Psychology from Stigmergy

H. Van Dyke Parunak

Abstract

Agents inspired by insect behavior are sometimes contrasted with agents that model human cognition (Belief-Desire-Intention agents, or systems like Soar or ACT-R). We have recently completed an extensive simulation project requiring psychologically and socially realistic agents, based on the insect model. SCAMP (Social Causality with Agents using Multiple Perspectives) generates realistic social data from a known causal framework. Because the psychological details are encoded in the environment rather than the agent, they can be configured by domain experts with no formal programming training, using common desktop tools such as spreadsheets, concept modeling frameworks, and drawing programs. This paper gives SCAMP's background, describes its biomimetic agent model and the environment that encodes its psychological and social behaviors, and reports our experience in its use.

1. Introduction

We[1] developed SCAMP under the DARPA GroundTruth program. GroundTruth used data generated from known causal ground truth in a realistic scenario to test methods deployed by social scientists, so the simulators had to reflect psychologically and socially realistic behaviors. [14] offers further discussion of SCAMP in this context.

The most direct approach to such constraints is to use an agent model such as Belief-Desire-Intention (BDI) [25], or based on Bayesian formalisms believed to reflect human cognition. However, these approaches embed cognitive behavior in the agent code. We wanted professional analysts, subject-matter experts with no computer programming experience, to generate our causal ground truth.

Our solution lies in "Simon's Law" [33]:

> An ant, viewed as a behaving system, is quite simple. The apparent complexity of its behavior over time is largely a reflection of the complexity of the environment in which it finds itself.

Simon extends this principle to human behavior:

> Human beings, viewed as behaving systems, are quite simple. The apparent complexity of our behavior over time is largely a reflection of the complexity of the environment in which we find ourselves.

We encode domain-specific model causality, including cognitive constructs, in the *environment* rather than the *agent*. SCAMP demonstrates that stigmergic agents can generate the required cognitive realism by interacting with such an environment.

Grassé [4] coined "stigmergy" from the Greek στίγμα (sign) and ἔργον (action) to describe insect actions that are mediated by signs in the environment (Figure 1). An agent's internal state and local environment determine its actions. In turn, each action may modify the agent's own state

[1] In addition to the author, the team included J.A. Morell of 4.699 LLC; L. Sappelsa of ANSER LLC; J. Greanya and S. Nadella of Wright State Research Institute. Kathleen Carley of CMU consulted on social network issues.

and the local environment. The environment's dynamics may modify its state, and many agents modify it locally, thus interacting indirectly with one another.

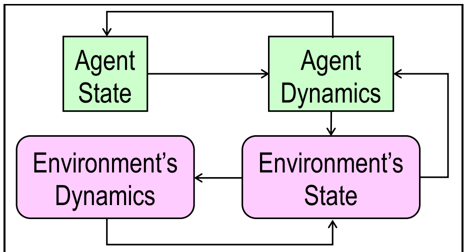

Figure 1: Basic stigmergic schema

Based on our experience with stigmergic agents [13,16,18,21,22,24], we implemented agents that are agnostic about the causal details of the world in which they live. The environment encodes those details as digital artifacts readily understood and configured by analysts who are not programmers. Cognitive agents put the domain model inside the agents. SCAMP puts the agents inside the model.

This paper describes SCAMP's basic mechanisms (Section 2), reviews its different perspectives on the environment (Section 3), and discusses our experience (Section 4).

2. SCAMP's Basic Mechanisms

A SCAMP agent repeatedly chooses among accessible *alternatives*, based on their *features* and its own *preferences*. Alternatives are nodes in a graph, and are accessible if they are adjacent to an agent's current location. Each agent belongs to one *group*, and may affiliate with others. Our current model of a conflict resembling Syria supports six groups: the oppressive Government, People who are just trying to get through life, an Armed Opposition seeking to overthrow the government and replace it with a democratic institutions, Violent Extremists (inspired by ISIS) with strong ideological motives, Relief Agencies, and the Military, initially affiliated with the Government but capable of rebelling.

2.1. Choosing with Preferences and Features

Each node that an agent can choose carries a vector of *features*.

Some features describe *intrinsic characteristics* of the choice, in [-1, 1]. A node in a geospatial lattice might be characterized by its gradient, while an event might be characterized by its impact on the physical, psychological, and economic wellbeing of participating agents.

Some features summarize the *recent presence* of agents belonging to various groups (one feature per group), in [0, 1]. These features are modified by agents as they traverse the graph, like insects depositing pheromones. Like pheromones, they evaporate over time.

Some features describe the *urgency* of a node for each group's goals, in [0, 1]. Like presence features, urgency features vary over time, depending on the state of the system.

