Complex Adaptive Systems and the Threshold Effect: Views from the Natural and Social Sciences:
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Using Complex Adaptive Systems to Simulate Information Operations at the Department of Defense

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Abstract

Irregular Warfare (IW), with its emphasis on social and cognitive phenomena such as population sentiment, is a major new focus of the Department of Defense (DoD). One of the most important classes of IW action is Information Operations (IO), the use of information to influence sentiment. With the DoD's new focus on IW comes the new need to analyze and forecast the effects of IO actions on population sentiment. Analysts at the DoD traditionally use Modeling and Simulation to analyze and forecast the effects of conventional warfare's actions on the outcome of wars, but IW and IO in particular are far more complex than conventional physics-based simulations. DoD analysts are in the early stages of looking for scientifically rigorous methods in the Modeling and Simulation of IO's complex effects. This paper presents the state of IO modeling and simulation in the DoD, using examples from several computer models now being used, in these early stages of IW analysis. It discusses how the ideas of Complex Adaptive Systems (CAS) and threshold events in particular may be incorporated into IO modeling in order to increase its scientific rigor, fidelity, and validity.

Complex Adaptive Systems and Validity

It is important to retain the principles of scientific rigor as we move from physics-based to social-based modeling. However, identifying these principles in a new application is not a straight-forward task. Many of the principles appear to conflict, because the roadmap to the epistemology of social simulation is still being negotiated.

A simulation's value is in "walking through" what is too complex to be solved analytically. In physics-based simulation, operations research (OR) analysts use conventional simulation to answer questions such as, "How many and what types of airplanes are needed to make it likely that a missing vessel is found?" Simulation makes this determination by walking through rules about the properties of simulated entities over time and space, including probabilities of detection and various other factors in the calculation. If the facts about the resources are put into the simulation correctly, many runs will give a reliable confidence interval for answers to questions like, "Given N of airplane A, will vessel B be found within M hours?"

"Walking through" rules about the properties of social entities in particular complex scenarios is the value in social simulation as well. In fact, nonlinearity is an important aspect of a simulation's epistemology: if a simulation's output is the direct, obvious and linear result of its input, then it is not finding an answer a question, but instead, it is parroting back simple transformations of the input. However, the output of many IW and IO models currently used in the DoD seems linear and predictable in relation to the input. For example, the United Kingdom's Peace Support Operations Model (PSOM) is an IW model that simulates a population's consent to be governed. Analysts have shown concern about linear relations between consent and other factors, making the outcomes of actions easier to predict than they are in real life (Marling, 2009). If a model is too linear, it will not reveal unintended consequences of actions, and won't even answer any questions that an analyst didn't have the answers to to begin with. More importantly, it is against the principles of scientific rigor to put the answer to the question in the question itself, and so nonlinearity is actually needed in computer simulation for validity's sake.

However, there is also a tension within the DoD about nonlinearity, because it seems to violate validation principles of transparency and traceability. Transparency and traceability are important to DoD analysts because they need to know why a result occurs and explain it to their leadership. If a simulation is rigged to parrot back the input, then at least it is traceable. Exploring the natural, unrigged implications of properties in new circumstances is more difficult to trace. Historically, the DoD has taken issue with CAS and Artificial Intelligence (AI) "black box" techniques such as neural networks. There is an apocryphal story in the DoD about the use of neural nets to detect camouflaged tanks, that illustrates the reason why. A neural network was used to classify pictures of terrain based on whether they have a camouflaged tank in them or not. It was fed input of pictures of camouflaged tanks taken on a sunny day and pictures without tanks taken on a cloudy day. The neural net mistakenly classified the pictures based on light intensity rather on than on whether they were camouflaged or not (Fraser, 2003). Without knowing why, human judges cannot determine if they trust the automated reasoning behind the technique.

