COLLABORATION IN WEB N.0: STIGMERGY AND VIRTUAL PHEROMONES

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Keywords

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 it provides emergent self-organisation where 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. We hypothesized that this phenomenon can be exploited by engineering it into websites more effectively.

The aim of this thesis was to develop a general theory of stigmergy and an abstract model. We developed this through a content analysis of influential literature documenting the theories and experiments. The model generated through the qualitative data analysis will be used as a template to assess existing websites through a series of comparative case studies to assess how stigmergy exists in those sites. The results of these studies provide the foundation for design how to engineer stigmergy into websites. This design is developed into a special theory describing a software design pattern for building Web 2.0 components exploiting this self-organizing phenomenon. To verify the software design pattern an experimental prototype website was built that incorporates various stigmergy examples that are seen in popular websites (e.g.: Facebook’s like feature). The prototype has been evaluated against the abstract model to verify that each of the identified features of stigmergy is present and supported by the design pattern.

During this research project we discovered that many websites demonstrate examples of stigmergy that fit our model perfectly. In most cases the stigmergic properties appear to have been haphazardly (but fortuitously) included. Through the course of the project we discover that previous research quantitatively verifies that incorporating stigmergy into websites improves collaboration results. What this research has provided is a more rigorous mechanism for systematically including stigmergy into websites. This project has produced a foundation design pattern for future researchers to more easily explore the full capability of incorporating stigmergy within collaborative Web environments to realise this benefit.

We consider that the development of an abstract model of stigmergy and the creation of a Web software design pattern based on stigmergy to be a significant contribution. We believe that this will encourage future research into improved collaboration on social sites where the number of users can reach swarm levels and decentralised management solutions are not only scalable, but essential.
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Publication 1 - Standing on the Shoulders of Ants: Stigmergy in Web N.0


Publication 2 - Stigmergy in Web 2.0: a Model for Site Dynamics


Publication 3 - General Theory of Stigmergy: Modelling Stigma Semantics


Publication 4 - Extending Web Modelling Language to Exploit Stigmergy: Intentionally Recording Unintentional Trails


Publication 5 - Web Modelling Languages: Positive Feedback Mechanisms


Publication 6 - Special Theory of Stigmergy: A Design Pattern for Web 2.0

List of Abbreviations

CAS – Complex Adaptive Systems

DC – Distributed Cognition

HTML – Hypertext Mark-up Language

MAS – Multi-Agent Systems

UI – User Interface
Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

QUT Verified Signature

Signature:

Date: 13/02/2015

In all cases, the first named author has made substantial contributions to the conception and design of the work; the acquisition, analysis, and interpretation of data for the work; drafting the work and revising it critically for important intellectual content.

The second and third named authors gave final approval of the version to be published; and agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.
Acknowledgements

Thank you to my supervisors Kerry Raymond and Michael Docherty for the years of assistance. Also thank you to Daniel Johnson and Keith Duddy who both provided valuable input into discussions that helped strengthen the outcomes of this body of work. Finally thank you to my partner Christine Jones who has maintained good humour over the years while listening endlessly about esoteric mumblings about stigmergy. Now she only has to put up with my new studies and future direction into biomedical science.
Chapter 1: Introduction

The World Wide Web (Web) is relatively young and its historically static content is rapidly transforming into more powerful applications. Present technology now provides a dynamic Web experience with the proliferation of collaborative or social websites. We should consider how we might harness this technology and prescribe a more trustworthy and verifiable environment. Combining bio-inspired designs and algorithms with social network analysis will facilitate the creation of a more sophisticated web application capable of harnessing the power-of-the-crowd in a design that is non-intrusive and reusable between websites. This thesis presents one such design pattern and documents its development and testing. The products of this research provide a sturdy foundation for future researchers to build on; the outcomes provide a strong framework for a designer to progress from basic examples of collaborative environments to more sophisticated environments based on new and innovative techniques.

The first three sections of this chapter outline the background, the context of the thesis, its purposes and resulting research. The next section of this chapter describes the significance and scope of the research and provides definitions of terms used. Finally, the last section includes an outline of the remaining chapters of the thesis.

Background

Websites have transitioned from the simple static pages of the 1990s into highly functional portals ranging from e-Commerce to social networking. As with any new revolutionary technology we witness new problems such as fraudulent activity and issues of trustworthiness. This new virtual world results in people no
longer being physically present when interacting with each other and introduces the 
opportunity to exploit the system. This subversive exploitation can range from 
simple mischievous misinformation through to embezzlement or property theft. The 
scale of the global user base is so vast that traditional policing techniques are 
unviable. If service providers were to provide support based on direct 
communication at these swarm-levels the resources required would quickly become 
overwhelmed. For our purpose, introducing effective triggers to elicit useful and 
contextual input from participants is expected to provide more trustworthy 
collaborative results. We believe a system is required that has no central 
management function to enable its scalability.

To achieve this we find inspiration in biology and a phenomenon called 
stigmergy that has received growing attention over the past decades. Stigmergy 
describes the way non-rational, autonomous agents collaborate to achieve complex 
tasks thereby displaying some type of *emergent* swarm-intelligence (Mason, 2003), 
or *self-organization*. These agents use traces embedded within the environment or 
other spatiotemporal structures to trigger behaviour or actions in other agents in the 
swarm. These resulting stimulating configurations do not require the participants to 
have any global level knowledge of the state of the system and do not require any 
memory or faculty greater than is required to achieve the immediate task presented. 
As we will discuss in the literature review, stigmergy is significantly more rich and 
powerful than original observations indicated. Stigmergy is a compelling 
phenomenon because it facilitates self-organization of both *active contributions* and 
*passive interactions*. Stigmergy manifests in four different varieties that fit within 
an orthogonal matrix; one side describing two mechanisms of contribution 
(quantitative or qualitative) and the other side describing two distinctions
(sematectonic or marker-based). These four varieties are explained in detail in Chapter 2: Literature Review (subsection A New Model). Each of the four quadrants of the matrix provides an inherent and compelling meaning separate to the primary purpose of the system that the stigmergy is found.

Research into stigmergy spans many fields and although it primarily is a source of inspiration for robotics (Multi-Agent Systems) and cognitive research it is also studied in areas ranging from construction to epidemiology. Software development of Web 2.0 sites is an area that can greatly benefit from its scalability. Websites display similar traits to ant colonies; massive number of users coordinating by depositing information within the site. Stigmergy creates equilibrium between positive and negative feedback within the system. Positive feedback is provided by agents contributing to a signal and results in the signal strength of a trail increasing as more agents contribute. This promotes rapid and successful task completion. In opposition to this, the environment provides a negative feedback that will diminish the contributions making up the signal as they become unused and irrelevant. Signal decay ensures old information dissipates as it becomes redundant. An example of this can be seen in ant food foraging: a trail of pheromones is created by the ants aiding to direct other ants within their colony to efficiently navigate to the food source. The pheromone trails from previous food sources is weathered away by the environment resulting in only the current trail being sensed and stopping the ants from erroneously following an old trail to a depleted food source.

With the rise of Web 2.0 this same mechanism of environment-embedded, indirect communication can be seen throughout numerous Web sites, such as Wikipedia, eBay and online stock trading sites. The behaviour of users benefits the community as a whole with the system fulfilling a greater role than the individual
agendas of its users. Websites such as Wikipedia show an excellent example of where indirect communication exists, as contributors are primarily interacting through knowledge artefacts and not the agents involved in artefact creation / modification. Within eBay buyers attract sellers, and sellers attract buyers based on the trail of previous transactions where user driven feedback on transaction satisfaction helps police fraudulent activity.

Just as form should follow function, environment structure and design should aid organisation rather than requiring a central management team. Our research presents how to engineer stigmergy into Web 2.0 sites to improve coordination amongst site users through the inherent meaning portrayed by user behaviour.

**Context**

We observe stigmergy in existing websites and see it manifest as social buttons or similar coordinative feedback mechanisms. The inclusion of the Facebook *Like* button has become so ubiquitous that it has become a social meme. Competing sites mimic this behaviour such as Google+ where a *+1* button is provided to represent the same type of voting system to indicate user sentiment. The website eBay provides a similar sentiment-based system for indicating transaction satisfaction amongst site users to identify the trustworthiness of site participants. The proliferation of these User Interface (UI) designs illustrates their effectiveness to the extent that we witness sites dedicated to providing mash-up functionality to help web developers incorporate the mechanisms into third-party websites.

This highlights what we see as a problem of how we might standardise the design of these social UI mechanisms. There is significant research into stigmergy, virtual pheromones and swarm intelligence to model and predict behaviour. There is equally a substantive amount of research into how to program the behaviour of
robots to mimic stigmergy. There is limited research into creating a design pattern that exploits stigmergy in context to the natural behaviour of users. This study focuses on how to incorporate a design into websites to proactively exploit the natural stigmergic behaviour of users in a website-agnostic way and to provide better coordination and collaboration. This research focuses on defining an architectural design pattern to aide application development when introducing stigmergy UI components at website design-time. The design pattern that has been produced as a result of the research is not a final destination but instead a launch-pad for future research. From the well-defined starting-point developed from this research we expect that further research will provide innovative mechanisms that will enhance collaborative environments in the future.

**Purposes**

The primary aim of this research project has been to create a model for identifying stigmergic attributes and dynamics in Web environments. The purpose of building this model has been to create a design pattern for prescribing how to build sites benefiting from stigmergy. A secondary requirement of the research has been to understand the full breadth of the stigmergy phenomenon and how it is applicable to virtual environments. This has been done with the aim of providing a solid foundation for the development of a design pattern to include stigmergy into Web 2.0 sites. The design pattern facilitates consistency throughout any introduction of stigmergy into new (and existing) websites. The practical outcome of developing such a design pattern is that websites will provide content that is not only relevant through self-organisation, but will support a user-generated representation of its trustworthiness.
Stigmergy results in an emergent behaviour through the dynamics applied to the inherent attributes of the environment, agents, and artefacts. The dynamics of agents are usually described as pheromone evaluation, task prioritisation, and clustering behaviour. Pheromone dynamics in stigmergy provide implicit communication through decay rates, which result in a negative feedback force. The negative feedback can achieve equilibrium against the positive feedbacks contributed by users. This leads to the question: How do you build collaborative Web 2.0 sites in a consistent and efficient way when the attributes and dynamics of stigmergy are fully exploited? Understanding how stigmergy benefits the collaborative process required answers to the following additional sub-questions:

What mechanisms support virtual well-worn paths (or pheromones), which can be identified and recorded within the existing Web specification and protocols?

How can we support alternative needs and motivations to encourage participation from users who would otherwise not contribute actively to the collaborative process?

**Significance, Scope, and Definitions**

Software development is a complex discipline that has been made more manageable through the introduction of design patterns. Design patterns demonstrate the current state-of-the-art to other developers while also encouraging a consistent and common approach. As we witness the adoption of stigmergic feedback mechanisms in websites (e.g.: Facebook’s *like* and eBay *feedback* buttons) we see an important opportunity to introduce a design pattern for this emerging trend. We observe research that measures the impact and efficacy of stigmergy within websites (den Besten, Gaio, Rossi, & Dalle, 2010), (Ba, Whinston, & Zhang, 2003),
(Marsden, 2013), (O’Donovan, 2013), however there is a gap in the literature suggesting where a prescriptive design might be possible.

If we intend to provide a design pattern to exploit stigmergy then we must first understand the phenomenon in fine detail and how it exists within entomological, human-based and engineered environments. We will begin our research through a detailed content analysis of literature on stigmergy. To transition our understanding from entomology to engineered environments we must analyse existing websites displaying stigmergic traits as case study subjects. We use the definitions from literature and our case study observations to develop a model for identifying attributes and dynamics of stigmergy. We use the developed model as a template to create a design pattern that describes how best to build sites benefiting from this phenomenon. Finally, we build an experimental prototype that we use as a case study to test the efficacy of the design pattern, and present the test case results as evidence. If we prove that the stigmergy design pattern successfully incorporates those functions into a website we believe that its efficacy in self-organisation is a corollary to previous research that quantifies the benefit of stigmergic autopoiesus.

**Thesis Outline and Research Papers**

This thesis is structured to explain and organise the work published through the course of this project. The format of the thesis is consistent with that prescribed by Queensland University of Technology.

Chapter 2 contains the Literature Review referencing seminal literature in the field of Web history and in stigmergy. This provides the foundation of knowledge for the reader to understand the context of the research and the inspiration for selecting stigmergy as a subject for a software design pattern.
Chapter 3 explains the Research Design chapter by formally describing the objectives of our research question, the methodologies that are employed to collect data and answer the questions. Also included in the Research Design chapter is an explanation of how the data collected has been analysed to ensure that conclusions are valid.

Chapter 4, 5, 6, 7, 8, and 9 present the peer-reviewed and published results from this project addressing specific parts of the project research questions. These previous publications provide significant depth of understanding for the topics and implicitly illustrate the project progress. The publications are described in more detail below.

Chapter 10 provides a detailed Analysis and Conclusion of the results presented in Chapter 4, and includes a discussion on their interpretation. This is followed by the Bibliography and Appendices.

The research papers produced from this project are listed in Table 1 along with descriptions of their relevance to the research problem and research question. The papers are presented in their entirety in each of the designated research paper chapters (Chapters 4, 5, 6, 7, 8, 9) along with a more thorough preamble describing their contribution to addressing the research objectives and so that the chain of evidence is apparent.

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<td><strong>RESEARCH PROBLEM</strong></td>
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<td>Some social websites incorporate mechanisms for self-organisation in collaborative environments. These mechanisms are indicative of stigmergy and have proven to be both effective and scalable. Yet there remains no prescriptive software design on how best to incorporate these mechanisms into websites to proactively exploit the natural stigmergic behaviour of users in a website-agnostic way to provide better coordination and collaboration.</td>
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<td>RESEARCH QUESTION</td>
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| OBJECTIVES | **O1:** Study selected Web sites which successfully implement Web N.0 as a collaborative environment identifying how specific technologies and mechanisms support stigmergy.  
**O2:** Create a model of stigmergy in Web N.0 to clearly identify the attributes and dynamics as outlined in papers covered in the Literature Review.  
**O3:** Analyse and interpret the data to evaluate the model and validate the model efficacy.  
**O4:** Design a software design pattern to prescribe system architecture for collaborative generation of domain knowledge. |
**Relates to Main Research Problem**  
The initial literature review and resulting problem definition from stage 1 of the project was presented at conference. This paper provides insight into stigmergy that guided our further reading. The initial review identified a significant corpus of Ant System (AS) algorithms enabling a detailed content analysis of empirical experiments used when developing the model of stigmergy. The initial review demonstrated that there was enough detailed study on the subject and that a general theory consolidating the mathematical modelling and emerging nomenclature was absent and needed. |
**Relates to O1**  
This paper documents the results of the comparative case study of websites that provided the data assessment during the evolutionary development (stages 2, 3, 4 and 5) of the attributes and dynamics included within the model of stigmergy. The results of the comparative case study and an early version of the model were presented at the ACM Web Science international conference. |
**Relates to O2**  
This paper provides a thorough analysis of existing research based on stigmergy and presents the abstract model developed as part of stage 3 of this project. This model is environment agnostic and applies to entomology, human and engineered environments. The model (and theory) clearly identifies the attributes and dynamics of stigmergy and provides an epistemological discourse on the sources of each concept as outlined in the Literature Review chapter. |
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<td>7</td>
<td>CHAPTER 7: Dipple, A., Raymond, K., &amp; Docherty, M. (2013). <em>Extending Web Modeling Language to Exploit Stigmergy: Intentionally Recording Unintentional Trails</em>. Paper presented at the WEB 13, The First International Conference on Building and Exploring Web Based Environments, Seville, Spain.</td>
<td>Relates to O3</td>
<td>This paper documents the evaluation of the model efficacy and presents the final analysis of the comparative case study. The paper presents the retrospective analysis against the initial case study subjects (stages 3 to 5), and the additional website that was not assessed during the model development. This additional website was used to verify the efficacy.</td>
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<td>8</td>
<td>CHAPTER 8: Dipple, A., Raymond, K., &amp; Docherty, M. (2013b). <em>Stigmergy within Web Modelling Languages: Positive Feedback mechanisms</em>. Paper presented at the ICIW 2013, The Eighth International Conference on Internet and Web Applications and Services.</td>
<td>Relates to O4</td>
<td>This paper documents the iterative software design pattern development covering stages 6 and 7 of the project. The design process began with an initial proof-of-concept prototype to determine the suitability of the selected development environment. This prototype was focused on the positive feedback attributes and dynamics and was presented at conference.</td>
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<td>9</td>
<td>CHAPTER 9: Dipple, A., &amp; Docherty, M. (2013). Special Theory of Stigmergy: A Design Pattern for Web 2.0 Collaboration. <em>ACM Transactions on Internet Technology (under review)</em>, 37.</td>
<td>Relates to Main Research Question</td>
<td>This paper documents the final software design pattern for the abstract model of stigmergy, and how to encapsulate stigmergy in components separate a core website development project. This encapsulation provides the hypothesised stigmergic components that can be added to existing and new website architecture for collaborative generation of domain knowledge. The paper includes an evaluation of the design using an experiment prototype as a case study. Performance testing of the self-organising properties and comparison of the design-pattern against other approaches is considered outside the scope of this paper.</td>
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Chapter 2: Literature Review

Over the past 50 years enhancements and innovation in technology have accelerated at such a rate that modern society no longer considers what future concepts are impossible, but what might be plausible. This is evident within the World Wide Web where we see collaboration on a massive scale, and where Web sites focus on harnessing the power of the collective intelligence of users. Ideally we can design a pervasive system which facilitates collaboration, capturing tacit knowledge through the interaction of all system users, and not just that from users who actively contribute to the collaborative effort.

The purpose of this literature review is to explore the potential of developing a bio-inspired design pattern that can be incorporated into a Web-architecture to enhance the current collaborative environment and support the emergence of domain knowledge. The review will cover the implicit coordination mechanism where the volume of users provides a self-organising, self-optimising and self-contextualisation of content (Baumgarten, Greer, Mulvenna, Curran, & Nugent, 2007), and considers the potential of designing the Web of the future to harness both active and passive contributions.

The sub-sections of this literature review are as follows:

- Background

- The History of Stigmergy

- Understanding the Depth of Stigmergy

- Evolution and Emergence
- From Entomological to Cerebral
- The Meaning of Stigma
- A New Model
- Summary and Implications

This project is presented as thesis-by-publication and therefore this literature review will focus on the pre-project state-of-the-art and consequently introduce work that we have published.

Readings in the Background section explore current trends and definitions of the Web N.0 namespace (Web 1.0, Web 2.0 and Web 3.0), and provide an outline of the arguments of what these terms mean conceptually and technically. The review will outline example web sites illustrating how the Web as a technology is supporting human communication and aggregating domain knowledge through inherent dynamics of user interaction.

Readings in The History of Stigmergy provide insight into what has historically been called the coordination paradox. This paradox describes the complex societies and structures that develop in some insect societies, despite there being no apparent central management function.

Readings in Understanding the Depth of Stigmergy explore the attributes and dynamics of stigmergy and how they have been modelled using mathematics. This sub-section will provide insight into the mechanics of the phenomenon and how the variables might associate to the features of a software design pattern.

Readings in Evolution and Emergence expand on the modelling of stigmergy and demonstrates how stigmergy might develop in a society. Where early work mimics stigmergy it provides no suggestion of how it initially developed.
Readings in *From Entomological to Cerebral* describes how stigmergy applies within the human world: both physical and virtual. The sub-section will cover how users interact with web sites achieving different results, and having different agendas. This describes the social topology creating a form of knowledge greater than the sum of its parts through self-organisation, self-optimisation and self-contextualisation.

Readings in *The Meaning of Stigma* transitions the development of understanding within stigmergy and expands on how unintentional dynamics describe a coordination mechanism that is based on information flow, virtual proximity and contextual priority. This sub-section will introduce the concepts that provide the scope that a design pattern must cover.

Readings in *A New Model* sub-section summarise the important concepts of our stigmergy model. The model homogenises many of the conflicting nomenclature encountered in the work of preceding researchers and provides the solid theoretical foundation that the stigmergy design pattern of based on.

Finally readings in *Summary and Implications* will discuss each of the previous sub-section and explain the relevance of each to the research project. The relationships between the variables will be highlighted to establish the need for this study and the contribution that it makes.

This literature review is intended to show that research into stigmergic behaviour suggests a metadata structure which would enhance collaboration and where the introduction of stigmergic components will support an emergent knowledge through both active and passive user interaction. Web N.0 topology affords an excellent environment for accumulating tacit knowledge and potential to provide a new emergent knowledge across domains. The following sections are
structured in a way to lead from the overview of the technical platform being discussed, the original concepts of stigmergy, and the mechanisms which provide the emergent properties of stigmergy in human and engineered environments.

**Background**

"A common mistake that people make when trying to design something completely foolproof is to underestimate the ingenuity of complete fools." – (Adams, 1992)

When the Web was conceived by Sir Tim Berners Lee, he imagined it as an information melting-pot enabling individuals to publish content to, and interact with, an immediate and vast audience (Berners-Lee, Hall, Hendler, Shadbolt, & Weitzner, 2006). The Web (Web 1.0) was the initial, partial implementation this vision, and (much like most software development) only implemented part of the original specification. It provided a platform where authors were able to create static Hyper Text Mark-up Language (HTML) pages, and push them out to other users’ browser. Through the past 20 years the underlying technologies have expanded and matured, creating a much richer experience compared to the original static page in a browser. Current HTML trends point towards the internet as a social networking tool utilising these new technologies and have subsequently seen the term Web 2.0 emerge.

There is much debate within this area regarding definitions of what constitutes Web 1.0 and Web 2.0, also known as the Social Web (Anderson, 2007).

The term Web 2.0 was originally coined by Dale Dougherty for marketing purposes (O'Reilly, 2007). However it became accepted as a technical term following the publication of O'Reilly's paper, *What is Web 2.0: Design Patterns and Business Models for the Next Generation of Software*, which prescribes seven principle concepts of Web 2.0.

These Principles are:
1) The Web as platform;

2) Harnessing collective intelligence;

3) Data is the next Intel Inside;

4) End of the software release cycle;

5) Lightweight programming models;

6) Software above the level of a single device;

7) Rich user experiences.

In contrast to O’Reilly’s 7 Principles, Anderson proposes that Web 2.0 embodies 1 or more of 6 Big Ideas (Anderson, 2007). What is important in Anderson’s view is how well a solution embodies a number of these ideas as opposed to trying to embody all of them.

These Big Ideas are:

1) Individual production and User Generated Content;

2) Harness the power of the crowd;

3) Data on an epic scale;

4) Architecture of Participation;

5) Network Effects;

6) Openness.

