COPING WITH COMPLEXITY AND UNCERTAINTY

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Summary

The computational and heuristic strategies used by decision makers to manage uncertainty in complex systems originated with the early landmark contributions of J. von Neumann. These contributions took the form of artificial intelligence and artificial life concepts, and then evolved more specifically into game theory, expert systems, neural networks, genetic algorithms and evolutionary computations, cellular automata, and techniques specific to the control of deterministic chaos. Psychological heuristics for the control of uncertainty in chaotic, and otherwise complex, organizational or economic systems take the form of tracking nonlinear dynamic patterns, parameter control, targeting, and forced periodicity. Problems in and challenges to the establishment of the external validity of expert systems and other decision-emulation programs are described.

1. Introduction

Decision theories and decision-support techniques and computer programs are almost universally designed to assist decision makers to maximize their decision outcomes and minimize decision errors. Decision theory and decision support are interesting and valuable endeavors because the decisions in question typically occur in situations where the information on which the decision is based is incomplete, error-prone, and changing over time. Additionally, decision makers are likely to pay for certainty; they do so by selecting decision choices that involve less risk, or by accessing the missing information sources that would serve to reduce uncertainty.

Uncertainty in decision making takes several forms: (a) The decision maker knows what the possible outcomes would be, knows the probabilities associated with each outcome, but is compelled to guess which of the outcomes will actually take place. (b) The decision maker knows what the possible outcomes would be, but does not know the
probabilities associated with each outcome; guessing which of the outcomes will actually take place is a more specious endeavor. (c) The decision maker has an incomplete knowledge of the possible outcomes, and hence the probabilities associated with any of the known options are speculative. (d) The decision maker has incorrectly identified the problem, and as a result identified all the wrong options; the probabilities associated with any of the incorrect options thus become meaningless if they were known.

In light of the potential complexity of situations, probabilities, and alternatives that face decision makers, it would be valuable to have decision aids that would identify scenarios, probabilities, and make related calculations. Decision aids may take the form of singular simple equations, such as a multiple linear regression equation, or a complex computer program such as some of the expert systems that currently exist. It is here that the linkage between complexity theory and the control of uncertainty dates back to the late 1940s. The landmark contributions are chronicled here in three epochs: artificial life and artificial intelligence, control of chaos from the mathematical point of view, and control of dynamical events from the point of view of social processes.

2. Artificial Life and Artificial Intelligence

Although John von Neumann is perhaps best known for the theory and development of electronic computers, he also created a vision for software that became known as "artificial life." The central premise was that all life could be expressed (reduced to) the processing of information. Artificial life unfolded in a series of important and complex steps over the subsequent fifty years. The following sections thus pertain to game theory, expert systems, and evolutionary programming.

2.1. Game theory

Game theory is the 1953 joint product of John von Neumann and economist Oscar Morgenstern. It offers many possible models to describe strategic, utility-driven interactions between two or more players or negotiating parties. Two opposing decision makers have a series of action options, and the utility of each action option depends on which option the opponent chooses. Joint utilities may favor strictly competitive behavior, cooperative behavior, or mixed motive (choices between competitive and cooperative) options.

In a strictly competitive game, a gain for one player is a loss for another player. Thus strategic decision makers seek to maximize their own gains and minimize gains for their opponents; this is the minimax principle. Depending on the array of options facing each player and the utilities associated with each option, there may be a saddle point (also known as a Nash equilibrium) in the game, which would be a combination of game actions that the two opposing players would take. The existence of a saddle point implies that the outcome of a game is perfectly determined. Perfect determinism can occur if one player has full knowledge of the utilities and options facing the opponent. The theory behind the strictly competitive games has become a valuable decision aid in interpreting historic military decisions.
Prisoner's Dilemma is a mixed motive game that captured a great deal of attention as an explanation of virtually all phenomena that involve a conflict between cooperation and competition. In the Prisoner's Dilemma the players have the option of acting in cooperation with their partners, in which case both partners receive the same desirable payoff. Players' alternative option is to defect on their partner to receive greater personal payoff at their partner's expense; this is the competitive outcome.

