The Emergence of Complex Hierarchical Hub Social Network in the Mesa Verde Village Simulation Using Cultural Learning

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Abstract

In this paper we extend the cultural framework previously developed for the Village multi-agent simulation in Swarm to include the emergence of a hub network from two base networks. The first base network is kinship, over which generalized reciprocal exchange is defined, and the second is the economic network where agents carry out balanced reciprocal exchange. Agents, or households, are able to procure several resources. We use Cultural Algorithms as a framework for the emergence of social intelligence at both individual and cultural levels. Successful agents on both networks can promote themselves to be included in the hub network where they can develop exchange links to other hubs. The collective effect of the hub network is representative of the quality of life in the population and serves as indicator for motives behind the mysterious emigration from the region. Knowledge represents the development and use of exchange relationships between agents. The presence of defectors on the hub network improved resilience of the social system while maintaining the population size as that observed where no defectors were present. This suggests a tendency for the social system to favor larger hub formations over less social individuals or those with weaker ties.

Introduction

Archeologists excavating the Mesa Verde region in southwestern Colorado stumbled on one of the greatest mysteries of pre-Hispanic history. Many uncovered ruins and settlements scattered in the region reveal the presence of an ancient civilization. These were the early pre-Hispanic settlers known as the Pueblo Indians or ancient Anasazi. Scientists scouted the sites and collected detailed information using the latest GIS technology, geological and archeological surveys. As a result, we have ample information on elevation, soil degradation, environmental and productivity information based on tree ring data (Van West 1994) to name a few. An important observation of the sites discloses an event around A.D. 1300 where the settlers abandoned the region. Despite the fact that these settlers occupied the region for over 700 years, and that they farmed the land, built settlements, domesticated and hunted various animals, their disappearance is apparent from the abandoned sites. An important question now posed is why did these Pueblo Indian settlers to abandon 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 (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.

Follow-up work by Reynolds, Kobti, and Kohler (2003, 2004) suggested that social and cultural factors motivated the population to evacuate the region along with environmental variables. The unearthed artifacts 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 modeled population so as to reflect a more realistic scenario.

Previously we allowed the population to exchange resources via generalized reciprocal exchange over a kinship network. The emergent network had the properties of a small world networks. In this paper we take a model of Kohler and Yap for balanced reciprocal exchange and implement that in the model along with the previous network. Our goal is to assess the relative impact of the two emergent networks with regard to their ability to improve system resilience in light of environmental changes.

The current model was developed on Swarm 2.2 with environmental data ranging from A.D. 600 to A.D. 1300 with added protein resources from deer, hares, rabbits and burnable calories from firewood. The additional resources increased the complexity of the system and consequently restricted the ability to run the model within reasonable time on current hardware. Pentium III dual processor PC's and Pentium IV 3.0GHz machines require several weeks to run the model for all the years. The hardware limitations were overcome by porting the model to a high-speed grid computing distributed environment. Sixteen independent nodes with dual Xeon processors were configured to compute the simulated model. The model was modified to execute on the grid by implementing batch mode and enable parallelization in the model to use the Swarm engine's parallel abilities.

In the first section we introduce the cultural evolution model and the cultural algorithm (CA) framework used to embed social intelligence in the system. Next we provide an overview of the social network and the composition of the kinship, economic and hub networks. The exchange over these networks is then described. We define the Generalized Reciprocal Exchange as well as the Balanced Reciprocal Exchange that agents can participate in and learn to evolve better exchange choices. Historical, situational and normative knowledge is collected in the belief space which allows both individual and cultural learning of the exchange networks. In these experiments we enable all the resources available to the agents including: maize, deer, rabbits, hares, water and firewood, but we only allow maize to be exchanged. The experiments and results section describe the effects of adding the hub network to the system, and then allowing exchange on the hub network, and then enabling defectors The trends generalized from these results are then described and show how social intelligence is reflected in population and network volumes at the hub level.

Cultural Evolution

Evolutionary Adaptation

Holland developed a formal framework for any generic adaptive systems (Holland, 1975). His framework for adaptation concerns a system that is able 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). 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 1. 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 which to learn and communicate knowledge both the cultural and individual levels.

Knowledge Types

There are at least five basic categories of cultural knowledge that are important in the belief space of any cultural evolution model: 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. Currently planting and harvesting techniques are held static. The amount of annual rainfall is also fixed based on tree ring data that is used to estimate the amount of rainfall during each model year.

