General theory of stigmergy: Modelling stigma semantics

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Abstract

Stigmergy is a biological term used when discussing a sub-set of insect swarm-behaviour describing the apparent organisation seen during their activities. Stigmergy describes a communication mechanism based on environment-mediated signals which trigger responses among the insects. This phenomenon is demonstrated in the behaviour of ants and their food gathering process when following pheromone trails, where the pheromones are a form of environment-mediated communication. What is interesting with this phenomenon is that highly organised societies are achieved without an apparent management structure.

Stigmergy is also observed in human environments, both natural and engineered. It is implicit in the Web where sites provide a virtual environment supporting coordinative contributions. Researchers in varying disciplines appreciate the power of this phenomenon and have studied how to exploit it. As stigmergy becomes more widely researched we see its definition mutate as papers citing original work become referenced themselves. Each paper interprets these works in ways very specific to the research being conducted. Our own research aims to better understand what improves the collaborative function of a Web site when exploiting the phenomenon. However when researching stigmergy to develop our understanding we discover a lack of a standardised and abstract model for the phenomenon. Papers frequently cited the same generic descriptions before becoming intimately focused on formal specifications of an algorithm, or esoteric discussions regarding sub-facets of the topic. None provide a holistic and macro-level view to model and standardise the nomenclature.

This paper provides a content analysis of influential literature documenting the numerous theoretical and experimental papers that have focused on stigmergy. We establish that stigmergy is a phenomenon that transcends the insect world and is more than just a metaphor when applied to the human world. We present from our own research our general theory and abstract model of semantics of stigma in stigmergy. We hope our model will clarify the nuances of the phenomenon into a useful road-map, and standardise vocabulary that we witness becoming confused and divergent. Furthermore, this paper documents the analysis on which we base our next paper: Special Theory of Stigmergy: A Design Pattern for Web 2.0 Collaboration.
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1. Introduction

Stigmergy is a phenomenon that has received growing attention over the past decades. The term stigmergy was first documented in 1959 where a French zoologist named Pierre-Paul Grassé (Grasse', 1959) revisited research into how termites appear to coordinate without an obvious management structure. Preceding theories describing insect swarm behaviour existed, however Grassé believed they failed to accurately understand the phenomenon. Grassé's research described a method of indirect communication using mediated signs to trigger responses from other colony members. Simply put, an individual's actions and their

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traces left in the environment affect subsequent behaviour of both themselves, and of other individuals.

This environment mediated form of communication has intrigued researchers in many diverse fields and perhaps none more so than in robotics and computer science. The interest stems from the concept of a system having no central management function and how that benefits building scalable systems. Direct communication into management functions at swarm-levels would quickly become overwhelming. For our purpose, introducing effective triggers to elicit useful and contextual input from participants is expected to provide improved collaborative results.

We witness this phenomenon in a number of real-world examples, which we discuss throughout this paper. Ant food-foraging is an obvious and extensively used example where an explicit trigger is present: the pheromone trail. Another example is the paper-wasp nest-building process where the state of the nest completion triggers a predictable subsequent action. The nest building example illustrates how an environment structure provides the stimulus instead of a pheromone secretion. We also discuss ant corpse-clustering activity as an example showing where the agents themselves (when deceased) become the triggering stimulus. To illustrate stigmergy in human environments we discuss trails worn into grass where people take shortcuts. Each of these examples illustrates different types of stigmergic algorithms (Dorigo, Bonabeau, & Theraulaz, 2000) and we will draw on them extensively throughout this paper.

One area that can greatly benefit from this scalability is software development of Web 2.0 sites which display many similar traits to ant colonies; massive numbers of users coordinating by depositing information within the site. Ideally, environment structure and design should aid organisation rather than requiring a central management team. We are researching ways to engineer stigmergy into Web 2.0 sites to improve coordination amongst site users. An excellent example of this can be seen in the online auction site eBay (ebaY, 2009) that provides user driven feedback on transaction satisfaction which helps police fraudulent activity.

We considered that stigmergy is an important phenomenon that can be exploited to provide powerful collaborative environments. Theraulaz and Bonabeau (1999) provided a seminal paper on the subject called "A Brief History of Stigmergy". We are inspired by this paper in a similar context to Stephen Hawking's "A Brief History of Time" (Hawking, 1996) where an esoteric subject potentially drowned in mathematics is made accessible to the layperson. When considering the title of this paper, we hoped to achieve a similar level of accessibility by creating a paper that will benefit the academic community and the layperson both. We have encountered a comment from a mathematician stating, "stigmergy is simply a finite state machine where by the state is stored in a construction. Ants and people (agents) simply advance the state by blindly responding to previous states" (anonymous, 2013). This epistemological nihilism takes an almost creationist view that ants (and people) have no capacity to evolve or develop their state machine but exist as automata. Certainly mathematical modelling of stigmergy has generated some profound research explaining how stigmergy achieves what it does, but from the stated perspective we fear the full potential of the phenomenon would never be realised.

We believe that there is overwhelming need for a general theory of stigmergy including a holistic and standardised model to unify both the broad and narrow views on the topic. To develop a rich picture of stigmergy we must deal with the difficulty of Grassé's original paper being published in French. Therefore we base our model on available translations of Grassé's work and a content analysis of peer reviewed papers based on stigmergy. Multidiscipline research spanning entomology, sociology, immunology, Multi-Agent Systems (MAS) and Complex Adaptive Systems (CAS), information theory and computer science (to name just a few) has been inspired by Grassé's research. The papers we have reviewed have provided insight into practical applications of how this phenomenon manifests in environments, while illustrating additional detail and interpretation of various nuances and inconsistencies.

This paper provides a macro and phenomenological level deconstruction of stigmergy, and attempts to address the *what*, *how*, *why*, *where* and *when* of the subject. The structure of this paper will be as follows: Section 2 will discuss *what* stigmergy is by reviewing its history. Sections 3-6 will cover *how* stigmergy works by analysing mathematical models, *how* it forms, *how* it applies to humans and *how* signs manifest. Sections 7 and 8 will discuss *why* stigmergy exists through meaning and participant motivation. Section 9 explains *when* a particular form of coordination is stigmergic and when it is not. Section 10 will discuss *where* stigmergy can be found. Section 11 presents our abstract model of the semantics of stigma in stigmergy. Section 12 will provide the conclusion, with acknowledgments in Section 13 and References in Section 14.

2. What is stigmergy: The origins

The initial difficulty we encounter when developing our proposed model is that the original paper by Grassé is published in the French language; first hand interpretation and analysis is not possible by us. However we have found a number of direct references quoting the original work containing translations thus providing an association of research concepts to the original work by Grassé.

Perhaps the preeminent anthology of work on stigmergy is the book Stigmergic Optimisation (Ajith & Crina, 2006) with Chapter 1 introducing Grassé's work. While the original French quote is not provided, Crina & Ajith quote Grassé as saying, "*Self-Organization in social insects often requires interactions among insects: such interactions can be direct or indirect. Direct interactions are the "obvious" interactions: antennation, trophallaxis (food or liquid exchange), mandibular contact, visual contact, chemical*