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A moderate role for cognitive models in agent-based modeling of cultural change

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Abstract

Purpose: Agent-based models are typically "simple-agent" models, in which agents behave according to simple rules, or "complex-agent" models which incorporate complex models of cognitive processes. I argue that there is also an important role for agent-based computer models in which agents incorporate cognitive models of moderate complexity. In particular, I argue that such models have the potential to bring insights from the humanistic study of culture into population-level modeling of cultural change.

Methods: I motivate my proposal in part by describing an agent-based modeling framework, POPCO, in which agents' communication of their simulated beliefs depends on a model of analogy processing implemented by artificial neural networks within each agent. I use POPCO to model a hypothesis about causal relations between cultural patterns proposed by Peggy Sanday.

Results: In model 1, empirical patterns like those reported by Sanday emerge from the influence of analogies on agents' communication with each other. Model 2 extends model 1 by allowing the components of a new analogy to diffuse through the population for reasons unrelated to later effects of the analogy. This illustrates a process by which novel cultural features might arise.

Conclusions: The inclusion of relatively simple cognitive models in agents allows modeling population-level effects of inferential and cultural coherence relations, including symbolic cultural relationships. I argue that such models of moderate complexity can illuminate various causal relationships involving cultural patterns and cognitive processes.

Keywords: Simulation; Culture; Cognition; Analogy; Metaphor; Hermeneutics

Background

Introduction

This essay argues that an underused style of computer modeling—what I call "moderate-complexity" agent-based modeling—has the potential to serve as a source of new insights about processes of cultural change. I'll argue that this style of modeling can be sufficiently fruitful, and sufficiently tractable, to make it worth pursuing. I illustrate this strategy with concrete examples, simulations of processes of cultural change described by anthropologist Peggy Sanday (Sanday PR 1981).

Modeling of cultural change and other social processes has focused primarily on three classes of mathematical and simulation models:

Aggregate models: These are mathematical or computer models which use quantities describing groups of people, institutions, or other broad social factors without representing individual persons by distinct variables (Boyd R and Richerson PJ 1985; Cavalli-Sforza LL and Feldman MW 1981).
Simple-agent models: These models include representations of individual people, but represent individuals' states by a few simple variables. When models of social phenomena are described as complex adaptive systems models, they are typically of this kind.
Complex-agent models: These models represent people by intelligent agents that incorporate complex "heavyweight" (Alam SJ et al. 2010) internal cognitive architectures. This kind of model is common in artificial intelligence research and cognitive science (e.g. (Sun R 2006)).

All three strategies produce useful results. By design, aggregate and simple-agent models ignore most aspects of human thought and interaction, allowing focus on broad patterns within populations. These strategies are not designed to model the effects of more complex, subtle processes within individuals; such processes are the focus of complex-agent models. However, complex-agent models tend to become intractable when more than a handful of individuals are modeled. A fourth approach, though not new, is not common (e.g. (Alam SJ et al. 2010; Bleda M and Shackley S 2012; Reynolds RG 1994; Reynolds RG and Ali M 2008; Thagard P 2000, ch. 7):

Moderate-agent models: In "moderate-complexity-agent", or "moderate-agent" models, agents incorporate abstractions of cognitive processes at a level of complexity intermediate between that of simple-agent and complex-agent models.

The distinction between between moderate-agent models as opposed to simple-agent or complex-agent models is intentionally vague, but I give an illustration below. The difference is partly one of design goals. Like simple-agent models, moderate-agent models abstract from the complexities of human behavior in order to gain insight about patterns in populations. Unlike complex-agent models, moderate-agent models are not intended to capture behavior in a way that might one day approach the sophistication of real humans. Instead, a moderate-agent model trades some of the elegance and tractability that comes from use of simple agents, for the sake of the ability to model *some* effects of the complexities of real human behavior within populations. I argue that moderate-agent models have benefits that justify their exploration, despite challenges they face.

More specifically, I argue that ideas about culture from the humanities and humanistic research traditions within the social sciences—ideas traditionally thought to be resistant to or antithetical to modeling—can be incorporated into agent-based modeling through the use of moderate-agent models. This strategy opens up the possibility of increasing the scope of agent-based modeling to investigating effects of subtleties of human interactions and cultural processes which have rarely, if ever, been addressed by modeling of any kind. If successful, the strategy would give agent-based models broader scope, allowing models of cultural processes with greater realism. This could support more robust interdisciplinary discussion and collaboration with humanistic researchers in areas such as as cultural anthropology, cultural sociology, history, and literature.

In the next section I motivate both the general strategy of moderate-agent modeling of cultural change and my particular modeling framework, POPCO. In the "Methods" section, "POPCO framework" describes this framework. POPCO involves agent-based models at two levels, since it represents cognitive processes of interacting persons (agents) in a population in terms of networks of simple nodes (also agents). "Models of Sanday's hypotheses" illustrates the use of POPCO with models based on Peggy Sanday's (Sanday PR 1981) cross-cultural hypothesis about the origin of relationships between creation stories, sex roles in childrearing, and means of subsistence. The "Results and discussion" section discusses implications of the models I present, and discusses costs and benefits of POPCO and similar modeling strategies. "Conclusions" presents overall conclusions. The appendix provides additional details of the models described in "Models of Sanday's hypothesis".

Motivation

Work by anthropologists and other social scientists illustrates the idea that some elements of a society's culture may "fit together" in a sort of "harmony", or may "cohere" in various respects. For example, Lansing (Lansing JS 2006, 2007) describes a complex water distribution system in one region of Bali. Farmers benefit most, on average, if they coordinate planting and irrigation according to specific schedules. These schedules are coordinated by "water temples", which represent gods and spiritual congregations corresponding to physical components of the water distribution system. Lansing argues that the way in which elements of the religious system symbolize corresponding elements of the physical water system plays a crucial role in guiding individuals' participation in the water distribution system. Effective water management practices thus depend on and reinforce a complex set of religious beliefs, which themselves exhibit some internal harmony. Here we see certain sorts of "fit" not just between physical components of the system of water distribution and practices involving its use, but also between these elements and religious values, symbols, and practices. Lansing and colleagues have simulated relationships between water flow, pest prevalence, and rice production, and modeled game-theoretic interactions between managers of components of the system. However, relationships between these elements and the religious aspect of the cultural system have not been modeled, as far as I know. Capturing change involving similarly complex interrelationships between cultural elements in a population of agents would be difficult with existing modeling strategies. Current models of culture typically represent cultural variation with a few simple variables, in aggregate or simple-agent models (e.g. (Acerbi A et al. 2012; Afshar M and Asadpour M 2010; Alexander JM 2007; Boyd R and Richerson PJ 1985, 2005; Cavalli-Sforza LL and Feldman MW 1981; Enquist M et al. 2010; Grim P et al. 2004; Mueller ST et al. 2010; Nakahashi W 2010)), or represent interactions between cultural components without reference to the role of interacting individuals in a society (Dehghani M et al. 2008; Klüver J and Klüver C 2010; Thagard P 2012).

Internal relations of harmony between elements of culture play a large role in humanistic, and particularly so-called "hermeneutic" studies of culture in anthropology and other disciplines (e.g. (Clark S 1999; Geertz C 1973; González RJ 2001; Lienhardt G 1961; Tilley C 2000)). These approaches often treat culture as composed of a complex fabric of symbolic relationships involving language, arts, behavior, and various relations to the physical world, and exhibiting relations of harmony and tension. Authors in such traditions often argue that culture cannot be studied scientifically. Such authors sometimes argue that explanations involving culture depend on interpretive relationships between elements of language or other cultural elements, rather than causal relationships. There are also authors who argue that though some aspects of culture can be studied scientifically, other aspects are beyond the reach of scientific methods, including modeling (cf. (Fracchia J and Lewontin RC 1999; Peña A 1999)).

I disagree, but I note that it is scholars working in hermeneutical traditions who attempt to study the most subtle of cultural relationships in depth. Even when hermeneutical research does not meet standards of scientific evidence, I believe that it often generates plausible, potentially important insights about human behavior and cognition in particular contexts. Hermeneutical research in anthropology, sociology, history, literature, and other humanistic disciplines matters, because it often focuses on real aspects of human life, which may be ignored if we restrict our vision to phenomena that are most easily studied with current scientific methods. It's thus worth attempting to stretch the boundaries of scientific methods available to us, in order to attempt to bring more of the insights that hermeneutical research provides into scientific research (as social science research has done in the past, e.g. (Atran S and Medin D 2008; Brown MJ and Feldman MW 2009; Dressler WW et al. 2007; Kashima Y 2000; Romney AK et al. 1986; Schultz E 2009)).

I am proposing a somewhat new strategy for modeling culture so as to incorporate more insights from hermeneutical studies into scientific approaches. Claims about interpretive, symbolic, or other supposedly non-causal relationships between cultural elements can in many cases be treated as hypotheses about relationships mediated by cognitive processes. There is no reason, in principle, that we can't model such causal processes in ABMs in order to help understand patterns of cultural change. Other authors have made related points about modeling relationships between cognitive processes and culture (Bleda M and Shackley S 2012; De Block A and Cuypers SE 2012; Kahan DM 2012; Klüver J and Klüver C 2010; Mantzavinos C 2005; Slingerland E 2008; Thagard P 2012) but there have been few attempts to incorporate such ideas into modeling cultural processes in populations of individuals. Moderate-agent strategies are needed to try to model more of the complexity of intracultural interaction characteristic of real human culture. My goal here is to illustrate one such strategy.

The idea that there are metaphorical relationships between cultural elements plays a large role in hermeneutical understandings of culture. For example, (Bird-David N 1990) argues that in some hunter-gatherer societies, a variety of behaviors and attitudes derive from viewing the forest as peoples' parent (cf. (Tilley C 2000, p. 50)), and (Geertz C 1973) argues that betting decisions in Balinese cockfighting events metaphorically represented alliances and antagonisms between groups and individuals. Tilley C (2000) surveys a wide variety of cases in which anthropologists have argued that metaphorical relationships involving natural objects and artifacts play an important role in culture in particular societies. Outside of the study of culture as such, the idea that metaphor can have an important influence on thought has been advocated by Lakoff and his collaborators (e.g. (Lakoff G and Johnson M 2003; Lakoff G 2002)).

Gibbs RW Jr and Colson HL (2012) surveys related behavioral research and evidence from analysis of speech data.

