Understanding Stigmergy as a Pattern in Self-Organizing Adversarial Systems of Systems

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Stigmergy is a method for indirect communication in natural multiagent systems that influences collective behavior in ways typically called intelligent. Here we will explore the concept of stigmergy and show how it is applied by the Iraqi insurgency—an adversarial self-organizing system of systems—with the intent to expose a pattern that if understood might provide avenues for adversarial system disruption as well as strategies for self-organizing security.

A pattern project started at Stevens Institute of Technology's School of Systems and Enterprises, and now also being developed by INCOSE's System Security Engineering Working Group, is cataloging examples of fundamental self-organizing security patterns. The purpose is to provide a better understanding of the adversary strategies and operational modes, and to develop architectural patterns for the next generation of security strategies. The work seeks to categorize self-organizing agile security patterns to facilitate communication and understanding between system engineers, security engineers, and decision-makers to facilitate the discussion and development of security systems.

Six characteristics of self-organizing adversarial communities have been identified, with the expectation that next-generation security must at least provide parity with the agility of intelligent attacking systems (Dove 2010). These six characteristics are summarized in table 1, and are referred to as the SAREPH characteristics. Three guidelines are currently employed on the pattern project for nominating candidate patterns for the catalog:

1. The system must manifest both the self-organizing characteristic and the harmonious characteristic.
2. The system must manifest the evolving characteristic and/or the adaptive characteristic.
3. The system must manifest the proactive characteristic and/or the reactive characteristic.

Table 1. Pattern-qualification filters

S	Self-organizing	With humans embedded in the loop, or with systemic mechanisms
A	Adapting to unpredictable situations	With reconfigurable, readily employed resources
R	Reactively resilient	Able to continue, perhaps with reduced functionality, while recovering
E	Evolving with a changing environment	Driven by situation and fitness evaluation
P	Proactively innovative	Acting preemptively, perhaps unpredictably, to gain advantage
H	Harmonious with system purpose	Aiding rather than degrading system or user productivity

This article first identifies the unique stigmergic pattern, explores its nuances, and presents it in a format identified by the pattern project. Then the stigmergic pattern is applied as a

mold to analyze the Iraqi insurgency in an effort to regard it within a familiar context. The Iraqi insurgency was selected as a prominent opponent that provides significant consternation to security experts. It is first identified as an agile system, per the characteristics defined by the pattern project, then studied in the context of the stigmergic pattern. For a fuller treatment see Lugosky and Dove (2011).

An Introduction to the Stigmergic Pattern

Any stigmergic system is comprised of a population of agents and their defined environment. Each agent, as defined by Parunak (2005a), has the following features:

- An internal state, which generally is not directly visible to other agents
- Sensors that give it access to some of the environment's state variables
- Actuators that enable it to change some of the environment's state variables
- A program (its "dynamics") that maps from its current internal state and the readings of its sensors to changes in its internal state and commands given to its sensors and actuators

Notably, the agents are not necessarily able to sense all signals presented in the environment. Additionally, the agents vary in their ability to perceive, interact, and react to the environment. The environment is defined by Parunak (2005b) as

- a state, aspects of which generally are visible to the agents; and
- a program (its "dynamics") that governs the evolution of its state over time.

"The most important distinction between agents and the environment is that the internal state of agents is hidden, while the state of the environment is accessible to an agent with appropriate sensors" (Parunak 2005b, 3). Each agent can be conceived as a discrete unit, or as a self-contained object with a well-defined boundary. The environment is a localized, shared problem space defined by its structure and dynamics, where the agents interact indirectly.

The beauty of the stigmergic pattern is perhaps its universal simplicity. Stigmergy is manifested in the form of figure 1.