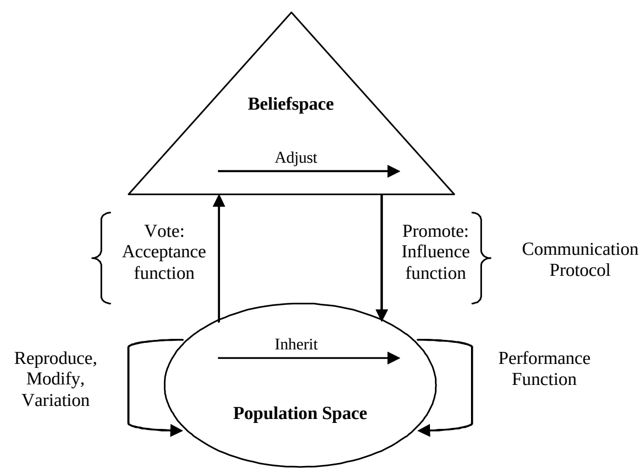


Figure 1: Cultural Algorithm Framework (Reynolds, 79).

Social Networks

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 layout of the generalized reciprocal network (GRN) from the perspective of a household is described in table 1.

The household (agent) rules for marriage and kinship dynamics were described in earlier work (Reynolds, Kobti 2003). The social network is therefore defined as the set of all kinship links. The simulated 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.

TABLE 1: Connected nodes identified by the kinship social network

ParentHHTagA	a link to the parent from the mother's side
ParentHHTagB	a link to the parent from the father's side
ChildHHTag	one link to each child that moves away from this household and form its own household
RelativeHHTag	one link to each extended family member

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. Overtime 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 became good donors, and those in less productive locations needed to 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. Overtime, 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.

Economic Network

The next phase of development proceeded to implement a second important baseline network: the economic network. Archeological findings reveal pottery, tools, and wood among other artifacts that can be exchanged between individuals. This suggests the potential for economic based exchange as a mechanism for distributing resources among the agents. In order to do this each household essentially maintained a list of trading partners formed mainly from nearby agents that are independent from the kinship network. Individuals adopted a strategy to decide when to exchange and with who to exchange with. In this model, unlike the reciprocal exchange model, individuals needed to keep balances of the amounts owed and traded. The ability of agents to repay their debts reflected their reliability, generalized here as reputation. A well reputed household is a good producer and without debt, typical of settlers in productive lands or with stronger social ties, whereas less reliable households resided in less productive lands and had 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.

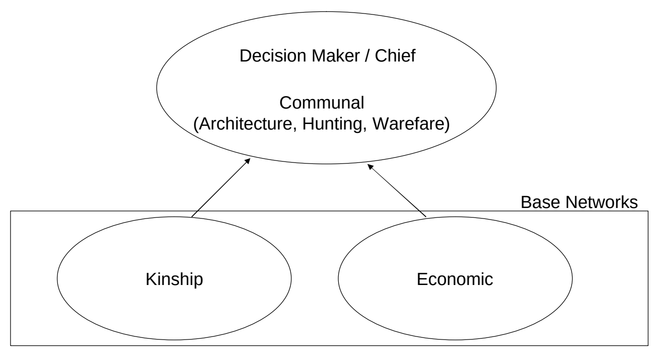


Figure 2: Overall social network structure including the two base models and the evolving communal network.

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 with important number of links in the network. They are defined as those nodes that are large enough on either the GRN or BRN, or both. In this paper 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 others (Co-op 6) and the ability to defect on their trades. A defector threshold is defined for a hub to trigger itself to defect.

Using The Social Networks To Support The Exchange of Resources

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

Generalized Reciprocal Exchange

The generalized reciprocal network (GRN) was introduced in previous work (Reynolds, Kobti 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. One individual can request goods from a related individual without the donor expecting payback explicitly.

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 agent.

TABLE 2: Description of the different cooperation methods at the kinship level

0	No cooperation. No exchange of food between households.
1	When an agent requires food, it is allowed to select and request food from within its kinship network in order to survive.
2	When an agent has excess food, above a determined threshold amount, it is allowed to select an individual(s) from its kinship network and donate the excess.
3	Both methods 1 and 2 are enabled.
4	Full cooperation across the Kinship and Economic Network (Generalized and Reciprocal Exchange simultaneously)
5	Hub network emergence based on the INTERSECT of hubs from GRN and BRN networks, and accepted based on a Discrete Poisson distribution.
6	Hub Network developed in co-op 5, with addition of exchange with other hubs.

The overall agent strategy for exchange using both the GRN and the BRN is given below. 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 they first try to satisfy their resource need 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 acquire it.

Resources

According to archeological records the Indians were able to harvest maize, and hunt deer, rabbits, and hares. In addition they collected firewood for cooking and heating. Water is of course another requirement necessary for life. In the current model all these resources are enabled and computed. The household is capable of accessing all of these resources. In this paper, the exchange is limited to maize on all networks.