Experiments by Thibodeau and Boroditsky (Thibodeau PH and Boroditsky L 2011) provide evidence for the influence of metaphor in culturally influenced thought processes. For example, in one experiment, American participants were randomly assigned to read either "Crime is a beast ravaging the city of Addison" or "Crime is a virus ravaging the city of Addison." In either condition, the initial sentence was followed by an identical paragraph describing an increase in crime in the fictitious city of Addison. There was a statistically significant effect of the initial sentence on participants' recommended solutions to the crime problem: Those who read the sentence containing "virus" recommended reform and prevention measures relatively more often than those who read the "beast" sentence. Participants who saw the "beast" sentence were relatively more likely to recommend capture and punishment solutions. Apparently, the initial metaphor influenced participants to favor crime prevention measures analogous to those appropriate for preventing the spread of viruses, or analogous to those appropriate for preventing attacks by beasts. Since particular beliefs about viruses and beasts, and attitudes about crime, are specific to some cultures and not others, Thibodeau and Boroditsky's results are evidence of an intracultural influence of metaphor.

It's plausible, though, that the cognitive processes involved in generating and understanding metaphors are often the same as those involved in processing analogies (Gentner D et al. 2001; Holyoak KJ and Thagard P 1995). Some authors explicitly argue for the importance of analogy in relationships between cultural elements (Dehghani M et al. 2009; Hofstadter DR and Sander E 2013; Holyoak KJ and Thagard P 1995; Thagard P 2012). The idea is that analogy might influence culture because it makes certain ideas "feel right" or seem more plausible as a result of analogical relations to propositions the person already accepts. Analogy would therefore provide a subtle influence on culture, making analogically related patterns of thought more likely. This role for analogies is partially supported by existing claims about the role of analogy in defeasible inferences in general problem solving (Forbus KD 2001; Holyoak KJ and Thagard P 1995), science (Bartha PFA 2010; Hesse MB 1966), and law (Picinali F 2011).

There are a number of computer models of analogy processing, with a great deal of associated experimental research validating some of the assumptions of these models (Gentner D et al. 2001; Gentner D and Forbus KD 2011; Holyoak KJ and Thagard P 1995). Neurologically plausible models of analogy processing have been developed (Eliasmith C and Thagard P 2001; Knowlton BJ et al. 2012), and there is research on neural correlates of analogy and metaphor processing (e.g. (Bassok M et al. 2012; Chettih S et al. 2012; Green AE et al. 2012; Knowlton BJ et al. 2012; Maguire MJ et al. 2012; Prat CS et al. 2012)). I attempt to capture interesting relationships between cultural elements, in part, by building Holyoak and Thagard's (Holyoak KJ and Thagard P 1989) ACME model of analogy processing into agents. ACME takes structured proposition inputs, and generates neural networks which identify analogies through the interaction of simple nodes on a network. ACME is a good choice here because it incorporates core assumptions common to most analogy processing models—and not much more—and because it's a relatively simple model whose outputs and operation are easy to investigate with graphical display tools.

My strategy is agent-based at two levels: At the top level, agents represent persons who communicate with each other, process analogies internally, and try to believe and disbelieve propositions in a way that is coherent. Within each person, though, these cognitive processes are modeled by two neural networks, whose nodes are very simple agents.

Methods

POPCO framework

POPCO overview

A POPCO simulation typically begins with the following steps (Figure 1), labeled in this section by top-level source code function names. Details are provided in later sections.

1. A population of POPCO agents, or "persons", is created as specified by the modeler. Each person includes its own list of representations of propositions in predicate/argument form (e.g. "`hunts (man animal)`").
2. `init-pop`: Each person's propositional representations ("propositions" to be brief) are processed by POPCO in order to generate two artificial neural networks in each agent:
   - Nodes in the *belief network* represent degrees of belief/significance for propositions. Weighted links represent inferential relationships, i.e. tendencies to give beliefs similar or dissimilar degrees of belief.
   - Nodes in the *analogy network* represent plausibility of components of an analogy, which are possible pairings of propositions, predicates, or predicates' arguments. Weighted links represent coherence between parts of an analogy, and competition between different analogy components.

   The two networks within each person are not connected by node-node links, but activations in the analogy network affect link weights in the proposition network.
3. The main loop is entered. This performs the following steps, in order:
   (a) `settle-nets`: Neural networks are partially settled.
   (b) `choose-conversers`: Pairs of persons ("speakers" and "listeners") are constructed.

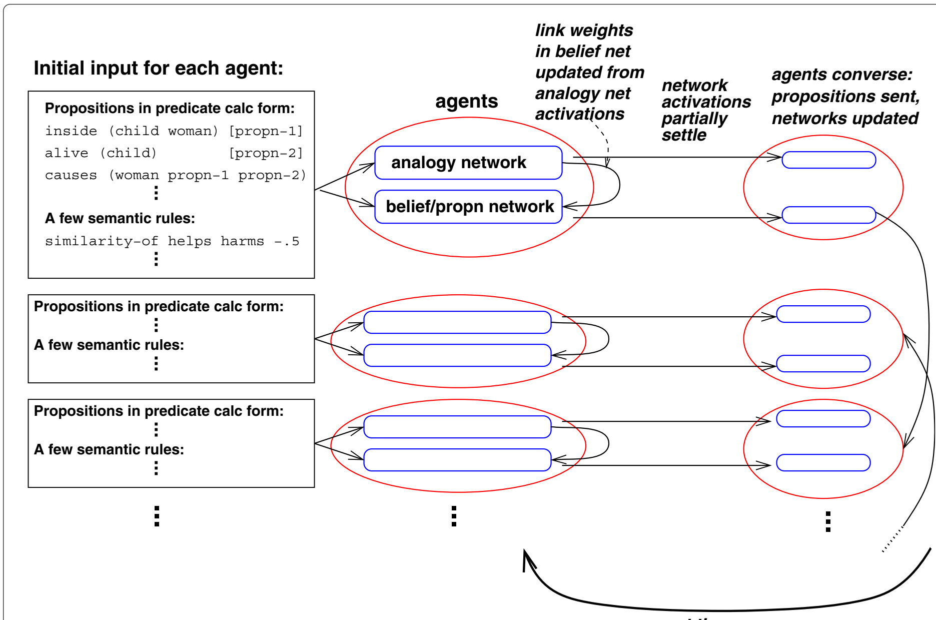

Figure 1 High-level causal structure and sequence of events for POPCO. Ellipses: persons. Rounded rectangles: neural networks. Arrows summarize causal interactions.

(c) `choose-utterances`: For each speaker and corresponding listener, at most one of the speaker's beliefs is chosen to be communicated.
(d) `transmit-utterances`: Utterances are transmitted from each speaker to each listener. This typically causes a persistent influence on the activation of the corresponding belief node in the listener. If the belief is new for the listener, it is added to the belief network.
(e) `transmit-environments`: For each person, perceptual "utterances" are transmitted from a personal "environment" to the person according to specifications by the modeler. These represent the influence of the external world on the mind.
(f) `update-analogy-nets`: If a proposition added in previous steps was new to a listener, new nodes representing possible pairings between the proposition, its components, and appropriate other propositions and components are added to the analogy network.
(g) `update-proposition-nets`: The weight of the link between each pair of belief network nodes, representing propositions P_1 and P_2, is set as a function of the activation of the analogy network node that represents a possible analogical mapping of P_1 and P_2.

The main loop starts over at step 3a, and continues until the modeler causes it to stop.

All activation values and link weights described below are Common Lisp long-floats in POPCO. In Steel Bank Common Lisp (SBCL), the implementation in which I usually run POPCO, long-floats are mapped to double-floats, as allowed by the ANSI Common Lisp standard (American National Standards Institute 1996). Double-floats have a minimum precision of 50 bits, with an 8-bit minimum exponent precision. In practice this means that activation values and weights are specified to 16 or 17 decimal places.

Concepts and initialization

The belief network and the analogy network are constraint-satisfaction networks, in that they attempt to determine an approximate solution to competing constraints. Constraints are represented by links and their weights. Both networks are constructed and updated from propositional inputs provided by the modeler.

Proposition input syntax The initial set of possible beliefs for an agent is specified by storing, in each agent, a set of very simple predicate calculus representations of propositions which the agent might "believe". Proposition inputs have a predicate followed by zero or more arguments in parentheses, and an arbitrary proposition name which can be used to refer to the proposition as a whole. Table 1 lists English sentences, with examples of stylized propositional representations for them on the right. The entry in the first line on the right says that `man`, i.e. males in a particular society, often hunt animals. The "*`propn-1a`*" on the far right is the proposition name. These names allow one to specify higher-order propositions such as the third one, which says that the fact that males hunt animals sometimes causes animals to harm males. The proposition names are also used as parts of node names in belief and analogy networks.

Table 1 POPCO propositional representations for English sentences

Meaning	POPCO representation
Males hunt animals.	`hunts (man animal)` *propn-1a*
Animals harm males.	`harms (animal man)` *propn-2a*
Men hunting sometimes causes harm from animals.	`causes (`*propn-1a propn-2a*`)` *propn-3a*

Analogy network concepts When specifying a POPCO model, the modeler divides the propositional representations for each belief into two sets ("analog sets"). The ACME module (Holyoak KJ and Thagard P 1989), written primarily by Paul Thagard as an implementation of Holyoak and Thagard's model of analogy processing, processes the propositional representations to generate the analogy network.

The core intuition underlying many theories of analogy processing, including Holyoak and Thagard's, is that to form an analogy is to construct a mapping between two sets of propositions, along with their components. Something is perceived as a good analogy if satisfies certain constraints well—if it does this in a way that takes in as much relevant information about the two domains as possible, and avoids conflicting mappings as much as possible:

1. If two propositions are mapped, it's preferable that their components be mapped as well.
2. It's preferable that two elements not be mapped to one element.
3. It's preferable to map concepts which have more rather than less semantic similarity.
4. Mapping more propositions is better than mapping fewer propositions.
5. Mapping causal claims and other higher-order propositions—i.e. those whose arguments are propositions—is more important than mapping other propositions.

To model these ideas, given two analog sets, ACME generates all possible mappings between propositions, predicates, and arguments which preserve syntactic structure and argument types. (ACME has no built-in knowledge of any natural language.) Each possible mapping between two elements is represented by ACME as single node in the analogy network. Links between nodes represent positive and negative constraints. These are designed to enforce the rules of thumb given above as well as possible. The network settling process should then give high activations to nodes representing mappings which compose a good analogy, and low or negative activations to other nodes.

For example, in 1991, before the U.S's entry into the first Gulf War, people working with President George H.W. Bush promoted the idea that Iraq in 1991 was analogous to Germany before World War II. This analogy was used to argue that the U.S. should go to war with Iraq. According to (Holyoak KJ and Thagard P 1995; Spellman BA and Holyoak KJ 1992) to see Iraq in 1991 as analogous to a situation around the time of World War II is a mostly unconscious process, which involves constructing a series of mappings between objects, predicates, and propositions.

Although two pairs of propositions are not enough to capture the idea of an analogy, they allow a simple illustration. Consider the following propositions.

1. Analog set 1:
   (a) Saddam Hussein is the president of Iraq.
   (b) Iraq invaded Kuwait.

2. Analog set 2:

    (a) Adolph Hitler was the führer of Germany.
    (b) Germany occupied Austria.