Strictly cooperative games involve outcomes that benefit all players if all, or enough, players select the correct action option. In many such games the correct actions need to be enacted simultaneously, in which case the game can be referred to as a coordination game. In Stag Hunt, players (hunters) must exert enough effort while working together to capture the prey. Stag Hunt would explain the social loafing phenomenon in human work groups. Loafing (or free rider behavior) occurs when a group shares a reward, but only a portion of the members are working toward the reward. The reward is attained so long as enough group members do enough work.

In Intersection, the players are vehicle drivers who are approaching a four-way stop intersection. Their task is to figure out what is the rule by which the vehicles are taking turns going through the intersection, and then go through the intersection at the correct time. The Intersection game has been studied as a general model for human work group coordination and the performance of collectives.

Bandwagon is a strictly cooperative game in which the costs of engaging in a behavior or strategy decrease to the extent that more people have already chosen that strategy. One application was an explanation for the aggregation of the large crowd of people whose protest ultimately resulted in the demolition of the Berlin Wall in 1989. It became less costly to join the protest as the existing crowd became larger. Another application of the bandwagon involved inverse utilities: It became more attractive to join large discussion groups on the Internet if there were larger numbers of people generating useful information.

The mechanisms behind economic decisions have a counterpart in evolutionary biology, according to the work of John Maynard Smith. Evolutionarily stable states occur when a game is played repeatedly by a pool of potential players. Often these iterated games are simulated on a computer program. Iterated games produce long-run proportions of cooperative and competitive responses. These evolutionarily stable states are related to, but not guaranteed to be equal to, the Nash equilibria.

Iterated gaming venues eventually produce oligarchic control strategies, according to the work of Robert Axelrod. Specifically, rates of defection in a Prisoners' Dilemma are substantially attenuated if the (computer simulated) players adopt a tit-for-tat strategy in which cooperation and defection from players is a predictable result from a player's prior use of cooperation or defection strategies. In other forms of oligarchic control, players may select cooperative behavior over defection, in spite of utilities to the contrary, if they are trying to protect a reputation.
2.2. Expert Systems

Expert Systems are computer programs that are designed to emulate the knowledge base and the problem solving capabilities of human experts. They may take the form of simulations of entire complex systems such as urban planning, where rules and heuristics are being discovered regularly by human experts. They might take the form of formal, closed logic systems such as games of chess. In either case, the expert system is designed for interaction with a human who can ask questions, be asked questions and be given requests for data or parameter choices, and receive the answer once the program has been executed.

An expert system contains three main parts: the knowledge base, the inference engine, and the interface. The knowledge base consists of data: tables of numbers, facts, important relationships, critical values, equations where applicable, or sets of qualitative descriptors.

Knowledge is represented within the expert system as rules which take the form of if-then statements.

An inference engine is a rule structure that allows us to answer a question by addressing the facts, or expert knowledge base, and drawing conclusions. Conclusions may be very simple or they may involve a complicated analysis. Inference engines can take on varying levels of complexity. The simplest system is the algorithmic system, which executes rules in the same order without variation. The second level of complexity is the rule-based system. Rule-based systems contain meta-rules; meta-rules are groups of rules that govern the execution of other rules.

A frame-based system is centered on a classification scheme that contains a hierarchy of abstracts, prototypes and examples of objects (entities). A frame will consist of a set of attributes and relationships among attributes for each object in the taxonomy. A well-developed frame system will enhance the potential for rule structure flexibility and a greater range of inferencing.

A recursive system may be frame-based or simply rule-based. Its distinguishing feature is that the system is capable of reading itself as a subroutine, altering its own programming, and returning to its normal (enhanced) functions. For instance, a recursive frame-based system would refresh its classification scheme periodically as new objects arrived for classification. Although some programs have been written with limited recursive capabilities, most updates to AI products are done manually.