Integrating base Networks to Facilitate Exchange

Every step the agent performs the following actions specific to exchange:

1. Update GRN
2. Update BRN
   a. Remove dead partners [and non active/out of region/expired]
   b. Search each neighboring cell within a trade radius and get its settlers list and add new ones to the trade list
3. Update Hub Net
   a. Self Promote/Demote to/from Hub Net based on current base status
   b. Remove dead partners and search for new ones in range
4. Request payback of dept from BRN and Hub Net partners
5. if HUNGRY/CRITICAL
   a. Request food from GRN (no payback)
6. if HUNGRY/CRITICAL
   a. Request food from BRN (with payback)
7. if HUNGRY/CRITICAL
   a. Request food from Hub Net (with payback)
8. if CRITICAL
   a. Agent is DEAD and removed
9. if PHILANTHROPIC/FULL
   a. [Donate surplus into GRN]
   b. [Pay back dept owing into BRN]
   c. [Pay back dept owing into Hub Net]

Methodology And Results

In order to understand the effect of the balanced reciprocal exchange on the overall population and network resilience we setup a series of experiments to establish controls and comparison baselines. In previous work (Kobti 2004) we execute a sequence of experiments from co-op 0 to co-op 4 and show the need for both baseline networks in order to better match the archeological estimates. In this phase of experiments we extend the model to include the emergence of the hub network. The first step is to execute the model without exchange on the hub network. This allows us to measure the baseline effects of base social networks on the population (figure 3). Even though the hub network was not used for exchange the basic structure of the evolved network was shown to be consistent with the other networks again as a small world network.

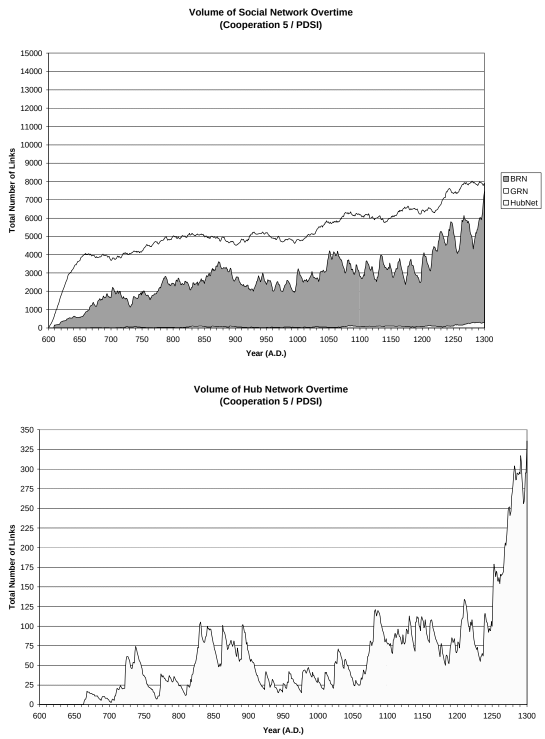


Figure 3: Network characteristics with the presence of cooperation over the kin network (GRN) and the economic network (BRN) and the emerging Hub network.

In the absence of exchange on the Hub network we identify the network volumes of the baseline networks with a steady increase for the BRN, larger than that observed for the GRN. The generalized reciprocal exchange allows the individuals to enhance the kinship network, producing a slightly more complex structure. Also, this suggests that the network extends and complements the more limited range of the GRN. There, the volume of the generalized reciprocal network exceeds that of the balanced reciprocal network. This suggests that there are social needs that are not met by the GRN on its own, and over time the groups learns to produce an economic network that gets better at fulfilling those needs.

In figure 4, 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.

Another issue is that around A.D. 1140 the impact of the Little Ice Age was to reduce available moisture in the valley. This drought impacts the social volume of the hub network as shown in figures 3 and 4 (bottom part). Notice that both cooperation types exhibit a dip in the network, but that the dip associated with the exchange configuration is larger and takes longer to recover from the environmental perturbation. It is clear that while the balanced reciprocal exchange in the hub network is necessary to improve the distribution of resources among the hub agents, this network is more sensitive to those drought situations.