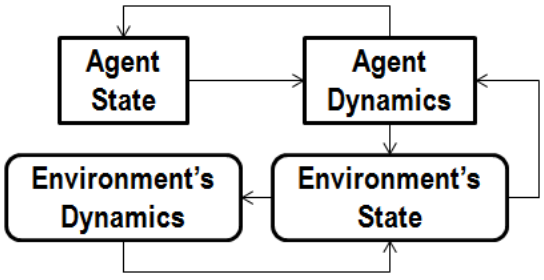


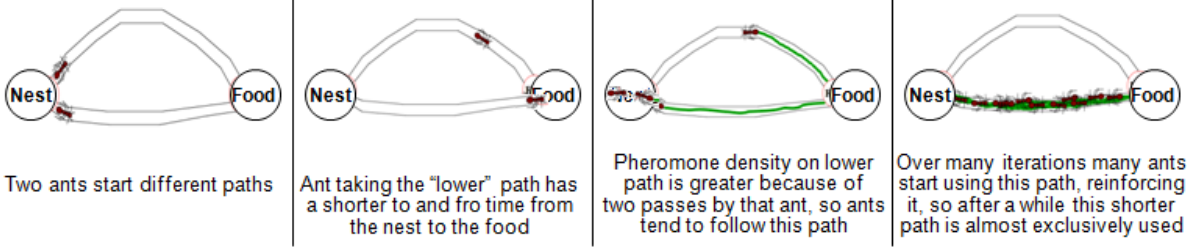
Figure 1. Basic architecture of stigmergy (Parunak 2005b)

The agent state is comprised of the physical, physiological, and emotional being, as well as all those historical and cultural experiences that integrate to form an agent's experience of self. It is the confluence of events that together influence the agent's perception and comprehension of the world, and in turn filter the observation of the agent's surroundings. It is through this filter that a given environment state communicates different information to diverse agents. Though the environment state is objective, the agent's realized internalization is subjective. In any stigmergic encounter, that agent's state combined with the perceived environment influence the agent's action on the physical environment such that the environment is altered. A trace of the agent remains, in the form of the altered environment (a new environment state), which serves as a signal for the next agent to process. The agent's response is dependent on both the agent's state and the filtered environment state, such that each agent behaves distinctly.

The stigmergic variety is integral to the interaction between the agent dynamics and the environment state. In marker-based behavior, the agent leaves its signature on its surroundings

(intentionally or not), to signal to another agent. In *sematectonic stigmergy*, the agent responds to a signal in the environment, either knowingly or unwittingly. So to complete a stigmergic cycle, the environment is changed by an agent (marker-based stigmergy), then that change influences the behavior of another agent (sematectonic stigmergy). The cycle continues further if the sematectonic response includes leaving a mark on the surroundings. In table 2 the pattern for stigmergic interaction is presented in the format adopted by the pattern project.

Table 2. Pattern for stigmergic interaction

Name	**Stigmergic Interaction**
Context	Indirect environment-mediated communication, such as traces left in the environment by one, incite an action of another agent.
Problem	A need to communicate effectively and indirectly among a group of agents to influence collective behavior.
Forces	Strength of signal: above a necessary threshold vs. dissipation or disappearance over time. Agent population makeup: quantity of agents vs. diversity of agent types. Statistical response: size of territory vs. likelihood of any one agent finding a signal; agent state vs. likelihood of an agent reacting to a signal.
Solution	Recognize and command the inherent possibilities for indirect communication available in the manipulation and modification of the surrounding environment. The generic stigmergic pattern is supplemented by four subpatterns that further classify interaction: marker-based, sematectonic, qualitative, quantitative.
 Marker-based quantitative stigmergy: Arriving at efficient routes for ants (Trivedi 2008) is similar to multiple Internet postings that converge on new effective terrorist methods.	
Examples	• Marker-base quantitative: ant-colony foraging (Parunak 2003), news of repeated terror methods that cause more of the same. • Marker-base qualitative: Dead ant detection and removal (Wilson, Durlach and Roth 1958); event posting that signals a terrorist target of opportunity. • Sematectonic quantitative: ants depositing dead ants in the ant cemetery (Beckers 1994), terrorist targeting of rescue crews attending to an IED event. • Sematectonic qualitative: wasp nest building (Parunak 2005b), IED construction-and-deployment network development (Swanson 2007).
Agility	SAREPH characteristics: Self-organization results from the uncertainty inherent in the system's stigmergic communication. Adaptation of signals occurs to adjust the response. Reactive resilience sustains signal meaning and communication norms for a given agent population. Evolution is driven by the multitude of individual agent states and unique filters. Proactive innovation occurs as parallel resources are incorporated in response to an unfamiliar environment state. Harmony underlies the integration of stigmergic communication into everyday interactions.