The interface is the method by which the system user can ask questions and have the questions understood, and read answers delivered by the program. Interfaces may be driven by highly structured commands, natural language processors that allow humans to ask their questions in a variety of language expressions, or point-and-click styles of interaction. The interface is also the medium by which the human operator can update data and rule structures.
We can, of course invoke equations that put a series of possible if-then rules into continuous form; this is small matter for the present moment. There are different types of rules. For instance some rules allow for certain outcomes or additional inference steps, while other rules prevent certain outcomes or inference steps. Some rules must be followed rigidly, while others are more flexible, taking on the characteristic of guidelines, rather than rules in the usual sense. Some rules positively classify an object, while other rules invoke a prototype in a classification problem and then cancel characteristics of the prototypes.

The first task in establishing the validity of a system is to establish the validity of individual rules contributing to the expert system. We might ask, therefore, how the initial knowledge base was identified and then converted into the if-then rules. Validity problems compound, however, when programmers pull rules together with meta-rules. Questions arise as to whether the rules are being assembled appropriately. Does the output -- both the facts and interpretations -- resemble the output from human decision makers?

Two additional problems for validity assessment proceed from the following: the Barnum effect, and the meta-interpretive problem. In order to appreciate these problems with validity assessment, it is important to bear in mind that expert systems do not typically conclude with a pile of numerical tables. They conclude with interpretations of those critical numbers in terms of the original questions posed to the expert: What is the diagnosis and preferred program of treatment? What are the policy implications based on the economic indicators? How might a person with certain measured personality characteristics behave in particular benchmark work situations? The elementary report statements would be generated from simple rules of the form: If [fact] then [report statement].

The Barnum effect in psychological testing and interpretation got its name from the circus master P. T. Barnum. He was noted for flamboyant statements that were true for most people and generally flattering. The audience would conclude that what he said was true. In a psychological measurement and reporting situation, the goal of the measurement and reporting is to make statements and forecasts regarding an individual's personality and behavior. If an interpretive report was stated in vague generalities that could apply to most people, and said something flattering about a person, the person would read the report and say that the results were accurate. We can transport the same principle to a policy making arena as well. There, the Barnum effect would take the form of vague forecasts that would be hard to falsify, and that are generally favorable to a reader's expectations. The reader would report, "It must be right. It agrees with my views entirely." Thus it was necessary to develop experimental designs that would isolate the Barnum effect and capture the extent to which the expert system is telling something new, unique, and verifiable.

The meta-interpretive problem arises when a complex simulation with many specific outcomes is interpreted in an integrative whole. Ideally, an expert can read the verbal output and translate it back to the numerical values that would have generated the statements. The extent to which this is possible is called the meta-interpretive reliability of the expert system. This form of reliability is, in turn, an upper limit to the external
validity of the expert system. Meta-interpretive reliability is attenuated to the extent that the test modules, which are generated in different combinations in complex reports, take on different shades of meaning because of their context. The susceptibility of statements to attenuation has been traced in part to poor word choices and vagueness in the elementary statements.

2.3. Situation Awareness

The interface is an important feature of the expert system, and it has been given some focused attention using the concept of “smart displays.” A smart display would convey information to the operator in a form that the user needs to make a decision. This often means changing the definition of the display from a report that it made from the system’s point of view to one that reflects the user’s point of view (Guastello, 2006). The concept of a smart display has carried over into more expansive work on the topic of “situation awareness,” particularly with military and emergency response applications in mind (Endsley, Bolté, & Jones, 2003).

One important challenge is to develop systems that facilitate group or team problem solving where team members are not in the same location. “Adaptive and timely information sharing does not mean that everybody has access to the same information at the same time, but means communicating the right information (and no more than this) to the right person at the right time” (Gorman, Cooke, & Winner, 2006, p. 1323). The newfound reliance on information technologies may possibly solve the geographic colocation problem and speed the delivery of information, but at the greater risk of communication outages and information overload.

