Learning in Dynamic Multi-layered Social Networks: A Mesa Verde Example

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Abstract

In this paper we take a multi-agent model of agricultural subsistence in the Mesa Verde region between 600 A.D. and 1300 A.D. and allow the emergence of a set of overlaid social networks over time in response to environmental dynamics. These overlaid networks include kinship, economic, and community level (hub) networks. Agents are able to participate in each of these networks and strategies for participation are learned using a framework for Cultural Evolution, Cultural Algorithms.

Agents are embedded in the Mesa Verde environment. The environment is divided into cells. Each cell of the model contains a modelled agricultural, animal, hydrologic, forest and shrub components. The value for each of these components is derived from paleo-productivity and archaeological data from the region. The values can change over time as a result of migrations, changes in available water etc. These changes are dynamically programmed into the model.

It is shown that changes in the environment can differentially affect the various layers and effects can ripple through to other networks. Thus, certain networks may be less resilient to environmental fluctuations than others and require additional maintenance from the population in order to maintain them. The extent to which the social system is able to learn strategies to adjust the network in response to environmental stress will be discussed. The results of the model are then compared to the known distribution and content of archaeological sites found in the regions.

1. Introduction

The Mesa Verde region located in south-western Colorado is home to many ancient ruins and hidden remains, evidence of an ancient pre-Hispanic civilization known as the Pueblo Indians. The more the archaeologists unearth, the more information they gather and consequently the more complex the data to be modelled. For instance, GIS technology, coupled with numerous geological and archaeological surveys, yield a generous amount of information about terrain elevation and soil degradation. Additional environmental and productivity information based on tree ring data (Van West, 1994) identify the conditions that took place between A.D. 600 and A.D. 1300. The historical fact stands that the Pueblo settlers abandoned the region around A.D. 1300, ending nearly 700 years of occupation. The mystery presented to the modern scientists is to explain why these settlers left the region.

Many theories have been posed to answer this question. They include the mini ice age by Douglas, in the 1930's, erosion, great disease hypothesis, warfare, aggregation activities and social interaction. A prominent one tested by Kohler (Kohler, 2000) in a multi-agent simulation model is that environmental factors, especially the long drought in the late eleventh century caused the inhabitants to move to more sustainable land away from the Mesa Verde region. The model however failed to predict the reduction in population associated with known drought conditions in the mid to late 1100's. Hence it was suggested that other factors might play a role as well.

Figure 1. Snapshots of the Mesa Verde settlements as seen today. The image on the left depicts a large sophisticated structural settlement evidence of the presence of advanced social organization. The image on the right depicts the strategic location of a settlement site beneath a productive farm land.

Figure 1 illustrates some of the settlements in the study area. In particular, the magnitude and the sophistication of the buildings are evidence of the presence of a high social structure. Follow-up work by Reynolds, Kobti, and Kohler (Reynolds, Kobti 2003) suggested that social and cultural factors motivated the population to evacuate the region along with environmental variables. The unearthed artefacts and large settlements reveal a sophisticated society rich with language, culture and community aspects. Kohler's initial model was then extended to weave a social network and embed cultural evolution in the modelled population so as to reflect a more realistic scenario.

Populations may exchange resources via generalized reciprocal exchange over a kinship network, and balanced reciprocal exchange. In this paper we introduce the protein resources and specifically the ability of agents to hunt for the deer, rabbit and hare based on the marginal value theorem (Charnov, 1986). Agents, within the cultural algorithm framework (Reynolds, 1974) learn to make better selection strategies for exchange partners across the hierarchical social networks.

The current model was developed on Swarm 2.2 and modified to execute on a high speed distributed grid computer by implementing batch mode and enable parallelization in the model to use the Swarm engine's parallel abilities.

2. Modelling the Region

The initial model design (Kohler, 2000) divided the region into smaller cells of equal area. Each cell is modelled as an object with specific properties retrieved from a database as shown in Figure 2. Every year, the cells are updated to conform to new environmental factors as collected in the database, and updated to reflect the outcome of occupation and degradation effects.