A reasonable way to understand the proposed analogy between Iraq in 1991 and Germany in 1939 would pair proposition 1a with proposition 2a, and 1b with 2b. Saddam Hussein would then be paired with Hitler, Iraq with Germany, being president with being führer, and so on. As noted above, though, ACME's procedure is to generate nodes for all possible mappings that are syntactically appropriate, and then determine which mappings are correct through the process of settling the analogy network. I summarize the possible mappings that ACME would construct involving elements of the four propositions in Figure 2. Representations of propositions are given in the top and left margins. The existence of a box at the intersection of a row and a column means that ACME will construct a network node representing a possible mapping between those propositions. When ACME creates a node for each of these mappings, it also creates links which capture the constraints mentioned above. For example, the node representing the mapping

fuhrer-of (Adolph Germany) ↔ president-of (Saddam Iraq)

will receive positively weighted links to the nodes representing these mappings:

fuhrer-of ↔ president-of
Saddam ↔ Adolph
Germany ↔ Iraq.

Each of these nodes will get positively weighted links to each other, as well. This collection of nodes represents a potentially coherent set of mappings. The same point applies to the mappings associated with each of the other three boxes. Further, any pair of nodes which map the same element to different elements is an incoherent pair of mappings. ACME will thus generate a negatively weighted link between such nodes. For example, ACME will generate a negatively weighted link between the two nodes representing these mappings:

fuhrer-of (Adolph Germany) ↔ president-of (Saddam Iraq)
occupy (Germany Austria) ↔ president-of (Saddam Iraq).

Figure 3 shows the network that would be generated by ACME for the four propositions given above.

	president-of (Saddam Iraq)	invade (Iraq Kuwait)
fuhrer-of (Adolph Germany)	fuhrer-of ↔ president-of Adolph ↔ Saddam Germany ↔ Iraq	fuhrer-of ↔ invade Adolph ↔ Iraq Germany ↔ Kuwait
occupy (Germany Austria)	occupy ↔ president-of Germany ↔ Saddam Austria ↔ Iraq	occupy ↔ invade Germany ↔ Iraq Austria ↔ Kuwait

Figure 2 Mapping relations in simplified Iraq-Germany analogy.

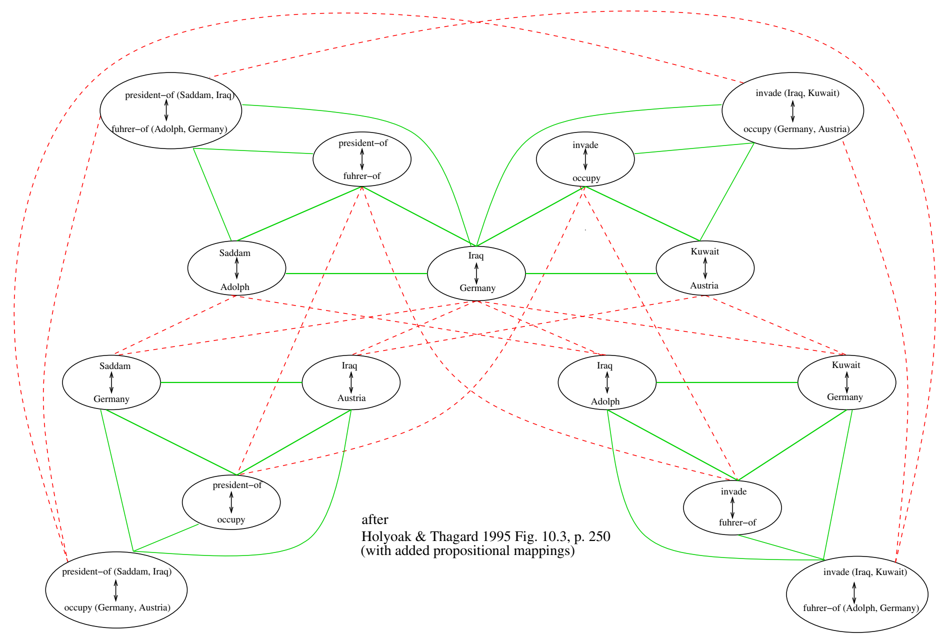

Figure 3 Analogy network generated from propositions 11a, 11b, 22a, and 22b. Ovals represent nodes, with represented mappings listed inside each oval. Solid green lines: positively weighted links; red dashed lines: negatively weighted links.

Note that since ACME doesn't have any built-in knowledge about the meanings of words, it's up to the modeler to supply abstract information about semantics to ACME. This can be done in three ways:

1. Through the choice of how to structure representations of propositions.
2. Through the choice of predicates: If identical predicates are used in the analog sets, and ACME ends up creating a node representing a mapping for these two predicates, this node is always given a little bit of extra positive activation, 0.1.
3. Through explicit specification of semantic similarity between predicates: The modeler can add code that specifies that two predicates are similar to any particular degree, represented by values from -1 to 1. A positive value makes the two nodes more likely to have similar activations; a negative value makes them more likely to have opposite activations. Larger absolute values increase these likelihoods.

Analogy network initialization Here is a more precise description of POPCO's algorithm for generating an analogy network from two analog sets containing proposition representations in predicate/argument form. It is almost the same as the algorithm given by (Holyoak KJ and Thagard P 1989).

1. Within each analog set, divide the propositions into recursively defined equivalence classes of propositions with the same type:
   (a) Propositions are of the same type if they have arguments of the same types in the same order (and therefore the same number of arguments).
   (b) Arguments to a proposition are of the same type if they are both simple names for things (not necessarily identical), or if they are both

propositions of the same type. (POPCO implements the intended behavior of the ACME model rather than a looser rule implemented in (Holyoak KJ and Thagard P 1989). (Example: The first two sentences in Table 1 are equivalent to each other; the third is equivalent to neither. More complicated examples can be found in the appendix. For example, proposition #15 there is not equivalent to proposition #22, despite superficial syntactic similarity. These propositions' first arguments, which are propositions, do not themselves have the same number of arguments.)

2. For each proposition which is a member of the corresponding equivalence classes from the two analog sets, make a "map node", a network node which represents a possible mapping between those two propositions. Do the same for corresponding predicates from each such proposition, and for corresponding arguments, i.e. arguments in the same places in the two propositions' argument lists. Example: These two propositions:
   ```
   helps (woman child) p-Woman-Helps-Child
   helps (s-god human) os-God-Helps-Human
   ```
   would result in four map nodes, one for each of these pairs:

p-Woman-Helps-Child	os-God-Helps-Human
helps	helps
woman	s-god
child	human

   Map nodes receive an initial activation value of 0.01.
3. For each proposition map node and its corresponding predicate and argument map nodes, create positive links of weight 0.1 between each pair of nodes. If such a link already exists, add 0.1 to its weight, until an upper limit of 0.5 is reached. (This restriction on analogy network link weights helps avoid large cyclic fluctuations in activation values.)
4. Create negatively weighted links, with weight -0.2, between each pair of distinct map nodes which share a proposition, predicate, or simple argument as one component of the mapping. If such a link already exists, do nothing.
5. If any map nodes for predicates concern identical predicates (i.e. found in propositions in distinct analog sets), create a link from the node *special* (which always has an activation of .99). The weight on this link is 0.1.
6. If the modeler has specified that other mapped predicates have semantic similarity, create a link from *special* to the map node, with the weight specified by the modeler.

Belief network concepts and initialization POPCO is based on the assumption that analogies can influence relationships between beliefs. For example, someone who believed that it was appropriate for the United States to go to war with Germany in World War II, and believed that Iraq in 1991 is analogous to Germany in 1941, might have been more likely to believe that it would be appropriate for the U.S. to go to war with Iraq in 1991. On the other hand, someone who thought that Iraq in 1991 was analogous to North Vietnam in the 1960s, rather than Germany in 1941, might therefore reject the suggestion that the United States should go to ware with Iraq (cf. (Holyoak KJ and Thagard P 1995)).

Nodes in each person's *belief network* represent belief in either a particular proposition or its negation. Activation values of nodes represent degrees of belief, with .99 representing full belief in the proposition associated with the node, and -.99 representing full belief in its negation. Belief nodes are created for each person as specified by the modeler during initialization. Nodes are initialized with activation value 0.0.

Positively weighted links between pairs of nodes represent tendencies to give each node similar degrees of belief; negatively weighted links represent tendencies to give each node opposite degrees of belief. These links are typically created and modified in response to the state of the analogy network (see below), but can also be specified directly by the modeler. There is also a special node, labeled *salient*, which always has the maximum activation, .99. Links from *salient* to belief nodes represent influences external to the person, and result either from explicit specification by the modeler, or from conversational input from other persons in the population. (In practice, the modeler must specify that some nodes in some persons are "perceived"—i.e. that they will have links to the *salient* node; otherwise all belief network activations will remain at 0.0.)

More precisely, weights on links between belief nodes are a function of activations of proposition map nodes in the analogy net, and occasionally, explicit specifications by the modeler, according to the following rules:

1. If there is a map node in the analogy network representing a possible mapping between proposition P_1 and proposition P_2, set the weight of the link between the nodes representing belief in/against P_1 and P_2 to
   - 0.2 times that map node activation, if the activation is > 0, or
   - 0.025 times the map node activation, if the activation is ≤ 0.
2. If the modeler has explicitly specified a weight for a link between P_1 and P_2 (using the function `semantic-iff`), then there will be a link between P_1 and P_2 with that weight, or with the sum of this weight and the weight generated by the previous step (as long as the sum does not exceed the minimum and maximum weights of -1 and 1).

The reason for the difference in the strength of map nodes' effects on negative and positive links is the following. For each successful analogical mapping between two propositions (represented by a map node with high activation), the analogy network will typically contain several unsuccessful mappings involving the same two propositions (represented by map nodes with negative activations). Many mappings are syntactically possible, after all, but no more than one proposition-proposition mapping should be successful. However, it seems reasonable to assume that disanalogies typically have less effect on our thought processes than analogies. If the resulting single positive link and several negative weights to a given belief node were of similar strength, the effects of the negative links would usually overwhelm the effect of the positive link: The disanalogies would have the primary effect. So it's important that the effect of negative map node activations be significantly smaller than the effect of positive activations. However, the precise value of this ratio doesn't seem to make a big difference to POPCO's qualitative results. Setting the multiplier for negative weights (0.025) to 1/8 the size of the multiplier for positive weights (0.2) works well in practice, and reflects the typical number of competing negative links per positive link.

Initialization sequence (init-pop) The full initialization sequence goes like this:

1. Create each person, storing specifications of proposition inputs, analog sets, a list of which propositions should be "perceived" initially, and additional semantic rules for propositions and predicates.
2. For each person, create analog sets and process semantic directives.
3. For each person, create its belief nodes, with activations set to 0.0.
4. For each person, create an environment (a simplified person) containing those propositions (beliefs) which will be perceived.
5. For each person, create the analogy network: Create map nodes and links as described above.
6. For each person, create links between belief nodes, with weights determined as described above.