Each group has a baseline set of scalar *preferences* in [-1, 1] over the feature space. When agents are initialized, they draw their preferences from distributions whose means are defined by their group's baseline.

At any moment, an agent has a current event and a set of accessible alternatives. To make its choice (Figure 2), it computes the cosine distance between its preference vector and the feature vector of each accessible alternative, exponentiates these distances (to make them positive), and normalizes them to form a roulette wheel.

This fundamentally stochastic decision process recognizes recent research in decision making. Deterministic theories of decision-making [35] predict that in an experiment that offers wagers with varying probabilities for A and B, each subject should always accept if the probability of receiving A is greater than that for B, and otherwise always reject. But empirically [12], the probability of accepting such wagers is a logistic curve, not a step function. The basis for human choice is not deterministic preference, but a probability *Pr*(A, B) of choosing A over B. SCAMP is heavily influenced by the decision field [1] model of stochastic decision theory.

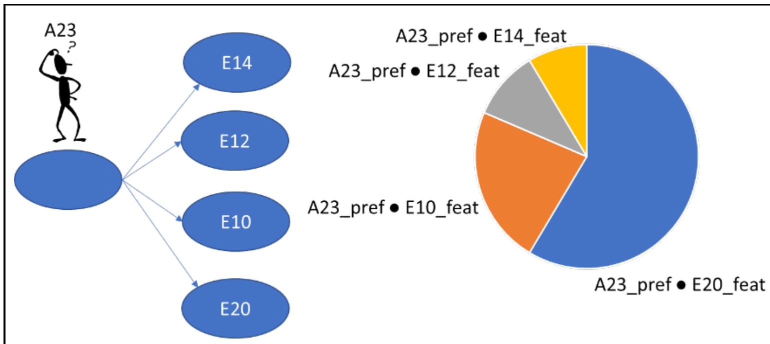

Figure 2: Agent choice mechanism

2.2. Polyagents

People make decisions using mental simulations. Klein has shown [9] that when experts' initial recognition of a situation fails, they tell stories about how the current situation might unfold. Kahneman and Tversky document the simulation heuristic [8], a mental rehearsal of possible story trajectories to decide how to proceed.

SCAMP implements this insight by representing each active entity as a set of agents, a *polyagent* [19]. One agent, the *avatar*, is persistent, and manages a population of transient *ghosts* that simulate its possible future courses of action to a limited horizon. Each ghost explores one possible future, using preferences and features. As it moves, it augments the presence features for the groups with which its avatar is affiliated. Collectively, the ghosts develop a field[2] over alternative trajectories. To simulate a scenario, the avatar selects from its alternatives, weighting its choice by the presence features on each accessible alternative.

3. SCAMP's Stigmergic Environments

We want domain experts without programming experience to configure and modify psychologically realistic agent-based models. Simon's law suggests encoding this knowledge in the *environment* rather than the *agents*.

The environment of a SCAMP agent is a graph, with nodes and edges. Multiple graph components represent different domains. The current implementation has two graphs over which agents make choices (a Causal Event Graph and a Geospatial Lattice), and a third set of graphs (Hierarchical Goal Networks) showing the goals of various groups. The first two graphs support a mechanism for involuntary agent movement. We call this approach, "multi-perspective modeling" [17].

3.1. The Causal Event Graph

Several formalisms have been proposed for the internal mental models that people use in reasoning about the world, including differential equations, Markov processes, logical inference, and graphical models of factored probability (e.g., Bayes networks). These formalisms have

[2] Up to normalization, this field is a probability field. In quantum physics, the term describes the amplitude of a particle's wave function, giving the probability of finding the particle at each location; in SCAMP, the field gives the probability of finding the avatar at each location. Our estimation of the field using a swarm to explore possible futures recalls Feynman's path integral formalism of quantum mechanics [2].

considerable computational power, but lack psychological realism [20]. The fundamental construct underlying human cognition is the narrative [3], a sequence of events.

The Causal Event Graph (CEG) at the heart of SCAMP is inspired by narrative graphs in common use in intelligence analysis [5], cyber security planning [30], discrete event simulation [28], analysis of social disagreement [29], computer games [10] and the study of natural-language texts [26], among other applications. These formalisms share the following features with the SCAMP CEG:

- Nodes are events, not the variables used in other causal formalisms.
- A directed edge between two nodes indicates the narrative coherence of moving from one event to the next.
- Any trajectory through the graph represents a possible narrative.
- The graph summarizes many possible narratives.

A Causal Event Graph (CEG) has nodes describing different types of events in which agents can participate [20,27]. Figure 3 shows the CEG for our civil conflict scenario, with 466 separate events.

