

# The Nexus Cognitive Agent-Based Model: Coevolution for Valid Computational Social Modeling

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## ABSTRACT

This paper discusses the central problems with creating valid computational social science simulations, and then suggests answers to these problems that involve co-evolution, autonomy, interpretation, and data processing under uncertainty. We also present the use of these techniques in the Nexus cognitive agent simulation, used at the US Department of Defense (DoD) in multiple major analyses of Irregular Warfare. We introduce the technique of data absorption, which leverages co-evolutionary pressure to reproduce the same dynamic structures that caused observable real world data in the simulation through the motivations of the agents. This technique gives a causal explanation for the data, and sets the stage for testing the effects of interventions never seen by the system on the system. By mimicking the state of equilibrium reached by the natural system, data absorption closes the gap between theory-centric simulations and data centric simulations.

## Categories and Subject Descriptors

I.2.0 [Artificial Intelligence]: General – *cognitive simulation, philosophical foundations.*

J.4 [Social and Behavioral Sciences]: *Economics, psychology, sociology.*

## General Terms

Measurement, Economics, Experimentation, Theory, Verification.

## Keywords

Agent-based model, technical assessment, co-evolution, autonomy, interpretation, uncertainty.

## 1. INTRODUCTION

Naming the qualities of a scientifically valid human social cultural behavioral (HSCB) simulation is easier than attaining the standards to implement the qualities. Whether the simulation is a generalization of a social process that draws an analogy to real world processes, or whether it specifically draws a correspondence to a real world scenario, we would like to see

emergence. That is, we would like to input phenomena known to exist, and have the simulation output more phenomena known to exist. Such a simulation would be a good explanation by the principle of Occam's razor - the principle of parsimony.

However, to be valid, this output phenomena cannot be pre-determined. That is, the agents must have the option to behave differently. For example, we cannot explain Weberian institutions, or expected similar behaviors, solely with an agent algorithm that copies behaviors, because then the agents would have no choice except to have similar behaviors. The output would then be an artifact of the implementation as opposed to a computation from assumptions.

Additionally the goals agents optimize should not be the same as the explained behavior. For example, in the Symbolic Interactionist Simulation of Trade and Emergent Roles (SISTER) program, utility is optimized and trade is more or less the only way to increase utility, and so the SISTER program would not be a valid explanation of trade. However, it is valid for SISTER to explain behaviors which may or may not come to be agent sub-goals. For example, a standard of trade (money) arises from barter behavior in about a third of the SISTER runs, and in the other two thirds of runs, a rich system of barter arises, which is an alternative behavior to reach the same goal[1].

SISTER's co-evolutionary reinforcement learning algorithm offers a separation between agent goals and the methods to attain them. We want to explore the conditions under which a given behavior arises, or does not arise. This is opposed to simulations with static rules that can only form one kind of social structure.

We want agents to be autonomous in both decisions of action and perception. Also we want to explain social institutions as the emergence of corresponding behaviors in agents that autonomously perceive and act based on their personal utility, all the while having options to behave otherwise. If the programmer directs either the behaviors or the perceptions from which the behaviors are derived, then outcomes are pre-determined. This is an example of putting the answer to the question in the question.

"Clumping" is another quality desirable in scientifically valid models. This is the concept of behaviors falling into a system of ideal states or roles. Weberian institutional behaviors are interlocked and based on the projection of separate wills and volitional "votes". Therefore we cannot expect every possible combination of behaviors to exist. Rather, because many different agents get a "vote," behaviors fall into a system of ideal types, or roles, some combinations of which are possible and some are not. These types arise organically, and, because of their complexity,

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are not subject to foresight of a programmer or of a policy designer. For this reason, a good co-evolutionary simulation will fall into states.

Autonomy is such an important part of the human condition that to take it away and direct agents is to unfairly influence the answer, while modeling the processes of individuals learning and acting is to compute from first principles. In a valid simulation, emergence is organic, as in Adam Smith's invisible hand, where agents, in selfish and blind pursuit of their self-interests, indirectly benefit the public. In the development of corresponding behaviors in pursuit of individual goals, we want to see agents react to other agents' behaviors, rather than be independent of each other. We want to see emergent structure formation, and higher order effects that are at times counter-intuitive because of the complexity that goes into their computation. If simulations were always intuitive, and we used intuition to judge their merit, then we might as well ask a subject matter expert (SME) rather than run a simulation. To be a good explanation, a valid simulation should give more than obvious insight.

