The Control of Multi-Agent Systems (MAS)

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Background (metaphor of logical individualism versus mathematical physics of social organizations)

- **"methodological individualism"** (Nowak & Sigmund, 2004)
  - Darwin, Von Neumann
  - Allport (1922): "Groups" do not exist
  - However, "contradictions do not exist in nature … [but are] unavoidable … within formal frameworks" (Tessier et al., 2000, p. 24)
- **Organizational physics**
  - Allport (1962): The major unsolved problem in social psychology is the shift from individual to group member
  - Lewin (1951): a group is more than sum of parts
  - Luce & Raiffa (1967): individual rational perspective cannot account for the "social" (viz., game and decision theory)
  - Kelley, 1992, **Measurement problem**: given matrices (self-reported choices) ≠ effective matrices (choices actually selected)

Paradoxes

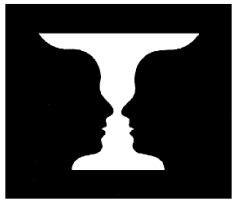
- **Rational Paradoxes**: $\sum x_i$ d.m. ≠ group d.m. (Arrow's Impossibility Theorem); Kornhauser's doctrinal paradox; Condercet's voter's paradox
  - CR -> individual rationality (Group d.m. -> $\sum x_i$)
  - CR: nothing wrong with consensus, per se, unless coerced (groupthink; Janis, 1982)
- **Organizational paradox**: surveys ≠ groups (Levine & Moreland, 1998)
  - Adam Smith's "invisible hand" => competing groups easily resolve rational paradoxes
- **Rational individual d.m. ≠ group d.m.**

Yet current ABMs are primarily rational **individual cooperative** agents

When Cooperation Works	When Cooperation Does Not Work
The evolution of cooperation may preclude nuclear war (Axelrod, 1984)	• Social loafing (Latane, 1981) • Asymmetric *I* (**terrorism, corruption, blackmail**) • Computational blowup as *N* cooperating agents exceed 100 (Darpa, 2002)
Cooperation requires **coercion** (Axelrod, 1984)	• Coercive gov't reduces social welfare (Hayek, 1944) • However, Axelrod's claim is true if meaning of "cooperation" is reversed
Cooperation under single WV implies that "moral" judgments reject compromise to reduce bloodshed (Worchel, 1999)	• Government by Consensus o Japan: Unable to reform o Germany: More Corrupt (from 14th in 1999 to 20th in 2000, TI, 2002); Tietmeyer (2002), ex-president Bundesbank, "… what we need are majority decisions ... [not] consensus." o WTO collapse in 2003 attributed to consensus d.m. (CDM): "almost impossible for the 146 nation group to reach agreements." (WSJ.com)
Mathematically, less diversity => + stability (May, 2001, p. 174) • e.g., single WV, gender, race, religion, and polity -> + stability • But this implies **dictatorship** (Lawless & Schwartz, 1992)	EC: **"The requirement for consensus in the European Council often holds policy-making hostage to national interests in areas which Council should decide by a qualified majority."** (WP, 2001, p. 29)
Solving well-defined problems (*wdp*'s) (Lawless et al., 2000b)	Solving ill-defined problems (*idp*'s) (Lawless et al., 2000a)

Research Impetus: Robot Autonomy

- Based on "individualism":
  - Bankes (2002): validating social ABMs not possible
  - Tambe (2003): ABM autonomy currently not possible
  - 5-6 humans per Predator w/staff of 20 (Russ Richards, JFC, 2003); 4 airborne over OIF (Moseley, 2003)
  - DARPA: 1 soldier + R2D2 + 300 less-intelligent but "hot" agents
  - However, politically, swarms will not go "hot" w/o validation of autonomy
- Based on organizations:
  - Bistable
  - Can a bistable entity (MAS) be controlled?



Bistable *R* => Multiple Frames for a single context

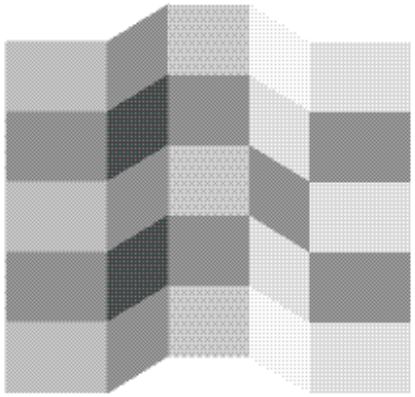
1. Physically: Organism exists simultaneously **superimposed** as
   - Observer and actor
   - Individual organism and member of a group
   - Member of a group A and group B

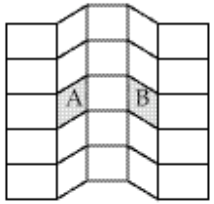
2. Measurement disturbs superposition (Carley, 2003; Lipshitz, 1996; Zeilinger, 1999)