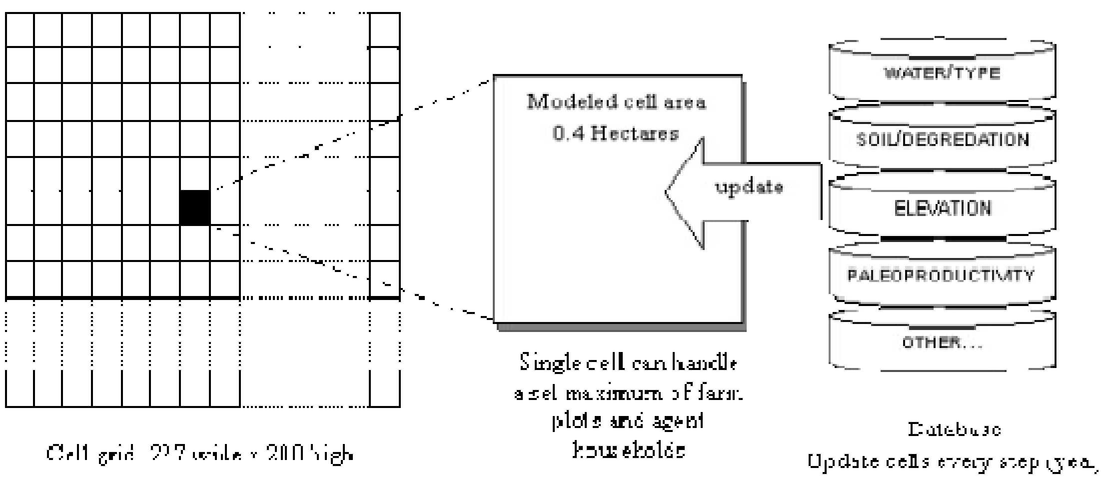

Figure 2. Model area based on a grid of cells updated yearly from a database.

Agents, represented as households, reside in cells across the region. In previous work (Kobti, Reynolds, 2003, 2004) households were able to exchange their resources within a limited distance. Figure 3 illustrates the coverage area a household can access to exchange its resources. Agents within the Generalized and Balanced Reciprocal Exchange networks occupy a distance $D_{BRN/GRN}$ that is smaller than what a larger Hub can access (D_{Hub}). In the model, we define the distance in terms of cells.

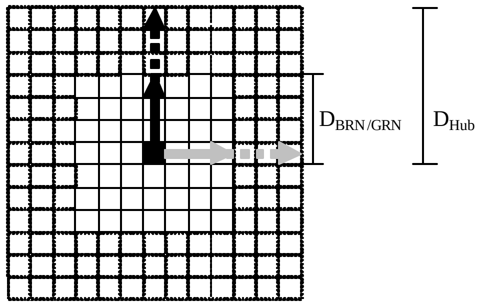

Figure 3. Spatial coverage for exchange across cells within the BRN, GRN and Hub networks.

3. Cultural Evolution Framework

Based on John Holland's formal framework for generic adaptive systems (Holland, 1975), Reynolds' system allows the system to alter its structure and/or behavior based on the experience in some set of performance environments (Reynolds, 1979). Adaptability is the capacity to function in an uncertain or unknown environment, and to use information to evolve and learn (Conrad, 1983). Adaptation can take place at three different levels: population, individual and component (Angeline, 1995). Hence, Cultural Algorithms were designed to allow the emergence of social intelligence at both the individual and cultural levels.

Cultural Algorithms consist of a social population and a belief space (Reynolds, 1979) as shown in Figure 4. Selected individuals from the population space contribute to the cultural knowledge by means of the acceptance function. The knowledge resides in the belief space where it is stored and manipulated based on individual experiences and their successes or failures. In turn, the knowledge controls the evolution of the population by means of an influence function. A Cultural Algorithm thereby provides a framework in whic h to learn and communicate knowledge both the cultural and individual levels.

The belief space can support a number of knowledge types including situational, normative, topographic, historical or temporal, and domain knowledge. These knowledge sources are derived from work in cognitive science and semiotics that describe the basic knowledge used by human decision-makers. In our Cultural Algorithm all of these knowledge sources can be represented and learned. For example, in our current model we assume that agents can acquire knowledge about the distribution of agricultural land as well as wild plant and animal resources (topographic knowledge), the distribution of rainfall and water resources (history or temporal knowledge), agricultural planting and harvesting techniques (domain knowledge), hunting technology, and fuel collection and use.