A further classification breakdown distinguishes between qualitative and quantitative signaling. *Qualitative* refers to the variable nature of the signal. In qualitative marker-based stigmergy ants react to the nature of the chemistry, as in oleic acid signifying a dead ant to be removed; and in qualitative sematectonic stigmergy, for instance with nest-building wasps, agents react to the nature of the structure already in place. *Quantitative* refers to the amount of signal present in the environment: in quantitative marker-base stigmergy, ants favor a trail with more pheromone over an alternate trail with less, and in quantitative sematectonic stigmergy ants move dead ants from a smaller pile to a larger pile.

Iraqi Insurgency as an Adversarial Stigmergic Pattern

The myriad of websites dedicated to extremist terrorism in Iraq are stigmergic traces of an agile, technically savvy, and politically astute Iraqi insurgency that acts deftly on trails left by the opponent while cultivating a solid, web-based indirect-communication system. First we identify the Iraqi insurgency as an example of the stigmergic pattern, by demonstrating that it embodies agility as presented in the SAREPH characteristics and guidelines previously discussed. Then we develop the example of the adversarial stigmergic pattern by examining how the insurgency exhibits stigmergic behavior.

Self-Organization

A multitude of different factions driven by diverse tribal histories, interests, loyalties, and beliefs, have found effective stigmergic communication of their cause through guerilla tactics. These diverse organizations, traditionally consumed with internal conflict, have effectively self-organized to demonstrate through kidnappings, brutal murders, sniper attacks and IED bombings, their collective opposition to the coalition forces and mission. The indirect communication of effective disruption, via television, Internet forums and websites, or public uncertainty and mood, goad other agents into action, and the stigmergic cycle is fueled.

Adaptable Tactics

One sect's effective transgression spurs others to adapt the successful tactic. When coalition forces neutralize one method, the media seize it and announce this shift in the environment—and the adversaries, alerted, alter their game. For example, the insurgency websites published images of gory beheadings, signaling to the coalition countries the futility of their cause and the control and power of the insurgency. Stigmergic response to Iraqi public backlash drove the removal of the offensive videos.

Reactive Resilience

The unrest in the Middle East has been a stalwart of the region throughout history. The resilient quality of the insurgency may be in its persistence in the region, continuing to cause unrest and instability and limiting security and economic growth, as it bleeds the pocketbooks of the coalition nations. As radical Muslim scholars spread their message worldwide on mainstream Islamist websites (Adhami 2007, 861), they attempt to win the hearts and minds of the moderates by accusing their enemy of waging a "war on Islam" (Adhami 2007, 863). The insurgency's tactic of maintaining regional instability is built upon a long tradition of success.

Evolvable Strategies

Over the course of the conflict, the Iraqi insurgents' strategies have evolved to meet the shifting face of the environment. They began as many small factions, then via the Internet, aligned their vectors to the common cause of jihad. Most significantly from a stigmergic sense, the insurgency learned from its own mistakes and from changes in the coalition's tactics, as they were communicated via Internet sites, and modified its behavior to reflect the new environment (International Crisis Group 2006).

Proactive Innovation

Time and again, the Iraqi insurgency has innovated to maintain an advantage over their enemy. Some innovations are indicative of the horizontal meme-transfer pattern (Dove 2010). Pulling from other fields, the insurgency has relied heavily upon the Internet for information exchange, transforming what began as an academic medium, then social playground, into a tool of war. Their methods evolve as necessary to continue the fight employing innovations fueled by the foreign successes that are virtually relayed.

Harmonious Operation

General harmonious interaction between factions of the Iraqi insurgency has prevailed. Responding to public opinion, which should be regarded as an extended "environment," individual groups "standardized their practices, resorting to those deemed most legitimate and defensible pursuant to what Islamic jurisprudence calls the 'ethics of jihad' (Adab al-Jihad)" (International Crisis Group 2006, 12). They are focusing on cultivating that environment of public opinion and allowing it to guide their actions.

Summarizing

The insurgency makes extensive use of marker-based stigmergic communication, apparent in the variety of websites that present distinct perspectives on the conflict, and each encourages a specific behavioral response. Websites range from those that portray resistance to occupation from a strict Muslim doctrinal point of view to those that portray the insurgent armed response to the occupation of Iraq as legitimate jihad (Adhami 2007, 861), and those that serve as the protected official communication channels for the insurgent groups fighting in Iraq (Adhami 2007, 865).