Agent-Based Modeling (ABM) is a CAS technique that embodies this validity conundrum. An ABM models entities that have agency, the ability to perceive and react to their environment in an autonomous manner. An ABM exhibits emergent behavior: the properties of entities that are input to the simulation are supposed to recombine and result in patterns that are nonlinear, or more than the sum of their parts. The more you can explore the natural, unintended consequences of the configuration, the more valid it is because it lacks being "rigged," but at the same time, the less traceable it is. In fact, when true emergence occurs in natural systems, one no longer needs the rules of the lower level system to describe the newly formed upper level system behaviors, because they have become new entities with new rules. For example, one need not refer to the rules of lower level quantum mechanics that apply at the molecular level, when one is describing the physics of bridges, even though bridges are ultimately composed with molecules. Instead, the properties are described with Newton's laws, which do not reduce to quantum mechanics. Some CAS experts feel that this irreducibility implies that we cannot know the reason for true emergent behavior and that it is untraceable in principle (Bar-Yam, 2004). True, irreducible emergence, also called strong emergence, applies to social emergence as well. As in quantum mechanics vs. Newtonian mechanics in physics, the properties of the micro level in a social system, are different from, are described with a different language than, and are not referred to in the language of, the macro level. In physics and in sociology, the micro level and the macro level are different levels of description, and the macro does not reduce to the micro. For example, micro-sociology and macro-sociology are two independent disciplines that do not refer to each other. However, bridging the gap between the micro and macro in the social sciences is not quite as difficult as finding a unified field theory to bridge the gap in physics. In fact, in sociology, there is a field of study of how one level of description leads to the other, called "micro-macro integration."

It may be that it is difficult to imagine how the micro and macro influence each other in the social sciences, but it is not untraceable in principle. In fact, an agent-based model is a good way to bring micro-macro integration into our comprehension. If the micro and macro influence each other in ways too complicated for our minds to compute, the computer is able to do that computation for us. We could put the rules of the micro level in, see how macro patterns known to exist are derived, and then test the system using statistical and debugging techniques to tease out which particular sets of micro rules cause the macro patterns and how. Because an agent-based model walks through the implication of the properties of agents in time and space, including the agent's reaction not only to the scenario but to each other, we are able to examine and describe the process by which the micro derives the macro and vice versa. This process is one that the simulation was not programmed to come up with in advance. If we find this process to exist in the real world, then the agent based model has helped us to discover a theory to test. It may be hard to find out exactly how the micro and macro interact, but the reason is contained "within the box," inside of a computer program, in which all else may be held the same and cause may be traced.

In fact, the cause of any emergent phenomena within an ABM should be traced in order to ensure that it is not an artifact such as occurred in the "camouflaged tanks" neural network example. Once we ensure that the input micro rules, the emergent macro patterns, and the emergent interactions between micro and macro all have fidelity with processes in the real world, then we have reason believe that the theory of Micro Macro Integration expressed by the ABM is valid. By the principle of Ockham's razor, if a few micro phenomena known to exist derive many macro phenomena known to exist, then it is likely we have chosen the correct micro phenomena. The smallest primordial soup of micro phenomena is the most parsimonious explanation of the macro, and the most likely to be correct. Because Agent-Based Models have a good epistemology, the DoD should not over-emphasize transparency and traceability in their validations, but rather support the development of tools to trace out the cause of emergent phenomena in ABM.

ABM and IO Modeling

Agent-Based Modeling's "emergence" of social phenomena is not only good epistemologically, it also has importance to IO modeling. Micro-macro integration can tell us how our actions on the micro level effect the macro level, and in the military, the micro level is the tactical level, and the macro level is the strategic level. As Michael Bauman, director of the Army's Training and Doctrine Command Analysis Center (TRAC) said, "IW is what happens between soldiers and people at the tactical level." (Peck, 2009). Our goal in the analysis of IO is to understand the effects of our individual actions on the war fight, that is, to see how actions at the tactical level affect the strategic level. This is precisely what micro-macro integration tells us, and ABM is the tool of choice for that.