2.4. Artificial Life and Related Computations

Artificial life models involve different classes of applications and rule structures compared to expert systems, but the underlying issues are relatively the same. Artificial life computations, in some opinions, could produce more realistic models than did expert systems because the behavioral systems that are being modeled involve a comparably small number of rules. Three principal types of complex computations have evolved nonetheless. Although they have some relevance as tools for forecasting and policy development for complex system, their potential remains to be explored more fully in these regards.

A neural network is a computation that is designed to emulate the behavior of neural structures. These originated as structures for robotics where the motion of limbs required modeling along with some semblance of learning and binary decision making capability.

There have been some reported attempts to use neural networks as black box computational devices that would search for nonlinear patterns of events, create a model for those events internally, and proceed to use that model to predict the outcome of new cases. Neural networks have some attractiveness because they allow decision makers to engage the computation without a theory, hypothesis, or clue regarding what nonlinear structure could underlie the process. It remains to be shown whether, and under what
conditions, neural networks can describe non-neurological events with any greater accuracy than other state-of-the-science statistical practices.

Genetic algorithms are computational strategies designed to track possible mutations of genes, or entire species, as a result of different mutation rates, breeding conditions, and environmental assaults. They are particularly attractive for their ability, in principle, to identify emerging life forms. There exists a counterpoint, however, between the theoretically grounded biological processes that comprise the rule structure of a true genetic algorithm, and the locally-modified deviation from theory, known as the evolutionary computation. The theoretically-pure varieties tend to be less accurate than the situationally modified varieties, although the latter sacrifice generalizability for adaptiveness to localized, constrained problems. It also remains to be shown whether, and under what conditions, genetic algorithms and evolutionary computations can describe non-genetic events with any greater accuracy than other state-of-the-science statistical practices.

Cellular automata are computations that have been useful for illustrating how local interactions between elementary system members can produce global structures and patterns. Although “cell” in this case is analogous to the cell of an organism, it need only be a patch of space in any topography, or the cell of a grid or sheet of graph paper. Each cell can take on two or more discrete states. A cell’s state is determined by rules that are based upon what the cell’s eight surrounding neighbors are doing. There is no restriction to the nature or complexity of the underlying rules, which should be chosen based on the constraints and properties of the system under study. To date, cellular automata have been used to describe the diffusion of attitudes, patchiness of aquatic ecological systems, and the irregularities of land use across countries such as Belgium and Senegal.

3. Control of Chaos

This section describes techniques for controlling dynamical processes, especially those that involve chaos. The principal means of control originated from the underlying mathematical theory for the nonlinear dynamics. Some of the ideas have crossed into psychological theories of cognition, organizational behavior, and economics. Some ideas have, to date, received attention from experimentalists. The four methods are tracking nonlinear processes, adding chaos to control chaos, using system control parameters, and the method of forced periodicity.

The interest in controlling chaos applies to both directions of control: Sometimes decision makers want to minimize the unpredictability associated with chaotic processes. They might do so by regularizing the business stimuli in some fashion. At other times decision makers seek to identify future business states and options that will become available, and compute the odds of success for various responses they could make.

On the other hand, organizations might want to increase entropy to propel an organizational change, enhance its repertoire of adaptive responses to the economic and social environment, or to introduce original business initiatives. These three objectives
are often interrelated (see chapter on Complexity and Organizational Behavior, this volume). As a result, an organization needs a well-developed culture that is conducive to creative thinking with respect to both original initiatives and adaptive responses. The definition of sufficient capability takes the form of the Law of Requisite Variety. The Law states that the controller of a system must be at least as complex as the system itself.

“Complex” in the foregoing context usually implies the number of discrete states that a system can assume. The notion of discrete states, in turn, implies a sense of discontinuity. There may be underlying continuities, however, as catastrophe theory has illustrated. Specific means for controlling or managing the uncertainties associated with complex systems are detailed next.