The biggest contrast between O’Reilly’s Principles and Anderson’s Big Ideas is that the Principles describe a prescriptive architecture for building Web 2.0 sites. The Big Ideas are more descriptive of the resulting traits of the developed web-sites. O’Reilly’s Principles describe a move toward highly modular, distributed software
which is downloaded at run-time (as needed) enabling massive collaboration on data in a way that is far more sophisticated than the static HTML page experiences of the 1990s. Anderson’s ideas describe the benefits of Web 2.0 as facilitating users to have a lower entry barrier to participation in content generation, while suggesting that the content is generated in a collaborative way decentralising power to the collective of amateurs. Certainly both authors identify the core importance of data in this new webscape but where O’Reilly is focused on how the data is distributed Anderson is more focused on how it is used, and what it represents.

The most interesting of the Big Ideas are numbers 2, 4 and 5. Anderson articulates that the “Architecture of Participation” is not specifically focused on the participation facet, but more the architecture, and how it adds value to the participation process more than merely enabling multiple people to edit some content (Anderson, 2007). What is alluded to is a more complex platform, which can provide information on the collaborative process as much as the end content. This would appear to be indicative of the metadata of stigmergy which will be explored later within the literature review. Harnessing the power of the crowd and the network effects describes the economy of scale that grows exponentially in a networked environment. This scale leads to a representation of an emergent global knowledge providing an assessment of data (and user) trustworthiness where reputation becomes significant and substantial. The architecture of Web 2.0 supports volumes which would otherwise be inconsequential, and equally supports volumes which would otherwise be too excessive to maintain.

Actual examples of the Web 2.0 phenomenon can be seen in websites such as Wikipedia, YouTube and Facebook (O’Reilly, 2007). These sites embody the concepts outlined above in ways that Web 1.0 was simply not capable of achieving.
For example, Wikipedia as a site enables users to access and contribute to pages representing specific knowledge. The architecture is a web-application distributed to the browser facilitating the access and editing of content, and also adds value by tracking changes and links to other pages which can be related as suggested associated areas of interest.

The term Web 3.0 has recently emerged which describes a future Semantic Web ("W3C Semantic Web Activity," 2009) evolution. An internet search returns results describing Web 4.0, Web 5.0 and onwards ("Google search: Web 4.0 Web 5.0," 2009). These latter version labels are somewhat farcical, but certainly the concept of Web 3.0 has clearly defined functional attributes providing differentiation. Web 3.0 describes an evolution where the social interaction and content generated might be processed by automated agents. Where Web 2.0 focuses on harnessing the power of the crowd (Anderson, 2007), Web 3.0 focuses on machine readable data retaining some sense of meaning presumably through a supporting metadata. This Semantic Web is starting to be realised with sites such as Amazon.com monitoring and recording customer activity to provide future customers with computer-generated suggestions on purchases.

The Web 3.0 concepts of content processing (specifically human communication and domain knowledge) and user / agent dynamics are indicative of stigmergy (and virtual pheromones). These topics will be covered by the remainder of the literature review where we build on and encapsulate the concepts and how they are applicable to Web N.0 instead.

**The History of Stigmergy**

"Standing on the shoulders of termites" (Aiden Dipple, 2009)
The term stigmergy was first documented in 1959 where a French zoologist (Grasse’, 1959) revisited research into how termites appear to coordinate without an obvious management structure. Grasse’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 traces left in the environment affect subsequent behaviour of both themselves, and of other individuals.

The initial difficulty we encounter when developing our proposed model is that the original paper by Grasse 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 Grasse.

Perhaps the preeminent anthology of work on stigmergy is the book Stigmergic Optimization (Ajith & Crina, 2006) with Chapter 1 introducing Grasse’s work. While the original French quote is not provided, Crina & Ajith quote Grasse 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 contact (the odor of nearby nestmates), etc. Indirect interactions are more subtle: two individuals interact indirectly when one of them modifies the environment and the other responds to the new environment at a later time. Such an interaction is an example of stigmergy” [(Ajith & Crina, 2006), p. 3].

Crina & Ajith (Ajith & Crina, 2006) identify that the termite does not require any global level knowledge of the state of the system and does not require any memory or faculty greater than that which is required to achieve the basic task.
presented. To illustrate this they again quote Grassé’s observed set of simple rules that termites follow when constructing a nest.

“First, they simply move around at random, dropping pellets of chewed earth and saliva on any slightly elevated patches of ground they encounter. Soon small heaps of moist earth form.

These heaps of salivated earth encourage the termites to concentrate their pellet-dropping activity and soon the biggest heaps develop into columns which will continue to be built until a certain height, dependent on the species, is reached.

Finally, if a column has been build close enough to other columns, one other behaviour kicks in: the termites will climb each column and start building diagonally towards the neighbouring columns.” [(Ajith & Crina, 2006), p. 3]

The generally accepted translation of Grassé’s (from French to English) is: "The stimulation of the workers by the very performances they have achieved is a significant one inducing accurate and adaptable response, and has been named stigmergy." [(Holland & Melhuish, 1999), p. 173]

The crux of Grassé’s research is to explain the coordination paradox where seemingly independent agents appear to coordinate with no central management. Grassé was not the first person to study the insect coordination paradox though he is acknowledged as identifying the “emergence, regulation and control of collective activities in social insects” (Theraulaz & Bonabeau, 1999). The historical theories predating stigmergy provide insight into the paradox of insect coordination which is fundamental to the concept of environment mediated communication that triggers behaviour without requiring central management control.
In 1877 a French zoologist (Espinas, 1877) predated stigmergy with an analogy-based concept of a super-organism to describe various collective insect societies. As per Grassé, Espina’s work is published in French so our understanding of his theory is second hand and we rely on the interpretation of Theraulaz & Bonabeau. Espina’s work was based on the strong parallels drawn between the adaptive structure of insect colonies and those of a single organism. The problem with this metaphor is that the “analogy did not provide any insight because it did not have any explanatory value.” (Theraulaz & Bonabeau, 1999). The weakness of this metaphor highlighted the need to understand the behaviour, interactions and exchanges between individual agents.

Half a century later another French biologist (Rabaud, 1937) provided an alternative theory on insect social structure proposing that insects behave as a collection of individuals. Each individual (by collective nature) responds to stimuli in the same way. This results in an aggregation of efforts and therefore any apparent coordination is merely by chance. This lack of coordination implies a similar lack of needing a plan for the successful survival of the society. Given the complex social structures within various insect colonies this lack of coordination would seem improbable. Addressing this issue, Rabaud introduced two important concepts for understanding collective behaviour that provided the foundation of Grassé’s model: interaction and inter-attraction.

Interaction describes how “one individual’s action may influence another individual, thereby modifying its behaviour” [(Theraulaz & Bonabeau, 1999), p. 100]. Conversely, inter-attraction describes the social phenomenon where animals belonging to a social group will be attracted to the behaviour of other animals in the same group. This describes the binding dynamic that gives societies their identity.
Grassé built on these concepts by considering that “sociality is not a trivial consequence that results from interattraction” [(Theraulaz & Bonabeau, 1999), p. 101]. There must also be reciprocal behaviour modification of individual agents living in close proximity within the collective. Interaction and inter-attraction establishes “a bridge between the individual and collective levels” [(Theraulaz & Bonabeau, 1999), p. 100] of the society. Interaction and inter-attraction define the feedback mechanism upon where the actions of an individual will trigger a response from its peers. Furthermore, the response of these peers will create stimuli which will trigger a response in the individual. A profound assertion of Grassé’s is that the behavioural changes to individuals as a result of inter-attraction lead to group effect, or an emergent self-organization. This group effect leads to changes in behavioural responses in individuals to certain stimuli effectively facilitating the collective’s ability to evolve managed responses by understanding the shared meaning of a given state of the stimuli.

This autocatalytic system leads to the emergence of “spatiotemporal structures” [(Theraulaz & Bonabeau, 1999), p. 104] through positive feedback, which achieve an equilibrium through an atrophic negative feedback. Grassé is described as observing how termite nest building “activity is organizing the environment in such a way that stimulating structures are created; these structures can in turn direct and trigger a specific action” [(Theraulaz & Bonabeau, 1999), p. 102]. This highlights that identified interactions do not have to be directly observed therefore indicating that the mechanism facilitates indirect communication. Appreciating the spatiotemporal structures providing a triggering stimulus, Grassé introduces the term stigmergy: stigma (sign) and ergon (action).
Understanding the Depth of Stigmergy

"Most people make the mistake of thinking design is what it looks like. People think it's this veneer – that the designers are handed this box and told, 'Make it look good!' That's not what we think design is. It's not just what it looks like and feels like. Design is how it works.” – Steve Jobs (Walker, 2003)

Grassé's original definition is very generalised and vague. This leaves us to consider how stigmergy is able to provide the self-organizing effect observed. Theraulaz & Bonabeau (Theraulaz & Bonabeau, 1999) state in their example of termite nest building that a pheromone scent contained in the mud balls (as a result of the insect saliva) incites other termites to begin the nest building process. As this continues, “the accumulation of material reinforces the attractiveness of deposits through the diffusing pheromone emitted by the pellets” [(Theraulaz & Bonabeau, 1999), p. 104]. While this previous statement describes the positive feedback process, the spatial characteristics of the environment provide an equalization through negative feedback as illustrated with a food-foraging example: “when the distance between a food source and the nest is long, the time interval between the trips of two foragers may exceed the evaporation latency of the pheromone and the trail disappears” [(Theraulaz & Bonabeau, 1999), p. 111]. Theraulaz & Bonabeau identify the dynamics of equilibrium between positive feedback and negative feedback: positive feedback contributed by the agent, and negative feedback enforced by the environment.

The two examples of stigmergy in nature described by Theraulaz & Bonabeau have spawned an entire area of research in mathematical modelling based on algorithms that describe different forms of stigmergy. Succinctly put by Dorigo et al, an “ant algorithm is informally defined as a multi-agent system inspired by the observation of some real ant colony behaviour exploiting stigmergy” [(Dorigo, Bonabeau, & Theraulaz, 2000), p853]. The initial algorithm researched was the Ant
System (AS) foraging algorithm that describes how ants will lay down pheromones for others to follow in order to find the most optimal path. The AS algorithm has successfully been applied to the Travelling Salesman Problem (TSP) and compares very well against other meta-heuristic methods. This ant-inspired approach has given rise to a whole set of meta-heuristics collectively known as Ant Colony Optimization (ACO) algorithms.

Researchers are interested in ant algorithms because they illustrate stigmergic variables along with the algorithms that provide the coordination that is observed in these systems. One area that stigmergy heavily influences is research into Multi-Agent Systems (MAS). The algorithms illustrate how these variables are “specifically (sic) used by ants to adaptively change the way they build solutions to the considered problem” [(Dorigo, et al., 2000 ), p871]. If we consider the structure of the ant algorithms presented, we notice that the variable can be internal to the ant, part of the environment state, or part of the sign state. As descriptive supersets to the term stigmergic variables we adopt the term attributes and suggest that our stigmergic attributes and dynamics are parallels to variables and algorithms.

There are many ant algorithms (Mizunami, Yamagata, & Nishino, 2010) ranging from alarms, sorting, scheduling, routing and task-selection to name a few. Each describe one facet of ant life and illustrate through simple rule sets how emergent behaviour can occur in context to the coordination paradox.

Tsankova et al (Tsankova, Georgieva, Zezulka, & Bradac, 2004) illustrate the dynamics of actuate based on the popular ant algorithm of corpse-clustering activity. The ant corpse-clustering activity is a sorting behaviour observed within ant nests. Deceased ants’ corpses are removed from the nest and deposited in a location away from the nest, creating the appearance of coordinated effort to create an ant grave.
yard. Tsankova et al demonstrate a stochastic algorithm example showing how automata agents can appear to coordinate together. The algorithm replicates the behaviour of termites depositing mud balls in a similar manner that Grassé originally observed in termite nest building. From a mathematical point of view the most important aspect of the work by Tsankova et al is that it presents an effective meta-heuristic with very little processing outside of simple, cause-effect rules chosen probabilistically. It clearly shows how the phenomenon works without agents requiring internal memory or cognition purely by responding to the state of the environment.

The environment performs the role as the external memory for the agents. The fact that the agents have no awareness of the current state of the overall solution is very important as it illustrates how the agents are able to operate without any internal memory or cognitive process acting on such memory. The current applicable rule is based on the current state of the agent and immediate environment.

The results of the different trials are illustrated and provide compelling proof of the algorithm’s sorting efficacy through the results of the researcher’s experiments. We summarise the experiment results as presented by Tsankova et al in Figure 1 for stage (b), (d) and (f) [(Tsankova, et al., 2004), p. 279].

![Figure 1 – Heuristic Clustering Results as presented by Tsankova et al](image)

The clustering tasks documented are a facsimile of observed behaviour in some insect colonies and illustrate the process where one agent might start part of a task
and how that task can be completed by either the same or a different agent. This highlights how each agent responding to its own cause / effect rule system can create the appearance of inter-agent cooperation (or at the very least inter-agent coordination) despite that not being encoded within the system. The experiment illustrates how the tasks being performed by the agents are divorced from the solution as a whole. Tasks are not defined in terms of the overall goal of clustering or world-state; but specifically focused on the state of the agent’s immediate surroundings.

The system is a metaheuristic solution rather than a 100% product algorithm. There is a random, uncoordinated phase through the task execution. The experiments identify a phase of task duration where the activity of the agents can inadvertently distribute the objects being clustered in contrast to the objective. Nevertheless research reinforces that the process is able to be performed (over the long term) reliably demonstrating robustness rather than optimal efficiency. This provides reliable results when undertaken by agents either on a swarm level, or over a significant enough time span (or program iterations). Tsankova et al draw attention to the random, uncoordinated phase as being similar to agents within the system who are not cooperating toward the objective, but instead provide disruptive behaviour. This illustrates how stigmergy is able to withstand counterfeit signs and disruptive actions where a sub-set of agents operating within the shared environment might try to extort the system unfairly. These simple experiments verify how unintelligent agents such as insects can achieve what appears to be an organised outcome via a decentralised, coordinated effort.

Klyubin, el al (Klyubin, Polani, & Nehaniv, 2004) provide research grounded in classical information theory (Shannon & Weaver, 1959) to understanding the
principles of adaptive behaviour. Klyubin et al focus on creating a quantitative way to measure information flow to understand and prescribe system behaviour, including within stigmergic systems. Information theory introduces the concept of entropy as a quantitative way to measure *probability distributions* of the information flow.

The research tests the concept of *gradient sensors* by providing a test bed comprised of a symmetric signal field, which is designed to broadcast a signal from a central point (See Figure 2). The experiment is quite simple in demonstrating how a deterministic algorithm can replicate the sensing behaviour of automata, and how it follows a graduated pheromone trail to its source. This pheromone gradient concept is called *osmotropotaxis* (Borst & Heisenberg, 1982) within entomology, and creates the ability for agents to sense a signal when they are not located at the same position as the sign.

![Figure 2 – Klyubin’s Sensor Input gradients](image)

To provide a more sophisticated example, a second experiment describes how the behaviour of an agent within the environment can interact with structures that then contribute to the environment modifications to create signals to subsequent agents. As stated by Klyubin et al, “in addition to the required information the sender offloaded some extra information about itself, some of which was later occasionally acquired by the recipient” [(Klyubin, et al., 2004), p. 568].
Mathematical models illustrate how a simple set of rules provides the same apparent self-organization displayed by social insects. Both experiments provide insight into the fact that there are a definable set of algorithms and variables to achieve this.

**Evolution and Emergence**

"I know who I WAS when I got up this morning, but I think I must have been changed several times since then." - (Carroll, 1865)

The mathematical modelling of stigmergy is presented with a significant problem: stigmergy originates from biological systems. Although we have seen how mathematical models and algorithms can mimic stigmergic behaviour, they only illustrate a static environment. This provides no insight into how stigmergy develops and evolves. Mittal (Mittal, 2013) highlights the limitation of Multi-Agent Systems (MAS) stating that agents in such systems are purely reactive. MAS fails to answer how new rules and meaning that facilitate emergence develop and evolve within a system. To address this limitation we turn to the field of Complex Adaptive System (CAS) research.

Before proceeding we should question what we mean by *emergence*. An excellent example of emergence is provided by Theiner et al where “brains are assumed to have cognitive properties that no individual neuron has” [(Theiner, Allen, & Goldstone, 2010), p.381]. Marsh & Onof clarify “that *emergence* (novel behaviour emerging from a lower level specification of a system) and its corollary *immergence* (individual interaction informed by a global state of affairs)” [(Marsh & Onof, 2008), p.139] each correlate to stigmergic autopoiesus and self-organization (emergence) and its coordinating mechanism (immergence). Grassé described observing how termite nest-building “activity is organizing the environment in such a
way that stimulating structures are created; these structures can in turn direct and trigger a specific action” [(Theraulaz & Bonabeau, 1999), p. 102]. The stimulating structures are localised sections of the overall nest where any given ant is solely aware of the state of their particular section. According to Mittal “emergence happens only at levels above the interacting agents” [(Mittal, 2013), p28] where a hierarchy forms. The termite nest itself becomes an emergent structure; no termite is aware of the overall structure as seen by humans witnessing it from outside (or similar bird’s eye perspective). Mittal differentiates emergent it into weak and strong categories (Mittal, 2013). Weak emergence is the simple property of stigmergy observed in ant systems where the ants are not aware of the self-organising behaviour and observers of the system do not impact on that behaviour. Strong emergence is where an observer at a higher hierarchical level has causal powers effecting lower levels in the system. This strong emergence gives the observing agent a competitive advantage in the environment.

With our definition of emergence we must address the limitations of MAS with Marsh & Onof acknowledging the need to borrow from evolutionary algorithms to describe the inclusion of new nodes. Mittal suggested that MAS modelling lacks the features required to formally model “components, interactions between the components, and emergent properties that are manifested” [(Mittal, 2013), p.22]. Mittal explains that “CAS is fundamentally different from MAS in portraying self-similarity (scale-free), complexity, emergence and self-organization that are at a level above the interacting agents” [(Mittal, 2013), p.22]. “The dynamic nature of a network is one of the keys to understand complexity” [(Mittal, 2013), p.23].

Ant System (AS) and Ant Colony Optimization (ACO) explain the coordination paradox but fail to explain evolution of rules. Mittal examines
stigmergy through CAS environments that are “adaptable systems where emergence and self-organisation are factors that aid evolution” [(Mittal, 2013), p.22]. CAS is a graph-theory centric research area and is still a mathematical language that models fluctuations in topological formation. CAS describes a mechanism where “self-organization is an adaptive collective behaviour” [(Mittal, 2013), p.29] enabling complex networks to form because the system “continues to redefine the topology, display the emergent properties and refine the properties themselves” [(Mittal, 2013), p.30]. Mittal explains that stigmergy is a specialised and sub-set of CAS and outlines 18 categories that describe CAS; 11 of the categories specifically pertain to stigmergy. Mittal describes four key processes within CAS: hubs that can form through clustering, stratification of hubs, strong emergence of self-organization with embedded observers at specific tiers capable of causal behaviour, and capacity for a dynamic environment allowing new abstractions to adapt. Adaptability is essential if we are to model stigmergy in a manner that will allow scale-free, spontaneous creation of rules.

CAS appears to provide a compelling explanation in how meaning and rules develop within stigmergy. If we consider that nodes can represent agents or signs then we begin to resolve the threshold limitations described by Dorigo et al when working purely within MAS. Dorigo et al propose a threshold where stimulus “s can be a number of encounters, a chemical concentration, or any quantitative cue sensed by individuals” [(Dorigo, et al., 2000), p.859]]. CAS now describes how stimulus can evolve and reach a tipping point to generate new quantitative sensed queues. Similarly Mittal illustrates the mechanisms developing a follow-the-leader style influence on social-network topology (Lewis, 2013) suggesting how information diffuses and spreads within a complex network. Models transition where they “adapt
their own interaction structure and their own behaviour as a result of those interactions through a newly added transition function” [(Mittal, 2013), p.33]. CAS illustrates the maturing of our understanding of stigmergy and how it evolves through the interaction and inter-attraction of agents where the emergence of the system “continues to redefine the properties themselves” [(Mittal, 2013), p.30].

**From Entomological to Cerebral**

"If you want to estimate the intelligence of a committee (IQc), take the average intelligence of the members of the committee and divide it by the number of members on the committee squared (N2).” (Kremer, 2006)

We now question whether stigmergy is confined to the realm of insects, or whether the phenomenon is observed within organisations where the agents have higher cognitive function. Parunak (Van Dyke Parunak, 2006) introduces stigmergy observed within humans systems (physical and virtual) through a series of case studies, and illustrates the emergent system behaviour (stigmergic autopoiesis). The value and performance of including stigmergy-based design has been well documented [(den Besten, et al., 2010), (Ba, et al., 2003), (Marsden, 2013), (O’Donovan, 2013)] so our research focuses on the capability and efficacy of the design pattern providing those mechanisms instead.

We might suspect that humans’ freedom-of-choice to be a hindrance to what stigmergy provides as a coordination process. Social activity (Susi & Ziemke, 2001) is a context that belongs to the collective despite the activity pertaining to the individual (viz.: inter-attraction). We understand that stigmergy is a process that is “largely unconscious of and not guided by plans or goals” [(Susi & Ziemke, 2001), p20]. However one theory of human behaviour, Distributed Cognition (DC), focuses on analysing the nature of how a *sign becomes a signal* to sub-sets of agents in the world. Certainly for humans, concepts of cultural and historical meaning are what
transform the signs to signals. This meaning then defines how the signs are perceived, how they are interpreted, and how agents react to them. Susi & Ziemeke state that DC “looks for cognitive process on the basis of the functional relationships of elements that participate together in the process, and the process is delimited by the functional relationships” [(Susi & Ziemke, 2001), p22]. In addition to being a form of situated cognition, stigmergy “distinctively emphasizes the cybernetic loop (sic) through an ongoing and mutual process of modification and conditioning” [(Marsh & Onof, 2008), p.148]

Parunak introduced stigmergy as a pattern of coordination and a rich set of metaphors when applied to Multi-Agent Systems (MAS) research. Parunak’s interest in stigmergy stems primarily from its ability to achieve system level results by resource-constrained agents within distributed computing systems. Stigmergy is shown as being pervasive within human systems and the power of the phenomenon stems from the lack of requiring a central control mechanism. Parunak provides examples of human based stigmergy covering both non-computational examples (e.g.: paths worn in vegetated terrain from pedestrians and other trail systems, and co-author document editing) and computational examples (e.g.: website ranking based on inter-linking algorithms, ad hoc peer-to-peer network creation and business workflow management analysis).

In most situations stigmergy results from localised interactions, which occur within the environment with each observed instance displaying the same economical use of resources. Parunak explains that there are two fundamental principles governing the success of stigmergy:

1) Regardless of how large the environment grows, because agents interact only locally, their limited processing capabilities are not overwhelmed.
2) Through the dynamics of self-organisation, local interactions can yield a coherent system-level outcome that provides the required control.

If we consider that stigmergy can exist within societies with greater cerebral capacity (e.g.: in human society), then we must also consider whether signs must be physical spatiotemporal constructs or whether shared knowledge or inter-relationship topologies might also be considered valid forms. Marsh & Onof (Marsh & Onof, 2008) believe this to be the case. They suggest extending the notion of stigmergy to include “the extra-cranial analogue of artificial neural networks or the extended mind” where it provides a coordinative function.