POPCO main loop

Each time through the main loop, the following operations take place in sequence.

settle-nets Each person's analogy network and belief network undergo 5 iterations of settling. The settling process sets new activations for each network node as follows:

First, new activations for each of a person's nodes are calculated; then each of the nodes' current activations are set to the value of the new activation. Thus node activations are effectively updated in parallel. Following (Holyoak KJ and Thagard P 1989), the new activation a'_i of a node i with current activation a_i is given by a rule based on (Grossberg S 1978). For node i, the sum p_i of inputs from nodes j with positively weighted links w_{ij} to i is:

$$p_i = \sum_j w_{ij} \max(0, a_j) \quad \text{for } w_{ij} > 0 \,.$$

Similarly, the sum n_i of inputs from nodes j with negatively weighted links w_{ij} to i is:

$$n_i = \sum_j w_{ij} \max(0, a_j) \quad \text{for } w_{ij} > 0 \,.$$

Note that negative activations do not affect neighboring nodes. The effects of p_i and n_i are scaled by the difference of a_i from the extreme values -.99 and .99. The effect of the previous activation a_i is scaled by a decay value, .1.

$$s_i = a_i * .1 + .99\, a_i + (.99 - a_i)\, p_i + (a_i - .99)\, n_i$$

The new activation a'_i of node i is then s_i, or the maximum or minimum activation values if s_i exceeds them:

$$a'_i = \min(.99,\ \max(-.99,\ s_i))$$

POPCO networks usually settle into a stable state in which activations fluctuate very little, after about 30–200 settling iterations, i.e. 6–40 passes through the main loop. (Since the course of a real person's thought processes needn't come to a stable resolution before being interrupted by input from others, POPCO networks shouldn't have to settle before communication modifies the networks.) The pattern of activations in each network then represents a (perhaps locally) optimal configuration that balances activations in response to weights between connected nodes. A "good" network configuration is one in which pairs of positively-linked nodes usually have activations with the same sign, while negatively-linked nodes usually have activations with opposite signs.

choose-conversers POPCO agents communicate by sending propositions from one agent to another; this is an abstract representation of speech. POPCO creates a list of "converser pairs", each consisting of a speaker person and a listener person. Each person is chosen as a speaker in one converser pair, along with a randomly chosen listener, each time that `choose-conversers` is run. More specifically, for each person, POPCO creates a list of the $n - 1$ other persons, in random order, and selects the first person in the list to be the speaker's listener. The randomized list is created using a Knuth shuffle algorithm. The resulting list of converser pairs is then passed to `choose-utterances`.

choose-utterances For each speaker in a converser pair, POPCO tries to select a belief to be communicated to the pair's listener: Beliefs P_i are randomly selected as candidates for communication in a way that depends on their activation values a_i: For each belief, POPCO generates a new random number $r \in [0, 1)$ from a uniform distribution. If $r < |a_i|$, belief P_i is included in a list of candidates for communication. One belief P_i is randomly chosen from this list. This belief is attached to the converser pair to create a "conversation". The list of all such conversations is passed to `transmit-utterances`.

transmit-utterances For each conversation, information about the speaker's belief is transmitted to the conversation's listener:

1. If the belief communicated is new to the listener:
    (a) A belief node is added to the listener's belief network with initial activation 0.0.
    (b) The original predicate/argument representation of the proposition is stored for processing later by `update-analogy-nets`.
2. If the modeler specified a semantic-iff rule (§1) between this belief and an existing belief in the listener, a link will be created between nodes for these beliefs, with the weight specified by the modeler.
3. If there is not yet a link between the the *salient* node and this belief's node, such a link is created.
4. The weight on the link to *salient* in the listener is set to $0.05 \times$ sign-of(speaker's belief activation), or this value is added to the existing link weight. If the result exceeds the extreme values of -1 or 1, the weight is set to the nearest extreme.

The purpose of the additional weight on the *salient* link is to capture the idea that what's said to someone tends to increase the proposition's salience for the listener, and increases his/her confidence in its truth. Since *salient* always has an activation of .99, a persistent weight on a link from *salient* to a belief node produces a persistent influence on the belief's activation. Note that in the real world, people usually don't convey information about their degrees of belief. Thus the effect of a POPCO utterance on a listener's belief activation depends only on whether the speaker says that the proposition is true (when the speaker's belief activation is positive) or says that its negation is true (when the speaker's belief activation is negative). Incorporation of the new belief's proposition into the analogy network, and subsequent updating of belief node link weights in response, occurs in later processing steps (but before the next round of settling).

transmit-environments As mentioned above, some persons have an "environment" which contains propositions that are repeatedly communicated to the person, as if they were perceived in the person's environment. This communication process differs from that between persons in that:

1. Every "belief" in a person's environment is communicated to the person.
2. The weight added to the link from *salient* is 1.0 rather than 0.05.

update-analogy-nets For each person, if a proposition added in previous steps was new to a listener, then there will be not yet be any nodes in the analogy network corresponding to the original predicate/argument representation of the proposition. This representation, which was stored in one of the preceding two steps, is now processed to add nodes to the analogy network. The procedure for doing this is specified by the analogy network algorithm described above under "Analogy network initialization".

update-proposition-nets For each person, weights of links between belief nodes in the belief network are updated in response to the state of the analogy network, as specified in above under "Belief network concepts and initialization".

Models of Sanday's hypotheses

Sanday's empirical and causal claims

Using an anthropological dataset, the Standard Cross-Cultural Sample, (Sanday PR 1981) reported pairwise correlations across societies between properties in adjoining columns of Table 2, i.e.:

- Between dependence on large game hunting, and greater degrees of male dominance over women.
- Between male dominance, and fathers' emotional distance from children and/or lack of involvement in childrearing.
- Between fathers' emotional distance and lack of involvement in childrearing, and societal emphases on stories about human origins in which humans are created magically by a male or animal creator from a distant place—as opposed to natural creation by a female or couple from nearby.

Sanday proposed an explanation of the correlations in terms of cognitive tendencies linking characteristics in the four dimensions, with the (leftmost) subsistence variable viewed as imposed by the environment rather than influenced by any of the other three. Though Sanday's (Sanday PR 1981, ch. 3) most explicit statement claims that the direction

Table 2 Summary of correlations between cultural variants from (Sanday PR 1981, ch. 3)

Main subsistence	sex roles	fathering	creation stories
large game hunting	men dominant	distant from child	far male/animal creates magically
intermediate/mixed	intermediate		couple creates by natural process
gathering or fishing	men less dominant	close to child	nearby female creates naturally

Correlated variants are listed on the same line.

of causation goes only from left to right in Table 2, other remarks show that she thought there were feedback relations between most of the four variables.

For example, Sanday argued that the danger and struggle for intermittent reward required by large game hunting encourages a view of the power of nature as something apart from humans, which must be mastered by males:

> Consider, for example, a society that relies on large game for food and, perhaps, clothing or items for domestic use. In these cases the hunter and the hunted are engaged in a game of skill in which both have the power to outwit the other .... In such instances power does not come readily to humans; power must be acquired, controlled, and manipulated for human purposes. (Sanday PR 1981 p.65)

I understand Sanday as arguing that, partly because such situations encourage emotional distance from the environment, men are then less likely to be intimately involved with raising young children. Large game hunting also encourages focus on stories in which creation of humans is the result of a magical process controlled by a male, animal, or abstract being in the sky, rather than a more intimate, natural process involving females:

> When large game are hunted, ... males engage in an activity whose outcome is unpredicatable [sic] and entails danger. ... the psychological energy expended in this effort ... is not directed inwardly toward nurturing children or family but toward acquiring and using powers beyond man's dominance. The major source of power is perceived as residing in a supreme being who resides in the sky or in animals. (Sanday PR 1981, pp. 65f)

Some of Sanday's remarks also suggest that creation stories can affect men's involvement with children:

> The nurturant father, on the other hand, is buttressed by the female creator. In these cases, the reproductive functions of women are celebrated both in myth and behavior. In the absence of the female creator, fathers are involved with children in infancy and early childhood either as disciplinarians or not at all. When their major role is to discipline and control, fathers are not unlike supreme beings. They are distant, controlling figures who are removed from biological processes. (Sanday PR 1981, p. 64)

These remarks can reasonably interpreted as proposing that cognitive processes are responsible for the cross-cultural correlations Sanday reported, even if she does not clearly spell out relevant cognitive mechanisms. Sanday also discusses possible social processes by which a culture might be transformed from one that doesn't fit the patterns she describes to one that does, but does not propose precise models.

Various passages in Sanday's book (Sanday PR 1981) are suggestive of the idea that analogical relationships between patterns of thought in the four domains (Table 2) encourage the correlations she reported. Thus I propose that if the causal relations between cultural patterns exist, they are partially mediated by tacit analogical inferences. By simulating a population of communicating persons in which such inferences are available, we can explore models which might provide "how possibly" (Brandon RN 1990; Grim P et al. 2011) explanations of correlations like those that Sanday reported.

These would be "generative" explanations in Epstein's (Epstein JM 2006) sense, not just in showing how the correlations Sanday describes arise from a collection of agents representing persons, but also in showing how they arise from relatively simple networks of "agents" inside persons. Such explanations would provide mechanistic accounts of population processes—processes that depend on hypotheses about symbolic cultural relationships.

More specifically, the simulations described below will illustrate the possibility of providing answers for two questions:

1. What might cause correlations between stories about human origins and concrete behavioral styles concerning male childrearing roles and means of subsistence?

The first simulation (model 1) will illustrate the possibility that these correlations are at least partly due to the influence of analogies, reinforced by communication between members of a society.

2. How might particular origin stories come to be entertained in the first place?

The second simulation (model 2) will illustrate the possibility that one part of an answer is that propositions that are not part of a coherent origin story spread through the population for reasons unrelated to origin stories, childrearing behaviors, or means of subsistence. However, when these propositions come to be entertained together, analogical resonance between concrete behaviors and these propositions can emphasize them in a way that suggests a coherent origin story.

Core features of the simulations

Persons in the models 1 and 2 have:

1. Propositions about current human interactions:
   - (a) Propositions concerning parenting and childbirth. (I call these "parenting" propositions.)
   - (b) Propositions concerning large-game hunting ("hunting" propositions).
2. Propositions about human origins:
   - (a) Propositions characterizing a creator who is from the earth, is female, is nurturing, and created humans from inside her body ("earth origin" propositions about an "earth-based" god).
   - (b) Propositions characterizing a creator who is male, comes from the sky, is both helpful and harsh, and created humans magically ("sky origin" propositions about a "sky-based" god).