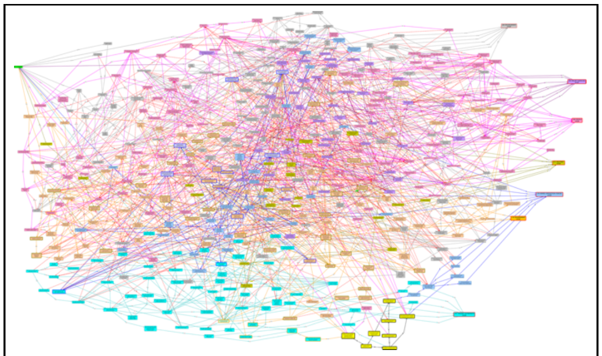

Figure 3: CEG for SCAMP in GroundTruth

For clarity, consider the much simpler CEG in Figure 4, covering three versions of a children's poem. The canonical version, represented by events 12-(2, 3, 4)-5 in parallel with 7-8, is

> Little Miss Muffet sat on a tuffet
> Eating her curds and whey.
> Along came a spider, and sat down beside her,
> And frightened Miss Muffet away.

At about age 10, boys discover they can get an entertaining response from girls by modifying the last line to "And she ate that too." The CEG captures this narrative with the events 12-(2, 3, 4)-10. Finally, pacifists might prefer a third conclusion, "And they began to play," 12-(2, 3, 4)-13.

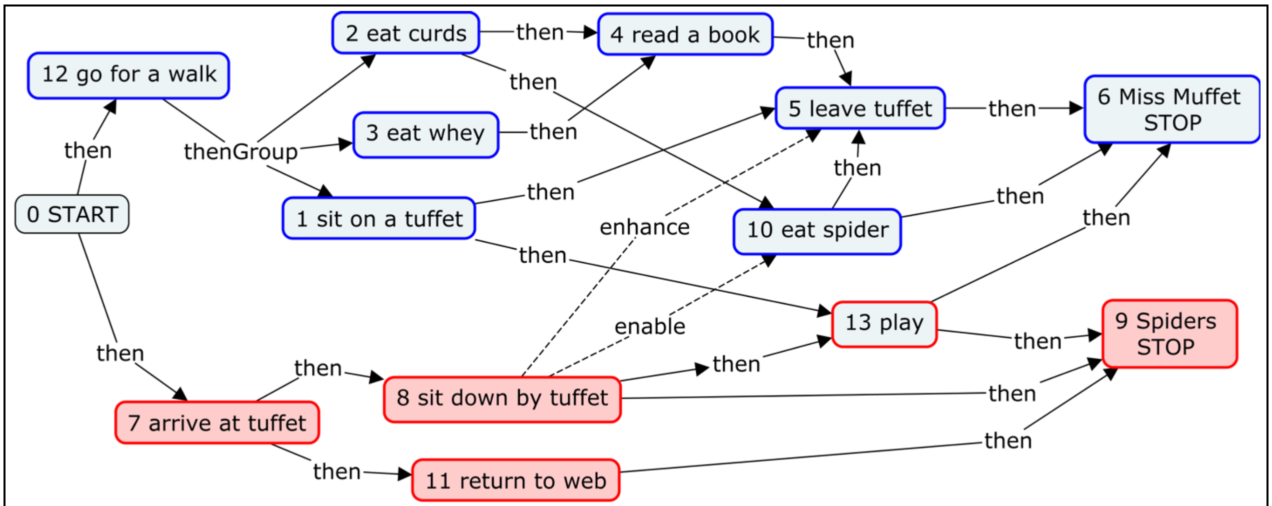

Figure 4: A CEG for Little Miss Muffet

The single CEG contains all three narratives, and more. The specific narrative that emerges depends on the choices made by Miss Muffet and the Spider.

Different colors on the events reflect the groups that have *agency* for those events—in this case, the Miss Muffet group and the Spider group. Agents affiliated with Miss Muffet can participate in blue events, while those affiliated with Spider can participate in red events. Both groups can participate in event 13.

Time in SCAMP is an integer, representing a unit of domain time (hour, day, week, …) appropriate to the domain. Each event has a transit time (how long an agent participates in the event before selecting another) and an effect time (how long the presence feature of the event for the agent's group remembers the agent's participation). The modeler specifies nominal values for these variables based on each event's semantics. SCAMP samples the actual time from an exponential distribution, reflecting interarrival times of a Poisson process.

CEGs have two kinds of edges.

Agency edges (solid arrows in Figure 4) capture an agent's possible choices. For example, if Miss Muffet is currently sitting on her tuffet, she can subsequently choose either to leave the tuffet (event 5) or play with the spider (event 13). The agency edges labeled "then" connect a single cause to a single possible outcome. The "thenGroup" multiedge specifies a group of events that execute concurrently.

Agency edges have two limitations.

First, they must define coherent snippets of narrative, so that an agent on one event can coherently choose a successor event.