This certainly is consistent with Parunak who identifies virtual forms of human stigmergy such as the creation of online knowledge communities [(Bolici, Howison, & Crowston, 2009), (Crowston, Wei, Li, Eseryel, & Howison, 2005), (Heylighen, 2006)] as being stigmergic. Open-source development projects illustrate a virtual process where developers work in a shared environment with little central control other than the environment and artefacts themselves. Throughout the software development process dependencies are coordinated via source-code repositories. Bolici et al explain how “coordination can occur more directly through the code itself, particularly as that code is dynamically constructed in a code repository” [(Bolici, et al., 2009), p.1]. They explain how software lends itself particularly well to this type of coordination because if the architecture is modular (if architected correctly), that then is highly instructive of any particular section’s function. This modularity reduces the need for coordination but does not remove it completely. The trail-of-evidence that modern source-code repositories provide (e.g.: check-in comments, particular developer identifiers, etc.) enable a significant percentage of the coordination by providing an environment-mediated communication mechanism.
separate to the code itself. Bolici et al (Crowston, et al., 2005) found that discursive communication between developers was rare, occurring only at times where developers were co-working on the same piece of code. We see a clear parallel to stigmergy where there is no central control system separate to the solution artefacts themselves. The coordination is provided by the current state of that solution as perceived by those working on it.

Ricci et al (Ricci, Omicini, Viroli, Gardelli, & Oliva, 2007) propose that cognitive and rational agents exploiting stigmergy require a more complex system supporting the higher-level, knowledge-based activities. Ricci et al differentiate ant-based stigmergy from cognitive stigmergy where ants are incapable of anything more than simple automated reactions to elementary pheromone-based signals coupled with diffusion, aggregation and evaporation dynamics. The scientific-synthetic viewpoint proposes that stigmergy describes that artefacts constitute the agents’ environment and are an abstraction of “(i) the subject of the agent activity, (ii) the enabler/rules for interaction, and (iii) the “loci” of the stigmergic processes” [(Ricci, et al., 2007), p.125]. This effectively means that the artefacts provide the sign (or contribution), the interface, the location and the processing defining the semantics of stigma in stigmergy.

Marsh & Onof (Marsh & Onof, 2008) describe cognitive stigmergy in context to extra-cranial coordination (by citing Clarke) that uses “environmental conditions as instigators of action and the overall ability of the group to perform problem-solving activity (sic) exceeds the knowledge and the computational scope of each individual member” [(Clark, 1997), p.234]. The Google Page Rank algorithm is provided as an example of cognitive stigmergy, highlighting the topological structure as defined by pages and interlinks. In this example the pages become the equivalent
Chapter 3: Literature Review


Collaborative software development is a form of extra-cranial coordination and as such is described as one form of cognitive stigmergy. Most importantly, artefacts are the result of the human cognitive activity facilitating the coordination activity. The emphasis is not on the environment acting as a shared memory that provides a greater amount of knowledge but instead a shared memory that enhances the cognitive reasoning against the information stored. In the case of collaborative software development the memory is now an aggregate of source-code, the software at runtime and the binary information stored on some persistent media on a server (both source-code and executable). Wikipedia presents those same characteristics of becoming an externalised common memory for knowledge.

The logical next question: what other forms can signs take? If virtual spatiotemporal structures such as source-code are able to be sensed as a sign then what about undocumented knowledge itself? Marsh & Onof explain how knowledge is culturally and rationality bounded within environmentally located agents. The knowledge shared by these agents and the way it propagates through other agents is essentially stigmergic. The agents themselves provide an environment topology through their relationships and that the knowledge itself (in whatever form: intracranial concepts, or recorded as source-code / Wikipedia entries) is the content of the sign. In support of Marsh & Onof, Lewis suggests “that cognitive stigmergy does not produce physical structures like those found in the real world” [(Lewis, 2013), p.9]. We consider that this highlights how cognitive stigmergy becomes one level further removed from the physical and virtual world. Even in the virtual world
of software development the sign content (viz.: source code) is very much a tangible object.

Cognitive stigmergy as an extended mind is a form of stigmergy where the emergence of the system is the higher level problem solving capacity. Three facets of emergence are identified in cognitive stigmergy: “[agent] dependence on the organizational structure of a group, the manifestation of individually unintended cognitive affects at a group level and the putative multiple realizability of cognitive properties by individuals and groups” [(Theiner, et al., 2010), p.382]. Theiner et al describe this as “organization-dependent cognitive capacities that go beyond the simple aggregation of the cognitive capacities of individuals” [(Theiner, et al., 2010), p.378]. The concept of cognitive stigmergy instigates a strong philosophical debate on the nature of cognition. Theiner et al identify perspectives ranging from folk-psychological (intelligence and consciousness), cognitive science (memory and learning) to abstract creative processing. Some argue that these traits are retained at the level of the individual rather than considered to exist at the group level.

Cognitive stigmergy illustrates the opposite end of the spectrum in format compared to the entomological observations of ants. The important aspect of cognitive stigmergy is that it illustrates how outcomes are achieved through the “division of cognitive labour among cognitive agents” [(Theiner, et al., 2010), p.379] that creates immergent problem-solving capabilities despite agents only being aware of their immediate task at hand. Separate to a formally managed process of dividing the labour-tasks, the social interactions of the agents lead to the “enhanced group capacities without the express intent of the agents” [(Theiner, et al., 2010), p.379]. This is clearly made possible by the content of our stigmergic sign to consist of cognitive artefacts (Norman, 1991).
When performing some confronting task if “a part of the world functions as a process which, were it done in the head, would be accepted as part of a cognitive process, then that part of the world is equally part of the cognitive process” [(Theiner, et al., 2010), p.384]. The corollary of this is that by social parity if a group collectively performs this same cognitive process then it becomes a distributed process that must be mediated by some form of information exchange. In this context, the environment mediated artefacts that are used for information exchanges become the externalised memory for the cognitive process.

The Meaning of Stigma

"Is that an art form? I'm not an art critic! But I can sure as hell tell you that that’s a crime!" (Silver, 1984)

In this section we introduce the varieties of stigmergy and how they are identified through two distinctions and two mechanisms of stigmergy and what their associated meaning is.

Theraulaz & Bonabeau [5] describe observations of stigmergy that illustrate two separate mechanisms: quantitative and qualitative. Quantitative stigmergy is based on an accumulation of “stimuli that do not differ qualitatively” [[5], p. 104] but that will reach a threshold and increase the probability of triggering a response. Grassé’s termite nest building observation is offered as an example of the quantitative mechanism describing pheromone gradients (from termite saliva deposited in mud balls) reaching thresholds triggering subsequent action types.

Qualitative stigmergy is defined as a specific sign that can trigger a response by itself, where different qualitative signs can elicit different responses. The paper wasp example given by Theraulaz & Bonabeau illustrates how the changing state of the nest structure changes the probabilistic algorithm of what nest building state is
next executed. Experimental results for mathematical models of this example illustrate the improved performance of a stochastic algorithm over a deterministic version also presented (viz.: probabilistic rather than rule-based execution).

We summarise the *mechanisms* of stigmergy as:

**Qualitative:** A single stimulus capable of triggering behaviour (discreet options)

**Quantitative:** An accumulation of ‘stimuli’ that do not differ qualitatively, but increase the probability of triggering behaviour (a graduated potential field)

Parunak (Van Dyke Parunak, 2006) introduces two *distinctions* of stigmergy: marker based and sematectonic. *Marker based* stigmergy corresponds to pheromone deposits as described by Theraulaz & Bonabeau. *Sematectonic* stigmergy is documented as being coined by Edward Osborne Wilson (Wilson, 1975) and is described as a modification of the environment as a by-product of actions being performed. Parunak provides some examples of sematectonic stigmergy borrowing from Theraulaz & Bonabeau description of ant corpse clustering and wasp nest construction. The value of sematectonic stigmergy is that the trace is honest and reliable because it is incidental to the task despite being a direct result of the task actions. Sematectonic stigmergy is a parallel of marker-based stigmergy with one primary difference; marker-based traces are left intentionally where sematectonic traces are left unintentionally. The definitions of the distinctions of stigmergy so far in our model are:

**Marker-based:** Intentional signs left by agents

**Sematectonic:** Unintentional traces left by agents
These distinctions are compared against the *mechanisms* as *varieties of stigmergy* in an orthogonal matrix [(Van Dyke Parunak, 2006), p. 165] reproduced here in Table 2.

Table 2 – Varieties of Stigmergy presented by Parunak

<table>
<thead>
<tr>
<th></th>
<th>Marker-Based</th>
<th>Sematectonic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantitative</strong></td>
<td>Gradient following in a single pheromone field</td>
<td>Ant cemetery clustering</td>
</tr>
<tr>
<td><strong>Qualitative</strong></td>
<td>Decisions based on combinations of pheromones</td>
<td>Wasp nest construction</td>
</tr>
</tbody>
</table>

We find the examples in Table 2 to be a serious hurdle against understanding some relatively simple concepts of stigmergy. Although Parunak is heavily cited by other researchers, the table confuses and obscures key concepts of stigmergy. This is a result of Parunak’s describing stigmergy solely in terms of environment configurations and not differentiating them as a first level abstraction: the sign. We believe that the omission of sign as a core component of stigmergy is the reason for the ambiguity in the examples.

As stated by Theraulaz & Bonabeau, interaction and inter-atraction establishes “a bridge between the individual and collective levels” [[5], p. 100] of the society. Interaction and inter-atraction define the positive feedback mechanism upon where the actions of an individual will trigger a response from its peers. Furthermore, the response of these peers will create stimuli which will trigger a response in the individual. A profound assertion of Grassé’s is that the behavioural changes to individuals as a result of inter-atraction lead to *group effect*, or an emergent self-
organization. This *group effect* leads to changes in behavioural responses in individuals to certain stimuli effectively facilitating the collective’s ability to evolve managed responses by understanding the shared meaning of a given state of the stimuli. This behavioural modification of agents creates social meaning within a society.

Previous research (Tummolini & Castelfranchi, 2007) illustrates how the sign provides an emergent *meaning* based on goal-directed behaviour. Tummolini & Castelfranchi reiterate that the concept of trace signals is “the process of indirect communication of behavioural messages with implicit signals” [(Tummolini & Castelfranchi, 2007), p.155]. The example given is that of a theatre-goer leaving a coat on a seat they wish to occupy if they leave the immediate area. The purpose of leaving the coat could be because it is not needed as the temperature is comfortable within the theatre; however the coat can also be exploited as a trace that is left to signal that the seat is not vacant. The coat left on the seat has a very implicit meaning given the context, even though the coat itself has no explicit communicative function. It is not stated but we can infer that this communicative function and meaning stem from the inter-attraction of polite and civil people.

Tummolini & Castelfranchi provide a clear definition of communication and that in the simplest sense a trace by itself is a *sign*. If the sign is left to be noticed and understood by others as suggested then it is also a *signal*. Tummolini & Castelfranchi describe trace signal stigmergic value in terms of whether they have been left intentionally or not. They focus on how the agent leaving the trace can exploit the trace by understanding the inherent implied and implicit meaning to agents that sense the trace. They use the term *trace* to equally apply to sematectonic, or marker-based signs.
Castelfranchi restricts stigmergy to the condition where the receiving agent “does not perceive the behaviour (during its performance) but perceives other post-hoc traces and outcomes of it” [(Castelfranchi, 2009), p.325]. Huang et al (Huang, Ren, & Jin, 2008) believe stigmergy to be based on direct observed behaviour or traces left from them. We side with Tummolini & Castelfranchi and reject that direct observed behaviour is a valid content form of *sign*. Behavioural Implicit Communication (BIC) is considered to be a communication form where “there isn’t any specialized signal, but the practical behaviour itself is the message.” [(Castelfranchi, 2009), p.324]. Castelfranchi describes that the communication exploits *signification* or “the semiotic ability of cognitive agents; for example the ability to take ‘smoke’ as a sign of ‘fire’” [(Castelfranchi, 2009), p.324]. The examples given by Castelfranchi (Castelfranchi, 2009) states where there is smoke there is fire. This can be considered the same cause-effect rule as that described in many ant algorithms. The understanding of the smoke-fire relationship does not require the agent to recall the principles of combustion, only a simple rule association and evaluation of immediate needs at the time.

Tummolini & Castelfranchi suggest that just through a single action, multiple meanings can be inferred. They break up the concept of performing a single action into seven conceptual implications: the action implies “that (1) an agent (2) intends to do the action, and (3) in presence of the right opportunities (4) and with the right skills, (5) she modifies (or forbears from modifying) the environment (6) in order that (7) a certain result is realized” [(Tummolini & Castelfranchi, 2007), p.146]. From this single sentence they explain seven trace-based *basic* behavioural messages that can be exploited by an inherent meaning associated to such actions. In each of
the cases the primary action serves its provided purpose, but there is an implicit meaning also.

These seven, trace-based basic behavioural messages provide insight into implicit meanings that can be understood and exploited using stigmergy. However we consider that they apply more to specifics (namely within human society) rather than the desirable general theory of stigmergy requested by Tummolini & Castelfranchi. They also break the basic meanings into two separate classifications: descriptive and directive. Descriptive traces are further refined as either describing an enabling facet of the environment, or a disposition influencing the environment. Directive traces are then clarified as a social motivation to influence the receiving agent beyond merely communicating a meaning.

**Descriptive (Enabling):** If a person is wet while at the beach, observers can infer that swimming at this location is possible.

**Descriptive (Dispositional):** If a person leaves their wallet in front of a known kleptomaniac and another person who is a new acquaintance observes the theft (resulting in a theft), the new acquaintance is made aware of the risk in the local environment.

**Directive:** An ashtray on a table (while describing that smoking is allowed here) prescribes that smokers use the ashtray and not the floor when discarding cigarettes and their by-products.

We consider that Tummolini & Castelfranchi describing descriptive and directive message meanings are significantly more useful in defining a general theory of stigmergy but have identified various incongruences with their examples with what has previously been stated as qualifying as stigmergy. Just as for the details of
Table 2, we directly address this in our research and will summarise our contribution in the *A New Model* section.

Castelfranchi explores the implications of intent and observed behaviour on stigmergy in context to communication and coordination: what is the criterion when considering which trace signals are considered to fall within stigmergy but that were not identified in the original observations by Grassé’s termites? According to Castelfranchi stigmergy requires “long-term *traces*, physical *practical* outcomes, *useful* environmental modifications, not mere signals” [(Castelfranchi, 2009), p.325].

The important concept of stigmergy being described here is that it excludes simple broadcast mechanisms such as notes or signs with directional arrows on them posted on walls. While these are environmental mediated trace signals, they have an explicit communicative function and meaning. They have been placed on location specifically for the purpose of communicating and they do not serve any practical goal other than for communication.

Tummolini & Castelfranchi question the explicit / implicit relationship that the marker-based distinction of stigmergy has when excluding signs solely with explicit communicative function. The *signification* is the fundamental principle of stigmergy as per the *stigma*. This brings into question how pheromones with specific food foraging meaning fulfil the implicit communication function demanded by their definition of stigmergy. Tummolini & Castelfranchi resolve this question by defining the relationship between the explicit sign and associated implicit meaning generated through an aggregation function of similar actions. The stigmergic communication in marker-based based examples is not in the pheromone itself (having a specific and explicit meaning such as to forage food), but is the
concentration of pheromones indicating the currency and *reliability* of a particular pheromone trail.

Tummolini & Castelfranchi continue by highlighting that a single trace can mean different things to different recipients. Similarly, there are different tacit agreements in social pre-expectations which interactions are regulated through. What is being described at a fundamental level are the mechanism through social context and understanding of the signals through inter-attraction. Castelfranchi reiterates the original observation that stigmergy applies to apparent agent *coordination*, and not necessarily agent *cooperation*. This is illustrated by an example of conflict and war. Two opposing forces are certainly coordinating with each other’s actions, though clearly each force is not doing so with the intention of cooperating with each other. Stigmergy triggers behaviour as a product stimulated by effects in the environment produced by previous behaviour. As such stigmergy is unable to (or does not require to) differentiate between *signification* and true *communication*. Similarly, it is unable to differentiate between pro-social or antisocial behaviours. An excellent example in nature of this is where some myrmecophagous caterpillars "secrete a pheromone that makes the ants act as if the caterpillar is one of their own larvae" to have ants carry them to the nest so the caterpillar can eat the larvae (Pierce et al., 2002). This illustrates the predetermined and predictable responses although it is an example external to the *grand purpose* of the ants with the pheromone being exploited parasitically. An interesting question here is whether we consider this counterfeit pheromone still as being stigmergy, because for the caterpillar it certainly is providing a level of self-organisation.

If the signs must be the mediating trigger for actions, and we associate different forms of coordination with different varieties of stigmergy, then what are valid sign
formats and what is the content of signs? Huang et al (Huang, et al., 2008) suggest a methodology for identifying stigmergy with the first step being an analysis of the independent dynamics of signs (also described as elemental characteristics of the sign). The agent derives meaning specifically via the “environmental representations of signs” [(Huang, et al., 2008), p.535]. In a temporal environment a sign displays different persistence profiles before being atrophied. These characteristics illustrate how signs persist within the environment and the roles the environment plays in transforming and transmitting them. We adopt the term elemental characteristics to avoid re-using the word dynamics in the nomenclature that use. The elemental characteristics of signs are presented and are illustrated in Figure 3:

(a) An observation of a behaviour or state, which has an instantaneous occurrence with no following persistence,

(b) A binary state of a given sign where it is produced (observable) through to where it is removed.

(c) A diminishing strength signal comparative to the concept of a pheromone trail that decays over time.

Figure 3 – Independent dynamics of signs as presented by Huang el at

The first characteristic (a) describes immediate observation of behaviour or state but with no enduring persistence within the environment (viz.: environment modification). The second characteristic (b) illustrates an effective binary state for a given sign state, and matches the qualitative mechanism of stigmergy. The third
characteristic (c) describes a variable state such as pheromone trails provided. This third example matches the quantitative mechanism of stigmergy indicative of marker based pheromone decay gradients. The elemental characteristic shown in (c) is a tapering gradient similar to that as presented in the experiments by Klyubin (Klyubin, et al., 2004). This illustrates a single marker that decays at a given rate, but that could still represent a qualitative stigmergy mechanism that appears immediately as for (b) but that atrophies over time.

Huang et al suggests a methodology for identifying a certain stigmergy in a given system through a series of steps:

1) Characterizing the signs;
2) Specifying the embodiment of the signs;
3) Identifying the relationships between signs and agent;
4) Describing their realization;
5) Finding out the relationships between signs and environment;
6) Analysing the implementation of them;
7) Acquiring the model of the whole system. [(Huang, et al., 2008), p.535]

A New Model

"Hindsight is always a satisfying advantage for historical commentary" from What the Wright Brothers Did and Did Not Understand about Flight Mechanics: In Modern Terms (Culick, 2001)

This research project has addressed some contradictions within stigmergy research where signs stopped being stigmergy and a different phenomenon begins (Aiden Dipple, Kerry Raymond, & Michael Docherty, 2013a). An important contribution of the project has been to standardise much of the nomenclature within the field of stigmergy and to document the development of our model of stigmergy.
It is relevant to note that the model of stigmergy developed as one outcome of this project is documented in a peer-reviewed journal paper. It provides a significantly more detailed analysis of stigmergy, the mathematical modelling of it, the meaning and motivation and revisions to the previously literature definitions and nomenclature.

The examples of stigmergy varieties in Table 2 do not clearly delineate the difference between the two distinctions of stigmergy and the relevance of the mechanisms. The marker-based examples are subtle examples of that particular distinction, but are more focused towards the descriptions of the mechanisms rather than the concepts at play. As described by Theraulaz & Bonabeau, quantitative stigmergy is “based on an accumulation of ‘stimuli that do not differ qualitatively’ but that will reach a threshold and increase the probability of triggering a response” [(Theraulaz & Bonabeau, 1999), p. 104]. Parunak describes the marker-based distinction as “gradient following in a single pheromone field” [(Van Dyke Parunak, 2006), p. 538]. Both of these statements describe how the gradient is inherently restricted to a localised area whether as a single immediate location or a graduated field that reaches a threshold. Similarly, if we consider qualitative stigmergy previously described as a single stimulus capable of triggering behaviour then Parunak’s example for qualitative, marker-based stigmergy “decisions based on a combination of pheromones” illustrates that the qualitative distinction can form from an aggregate of contributions as equally as it can from a single contribution. A single contribution might combine with others, like letters to create words that become the triggering stimuli. The emphasis on an aggregate of contributions creating a discrete stimuli of the sematectonic distinction (opposed to the threshold of an accumulation of stimuli as per marker-based) should not be confused with the
accumulation of *pheromones* that are the defining concept to marker-based stigmergy.

Adding to confusion, the sematectonic examples in Table 2 do not provide instructive insight into what is actually being described, and only re-states the observed subjects that Theraulaz & Bonabeau describe in their research. Our understanding of sematectonic stigmergy is one where previous behaviour results in leaving traces on the environment, where those traces have a meaning separate to the purpose of performing the trace-causing actions. Consequently these traces then become the triggering stimuli.

The *quantitative sematectonic* example describes ant corpses clustering activity introduced by Theraulaz & Bonabeau provide a density threshold guiding the clustering outcome. The corpse clustering activity is to remove corpses from general living areas. The result of this is that there is an increased concentration of corpses in one location away from the living area of the colony. This concentration of corpses is a change in the environment and as it reaches an ever increasing threshold it will have a higher probability (positive feedback effect through ongoing self-organisation) of attracting future clustering.

The *qualitative sematectonic* example describes wasp nest building and how the current state of the nest construction activity provides the stimulus for the next stage of nest construction. The nest building activity is a purpose in itself, but specific structural phases provide identifiable states of completion. The nest-building example considers these identifiable nest structure states as the discrete sign, and given that each state is inherently a different stimulus (e.g.: open, partially-open, and closed cell configurations when building hexagons) then we introduce a broader concept into the model of varying contribution types to the sign.
Our identification of stigmergy presented in Table 2 can be illustrated with our examples of the different varieties of stigmergy:

- **Quantitative marker-based**: the intentional marker is a sign that becomes a signal if it is intended to mean something to others (e.g.: explicit food foraging pheromone providing instruction) and facilitates coordination by the implicit meaning of signal strength denoting the most current (or powerful) trail to follow as being stigmergic.

- **Qualitative marker-based**: the intentional marker is a sign left as a signal that means something to others in its single form (e.g.: coat left on the chair in the theatre (Tummolini & Castelfranchi, 2007)) that facilitates coordination and exploits the implicit meaning of *this chair is taken* as being stigmergic.

- **Quantitative sematectonic**: the explicit unintentional grass wears from footsteps that become a sign of a shortcut over time. It is never intended to be a signal to others, as there is no intention for following the trail to mean anything. However it still facilitates coordination via the unintentional implicit meaning created by the worn grassless trail (e.g.: where to follow to exploit the signal) as being stigmergic.