The 37 propositional inputs I use to represent these four domains (Appendix) constitute an attempt to provide a simple and somewhat abstract representation of some of the core ideas in Sanday's hypotheses. Within each person, POPCO has the opportunity to map any proposition in set group 1 above to any proposition in set group 2. However, as we'll see, POPCO agents will able to construct two distinct sets of analogical relationships: those relating hunting to sky origin, and those relating parenting to earth origin.

Model 1: What causes the correlations?

1. What might cause correlations between stories about human origins and concrete behavioral styles concerning male childrearing roles and means of subsistence?

Model 1 implements a population which is small enough (100 individuals) so that everyone talks to everyone else. Each person entertains all 37 propositions about parenting, hunting, and both sky-based and earth-based gods. The model assumes that hunting plays a large role in this population: Each hunting proposition is made salient for each person. That is, in the belief network, hunting propositions have links of weight 1 to the *salient* node. All other propositions begin with an activation of 0.0, representing neither belief in the proposition nor in its negation. This last assumption is unrealistic, but allows a simple demonstration of the fact that salient hunting propositions can produce a tendency to encourage sky origin propositions. From this starting state, the model runs for 2000 time steps (iterations of the main loop). Since there is stochastic variation in who talks to whom and in whether a person says anything in a given time step, I ran the same model 50 times with a new random seed each time. The behavior of the model was qualitatively identical in all runs, so I'll simply describe a single run.

Figure 4 displays averages of activations of beliefs in each of four domains: parenting (P), hunting (H), earth origin (OE), and sky origin (OS). Each line in the plot displays the average activation for one person over the first 1500 time steps. (There was little change

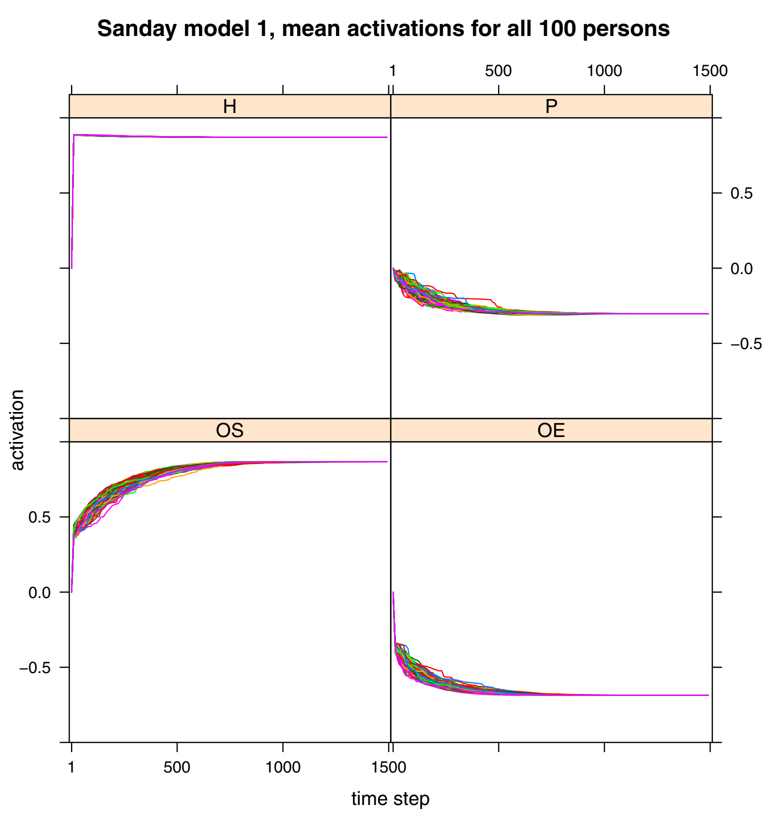

Figure 4 Model 1: Averages of each person's belief activations in the labeled domain, with hunting propositions salient during the run. H: hunting propositions, P: parenting propositions, OS: sky origin propositions, OE: earth origin propositions. One proposition (`o-Human-Alive`), common to both OS and OE, is not included since it doesn't belong exclusively to either domain. Points are plotted every 10 time steps, i.e. at 1, 11, 21, etc.

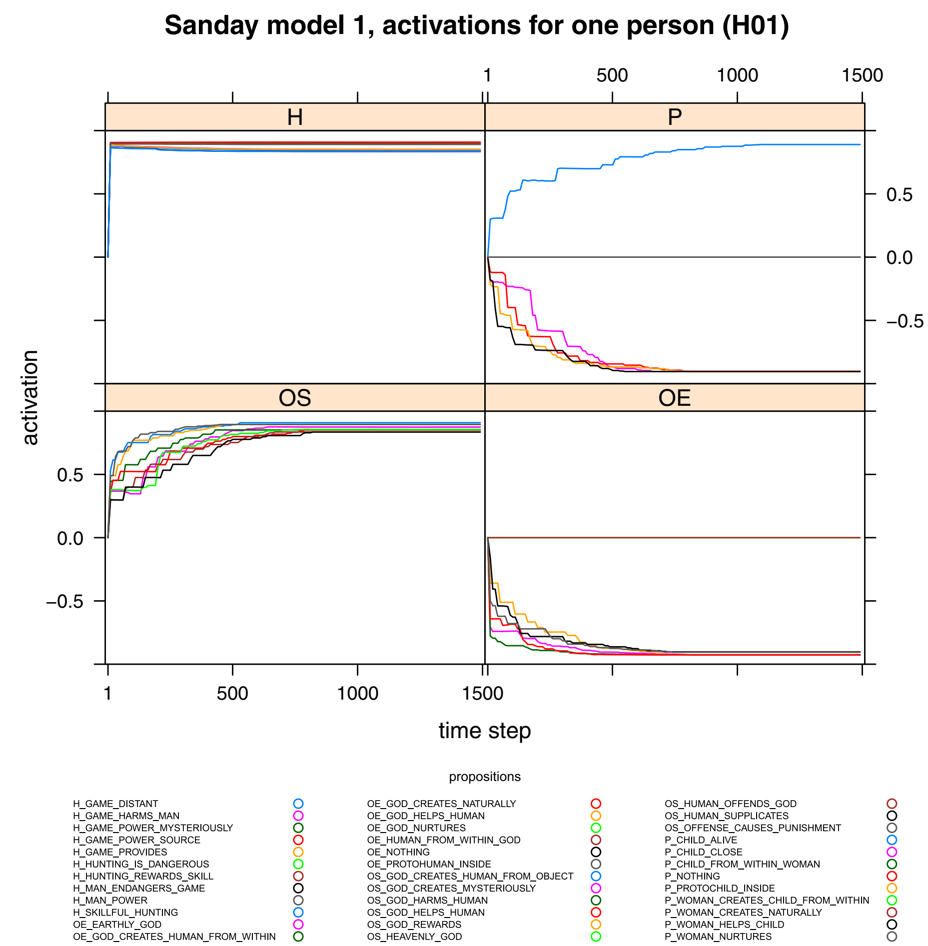

Figure 5 Model 1: Each line represents changing activation of one belief in a single person (H01) from the run summarized in Figure 4. One proposition (`o-Human-Alive`), common to both OS and OE, is not plotted. Points are plotted every 10 time steps.

during the last 500 time steps.) Figure 5 shows activations for individual propositions in a single person over the same time period. All 100 persons exhibited a very similar pattern, in each of the 50 runs.

Figures 4 and 5 show that sky origin beliefs, initially with activations 0.0, immediately acquire positive activations, and stabilize at values near 1 by step 1000. The initial rise in these activations is due to the fact that their pattern of relationships parallels relationships between hunting propositions. POPCO constructs an analogy between hunting propositions and sky origin propositions and as a result, creates positively weighted links between those hunting propositions and sky origin propositions that play similar roles in the two analog sets. Then since hunting propositions have high positive activations, positive activation is transmitted to sky origin propositions.

However, the gradual increase in activations of sky origin propositions after the first few steps is largely due to conversation. Once sky origin propositions acquire positive activations, they thereby acquire a significant probability of being communicated to others. When such a belief is communicated, it causes an increase in the activation of the same belief in the listener. It's this mutual reinforcement due to agreement and conversation

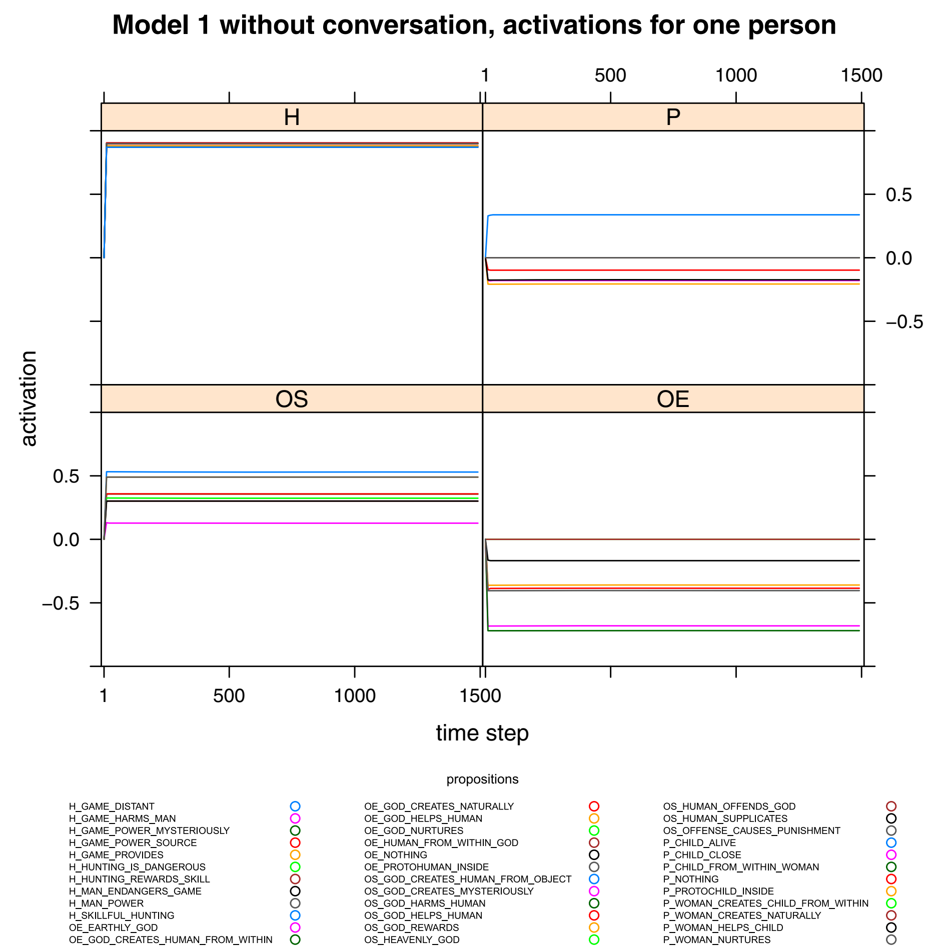

Figure 6 Belief activations for one person, with no conversation. As in Figure 5, one proposition is excluded, and points are plotted every 10 time steps.

that carries sky origin proposition activations to near 1 by tick 1000. The effect of conversation can be seen by comparing Figure 5 with Figure 6, which plots data from a similar model in which no conversation takes place.