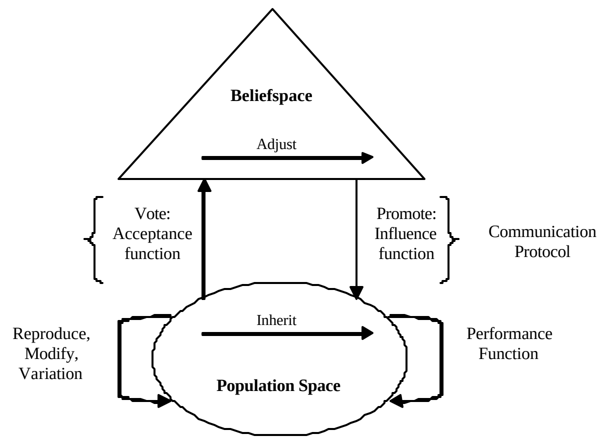

Figure 4. Cultural Algorithm Framework.

4. Exchange Networks

The social network developed by Kobti and Reynolds (2003;2004) is based on a hierarchical structure formed from two base networks that in turn evolve a third high level network as shown in Figure 5.

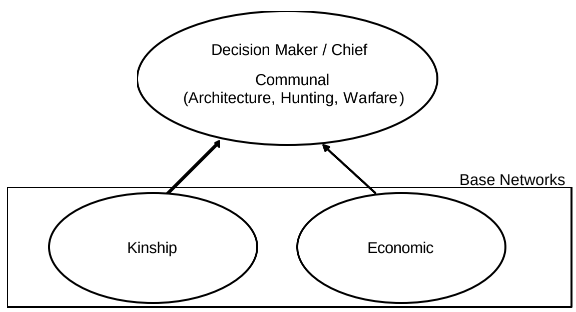

Figure 5. Overall social network structure including the two base models and the evolving communal network.

4.1 Kinship Network

The emergent networks in the model are composed of agents. Each agent is a nuclear family or household composed of a husband, a wife and their children. Household members live together in the same location, share their agricultural production, and are affected by the same environmental conditions. Children can grow up, marry, and move out to form their own households. Their connections to their parent households and siblings are maintained in our model. Similarly, the parents maintain ties to their children. When one of the parents in a household dies, the other can form a new household with an available single agent. The initial structure of the social network here supports the notions of parents, siblings, and grandparents on both sides of the family.

The household (agent) rules for marriage and kinship dynamics were described in earlier work (Kobti, 2003). The social network is defined as the set of all kinship links. The simulation model is based on massive amounts of collected settlement and productivity data with agents initially acting as individual households. The first extension of the model introduced gender, marriage rules, and other localized enhancements to allow individuals to co-exist and reproduce. At the next level, the first base network was introduced and known as the kinship network. This is a baseline network that links each individual household to its parents, siblings, children and other relatives. Over this network, generalized reciprocal exchange was implemented so as to enable the agents to mutually cooperate and exchange resources across the network in order to survive. A small world social network emerged and the resultant agent populations were shown to be more resilient to environmental perturbations.

Motivated by individual experience and population norms, an individual, by means of a CA, was able to learn and make more intelligent choices in cooperating over the kinship network. For instance, an agent can learn to make a better choice when it comes time to decide who to ask for food when in need. Over time, an individual can learn to select more cooperative kin, and, indirectly, a population identifies known exemplars and establishes its acceptable norms. As a result, established individuals can become good donors, and those in less productive locations can depend on the social network for survival. An underlying factor triggered by the dependency on such a social system enabled households to relocate closer to the productive kin and consequently relocated the population to the more productive farm lands. Over time, the clustering of individuals closer together around productive lands was reflected through the hubs in the small world social network. The simulated locations of these hubs were then compared to those community centers known archaeologically and a good fit was observed. This initial attempt at cultural evolution motivated the notion that culture indeed had a role in population relocations.