Second, an agency edge can only join two events if both are accessible to agents in the same group. Thus agency edges define subgraphs specific to each group. If multiple groups have agency for the same event, the subgraphs for those groups will joined on that event.

Influence edges (dashed edges in Figure 4) capture causal influences among events between which agents do not move directly. For example, a spider sitting by the tuffet (event 8) may influence Miss Muffet to leave her tuffet (event 5), but the spider does not have agency for that event and cannot participate in it.

An influence edge adjusts the segments in the roulette wheel corresponding to the influenced event, based on the total presence features on the influencing event (that is, the degree of recent participation in the influencing event).

The hard influences *prevent* and *enable* probabilistically exclude or include an event's segment in the roulette, depending on the total presence feature on the influencing event. Soft influence edges, *enhance* and *inhibit*, adjust the size of the influenced event's segment, based on the influencer's presence features. The dashed arrows in Figure 4 are *enhance* edges.

Modelers construct the CEG, with its events, agency edges, and influence edges, using CMapTools, a freeware concept mapping tool [7]. An Excel workbook captures the features and time parameters of the various events and the base preferences of the different groups.

3.2. The Geospatial Lattice

A hexagonal lattice models geographical space. Figure 5 shows a geospatial model for Miss Muffet. The gray-scale background is elevation data. Light blue marks water, while dark blue lines are highways. The shapes indicate three distinguished locations: the Muffet Residence in the SW, the Tuffet by the side of the river in the center, and the Spider Web toward the NE. SCAMP compiles the map into gradients leading to each feature. The Excel spreadsheet for groups defines where agents in each group start.

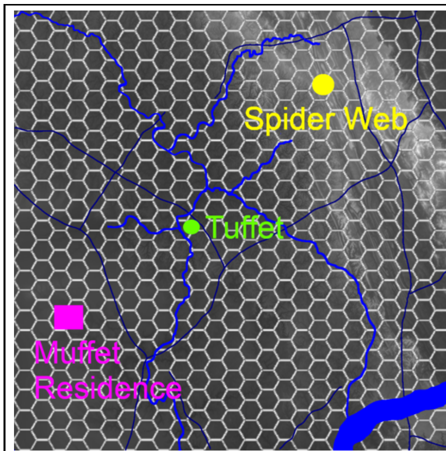

Figure 5: Geospace for Miss Muffet

Some events are "geospatial events," requiring physical displacement for their achievement. When an agent participates in such an event, it moves through geospace until it reaches its destination, at which point it has completed its event, and can choose another. The dwell for a geospatial event depends on the length of the agent's geospatial journey.

In Figure 6, Miss Muffet is initialized at the Muffet Residence, and the spider at the Spider Web (1). Miss Muffet moves from START to "go for a walk" (2). This is a geospatial event, so the agent drops into geospace at its current physical location (3a) and pursues the goal for its group associated with the event (3b), arriving at the Tuffet. Because the tuffet is the goal for "go for a walk," the agent returns to its event (3c). The next event that it chooses, "sit on a tuffet," is not geospatial, so it executes it, and then chooses "leave tuffet" (2). "Leave tuffet" is another geospatial event, so the agent enters geospace at its current location, which is now the tuffet (3a), makes its way to the destination for "leave tuffet" (the Muffet Residence) (3b), and having reached its goal, returns to event space (3c).

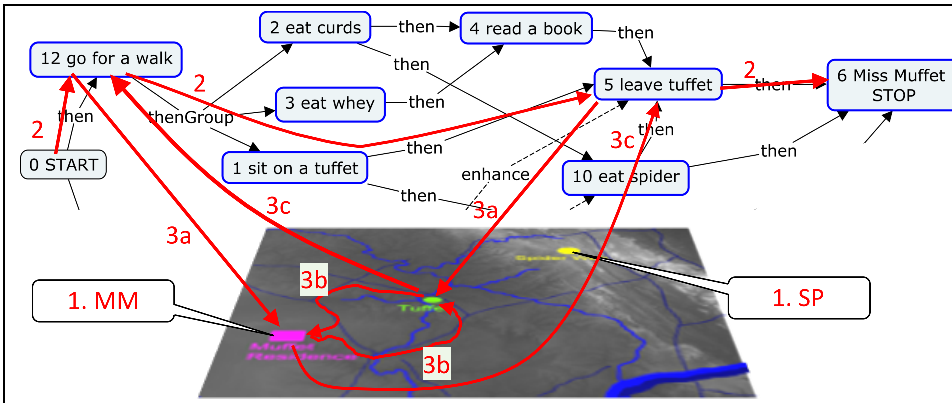

Figure 6: Interaction between Event Space and Geospace

Participation in an event moves an agent through time. Geospatial events also move agents through space.