- **Qualitative sematectonic**: the wasp nest construction is clearly a sign of a nest being built. It is never intended to be a signal to others, as there is no intention for building the nest to mean anything. However particular construction format is a signal that means something to others (e.g.: an opportunity exists to exploit a physical affordability) that facilitates coordination.

We prefer to redefine the sematectonic stigmergy in the same quantitative and qualitative terms as for marker-based. These examples are intended to be generalised
as per the nature of our model. Therefore we redefine Table 2 by providing accessible and intuitive examples in Table 3 below.

Table 3 – Redefined Distinctions & Varieties of Stigmergy

<table>
<thead>
<tr>
<th></th>
<th>Marker-Based</th>
<th>Sematectonic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantitative</strong></td>
<td>An accumulation of markers denoting a consensus</td>
<td>A trace accumulated through activity denoting a trend</td>
</tr>
<tr>
<td><strong>Qualitative</strong></td>
<td>A markers left with the intention of requesting an action</td>
<td>A trace denoting the presence or existence of a particular opportunity</td>
</tr>
</tbody>
</table>

Tummolini & Castelfranchi (Tummolini & Castelfranchi, 2007) described descriptive and directive message meanings and we acknowledge they are significantly more useful in defining a general theory of stigmergy. We agree with the differentiation of a qualitative description that might provide information on some form of disposition. However we disagree with the example provided for descriptive-dispositional as it represents a form of Behavioural Implicit Communication (BIC) that Tummolini & Castelfranchi have already stated is not stigmergic. We agree with the differentiation of a qualitative description that might provide information on disposition. However we disagree with the example provided for descriptive-dispositional as it represents a form of Behavioural Implicit Communication (BIC) that Tummolini & Castelfranchi have already stated is not stigmergic. The astute reader will have noticed that the descriptive-dispositional example illustrates a sematectonic distinction of stigmergy (e.g.: the nuance on the wallet not having any communicative value but is instead a trace and its subsequent state change). We find inspiration from Marsh & Onof (Marsh & Onof, 2008) and their concepts of stigmergic epistemology and stigmergic cognition that describe an
epidemic flow of information across a neural-net like topology (viz.: ideas flow extra-cranially). In fact we believe that what is actually being described is perhaps one of the first noted examples extra-cranial and epistemic flow of knowledge. As such we introduce the term Behavioural Implicitly Communicated Epistemology (BICE). What we see is a transfer of knowledge (from observed behaviour) that describes the environment. By the directive of Tumminini & Castelfranchi (and the fact that the word disposition inherently describes behaviour mannerisms), we cannot include descriptive (dispositional) as a meaning conveyed by stigmergy based on that example.

To replace the example that we have just removed we consider the Google Page Rank example provided by Marsh & Onof (Marsh & Onof, 2008). The example is a quantitative, sematectonic variety of stigmergy (given the page-link spatiotemporal structure exists for the purpose of navigation and not as a cumulative indicator of trustworthiness) which also provides an excellent example for cognitive stigmergy. Furthermore it suggests that the quantitative sematectonic variety of stigmergy illustrates the degree-of-trust as suggested by Marsh & Onof.

We agree with each of the examples provided by Marsh & Onof though we need to strengthen their concluding remarks where they suggest “social epistemology is essentially stigmergic” [(Marsh & Onof, 2008), p.147]. We reiterate that this is only the case where the epistemology (and cognition) is represented by “modifications of the environment” [(Marsh & Onof, 2008), p.136]. In cases of directly observed behaviour such as the wallet-theft example we suggest a super-set of stigmergy is being described that falls under our definition of BICE. This also puts into question Lewis’s statement that “cognitive stigmergy does not produce physical structures” [(Lewis, 2013), p.9] and whether the topology and follow-the-
leader rules might also fall within BICE. Is the leader being followed themselves, or the traces (potential as knowledge or traceable phone records) that they leave are being followed? Lewis’s statement is more likely just an acknowledgement of the virtual nature of the examples usually defining cognitive stigmergy (e.g.: Wikipedia) rather than removing the need for a marker or trace.

We consider the descriptive-enabling meaning to be a parallel to the paper wasp nest building example of qualitative sematectonic stigmergy. This obviously leads us to consider what might be a meaning conveyed by quantitative sematectonic stigmergy. We suggest this as descriptive-trustworthy where the term trustworthy implies the authenticity of an enabling environment through the volume of agents contributing to the sign. We illustrate this with the example of a path being worn in grass by a suitable number of users. The observer is made aware of the enabling situation but in a manner that suggests a trustworthy solution by previous actions.

We now consider what the core meanings for marker-based stigmergy are when considering the different mechanisms. Marsh & Onof suggest an associated degree of authority provides further meaning but they identify that “popularity (the pheromone) is the mark of significance but of course does not guarantee quality or relevance” [(Marsh & Onof, 2008), p.143]. Certainly in context to cognitive stigmergy enabling technologies have “corroded tradition notions of intellectual authority” with experts potentially trolled against and anecdotal evidence promulgated [(Marsh & Onof, 2008), p.140]. Rather than chose the term authority we suggest consensus provides a more accurate description. We split directive into meanings of instructive or consensus where consensus provides the similar authority-through-volume of instruction as the quantitative mechanism should demand. If we consider our examples of implicit meaning as provided for each variety of stigmergy
in Table 3 then we suggest the functional messages possible are those illustrated in Table 4.

Table 4 – Core Stigmergy Meaning by Variety

<table>
<thead>
<tr>
<th>Stigmergy Varieties</th>
<th>Marker-Based</th>
<th>Sematectonic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quantitative</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quantitative</td>
<td>Quantitative</td>
</tr>
<tr>
<td>Directive</td>
<td>Directive</td>
<td>Descriptive</td>
</tr>
<tr>
<td>(consensus)</td>
<td>(trustworthy)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Qualitative</td>
<td></td>
</tr>
<tr>
<td>Directive</td>
<td>Directive</td>
<td>Descriptive</td>
</tr>
<tr>
<td>(instructive)</td>
<td>(enabling)</td>
<td></td>
</tr>
</tbody>
</table>

Based on our developing understanding of stimulus threshold, the elemental characteristics of signs (Huang, et al., 2008) appear deficient. This research suggests a fourth elemental characteristic (Aiden Dipple, et al., 2013a) illustrated here in Figure 4.

(d) An aggregation of content that reaches a triggering threshold, and then decays due to atrophic forces that diminish the content until the sign drops beneath the threshold (significant dimensions).

![Figure 4 – Elemental Characteristics of Signs](image)

Our abstract model of stigmergy describes both the core components of the system along with the attributes and dynamics which dictate the phenomenon’s
mechanics. There are three core components of stigmergy: agent, sign and environment. These components coexist to support a grand purpose. Each is comprised of attributes and dynamics that govern the positive and negative feedback processes of stigmergy. We illustrate the attributes and dynamics together in Figure 5 – The Stigmergy Cycle.

![Figure 5 – The Stigmergy Cycle](image)

**Summary and Implications**

Giving a version number to the Web is academic at best. Web N.0 best describes the original specification, the current technologies and collaborative behaviour and the future emergent intelligence which ultimately will be developed. Without this sophisticated embedded processing, existing searching and ranking algorithms will only ever provide a fractional value of the wealth contained within the Web. A more sophisticated architecture must be developed for these concepts to become integrated into websites and provide a scalable design. However, these enhancements ideally should fit within the original Web specification and protocols.
The research question for this project suggests that we can build collaborative Web 2.0 sites in a consistent and efficient way when exploiting the attributes and dynamics of stigmergy. We believe that stigmergy provides a powerful example of how to improve website coordination. Researchers in varying disciplines appreciate the power of stigmergy and have studied how to exploit it. Unfortunately as stigmergy becomes more widely researched we see its definition mutate as papers citing original work become referenced themselves. Each paper interprets earlier work in ways very specific to the research being conducted. We agree with the findings and conclusions described by the researchers we cite, however the reinterpretation we provide forms a clear and concise set of terms and definitions for our general theory.

Tummolini & Castelfranchi (Tummolini & Castelfranchi, 2007) comment on the underutilisation of trace signals when introducing stigmergy, stating existing work being “too heavily influence by initial case studies (sic) probably due to a lack of a general theory of stigmergy” [(Tummolini & Castelfranchi, 2007), p.142]. They attribute this to an overuse of the pheromone metaphor. Subsequent research has improved on the overall understanding of stigmergy, however the introduction of new terminology introduces unresolved contradictions between papers and could propagates confusion. The broad statements and conclusions in some of these papers leaves the reader believing that everything that can be seen or heard is stigmergic if an agent responds to it.

We agree 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. This research project provides a thorough epistemological discourse on stigmergy as a phenomenon and provides the model that we use as the foundation for
our research, answering the question of what mechanisms support virtual well-worn paths or pheromones (within the entomological, human and virtual environments).

These foundations provide the basis that the project contribution makes: the development of a software design pattern. This design pattern answers the final project sub-question of how we can support alternative needs and motivations to encourage participation from users who would otherwise not contribute actively to the collaborative process.
Chapter 3: Research Design

This chapter describes the research design adopted by this project. The first section of this chapter discusses the methodology, and the stages of the project executing the methodology. The first section will also associate the research question with project objectives and how the project is designed to address them. The second section details the participants in the study; the third section lists all the instruments when addressing the objectives, and justifies their use. The fourth section outlines the procedure used to execute the plan, along with the timeline for completion of each stage of the study. The fifth section discusses how the data was analysed. The last section acknowledges any ethical considerations applicable to the research.

Methodology and Research Design

This section outlines the research methodology and research plan which was utilised in this project.

Methodology

The research plan was composed of qualitative analytical activities and descriptive and empirical activities. The core activities for the research plan were:

1) Literature review and problem definition;

2) Analysis of stigmergy definitions, attributes and dynamics;

3) Building a model of stigmergy pertaining to Web environments;

4) Comparative case study of the model patterns against selected Web sites;

5) Analysis of the results from the case studies;
6) Develop a prescriptive design pattern for including stigmergy into websites;

7) Test the design pattern with an experimental prototype case study;

8) Analysis of the results of the experimental prototype case study.

Stages 2 through 5 were iterative where results from later stages were input into prior stages to refine the project artefacts and process. This was also the case for Stages 6 and 7.

**Stage 1 – Literature review**

Separate to the literature review provided in this thesis, the project involved an extensive content analysis of additional, existing literature to resolve many of the contradictions that the thesis Literature Review chapter identified. This thorough content analysis performed in Stage 1 highlighted the contradictions within the documented attributes and dynamics of stigmergy. The content analysis review covered multi-discipline areas such as network theory, chaos theory, bio-chemistry, human motivation and the psychology of participation. This provided raw data that was used for substantiating grounds while developing the model of stigmergy and the subsequent software design pattern.

**Stage 2 – Analysis of stigmergy attributes and dynamics**

A comparative analysis was undertaken on the data generated from Stage 1 and used to create a complete and consolidated model of stigmergy. Many of the attributes defined in peer reviewed papers on stigmergy strongly overlap, with clearly identified attributes described using synonyms. In other literature some attributes and their definitions are merged, generalised, or non-existent in early research. Similarly, researches into stigmergy algorithms (such as optimisation of pheromone evaluation) identify implementation-specific properties which create a
more sophisticated stigmergy model. These incongruences needed to be understood before creating the generalised model.

**Stage 3 – Conceptualise and build Web based model of stigmergy**

This stage designed a model to describe stigmergy within collaborative Web N.0 environments. Much of the existing work described in the reviewed literature pertains to purely empirical experiments with no consideration given to its applicability to the physical world. The model produced from this stage needed to incorporate a standardised definition of attributes and dynamics as described within the literature content analysis. It also needed to provide a design that could be readily used when developing web based applications that incorporate stigmergy as a design pattern.

In contrast to entomological stigmergy, human behaviour and cognitive stigmergy is more complex than early research suggests. Therefore the model designed within this stage of the project needed to accommodate multiple (and potentially incongruent) concepts to facilitate motivation and incentive among other cognitive complexities.

**Stage 4 – Data Collection: Comparative case study of selected Web sites**

A comparative case study approach was chosen for this stage due to the qualitative nature of the data and collection. The pattern highlighted by the model’s attributes and dynamics was verified against the selection of case study websites. The selected websites were chosen based on their popularity and volume of users. This ensured that we were assessing stigmergic behaviour at swarm levels and ensured that we witnessed a scalable design.

**Stage 5 – Interpretation: Analysing case studies results**
The data collected from the case studies was analysed and interpreted against the model. Strengths and weaknesses of the model were identified, and subsequent iterations of model refinement were undertaken. The development of the design pattern followed the verification of model efficacy in identifying the stigmergic attributes and dynamics.

**Stage 6 – Develop a prescriptive design pattern for including stigmergy into websites**

A prescriptive design pattern was developed to explain what mechanisms best support knowledge building collaboration, as identified in the previous case studies. This design pattern prescribes the integration of stigmergy with existing web technologies and structures them in a way to support the attributes and dynamics of stigmergy. The design integrates seamlessly with non-stigmergic behaviour enabling existing websites to fully exploit the functionality.

**Stage 7 – Test the design pattern with an experimental prototype case study**

A prototype website was created for the purpose of verifying that each of the attributes and dynamics defined by the design pattern operate as expected. A suitable set of test cases (and test plan) were used to generate data to validate efficacy of the developed design pattern.

**Stage 8 – Analysis of the results of the experimental prototype case study**

The data generated from the experimental prototype case study was used in a qualitative comparative analysis against the data collected in the previous case studies. The success in creating a design pattern that exploits stigmergy was assessed based on the completeness of features that are included in the implemented prototype.
Research Design

Research Question

The research question addressed by this thesis is as follows:

Q1: How do you build collaborative Web 2.0 sites in a consistent and efficient way when the attributes and dynamics of stigmergy are fully exploited?

Research Objectives

Our research question has been broken into the following objectives:

O1: To study selected Web sites which successfully implement Web 2.0 as a collaborative environment identifying how specific technologies and mechanisms support stigmergy.

O2: To create a model of stigmergy in Web 2.0 to clearly identify the attributes and dynamics as outlined in papers covered in the Literature Review.

O3: To analyse and interpret the data to evaluate the model and validate the model efficacy.

O4: To design a software design pattern to prescribe system architecture for collaborative generation of domain knowledge.

The inter-relationships and process for addressing these sub-problems will be described in the sub-section Instruments.

Participants

All data collection and experimental prototyping of the design pattern has been done in a passive context requiring no participants to the project. All case study data collection has been performed through content analysis of peer reviewed papers or through assessment of the personal website accounts of the Ph.D. candidate.
Instruments

The research project uses a mixed-methodology and as a result a number of instruments will be adopted. These are listed below and correlated to each phase of the research project.

**Qualitative content analysis of literature:** A detailed content analysis of literature was performed to identify the attributes and dynamics of stigmergy. When endeavouring to build a model of any phenomenon it is important to understand the full depth of the subject. Unknown variables existed in our understanding of stigmergy, where the initial review of literature did not present a clear definition of the phenomenon. The initial literature review performed in stage 1 of the project was expanded upon in stage 2 and provided the foundation of the model that is developed in stage 3. The results of the initial analysis stage led to the development of a rich conceptual model describing the attributes and dynamics of stigmergy. This model provided a guide to identifying and assessing stigmergy in entomology, human-based and engineered environments.

**Comparative case study of existing websites:** A comparative case study was performed in stage 4 of the project assessing a selection of popular websites that were believed to display stigmergic traits during the model development. Stage 5 of the project iterates back to stages 3 and 4 providing refinements to address deficiencies in the model or understanding of the phenomenon.

To verify the efficacy of the model of stigmergy in websites the model was used to assess multiple real-world sites with potentially varying levels of alignment. This identified limitations in the model and illustrated where real-world examples embodied stigmergic properties not properly addressed. These sites were evaluated to understand how stigmergy facilitates and benefits the process of recording active
contributions and passive interaction to provide an emergent form of self-organisation and domain knowledge. The developed model was used to identify where the selection of websites illustrated pattern matches (or deviations). These common solution patterns and proto-patterns identified features which are not currently utilised but might be desirable.

**Experimental prototype case study:** Stage 6 resulted in the main contribution of the project in the form of a software design pattern. This design pattern encapsulates the attributes and dynamics of stigmergy when applied to websites. The software design pattern was implemented as an experimental prototype that was tested in stage 7 with the results analysed in stage 8. The experimental prototype took the form of an independent set of components that can be included into new or existing websites at design time.

The testing was based on using a case study where the test plan was structured to verify the design pattern efficacy. It achieved this by assessing the presence and functionality of attributes and dynamics of stigmergy that were observed in the comparative case studies and that represented features documented in the model from stage 3. The extent of the test cases were designed to cover all concepts defined in the model of stigmergy. This validated that the functionality of the design pattern operates as prescribed, and also verified that the concepts outlined in the model have been included.

The successful results of the test plan verified our hypothesis that stigmergic mechanisms can be introduced into websites providing a specific configuration of tools to facilitate the indirect collaboration and self-organisation among users. The execution of the Test Plan was designed to be performed in its entirety within a stipulated timeframe. This ensured consistency with the results, where a number of
the tests have a temporal interdependency. When replicating the experiment and test-cases, observing the time limitations will ensure that the results of the test plan are reproducible.

**Analysis**

This project adopted multiple research methods to deliver the final conclusion. Therefore the reliability of results will be determined from rigorous analysis of data from each stage and its scrutiny against the developed model and design pattern.

The analysis of literature was used to establish a log of all attributes and dynamics of stigmergy. Each paper reviewed provided qualitative and theoretical inductive reasoning into stigmergy as well as empirical experiments on various algorithm performances.

The collection of logged attributes and dynamics were placed in a spreadsheet using a score-card type format. This spreadsheet lists each of the subject websites in the comparative case study as columns, with the attributes and dynamics as rows. This was used to record the results of the case study observations. Case study subjects were selected where there is substantial enough site traffic to correctly support stigmergic behaviour at a swarm level. Similarly, subject websites chosen had to fit within a function of creating collaborative content showing indirect communication, and knowledge based content to compare and contrast the model efficacy.

The development of the model was based on synthesizing the collection of attributes and dynamics in a manner that removes duplication (viz.: papers adopting terms that are synonyms of other introduced terms). The model differentiated concepts into suitable groupings that correctly identified previous empirical
experiments. This deductive approach on qualitative data analysis introduces the potential for results that would not be reproducible by other researchers due to their subjective nature. The model of stigmergy provides a discourse on the subject and is published as a peer-reviewed paper. It is expected that if core researchers in the field agree with the model then the analysis of paper and the conclusions can be taken as a priori for the development of the design pattern.

The design pattern developed from the model and from the empirical observations from the comparative case study was used to create our own experimental prototype. This prototype supported our research question posteriori. This was verified through a case study of the prototype implementation and a test plan to enable a qualitative verification that the attributes and dynamics of the model have been successfully supported.

**Ethics and Limitations**

This research project developed a model of stigmergy within Web N.0 collaborative environments, and an associated design pattern for prescribing how to introduce stigmergy into website environments. The primary data collection was through the review of existing literature, comparative case study analysis of existing web sites and a case study of an experimental prototype. To access the functionality of these web sites, a user account (or several) was created to analyse the full functionality and features of each site.

No personal information or personal content was recorded and collected test data is only used to discriminate between site functionality and features; not on the specific content or any personal information of the person/s that developed the page/s. The PhD supervisor sought advice from the ethics committee as to whether
this project required an ethical statement or approval. The advice given was that no approval was required.

The tasks and activities do not involve animal testing outside what is stated above. Similarly, there is no component of the project pertaining to scientific modification of organisms or genetics. Therefore there is no required clearance regarding ethical issues.

The results of all research are documented and reflect all observations appropriately without discrepancies. This is done whether the results reflect successfully or poorly on the project, the created model and subsequent design pattern, along with the testing used to achieve the results and any justification of all claims.
Chapter 4: Standing on the Shoulders of Ants:

Stigmergy in Web N.0


Preamble

The initial literature review and resulting problem definition from stage 1 of the project was presented at conference (Aiden Dipple, 2011). This paper provided insight into stigmergy that guided our further reading. The initial review identified a significant corpus of Ant System (AS) algorithms enabling a detailed content analysis of empirical experiments used when developing the model of stigmergy. The initial review demonstrated that there was enough detailed study on the subject and that a general theory consolidating the mathematical modelling and emerging nomenclature was absent and needed.
Standing on the Shoulders of Ants: Stigmergy in the Web

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ABSTRACT

Stigmergy is a biological term used when discussing insect or swarm behaviour, and describes a model supporting environmental communication separately from artefacts or agents. This phenomenon is demonstrated in the behavior of ants and their food gathering process when following pheromone trails, or similarly termites and their termite mound building process. What is interesting with this mechanism is that highly organized societies are achieved without an apparent management structure.

Stigmergic behavior is implicit in the Web where the volume of users provides a self-organizing and self-contextualization of content in sites which facilitate collaboration. However, the majority of content is generated by a minority of the Web participants. A significant contribution from this research would be to create a model of Web stigmergy, identifying virtual pheromones and their importance in the collaborative process.

This paper explores how exploiting stigmergy has the potential of providing a valuable mechanism for identifying and analyzing online user behavior recording actionable knowledge otherwise lost in the existing web interaction dynamics. Ultimately this might assist our building better collaborative Web sites.

Categories and Subject Descriptors
H.3.4 [Social Networking]: Model construction and analysis – virtual pheromones, environment embedded communication, implicit and explicit communication.

General Terms
Design, Human Factors, Theory

Keywords
Web Collaboration, Virtual Pheromones, Stigmergy

1. INTRODUCTION

The World Wide Web is transitioning from its historically static content to a new, dynamic experience emerging through collaborative websites and social networking. However what are missing are good design principles for these new dynamic Web sites. We seek to understand how to build a more effective collaboration framework.

In biology, stigmergy describes a mechanism of indirect communication where the actions of individuals affect the behavior of others (and their own). This communication mechanism describes the apparent cooperative behavior of insects’ nest building and food gathering activities.

For example, the food gathering activities of ants are structured around the use of pheromone trails, where the ants are triggered to perform food gathering tasks. To find the most recent and relevant food source the ants follow particular paths based on the strength of any given trail. The interesting communication here is not only the explicit signal in the pheromone (to gather food) but the implicit signal through the level of decay: information within the trails themselves show which trail will currently lead to a food source opposed to trails leading to a depleted food source.

Combining bio-inspired designs and algorithms based on stigmergy with social network analysis might facilitate the creation of a more sophisticated web application. We can draw a parallel between stigmergy and the Web, where the Web is the environment, the users are agents, and the artifacts are the Web site content.

With the rise of Web 2.0 this same mechanism of environment-embedded, indirect communication can be seen throughout numerous Web sites, such as Wikipedia, eBay and online stock trading sites. The behavior of users benefits the community as a whole with the system fulfilling a greater role than the individual agendas of its users. Web sites such as Wikipedia show an excellent example of where indirect communication exists, as contributors are primarily interacting through knowledge artefacts and not the agents involved in artefact creation / modification. Within eBay buyers attract sellers, and sellers attract buyers based on the trail of previous transactions. This same example can be seen in stock market share trading sites, where stock availability and trade volume illustrate additional information separate to the message that specific shares have been transacted at a given price and time.