3. Observer: Object acquisition based on + *E* -> convergence (γ waves => + *E*)
   - (K&T, 1981): "Framing" convergence of beliefs reduces dissonance; e.g., "culture A" (Bohr, 1955)
   - M's => participants perceive "frame" A or B, but not both simultaneously (Cacioppo et al., 1996)
   - Opposite K&T frames -> tension, disagreement, or conflict (Janis, 1982)

4. **Managing opposed frames = argument -> optimal d.m.** ≈ compromise (Schlesinger, 1949); best fit by + # dm participants => more Fourier components; e.g., science, courtroom, business (Lawless & Grayson, 2003)

Illusions, conflicts, interpretations, and justifications reflect bistable phenomena





- AI cannot resolve illusions (Brooks, 2003)
- The traditional belief that rational decisions are superior to democracy remains an illusion (Benardete, 2002)
- Perception of reality may be a quantum illusion (Bekenstein, 2003)
- Yet, humans resolve bistable reality into classical *I*

What could a Model of Bistable Reality Mean?

- Feynman (1985) found:
  - Traditional computers model quantum *R* inefficiently
  - Quantum computers model *QR* efficiently
- Can bistable ABM's efficiently model *SR*
  - Traditional models are inefficient
  - Bistable models -> efficiency, power => QIP ≈ ?? ≈ SIP (Lawless &Grayson, 2004)

Support for a social bistable (quantum) model

Action-observation uncertainties -> multiple interpretations -> multiple cultures	Bohr (1955)
Differences between definitions and word use	Heisenberg (1999)
Humans can focus on only one aspect of an object at a time; convergence increases outgroup uncertainty	Gibson, 1986; Tajfel, 1970
Quantum human hearing model is an acceptable alternative to classical SDT; i.e., either a) Bèkèsy-Stevens discrete E levels; or b) Swets ROC YY-YN curves.	Luce (1963), HMΨ. Luce (1997). "Several unresolved conceptual problems of mathematical psychology." Journal of Mathematical Psychology **41**: 79-87.
Measurement changes the properties of what is measured.	Lipshitz, R. (1997). Naturalistic decision making perspectives on decision errors. Naturalistic decision making. C. E. Zsambok & G. Klein. Mahwah, NJ, Lawrence Erlbaum**:** 49-59. Carley, DNA analysis (R. Breiger, K. Carley, & P. Pattison, *Ed.* , Committee on Human Factors, NRC, forthcoming)
Superposed data forms robotic social maps of the physical environment	Zlot, R., Stentz, A., Dias, M.B., & Thayer, S. (2002). Market-driven multi-robot exploration (CMU-RI-TR-02-02).
The eye is a quantum I processor; all reality is an **illusion**	French & Taylor, 1978; Bekenstein, 2003

CIP versus QIP

- Classical *I* is either 0 or 1 = bits
- Exponential increase in CIP requires exponential increase in # processors and physical space (e.g., n x n = n^2 processors)
- Quantum *I* is simultaneous 0 and 1 = qubits => 2^n values
- Thus, exponential increase in QIP requires a linear increase in processors and physical space (e.g., each n => 2^n processors)
  - Lloyd (2000): + QIP w/ + *T* (similar to emotion for humans and organizations)

Measurement Problem: M bistable *I* -> classical *I*

- Superposition of two states $\alpha|\uparrow> + \beta|\downarrow>$, with prob($\uparrow$) = α^2, prob($\downarrow$) = β^2, giving $|\alpha|^2 + |\beta|^2 = 1$
- Superposition corresponds to average of E_0 and E_1;
  - Mixture of rational (ground state, E_0, = $|\downarrow>$) and emotional (excited state, E_1, = $|\uparrow>$) -> QIP ≈ SIP??
- **M -> bistable shift to $|\uparrow>$ or $|\downarrow>$, E_0 or E_1, w/P(1) (Gibson, 1986; Caccioppo, 1996) -> increases entropy**
- Thus, M -> individual Event Histories ≠ reconstruct interaction at atomic (Zeilinger, 1999) or social levels (Levine & Moreland, 1998; Eagly & Chaiken, 1993; Carley, 2003)

Superposition (bistability -> interference patterns)

- Entanglement => feedback is stronger than context
- Given 2^n states, the superposed "extra" states have no classical analog, producing the EPR paradox
- Basis for 2-qubit system: {|↓↓>, |↓↑>, |↑↓>, |↑↑>} => $2^2 = 4$ states; basis for 3 qubits => $2^3 = 8$ states
  - Non-entangled state: $1/\sqrt{2}$ (|↓↓> + |↓↑>) = decomposes)
  - Entangled state: $1/\sqrt{2}$ (|↓↓> + |↑↑>) ≠ decomposed)
- **The quantum state |↓↓> + |↑↑> cannot be decomposed into classical components => entangled, no classical counterpart & no intuition** (Rieffel & Polak, 2000, ACM, 32(3), p. 308)
- **The "social" state of 2 neutral humans cannot be decomposed** (Lawless &Grayson, 2004)