Sky origin propositions compete with earth origin propositions to be mapped to hunting and parenting propositions. The analogy network will include a negative link between (a) a node representing a possible mapping of a sky origin proposition to a hunting or parenting proposition P, and (b) a node representing a possible mapping between an earth origin proposition and P (§1). Thus when, for example, a hunting/sky origin map node acquires a high activation because of its role in the hunting/sky origin analogy, this tends to push down the activation of a competing hunting/earth origin node. If this second node acquires a negative activation, it will usually result in a negatively weighted link between nodes representing the hunting proposition and the earth origin proposition. But the hunting proposition always has a high activation in the (conversational) model described above, so there will be a tendency for the earth origin proposition to receive negative activation. It's because of such effects that most of the earth origin propositions end up having negative activations. Many parenting propositions have negative activations in the model because of similar effects involving possible mappings between parenting propositions and sky origin propositions, as well as positive links between parenting propositions and earth origin propositions. Of course the full story involves effects of many nodes and links at once. (One parenting proposition, `p-Child-Alive`, has high activation. This is due in part to the fact that this proposition gets mapped to `o-Human-Alive`, an origin proposition that plays roles in both sky origin and earth origin analogies. `o-Human-Alive` is also mapped by a hunting proposition, `h-Man-Power`, that has positive activation.)

Though the principles governing the generation of the analogy and belief networks are relatively simple, the generated networks are often complex. Figures 7, 8, and 9 show the analogy network (bottom) and belief network (top) at time steps 0, 10, and 100 in the person whose activations were plotted in Figure 5.

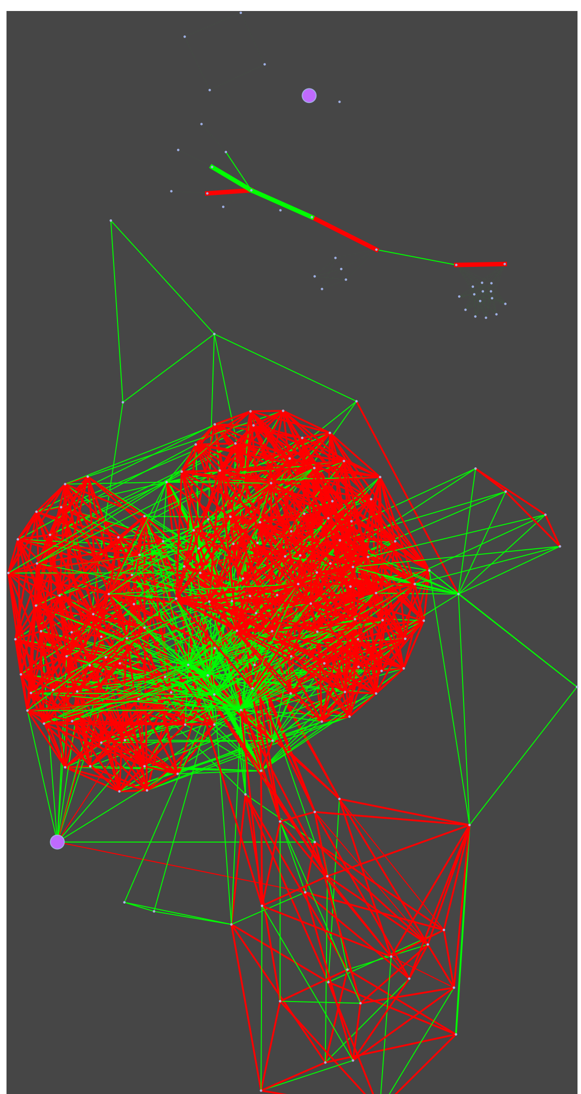

Figure 7 Model 1: Networks in one person at time step 0. Bottom: analogy network; top: belief network. Green links are have positive weight; red links have negative weight.

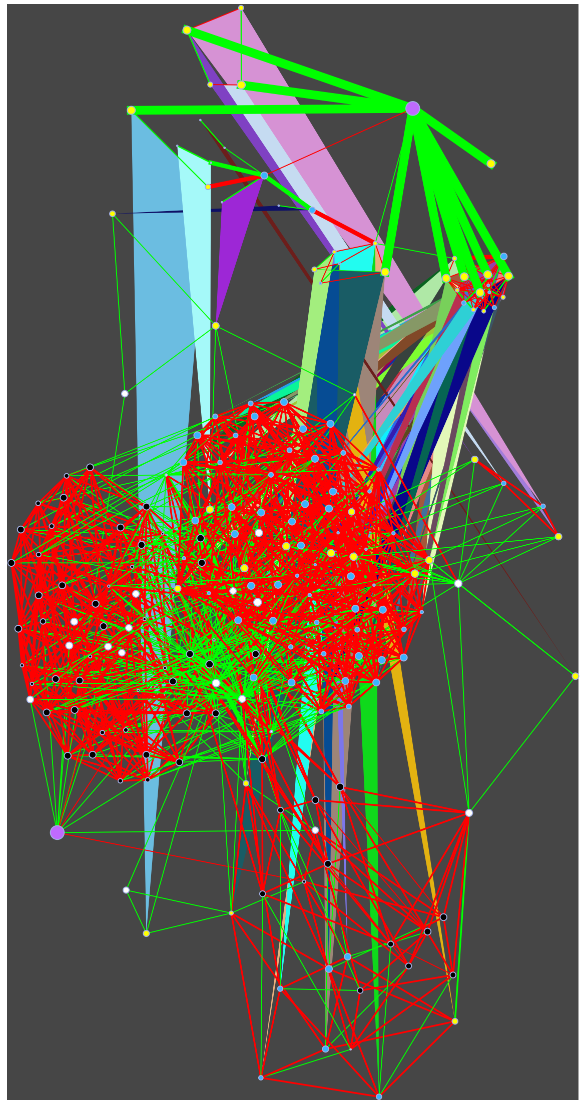

Figure 8 Model 1: Networks in same person at time step 10. Bottom: analogy network; top: belief network. Thickness of lines indicates absolute value of link weight. Colored triangles show relations between proposition map nodes and belief network links.

(I also performed 50 runs of a model in which parenting propositions rather than hunting propositions were made salient. Again, all runs were qualitatively similar to each other. All runs were like those in model 1 described above, but with behaviors switched to different proposition domains: Earth origin rather than sky origin propositions roughly converged to a high activation. Sky origin and hunting propositions acquired relatively low activations in contrast to their high activations in the original model. Figure 10 shows a typical run of this model.)

What model 1 illustrates is that analogies between beliefs derived from the experience of large game hunting could increase the plausibility of stories which see humans as being created by a physically and emotionally distant, magical being. The model illustrates the possibility that once such an set of origin beliefs became widespread, mutual

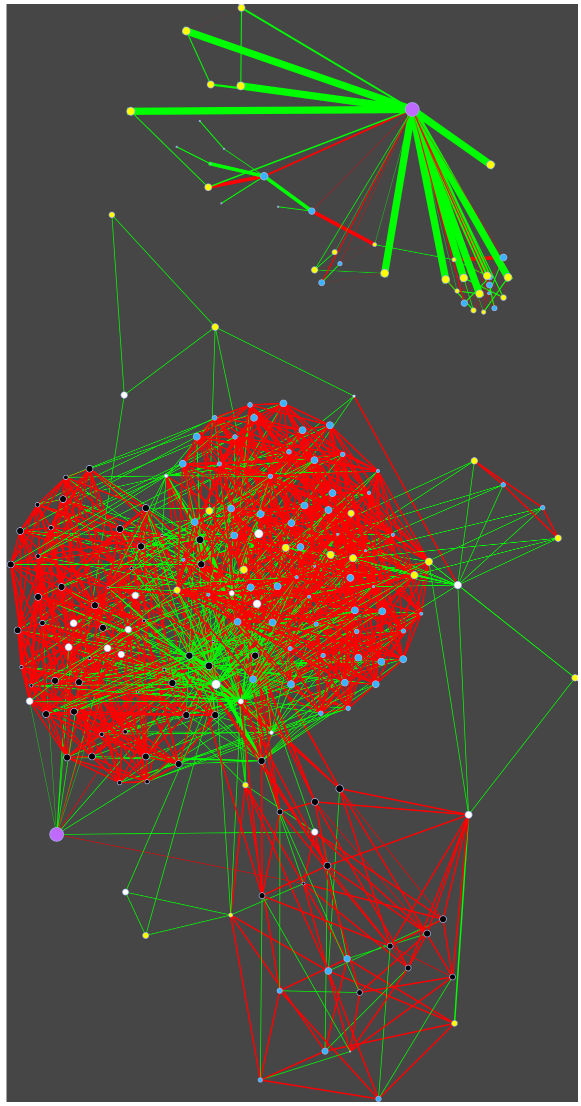

Figure 9 Model 1: Network in same person at time step 100. Bottom: analogy network; top: belief network. White and yellow: positive activation; black and blue: negative activation. Absolute value of activation: size of circle. White/black are used only for proposition map nodes.

reinforcement through social interaction could increase the strength of such beliefs. The model thus suggests a possible mechanism for generating phenomena like those described by Sanday.

Model 2: Where do origin stories come from?