4.2 Economic Network

We now describe a second important baseline network: the economic network. Archaeological findings reveal pottery, tools, and wood among other artifacts that can be exchanged between individuals. This suggests the potential for economically based exchange as a mechanism for distributing resources among the agents. In order to do this, each household essentially maintains a list of trading partners (formed mainly from nearby agents) that are independent from the kinship network. Individuals adopt a strategy to decide when, and with whom, to exchange. In this model, unlike the reciprocal exchange model, individuals need to keep balances of the amounts owed and traded. The ability of agents to repay their debts reflects their reliability, generalized here as reputation. A well reputed household is a good producer and lives without debt. This is typical of settlers of productive lands or those with strong social ties. Less reliable households reside on less productive lands and have weak social ties. A Cultural Algorithm is adopted again in the economic network to guide the decisions that an agent and the culture makes in selecting reputable trading partners.

4.3 Hub Network

A hub network is one that emergences from both the GRN and balanced reciprocal networks (BRN). The implementation of the two base networks allows the agents to elaborate their importance by promoting themselves to the next network: the hub network. Hubs are agents considered important with a number of links in the network. They are defined as those nodes that are of sufficient complexity in either the GRN or BRN, or both. Here, we use the intersect, where a hub node must be prominent in both the GRN and BRN. In addition, a hub node promotion is

based on a probabilistic discrete Poisson distribution based on its number of links to other hub nodes. Similarly, a hub node is able to demote itself and remove itself from the hub network if it is re-evaluated and lost its importance on either the GRN or BRN. Hubs have the ability to exchange between each other and the ability to defect on their trades.

5. Exchange Models

In this section we describe how the two networks are integrated and evolve with the agent population. We begin with Generalized Reciprocal Exchange and follow with Balance Reciprocal Exchange.

5.1 Generalized Reciprocal Exchange

The generalized reciprocal network (GRN) was introduced in previous work (Kobti, Reynolds 2003, 2004) using a kinship network. The GRN links agents with one another based on their kinship relations. The GRN serves to guide the flow of resources between relatives based upon the states of a giver and a receiver. An individual can request goods from a related individual without the donor explicitly expecting payback.

5.2 Balanced Reciprocal Exchange

The balanced reciprocal network (BRN) is an economic network that supports the exchange of goods between neighboring agents. In a balanced reciprocal transaction the giver expects an immediate payback of an equivalent amount, or a deferred payback plus interest. The localization of the exchange between agents in the model is to enforce the physical constraints of travel distance limitations when an agent engages in exchange. This constraint is consistent with what was implemented in the generalized reciprocal network. Each agent maintains a set of trading partners who are not necessarily associated with the kinship network. A trading partner can be any agent within a given radius from the focal agent.

The overall agent strategy for exchange using both the GRN and the BRN is given below for hunting. Exchange of maize takes place in a similar fashion. The key idea is that exchange in the current model occurs when an individual is in a state of need in terms of resources. After updating their networks agents first try to satisfy their resource needs by calling in debts from their neighbors using the BRN. If they are not successful, then they request aid from their relatives through the GRN. If they still are deficient in terms of resources, then they go back to the economic network to initiate further exchanges to satisfy their needs.

6. Hub Network

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7. Methodology and Tools

We describe the results of a run of the simulation model using all of the resource models described above. Agents cultivate maize, hunt animals, and collect fuel wood and water. They can exchange animal and plant resources through both the GRN and BRN networks. The HUB network can emerge from them if needed by the population.