Interactions => Bistable Uncertainty (bistability can be suppressed; e.g., Milgram, 1963)

- Let ΔK = belief uncertainty = I (Shannon's I);
- Let $\Delta v = \Delta\ (\Delta K/\Delta t)$ = action uncertainty;

$$\mathbf{\Delta v \Delta K \geq c} \qquad \mathbf{(1)}$$

- **USAF**: Traditional SLT => L improves skills; however, in combat pilot experiment, book K (ΔK -> 0) did not predict wins-losses, E availability, or expert ratings, but training did (Δa -> 0) (Lawless et al., 2000a)
- **DOE**: SRS CAB (majority) v HAB (consensus): "competition of ideas" ($\Delta K \rightarrow \infty$) improved nuclear waste cleanup + trust
- **Nations**: May's 1997 data base: competition between nations increased SW, H, E, EF, and trust while reducing corruption (Lawless et al., 2000b)
- **Computational**: Experts forecasters best over short term, CCFP close 2nd and better over longer term, NCWF worst

Decision-Making: Conclusions

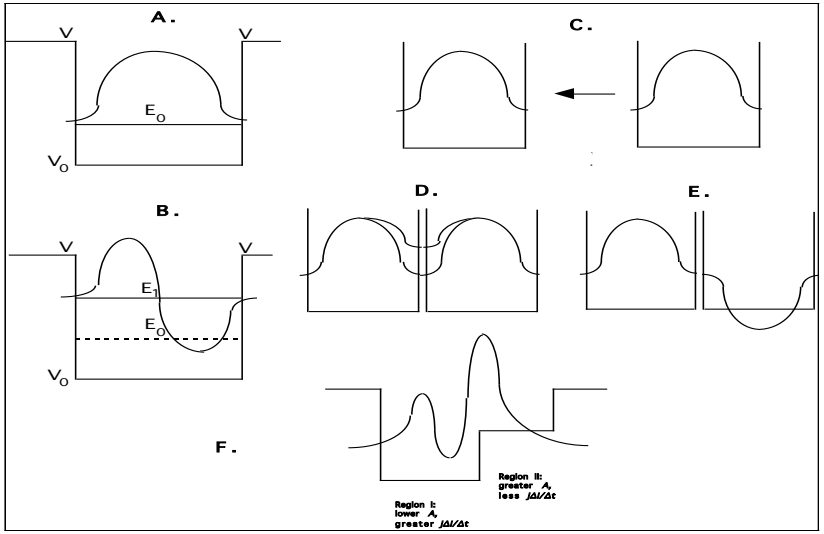
- Bistable *R* = orthogonal operators and neutrals produces optimal solutions and decisions (Lawless & Grayson, 2004)
  - Solving *idp*'s best under competition
    - SW, H, E, trust increase, corruption decreases
    - Overheating => conflict
  - Solving *wdp*'s best under cooperation
    - Underheating => corruption, low creativity
  - **Resonance** (**??**) and social barriers

Revising Equation (1)

- Given reactance, j, $\Delta v \Delta K = \Delta\,(\Delta K/\Delta t)\ \ \Delta t/\Delta t\ \ \Delta K = j\,\Delta\,(\Delta K/\Delta t)^2\ \ \Delta t$, giving
- $$\boldsymbol{\Delta v \Delta K = \Delta t \Delta E \geq c} \qquad (2)$$
- Case iii: $\Delta t \rightarrow 0$, $\Delta E \rightarrow \infty$ (e.g., big court cases & science)
- Case iv: $\Delta E \rightarrow 0$, $\Delta t \rightarrow \infty$ (e.g., vocal resonance)
- Human cognition
  - 40 Hz Gamma waves (object binding) ≈ 75-150 ms
  - 16 mm movie film ≈ 62.5 ms
  - $\Delta t \Delta E \geq c = \Delta t \Delta hw = h$
  - $\boldsymbol{\Delta t = 1/\Delta w = 1/(40\ \text{Hz}) = .025\ \text{s} = 25\ \text{ms}}$ **(Roger Penrose)**
  - 5 Hz theta waves (memory coordination) ≈ 200 ms (Hagoort, 2004)

Community Set-Point Theory (C-SPT): Square wells of *E* form emotion = set points => SPT (e.g., food, lotto; Diener & Oishi, 2000). Baseline E_0 associated with emotion potential energy, *V*. As excitation *E* attempts to redefine meaning, *V* keeps beliefs stable. C, D, E: Groups. C-D illustrates E_0, D-E shows first excited state, E_1. F. Experts at I, Novices at II