## 2. TOWARDS SCIENTIFICALLY VALID COMPUTATIONAL SOCIAL SCIENCE

The moving fitness-landscapes of co-evolution are an excellent way to implement the development of interlocking dependencies. However, simpler forms of reaction to the other agents can model interlocking dependencies as well. A role-based division of labor, prices, and money emerged from the SISTER through coevolving genetic algorithms in agent minds, but the institutions of social class, status symbols and racism emerged from its predecessor SDSS through changes in architecture of neural networks in agent minds[2]. Axtell, Epstein and Young's program on the emergence of social class subsequently made use of simple rules to do the same thing[3].

Simulations that specifically draw a correspondence to a real world scenario have additional requirements for validity. We would also like to check forecasting accuracy through standard statistical techniques such as separating the testing set from the training set. Simulations that use predetermined rules, obvious agent behavior directly from the input, or over-fit system dynamics models can never be valid in principle because these methods tend to put the answer to the question in the question itself. Klein states that simulations may be tailored towards a scenario that never happened. This complicates validation when using similar real-world data because it makes few examples available, when more are actually needed for statistical significance (more, for example, than for physics-based models), because data is translated into HSCB models with uncertainty, and because models can only capture a portion of the space, leading to error[4]. However, Klein's argument about being tailored towards a nonexistent scenario implies that generalizations cannot be made. There is no intrinsic reason that, given the correct concepts at the correct level of generality, generalizations cannot be made and measured against HSCB data. HSCB data falls into types or states: that is, we may characterize societies by the type of behaviors they exhibit, say, "a corrupt society" the same way that persons may fall into psychological states such as schizophrenia. This is a good analogy because, we do not have the ability to forecast exactly what a schizophrenic will do and when, but we know what a schizophrenic type of behavior is, and we know how to mitigate it. In the same way, we know of general types of social outcomes, and what may mitigate them. The key is to express concepts at the right level of generality so that they may

apply across scenarios, in a sort of DSM IV for societies. Discovering generally applicable concepts, as well as federating models, helps to put us on a path towards completeness, enough so that the modeled phenomena in conjunction with random variate draws can approximate the probabilistic state space of outcomes. These generally applicable concepts need not be fed with exact data - many models use ill-defined concepts - but social models should be able to consume data that is crisply defined and measurable. For instance, the social model in Nexus Network Learner can accept data that is measurable (such as employment rate) and infer non measurable and unexposed data from the measured data.

A valid model would be able to forecast outcomes as a probabilistic state space, in the same general sense that we may forecast a schizophrenic's type of behavior, given data that the model has not seen before. To do this, a model must "clump" the same way that the real world does, so that what is correlated in the model is correlated in the real world. Because it is a simulation, the model should do this by walking through causal processes that correspond to reality, rather than by statistical or rule based models. Focusing on motivation and cause allows a simulation to forecast new combinations of qualities that the simulation has never seen before. To achieve accurate forecasts, social simulations should correspond to reality though the concepts of social theory[5].

Additionally, valid social models should use concepts of social theory in proportion to their importance to social theory. Contradictory social concepts should be treated as any other form of uncertainty, so that analyses should cover all major schools of social thought. The computational social science community has unfortunately concentrated on models that are easy to implement, such as homophily-based models of message propagation. Despite being widely used due to its simplicity of implementation, homophily carries little weight in the social sciences. Cognitive dissonance, on the other hand, is far more important to social psychology, and has the ability to model the sense that an action makes to agents, and the reason that an action is interpreted a certain way. Nexus models cognitive dissonance, but few other models of information do.

### 2.1 Nexus

The Nexus cognitive agent model was used in three of the largest and most important studies of Irregular Warfare (IW) at the Department of Defense, the Africa Study (the first IW analytical baseline) at the Office of the Secretary of Defense, and two iterations of the US Army Tactical Wargame. At present, Nexus consists of two modules, Nexus Schema Learner[6],[7] and Nexus Network Learner[8],[9]. The Nexus model is described in detail elsewhere. Here we briefly describe how Nexus' methodology captures social processes. Klein states that explaining why the representation methodology captures the social process is important to HSCB validation: the representation is trivial in physics based models, but it is a difficult and too often overlooked in HSCB models.

Nexus has the ability to adapt to data - to recreate the same dissipative structures that created the data in the first place, so that interventions can be tested against a similar underlying system. This quality combines the basis in scientific validity of general theory-centric models - computing from assumptions - with the basis in scientific validity of data-centric models - having correspondence to a real world scenario in detail.