ABM is also the tool of choice for IO and particularly PSYOPS modeling, because ABM facilitates the modeling of cognition. Intelligent agents and agents that have cognitive architectures are particularly well-suited. Many experts in ABM believe that learning and cognition are essential traits of agents, and that simple, reactive agents which do not interpret their environment and learn should be called "proto-agents" because they do not have full agency (North and Macal, 2007). Amongst cognitive agents, interpretive agents are the best suited for IO modeling because they simulate the interpretation of meaning.

However, the state of the art in IO modeling is not at the point where we can effectively test the strategic effects of tactical actions. Most models of IO in the DoD compute at a single level of description.

IO Models at the Strategic Level

Agent-Based Models are not the only ones that compute unintended effects: any model that incorporates non-linearity has that potential. System Dynamics Models (SDM) use differential equations to model the change in amounts over time, incorporating positive and negative feedback loops. While the variables of a System Dynamics model usually stay at the same level of description, the feedback makes them non-linear, so that unexpected results may occur. The problem with using these models for IO is that the individual is taken out of the equation and "averaged" individuals are used instead. IO is one of those cases where the tails of the distribution matter, that is, the times when an agent behaves or thinks outside of the norm matters, because changes in belief often start with the breaking of norms. Further, with a single level method such as System Dynamics, we cannot explore how the relations at the micro tactical level change the relations at the macro strategic level, because the individual relations at the single level are set statically in advance, and do not change during the simulation to create patterns at a macro level. The relations that exist dominate and are many in relation to the new "unintended consequence" relations that a run of the simulation reveals in the existing variables. Instead of a primordial soup of few assumptions and many computed unexpected consequences at a different level of description, you have many assumptions with few unexpected consequences at the same level. System Dynamics models are typically less parsimonious than Agent-Based Models, and Ockham's razor does not apply. Thus, System Dynamics models are more descriptive than analytic, and more suited for seeing what happens when you already know what the relations between variables are rather than for exploring what other relations exist given only a few.

One example of a System Dynamics model used for IO by the DoD at the Joint Services level is Brett Pierson's "Hairball that Stabilized Iraq" (Pierson et al 2008), a model of the Army's FM 3-24 counter-insurgency(COIN) manual. Pierson's COIN SDM model contains a comprehensive IO loop that forms a conceptual map of IO in FM 3-24. It includes PSYOPS effectiveness, expectations of and satisfaction with essential services, security forces, and many more variables from the FM 3-24. Thus, the model includes the context of the messages, appropriately weighing the population's situation equal with or greater to PSYOPS messages. However, the COIN model states explicitly what the relations between these variables are, and so these givens form the assumptions of the model, rather than hypotheses to be explored with the model. The many equations require many parameters, which require precision to determine where the tipping points of the system are, for instance, at what point the system will be sent from a vicious cycle of support for the insurgency to a virtuous cycle of support for the government. However, the model's authors see the value in their model in terms of knowing direction of values, and as an conceptual map, rather than for knowing the exact time events occur and the exact relation between variables. This is perhaps because the variables in the model are not precise by nature: they are not countable indicators, but are more verbal indicators of sentiment without measurable units. Since the tipping points of the model are sensitive to the exact parameters entered, the author asks us to not pay as much attention to exactly when they occur as to the fact that they may occur.

IO Models at the Operational Level

Some IO models used at the DoD are at a level midway between Strategic and Tactical, which in the military is the Operational level. In these models, the opinion of populations is averaged into one "population opinion", and the complexity of interactions of opinions within the various roles of the population is not taken into account. However, the various influences upon the population are walked through step by step, in an Agent Based Model, and in accordance with social theory.