Similar user generated, trace data can be seen in web logs created during user browsing behavior. The Web provides a multitude of trace data which effectively constitutes trace signs and signals. If we can better understand the application of stigmergy in the Web we might build better future sites fully exploiting it.

When considering stigmergy in the Web we need to understand how human behaviour is different to that of insects as we cannot be guaranteed of the same clean dynamics which apply to insects. The basic food gathering need must be replaced by numerous human, higher-level needs (e.g.: pride, status, personal gain) but where we see the dynamic of individual agents contributing for the benefit of the whole.
This paper will explore the potential of defining a stigmergy-based model which will assist identifying these mechanisms and triggers. Furthermore it will explore the potential of web sites fitting within the model of stigmergy when appreciating that the response triggered might not be one that is pre-expected. This novel approach has the potential of identifying and analyzing online user behavior recording actionable knowledge.

2. RESEARCH PROBLEM

The purpose of this study is to investigate the problem of how we can implement collaborative environments in the Web to exploit all attributes and dynamics of stigmergy. It is hypothesised that stigmergic behaviour is inherent in collaborative Web environments and that a framework to support all attributes and dynamics of stigmergy will facilitate higher quality collaborative outcomes.

This leads to the question: Does the Web enable us to build better collaborative sites for when the attributes and dynamics of stigmergy are fully exploited? Are there facets of stigmergy missing in the Web environment that could be used in capturing implicit communication otherwise lost?

There is significant research into stigmergy, virtual pheromones and swarm intelligence on academic levels, but limited research into its influence and relevance as a design pattern. If we can build a model for identifying stigmergetic attributes and dynamics in Web environments then we might speculate that we can create a methodology for describing how best to build sites benefiting from this phenomenon.

Stigmergy facilitates a grand purpose (or emergent behaviour) through the dynamics (or mechanisms) applied to its inherent attributes (or components) of the environment, agents, and artefacts. Further clarification and the categorisation of virtual pheromones and their role as triggers are needed. The dynamics of agents are usually described as pheromone evaluation, task prioritisation, and clustering behaviour through perception and action. However pheromone dynamics specifically pertaining to the stigmergic process describe implicit communication through decay rates and decay levels as key facets of the phenomenon.

We must understand that human-human stigmergy is expected to be more sophisticated and complex than the simplistic version identified in the insect world. Humans are capable of understanding goals and interpreting / adapting each other’s behaviour and therefore there are additional dynamics and mechanisms than simple pheromone triggers influencing behaviour. Similarly, humans have a more complex social structure and associated social needs.

These needs and their impact on the clinical or entomological representation of stigmergy need to be better analysed by forming a model of stigmergy specifically supporting collaboration in human and Web-based environments. This model needs to distinguish between mechanisms facilitating indirect communication versus direct communication in tandem to understanding explicit and implicit communication dynamics.

Defining these concepts of implicit and indirect communication mechanisms within the Web and how they can assist social network analysis through the creation, use and dissipation of virtual pheromones will be a significant contribution to knowledge.

3. STATE OF THE ART

Over the past 50 years enhancements and innovation in technology have accelerated at such a rate that modern society no longer considers what future concepts are impossible, but what might be plausible. This is evident within the World Wide Web where we see collaboration on a massive scale, and where Web sites focus on harnessing the power of the collective intelligence of users. Ideally we can design a pervasive system which facilitates collaboration, capturing tacit knowledge through the web interactions of all system users, and not just that from users who actively contribute to the collaborative effort.

When the Web was conceived by Sir Tim Berners Lee, he imagined it as an information melting-pot enabling individuals to publish content to, and interact with, an immediate and vast audience[1]. Through the past 20 years the underlying technologies have expanded and matured, creating a much richer experience compared to the original static page in a browser. Current HTML trends point towards the internet as a social networking tool utilising these new technologies and have subsequently seen the term Web 2.0 emerge. There is much debate within this area regarding definitions of what constitutes Web 1.0 and Web 2.0, also known as the Social Web [2]. The term Web 3.0 has also emerged which describes a future Semantic Web [3] evolution and Google searches show some people using Web 4.0, Web 5.0 and onward [4]. These latter version labels are somewhat farcical, but certainly the concept of Web 3.0 has clearly defined functional attributes providing differentiation. To clarify that all perceived versions of the Web are encapsulated within this research, the term Web N.0 will be used as a panacea definition.

What is important is that the “Architecture of Participation” is not specifically focused on the participation facet, but more the architecture, and how it adds value to the participation process more than merely enabling multiple people to edit some content [2]. What is alluded to is a more complex platform that can provide information on the collaborative process as much as the end content. Novel and innovative architectural design patterns can be found in bio-inspired arenas, specifically within swarm behavioural models such as stigmergy.

The word stigmergy “is formed from the Greek words stigma ‘sign’ and ergon ‘action’” [5] and is used within biology to describe the way non-rational, autonomous agents (such as termites or ants) collaborate to achieve complex tasks thereby displaying some type of emergent swarm-intelligence [6]. These agents use pheromones as signs embedded within the environment to trigger behaviour or actions in other agents in the swarm.

The many papers within the area of stigmergy [7-9] attribute the introduction of the term by Grasse to describe this behaviour of termites along with their collaborative efforts when building nests. A simple definition of stigmergy is: a process by which agents communicate indirectly between one and other through their environment. In a more sophisticated perspective, the behaviour of agents is influenced or determined by the behaviour of agents which have interacted with the spatial and temporal environment previously [10].

In essence stigmergy describes an autonomous system enabling self-organisation, self-optimisation and self-contextualisation in a light-weight and scalable mechanism [9]. This is interpreted as the associated mechanisms and emergent behaviour enabling the
selection of the most optimal solution without the prerequisite of knowing anything about the environment.

Interest in bio-inspired algorithms has been increasing over recent years, including researching evidence of stigmergic behaviour in numerous existing human systems. Using stigmergy as a metaphor is not new when describing dynamics within human environments. Van Dyke Parunak [5] provides a thorough review of both computer-based and non-computer-based examples of human-human stigmergy. Indeed many of the examples cover websites within the Web 2.0 namespace and analyses the mechanisms of stigmergy such as environment’s topology, state and dynamics, and agents’ sensor, actuator and dynamics.

Ricci et al [7] suggests that a more sophisticated model (Cognitive Stigmergy) should be considered when analysing humans or rational agents. People are proactive in their dynamics and will observe the behaviour of other agents directly. While behaviour observation within the Web environment is restricted to being represented by signs in the environment Ricci et al also suggests the environment is more than a pheromone container and therefore capable of supporting embedded processing. While these mechanisms might very well assist stigmergy, we must not confuse Behavioural Implicit Communication (BIC) with stigmergy as not all behaviour is communication, and not all BIC is stigmergy [11].

As stated by Tumolini et al [11], the generally accepted definitions of stigmergy are too broad and are “unable to differentiate between the communication and the signification processes.” This point clearly illustrates the difference between the explicit meanings of the pheromone versus the implicit communication of tacit knowledge hidden within the signal.

Much of the appeal of stigmergic behaviour lies within its ability to enable seemingly unintelligent agents to create sophisticated solutions while cooperating with no centralised coordination. This would imply even the most elementary implementations can yield startling results. However, further research considers what benefit there can be to making the pheromone evaluation more sophisticated. This ranges from facilitating team collaboration of agents to quickly prioritise problems [12], and cognitive stigmergy where agents can have a more sophisticated level of judgement within the environment, or where artefacts have an ability to perform processing themselves [7]. One immediate concern is whether more sophisticated processing would destroy the naturally emergent behaviour of stigmergy. Would a simplified and minimalist model provide a more pure, unbiased solution [13].

4. RESEARCH METHODOLOGY
This research project focuses on identifying the attributes and dynamics of stigmergic behaviour and how it facilitates and benefits the process of recording active contributions and passive interaction of users when participating in the grand purpose.

A literature review will provide a thorough analysis of stigmergy to fully understand all facets of the phenomenon and how to best incorporate the properties of stigmergy into a Web environment. The results of the initial analysis stage will lead to the development of a rich conceptual model describing the attributes and dynamics of stigmergy, and how Web N.0 mechanisms support them. This development of the model will be documented tracing its components back to the work performed by previous researchers. This will provide the chain of evidence to validate the model and enable its correctness to be reviewed.

Due to the qualitative nature of the data collection, a comparative case study approach will be used to provide legitimacy to the repeatability of the research findings. The patterns in the developed model will allow a comparative case study to be performed against the selection of existing web sites with varying levels of model alignment. Analysis of the case studies should interpret common solution patterns as well as proto-patterns that represent solutions which are not currently utilised but might be desirable. This is expected to identify any limitations of the model or where real-world examples embody new stigmergic properties not already addressed by the model.

This model will incorporate instruments to be used when classifying sites which are the subjects of the case studies. These instruments will be applied against each of the sites to classify the level of stigmergic attributes and dynamics they employ. The instruments which will be included in the model are:
- A series of questions to identify stigmergy
- A list of specific attributes and dynamics stigmergy employs
- A hierarchy of stigmergy levels identifying the completeness and extent a site might display stigmergic properties

As part of the construct validity, the model will be assessed against entomological systems, human systems, and Web N.0 systems. This will aid in evaluating the correctness of the model.

Targeting multiple sites for case studies will ensure a sufficient cross section sites are studied which are indicative of cognitive social aspects which might impact on the simplistic entomological concept of stigmergy when applied to complex and cognitive human systems. Targeting multiple sites over a broad spectrum of different social aspects of the Web will evaluate the literal repeatability of tests and further enforce the generalisation of the developed model. Cases must be selected where there is sufficient site traffic to correctly support stigmergic behaviour at a swarm level. Similarly, cases must have content with a significant rate of flux and transition to provide complex enough scenarios.

5. PROGRESS TO DATE
Preliminary stages of the research plan have been completed including the literature review and initial case study site selection. The initial literature review includes the analysis of the attributes and dynamics of stigmergy as a phenomenon and from the perspective of various algorithm designs. The data collected will be used in the creation of the proposed model. The model will be an elegant and concise distillation from these attributes and dynamics, refined to focus on those facets specifically pertaining to the Web N.0 environment. These two items of work will evolve over the duration of the research project.

We have compiled an exhaustive list of over 70 attributes and dynamics for the major components of stigmergy during the literature review. This list is unwieldy and presents the significant challenge of how it can be distilled into an elegant model. If we consider stigmergy purely as the communication mechanism, then a clear subset of attributes and dynamics are relevant. But when considering the resulting impact on the whole system, then we risk losing important granularity for this complex phenomenon.

Reviewing this list raises the questions; where are the boundaries of the Web systems? For example, does eBay end at the
conclusion of the online transaction, or does it end at the final delivery of goods? When considering the boundaries which fully impact the social phenomenon we must factor in attributes wider than the virtual world. Online auctions interface with shipping and payment services; stock trading interacts with national fiscal systems and the financial health of corporations.

The first iteration of model development has begun. An initial set of questions has been designed to identify what is and is not stigmergy. These questions can be applied when analysing insect systems, human systems, and Web environments. The sequence of questions is:

1) Does the agent leave a physical and measureable difference in the environment (i.e.: a sign)?
2) Is the sign left with the intent of contributing to the grand purpose (i.e.: a signal)?
3) Does the receiving agent understand the signal and react in a way expected to contribute to the grand purpose?
4) Does creating the signal unintentionally introduce an emergent communication which is vital to the grand purpose (i.e.: an implicit communication)?

NOTE: For the purpose of Web environments a signal is interpreted as users creating / modifying Web content, such as bids on eBay sale items, edits to Wikipedia articles, or Web logs of user browsing activity.

A second iteration of refinement of the questions has been triggered as a result from exploring the nuances and hidden meaning within these questions. During the second iteration of model development various complexities of the stigmergy phenomenon have been appreciated with challenging philosophical discussions resulting. As might be expected many of these discussions revolve around the transition of stigmergy from the entomological environment to the human environment and through to the Web environment. Specifically these interconnected issues to be resolved are:

a) Does intention play a role in the signalling process?
b) Does providing counterfeit signals mean the predicated response is not stigmergic?
c) If senders and receivers have different agendas, then whose grand purpose is it anyway?
d) What is the impact on stigmergy when systems have both direct and indirect communication?

Issue a) revolves around the concept of intent, or more specifically whether ants intentionally or involuntarily leave pheromones. The issue arose when considering question 2 and its application to entomology. If stigmergy was a model for describing insect behavior we have a problem proving a signal is a sign left with intent. The question arises: Do ants leave pheromones with intent and is there a choice as to how an ant responds to the behavioral trigger? While this might seem philosophical it is fundamental to the premise of stigmergy being a mechanism where sending agents can trigger a predetermined response in the receiving agent in a predictable way. In fact, if we understand that stigmergy is based on completely involuntary reactions which do not map across to the human or Web environments, we find a clear divergence of stigmergy as a phenomenon to stigmergy as a metaphor.

Given that stigmergy is understood as the combination of an explicit signal and associated implicit meaning within the signal transmission, what impact does the intention (or lack thereof) of the signal transmission mean? Through vigorous review of the literature it is strongly asserted that the sign must be emitted on purpose for it to be a signal [14], but whether this excludes unintentional signs from stigmergy is contentious. We don’t consciously have intent to leave a path worn in the grass when we take shortcuts away from paved areas, but the interpretation of “this is a shortcut” is undeniable. But if it is not the intention of the path-wearing-pedestrians to communicate that message, then the sign does not become a signal.

This presents itself as a problem as there certainly appears to be value in this sign denoting a short cut! In fact, in Web parallel examples we see unintentional signs from people bidding in eBay which show significant value for other users identifying objects of interest. The compelling problem is that the unintentional trails seem to be equally important when considering what information we can leverage off. We must consider whether we are misconstruing ‘stigma’ from the Greek word ‘sign’ into ‘signal’.

Issue b) concerns how counterfeit, intentional signs might impact stigmergy. Ants use a range of different pheromones in intercommunication [15]. However some myrmecophagous caterpillars “secrete a pheromone that makes the ants act as if the caterpillar is one of their own larvae” to have ants carry them to the nest so the caterpillar can eat the larvae [16].

This certainly supports the concept of predetermined and predictable responses resulting from pheromone evaluation. We see that a counterfeit signal is possible, but how does this translate to human and Web environments? This issue stems from considering whether the signal-associated, implicit meaning could intentionally be counterfeited. Even if this communication were to be counterfeit would that mean it were not stigmergic when considering the fundamental definition of the phenomenon as an environment mediated, indirect communication triggering a predictable response?

If we move our attention to the Web environment we consider how our observations compare to eBay trails as signals. Shill bidding in eBay refers to sellers who create an alias account so they can bid against their own products for the purpose of driving the sale price higher. This is done because the seller hopes to use the trail of bids to trigger a higher bid from legitimate buyers. What we see is the introduction of a counterfeit signal for subversive purposes. Conversely, we observe counter-tactics used by buyers trying to cover their bidding (signals to the seller) realizing that they are unintentionally leaving trails which others can respond. Sites are now available which provide last-second, automatic bidding against eBay items enabling the bidder to make the lowest possible bid at the last moments of an auction (known as Sniping software). This effectively enables buyers to leave no trails for others to follow until an auction has ended and it is too late to counter bid.

Given the previous examples of agents creating counterfeit signals as a result of conflicting agendas we are faced with Issue c): If trails are being left as signals, and signals are provoking expected responses, then which of the buyer’s or seller’s grand purpose is being contributed to? In fact the grand purpose is separate to
individual agents operating within the respective environment. The *grand purpose* is relative to the entire swarm of agents. In the case of eBay the *grand purpose* is to have a site facilitating commerce and the disposal or acquisition of real world property. The fact that some people will cheat the system does not change the fact that the system is designed to help this *grand purpose* flourish.

Even in the presence of cheating, large numbers of legitimate contributors in the web environment support the system. Large numbers of people can contribute in a very constructive way, despite potentially conflicting agendas during the collaborative process. For example, in Wikipedia multiple perspectives of objective information on a given subject distill into something cogent despite conflicting opinions. This occurs as the initial statement of knowledge is iteratively refined by people who review previous contributions.

This same process applies in eBay where accurate values of sale items are determined through prices as indicated from previous transactions. The anonymous bidding process can trigger various behavior in all parties and distinct patterns identifying shill bidding, snipe bidding and rage bidding can be observed. This presents itself as an immediate challenge if using stigmergy as a behavioral model, as we have to consider the different social complexities of human interaction versus insect interaction.

Issue d) presents itself through the complexity introduced when replacing simple processing agents such as insects with humans (viz.: there multi-mode communication methods). eBay operates through indirect communication where sale items represent the artefact, but the additional use of E-mail between the agents represents a direct communication channel, as opposed to indirect. There still is the initial environment embedded sign (in the form of items for sale) as the catalyst, but one significant objective of the research is to understand where mechanisms such as site email, bidding history and bidder feedback do or do not describe stigmergic communication and ultimately impact the result.

What we begin to see is that stigmergy within the Web environment appears to be based on levels to which a given site might exploit the mechanisms of stigmergy.

What is common in these examples is that the environment embedded communication instigated by the sending agent triggers a response in the receiving agent. The receiver agent changes the environment as a result of the actions of previous agent in the environment. The phenomenon of stigmergy is dependent on the resulting user reaction is one that fits a predictable response.

6. CONCLUSION

Stigmergy can be seen throughout entomological, human and Web environments. It appears to be implicit in many emerging Web sites yet is not fully understood and therefore cannot be fully exploited. As highlighted in Section 5 there are still many questions which are unanswered and we don’t yet have a clear definition of stigmergy. It is apparent that there are parallels in the observed environments where signs and signals left by agents trigger responses in agents which interpret them.

If this research proves that specific signals will trigger a predictable response and that this applies for entomological through to Web environments, then we see a very powerful tool for building collaborative web sites. We hypothesise that not only does the phenomenon of stigmergy provide a valuable tool for analysing online user behaviour, but also provide a design pattern for facilitating explicit and implicit communication for the benefit of the collaborative process.

7. REFERENCES


Chapter 5: Stigmergy in Web 2.0: a Model for Site Dynamics


Preamble

The comparative case study of websites provide the data assessment during the evolutionary development (stages 2, 3, 4 and 5) of the attributes and dynamics included within the model of stigmergy. The results of the comparative case study and an early version of the model were presented at the ACM Web Science international conference in a paper titled *Stigmergy in Web 2.0: a Model for Site Dynamics* (Aiden Dipple, Raymond, & Docherty, 2012).
Stigmergy in Web 2.0: a Model for Site Dynamics

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ABSTRACT
Building Web 2.0 sites does not necessarily ensure the success of the site. We aim to better understand what improves the success of a site by drawing insight from biologically inspired design patterns. Web 2.0 sites provide a mechanism for human interaction enabling powerful intercommunication between massive volumes of users. Early Web 2.0 site providers that were previously dominant are being succeeded by newer sites providing innovative social interaction mechanisms. Understanding what site traits contribute to this success drives research into Web sites mechanics using models to describe the associated social networking behaviour. Some of these models attempt to show how the volume of users provides a self-organising and self-contextualisation of content. One model describing coordinated environments is called stigmergy, a term originally describing coordinated insect behavior.

This paper explores how exploiting stigmergy can provide a valuable mechanism for identifying and analysing online user behavior specifically when considering that user freedom of choice is restricted by the provided web site functionality. This will aid our building better collaborative Web sites improving the collaborative processes.

Categories and Subject Descriptors
H.3.4 [Social Networking]: Model construction and analysis – virtual pheromones, environment embedded communication, implicit and explicit communication.

General Terms
Design; Human Factors

Keywords
Guides; conference publication

1. INTRODUCTION
The growth of Web 2.0 continues to deliver improved Web sites providing functionality ranging from social networking on Facebook, to business and commerce on Amazon. These Web sites provide user interfaces which adapt by creating additional feedback to users based on other site users’ experiences and contributions. This is done in conjunction with the core information defining the purpose of the site.

The numbers of people using these sites are sufficient such that behavioral trends become apparent and begin to display behavior similar to that studied within Multi-Agent System (MAS) research. Recording and displaying user activity is able to be incorporated as integral site functionality. We seek to understand how to build a more effective collaboration framework exploiting these apparent trends. We hypothesise that this can be done by developing a model that provides new insight on group dynamics in an environment which supports indirect communication much the way Web 2.0 does. Specifically, we consider a phenomenon from entomology: stigmergy. Stigmergy is an indirect communication mechanism describing the coordinated behavior of insects during their nest building and food gathering activities.

For example, the food gathering activities of ants are structured around pheromone trails where the pheromone acts as a sign placed in the environment. This sign is actually a signal to the ants which triggers more food gathering activity. Over time, previous pheromone trails will have dissipated, and therefore the stronger and most recent trails will also be the more relevant for the ants when finding the food source. Therefore stigmergy consists of both the explicit signal in the pheromone (to gather food) and the implicit signal through the level of decay: information within the trails themselves show which trail will currently lead to a food source opposed to trails leading to a depleted food source.

Web 2.0 sites have many similarities to the environment described in stigmergy where the users are a parallel to the ants, and the Web site content represents the pheromones (signs). Examples of this environment-embedded, indirect communication can be seen throughout numerous Web sites, such as eBay, Facebook and Wikipedia. The behavior of users benefits the community as a whole. Web sites such as eBay show an excellent example of where indirect communication exists, as buyers attract sellers, and sellers attract buyers based on listed sale items. This creates a rich trading environment where product and price discovery provide a market for boutique / specialist items while also creating an awareness of fair market-value for items.

Perhaps more significantly, the behavior of users influences other users within the community with the system providing a utility equally as important to the primary functionality of the Web site. An example of this is the seller reputation metric in eBay where credibility of an unknown user is established with the trail of feedback a user receives from previous transactions. This trail is effectively the same relevancy / reputation mechanism as seen in ant pheromone trails. We see a growing number of Web sites providing summarised views of their users’ activity displaying further parallels of virtual pheromones. Further to the eBay,
similar examples can be seen in user Facebook contributions receiving “Like” acknowledgements shown as a count.

A model of stigmergy provides a valuable way to think about Web site user behavior and as such interest in the field of Human-to-Human stigmergy has been steadily growing over the past decade. Web site providers are designing virtual pheromone functionality into their sites hoping to capture and influence user behavior. There is increasing research within the computer sciences field focusing on creating algorithms which model and optimise various ant algorithms. These approaches are based on observing the behavior and response of virtual ants as they perform sorting or searching tasks. These models become inadequate when considering Web sites given that users perform the role of the agent, and that it is not an algorithm defining their behavior but the Web site functionality.