Hexes in geospace, like events in event space, have feature vectors. Presence features record the recent presence of agents of different groups. Urgency features record the proximity to the destination for each group, while the wellbeing features record the gradient of the local terrain. The transit time for an agent to move through one hex depends on its group (Miss Muffet walks faster than the spider over long distances) and the local terrain (it takes longer to cross water than to travel on land).

Modelers construct the geospatial model using the freeware GIMP drawing program [34]. The Excel workbook records the distinctive regions in the model with their effect on movement speed and the colors that identify them, the starting regions and base movement speeds for agents of different groups, and the destinations for geospatial events.

3.3. Hierarchical Goal Networks

The decision process so far is purely tactical. Agents consider only immediately accessible events or adjacent physical locations, basing decisions only on the features of those alternatives. But people reason strategically as well as tactically. SCAMP supports a hierarchical goal network (HGN) [31] for each group, capturing the high-level goal for the group and its decomposition into subgoals. The lowest level subgoals in each HGN are connected to events in the CEG that either support or block them [15]. Agents do not move over the HGN as they do over the CEG and geospatial lattice, but the HGN modulates their movement in event space.

Figure 7 shows an HGN for Miss Muffet and its relation to the CEG. The rounded rectangles across the bottom are events in the CEG. For clarity, we suppress agency and influence edges. The squared rectangles are goals in the HGN, culminating in the top-level goal. Black arrows between goals show how subgoals contribute to their higher-level goals. *Or* edges indicate that any subset of subgoals can satisfy the higher-level goal. *And* indicates that all of the subgoals are required to achieve the higher goal.

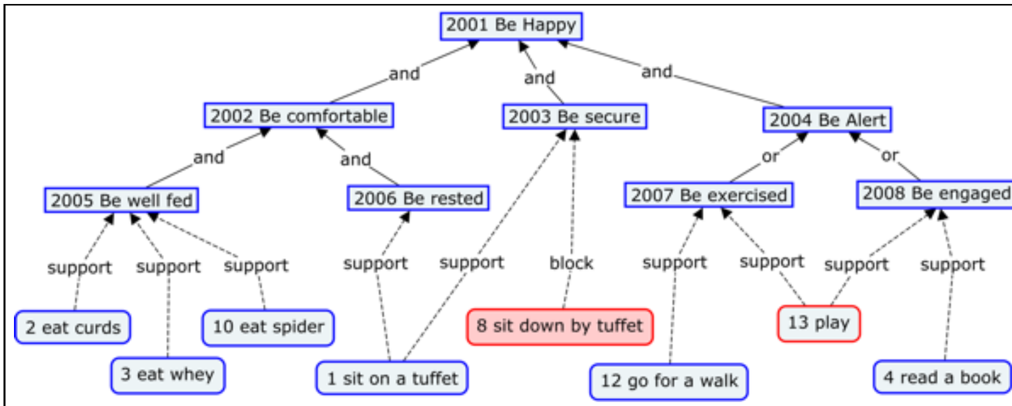

Figure 7: HGN for Miss Muffet

Each goal maintains two scalar variables: its *satisfaction,* and its *urgency*. Satisfaction accumulates through a sigmoid, so it saturates at 1. At the root, *urgency* is 1 – *satisfaction*. The root determines its satisfaction by querying its subgoals recursively. Satisfaction propagates upward through *or* relations as the maximum of the satisfaction levels of the subgoals, and through *and* relations as the minimum. The lowest-level subgoals determine their satisfaction from the presence features of events in the CEG. Once the root goal knows its satisfaction, it propagates its urgency down to its subgoals. The urgency of a higher-level goal is passed directly to subgoals that support it via *and*. Subgoals joined by an *or* subtract their own urgency from that of their parent goal. This process is inspired by the quality construct in TÆMS [6], as implemented in our earlier work [15].

Satisfaction and urgency are thus driven by the agent participation (reflected in presence features) in CEG events “zipped” to the HGN. The dashed arrows in Figure 7 from CEG events to the bottom level of subgoals indicate whether those events support or block each subgoal. The presence features on CEG events determine satisfaction of leaf subgoals, while urgency on those subgoals modifies the urgency features of events zipped to them. The HGN mechanism converts the *presence* of agents on events in the CEG into the *urgency* of those events in view of the strategic objectives of each group.

An event for which one group has agency can change the satisfaction of goals of other groups, and also respond to the urgency levels in other HGNs, if it is zipped to subgoals in those HGNs: the HGN in Figure 7 is for Miss Muffet, but is blocked by spider event 8. As a result, agents can modulate their decisions by the desire to advance or hinder the goals of other groups.

