged by Von Neumann's insight, we combine Nash's (1950) criteria for the absence of conflict as a prerequisite for negotiation with the quantum *I* approach which allows us to combine two orthogonal states simultaneously, specifically cooperation and competition. If opinions are diametrical (180 deg out of phase; e.g., "Concept A is right"and "Concept A is wrong"), versus orthogonal ("Concept A is right" and "Concept B is right"), diametrical concepts represent conflict while orthogonal concepts represent *I* processing.

In sum, it has been found that the weakest decisions are made by individual rational logic, teams, or consensus seekers, the underlying rationale to CDM (e.g., authoritarian decisions, military failures such as the USS Vincennes incident, and bureaucracies; in Lawless & Schwartz, 2002). Even the previously consensus-minded European Council has rejected the consensus method as inefficient (WP, 2002). Thus, to build a computational system aware of its goals and internal states to determine where and why its *B* strayed from the desired, while laudable, is a traditional approach unlikely to solve *idp*'s, to save scarce resources, or to be computationally efficient, making it unwise to assemble these agents into teams or systems that would be able to coordinate in unprecedented ways.

As an alternative, because social reality is bistable (action *I* and observation *I* are conjugate), to eliminate redundancies and gaps in large complex systems and reduce their overall cost, a system of agents with multiple factions of complementary beliefs and actions, producing something akin to a virtual *K* characterized by increasing belief strength associated with decreasing observational accuracy about agent actions (Lawless et al., 2000a), *strangely*, will increase information processing power as the number of decision-makers increase (Lawless, 2001), precisely the opposite of what happens as traditional computational power increases: As systems get larger and more complex, there is evidence that utility and productivity are increasingly falling off the curve that tracks pure processor size and speed leading to the conclusion that no amount of pure computational power will afford us the kind of intelligent computations that we need to address new problems, thus investing in more of the same will not get us where we need to go (Darpa, 2002). Traditional models cannot easily account for information processing among agents, trust, the value of emotion between agents, or what it is about groups that make them superior or inferior decision makers, natural derivatives of conjugate or quantum models (Lawless, 2001). Nor can traditional models explain the power of a plan that succeeds, like the U.S. Constitution—an imperfect plan written by imperfect men that has allowed imperfect leaders and imperfect power centers to excel—with its system to maximize autonomy among multiple deciders and to minimize autonomy with checks and balances, yielding a system to reduce corruption, increase trust (from Montesquieu), and balance cooperation and competition with tension (Berken, 2002), but the quantum model can (e.g., Lawless & Castelao, 2001). The value of SQM is that it helps us to see that in contrast to the "efficiency" of CDM, and with it Plato's model of the "ideal leader", the social tumult associated with oppositional decision making in democracies and decision centers allows for continuous tuning of a decision with feedback that converts argument into a source of bifurcations and uncertainty (near zero or incommensurable social forces; i.e., $\sum F = 0 = Force(argument\ 1) - Force(argument\ 2)$), whereas a single leader or bureaucracy slows the rate of evolution by promoting consensus or homogeneity (Lawless & Schwartz, 2002).

To computationally simplify cognitive models, Simon believed that rationality was bounded, but that is insufficient to characterize conjugate *I*. The chief characteristic of an optimum decision-making system is one that can exploit the conjugate *I* that exists in every social interaction, yet at the same time accepts that conjugate I precludes participants from accurately articulating their own decision processes (Lawless et al., 2000a; also, see Zeilinger, 1999), e.g., legal decisions sometimes become highly valued as precedents even as the best rational justifications for them decline in social value (Polanyi, 1974); similarly in physics, Planck spent years attempting to rationalize his own accidental discovery of discrete energy packets that ended the traditional view of causality so important to his own mechanical view of reality, R.