2. How might particular origin stories come to be entertained in the first place?

A story about human origins is a relatively complex whole, including a number of beliefs. How does such a set of beliefs come to be entertained in the first place? Where do those thoughts come from? One possibility is that each component of an origin story originally arises in different persons for reasons that have nothing to do with the possible role of such propositions in an origin story. Such propositions might not have

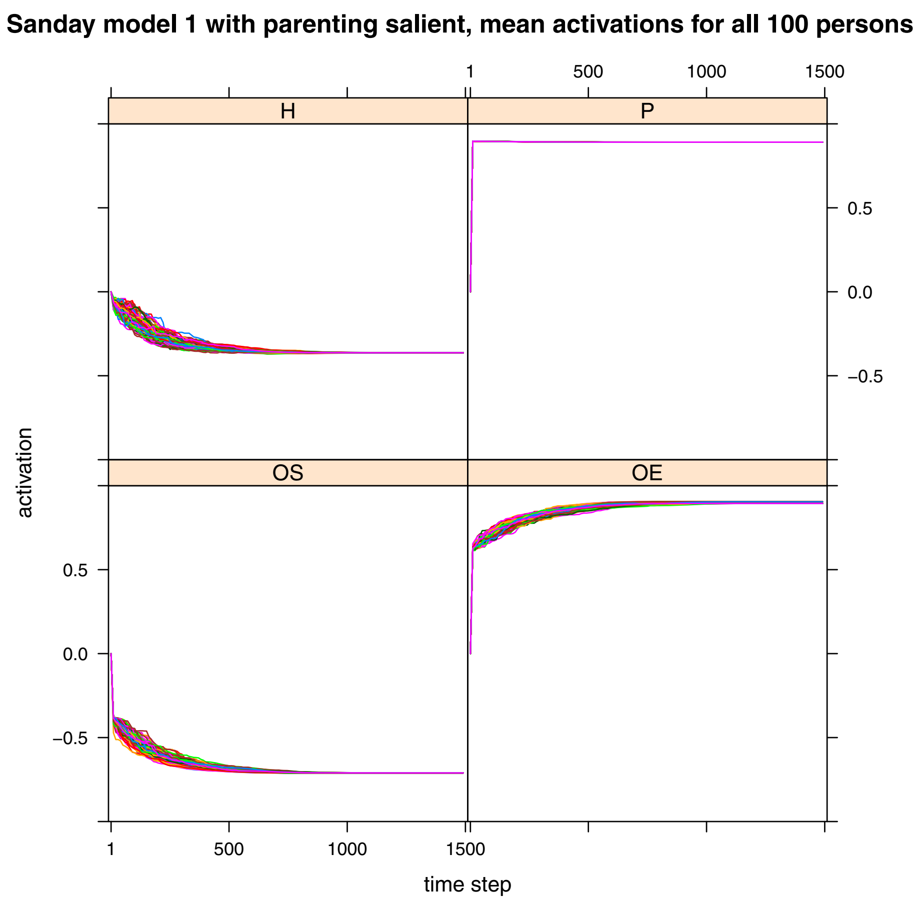

Figure 10 Model 1 with parenting rather than hunting propositions salient during the run. Other specifications are the same as for Figure 4.

great significance, but may nevertheless get mentioned from time to time. After most of the propositions have diffused through the population, a change in the physical or social environment might lead to patterns of belief that resonate analogically with the origin story.

We can model this kind of process by scattering beliefs which might play a role in an earth origin story across different members of the population. In particular, we can alter model 1 by starting with 92 persons who have only hunting propositions, parenting propositions, and sky origin propositions. To this we add eight persons, each of which has all of the propositions just mentioned, plus a single, unique earth origin proposition. We then allow the new model to run for 1000 time steps in the same way as the old model. Although, initially, none of the earth origin propositions in the eight individuals make up a full earth origin analog set, they do end up getting activations other than zero, due to mappings in which they participate imperfectly. Earth origin propositions thus occasionally get mentioned in conversation, and gradually spread through the population. As it turns out, most members of the population acquire most earth origin propositions by time step 1000. (I ran the model 50 times with different random seeds. In at least 27 runs, all 100 members of the population had all eight of the earth origin propositions by time step 1000. In no run were more than 99 of the 800 possible instances of earth origin propositions absent.) Assume, further, that at time step 1000, the physical and/or social environment changes. Intimate parenting becomes more important: We link parenting beliefs to *salient* with weight 1. Hunting become undesirable: We link hunting beliefs to *salient* with weight -1.

Behavior in all runs was qualitatively similar. Figure 11 shows one run (in which all persons had all earth origin propositions by step 1000). We see that once parenting beliefs become salient at step 1000, earth origin beliefs immediately come to have high average activation, as a result of the analogy with parenting beliefs. These activations are subsequently increased by conversation. The negative salience applied to hunting propositions at step 1000 counteracts the effects of earlier positive salience. The analogy between hunting propositions and sky origin propositions, as well as negative links involving earth origin propositions, then gives the sky origin propositions negative average activations. (Models which are the same except that there are no earth origin propositions present anywhere in the population produce similar patterns for sky origin propositions, but these average activations are not as low.)

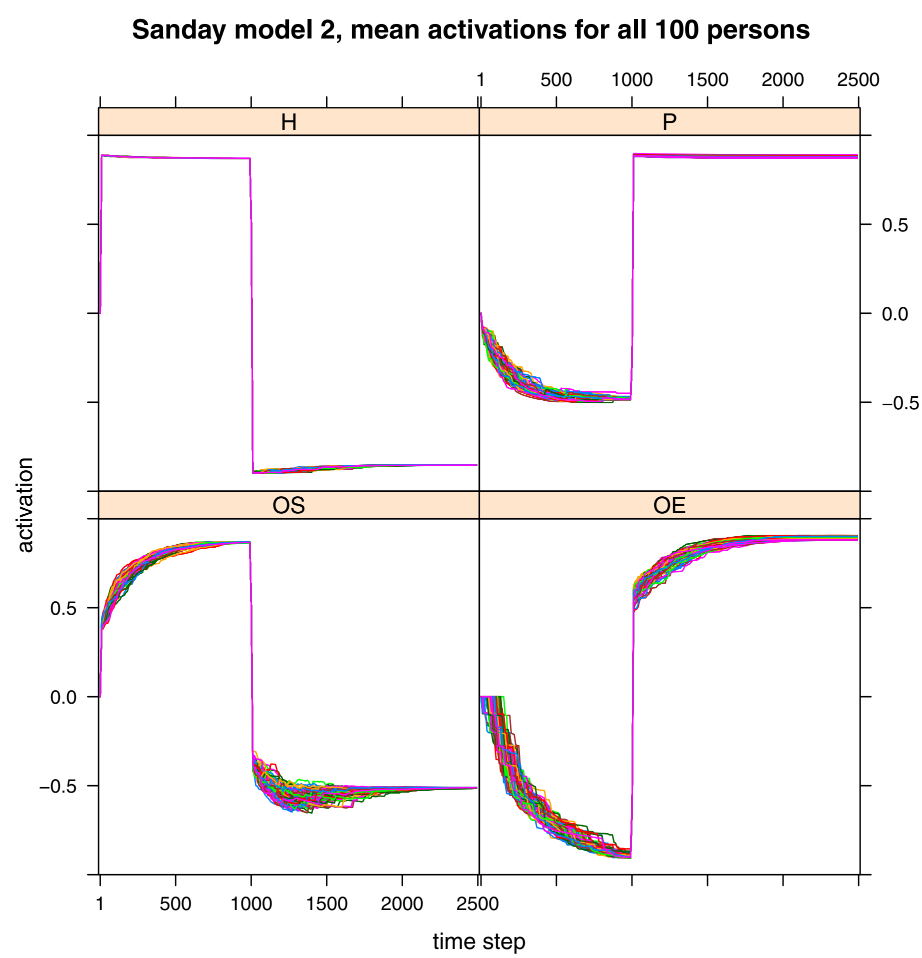

Figure 11 Model 2: Averages of each person's belief activations in the labeled domain. H: hunting propositions, P: parenting propositions, OS: sky origin propositions, OE: earth origin propositions. One proposition (`o-Human-Alive`), common to both OS and OE, is not plotted. Points are plotted every 10 time steps, i.e. at steps 1, 11, 21, etc.

Model 2 illustrates the possibility that an origin story might might come to play a significant role in a culture through a two-part process. First, the components of the story incrementally filter through a population, but play no very special role as a whole in patterns of thought. Later, a cultural change in another domain makes an analogy to this "neutral" set of thoughts salient, thus bringing the origin story into prominence in the culture.

Results and discussion

Models 1 and 2 provide simple illustrations of ways that patterns of culture reported by Sanday might come about. The models provide simple "how possibly" explanations (Brandon RN 1990; Grim P et al. 2011) or "generative" explanations (Epstein JM 2006). What is significant is not that the patterns can be generated by a computer model, but that they can be generated by particular kinds of processes (Epstein JM 2006, pp. 28f)—in this case, processes of analogy construction. Several specific points are worth noting.

First, POPCO is able to illustrate a process by which tendencies to believe cultural elements in different domains are influenced by modeled analogical relationships. Further, we saw that the relatively mild effect of analogy can be reinforced by communication within a population. The idea that the modeling of processes of analogy construction might be useful for understanding cultural relationships is not new (Dehghani M et al. 2009; Holyoak KJ 1982; Holyoak KJ and Thagard P 1995; Thagard P 2012, 1992), but there has been little work on modeling the role of analogical relationships on population-level cultural change. (Thagard (Thagard P 2000, Ch. 7) presents agent-based models of consensus-building in scientific communities, but his focus in these models was not on analogical relationships.)

Second, the simulations illustrated a way of modeling the influence of relations of coherence between elements of a culture on cultural dynamics. Such relations have not played a significant role in modeling of cultural change within populations. In the simulations described above, beliefs changed in frequency in response to inferential relationships connecting them. In most cases these inferential relationships were derived from analogical relations, which themselves are the result of a kind of evaluation of coherence by the analogy network (Thagard P 2000). Also note that many existing models of cultural change are derived from models in population genetics, and the roles that coherence plays in POPCO models suggest properties that are important in biological evolution—epistasis, pleiotropy, and genetic distance.

Third, it's significant that POPCO can model processes by which different ideas diffuse through a population randomly, and then come together to create a new cognitive structure which later becomes important. POPCO should be able to model cases in which propositions spread for one reason—say, because they cohere with propositions X—but later come to influence propositions Y for other reasons (cf. (Gould SJ and Vrba ES 1982; Hurst LD and Peck JR 1996; Wimsatt WC 1999; Wimsatt WC and Griesemer JR 2007)).

Fourth, since the effect of one belief on analogical relationships depends on the presence of other, related beliefs, POPCO illustrates one way to model the idea that elements of real culture often interact in a non-additive manner (Wimsatt WC and Griesemer JR 2007). POPCO also provides a way to model some kinds of cultural "scaffolding" in

Wimsatt and Griesemer's (Wimsatt WC and Griesemer JR 2007) sense, and "attractors" in Sperber's (Sperber D 1996) sense: The effect of an utterance on the internal state of a listener in POPCO depends on the listener's other background beliefs and experiences.

The reader will have noticed that in the simulations described above, members of a population ultimately converged to the same beliefs. Large scale societies are nothing like this, of course, and anthropological studies of small, self-contained societies don't always show uniformity of opinion. However, convergence to consensus is what we should usually expect in models in which everyone influences everyone else. Lehrer K and Wagner C (1981) derive this conclusion from basic facts about matrices for a specific model of communication, but the point seems more general. Alexander JM (2007) presents a number of models involving imitation of neighbors' behavior in games, in which maintenance of diversity requires social network structures other than full communication between all agents. Morris S (2000) (cf. (Vega-Redondo F 2007)) showed that for players which imitate the best responses in simple multi-player coordination games on a network, the spread of a response depends on ratios between certain node degrees. In more recent investigations I have been exploring effects of social network structure in POPCO models, and have found that POPCO models can maintain diversity of opinion on a structured network. (POPCO's social network functions were added by Kristen Hammack.) Finally, note that interactions between opinions in real societies are much more complex than in any model, and are influenced by changes in the physical environment as well. It may be that such interactions can by themselves prevent convergence of opinion in real societies, even if everyone were influenced by everyone. Indeed, (Mueller ST et al. 2010) have illustrated the possibility of maintaining distinct clusters of beliefs in a population because of dependence of some beliefs on others, rather than because of network structure. POPCO may able to implement similar patterns, but this is a topic for future investigation.