## 2.2 Nexus Schema Learner

Nexus Schema Learner (NSL) simulates cognitive dissonance and narrative coherence in social groups. It was used to simulate popular support at OSD's Africa Study. In the Africa study[10], agents represented tribal and government stakeholders. Nexus Schema Learner models agent minds with a constraint satisfaction neural network. This network computes whether another agent is supported, and whether the agent credits it or blames it for actions, based on its past actions and its support relations to other agents. These other agents also have committed actions in the past that hurt or helped the thinker and other agents, friend and foe. Support for supported agents, helpful behaviors towards supported agents, support for the thinker, and helpful behaviors towards the thinker are positive links in the network, while disaffection for supported agents or self, or harmful actions towards supported agents or self, are negative links in the network. Conversely, disaffection for unsupported agents and harmful actions towards them are positive links, while support and helpful actions towards unsupported agents are negative links. The nodes of the network represent support levels and credit or blame for particular actions. When actions come in from other models in a federation of simulations, a court-level type of evidence is put into the nodes of the network, as well as current declarations of popular support for the other agents. All the factors are taken into account in a holistic schema of whom to support, who gets credit and who takes blame, in a consistent set of beliefs after bias is considered. The individual agents support levels are then publicly declared, and agents then adjust their network to the new actions and new support declarations, ready for the next incoming action.

Nexus Schema Learner is a model of cognitive dissonance and narrative coherence and as such is appropriate for irregular warfare scenarios. It captures cognitive dissonance theory, one of the most important theories in social psychology, in the minimization of facts that go against where evidence lies as a whole, and in support of the self. It also captures the idea of narrative coherence, for example, as it exists in the belief that the Americans caused the Egyptian revolution despite evidence that it was organic and despite the fact that America has never attacked Egypt, just because it is something that the American crusaders "would" do. In the same way, Nexus captures blame that goes against evidence because of biasing factors. It does so through the constraint satisfaction neural net in the head of every agent - a Boltzmann machine that has the properties of schema formation in accord with consistency theories like Festinger's cognitive dissonance[11], Heider's balance theory[12], and the Fischer's narrative paradigm[13]. Nexus can even model a paradigm shift, as it is based on software that was used to model a Necker cube, which can either be seen one way or the other, but not both. A paradigm shift is exactly the goal of Irregular Warfare: the US spreads ideas through Information Operations (IO), and actions through Civil Military Operations (CMO), in order to convince the populace that the terrorist narratives do not deserve their support as much as the host nation government does. Most models of IO do not model the cognition of popular support, but rather model homophily networks, where an IO message is accepted if the hearer is liked. Although Nexus doesn't model IO message content, it is a step towards it.

## 2.3 Nexus Network Learner

Nexus Network Learner (NNL) incorporates a co-evolutionary genetic algorithm to model a dynamic role based network. In the Africa Study, NNL represented corruption, and in the US Army

Tactical Wargame (TWG), NNL represented dynamic role networks of key leaders and terrorists from which emanated intelligence messages. Every NNL agent uses a Bayesian Optimization Algorithm to decide strategies for behaving: in the Africa Study these include bribing and stealing behaviors, as well as strategies for choosing network partners based on preferred attributes. An NNL iteration starts with each agent choosing network partners in different networks in which it is qualified to choose relationships. In the Africa Study there were 65 roles in three networks: kin, bureaucratic, and trade networks. For example, a young single male may qualify as a husband and choose a wife according to his preferred attributes, such as gender, age, ethnicity, etc. Networks, behaviors, roles, attributes, and whether attributes are subject to learning are inputs to a Nexus scenario. There is a chance of relationship attrition at every cycle. Next, the agent behaves with their role relations, and this behavior may be witnessed and even revealed to other agents depending on role relations. For example, in the TWG scenario of Afghanistan, a terrorist might fly kites with his cousin, performing a behavior that, if the store owner observed and told the human intelligence (HUMINT) agent, could be used to infer that the men are cousins. In the Africa Scenario, a father might buy food for his child and give a bribe at the same time because of a food shortage. In NNL, money is conserved and flows through accounts, and corrupt acts are defined as inappropriate transfers from one account to another, such as bribing an employer for hiring through a kick back, or police stealing money from citizens in a road block. Bribes and stealing are encoded in rules in the scenario rather than hard coded. Agents have utility as a result of behaviors that involve money transfers. The utility occurs upon direct consumption. For example, in the Africa Study scenario, utility occurs when the maternal grandmother of a matri-local tribesman eats fruit that she bought at the market. The particular behaviors and role relations that offer utility are inputs to the scenario as dictated by the culture. Utility for the time that a strategy is in effect is the fitness function for the BOA.