One such model is the Media Information Model (MIM), part of the Defense Advanced Research Project Agency's (DARPA) suite of composable models, the Conflict Modeling, Planning and Outcomes Exploration Program (COMPOEX) (Bennett, 2009). This model includes several theories of media influence and communication theory, including Latane's theory, the idea that to convince a population of a message, one must first gain credibility by sending the population messages that they agree with and then change their minds slowly. Messages are about the legitimacy, affinity, and competency of other simulated entities. Channel reach, message frequency, and blockage are included as well. Each message source has a queue of messages to send, and messages are sent automatically from simulation actions.

In the Media Information Model, agents are reactive to their social environments in accordance with theory.

However messages are accepted by groups on the basis of how close the message is what they already believe. Neither the sense that the message makes nor the content is modeled. It would take a far more complicated tactical level model, with cognitive abilities and perhaps even natural language understanding to relate message content to actual actions.

Another model of IO used in DoD analysis at the operational level is the Office of the Secretary of Defense's (OSD) Nexus Schema Learner, also designed to be part of a suite of composable models (Duong, 2009). Nexus agents, built as interpretive agents, are more cognitive than reactive, and rely on cognitive dissonance theory and the narrative paradigm to simulate a paradigm shift in the interpretation of messages and actions. Each agent represents the point of view of a social group. Like Pierson's COIN model and the COMPOEX Media Information model, Nexus attempts to model the context of messages. However, it does so with the greater amount of nonlinearity afforded by Hopfield Neural Networks. Phenomena that cause dissonance, such as in being the friend of your friend's enemy (according to Heider's balance theory), or in liking groups that have harmed you in the past, or in harming groups that are similar to you, are all taken into account so that cognitive dissonance is minimized, in accordance with cognitive theory. Cognitive dissonance is an important factor in convincing people of messages, and of IO: the book, *The Power of Persuasion* , states that "Cognitive dissonance is the mind controller's best friend" (Levine 2003) While still not taking content into account, and depending on other simulations in the composition for the effects of actions on the social groups, Nexus comes closer to simulating the whole context and the paradigm shifts in interpretation that come when agents re-write their histories in terms of blame for past actions and support for other groups. Groups in Nexus do experience the threshold phenomena of paradigm shifts, and Nexus can be used to explore the circumstances under which social groups come to change their opinions about each other.

IO Models at the Tactical Level

The Marine Corps' Pythagoras Counter Insurgency (P-COIN) model is a reactive agent model at the tactical level, used to find popular consent for the presence of US forces in the wake of a natural disaster (Eberth 2008). P-COIN has in common with Nexus Schema that affiliation with other groups, historical actions, and similarity to a group are all taken into account in the computation of how one group likes another. However, the implementation is different. Instead of one agent per social group, there are one hundred per social group, each representing 1000 individuals of the population. The representation of the individual puts P-COIN on the tactical level. Agents change their affiliation according to a Markovian matrix, a way of changing states based of probabilities that are set with the data about affiliation, actions and similarity. This change is implemented through "persuasion weapons" in which agents in close spatial proximity can persuade other agents to become more like themselves or less like themselves. Persuasion weapons also implement Markovian changes that happen as a result of marine actions. The result is an emergent combination of the influence of the marine actions, and the actions of the agents upon each other.

P-COIN agents are more data driven than theory driven. The little theory they have in the transmission of messages is the same Latane's theory of the MIM, that messages transmit better the more similar the agents and the messages are to each other. However, in this case the messages are not media messages, but every day contact between individuals, and between individuals and soldiers. As in the MIM, the higher the frequency of seeing the message, the more it is believed. However, the only motivation and goal of the agents is to spread their ideas: they are not spreading messages to achieve another goal as in the MIM and as is true to IO doctrine. The social context is used for probabilities of changing support, rather than for interpretation of actions, as in Nexus Schema and as would be in accordance with interpretive social theory. Validators speculate that the data, the Markovian Matrix, would always dominate, meaning that P-COIN would have a more linear than emergent relation between input and output (Eberth, 2008).