(Landers & Pirozzolo, 1990; Lawless & Chandrasekara, 2002)



Conclusions:

- **1st model of a group ≠ Σ disaggregated individuals**
- Models experts versus novices
- Models mixed *E* levels for groups

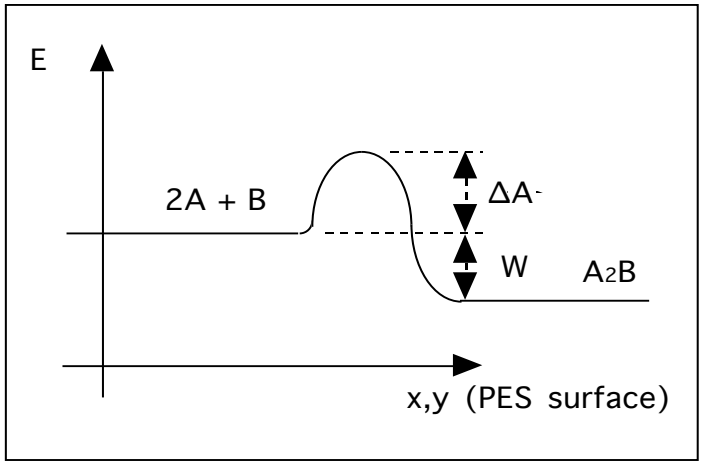
K-DFT (organization, mergers, and *K*)

- $E^{PES}(x,y) = min_{z,Rorg}\, E^{TOT}(x,y,z,R_{org})$ (3)
  - Function, hierarchy, organization (Sallach, 2002) => **Hamiltonian** (Lyapounov)
- $H = H_0 + H_{int}$ (4)
  - $H_0 = E_b^A \sum_k n_k + E_b^B \sum_k m_k + V^{A\text{-}B} \sum_k n_k m_k$ (0 if empty, 1 if occupied)
  - $H_{int} = 1/2 V_{1n}^A \sum_{k,a} n_k n_{k+a} + 1/2 V_{2n}^B \sum_{k,b} n_k n_{k+b} + 1/2 V_{1n}^B \sum_{k,a} m_k m_{k+a} + 1/2 V_{2n}^B \sum_{k,b} m_k m_{k+b} + 1/3 V_{trio}^B \sum_{k,a,a'} m_k m_{k+a} m_{k+a'} + \ldots$

Conclusions:

- W/growth heterogenous island stresses reduce from Hi to Low (**terrorism**)
- Revises Utility theory for χ's: $\Gamma_P = n_A n_B\, v\, \sigma_{AB}\, exp\,(-\Delta A/k_B T)$ (5)
- **Interaction cross-section $\sigma_{AB} = \alpha_\chi (\omega^4/(\omega^2-\omega_0^2)^2)$** (6)
  - Matching theory (w/experiences -> + treatment) => **resonance** = HXS
  - Friends ≈ vocal harmonic oscillators => **resonance** = HXS
  - terrorists seek a LXS w/cooperation to preclude warnings => **reactance ≈ 1/resonance**

Perturbation Theory (explains why $\sum x_i$ in g.t. ≠ organization)



(Lawless & Chandrasekara, 2002)

1. ***E_{min}*****:**

- Social Loafing (Latane, 1981)
- Audience Skills enhancement (Zajonc, 1998)
- Terror Mgt (Rosenblatt et al., 1990)
- Health (House et al., 1988)

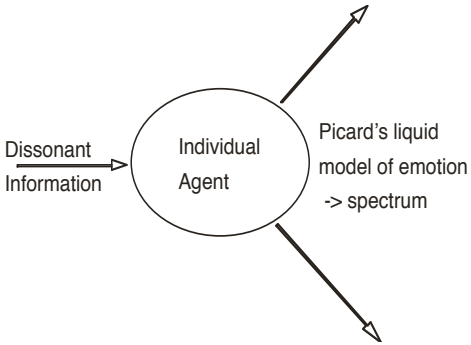
2. **Mergers require *E (ΔA)* to form** (Lawless & Grayson, 2004)

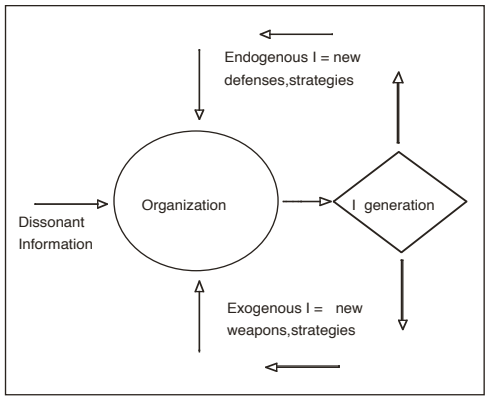
3. ***E_{min}*** **=> Perturbation Theory** (Lewin, 1951)