Domain experts capture HGNs in the CMapTools concept modeling tool used for generating the CEG. In fact, for small models, the HGNs and the zip relations can be included in the same CMap file containing the CEG. It is also possible to generate separate HGNs, and capture the zips between events and leaf-level subgoals in a spreadsheet in the Excel workbook.

3.4. Involuntary Agent Movement

So far, all agent movements between events or geospatial locations are voluntary, weighted by the agent's comparison of its preferences with the features presented by the options available to it. Sometimes, people experience things that they have not chosen. In our conflict scenario, we model (for example) assassinations, forced recruitment of civilians into the violent extremists, and movement of wounded combatants to a hospital.

SCAMP can attach dynamic rules to specific events or geospatial regions, thus extending the action of the environment (Figure 1 bottom). When the appropriate agents begin participation in an event or enter a geospatial tile, they may trigger the rule, which in turn may change the existence, group affiliation, or location of one or more agents anywhere in the model.

The rule can specify agent movement between groups. In addition to the groups defined in the model (in our example, the Miss Muffet group and the Spider group), we define the group Gufe, the repository of souls in Jewish mysticism. To add a new agent, we transition it from Gufe to one of the regular groups. To kill an agent, we transition it from its home group to Gufe. In addition, for a birth event, the source location is Gufe.

Rules specify a set of conditions, and a probability. If the conditions are satisfied, the rule fires with the specified probability.

Each rule specifies the following details:

- Trigger to which the rule is attached: An event ID in CEG, or a region in geospace (which expands to a set of tiles)
- What groups must be participating in the trigger to enable the transition
- The group(s) whose agents are vulnerable to the action of the rule
- The group to which vulnerable agents are transitioned
- The location (event, region, or Gufe) from which the vulnerable agents are drawn
- The maximum number of agents to transition
- The location (event, region, or Gufe) where the agents reside after the transition
- What groups must be present on the from location to enable the transition
- The base transition probability for the event
- PromoterGroups: groups whose level of participation on either the trigger or the from location increases the base probability of the transition
- BlockerGroups: groups whose level of participation on either the trigger or the from location decreases the base probability of the transition

These rules are recorded in the Excel workbook.

4. Experience and Discussion

The agent behaviors described in Section 2, applied to the environment described in Section 3, yield behaviors that reflect numerous psychological and social dimensions [23], including

- Deliberate tactical choice guided by preferences over alternatives
- Non-deterministic decision-making
- Strategic (goal-driven) as well as tactical decisions
- Use of mental simulation to look ahead in time
- Interactions with other agents encountered on events or geospatial tiles as a mechanism for adjusting individual preferences
- The centrality of narrative as a mental representation
- Naturally bounded rationality

Let's expand the last point. An important insight, at variance with the classical rational decision-maker, is that people's rationality is bounded [32]. SCAMP bounds rationality in four ways, from the interaction of agents with their environment [11].

Agents who meet in the CEG or geospace learn of one another's existence, setting up a *realized network* among them. This network modulates agents' preferences by the preferences of others, and may lead them to change their home group.

Influence edges in the CEG modulate the availability of events for selection by agents by the participation on other events.

Two agents of different groups can encounter each other in *geospace*, either for weal (as when an agent representing a relief agency meets a refugee needing help) or woe (as when members of different sides in an armed conflict encounter one another).

The events that support or block subgoals in an *HGN* can belong to different groups. Actions of otherwise unrelated agents that impact one group's HGN can in turn modulate the urgency of events in different groups. Urgency not only enables members of one group to prioritize events likely to advance their objectives, but also enables strategic choices by agents in other groups either to advance or to frustrate the objectives of agents not in their own group.

One measure of the realism of SCAMP is the range of questions that the social science teams were able to ask our agents. Here are some examples that we were able to answer from our logs.

- What were you doing on a given date?
- What was the last thing you were doing before your present activity?
- What other options did you consider at that time?
- What influenced your choice of this option?
- What options are you considering next, and how would you prioritize them?
- Whom have you met recently?
- How strong is your relation to them?
- How satisfied are you with your achievement of your objectives?
- How happy are you about your current condition (economic, physical, psychological)?
- How sympathetic are you to a specific group (e.g., the government)?