Given the complexity of a POPCO simulation, the following related questions express natural worries:

- Can't *any* result be gerrymandered using a POPCO simulation? There seem to be too many degrees of freedom.
- Doesn't the complexity of POPCO models obscure the patterns that are in fact responsible for the simulation results? If you get an interesting result using POPCO, how will you know which features of the model were responsible for it?

In trying to construct the models described above, I did make a number of somewhat arbitrary choices, as the Appendix illustrates. On the other hand, you can't just put *anything* into a POPCO model—not if the goal is to try to capture preexisting ideas about how certain complex cultural variations interact with each other. My experience so far is that it's in fact quite difficult to capture ideas like Sanday's in a POPCO model. I think that the goal of trying to model a certain kind of cognitive process which plausibly might operate in the world places severe constraints on modeling with POPCO.

POPCO agents do lack the transparency of agents in simple-agent models, and this is a drawback. In order to understand why POPCO agents behave as they do, one sometimes has to investigate their internal processes. POPCO is designed to make this process as easy as possible, though. A person's neural networks can be investigated using interactive network display tools such as GUESS, and I have also built a tool in NetLogo (Wilensky U 1999) for quick observation of certain patterns. Further, Common Lisp, in which POPCO is implemented, makes it easy to interactively query any aspect of a simulation's state at any time.

Finally, investigation of what's responsible for a result in POPCO may require varying parameters and constructing alternative models, as in other contexts (cf. Figure 6). In the case of POPCO simulations, sometimes this means going outside of POPCO. For example, I've found it helpful, in investigating effects of network structure in POPCO, to build related simple-agent models in NetLogo.

Conclusions

I've described the POPCO agent-based framework for simulating cultural variation in populations, and presented models illustrating some of its capabilities. POPCO is unusual in providing a relatively simple framework for studying cultural variation, which at the same time allows changes in culture to depend on analogical and other coherence relationships between beliefs. This allows us to model the effects on cultural dynamics of some of the symbolic relationships thought to be important in hermeneutical studies of culture.

Sanday PR (1981) used statistical methods and proposed hypotheses relating cultural variants that were explicitly causal. Sometimes researchers in hermeneutical traditions consider such strategies inappropriate for the study of culture. Nevertheless, because of the kinds of cultural variants that Sanday discussed, the complex and subtle nature of their relationships, and the authors upon whose work she drew to construct her hypotheses, I view Sanday's research in (Sanday PR 1981) as substantially indebted to hermeneutical research traditions. (The quotations in section "Sanday's empirical and causal claims" hint at this dimension of her work.) The models I describe above attempt to capture some of the subtle relationships Sanday proposed, albeit in an abstract form. These models thus represent initial steps in modeling effects of such complex and subtle cultural phenomena in populations. I believe that the models described above suggest some of the potential of moderate-agent modeling for investigating relationships between cultural phenomena. I suggest that moderate-agent strategies, though currently rare, have the potential to help bridge gaps between insights from humanistic research and scientific methods.

Appendix: Propositional specifications for Sanday models

Table 3 lists the propositional representations used as inputs to POPCO in the Sanday simulations. Figure 12 gives Lisp source code input to POPCO to specify additional semantic relationships, which go beyond those captured by analogical relationships discovered by POPCO. Proposition prefixes such as "oe-", "os-", "h-", and "p-" mainly serve to remind the modeler about how propositions are grouped, although they are used in some routines used to display data. The prefixes "s-" and "e-" in "s-god" (sky-based god) and "e-god" (earth-based god) cause POPCO to treat s-god and e-god as distinct objects, rather than one object with the properties of both sorts of creator. Note that although the correlations that Sanday found involved male parenting, her explanation of these correlations had more to do with female parenting.

Table 3 Propositional inputs for models 1 and 2

Predicate	Arguments	Proposition name	Intended meaning
Parenting:			
1. alive	(child)	*p-Child-Alive*	A child is alive.
2. intimate-agent	(woman, child)	*p-Child-Close*	Women, children are emotionally intimate.
3. inside	(child, woman)	*p-Protochild-Inside*	A child (fetus) is initially inside a woman.
4. process-from-to	(*p-Protochild-Inside, p-Child-Alive*)	*p-Child-From-Within-Woman*	There is a process that leads from (3) to (1).
5. creates	(woman, *p-Child-From-Within-Woman*)	*p-Woman-Creates-Child-From-Within*	Woman are the cause of the process in (4).
6. natural-process	(*p-Woman-Creates-Child-From-Within*)	*p-Woman-Creates-Naturally*	The preceding process is natural.
7. helps	(woman, child)	*p-Woman-Helps-Child*	Women help (nurture, etc.) their children.
8. causes	(nothing, *p-Woman-Helps-Child*)	*p-Woman-Nurtures*	Nothing causes women to nurture children.
9. nothing	(nothing)	*p-Nothing*	(Has no real meaning, but is useful.)
Hunting:			
10. feels-power	(man)	*h-Man-Power*	Men feel powerful, able to control nature.
11. power-source	(game, *h-Man-Power*)	*h-Game-Power-Source*	Game is a source of this power.
12. mysterious-process	(*h-Game-Power-Source*)	*h-Game-Power-Mysteriously*	Game being source of power is mysterious.
13. hunts-endangers	(man, game)	*h-Man-Endangers-Game*	Men hunting is dangerous to game.
14. harms	(game, man)	*h-Game-Harms-Man*	Game sometimes harms men.
15. causes	(*h-Man-Endangers-Game, h-Game-Harms-Man*)	*h-Hunting-Is-Dangerous*	(13) is a cause of (14)
16. hunts-skillfully	(man, game)	*h-Skillful-Hunting*	Hunting involves skill.
17. helps	(game, man)	*h-Game-Provides*	Game helps men (by providing food, etc.).
18. causes	(*h-Skillful-Hunting, h-Game-Provides*)	*h-Hunting-Rewards-Skill*	Skill in hunting causes game's benefit.
19. distant-agent	(game, man)	*h-Game-Distant*	Game and men are emotionally distant.
Both origin domains:			
20. alive	(human)	*o-Human-Alive*	Humans are alive.

Table 3 Propositional inputs for models 1 and 2 *(Continued)*

Earth origin:			
21. inside	(human, e-god)	*oe-Protohuman-Inside*	Human(s) began inside e-god.
22. process-from-to	(*oe-Protohuman-Inside, o-Human-Alive*)	*oe-Human-From-Within-God*	There's a process leading from (21) to (20).
23. causes	(e-god, *oe-Human-From-Within-God*)	*oe-God-Creates-Human-From-Within*	An e-god causes this process.
24. natural-process	(*oe-God-Creates-Human-From-Within*)	*oe-God-Creates-Naturally*	An e-god doing so is a natural process.
25. helps	(e-god, human)	*oe-God-Helps-Human*	An e-god helps humans, is nurturing, etc.
26. causes	(nothing, *oe-God-Helps-Human*)	*oe-God-Nurtures*	Nothing causes an e-god to be nurturing.
27. close	(e-god, human)	*oe-Earthly-God*	e-god is physically close to humans.
28. nothing	(nothing) [Has no real meaning, but is useful.]	*oe-Nothing*	(Has no real meaning, but is useful.)
Sky origin:			
29. creates	(s-god, *o-Human-Alive*)	*os-God-Creates-Human*	An s-god causes (20).
30. mysterious-process	(*os-God-Creates-Human*)	*os-God-Creates-Mysteriously*	The process in (29) is a mysterious process.
31. offends	(human, s-god)	*os-Human-Offends-God*	Humans offend s-god (sometimes).
32. harms	(s-god, human)	*os-God-Harms-Human*	s-god harms humans (sometimes).
33. causes	(*os-Human-Offends-God, os-God-Harms-Human*)	*os-Offense-Causes-Punishment*	Offending s-god causes punishment.
34. supplicates	(human, s-god)	*os-Human-Supplicates*	Humans supplicate, pray, etc. to s-god.
35. helps	(s-god, human)	*os-God-Helps-Human*	s-god helps humans (sometimes).
36. causes	(*os-Human-Supplicates, os-God-Helps-Human*)	*os-God-Rewards*	Supplicating is what causes s-god to help.
37. distant	(s-god, human)	*os-Heavenly-God*	s-god is physically distant from humans.

```
; Semantic similarities between predicates, with negative values for antonymic
; relationships.  Note: *ident-weight* is a number which represents the semantic
; similarity between identical predicates in ACME.  Asterisks appearing just
; after a left parenthesis are multiplication operators; others are parts of names.
(similar 'helps 'harms (* -1 *ident-weight*))
(similar 'feels-power 'alive (* -.75 *ident-weight*))
(similar 'woman 'human (* .5 *ident-weight*))
(similar 'man 'human (* .5 *ident-weight*))
(similar 'distant 'distant-agent (* .5 *ident-weight*))
(similar 'close 'intimate-agent (* .5 *ident-weight*))
(similar 'offends 'harms (* .5 *ident-weight*))
; "Soft-iff" semantic-like relationships between propositions:
(semantic-iff 'oe-Earthly-God 'os-Heavenly-God -.5)
(semantic-iff 'oe-God-Creates-Naturally 'os-God-Creates-Mysteriously -.5)
(semantic-iff 'os-Heavenly-God 'os-God-Creates-Mysteriously .1)
(semantic-iff 'oe-God-Creates-Naturally 'oe-God-Creates-Human-From-Within .5)
(semantic-iff 'oe-God-Nurtures 'oe-God-Creates-Human-From-Within .1)
(semantic-iff 'oe-Human-From-Within-God 'oe-God-Creates-Human-From-Within .5)
(semantic-iff 'oe-God-Creates-Human-From-Within 'os-God-Creates-Human-From-Object -.5)
```

Figure 12 Input specifications for additional semantical relationships.

Competing interests
The author declares that there are no competing interests.

Author's contributions
All writing, program design, simulation runs, and analysis were performed by Marshall Abrams. As noted in the text, POPCO includes the ACME component, which was written primarily by Paul Thagard. Kristen Hammack added social network functionality to POPCO and modified procedures for communication between persons. (Social network functionality was not used in the simulations reported here, but Hammack's communication code was used.) All other coding of POPCO, and all coding for particular simulations were performed by Marshall Abrams.

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