- **Only way to gain *I* is to attack (perturbations)**
- **However, attacks re-create the M problem** (M bistable *I* -> classical *I)*

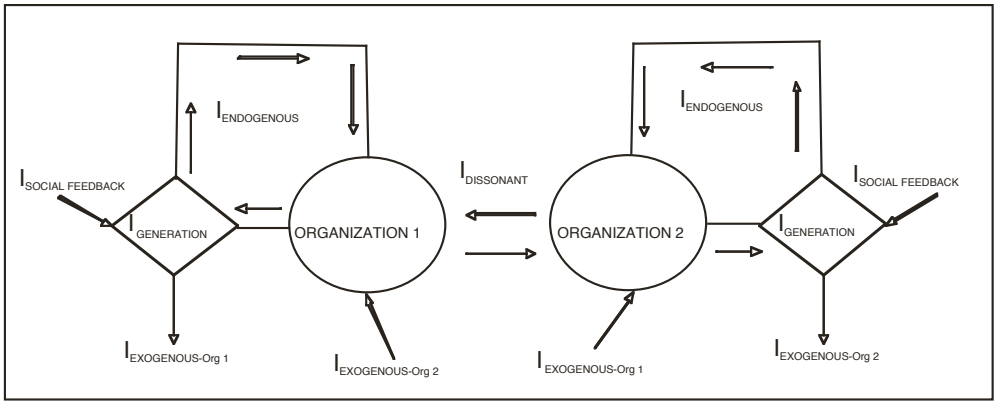
Perturbation Model Revises Game Theory

$\Delta E \approx h * \Delta v$ (Penrose: 40 Hz, gamma; Hagoort, 2004: 5 Hz, theta)





$\Delta E \approx h * \Delta v$ (Kang: Anger $\approx$ + 100 Hz)

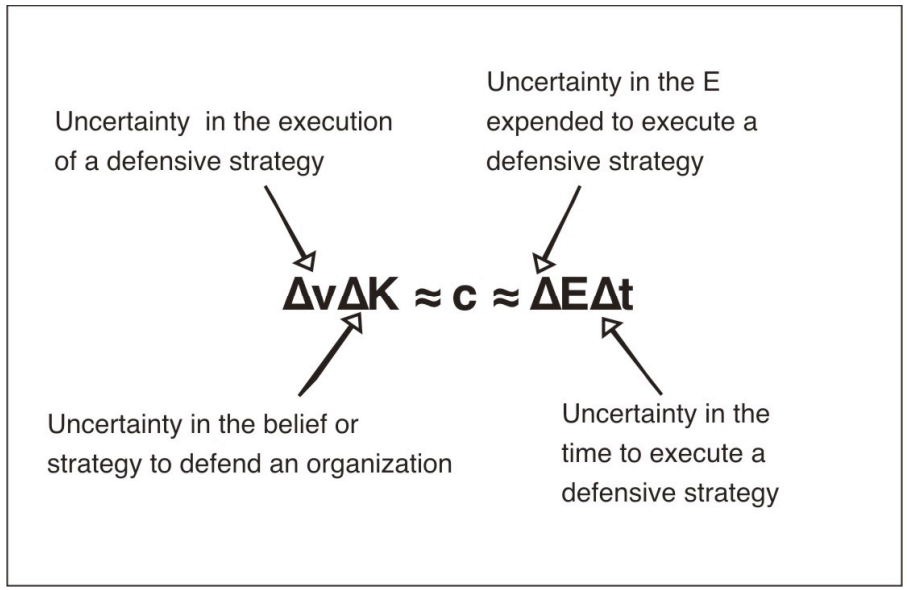


After perturbations, negative feedback stabilizes, positive feedback emerges as strategy(PeopleSoft, a business software company merging w/JDPower and threatened w/hostile takeover by Oracle, implemented poison pill defense by invoking antitrust law; Oracle changed its initial hostile offer from stock only to stock + cash). Speed determines the winner: In the 2003 war with OIF, coalition decision-making and implementation was faster than Iraq's Defense Forces, causing the latter to panic (Kagan, 2003; Lawless & Grayson, 2004a,b).