The dynamics of the system are non-trivial and interesting. Figure 8 shows an example from our conflict scenario, showing three distinct phases. Up to about day 450, group populations stay

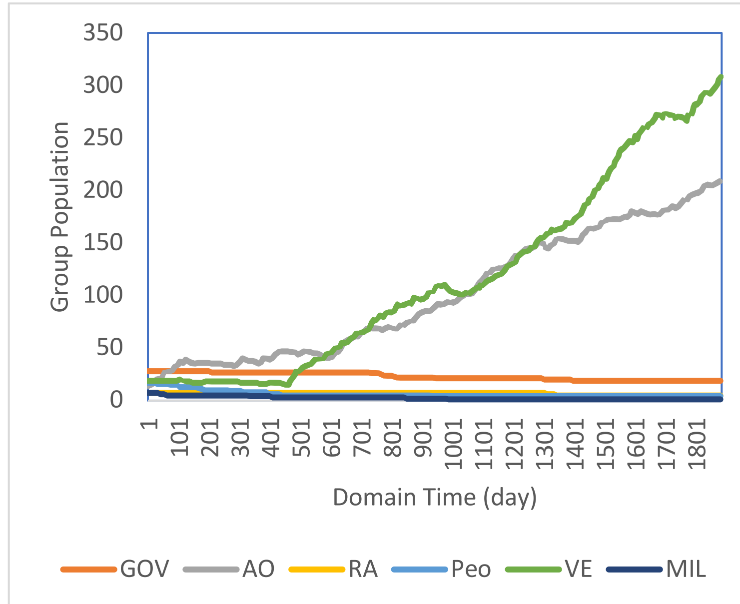

Figure 8: Number of Agents over Time

fairly close together, with Armed Opposition (AO) dominating the others and the Violent Extremists (VE) weaker than the Government. Then the strength of the Violent Extremists begins to grow, and from day 600 to about 1300, they struggle for control with Armed Opposition, until they begin to obtain a clear ascendancy. We can examine the events responsible for these transition points, and identify elements of the overall causal structure that are ultimately responsible for them. The transitions in Figure 8 could not be predicted in advance by examination of our configuration files, but emerge as the system executes.

One motivation for our architecture was enabling non-programmers to construct and modify a psychologically and socially realistic agent-based model. All the configuration inputs to SCAMP are prepared in CMapTools (CEG and HGNs), GIMP (geospatial environment), and Excel. All of our models were prepared by non-programmer analysts from ANSER, a not-for-profit organization that provides analytic services to customers such as the Department of Defense and the Department of Homeland Security. They were able to construct a rich behavioral model and evaluate its realism from the logs it generated, without knowledge of SCAMP's code.

Acknowledgments

The development of SCAMP was funded by the Defense Advanced Research Projects Agency (DARPA), under Cooperative Agreement HR00111820003. The content of this paper does not necessarily reflect the position or the policy of the US Government, and no official endorsement should be inferred.

References

An ODD protocol for SCAMP is in preparation and expected to be ready by the conference.

The author's papers are available via Javascript at www.abcresearch.org/abc/papers.

[1]J.R. Busemeyer, J.T. Townsend. Decision Field Theory: A Dynamic-Cognitive Approach to Decision Making in an Uncertain Environment. *Psychological Review*, 100(3):432-459, 1993.

[2]R. Feynman, A.R. Hibbs. *Quantum Mechanics and Path Integrals*. McGraw-Hill, 1965.

[3]W.R. Fisher. *Human Communication as Narration: Toward a Philosophy of Reason, Value, and Action*. Columbia, SC, University of South Carolina Press, 1989.

[4]P.-P. Grassé. La Reconstruction du nid et les Coordinations Inter-Individuelles chez *Bellicositermes Natalensis et Cubitermes sp.* La théorie de la Stigmergie: Essai

d'interprétation du Comportement des Termites Constructeurs. *Insectes Sociaux*, 6:41-84, 1959.

[5]R.J. Heuer, Jr., R.H. Pherson. *Structured Analytic Techniques for Intelligence Analysis*. Washington, DC, CQ Press, 2010.

[6]B. Horling, V. Lesser, R. Vincent, et al. The Taems White Paper. Multi-Agent Systems Lab, University of Massachusetts, Amherst, MA, 2004. http://mas.cs.umass.edu/pub/paper_detail.php/182.

[7]IHMC. IHMC CmapTools - Download. Pensacola, FL, 2013. http://cmap.ihmc.us/download/.

[8]D. Kahneman, A. Tversky. The Simulation Heuristic. In D. Kahneman, P. Slovic, and A. Tversky, Editors, *Judgment under Uncertainty: Heuristics and Biases*, 201-208. Cambridge University Press, Cambridge, UK, 1982.

[9]G.A. Klein. *Sources of Power: How People Make Decisions*. Cambridge, MA, MIT Press, 1998.

[10]C.A. Lindley. Story and Narrative Structures in Computer Games. In B. Bushoff, Editor, *Developing Interactive Narrative Content*, High Text Verlag, München, 2005.

[11]F. Michel. *Formalisme, méthodologie et outils pour la modélisation et la simulation de systèmes multi-agents*. Thesis at Université des Sciences et Techniques du Languedoc, Department of Informatique, 2004.

[12]F. Mosteller, P. Nogee. An experimental measurement of utility. *Journal of Political Economy*, 59:371-404, 1951.