Human cognition and freedom of choice result in humans being smarter and more unpredictable than insects. Therefore, using stigmergy to model human social interaction might be inadequate due to the inherent cognitive process involved with people. However, there is a distinct lack of research into understanding how Web site functionality removes a significant amount of user freedom of choice. This effectively removes much of this social complexity enabling the provocation of a smaller set of useful responses in the context of the Web site. An example of this is the distinct lack of buyer-to-buyer, direct communication in eBay. Buyers are aware of each other through the disclosure of competing bids, but with the lack of explicit and direct communication the buyer’s bid-reaction is triggered through this indirect signal.

Human cognitive processes and higher-level needs (e.g.: pride, status, personal gain) are inextricably linked to Web 2.0 site use. If web site functionality and the information available to users are controlled by the web site design then we would expect to see stigmergy being a significantly more useful model for analysing user behaviour as their options become more restricted. This paper will explore the potential of defining a stigmergy-based model which will assist identifying these mechanisms and triggers. Furthermore it will explore the potential of Web sites fitting within the model of stigmergy when aligning sites users’ priorities and requirements to site providers’ agenda. This novel approach has the potential of analysing online user behavior and how that can be incorporated with Web site functionality to improve leverage of social interaction in collaborative processes.

2. RESEARCH PROBLEM

Whether a given site can achieve massive user uptake or become defunct through failing to achieve a critical user base is not immediately understood. This raises the question of what makes a particular site successful, or attracts users to one Web site over a different site competing in the same market segment.

Examples exist within the Web where defining features of popular Web sites get mimicked by other sites hoping to reproduce the same success. An example of this can be seen in the Facebook “Like” option. This feature has now become a meme and the concept and benefit of crowd sourcing opinion is being copied by rival sites: Google is now including a “+1” button feature. This equates to a signal to other users inciting similar responses. The cumulative “Like” count provides the equivalent to a virtual pheromone triggering stigmergic behaviour in other users. Our research has begun with a literature review of current work in the area of stigmergy. This review provided the basis for a content analysis leading to the development of a model of stigmergy and will be the basis for the creation of a methodology and framework for engineering stigmergy enhanced Web sites.

There is significant research into stigmergy [1-3], virtual pheromones [4, 5] and collaboration [6] on academic levels, but limited research into its influence and relevance as a user interface design pattern. If we can build a model for identifying stigmergic attributes and dynamics in Web environments then we can apply that model when analysing Web 2.0 sites to understand the role it plays.

Stigmergy facilitates a grand purpose (or emergent behaviour) through the dynamics applied to its inherent attributes. The three components of the phenomenon are: the agents, the signs and the environment. Further clarification and the categorisation of virtual pheromones and their role as triggers is needed. The dynamics of agents are usually described as pheromone evaluation, task prioritisation, and subsequent activity through perception and action. However, pheromone dynamics specifically pertaining to the stigmergic process also describe implicit communication through decay rates and decay levels as key facets of the phenomenon.

We understand that human social structure is significantly more sophisticated than those of insects. This raises caution that stigmergy is possibly too simplistic to describe the full behaviour of human social interaction. Understanding the goals of our peers and having the cognitive ability to interpret and adapt to them introduces complexity through freedom of choice, thereby being the basis for scepticism to the significance of stigmergy and simple pheromone triggers influencing human behaviour. However, when users interact within specific Web sites, they are only provided a limited set of interface options, usually explicit to the sites’ intended purpose. This predefined purpose and associated functionality removes much user freedom of choice, effectively reducing humans’ instruction-set to something more akin to insects.

Stigmergic mechanisms are being introduced into numerous Web sites but at present this appears to be based on simplistic implementations. For example, we see the “Like” acknowledgment in Facebook as a sort of pheromone build-up. Observing that other sites are mimicking this mechanism shows that Web designers are appreciating the basic dynamics of this phenomenon. We identify that stigmergy is much more complex than user cumulated “Likes” and believe further development of stigmergy will provide more sophisticated solutions. When comparing noticeboard Web sites to the anonymous-bidder auctions of eBay, the approach of reducing disclosed information seems to promote focused user participation. However, there are additional facets of stigmergy including the signal produced from pheromone trails facilitating coordination among agents. This phenomenon needs to be better analysed by forming a model of stigmergy supporting coordination in human and Web-based environments and understanding how it is impacted by cooperative-competitive agent agendas. Identifying the stigmergic benefit of a given user interface design will differentiate using indirect versus direct communication, and help understand explicit and implicit communication dynamics.

Defining how the concepts of implicit and indirect communication mechanisms within the Web assists with user interface design (through the creation, use and dissipation of virtual pheromones) will be a significant contribution to knowledge.
3. LITERATURE REVIEW
The word stigmergy “is formed from the Greek words stigma ‘sign’ and ergon ‘action’” [1] and is used within biology to describe the way non-rational, autonomous agents (such as termites or ants) coordinate to achieve complex tasks thereby displaying some type of emergent swarm-intelligence [7]. These agents use pheromones as signs embedded within the environment to trigger behaviour or actions in other agents.

During the course of the literature review we see that many papers within the area of stigmergy [2, 8-10] attribute the introduction of the term by Grasse. The term was used to describe his observations of termite behaviour during their coordinated nest building efforts. Grasse observed that the termites communicated indirectly via the signs they were placing in their environment. The signs acted as a catalytic signal triggering similar nest building responses in other termites within the nest. The behaviour of the termites is influenced by the behaviour of agents which have interacted with the spatial and temporal environment previously [4].

Stigmergy describes an autonomous system enabling self-organisation, self-optimisation and self-contextualisation in a light-weight and scalable mechanism [2]. To achieve this, the phenomenon utilises a mechanism that enables agents to inherently select the most optimal solution without the prerequisite of knowing anything about the environment. When the aggregate total number of agents is significantly large enough, this mechanism facilitates the autopoiesis (self-organising) of content within the system.

Using stigmergy as a metaphor is not new when describing dynamics within human environments [1]. Further exploration on the mechanisms of stigmergy clearly identifying the three components such as the Agent, the Sign and the Environment [11]. Chuanjun, Huang and Jin document the relationship between the components as the denotation of the sign (content), its representation within the environment (embodiment) and the connotation it has to the agent (meaning) [11]. Viewing this combined research provides insight to the nature of the phenomenon.

Susi & Ziemke [6] compare human specific theoretical frameworks of Activity Theory, Situated Action and Distributed Cognition against stigmergy and identifies that there are significant similarities between the artefact-mediated models. Each theory appears to have strong similarities with stigmergy, each outline conflicts when comparing human cognition to insect instinct. Detailed explanation of these theories is outside of this papers scope. It is suffice to say that Activity Theory strongly describes the grand purpose concept, Situated Action describes how actions become triggers, and Distributed Cognition focuses on how signs become signals.

The primary difference highlighted between stigmergy and the three human theories is the “human consciousness and the role it plays” [6] and that “cooperative behaviour among insects is performed without any conscious goals” (that we know of) [6]. Given the simplicity of stigmergy as a model and what we understand to be the significant impact of cognition on it, the usefulness of stigmergy as anything but a metaphor is an unavoidable question.

Ricci et al [8] suggests that a more sophisticated model (Cognitive Stigmergy) should be considered when analysing humans or rational agents. People are proactive in their dynamics and will observe the behaviour of other agents directly. Tummolini cautions that it is important not to confuse Behavioural Implicit Communication (BIC) with stigmergy as not all behaviour is communication, and not all BIC is stigmergy [12]. However, our arguments priory is that observed behaviour within the Web environment is inherently restricted to that represented by signs in the environment transformed into signals embodying meaning.

Insects react on instinct and the lack of conscious goals removes the complexity and time-cost of making decisions when choosing from options that present themselves through cognitive freedom of choice [6]. The lack of the cognitive process means that insects follow rigid patterns which confine the amount of flexibility and creativity [13] which is distinctly similar to the options presented to users of Web 2.0 sites. While insects’ high degree of harmonisation is achieved by the structuring of the environment and this simple, instinctive response to triggers, Web 2.0 sites would provide a similar rigidity enforcing “some type of external structure or ‘scaffolding’ to mould and orchestrate behavior” [13] to contribute to human collective success. Clark notes that actively restructuring the environment might “better support and extend our natural problem-solving abilities.” [13]

Stigmergy is appealing because the phenomenon provides a solution to the paradox where seemingly unintelligent agents create sophisticated solutions while coordinating with no centralised management. The appeal lies in the fact that the coordination is based on the situated awareness and response of the agents and not with the agent’s ability to rationalise the solution. Ricci et al [8] acknowledge that while stigmergy in the purest sense lacks the complexity required within human social analysis there is no simple transition if introducing cognitive stigmergy where agents can have a more sophisticated level of judgement within the environment, or where artefacts have an ability to perform processing themselves [8]. Klubin et al [5] believe that an immediate concern is whether complex processing would destroy the naturally emergent behaviour of stigmergy.

There are two distinct types of intentional signal (marker based) within the stigmergic mechanism: quantitative and qualitative [10, 14]. The quantitative mechanism is marker-based signals embodied by the accumulation of stimuli that increases the probability of a response determined by some significant threshold. The qualitative mechanism is also marker-based and corresponds to a specific modification to the environment which acts as a prescriptive trigger. We see both of these mechanisms employed in Web 2.0 sites as will be explored within this paper. Furthermore an unintentional form of stigmergy labelled seamentectonic describes a response triggered through the work (or actions) of a preceding agent [3]. We will examine these mechanisms of stigmergy and how they manifest themselves in Web 2.0 environments.

4. A MODEL OF STIGMERGY
This research project focuses on identifying the attributes and dynamics of stigmergic behaviour and how stigmergy facilitates and benefits the process of recording active contributions and passive interaction of users participating in the grand purpose.

The initial stages of our research included a literature review to analyse existing research into stigmergy. Much of the research found pertained to computer science research in ant colonisation algorithms and their optimisation. This provided insight into the
mechanics of stigmergy where each paper described the parameters considered relevant for the particular algorithm targeted by the research. It is no surprise that our content analysis shows there is a strong intersection of these attributes and dynamics, especially pertaining to the environment coordinate system, agent identification and artefact interaction.

Further to research papers based on algorithm analysis, numerous theoretical papers were analysed considering stigmergy as a phenomenon. Analysing these papers in conjunction with the computer science papers has enabled us to devise a set of questions which can be applied when assessing an environment and whether it embodies the mechanics of stigmergy. These questions were discussed in depth within a previous paper [15] but are reiterated here for convenience.

The sequence of questions is:

1) Does the agent leave a physical and measureable difference in the environment (i.e.: a sign)?
2) Is the sign left with the intent of contributing to the grand purpose (i.e.: a signal)?
3) Does the receiving agent understand the signal and react in a way expected to contribute to the grand purpose?
4) Does creating the signal unintentionally introduce an emergent communication which is vital to the grand purpose (i.e.: an implicit communication)?

The list of attributes and dynamics identified during the content analysis has been distilled down to the major common themes in the fundamental mechanics of stigmergy. The data collected has been used in the creation of the model presented in Figure 1 – The Stigmergy Cycle.

The core of Figure 1 shows the model foundation is based on the three components of the stigmergic mechanism: The agent, the sign and the environment. Bound to each of these are the conceptual phases that give significance to the system. The sign consists of the content; the environment provides the embodiment of that content sensed by the agent, and ultimately it is the agent giving meaning to the sign. The process of content becoming an embodiment and having meaning occurs through the series of dynamics (the outer band) affecting the attributes (the inner band).

4.1 The Agent
The agent gives meaning to the system and the agent owns the dynamics which define the boundaries between it and the other two components (viz: the agent senses from the environment, and produces the sign). The agents within the system all participate in the grand purpose of the site. The grand purpose is one that all participants agree to adhere to even where individual agent agendas might differ. For example, eBay has agents buying and selling items, even though buyers want to pay the lowest price but where sellers try to achieve the highest price. Rather than seeing this as a conflict of interest it is actually a function of the site that promotes its use. As previously highlighted in Activity Theory [6] the actions of individuals are often buried beneath the complexity of the system as a whole. The activities of individuals that appear to be in conflict are not necessarily contrary to the grand purpose.

As illustrated within the inner band in Figure 1, the agents have 4 attributes: progress, completion point, goal and strategy. The agent also has 3 dynamics as illustrated in the outer band in Figure 1: sense, evaluate, and actuate. The agents will have a goal, and to achieve that goal they will have a strategy. To understand whether they have achieved the goal they must also have an understanding of progress and an associated completion point to evaluate progress against. These attributes are internalised states of the agent and correspondingly the evaluate dynamic is also an internalised process. Conversely, the agent requires an externalised sense dynamic through which to engage the environment, and the actuate dynamic to engage the sign. The signal is sensed (input) from the external environment to ascertain the current level of progress. This is followed by an internalised evaluation of the progress against the completion point to achieve the goal of the agent. Based on this goal a strategy will determine the externalised action (output) the agent makes manifesting as the contribution made to the sign.

4.2 The Sign
Figure 1 shows the sign is made up of 4 attributes: contribution, position, significant dimensions and decay rate. The sign represents a conceptual and significant accumulation of agents’ contributions. This is a physical manifestation such as a wall of mud balls contributed by a termite when building a nest or the erosive effect on grass resulting from a person’s footsteps in the case of the creation of a path denoting a short-cut. The sign is the content in stigmergy, and the meaning that it has to other agents sharing the grand purpose that means this sign becomes a signal the agent will ultimately sense from the environment. The sign has an initial position where it is left by the agent; however it is possible for that position to change over time through influence via agents or the environment. Significant dimensions will be determined by its persistence within the environment as a function of its decay rate (susceptibility to environment forces). This can be seen in Figure 1, the sign only has 1 dynamic in the outer band,
being persist. Apart from the process of agents contributing to the sign, and the environment decaying the sign, it is static in its persistence providing no dynamics other than existing and the inherent traits to resist decay from the erosive forces.

4.3 The Environment
The final sector within the core of Figure 1 represents the environment 4 attributes: erosion, topography, difficulty and signal diffusion. The environment has 2 dynamics as illustrated in the outer band in Figure 1: atrophy and entropy. Both dynamics combine to complete the cycle feeding back to the agents' sense dynamic. It is the environment that provides the catalyst transforming the static content of the sign and its meaning into an emergent implicit signal with additional meaning to the agent.

The environment has an erosive level (erosion) which is interdependent with the sign's decay rate. The decay rate not only prescribes susceptibility but also resistance to erosion during atrophy. The dynamic atrophy interplays between the sign and the environment working to break the sign down. As the agent exists in the environment the agent's ability to sense the sign subsequently depends on the environmental attributes of the topography, and the difficulty level of traversing that topography. Topography describes the coordinate system of the environment and can be the x, y, z Euclidean geometry. Similarly it might describe a coordinate system based on graph theory as in the Web and hyperlink based addressing. Fundamentally topography describes how an agent traverses within the environment as well as where signs are situated.

Difficulty describes any environmental resistance which influences the capability to sense or navigate through the topography. In the natural physical world this could equate to a cliff or a barrier of some kind. In the Web it could equate to a functional barrier of access privileges, etc. Difficulty describes a resistance to other agents' ability to navigate the environment or the dispersal of a sign undergoing atrophy and entropy within the environment.

The final attribute is signal diffusion. This is the broadcast mechanism of the original signs and the emergent and implicit embodiment of the signs' transformation to the user. For example, food-foraging pheromones have been placed in the environment as a sign. This explicit sign to gather food will signal other ants to gather food and constitutes the original contribution. However it is the environment transforming the signs which provides the additional meaning denoting that a particular pheromone trail is current. The transformation of the original signs will occur in an irreversible way diminishing the signs until they drop below a level of interest (significant dimension).

What should be noted is that there are two signals: explicit and implicit. The food foraging pheromone sign is an essential signal in itself to influence other ants. But the emergent signal, the implicit relevance and currency of the signal strength is what completes the cycle with the agent sensing and evaluating progress against a completion point resulting in the appropriate strategy to achieve the goal.

5. DERIVING THE MODEL
In this section we will outline the case study observations and how they pertain to the components, the attributes and dynamics of stigmergy as modeled in Section 4. The model was developed through iterative content analysis of research papers on stigmergy. During this process a number of Web sites were used as comparative case studies to highlight any weaknesses. The case studies were based on a number of popular, international Web 2.0 sites chosen because of their existing volume of user traffic and broad demographic of users. This paper will focus on three international sites: eBay [16], Facebook [17] and Wikipedia [18].

During the analysis of the web sites it has become apparent that there are examples of quantitative and qualitative stigmergy signals observed in these sites. At one end of the spectrum we observe user interface elements which provide functionality mimicking sign buildup to be represented as a signal. For example, within Facebook the “Like” functionality is an explicit, quantitative signification of a user’s acknowledgement of a given article. The representation is an aggregation of users’ activity denoting the popularity of the specific article and clearly is an embodiment of marker-based signals. At the other end of the spectrum we observe a qualitative signal intended to trigger a more sophisticated response. An example of this can be seen in Wikipedia where user contributions are fragments of a given knowledge-based, topical entry. Each contribution or edit represents a part of the sign: however each contribution is almost completely unique in nature assisting in the combined representation and understanding of the given topic.

Wikipedia presented some confusion while refining the model when considering what constitutes the signs and what constitutes the emergent and implicit signals. Wikipedia is undoubtedly successful as a collaborative site in the process of gathering a highly valuable and diverse set of knowledge. It is not surprising that it proves to be a valuable case study subject and we will explore the reasons why in this section.

5.1 The Agent
The agent in the Web 2.0 sites is invariably the user of the site. Users have ability to sense from the site and the goal of which they are trying to achieve through using the site. The differences between each site are the concepts of progress and completion point.

eBay is a site that provides an auction bidding system where users can buy and sell goods. eBay users have quite a clearly defined completion point, and reasonably defined goal. For example, the purchase or sale of an item is clearly the goal and a successful sale or winning bid is the completion point. It should be noted that for unsuccessful sales or bidders this might require multiple iterations of the process. Progress is understood through the mechanisms in the site that shows the number of competing bidders, the rate they are placing bids, and the differing amount each subsequent bid is incremented by. Each of these help the user evaluate how popular or desirable a given item is, how likely they are at being successful in achieving their goal and what strategy to employ to achieve it. For example, if a particular item on eBay is scarce but is also achieving a high volume of bids at ever increasing increments, then a user can determine whether the value of a likely winning bid will be outside what they consider is fair value. Clearly within eBay strategy is based on a diacratic of buyers minimising expenditure and sellers maximising profit.

Facebook is a social networking site where users are able to share messages and multi-media in a forum restricted to selected friend groups. The attributes of stigmergy are not as obvious primarily because the goal of the users is not as clearly defined as with eBay due to the social nature of the transactions. The user might
have the goal of communicating with a large group of friends, or alternatively the user might represent a company or music group interested in broadcasting current offerings as a marketing tool. In each case, there is no clear completion point although the progress can still be seen in the number of "Likes" or comments associated with a specific entry. Strategy in Facebook is a difficult concept as the goal of individuals varies. For users of the site seeking to maintain contact with friends, the goal might not be to maximise exposure but instead simply maintain a steady (albeit intermittent) flow of contact with friends. For some users of Facebook the goal is to have the maximum number of "friends". For users seeking to self-promote through the site achieving a high volume of attention to contributions will be seen as positive progress. This goal does not alter the fact that contributions to the signs will be made specific to the agents' goal. In each case the strategy will be that the contribution is placed into the environment with the intent to trigger a reaction from other Facebook friends.

Wikipedia is an online encyclopedia where users are able to define and refine the content on particular topic pages. It is similar to Facebook where there is a more flexible format enabling more cognitive contributions. The stigmergic mechanism in eBay is based on unintentional contributions from agent activity which identifies the implicit behavior. However, Wikipedia records intentional contributions which aggregate into a topic page, where the correctness or completeness of the article (including recent modifications) will trigger a response from other agents. What is of particular interest here is that the grand purpose of the site is to have a thorough documentation of the specific pages' topic. An agent might sense that the article is not correct or complete pertaining their understanding (or belief) of the topic. Agents will have a completion point relative to their individual understanding and will also have a goal on what the page should contain to represent their understanding. The agent's strategy will be an explicitly cognitive process on how they can modify the page to achieve this.

One particularly notable point when analysing Wikipedia is that conflicting knowledge and beliefs regarding a specific topic appear to strengthen the content through the pursuit of achieving topics with a neutral point of view. Inflammatory remarks and unconstructive contributions are generally rectified by the mass of contributors using the Neutral Point Of View (NPOV) tags resulting in a more comprehensive documenting of perspectives. In fact, conflicting views will splinter off into specialised pages where a parent article will outline the conflicting viewpoints. This facilitates each user's strategy of getting their knowledge documented while providing their contribution to the grand purpose.

5.2 The Sign
The target Web 2.0 site in each case study performs a different primary purpose and has a different format of content. We consider the signs are the contributions provided by the users. What is interesting when considering the signs is if they are intentional or not, and how they relate to the grand purpose.

eBay displays the sign as the intentional bidding on items, selling items, subsequent payment and feedback creating unintentional trails over time. Both the sale item and the associated bids constitute the agent's contributions. The contribution of the sale item matches the qualitative type signal intending to trigger a response, where the bids align closer to the sematectonic type of stigmergy. The nuance with the sematectonic mechanism is that while an individual must intentionally bid to win, it is not their intention (or in their best interest) to signal to other bidders their activity. Therefore the bids are a parallel to footsteps wearing a path in the grass leaving unintentional trails that others can read. The position of these contributions is against the agents' eBay account identity for payments and reputation assessment. Similarly, the bids by buyers are positioned against the actual item for sale's entry (linked to the seller agents' accounts). The concept of significant dimensions can be seen in site functionality such as reserved price (as set by the seller), minimum bid, size of specific bids, or the number of similar items for sale by other agents when searches are performed. The decay rate of signs is a difficult concept in the digital world. In contrast to the natural world's continual state of flux and transition the Web is composed of explicit transactions stored in their original format. When considering the ability to see individual signs in eBay we observe that the decay rate is based on temporal expiration boundaries.

When a specific auction has completed, then after a pre-determined amount of time the details of the auction are no longer available on the site. The environment directly influences the signs by changing the contributions. In the digital world the sign is part of the web site functionality and therefore only a conceptual division exists between the sign and the environment. Agents in Facebook leave signs in the form of personal information, free-text messages, photos (or other media), and “Liking” the contributions of other users. Here we see a mix of both quantitative and qualitative signaling. The signs are positioned against a personal account, against the account of friends (a bi-directional, mutually agreed contact list) or that of public groups. The concept of significant dimensions is a subjective value based on a personal assessment of the signs, the contributions and how they are perceived against personal goals.

The decay rate of the sign is directly proportional to the activity within an agent's account. The more friends and groups a user has linked to, then the more activity will be presented to the user via other users' contributions. Contributions are displayed as a function of chronological and activity-prioritised listing on their account page showing recent activity. As new contributions are made the previous ones are pushed into a lower position until they seem to disappear; however older contributions are relisted at the top as new additional contributions are added. This observed re-prioritisation effectively decreases the decay rate modifying the atrophy dynamic between the sign and the environment. This draws attention to the differences of the discrete stored digital web site in contrast to the natural physical world.