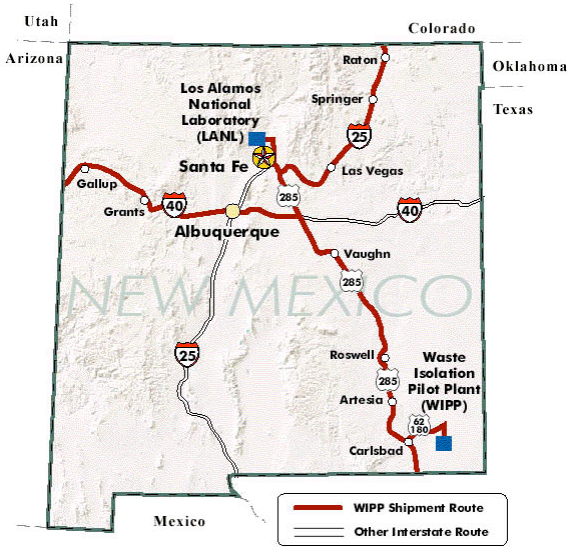
Perturbation conclusions

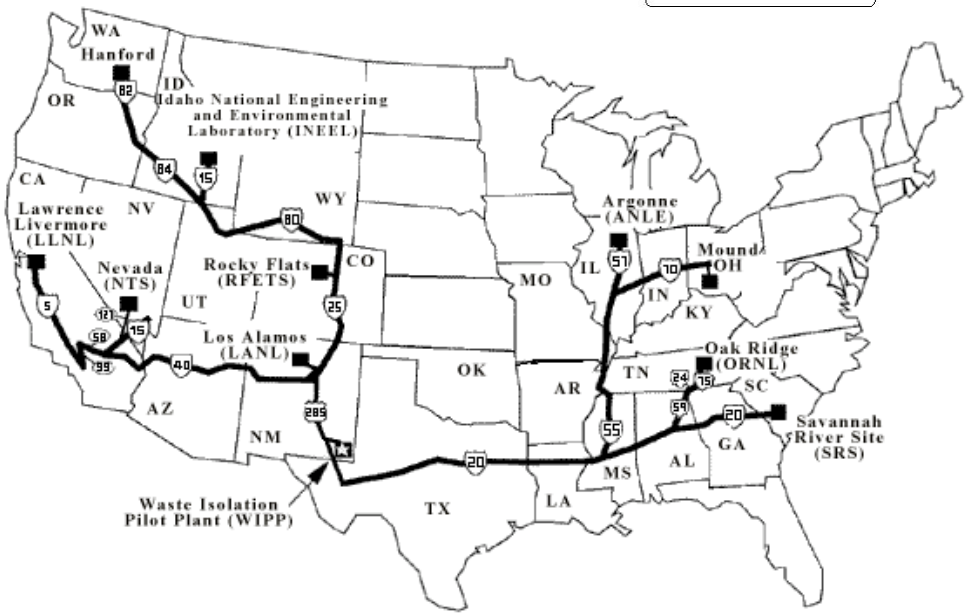
- Organizations under stress coalesce (from λ_0,E_0 to λ_1,E_1; $\lambda_0 > \lambda_1$ but $E_1 > E_0$ -> tighter, closer groups, + cooperation, + emotion; Rosenblatt et al., 1990)
  - Ants (May, 2001; Nicolis & Prigogine, 1989)
  - Slime Molds (Nicolis & Prigogine, 1989)
  - Iraqi Defense Forces (Kagan, 2003)
  - Terror impacted elections in Spain and Israel, 2004
  - **Corporate mergers** (Lawless & Grayson, 2004)
    - Transformation strategy success: fcn => + # Fourier elements
- $\rho = K/V$ (Glaeser, 1996) and $\partial\rho/\partial t = -\nabla\bullet(\rho \boldsymbol{v})$
  - $F = -\nabla(K\ potential)$ -> 0 => structures, channels

For Control: Perturbations exploit Measurement problem (e.g., merger perspective)



M (field test): DOE Tru waste reposity at WIPP opens March 26, 1999





TRU: Radioactive waste contaminated with uranium 233 or elements beyond uranium on the periodic table and existing in concentrations of more than 1 ten-millionth of a curie per gram of waste. These isotopes, mostly pu-239, have half-lives of over 20 years and are all manmade.
clinton2.nara.gov/OMB/inforeg/glossary.html

M (field test): 13 Recommendations by DOE Scientists to Citizens to accelerate disposition of Transuranic wastes, at WIPP, NM