[13]H.V.D. Parunak. 'Go to the Ant': Engineering Principles from Natural Agent Systems. *Annals of Operations Research*, 75:69-101, 1997.

[14]H.V.D. Parunak. SCAMP's Stigmergic Model of Social Conflict. *Computational and Mathematical Organization Theory*, (forthcoming):(forthcoming), 2020.

[15]H.V.D. Parunak, T. Belding, R. Bisson, et al. Stigmergic Modeling of Hierarchical Task Networks. In *Proc. the Tenth International Workshop on Multi-Agent-Based Simulation (MABS 2009, at AAMAS 2009)*, 98-109, Springer, 2009.

[16]H.V.D. Parunak, T.C. Belding, S.A. Brueckner, et al. Hierarchical Ant Clustering and Foraging. USA Patent # 8,112,374, Altarum Institute, 2012.

[17]H.V.D. Parunak, R. Bisson, S.A. Brueckner. Agent Interaction, Multiple Perspectives, and Swarming Simulation. In *Proc. the International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS 2010)*, 549-556, IFAAMAS, 2010.

[18]H.V.D. Parunak, S. Brueckner. Ant-Like Missionaries and Cannibals: Synthetic Pheromones for Distributed Motion Control. In *Proc. Fourth International Conference on Autonomous Agents (Agents 2000)*, 467-474, 2000.

[19]H.V.D. Parunak, S. Brueckner. Concurrent Modeling of Alternative Worlds with Polyagents. In *Proc. the Seventh International Workshop on Multi-Agent-Based Simulation (MABS06, at AAMAS06)*, 128-141, Springer, 2006.

[20]H.V.D. Parunak, S. Brueckner, L. Downs, et al. Swarming Estimation of Realistic Mental Models. In *Proc. Thirteenth Workshop on Multi-Agent Based Simulation (MABS 2012, at AAMAS 2012)*, 43-55, Springer, 2012.

[21]H.V.D. Parunak, S.A. Brueckner. Engineering Swarming Systems. In F. Bergenti, M.-P. Gleizes, and F. Zambonelli, Editors, *Methodologies and Software Engineering for Agent Systems*, 341-376. Kluwer, 2004.

[22]H.V.D. Parunak, S.A. Brueckner, R. Matthews, et al. Swarming methods for geospatial reasoning. *International Journal of Geographical Information Science*, 20(9 (Oct)):945-964, 2006.
[23]H.V.D. Parunak, J.A. Morell, L. Sappelsa. The SCAMP Architecture for Social Simulation. Wright State Research Institute, 2020.
[24]H.V.D. Parunak, M. Purcell, R. O'Connell. Digital Pheromones for Autonomous Coordination of Swarming UAV's. In *Proc. First AIAA Unmanned Aerospace Vehicles, Systems,Technologies, and Operations Conference*, AIAA, 2002.
[25]A.S. Rao, M.P. Georgeff. BDI Agents: From Theory to Practice. In *Proc. the First International Conference on Multi-Agent Systems (ICMAS-95)*, 312-319, AAAI, 1995.
[26]W. Richards, M.A. Finlayson, P.H. Winston. Advancing Computational Models of Narrative. MIT-CSAIL-TR-2009-063, MIT CSAIL, Cambridge, MA, 2009.
[27]L. Sappelsa, H.V.D. Parunak, S. Brueckner. The Generic Narrative Space Model as an Intelligence Analysis Tool. *American Intelligence Journal*, 31(2):69-78, 2014.
[28]E.L. Savage, L.W. Schruben, E. Yücesan. On the Generality of Event-Graph Models. *INFORMS Journal on Computing*, 17(1):3-9, 2005.
[29]B.P. Shapiro, P. van den Broek, C.R. Fletcher. Using story-based causal diagrams to analyze disagreements about complex events. *Discourse Processes*, 20(1):51-77, 1995.
[30]O.M. Sheyner. *Scenario Graphs and Attack Graphs*. Ph.D. Thesis at Carnegie Mellon University, Department of Computer Science Department, 2004.
[31]V. Shivashankar. *Hierarchical Goal Networks: Formalisms and Algorithms for Planning and Acting*. Ph.D. Thesis at University of Maryland, Department of Computer Science, 2015.
[32]H. Simon. *Models of Man: Social and Rational*. Hoboken, NJ, Wiley, 1957.
[33]H.A. Simon. *The Sciences of the Artificial*. Cambridge, MA, MIT Press, 1969.
[34]The GIMP Team. GIMP: GNU Image Manipulation Program. 2020. www.gimp.org.
[35]J. von Neumann, O. Morgenstern. *Theory of Games and Economic Behavior*. Princeton, Princeton University Press, 1944.