The sign in the Wikipedia case is represented by user contributions, and a defined set of qualitative tags and templates designed to trigger the creation and refinement of articles. As den Besten et al show [19], site users can employ the NPOV tag denoting that a particular type of revision (a neutralising of article perspective) is suggested. These tags act as the initial qualitative trigger contribution, and where the content modification activity keeps the contribution momentum going. The position of the contribution correlates to the specific topic page (and location there within), where the topic can be split over multiple pages. The significant dimensions are subjective and the completeness of a given topic will be viewed differently by each agent within the environment through an individuals’ understanding or viewpoint of that topic. The significance of a single contribution can span from entire paragraphs through to corrections of spelling and punctuation. Clearly what we see in the case of Wikipedia is that the significant dimensions are a highly cognitive process resulting
in intentional contributions. The decay rate of the sign will be impacted by the knowledge level and beliefs of other agents also contributing to the topic during article refinement and the goal of impartiality. In the case of Wikipedia external factors also come in to play where actual changes in the physical world (e.g.: research breakthroughs into topics such as String Theory) impact on the validity and correctness of the contributions.

5.3 The Environment
The environment represents the target sites which our case studies are based on. They represent the functional infrastructure that the agents make their contributions through. Similarly they are responsible for containing and transforming the signs into the signals that the agents are then able to sense thereby completing our first iteration of the Stigmergy Cycle. It should be noted that site dynamics of the case study sites are understood purely through observation, and the case studies are not based on direct knowledge or access of the site algorithms and business rules.

eBay as an environment exerts its erosive (erosion) forces which atrophy the sign by not allowing agents to search for sales which have completed. This effectively erodes the sign from the environment to agents looking for similar items. Functionally, this serves the purpose of letting the agents of the site not be influenced by historic sales and the price that similar items have sold for, thereby ensuring that a current real-value for items is realised based on current supply and demand. This is a parallel to entomological stigmergy where previous pheromone trails no longer exist to influence agents current activity. The topography and difficulty of the environment are designed to provide as little barrier as possible within the site for current listing discovery. It is for the benefit of the grand purpose for the sellers and the buyers to have simple access to find desirable items to bid on. However, the environment does transform agent contributions into an emergent (quantitative marker-based and sematectonic) signal. This is manifested as summarised user experiences provided by the frequency of activity, how recent that activity is and the cumulative feedback denoting the credibility of given agents as buyers or sellers. It should be noted that these environmental created signals being dispersed might be unintentional from the agents perspective. The environment is also responsible for automatically creating additional sematectonic signals in the form of suggested sale items. While these items are not the immediate target for the buying agents, they are generally determined to be of interest to an agent based on the environment presenting previous agent behavior.

Facebook provides a more complex set of possible agent interactions, but a more simplistic application of the attributes and dynamics of stigmergy. The decay rate within Facebook appears to be chronological erosion of contributions. This causes atrophy of the sign as a result of contributions by the agent. The entropy within the environment is a function of a given agent’s friend network, where the volume of contributions from widely varying sources can result in infrequent contributors’ activity being lost in the content noise of others’ contributions. eBay endeavors to provide a highly accessible topography and low difficulty with regard to sensing and navigation. Facebook is quite the opposite. The topography is designed with strong barriers of entry to individual agent contributions. A bi-directional, mutual agreement must be accepted to be classified as friends thereby enabling access to each other’s contributions. Irrespective of this introduced difficulty in sensing and navigating to users who are not friends, there are environment generated signals which offer suggestions of potential friends which appear to follow the sematectonic signal type. As with eBay, Facebook provides the original contributions for agents to sense, but also transforms them into a quantitative signal which the agents see as an implicit communication.

Wikipedia environment differs in that sematectonic trails are created when articles are revised and modified. The atrophy dynamic from the environment is not readily apparent. The site does not benefit from deteriorating the signal and in actual fact the ability of revisions to be rolled back directly depends on maintaining this trail. Despite this, the trail of revisions is again a strong parallel to real-world stigmergy such as a path being worn in the grass. As with eBay and Facebook, the topography is based on a graph with the links between documents and topics providing navigation. The intention of the site is to create an open environment of highly accessible knowledge and therefore mandates that navigation difficulty is kept to a minimum. The Wikipedia site design is aimed to make it easy to observe subversive activity by incorporating a tool which shows recently changed pages. It is very difficult to make modifications that are not able to be scrutinised by peer review. The signal diffusion in Wikipedia edits is not based on a marker-based summarisation or transformation such as with the eBay reputation or Facebook “Like” counts. Instead there is an annotation of edits which give insight into the life-cycle of a given topic article. Within this trace it is possible to see facets of the topic that might not be apparent when reading the actual article. The emergent signals are in the form of the frequency of edits, and the frequency of rollbacks of edits indicating potential controversy or conflicting opinions on the topic. Within the last year Wikipedia has introduced a crowd-sourcing interface feature which is a quantitative mechanism [20] designed to denote the quality of a given article page. This approach is intended to deliberately introduce a marker-based signal where the environment embodiment of an article’s quality and reputability is strengthened as site users explicitly verify the article content.

6. APPLYING THE MODEL
The model of stigmergy has been developed and refined over a number of iterations of comparative case studies. Therefore it is expected that we would see the model conforming to our definition of stigmergy and how we perceive it in Web 2.0 sites. To draw out any weaknesses in the model this section documents applying the model to the Mendeley web site. This web site was not observed or known of prior to the model development. Mendeley is a site that provides a repository of research articles for users, and facilitates group collaboration within common research areas.

6.1 The Agent
As a collaborative web site, the goal of users appears to be based on creating a searchable repository of quality research papers, for both themselves and the groups which they are part of. As a tool for academics it can also serve as a consolidated, self-managed list of personal publications. It shares strong similarities to eBay in that the functionality provided is quite restrictive in what can be added. For example, eBay allows the listing of sanctioned items (viz: items that are legally able to be sold in the users’ home country) where Mendeley allows listing of publications. Conversely, it is also similar to Facebook where there is no explicit completion point. We observe the same ambiguity over what constitutes the current level of progress.
Current progress as sensed from the site is represented through a buildup of quantitative marker based and sematectonic signs, such as the number of readers of given papers and number of shared user associations. Despite the completion point and goal varying between users, the strategy does seem to be driven by a quantitative threshold on whether the user evaluates that a greater level of contribution is required. This in turn will trigger the action where the user will actuate a contribution much in the same way as for Facebook.

6.2 The Sign
Contributions in Mendeley are predominantly made up of submissions of currently unlisted papers, or linking to existing papers to have them listed within the users’ library. Similarly, lesser obvious contributions are the identification of user inter-associations or group membership. This is comparable to what we see within Facebook, and furthermore membership to groups can be configured in such a way that it can range from private through to public. Agents leave their contribution to the sign at a position which is defined by their own user account and the groups which they belong to. Unlike Facebook however, the contribution of a publication listing is discoverable by all agents in the environment irrespective of their group membership or user association to the original contributor.

Significant dimensions of the sign are similar to Facebook where a subjective value is determined by individual assessment of the contributions and the individual goal of the user. For example, early adopters of the site who create and own a group might strive to attract new members to that group. Students wishing to minimise research effort might consider a grand purpose to their research. Within these environments, the user associations. Despite the number of readers to be more attractive and therefore are sensitive to smaller significant dimensions.

Decay rate within Mendeley appears to be based on a chronological track of activity for users and groups similar to the activity seen in Wikipedia modification history. It differs from Facebook in that there is no sematectonic mechanism reprioritising contributions within the list. Mendeley functionality will atrophy the trail of contributions and eventually they will disappear. Previous contributions will only be able to be sensed through the marker-based signal types that the Mendeley environment provides. E.g., the chronological listing of which users are linking to specific articles will be excluded from the pages which display current activity. Eventually, only the summarised total number of users linked to the article will be displayed.

6.3 The Environment
The Mendeley site is a hybrid of eBay, Facebook and Wikipedia. Erosion is temporal where the chronological based listing of contributions drives the atrophy dynamic against the sign. There is no resistance slowing this decay as has been seen in Facebook. As with eBay and Wikipedia, this is not significantly impacting on the stigmgeric process as the environment created quantitative signal is the emergent, implicit signal.

The topography of the Mendeley environment is similar to Facebook given that it provides search features designed to maximise discoverability of people, groups and listed papers. Corollary the environment difficulty provides restrictive group visibility and content access, where only public groups are discoverable and only members of private groups are able to contribute to that position. As with Facebook, there are a number of privacy levels ranging from restricting contributions through to the complete invisibility of groups.

The environmental instigated signal diffusion that we see in Mendeley is solely manifested as sematectonic signals facilitating an agent’s ability to sense valuable contributions. These signals can be seen in the form of environment-generated trails against each paper’s listing identifying the total number of users who have linked to that specific paper. Similar to eBay and Facebook, the site provides additional representations of these signals. For example, the environment provides auto-generated alternative paper suggestions created based on the contributions that users have made or searched for.

7. DISCUSSION
When applying our model against our case study web sites we see a clear alignment of the components, the attributes and the dynamics of stigmergy. The model is generic enough to facilitate complexities such as the mechanisms of stigmergy (viz: marker-based and sematectonic) irrespective as to whether the agents are operating in a cooperative environment or a cooperative/competitive environment. When considering the usefulness of quantitative signals we see successful examples of implicit, emergent signals in both eBay and Facebook. These intentional, quantitative signals provide a popularity indicator of the user reputation or content. We also see unintentional, sematectonic trails which provide a trustworthy indicator where agent actions might otherwise not be disclosed due to individual agenda within the collaborative environment. Clear example qualitative signals are seen within Wikipedia supporting a more open architecture which might prove more valuable when attempting to trigger a cognitive based contribution. Wikipedia user-created artefacts are a sophisticated amalgamation of knowledge contributions and yet we still see a self-organising and self-contextualising of content supported by the environment.

What we do observe is an ambiguity in the concept of progress and completion point where the site does not define a clearly bounded objective. When evaluating well defined tasks such as in eBay we have a clear correlation to these concepts. However the tasks identified in Facebook and Wikipedia are based on self-actualisation and social activities which are intrinsic to life and are ongoing. In fact what we are seeing are two tiers of progress and completion point within the system. If we consider eBay, it is not that dissimilar to anti food foraging and the grand purpose of the colony not being hungry. There might be a single transaction which will make a contribution to the process, just as there can be a bid towards a successful eBay transaction that will satisfy a consumerist desire (or need) to acquire a product. There still remains the requirement of starting the process again when food stocks deplete to a threshold or the recurrence of a new consumerist desire to obtain more products.

This is similar to the Facebook and Wikipedia process where the social and self-actualising needs are ongoing, but yet they are satisfied by separate social interactions. For example, in Facebook the contributions towards a single sign will be made by the users. This continues until the size reaches a threshold considered by each of the contributors to equal their completion point when achieving the goal of sharing information with friends on a given topic. However, the completion point of using the site in general will be ongoing in itself as long as the site provides a valid social network.
A second notable ambiguity when applying the model to Web 2.0 sites is the subtle differences between the attributes of difficulty and decay rate. When analysing Facebook we observe that there is a clear inability to search for old contributions. This lack of search functionality is part of a web site’s design. If difficulty is defined as a set of barriers to sense or navigate the topography, then clearly a lack of search functionality is an intentionally introduced level of difficulty. However as we understand it, within a digital environment there is no real decay occurring and that it is a facsimile of the natural environment. To emulate atrophy the site needs to provide atrophy as a design of the site otherwise the inherent mechanism of stigmergy of trails fading over time is unobtainable. There is a clear conflict here where we see that our entire system is a set of encoded functionality. Which stigmergy attribute or dynamic they represent becomes open to interpretation. Therefore we should clarify that in the digital world we consider decay rate to be functionality or lack thereof which obscures or obfuscates contributions over time (which was previously observable by users). Difficulty is then clarified as functionality that obscures contributions by providing a barrier of navigation through standard topography at all times to subgroups of users. This same issue applies to the erosion attribute, where attention must be given between the environment-centric functions opposed to the sign-centric functions whereas both are actual facets of the single web-site. Erosion is environment specific functionality such as the automated processing that acts upon the contributions made by the users. Conversely, the decay rate (or ability to be decayed) is functionality which enables the sign’s resistance to the erosion functionality of the site primarily initiated as a result of user interaction.

8. CONCLUSION

When applying our model to Web 2.0 sites, we observe patterns which clearly fit what our model predicts. It is not surprising to see that similar patterns are identifiable between sites despite the fact that they are provided to serve vastly different primary purposes. What is encouraging is that we can see that the stigmergic mechanisms observed within these sites do appear to support and enhance the site’s primary purpose.

Despite the encouraging observations, stigmergy in the digital world still presents some issues when compared to stigmergy in the natural world. The natural world where stigmergy originates is analogue in nature and is rich with subtlety. Conversely Web 2.0 sites are inherently discrete due to their digital nature; all activity can be measured in atomic transactions. In a digital environment such as Web 2.0 the concepts of environment and sign can be difficult to differentiate as both are artificial constructs.

Stigmergy is a valuable model for understanding how users provide a self-organising and self-contextualisation of content. The skepticism regarding the value of using stigmergy to model human behavior is overstated when focusing on human behavior as constrained within Web 2.0 sites. This is due to user freedom of choice being restricted by site functionality.

The next stage of our research will be to exploit our model of stigmergy and develop a methodology and framework that supports engineering Web 2.0 sites to improve collaboration. We are currently investigating Web Modeling Language [21] as the notation to extend incorporating stigmergy specific mechanics. This is aimed at recording user activity (markers and trails) and providing suitable representation in the presentation layer.

9. REFERENCES

Chapter 6: General Theory of Stigmergy: Modelling Stigma Semantics


Preamble

The development of the model (sub-problem 2) occurred in conjunction with the comparative case study. As a result, the *Stigmergy in Web 2.0: a Model for Site Dynamics* paper provides explanatory examples of how the model applies to the case study websites. However that paper did not include clear justification of how the model was derived from the literature content analysis. Additionally, model development underwent further refinement that was not documented. To provide a chain of evidence from the original literature to the final model a journal paper title *General Theory of Stigmergy: Modelling Stigma Semantics* (Aiden Dipple, et al., 2013a) was generated. This paper provides a complete analysis of stigmergy and the resulting developed model. This model is environment agnostic and applies to entomology, human and engineered environments. The model (and theory) clearly identifies the attributes and dynamics of stigmergy and provides an epistemological discourse on the sources of each concept as outlined in the Literature Review chapter.
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Chapter 7: Extending Web Modelling Language to Exploit Stigmergy: Intentionally Recording Unintentional Trails


Preamble

To evaluate the model efficacy (sub-problem 3) and to document the final analysis of the comparative case study, a presentation was made at conference titled Extending Web Modelling Language to Exploit Stigmergy: Intentionally Recording Unintentional Trails (Aiden Dipple, Kerry Raymond, & Michael Docherty, 2013). The paper documents the retrospective analysis against the initial case study subjects (stages 3 to 5), and the additional website that was not assessed during the model development.
Extending Web Modeling Language to Exploit Stigmergy: 
Intentionally Recording Unintentional Trails

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Abstract—Software development and Web site development techniques have evolved significantly over the past 20 years. The relatively young Web Application development area has borrowed heavily from traditional software development methodologies primarily due to the similarities in areas of data persistence and User Interface (UI) design. Recent developments in this area propose a new Web Modeling Language (WebML) to facilitate the nuances specific to Web development. WebML is one of a number of implementations designed to enable modeling of web site interaction flows while being extendable to accommodate new features in Web site development into the future. Our research aims to extend WebML with a focus on stigmergy which is a biological term originally used to describe coordination between insects. We see design features in existing Web sites that mimic stigmergic mechanisms as part of the UI. We believe that we can synthesize and embed stigmergy in Web 2.0 sites. This paper focuses on the sub-topic of site UI design and stigmergic mechanism designs required to achieve this.

Web Collaboration; virtual pheromones; stigmergy;

I. INTRODUCTION

Our research analyses a number of User Interface (UI) designs within popular Web 2.0 sites. The UI designs observed provide representations of user feedback along with representations of behavior trends from unintentional interactions which have been recorded. Examples of these UI designs can be seen in Facebook where users “Like” other user contributions causing an area of focused interest. Another example can be seen where Facebook has introduced a new “Seen By” representation of feedback where the number of users navigating to a specific article that has been broadcast is presented as a trail of evidence or virtual footsteps. This mechanism of users indicating content of interest and trail forming through unintentional footsteps closely matches a phenomenon called stigmergy. Stigmergy is a term originally used to describe the apparent decentralized coordination amongst certain insects when performing tasks such as food foraging and nest building [1]. While we observe that popular Web 2.0 sites contain these features there is no evidence to suggest that these designs were influenced by stigmergy. The UI designs observed in Facebook might have been introduced without initially understanding their similarity to stigmergy but we see an increasing number of web sites introducing similar mechanisms trying to emulate the same success that has been achieved in Facebook. The primary research question we are working on is whether these mechanisms can be synthesized into a generic design pattern that can be introduced as standard Web site UI elements to enhance coordination.

Web Modeling Language (WebML) is a method of modeling data content, user interaction and navigation flow for various Web 2.0 applications. WebML provides a way to design the mapping of a data model to different UI views and the navigation paths between those views. Given the unique requirements of web site development compared to traditional software development the Object Model Group (OMG) is establishing a standard in the area. The OMG has released a current Request for Proposal (RFP) [2] to formalize syntax, metamodel, UML profile and associated interchange format for languages used to model interaction flow. WebML is one modeling language implementation currently being considered for inclusion in the standard. The most pertinent aspect of the WebML framework to our research question is that WebML is designed to be extensible to facilitate new concepts, interface types and event types. Given the Web 2.0 UI designs which we have observed and a thorough analysis of how they correlate to stigmergy we believe that we can introduce the UI mechanisms as standard elements during web site implementations.

II. STIGMERGY

Stigmergy is a biological term that was first introduced in 1959 by a French zoologist named Pierre-Paul Grasse [3]. The term was used to describe how insects appear to coordinate successfully despite having no centralized management structure or direct observable intercommunication [1]. Stigmergy specifically refers to an indirect communication where the insects use signs mediated within the environment to aid their coordination. An example of stigmergy can be seen in the way that ants leave a pheromone trail during food foraging activities. The trail provides a signal to other ants as to which direction a food source can be found while the strength of the pheromones indicate the relevancy of any specific trail as being the current trail to follow. A positive feedback system is created where the trail strength will increase as more ants follow the trail and successfully return with food. Furthermore, the environment enacts upon the sign causing atrophy and entropy to diminish the signal strength. This
decay provides the negative feedback to ensure only the most current trails can be sensed thereby ensuring that old trails don’t interfere with the food foraging activities after the associated food supply has been depleted.

Previously [4] we have introduced a model of stigmergy including the concept of a stigmergy grand purpose and the core components of stigmergy: the agent, the environment, and the sign. The model is illustrated in Figure 1.

![Figure 1. The Stigmergy Cycle.](image1)

The model as illustrated in Figure 1. ties together the core components of stigmergy, an inner band representing the attributes of the components, and an outer band representing the dynamics acting on those attributes. Furthermore, the outer band dynamics are either internal to each component, or defining the interface between components. Our model describes the dynamics of equilibrium between positive feedback (contributions) and negative feedback (decay) illustrating how the positive feedback is contributed by the agent, where the negative feedback is applied by the environment. The paper where we presented the model was focused on a holistic model of stigmergy which applies for the world of entomology, the human world and the virtual world. This paper is focused specifically on how the varieties of stigmergy manifest as Web environment UI elements. In context to this paper, these three components correlate to the users of Web environments, and the contributions that the users make.

There has been a significant amount of research focused on stigmergy in robotics and Web environments [5, 6]. Web environments provide a close facsimile to stigmergy in physical environments where a large number of users coordinate in a highly organized manner, specifically based on indirect communication through the contributions they make within the Web sites. In Facebook (see Figure 2.) there are similarities to the pheromone marker already observable in the Web.

Another variety of stigmergy describes the development of unintentional trails within the environment. An example of this is best shown by people wearing a path into a lawn when a short-cut is taken across the lawn. This unintentional trail is similar to another type of UI mechanism found within Facebook (see Figure 3.).

![Figure 2. Example of a Facebook LIKE mechanism.](image2)

Stigmergy provides a model of both active contributions and passive interaction with both varieties having numerous examples within the Web. The examples above for the two varieties of stigmergy have been categorized as marker-based [1] and sematectonic [7]. Marker-based stigmergy describes an explicit modification of the environment by leaving a sign with the intention of signaling other agents. Furthermore, Marker-Based stigmergy is broken into two sub-types: qualitative and quantitative [1]. This sub-type categorization is to clarify the difference between single contributions being sufficient to elicit a response as opposed to an accumulation of responses being required.

In contrast to the explicit method of leaving contributions, sematectonic stigmergy is defined as a modification to the environment as a by-product of actions being performed. These by-products are occurring inadvertently and unintentionally to the primary task being performed. For example, when considering a path being left in a lawn when people take a short-cut across it they have no intention of signaling to others that they have taken a short-cut. The short-cut is the purpose of the action, but the environment will retain the footstep impact as an alteration of the environment. There is no explicit foot-step left in the environment (obviously excluding cases such as wet feet leaving wet foot prints) however the action has altered the...
environment and the cumulative foot-step action manifests in the format of a path rather than something recognizable as an aggregation of individual feet traces.

If we consider the two different varieties of stigmergy we can divide the notion of intentionality of communication as being either explicit or implicit [8, 9]. Marker-based stigmergy can be considered as an explicit form of communication where the contribution made by the agent is intentional; it is explicitly left with the intention of the sign being interpreted as a signal. Sematetonic stigmergy can be considered as implicit communication where the primary activity being performed by a user leaves implicit modifications to the environment unintentionally just as with a trail. We would consider that an explicit sign left unintentionally would not constitute a signal, but could be interpreted as one. Similarly we would consider that an intentional generation of an implicit trail would be a counterfeit and also not be considered stigmergic, although it must be noted that it can trigger the same behavior in agents receiving the signal.

III. WEB MODELING LANGUAGE

Web Modeling Language (WebML) is a platform independent way to express the interaction design, data model and business rules of Web application development separately from the implementation platform [10]. WebML permits the formal specification of the data model, interface composition and navigation options and ultimately be supported by tools for the auto-generation of code. WebML describes a visual notation for designing Web applications which is intended to be exploited by the visual design tool WebRatio [11].

WebML specifications are based on four perspectives:

1) **Structural Model**: Data Model for dynamic content.
2) **Hypertext Model**: Site Views of the data model, which in turn are comprised of two sub-models:
   a) **Composition Model**: Page composition and how the data model maps to a view.
   b) **Navigation Model**: How pages are inter-linked (contextually and non-contextually via passed parameters).
3) **Presentation Model**: Layout and graphic appearance of pages independent to output device.
4) **Personalization Model**: Individualisation of pages based on User / Group categories, preferences, etc.