In the Africa Scenario, in the BOA of the mind of each agent, 20 chromosomes encode strategies for bribing, stealing, accepting bribes, accepting or rejecting network partners who bribe and steal, and more. Each chromosome is tested for 20 days. The strategies are first generated in proportion to the behaviors that are expected in the real world country based on the demographic attributes of the agent. Utility over the 20 day test, based on the amount of utility dependents incurred during their role transactions, is the fitness of the chromosome. Then, after every chromosome has been tested in each agent, on the four hundredth day, ten chromosomes are kept and ten child chromosomes are generated with the BOA in their mind.

NNL captures the processes of sociology in its emphasis on behaviors as a function of role relations. It models change in role relations and behaviors well because it bases these on utility. Coevolving BOAs seek individual utility, and as this occurs, social structures form. For example, bribing is social because in order to offer a bribe, you must believe that the bribe will be accepted, or at least that the person bribed will not inform the transparency program agent (the "authorities"). Therefore, agents must separately develop corresponding plans to bribe and expect bribing as part of the social environment. This is why, in nexus, bribing is an emergent social institution.

Nexus is a good simulation for IW because it allows courses of action, such as transparency programs with stiff penalties for corruption, to be tested against a natural system, allowing us to see what would happen once the interventions are taken away.

For example, there are natural forces at work that prevent stores from stealing from customers: the customers won't come back. If we present artificial incentives to prevent stealing, how will it interfere with the natural incentives? We want our CMO actions to be such that, once we pull out of a country, we do not have to go right back.

Additionally, NNL is a good model because of its realism. The input to Nexus is a Bayesian Network which describes measurable phenomenon based on demographic attributes from the country of interest, such as the chance of bribing for a particular tribe in a particular part of a country. The input network captures the actual relation between agent attributes and behavior in the real world. Nexus can generate agents based on those statistics. The output of Nexus is also a Bayesian network, which captures outwardly measurable statistics - a net that can also serve as an input to the program once again. The BOA that each agent has for its mind is unique in that it can start at any point in reality, and move from there, unlike most evolutionary algorithms. In Nexus, any agent starts out behaving with the propensities that it has according to its attributes as measured in real world data. Because it is a coevolutionary algorithm, agents expect each other to behave in the proportions of their class that are input from real world data, and lay selective pressure on each other according to their expectations. For example, if agents expect agent Mongos from Congo to bribe, then they offer bribes to this class of agents, placing selective pressure on Mongos to maintain the expectation. However, the agents within a class generally converge on one strategy or another according to their utility. For example, if agents believed that 60% of Mongos from Congo accept bribes and 40% do not, then NNL starts off with 100% of Mongo agents accepting bribes 60% of the time and not accepting bribes 40% of the time. However, as the simulation reaches equilibrium after 6 years, 60% of Mongo agents accept bribes 100% of the time, and 40% of Mongo agents reject bribes 100% of the time. They feed their utility by keeping their public expectations, and also by developing behaviors that are individually rewarded by their relations.

Thus Nexus adapts to data, taking the frequencies in statistical inputs and explaining them through motivation. It is important that a country representation in Nexus reach the same system, the same equilibrium that caused the input country data before interventions are tested on it. It is this "calibration of motivation" that allows new interventions that have never been tried before to be accurately forecasted. By walking one step back, and representing the motivations in the data, we can validly test walking forward on new social conditions.

### 3. NEXUS VALIDATION EXPERIMENT

We present experimental results from the Africa Study to demonstrate Nexus' ability to adapt to data. Nexus recreated dissipative structures that created the data originally so that interventions could be tested against a similar underlying system. We ran the Africa Scenario on extremes to verify expected behavior, for example food shortages. Nexus expects qualities like employment rate, supply and demand, and prices from other simulations in a federated architecture. However, because it is motivationally based, it does model market processes. Bribes can be seen as food price correction, and when we put severe shortages in, we saw bribing for food shoot up. Next we tested extreme international interventions. We added transparency agents to the scenario, which had 100% chance of observing every bribe, and 100% chance of reporting them to authorities, and increased the penalty to life in prison (when in prison, an

agent does not participate in trade). As expected, this eradicated all bribing, showing that the BOAs in the agents' minds function properly.