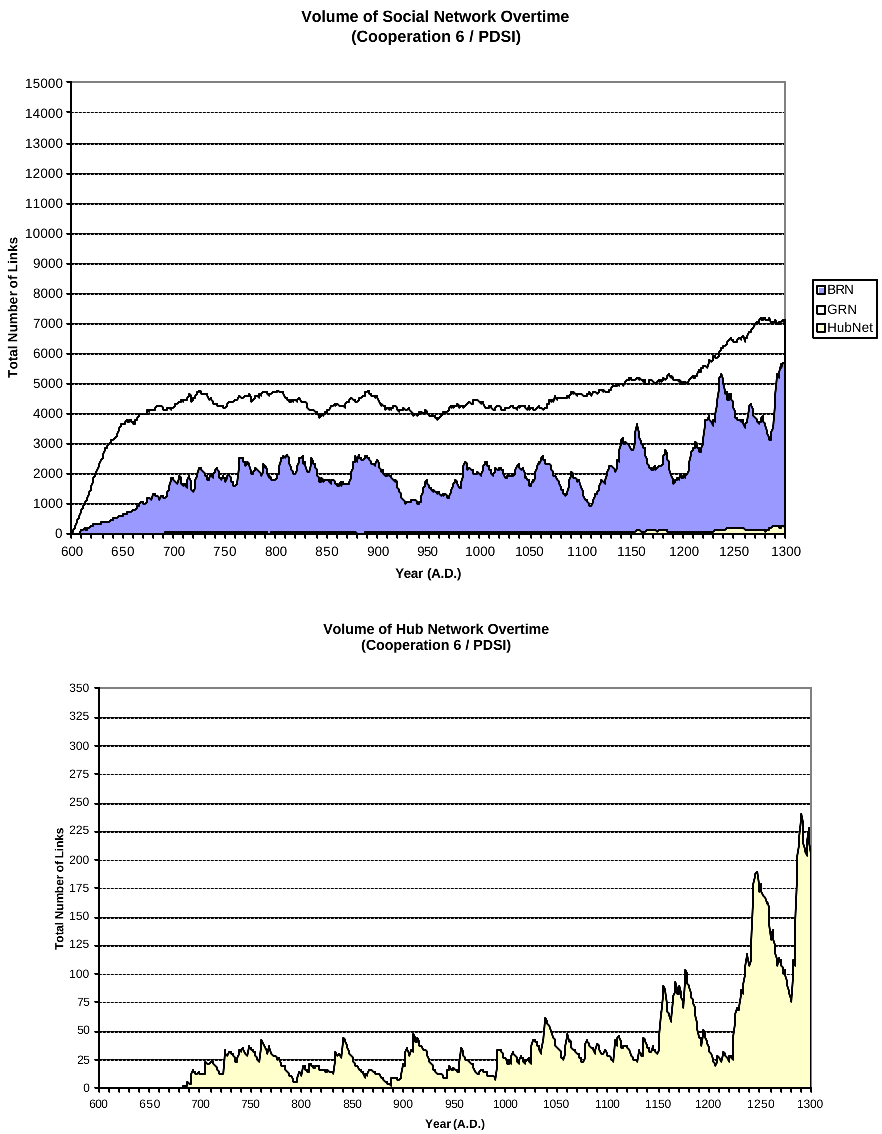

Figure 6. Network characteristics with the presence of cooperation over the kin network (GRN) and the economic network (BRN) and the emerging Hub network (bottom) including exchange across hubs.

In Figure 6, exchange is introduced across the hub network to allow the hub agent an added advantage to perform balanced exchange with other hubs. As a result, the volumes of the networks are smaller than that observed without the exchange. This suggests that when hubs are stressed to give away their resources for the sake of good social reputation and more likely to collapse.

Figure 7 illustrates the visualization tool developed to display these emerging networks and settlement locations. Illustrated is a sample year A.D. 980 where, for a given archaeological phase, the agents are mapped on the study area and the settlements are detected and highlighted with large circles, where the radius is a function of the exchange radius allowed in the model for the given network. Square boxes are known settlement locations based on archaeological finds. Notice an overlap with the white boxes and the highlighted circles indicating that the modelled settlements are close to the known locations; a way to validate the model as development progresses.