3.1. Tracking Nonlinear Dynamics in Systems

There are three groups of studies that address some aspect of human ability to track complex dynamic processes. In the first series of experiments, human participants were presented with numeric series that were generated from the Verhulst (or logistic map) equation:

\[ X_2 = CX_1 (1 - X_1) \]

The participants’ task was to predict the next value in the series. Correlations between actual and predicted values ranged from .55 to .85 in the most recent study from this series by Ward and West. Decision makers were found to have engaged in two heuristics that assisted their forecasts. The respondents ignored the fine differences in numerical values that were associated with extreme decimal places; thus the gross swings in actual values were more important to their forecasts than the fine details. The second heuristic was based on the forecasts on sequential pairs of actual values. Thus the intuition of a sequential point in the series depends on the direction and size of the previous movement in the actual values.

In the second series of studies, respondents played a computer simulation of a beer distributorship. Their task was to place orders and receive deliveries from breweries and make deliveries to restaurants, bars, and stores without overflowing their warehouse capacity or running out of stock. Meanwhile, the beer production and deliveries were interrupted by “strikes”, “transportation problems”, and “demand shifts.” Respondents’ beer inventories were found to be chaotic over time. It is noteworthy that only 11% of players were capable of maintaining a beer inventory between the two limits for the duration of the game.

A third series of studies centered on the management of work flows in a hierarchical organization. In these experiments, work organizations were contrived and consisted of three to six groups (or subunits). The “work” consisted of a complex ball tossing activity. When a group completed its work cycle, it sent a “report” to the management group. When the management group received a report from each of its work groups, a completed work unit was recorded. The “experimental groups” were organized into two or three levels of hierarchy. The organization’s work routine was aperiodically interrupted by “blackouts,” “strikes,” “personnel changes,” and other interventions.
The experimental results showed that the output of work groups was chaotic over time, but the relative amounts of determinism versus noise seemed to vary across experimental situations as did the extent to which management could help its own flow of performance. First-level work groups could be seen to be becoming gradually more efficient over time; they produced more work per unit of time as a general rule. Some management teams, however, improved performance gradually while others declined. Most management teams exhibited instability in performance with transient dynamics. The collective result of this group of studies showed that the cognitive control of work performance in hierarchies is unstable at best. Thus the type of top-down driver-slave relationship that is observed in physical systems with emerging hierarchies does not necessarily form in human work systems. Rather, it would appear that the dynamical forcing function would more often be from lower to upper management.

3.2. Control Parameter Manipulation

The Verhulst equation has received enormous attention in many complexity studies because of its one control that governs changes in system behavior from fixed to periodic, aperiodic, and chaotic states. Although there is no guarantee that a real system can be controlled through all those states by just one parameter, it is intriguing, nonetheless, that a wide range of behavior patterns could be controlled by a very few well-chosen parameters.

One application of chaotic control is found in the tatonnement process, whereby buyers and sellers strike a price for goods, where the final prices are Walrasian (classical) equilibria. The process begins by the two parties each setting a target price at which they want to buy or sell the commodity. The bargaining partners state their targets to each other, and, in the usual case, sellers set higher target prices than buyers. The bargaining partners then give each other adjusted price targets, the difference between the price targets narrows, and the process continues until a mutually acceptable price is reached. The typical fluctuations in price targets are thought to follow the logistic map pattern while the control parameter decreases in value over time.

The targeting method has also been shown to be an efficient remedy for organizations that are producing and selling goods at chaotic levels of profit. Sale prices are related to supply and demand levels. Supply levels in turn fluctuate in concert with changing production volumes and interest rates. Under these circumstances, organizations are likely to adjust their prices and production chaotically. Better results with respect to mean sales and profitability can be obtained by targeting a production policy that is dynamically an unstable fixed point. This form of targeting, once again, involves some systematic trial and error.

3.3. Periodic Entrainment

The Ott-Grebogi-Yorke (OGY) method for controlling chaos is based on the relationship between oscillators and chaos: Three coupled oscillations are minimally sufficient to produce chaotic time series. Many economic and biological events exhibit periodic behavior, or are the result of coupled periodic oscillators. Although not all
possible combinations of oscillations produce chaos, it is still a viable analytic strategy, nonetheless, to decompose chaos into its contributing oscillating functions.