**Table 1. Chi Square Tests . Squares contain number of simulation runs with the stated quality. Significant Results (p value < 1%) for Data Absorption of Service Bribing Behavior, but not Employer Bribing Behaviors. Significant results (p value < 2%) for a Service Bribing Behavior penalty that is applied then removed in three years improving corruption in the long term given the society was corrupt to begin with. Nearly significant results (p value < 10%) for a Service Bribing Behavior penalty that is applied then removed worsening the situation for societies that may not be corrupt. Significant results (p value < 2%) for a penalty for employment bribing behaviors improving the situation in societies that may or may not be corrupt.**

Service Behavior Data Absorption			
	Data From Country	Data From Run	
Like Original, Stayed Higher	19	20	
Unlike Original, Decreased	10	2	
		chi squared test	0.0078322
Employer Behavior Data Absorption			
	Data From Country	Data From Run	
Unlike Original, Stayed Higher	10	5	
Like Original, Decreased	19	17	
		chi squared test	0.1836474
Service Behavior under Penalty applied then removed in corrupt and non-corrupt societies			
	without treatment	with treatment	
Stayed High	19	17	
Decreased	10	3	
		chi squared test	0.0870244
Service Behavior under			

Penalty applied then removed in corrupt societies			
	without treatment	with treatment	
Stayed High	20	21	
Decreased	2	7	
		chi squared test	0.0145238
Employer Behavior under Penalty applied then removed in corrupt and non-corrupt societies			
	without treatment	with treatment	
Stayed High	10	5	
Decreased	19	15	
		chi squared test	0.0129708
Employer Behavior under Penalty applied then removed in non-corrupt societies			
	without treatment	with treatment	
Stayed High	5	9	
Decreased	17	19	
		chi squared test	0.1670642

Next we tested Nexus' data absorption property. We did this by running out Nexus with country data several times, observing the states that the simulation would fall into, and then taking the output Bayesian network of simulation in that state and feeding it into multiple runs of Nexus as an input file. This exercise showed that the particular state we were looking for, one where bribes for goods were high, but bribes for employment decreased, were regenerated in Nexus through the motivations of agents. See the first part of Table 1 for results.

Next, we tested an international intervention. On a system with the equilibrium that we determined to exist in the real world, we offered an international intervention in the form of a transparency and high penalty program that was in effect for 1500 simulation days and then removed. The equilibrium we chose was from the data from the simulation run with high goods bribing and decreasing employment bribing. We found that the intervention made a positive difference upon the goods bribing, because it was high to begin with, and a negative impact on the employment bribing, which was decreasing anyway.

However, when tried on data from the country, as opposed to data from the simulation output, which included equilibria other than high goods bribing and decreasing employment bribing, we found that the intervention made the goods bribing worse upon removal of the intervention, and the employment bribing in general better. It seems that the cure must be tailored to the situation. In any case, where the system was likely to adjust by itself, a government intervention made the situation worse, perhaps because the intervention came to be depended on for equilibration, as opposed to natural forces of agent motivation. This experiment illustrates government intervention worsening the situation in a natural system undergoing natural improvement.

## 4. VALIDITY

We see the kind of counterintuitive effect that we are looking for in complex adaptive systems, when a misapplied government intervention makes a natural social system worse. We also see that the output clumps into several equilibrium states, and that we should be selective about the equilibrium to test against. Perhaps the original equilibrium in the real world can be recreated in the simulation more effectively through the output of a simulation that had sought equilibrium rather than the real world data, because of differences between the system of the simulation and the system of the real world. What we are looking for is an analogous state in the simulation to the real world, one for which simulation generated data is more appropriate than real world data, to create the same state. We can only test interventions once we have recreated an analogous state within the simulation

## 5. SUMMARY

Data absorption is an important technique for getting a simulation to mimic the real world process that caused the data. In this technique, the selective pressure of co-evolution assists in replicating the vicious and virtuous cycles that form expected institutions as they exist in the real world. Co-evolution enables the representation of the emergence of institutions such as corruption as well as the simulation of changing networks of popular support. Data absorption through co-evolution results in a simulation which is simultaneously data-centric and theory-centric, explaining the data through motivation and causal theory.

This methodology is thus a good way to bridge the divide between data-centric and theory-centric agent based simulations. Additionally, data absorption is a good way to use co-evolution in a federation, where the consensus state is absorbed back into the simulation, and to set up a live connection with data for feedback between data and a simulation's interpretation of it. Such feedback would help both the analysis of the meaning of data, and the relevance of the data that is added to the simulation, refocusing the simulation on data of interest to both the intelligence and the analysis community.

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