Mathematical approach

The question of "groupness" has puzzled Aeschylus, Plato, Descartes, James, and Bergson, but it was finally solved by Heisenberg with his uncertainty principle for atomic objects, then extended to human systems as an interdependent interaction between action and observation by Bohr (1955; see also Von Neumann & Morgenstern, 1953, pp. 147-8). While considerable research into quantum effects has already addressed signal detection theory (i.e., the Békésy-Stevens model; see Luce, 1963, 1997, who considers it to be a satisfactory alternative), little research has added to Bohr's initial insights for social systems, leaving open many key issues. However, Bohr's approach has several advantages that have begun to pay off with SQM. Given conjugate action I uncertainty (Δa) and observational I uncertainty (ΔI), the relationship becomes:

$$\Delta a \Delta I \geq c \tag{1}$$

Since c is unknown, boundary conditions are necessary to solve (1). The first case, already discussed with the USAF study (as $\Delta I \text{ -> } 0, \Delta a \text{ -> } \infty$), found that expert versus non-expert K was conjugate, supporting the interdependence of training and learning (Lawless et al., 2000b).

The second case (as $\Delta I \text{ -> } \infty, \Delta a \text{ -> } 0$) establishes the value of argument (Lalwess & Schwartz, 2002), leading to the finding that the rational logic of an optimal individual (e.g., command and consensus decisions) is significantly inferior to group decisions that exploit randomness (e.g., decision centers and democracy), leading to the discovery of techniques that prevent decision stalemates (van Eeten, 2002) by engaging both sides ($\sum F = 0 = F_1 - F_2$) and those neutral to an argument, increasing I processing and creativity to solve *idp*'s, producing optimum decisions. It has also helped us to recognize similarities between signal detection theory and decision-making ("detecting" solutions to *idp*'s; Lawless & Schwartz, 2002).

Revising (1) with j as inertial reactance, with time, Δt, and energy uncertainty, ΔE (Lawless et al., 2000), $\Delta a \Delta I = \Delta\ (\Delta I/\Delta t) \bullet \Delta t/\Delta t \bullet \Delta I = j \bullet \Delta\ (\Delta I/\Delta t)^2 \bullet \Delta t$ becomes

$$\Delta t \Delta E \geq c \tag{2}$$

Equation (2) predicts that as time uncertainty goes to zero, E becomes unbounded (e.g., big courtroom cases, science, or urban renewal projects); inversely, when ΔE goes to zero, time becomes unbounded (e.g., at the low E expenditures around resonance, voice boxes operate for a lifetime). Equation (2) allows the interaction to be quantized, producing E wells localized around ideas or beliefs as set points, accounting for the stable reactance to social change we defined as information inertia, j. As increasing E levels approach set points, emotions increase, forcing a return to stability (e.g., in set point theory, an "insult" provokes an agent's response as its set points are engaged, or a group when its "laws" are broken; for a review, see Lawless, 2001).

Countering the current belief that prediction with agent systems is not possible (e.g., Bankes, 2002), mathematical formulations of a group (Lawless & Chandrasekara, 2002), including heterogeneous couplings (e.g., terrorist sleeper cells), can be determined *ab initio* with vocal cross-sections by construing the group as a series of interdependent interactions between individuals represented approximately as vocal harmonic *I* resonators. Then the growth rate of an organization fits a pattern, with different processes, *P*, like diffusing or adsorbing recruits, given by:

$$\Gamma_P = n_A n_B \, a \, \sigma_{AB} \, exp \, (-\Delta A/k_B T). \tag{3}$$

where n_A and n_B are the numbers of recruits and leaders interacting; $a = \Delta I/\Delta t$; σ_{AB} is the cross-section (the probability an interaction produces usable *E*, ΔA, is an area determined by the vocal frequency of indoctrinators, ω, and recruits, ω_0, increasing rapidly as language "matches" increase or differences decrease; i.e., $f(\omega^4/(\omega^2-\omega_0^2)^2)$); $exp(\bullet)$ is the probability of sufficient free *E*, ΔA, for the activity to go forward; k_B is Boltzman's constant; and *T* is emotion temperature (Lawless, 2001). Equation (3) indicates that the more ΔA required for an activity, the less likely it occurs; that friendship is optimal for those who listen to synchronize with each other, similar to a state of resonance between harmonic oscillators; and that terrorists cooperate to manipulate their cross-section to preclude warning observers about their hidden intent.