The OGY method for controlling chaos involves targeting unstable periodic functions, and strengthening the attractiveness of one periodic function so that it becomes dominant. As a particular oscillation increases in strength, points from nearby trajectories become entrained on the stable manifold of the dominant orbit. The complexity of temporal motion then simplifies to a simple periodic orbit.

In one simulated economic example of the OGY method, two competing firms became entrained with respect to their production and sales cycles. Market share was the behavior that changed chaotically. A first-strike advantage was also discovered, whereby the firm that locks into its own orbit first dominates the other firm.

The OGY method has some limitations in situations where its computations are to be taken literally to model behaviors of real, rather than simulated, systems. The principle problem is its susceptibility to disruption from noise. An external shock will be carried through subsequent iterations of a chaotic system. The disruptions become magnified and the tracking of the stable manifold becomes impaired. For this reason, the literal application of the OGY method may give way to targeting methods in practical or policy-making settings.

3.4. Cognitive Strategies for Complexity

The psychological methods for adapting to nonlinear dynamical processes, discussed so far, include several abilities and cognitive strategies. They include the ability to discern fixed point, periodic, and chaotic patterns over time. Individuals also differ in their ability to track chaotic behaviors where sensitive dependence is critical. They differ in their abilities to manage and produce stable work outflows from complex systems that typically have parallel processes. Although all of these strategies may be considered as “computations” made by living systems, there are also literal strategies of computation involved in the control of chaos. Heuristic substitutes in the form of targeting are useful also.

Five other cognitive strategies have been suggested as potentially relevant to organizational management. These candidates are based on the dynamics of boundaries, fractals, feedback loops, self-organization and coupling. All five have been offered as descriptions of internal behaviors of the organization. Four out of the five represent aspects of self-organization; the exception would be the fractals The substantiation for the claims have, to date, rested upon plausible analogies rather than literal data analysis.

The fractal concept implies that it is often instructive for organizations, when attempting to plot new strategies and solve problems, to examine how basic themes of organizational life and training repeat themselves throughout the organization. One might then look for themes that represent computations “seeds,” then search for evolutionary variety. One might also examine the extent to which there are “scaling effects” whereby a theme that is found at a micro-level of the system re-appears at a broader organizational level.
The dynamics of self-organization are described in other chapters in this volume. For present purposes, however, self-organization is the tendency for systems to create cohesive structures when they are subjected to prolonged states of chaos or entropy. Structures form through the development of feedback loops among subsystems. As a result of the feedback structure, subsystems may become tightly or loosely coupled. Strategists might want to examine the conditions under which structures have formed, and the nature and placement of the feedback loops.

A successful diagnosis of conditions and strategy formation is thought to be predicated on finding a dynamical key to the system. A dynamical key represents the central connections among feedback loops within a system. The failure to break up the key connections typically results in a reformation of the earlier structures, sometimes with small mutations that counteract an ineffectual intervention.

Boundary conditions, finally, are known to affect the self-organization of systems. Their shape, placement, and permeability affect the flow of information across the system's boundary and the formation of structures within. Although it is convenient to think of boundaries in concrete terms, boundaries are also well-known in creative problem solving where they take the form of situational constraints and assumptions. A strategist then considers the extent to which the constraint is really necessary or over-represented.

**Glossary**

(Glossary abbreviations indicate the origins of the concept, as follows: biol. = biology; econ. = economics; math. = mathematics other than topology; psyc. = psychology; sys. = systems science; topol. = topology.)

**Artificial intelligence:** math., psyc., sys. The study of computational techniques that emulate complex human decision processes. Also see artificial life and expert systems.

**Artificial life:** math., psyc., sys. The study of computational techniques that emulate simple or complex biological processes other than human decision systems. Also see cellular automata, evolutionary computation, genetic algorithms, and neural network.

**Attractor:** topol. A section of space into which points are attracted and from which they seldom leave. Attractors come in different levels of complexity of behavior, ranging from the fixed point to the chaotic attractor.

**Barnum effect:** psyc. An overly general, and often flattering, interpretive statement that could legitimately apply to a large segment of the population without providing any person-specific information.