Multiresolutional Combinations with IO Models

The strategic and operational IO models mentioned above have been used in combination with other models in integration tool kits. The problem of composing models comes to the forefront in the discussion of IO modeling, because the context of IO may be almost anything… a context that is too big to fit into a single model. However, because interpretive social science tells us that meaning is context dependent, we must find ways to compose models of IO with models that represent a particular social context on a deep enough level so that interpretations of meanings in IO can be derived from that context. These toolkits may run the models with a script, or can be stopped periodically to include human-in-the-loop (HITL) for war gaming.

COMPOEX, a DARPA product (Waltz, 2008) is an integration toolkit that composes MIM with other models. COMPOEX takes care of data mediation between models and the user interface for the input of moves and the examination of effects. COMPOEX has a "backplane" in which the wiring between individual models is determined. These models are designed to cycle in a particular order, so the outputs of one model may become the inputs of the other, after aggregation and other transformations have been applied to the data. The IO model that comes with COMPOEX, MIM, receives its message priorities and exogenous event messages from external models such as a model of population satisfaction and a model of power structure. MIM also feeds these models. However, in terms of nonlinear dynamics, there is no tight feedback between the models: one model finishes and determines its output before another starts, and there is no feedback to come to a consensus or resolve conflicts.

The OSD's Oz (Duong 2009) is another integration toolkit. Oz addresses the major problem of model composition, semantic integration, with ontologies. Oz uses ontologies as contracts to define and enforce a common conceptual model. Many models with their own conceptual model in the form of their own ontology are the "spokes," united to a central, detailed "Hub" ontology, rich enough to translate back and forth from spoke to spoke. The ontology allows the integration between an IO model and other models to be deep and detailed. Hub and spoke ontologies integrate Nexus into Oz.

The ontology also serves to store events in hierarchical format to facilitate data mining analysis. In terms of complex adaptive systems, Oz is designed to incorporate feedback between models and conflict resolution in the formation of a consensus of models. Feedback allows a tighter coupling between the IO model and the social context that depend on each other, as well as to express threshold phenomena of the composition of models.

Directions for the Future of IO Modeling

If IO is something that takes place in a human mind, between soldier and citizen, on the tactical level, then IO modeling needs to occur at the tactical level. As of now, the DoD does not have a model that can explore the strategic effects of tactical level IO actions. There are some tactical level cognitive agent social models used for analysis in the DoD, for example, the Nexus Network Learner Model (Duong, 2009), that has been used to model corruption rather than IO. There are some interpretive agent models from academia that are used to explain how micro level interpretation of messages and macro level social phenomena form each other, for example the Symbolic Interactionist Simulation of Trade and Emergent Roles (SISTER) (Duong and Grefenstette, 2005). Interpretive agent models are particularly attractive for IO modeling because they model the agent's interpretation of the meaning of messages, with the interpretation as context dependent and emerging during the simulation.

Models of IO used so far in the DoD have not yet modeled content, the most important part of a message. MIM and P-COIN model agreement with an unknown content based on similarity measures, rather than an interpretation of a content. The interpretive agent model, Nexus, models social groups' changing interpretations of blame for actions, and use these factors to interpret actions, but they do not interpret meanings of message content. SISTER on the other hand models content, but it is the content of a private language that has emerged during the simulation. SISTER models strong social emergence, where micro level symbolic interaction forms macro level institutions such as a role based division of labor, which in turn influences the interpretation of symbols. This strong emergence for IO modeling translates into the effect of the interpretation of IO messages on the strategic level war fight which in turn influences the interpretation of IO messages.

With the incorporation of the AI technology of metacognition, SISTER agents will be able to take the shoes of each other, facilitating the ability to understand nuances of meaning based on the motivation of the speaker. Combined with advances in the ability to absorb data, for example with the use of a Bayesian Network as in Nexus Network Learner and a text extraction engine, the next stage of SISTER can be a simulation of the interpretation of message content, driven with text based data from real world scenarios.

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