Information Density Functional Theory-IDFT

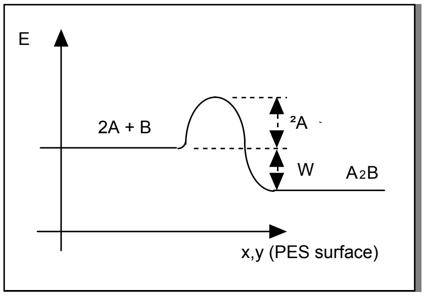
IDFT approximates the function of *I* density and discrete *E* effects in an organization of adding or removing members. A group forms or reforms by entangling *I* from an aggregation of individuals to solve an *idp* (Ambrose, 2001), like designing a complex weapon. The chief characteristic of an *idp* is that *K* concepts do not correspond to objects or actions in *R*. Once solved, however, an *idp* becomes a well-defined problem, *wdp*, characterized by a correspondence between *K*, skills and *R* (Sallach, 2002) (cooperation implies low *I* density, maximum *K*, and *E* ground state). In the solution of *wdp*'s, individuals function in roles bonded into a stable network oriented by a shared emotional potential *E* field (set point theory).

The potential *E* surface (E^{PES}) represents the function, hierarchy and geo-cultural differences across a group, organization, or society (Sallach, 2002). A recruit moves across the *E* surface of an organization, R_{org}, where E^{TOT} is the ground state and PES the minimum total *E* along the *z* coordinate of the organizational configuration, including its hierarchy, until reaching a minima (stability).

$$E^{PES}(x,y) = min_{z,R\text{-}org}\, E^{TOT}(x,y,z,R_{org}) \tag{4}$$

A bond forms between two members, A and B, proportionately as its joint ground *E* state becomes less than the aggregate ground state of its members, the difference being the binding *E*, *W*. The *E* required to reverse the process and break apart the group becomes $\Delta A + W$ (Figure 1). *W* is calculated from the configuration of barriers and nearest and next-nearest neighbors.

Figure 1. The binding *E* to form a group or break it up. Shown here, two followers (2A) bind together with each other and then to one leader (B) to form a group (A_2B).



Assuming that two recruits (A) bind to one another and to one leader (B), the Hamiltonian consists of a site contribution, H_0, and an interaction term, H_{int}, giving:

$$H_0 = E_b^A \sum_k n_k + E_b^B \sum_k m_k + V^{A\text{-}B} \sum_k n_k m_k \tag{5}$$

where k as a role site, n_k, is either 0 or 1 if k is empty or filled, m_k is the same for leader sites, V is an interaction parameter, and

$$\begin{aligned} H_{int} = {} & 1/2V_{1n}^{A} \sum_{k,a} n_k n_{k+a} + 1/2V_{2n}^{B} \sum_{k,b} n_k n_{k+b} + 1/2V_{1n}^{B} \sum_{k,a} m_k m_{k+a} + \\ & 1/2V_{2n}^{B} \sum_{k,b} m_k m_{k+b} + 1/3\ V_{trio}^{B} \sum_{k,a,a'} m_k m_{k+a} m_{k+a'} + \ldots \end{aligned} \tag{6}$$

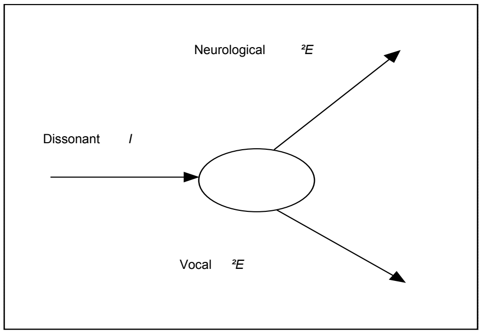
Here $k + a$ and $k + b$ denote nearest and next nearest sites.

The processes above (Equations 3-6) can be used to model a heterogeneous group. Stresses resulting from a mismatch between an organization and new members can also model the merger between two organizations (e.g., HP and Compaq). As a heterogeneous island nucleates on the surface of a consolidator, the tension on it to be absorbed relaxes the larger the island grows, creating a distance between the consolidator and the island's leaders, the release of E acting as a driving force in the island to choose a hierarchy of leaders less like those in the consolidator, motivating the need to integrate both cultures (e.g., the inability to integrate is the putative cause of the failure in 2003 of AOL and Time Warner).