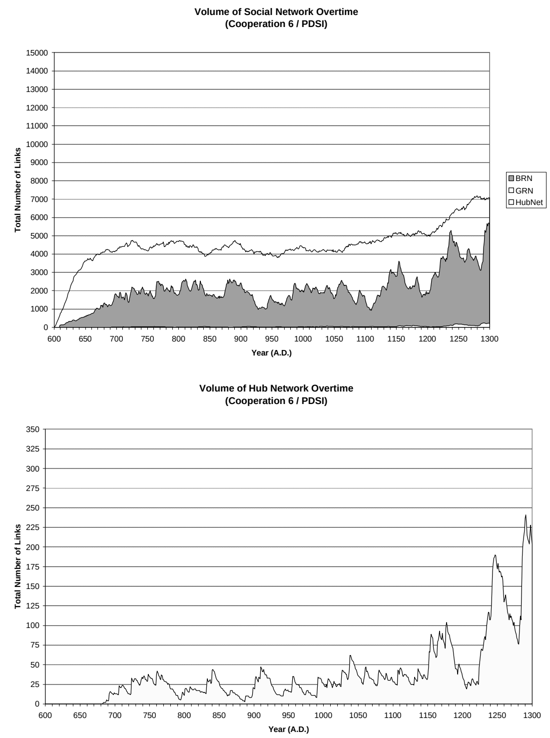
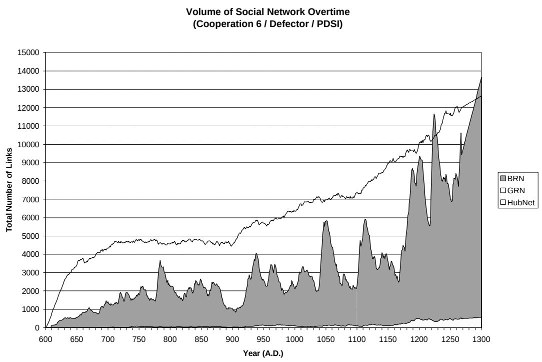


Figure 4: Network characteristics with the presence of cooperation over the kin network (GRN) and the economic network (BRN) and the emerging Hub network including exchange across hubs.

In figure 5 we show the network volumes as we introduce defectors on the hub network. A defecting agent is one that elects to request resources when needed, but strategically ignores repayment of dept or making donations to others. A discrete Poisson distribution relative to the hub size is used to elect the probability if a hub agent should defect or not. As a result, introduction of defectors in the hub network drastically increased the resilience of the network due to environmental perturbations and increased its volume to nearly double that observed without defections. In conjunction with this observation, we note in table 3 the population sizes for some selected years across the simulation under all the tested conditions. This reveals that although defectors increased the volume size and resilience, it however maintained the population size as if there were no defectors present. Also, the introduction of the hub network did achieve a better control of population sizes as population density increased. The presence of defectors in the hub network presents the hub agents a better opportunity to survive while it weeds out the smaller size hubs. This suggests that for agents to survive they needed to form into larger communities rather than living individually with little social links.



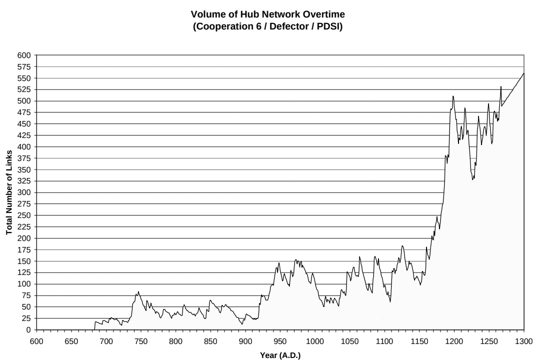


Figure 5: Network characteristics with the presence of cooperation over the kin network (GRN) and the economic network (BRN) and the emerging Hub network including exchange across hubs with the presence of Defectors.

TABLE 3: Agent Population Estimates during different periods.

Experiment Type (PDSI Data planes)	Agent Population Estimates		
	A.D. 900	A.D. 1140	A.D. 1300
Co-op 0	0	0	0
Co-op 3	0	0	0
Co-op 4	1200	1750	2240
Co-op 4+Defect	900	1700	2100
Co-op 5	800	1100	1350
Co-op 6	750	850	1200
Co-op 6+Defect	750	700	1200

Conclusions And Future Work

Emergent properties observed in simulated populations of the Mesa Verde Village region reveal a pattern of social intelligence that individual households use to collectively adapt in a Cultural Algorithm framework. In particular, the system is able to evolve and to use both a kinship network for generalized reciprocal exchange and an economic network to support balanced reciprocal exchange. The system is not able to develop sufficient social complexity without the inclusion of both resource redistribution networks. Their structures suggest a complementary role for the two networks where the economic network is adapted by the agents to extend the basic distribution of resources. The economic network's presence is necessary to generate a social complexity that is comparable to that predicted for the real-world. However, it also appears that this network is the most sensitive to environmental downturns in terms of the magnitude of its drop and the time it takes for recovery.

In future work we will enable agent strategies to exchange all the resources available at once so that we can compare the networks for each of the resources in order to identify any system fragility with respect to any given resource. This includes all the hunting and firewood collections. Furthermore, communal activities such as raiding can be investigated in the model in terms of their impact on the hub network.

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