- DOE characterize TRU waste as required to reduce risk and minimize transportation and handling of waste while making confirmation process cost effective
- Therefore, to meet Site Specific needs, DOE allocate and coordinate resources complex-wide to optimize shipping to maximize the receiving capacity of WIPP
- DOE in concert with stakeholders and regulators initiate an ongoing program to identify, correct and revise those requirements that interfere with the safe, prompt and cost effective management of TRU waste
- DOE identify volumes and disposition pathways for all potential TRU waste streams
- DOE in consultation with stakeholders and regulators initiate action to assure that WIPP has the capacity to accommodate all of the above listed TRU waste
- DOE accelerate TRU waste container design, licensing and deployment
- DOE streamline TRU waste management by accepting demonstrated process knowledge for TRU waste characterization
- DOE, in consultation with stakeholders and regulators, reexamine the categorization of TRU waste using a risk-based approach
- DOE identify the inventory of orphan TRU waste and assign a corporate team to identify a path forward
- DOE evaluate the concept of one or more locations to characterize TRU waste for WIPP disposal
- DOE finish its analyses and make a decision with adequate public involvement regarding where to characterize TRU waste for disposal
- DOE expedite the design, fabrication and certification of container transport systems Arrowpak and TRUPACT III and accelerate the adoption of rail transport as appropriate
- DOE revitalize its efforts in coordinating its transportation issues with States and Tribes and assist in updating and disseminating information to the public about transportation risks and safety and provide public participation opportunities on transport issues

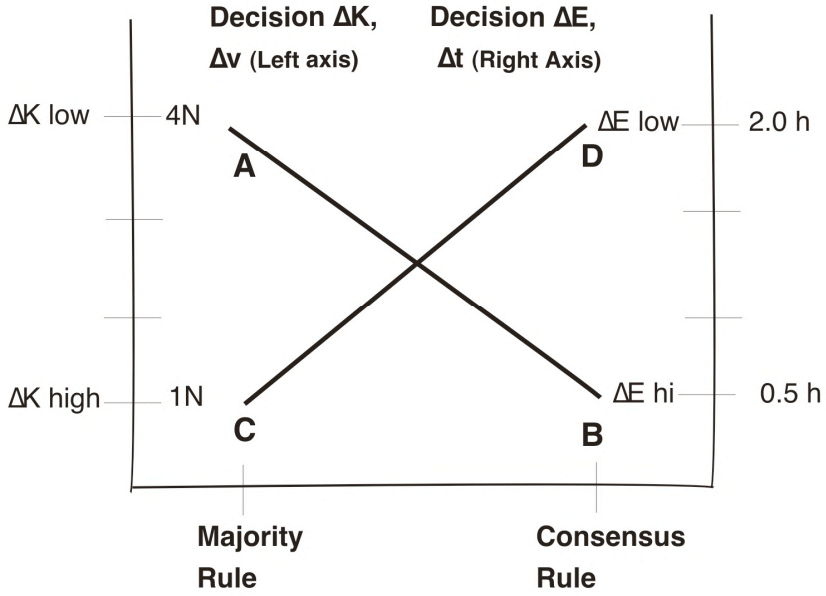
M (field test): Site Specific Citizen Advisory Boards (SSAB's) associated with DOE Sites

Active SSAB's (N = 9)	Decision Process	Inactive SSAB's (N = 3)	Decision Process
Fernald	CR	Pantex	CR
Hanford	CR	Sandia	CR
Idaho (ID)	CR	Monticello	MR
Nevada Test Site	MR		
Northern New Mexico (NNM)	MR		
Oak Ridge (OR)	MR		
Paducah	MR		
Rock Flats Plant	CR		
Savannah River Site (SRS)	MR		

Measurement Problem: A Field Test

- [Grover's search time ≈ O(n) steps v. O(√n); complexity ≈ Δt
  (Ahoronov & Bohr, 1961; Lawless, 2004)]

The SSAB Transuranic Workshop in Carlsbad, NM, reached consensus Recommendations Regarding Transuranic Waste Characterization across the DOE complex (2003, January; *N*=105). The result: Five of nine Boards returned to their respective sites and approved these Tru waste recommendations (*Majority Rule Boards*: SAB (SRS), Oak Ridge, Paducah, Northern New Mexico; *Consensus Rule Boards*; Rocky Flats Plant); four of the nine Boards disapproved (*Majority Rule Boards*: Nevada Test Site; *Consensus Rule Boards*: Hanford, Fernald, Idaho), giving $\chi^2(1)=2.74$, p≈.10.