**Cellular automata:** biol., math., sys. Computer program based on grid patterns of at least two dimensions where patterns of local interactions between adjacent cells are often seen to form emergent global structures.

**Chaos:** topol. A random-appearing time series that displays exponential expansion, sensitivity to initial conditions, boundedness, and non-repeatability. The amount of chaotic variance in a time series is
characterized in terms of turbulence, complexity, and dimensionality.

**Evolutionary computation:**
biol., math., sys. Computer program that emulates the computation of evolutionary processes that are based upon, but usually more situationally specific than, genetic algorithms.

**Expert system:**
psyc. sys. Computer program that emulates the reasoning of human experts in any of a variety of substantive areas.

**Expert system, frame:**
sys. A string of data that comprises a description of an element in an expert system that is based on classification strategies.

**Expert system, inference engine:**
sys. Section of an expert system, located between the knowledge base and the interface that computes the reasoning strategies.

**Expert system, meta-rule:**
sys. Rule used in inference engines that affect the sequence and execution of other rules in an expert system.

**Game theory:**
econ. A theoretical framework for defining and predicting strategic behavior of two or more decision makers, based on the utilities of joint outcomes for the decision makers. The theory is noteworthy for its use of cooperative and competitive behaviors, coordinated activities among strategists, and evolutionary outcomes with repeated exchanges.

**Game theory, minimax principle:**
econ. Formalization of competitive behavior whereby gains for one player directly translate into losses for another player.

**Game theory, Prisoner’s Dilemma:**
econ., psyc. Game requiring that players choose between competitive and cooperative behavior.

**Game theory, Stag Hunt:**
econ., psyc. Game requiring strictly cooperative strategies. Analogous to the social loafing phenomenon.

**Game theory, Intersection:**
econ., psyc. Game requiring strictly cooperative strategies whereby the players must figure out the rules of play. Analogous to behavior of automobiles at 4-way stop intersections.

**Game theory, Bandwagon:**
econ. Game requiring strictly cooperative strategies where the utilities to new players entering the game increase and costs to them decrease, as more players accumulate.

**Game theory, evolutionarily stable states:**
biol., econ. Outcome of iterated games.

**Genetic algorithm:**

**Law of Requisite Variety:**
sys. Engineering principle which states that the controller of a system must be at least as complex as the system itself.

**Logistic map:**
biol. math. Also known as the Fiegenbaum Map and Verhulst Equation. The iterative function \( X_2 = CX_1 (1 - X_1) \). The dynamical properties of \( X_1 \) change from fixed to periodic, to complex-periodic, to chaotic as control parameter \( c \) is allowed to increase.

**Meta-interpretive:**
psyc., sys. The extent to which the interpretive statements given
reliability: by an expert system can be retraced to their numerical sources.
OGY: math. Method of controlling chaos by deconstructing and then forcing periodic behavior, due to E. Ott, C. Grebogi, and J. Yorke.
Targeting: econ. A heuristic used by human decision makers as a necessary first step toward controlling a chaotic process or bringing a tatonnement process to equilibrium.
Situation awareness: psyc. An accurate perception of the environment that allows optimal decisions and forecasts of future states of the system.
Verhulst equation: biol. math. See logistic map.

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Biographical Sketch

Stephen J. Guastello is Professor of Psychology at Marquette University, and specializes in industrial-organizational psychology and human factors engineering. He is the author of Chaos, catastrophe, and human affairs: Applications of nonlinear dynamics to work, (1995, Lawrence Erlbaum Associates), Managing Emergent Phenomena: Nonlinear dynamics in work organizations. (2002, Lawrence Erlbaum Associates), and Human Factors Engineering and Ergonomics: A systems approach (2006, Lawrence Erlbaum Associates), and over 90 journal articles and book chapters. Dr. Guastello is also the editor-in-chief of the journal Nonlinear Dynamics, Psychology, and Life Sciences. He has served as a consultant to numerous organizations providing expertise in the areas of personnel selection and retention, occupational accident analysis and prevention, and management development.

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