In sum, joining a group promotes the survival of individuals by reducing E expenditures in exchange for membership: social loafing (Latane, 1981); audience effects enhance skills (Zajonc, 1998); greater interaction density promotes health (House et al., 1988); and protecting belief systems (Rosenblatt et al., 1990). In exchange, a group exploits the E and skills it collects (Ambrose, 2001), forming a structure around a network of interactions between roles bonded to each other (Sallach, 2002). Generally at the lowest E state, interaction exchanges —voice, visuals, products, and money— between agents cycle I back and forth in interactions coordinated by common K (Wendt, 1999). Among the groups that gain more E than it costs to survive (Coase, 1937), some gain sufficient free energy, ΔA, to grow in size, experience and wealth, deepening E wells to process more I, while others merge to offset competitive weaknesses (e.g., HP merged to offset its weakness in computer servers, Compaq's strength).

Most interactions within a stable organization serve to fulfill a mission, defend a worldview, or acculturate members, but interactions to solve *idp*'s are different. Modeled by Equations 1-2, these interactions temporarily shift members from roles to bring into play factions (underdetermined R), neutrals and decision making, where Δt is the time for the system to evolve to an orthogonal state to reach a decision (Aharonov & Bohm, 1961). For optimal decisions, dissonance (argumentation) between polar opposite views processes *I* uncertainty into *K* (e.g., political, legal, and scientific dissonance usually precede optimal decisions; in Lawless & Castelao, 2001). Identifying the optimum solution of an *idp* is analogous to signal detection, the time (Δt) to detect and adopt a solution lasting until the solution signal is separated from social noise; e.g., air-to-air combat, environmental cleanup, environmental disaster recovery, or weather prediction (Lawless & Castelao, 2001). However, given the unreliability of self-reports (measurement collapses the interaction into individual histories that cannot recreate it), a new approach must be initiated to measure physiological *E* states, such as vocal energy changes, to contrast normal and dissonant states (see Figure 2).

Figure 2: Picard's liquid model of emotion suggests that social perturbations caused by dissonant *I* produce a spectrum of emotional responses. Significant vocal *E* changes from normal to angry speech have been confirmed (Lawless, 2001).



In earlier work, we associated quantum-like square *E* wells with emotion and decision-making (e.g., Lawless, 2001). After finding that interaction cross-sections are related to vocal frequencies (Lawless, 2002), we speculated that it also applies to brain waves: if gamma waves (≈ 40 Hz) mediate the binding of sensory features into objects (Engel et al., 1999) and concepts (Lawless & Chandrasekara, 2002), transitions between opposing views in an argument act as concept reversals that reflect the time required to sufficiently grasp and apply difficult concepts to solve *idp*'s, linking solution "detection" to signal detection. It may be this time is necessary for decision-makers to determine whether an argument can be defended "against all contestations" (McBurney & Parsons, 2001, p. 76).

Conclusion

The primary advantage of using SQM is that it is an analytical model that simulates the conjugate aspects of decision making and organizational growth (IDFT). SQM explains why traditional models based on the individual perspective of rationality fail, or why ABM's cannot be validated; IDFT accounts for differences between an aggregation and a group constituted of the same individuals; and, more importantly, both suggest new approaches to study the interaction. If language is the assignment of meaning to physical vibrations between human oscillators (speech from vocal sounds), and if the primary tool of social science is the self-report, then SQM and IDFT suggest many opportunities for interdisciplinary collaborations that could lead to new tests of falsification by contrasting single versus social *E* states with neuro-physiological-psychological data (self-reports, voice, qEEG's, fMRI's, EMG's, Lie Detectors, etc.) to determine whether as predicted during decision-making for *idp*'s and *wdp*'s that ground and excited states can be distinguished, whether competition produces *I* and, and whether cooperation enhances deception. Finally, by recognizing how uncertainty is injected into decision-making via argument, the potential compatibility of SQM and Markovian models opens a new avenue of research.

Acknowledgements

The author thanks J.A. Ballas, Naval Research Laboratory, Information Technology Division, Washington, DC, where most of this research was conducted with an ASEE grant from the Office of Naval Research.

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