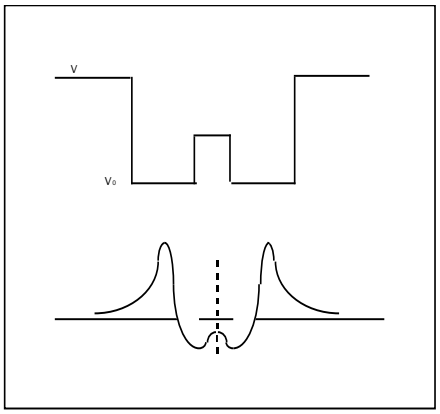


A.1. Initially (*idp*): As Δ*K* -> ∞, Δ*v* -> *0* (not shown)*; i.e.* to achieve the best action decision, bring together opposing beliefs about reality (Δ*K* -> ∞), as in science or politics; **2. Finally (*wdp*)**: as Δ*K* -> *0,* Δ*v* -> ∞ (i.e., high *N* shown). **B.1. Initially (*wdp*):** In contrast, as Δ*K* -> *0*, then Δ*v* -> ∞ (not shown); i.e., achieving a single vision or consensus (Δ*K* ->*0*) increases the actions to be taken (Δ*v* -> ∞*).* **2. Finally**: Δ*K* -> ∞, Δ*v* -> *0 (*i.e., low *N* shown*).* **C. 1. Initially (*idp*):** Next, as Δ*E* -> ∞, Δ*t* -> *0;* i.e., competition or conflict makes uncertain the expenditure of energy (Hagoort, 2003). **2. Finally**: resolution occurs with resonance and ΔE -> 0, resetting for the next decision. **D.** However, as Δ*E* -> *0*, Δ*t* -> ∞; i.e., as consensus rule reduces *E* uncertainty (Δ*E* -> *0*), time uncertainty increases (Δ*t* -> ∞). (Note: feedback renormalizes 0's and ∞'s.)

Conclusions

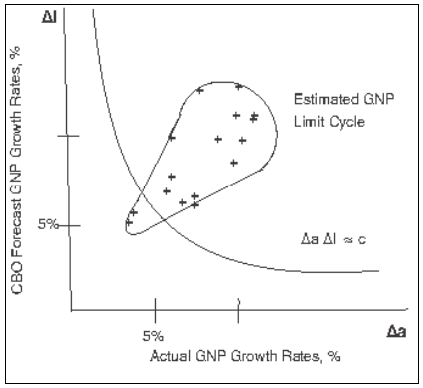
- Groups are at a lower entropy than $\sum x_i$; M(group) -> classical *I*, $\sum x_i \neq$ Group (Carley; Lipshitz; Zeilinger)
- The Field Test of the measurement problem justifies the quantum perturbation model; it is the 1st demonstration of a mathematical physics equation for competing organizations
- Why use a bistable model?
  - Exploits multiple interpretations of reality
  - May produce better decisions, controls and possibly autonomy for MAS's
  - Bistable agents may be more efficient models of social reality

Neutrals -> Superpositioning



Over time, competition for neutrals forces losers to adapt by "turning" (e.g., Democratic President enacts welfare reform; Republican President encourages Medicare reform)

Fdbk on Eqn (1)?



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Future Research: Can Superpositioning, Fourier comp. (*N*), F fcns (S.R.) & fdbk (L.C.'s) solve autonomy?

•**Bifurcations:** The double square well model represents *E* barrier between opponents and neutral middle, overcome in democracy by compromise or persuasion => regulation

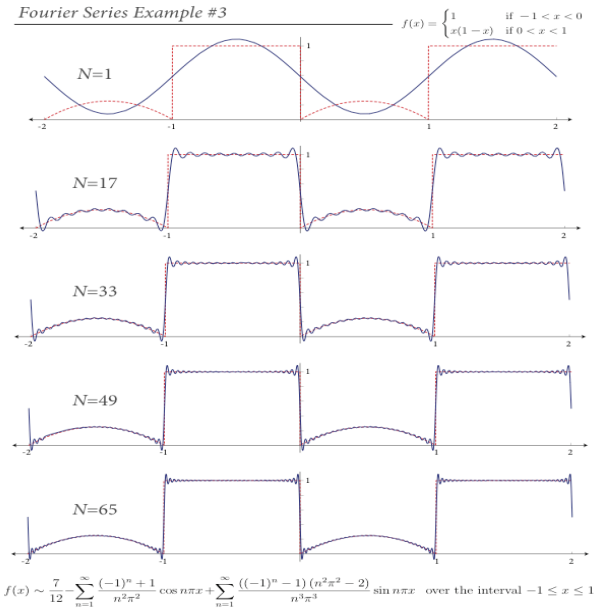
•**Stochastic Resonance:** Random "exploration of alternatives"; *dI/dt and dX/dt* are Kolmogorov coupled nonlinear equations w/ $F_E(t)$ as forcing function => dampening under CDM, self-organization under DDM -> + Fourier components in system (**Emergence**; **Power**)

- •Increasing # of neutrals improves dm

•**Regulatory Control: +/-** Feedback & "turning" produce non-linear limit cycles (**May's 2001 + fourier components, critical link**)

- •Math control theory: can + innovation under CDM by + competition -> instability
- • can - innovation under DDM by + cooperation or consensus -> instability

+ Fourier Components -> Emergence



•Representations improve w/+ Fourier components (also, music signals, data mining, system control). Similar to constructing a photograph by adding photons (French & Taylor (1978) Introduction to quantum physics, MIT press, p. 2-10).

•Fourier components reflect + competitive skills, + market gains (e.g., Toyota), and with Δt as the time to respond (as Δt increases, competitive skills lessen)

Additional Reading

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