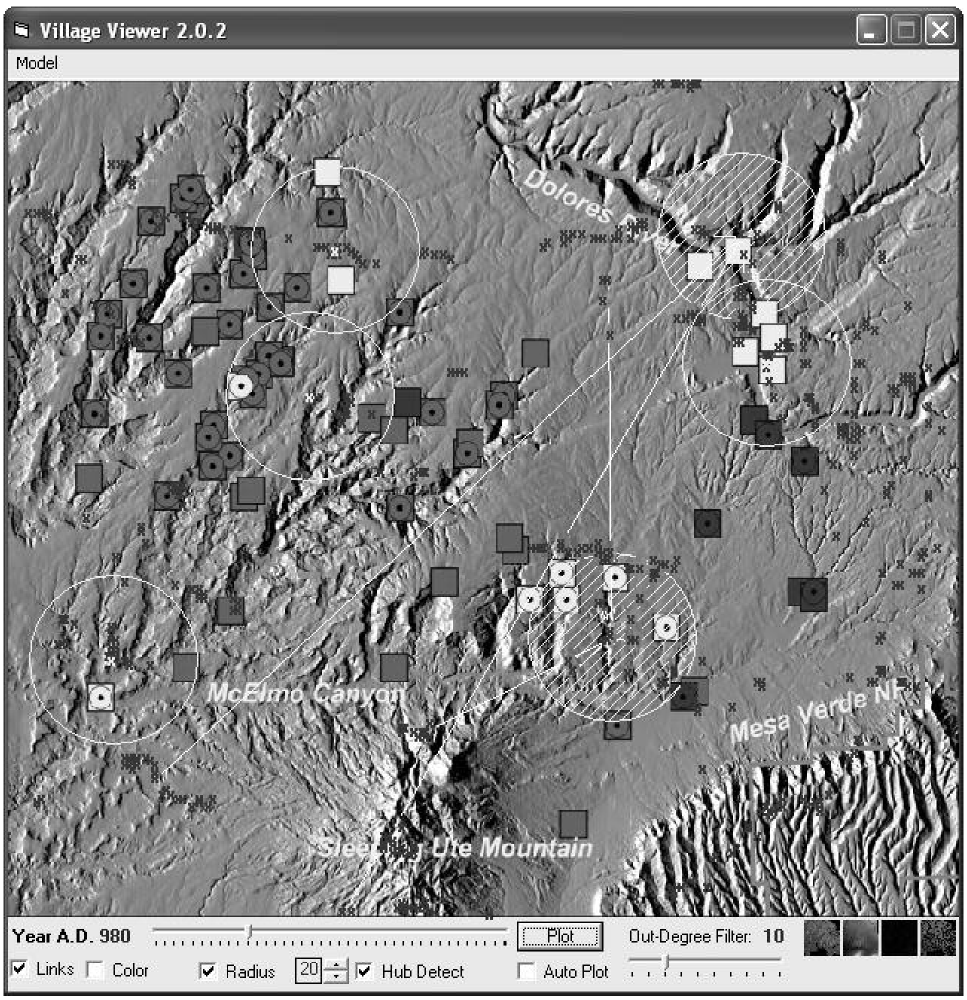

Figure 7. Modelled and actual settlements displayed using a graphical tool in order to demonstrate the validity of the model.

8. Conclusion and Future Work

Over the course of experimentation we found instances when agents need to resort to the hub network in order to survive. This, coupled with known archaeological finds of large settlements, suggest that when localized exchange fails, large settlements emerge and play an important role in maintaining the civilization. A hub takes the role of a community center and enables exchange across further distances, and thereby promoting communal events, in order to survive. On the other hand, when a hub fails to provide the exchange level of resources necessary for survival, the collapse of the hub becomes imminent. Consequently, when the hub fails, local neighboring households that depend on the failed hub, take the hit and die if their dependency level is too high on the hub.

A motivating factor for the hubs to survive is to defect, that is to take in resources and refuse to give away to needy and requesting agents. This strategy was shown in other studies (Kobti, 2004) to increase the survival rate of the hubs. Subsequently, an alternate strategy for the hub suggested by the observations from the runs is that hubs act as attractors and movers of the population. The rational follows that for a hub to succeed, it must be located in a highly productive region, or close to another successful hub that contributes towards its success. Should a hub relocate in the region, agents depending on the hub will alter their strategy to move closer to the hub, towards the same productive land that the hub selected, and thereby increasing their survival.

In future work, full parameter sweeps in the model are planned to calibrate the sensitivity of the agents to various environmental effects so as to best match the archaeological records. This way, by "fitting" the simulation parameters, we can better understand the social conditions that the agents experienced under the known environmental factors.

9. Acknowledgements

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