Each singular terrorist website that allows individual participants to deposit traces such as religious documents, graphic images, and individual postings is an example of marker-based stigmergy. The cumulative message incites others to act, and they do. Successful attacks, glorified in detailed descriptions and gruesome images, are disseminated to the masses via the website and, unsurprisingly, broadly emulated (International Crisis Group 2006).

Sematectonic stigmergic messages have been conveyed through intimidating acts in the physical environment. The brutality serves as stigmergic warnings, to some, while to others it conveys the weakness of the opposition and what the insurgents perceive as a "puppet" government. The lack of security influences the behavior of the population who, feeling frightened and vulnerable, do not then participate in rebuilding efforts.

The "environment" of any given province is readily available via the media. The broadcasting agent disperses a filtered perception of the environment, and the individual actors modify their behavior accordingly.

The Value of Understanding the Stigmergy Pattern

In understanding the stigmergic interactions of our terrorist adversaries, we make progress toward developing effective agile security strategies that are capable of sparing with that evolving and resourceful foe. The definition of the stigmergic interaction pattern and exploration of the SAREPH characteristics for both academic examples and notable adversaries is another step toward facilitating communication between the key players in security-systems development. By examining high-profile adversaries in light of the new pattern and identifying key examples that will be relevant and familiar to an array of backgrounds, this effort contributes new tools to the pattern project. This understanding may enable systems engineers, security engineers, and decision-makers to better understand and communicate the enemy's methodology, and in so understanding, develop agile security systems that effectively combat adversarial methods.

References

Adhami, Wael. 2007. "The Strategic Importance of the Internet for Armed Insurgent Groups in Modern Warfare." International Review of the Red Cross, 89:868, 857-858. December 31.

Beckers, R., O. E. Holland, and J. L. Deneubourg. 1994. "From Local Actions to Global Tasks: Stigmergy and Collective Robotics." In R. Brooks & P. Maes (Eds.), Artificial life IV (pp. 181-189. Cambridge, MA (US): MIT Press.

Dove, R. 2010. "Pattern Qualifications and Examples of Next-Generation Agile System-Security Strategies." Paper presented at IEEE International Carnahan Conference on Security Technology, San Jose, CA (US), 5–8 Oct. www.parshift.com/Files/PsiDocs/PatternQualificationsForAgileSecurity.pdf.

International Crisis Group. 2006. *In Their Own Words: Reading the Iraqi Insurgency*. International Crisis Group Middle East Report 5, 15 Feb. Brussels, Belgium.

Lugosky, J., and R. Dove. 2011. "Identifying Agile Security Patterns in Adversarial Stigmergic Systems." Paper presented at the Twenty-First Annual International Symposium of INCOSE, Denver, CO (US), June 20–22. www.parshift.com/s/110620AdversarialStigmergyPatterns.pdf.

Parunak, H. V. A. 2003. "Making Swarming Happen." Paper presented at "Swarming: Network Enabled C4ISR" conference, Tysons Corner, VA (US), 3 Jan. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.116.1990&rep=rep1&type=pdf.

———. 2005a. *Expert Assessment of Human–Human Stigmergy*. Analysis for the Canadian Defence Organization, Altarum Institute, Ann Arbor. MI (US), Oct. http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA440006&Location=U2&doc=GetTRDoc.pdf.

———. 2005b. "Survey of Environments and Mechanisms for Human–Human Stigmergy." Paper presented at "Environments for Multi-Agent Systems II," Second International Workshop, Utrecht, the Netherlands, July 25. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.100.6974&rep=rep1&type=pdf.

Swanson, S., 2007. "Viral targeting of the IED Social Network System", *Small Wars Journal* Vol 8, May.

Wilson, E. O., N. I. Durlach, and L. M. Roth. 1958. Chemical Releasers of Necrophoric Behavior in Ants. Psyche 65: 108-114.

Trevidi, S. 2008. "Adaptive Routing Taking Cues from Stigmergy in Ants." *Onionesque Reality* (blog), 31 Jan. 2008. http://onionesquereality.wordpress.com/2008/01/31/adaptive-routing-taking-cues-from-stigmergy/.