The four modeling perspectives describe the principal facets of data-driven Web sites and therefore provide an excellent experimentation lab for our research when attempting to test stigmergic mechanisms. WebML represents specifications using XML. Examples of XML for the data entities of the structural model, data within a page view and the navigation links (including parameters in the case of contextual links) are provided.

IV. INCORPORATING STIGMERGY WITHIN WEBML

At this stage we are determining whether our implementation would be an extension to the existing WebML classes or a design pattern within the modeling language using the existing classes. The simplest outcome of our research would be to prescribe a design pattern to follow when creating web sites which incorporate stigmergic mechanisms but we anticipate that a more prescriptive approach would be to create explicit stigmergic extensions to WebML. Initial examination of the WebML XML elements suggests that they would be easily extended to include additional attributes which support runtime instantiations of the stigmergic mechanisms. Furthermore the WebML submission to the OMG RFP describes ViewComponent as objects that display data or accept input [12]. This verifies that WebML can be extended to provide customized visualization components to display the stigmergic signals and trails to Web users.

We endeavor to design User Interface (UI) mechanisms to record both intentional and unintentional web site interaction based on our model of stigmergy. To provide environment mediated communication our UI mechanisms will need to trigger events which record user activity within a persistence layer specifically for stigmergy data. To enable the environment to provide negative feedback the environment must be able to trigger its own events to modify the stigmergy data. As discussed in Section III, WebML provides a collection of standard UI components with associated user and system triggered events to facilitate this within the Hypertext Model. WebML also provides the Structure Model that can facilitate stigmergy data persistence and access in conjunction to site specific data.

This section describes specific UI mechanisms available within the WebML Hypertext Model (including the ability to create custom controls) and how they apply to input and output components, events and persistence observed in examples of web-based stigmergy. We generalize these specific components into conceptual mechanisms which facilitate that contribution (input) and representation (output). For example, UI components such as drop-down lists, sliders and radio buttons are all representations of a single option selection, but each are different in their visual presentation. Understanding the fundamental mechanisms can extend the collection to encompass new UI components.

To incorporate stigmergy into WebML we need to understand the general ways the system would receive input, and how it should display output. If we consider our model of stigmergy (see Figure 1.) we understand that this will correlate with the environment having the facility to record contributions, process them and represent them back to users.

A. Qualitative, Marker-Based Stigmergy

Qualitative stigmergy is defined as discrete stimuli that can trigger a response in agents that encounter it. An example of this can be seen in Facebook with the “Share” functionality or within text messaging using emoticons [13]. Emoticons are icons included within the body of text messages to indicate to recipients the feeling or mood associated with the text (e.g.: “smiley faces”). The senders and recipients of text messages understand the associated meaning of the icons and as a result the emoticons add significant meaning to a text message without the use of language. The marker-based variety of stigmergy requires
an intentional contribution by the user, and must incorporate a UI control enabling the user to create the contribution.

In the example of the Facebook “Share” we observe that a single user can broadcast content discovered by the user performing the “Share” so that it is visible to that user’s group of friends (or level of privacy as selected). This represents the simplest input mechanism where there is only the requirement to intentionally trigger an interface element and that the user is aware of what signal it will contribute to.

The example of text messaging emoticons requires users to inherently know what emotions specific icons correlate to. There needs to be some UI mechanism for informing new users of the possible icons and their definition (e.g.: a context-sensitive, online help function). Depending on how esoteric the required knowledge of available icons and their meaning are there might need to be instructions on appropriate reactions. The UI requires an administration function to define the possible icons in a given context. This administration function is considered outside the scope of this paper and is listed as an outstanding issue in Section V.

Our examples all generalize to one case: existing Web UI components which trigger an event (e.g.: radio buttons, etc). Each mechanism in the examples above equate to the user being presented with single or multiple options, however only a single option can be selected. We consider the generalized input mechanisms observed in the examples in this sub-section are:

- Single option intentionally triggering event.
- Single selection from predefined options using controls restricting selection and intentionally triggering event.
- User generated/input of content with predefined meaning (e.g.: using ascii text such as “:)” to be transformed to an icon representing a smiling face).

If we consider the output representations in the Facebook “Share” example and the text messaging emoticon example, the pattern can manifest in virtually any form. There are some simple and reusable patterns observed where verbatim representation or image substitution per associated option is provided. E.g.: smiling face emoticon entered as text and displayed either verbatim as “:)” or transformed as “😊”. Conversely there might be customized, proprietary implementations required such as colour coding of warning types using the green for safe, red for danger representations. Again these UI components map to existing (or extendable) components within the WebML Hypertext Model which use event listeners to process data from the Structure Model.

Within Facebook we see the representation mechanism as an embedded link to the shared content providing a preview as a teaser to get other people to “View”, “Like” or “Share” further. NOTE: The sharing of content by a user doesn’t necessarily mean that the following user whose behavior is triggered by the signal will choose the same, single-option response. The emoticon example represents the user entered text within a text editor and requires the user to only enter tags with predefined meanings (and understand the connotation of those representations).

Our output examples clearly show that there are business rule requirements to access at stigmergy data layer and to present that data to the user with specific representation. The output mechanisms seen in our examples for this variety of stigmergy are:

- The (hyper-linking or verbatim) display of a UI component, whether contextually driven (e.g.: Display of the “Shared” content whether textual, image, html, multimedia, etc) or non-contextually (e.g.: “Terms and Conditions of Service” links).
- The input which was entered textually, but that requires recognition and interpretation by users who understand the signal representation (or the transformation where images are substituted).

We must remember that these abstractions are solely for our examples and is not intended to be an extensive list of all UI manifestations possible. An extendible WebML standard will enable future additions as required.

B. Quantitative, Marker-Based Stigmergy

Quantitative stigmergy is based on an accumulation of stimuli that do not differ qualitatively but that will reach a threshold and increase the probability of triggering a response. An example of this is demonstrated within the Facebook “Like” functionality which is a type of endorsement/acknowledgement system. A user who has made a contribution is hoping to provoke the response from their friends to “Like” it. The more people who “Like” the contribution increase the attention that the contribution receives. As the SUM total of people increases the probability of more people responding to the page increases, creating a positive feedback loop.

A more complex example of quantitative marker-based stigmergy is where there is more than just the single-option, signal contribution possible. In the online auction site eBay we have an example illustrated with the reputation feedback (see Figure 4). There are a number of different criteria to answer, and each criteria has a 0 – 5 choice options where 0 represents a very negative feedback and a 5 represents a very positive feedback. As with the example in Section A if we generalize the mechanisms then we observe a single-choice selection from a group of possible options, however in this example there are multiple categories aggregated into a single contribution. The eBay example uses a non-standard UI component of a 5 star rating system. However any single selection UI controls (e.g.: drop-down list, radio button group, slider, etc) could be effectively used.

![Figure 4. Example of an eBay feedback mechanism.](image)

Just as with qualitative contributions, the WebML Structural Model will store the contribution triggered by events from the Hypertext Model. The UI has no other purpose than to facilitate the contribution of the stigmergic
signal. The generalized input mechanisms observed in the examples in this sub-section are:

- Single option intentionally triggered.
- Single selection from predefined options using controls restricting selection and intentionally triggering event.

When considering output the Facebook example the response of “Like” is signaled to all parties with access to the original contribution and displayed as a simple SUM total of the number of people who have intentionally chosen to respond with a “Like” to the same contribution, and re-ordering the original contribution higher within the news feed. All contributions are based on the same qualitative stimuli, with the environment providing an accumulation function as part of the output mechanism presented to the user. As with qualitative contributions, the UI components link the WebML Hypertext Model through event listeners to process and present data from the Structural Model.

The eBay reputation feedback signal appears to be a composite, aggregation function of all purchase history for the user via multiple criteria. We see that the input parameters of multiple-choice to multiple criteria are transformed through the aggregation function and result in an output value that is applied to the users’ current reputation status value (either positive or negative). We can see how the environment (which consists of other users) and the user provide the positive and negative feedbacks to the signal and how the WebML Structural and Hypertext Models can facilitate that. An interesting observation is that Wikipedia has adopted this quantitative, marker-based mechanism for soliciting user feedback on the quality of specific articles and pages [14].

We consider the generalized output mechanisms seen in our examples for this variety of stigmergy are:

- UI component display or modification representing the aggregate function of the contribution.

C. Sematectonic Stigmergy

Sematectonic stigmergy is defined as a modification of the environment as a by-product of actions being performed. These by-products are occurring inadvertently and unintentionally to the primary task being performed.

If we consider the “Seen By” example in Facebook we understand that the user is not making any intentional contribution by viewing a specific piece of broadcasted contribution, however their action of viewing the contributions has been recorded in the environment. The user has left a trail for others to see. In the Facebook example the user has only clicked on a hyper link in response to another users suggested interest point (see Figure 3 ).

A more complex example of sematectonic stigmergy can be seen in the Amazon recommendation system (e.g.: “People who bought this also bought …”), where product purchases made by a user are used as suggested items of interest to other users. In this example the input is virtually any potential sale item as the contextual input to the aggregation function. Irrespective of what manifestation the contextual input takes, we can observe that while the content type can take virtually any form the abstract mechanism equates to hyperlinks and interaction flow points. These interaction flow points occur whether based on following hyperlinks or other action events (e.g.: selecting the “purchase now” button on Amazon).

In both examples we see unintentional user-triggered events which store that activity in the persistence layer. We consider the generalized input mechanisms observed in the sematectonic examples in this sub-section are:

- Unintentional trace logging via event-triggered interaction incidental to using primary functionality.

In the Facebook example the current state of “Seen By” is visible to all parties with access to the original contribution and displayed in two different ways: The first representation is a simple SUM total of the number of people who have intentionally chosen to view the contribution but who did not have the intention to let people know that. The second representation is the discrete list of the users who view the contribution and the date-time of viewing. This second representation can be seen in the top section of Figure 3. The instigating behavior in this example is the viewing or navigating to a user contribution with the unintentional by-product of leaving a trail.

The Amazon recommendation example shows how the contextual input can result in an aggregate function used to influence other site user purchasing behavior just as described in the qualitative, marker-based variety of stigmergy. Again we see that the output is represented through UI components linking the WebML Hypertext Model through event listeners triggering business rules to process and present data from the Structural Model.

A final and important example of output representation was demonstrated in a trial of Wikipedia article edit contributions [15]. In an attempt to display the verifiability of articles which had been edited (relatively) recently the article would have its page display a colour-tinted background. The background colour of the article page (or part thereof) would appear a pinkish-red colour to signal that article had previous un-validated modifications. This colour would slowly change through orange and yellow pastels until an undisclosed number of visitors to the article would presumably indicate that no ensuing modifications (indicating potential corrections) would imply that the original modification could be considered appropriate and correct. The importance of this example is that it relies on the user’s cultural understanding of colour association where warm colours such as red/orange imply caution and where green / white (default representing standard conformity) imply safe and reliable state. This illustrates the potential for new and insightful ways to provide implicit representation rather than using explicitly defined categories and numerical values.

We consider the generalized output mechanisms seen in our examples for this variety of stigmergy are:

- UI component display or modification representing the aggregate function of the contribution.

V. DISCUSSION

This paper has presented the varieties of stigmergy and briefly provided Web site examples of how the input and
output for each variety might be implemented. Our examples have explored simple implementations along with more sophisticated implementations. An initial analysis of User Interface (UI) components indicate that they might be independent to the variety of stigmergy they apply to. For example, we see that both qualitative and quantitative marker-based stigmergy can use a single selection type input element irrespective of the different types of output implementation. Similarly the output implementation of both quantitative marker-based stigmergy and sematectonic stigmergy appear compatible. If we are able to decouple the input/output implementations from the stigmergy varieties then we might enable a level of reuse of these mechanisms.

Our analysis has been focused on our UI observations which clearly correlate to the WebML Hypertext Model (both Content and Navigation Models). By definition stigmergy stipulates that communication occurs indirectly through environment mediated signs and indicates some form of data layer must exist.

Our model of stigmergy describes both positive feedback from users and negative feedback from the environment. The stigmergy data within the WebML Structural Model will therefore require data persistence accessible by the UI components as well as environment triggered events. This will be analyzed and included in the next phase of research when designing how stigmergy integrates with WebML. This metadata persistence is expected to also afford the administration of available qualitative marker-based options (e.g.: available text messaging emoticons and associated images/icons) and integrate into some form of tag disclosure through integrated online help. Our current work involves providing a model of how stigmergy as a design pattern integrates with WebML framework extending UI components and events within the Hypertext Model and how that maps to the Structural Model within WebML.

In the Facebook “Seen by” example we illustrate a single stigmergic mechanism resulting from a single input component (e.g.: The following of a link to a suggested content article) and how it can have two different output representations. The Facebook example showed that there can be a SUM aggregate function of the users who visited the suggested content, but also a chronological listing identifying the distinct database entry level data including the date/time of the event. This clearly highlights that when incorporating stigmergy into WebML we must accommodate multiple output visualizations (and different view locations where they are accessed) representing the single output state.

VI. CONCLUSION

What we hope we have clarified in this paper is how different stigmergic mechanisms might be implemented such that there is both an intentional and unintentional set of input elements. These input elements map to relevant output elements which include both visualization and representation (embodiment) of the contributions. This representation is determined by aggregation functions which are calculated using the business rules against persistent data for the specific stigmergic mechanism. These generate signals and trails ranging from simple SUM aggregate functions to multi-criteria and multi-selection aggregate formulation into a final representation.

Stigmergy is not merely input and output mechanisms as presented within this paper; they are only part of the stigmergy phenomenon. For the mechanisms to work as intended a web site must be built analyzing the grand purpose of the site, and how stigmergic mechanisms can be employed to improve site coordination. The intra-site location of where the mechanisms are deployed (e.g.: specific users or role groups) ultimately depends on the development project sponsor. Similarly the WebML Personalization Model of a Web site might employ a fee paying structure where access to the mechanisms might be restricted. These issues are accommodated for within WebML and are ultimately expected to make the efficacy of introducing stigmergic mechanisms into Web application design significantly value-added.

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Chapter 8: Stigmergy within Web Modelling Languages: Positive Feedback Mechanisms


Preamble

The software design pattern development (sub-problem 4) was an iterative process covering stages 6 and 7 of the project. The design process began with an initial proof-of-concept prototype to determine the suitability of the selected development environment. This prototype was focused on the positive feedback attributes and dynamics and was presented at conference in a paper titled Stigmergy within Web Modelling Languages: Positive Feedback Mechanisms (Aiden Dipple, Kerry Raymond, & Michael Docherty, 2013b).
Stigmergy within Web Modelling Languages: Positive Feedback Mechanisms

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Abstract—Stigmergy is a biological term originally used when discussing insect or swarm behaviour, and describes a model supporting environment-based communication separating artefacts from agents. This phenomenon is demonstrated in the behavior of ants and their food foraging supported by pheromone trails, or similarly termites and their termite nest building process. What is interesting with this mechanism is that highly organized societies are formed without an apparent central management function. We see design features in Web sites that mimic stigmergic mechanisms as part of the User Interface and we have created generalizations of these patterns. Software development and Web site development techniques have evolved significantly over the past 20 years. Recent progress in this area proposes languages to model web applications to facilitate the nuances specific to these developments. These modeling languages provide a suitable framework for building reusable components encapsulating our design patterns of stigmergy. We hypothesize that incorporating stigmergy as a separate feature of a site’s primary function will ultimately lead to enhanced user coordination.

Keywords—web collaboration; virtual pheromones; stigmergy.

I. INTRODUCTION

The World Wide Web has transitioned from its historically static content to a new, dynamic experience emerging through collaborative websites and social networking. We seek to understand a specific set of emerging designs that we believe are indicative of a natural phenomenon called stigmergy [1].

In biology, stigmergy describes a mechanism of indirect communication where the actions of individuals affect the behavior of others (and their own). This communication mechanism describes what has been considered as apparent cooperative behavior of insects’ during various activities. An example of this is the food gathering activities of ants which exploit pheromone trails. To find the most recent and relevant food source the ants select paths to follow based on the strength of specific trails. The environment embedded pheromones is considered a form of indirect communication. This stigmergic communication comprises of an explicit message in the pheromone to gather food, and an implicit signal through the current level of decay: information within the trails themselves show which trail will currently lead to a food source opposed to those leading to a depleted food source.

There are multiple varieties of stigmergy and our research to date has modeled and documented this [2, 3]. We have created generic design proto-patterns from observing stigmergy in numerous Web sites, however this paper will focus on those observed within Facebook. The User Interface (UI) designs observed provide representations of user feedback along with representations of behavior trends from unintentional interactions recorded as trace data. Examples of these UI designs can be seen in Facebook where users “Like” other user contributions causing an area of focused interest. Another example can be seen where Facebook has introduced a “Seen By” representation of feedback where the number of users navigating to an article is presented as a trail (or virtual footsteps).

Web Modeling Language (WebML) [4] is a method of modeling data content, user interaction and navigation flow for Web 2.0 applications. WebML provides a way to design the mapping of a data model to different UI views and the navigation paths between those views. The pertinent aspect of the WebML framework to our research question is that WebML is designed to be extensible to facilitate new concepts, interface types and event types. Our research uses WebML and the WebRatio development environment allowing stigmergy to be easily incorporated into a site as reusable components keeping the core code-base separate from the stigmergic features. Given the Web 2.0 UI designs that we have observed and a thorough analysis of how they correlate to stigmergy, we have implemented generic UI components as standard elements for web site development to exploit stigmergic communication.

Our research project focuses on creating a model of stigmergy that we can use to design feedback mechanisms into Web applications. From this model we can describe a
framework to exploit stigmergy in the collaborative environment provided by specific Web applications. This paper illustrates how we create design patterns in an Integrated Development Environment (IDE) to capture the features of stigmergy as a separate aspect to core Web site features. The research contribution of the PhD project is to determine the efficacy of incorporating stigmergy into site design; this paper makes a significant contribution by documenting our current progress capturing user input (positive feedback) using reusable stigmergic design patterns readily included into primary Web site functionality. Future work will involve testing our model of stigmergy using our design patterns in experiments with users to test how they react to the presence of stigmergic features in a Web 2.0 site when compared with a similar Web 2.0 site without the stigmergic features.

This paper will introduce our research question based on our hypothesis in Section II. Section III will provide a brief Literature Review describing previous work on Stigmergy providing key facets of our model development. Section IV will detail our research methodology and explain why we have chosen a multi-method approach. Section V will detail our current progress including an overview of our developed model of stigmergy, data model and interface components implementing the positive feedback mechanisms. Section VI will discuss problems yet to be solved and will be followed by the conclusion in Section VII.

II. RESEARCH PROBLEM

Our hypothesis is that stigmergic behaviour is inherent in collaborative Web environments and that a framework to support all attributes and dynamics of stigmergy will facilitate higher quality collaborative outcomes. This leads to the question: Does the Web enable us to build better collaborative sites when the attributes and dynamics of stigmergy are fully exploited? Are there facets of stigmergy missing in the Web environment that could be used in capturing implicit communication otherwise lost? To answer this question the project has required a clear definition of stigmergy and how it manifests in Web environments. There is significant research into stigmergy, virtual pheromones and swarm intelligence re-creating stigmergic behaviour; but limited research into its relevance as a design pattern to coordinate human behaviour. If we can build a model identifying stigmergy in Web environments, we speculate we can create a methodology to build sites benefiting from this phenomenon.

III. STATE OF THE ART

The word stigmergy “is formed from the Greek words stigma ‘sign’ and ergon ‘action’” [5] and is used within biology to describe the way non-rational, autonomous agents (such as termites or ants) collaborate to achieve complex tasks thereby displaying some type of emergent swarm-intelligence [6]. These agents use pheromones as signs embedded within the environment to trigger behaviour or actions in other agents in the swarm.

Stigmergy was first introduced in 1959 by a French zoologist named Pierre-Paul Grasse [7] to describe how insects appear to coordinate successfully despite having no centralized management structure or direct observable intercommunication [1]. A simplified definition of stigmergy is: a process by which agents communicate indirectly between one and other through their environment. More specifically, the behaviour of agents is influenced or determined by the behaviour of agents which have interacted with the spatio-temporal environment previously [8]. Essentially stigmergy describes an autonomous system enabling self-organisation, self-optimisation and self-contextualisation in a light-weight and scalable mechanism [9]. This is interpreted as the associated mechanisms and emergent behaviour enabling the selection of the optimal solution without the prerequisite of knowing anything about the environment.

Stigmergy is a compelling phenomenon because it describes a positive feedback system where the signal strength of a trail will increase as more agents follow that trail. This leads to more rapid successful task completion. In opposition to this the environment enacts upon the sign causing atrophy and entropy to diminish the signal strength. This decay provides the negative feedback ensuring only the most current trails can be sensed and that old trails do not interfere with the task as they become redundant. Stigmergy provides a model of both active contributions and passive interaction with both varieties being demonstrated within the Web. The two varieties of stigmergy have been categorized as marker-based [1] and sematectonic [10]. Marker-based stigmergy describes an explicit modification of the environment by leaving a sign with the intention of signaling to other agents. Marker-Based stigmergy is broken into two sub-types: qualitative and quantitative [1]. The sub-types differentiate where single contributions are sufficient to elicit a response versus an accumulation of contributions increasing the probability of triggering a response as signal strength increases.

In contrast to explicitly leaving contributions, sematectonic stigmergy is defined as a modification to the environment as a by-product of actions being performed. These by-products are occurring inadvertently and unintentionally to the primary task being performed. For example, when considering a path being left in a lawn when people take a short-cut across it they have no intention of signaling to others that they have taken a short-cut. The short-cut is the purpose of the action, but the environment will retain the footstep impact as an alteration of the environment. There is no explicit foot-step left in the environment (obviously excluding cases such as wet feet leaving wet foot prints) however the action has altered the environment and the cumulative foot-step action manifests in the format of a path rather than something recognizable as an aggregation of individual foot traces. These two
varieties of stigmergy highlight the notion of intentionality of communication as being either explicit or implicit [11, 12], with marker-based stigmergy being explicit communication and sematectonic stigmergy being implicit communication. 

There has been a significant amount of research focused on stigmergy in robotics and Web environments [5, 13]. Web environments provide a close facsimile to stigmergy in physical environments where a large number of users coordinate in a highly organized manner indirectly communicating through the contributions they make within the Web sites. Our research focuses on how the varieties of stigmergy manifest as Web environment User Interface (UI) elements and how they can be employed within Web site design to improve user collaboration and information categorization. We seek to do this using emerging web modeling technologies.

Web Modelling Language (WebML [4]) is a platform independent way to express the interaction design, data model and business rules of Web application development separately from the implementation platform. WebML permits the formal specification of the data model, interface composition and navigation options. WebML describes a visual notation for designing Web applications that to be exploited by the visual design tool WebRatio for the auto-generation of code. We have implemented proof-of-concept UI mechanisms to record and display both intentional and unintentional web site interaction based on our model of stigmergy that we present in this paper.

IV. RESEARCH METHODOLOGY

This research project focuses on identifying the attributes and dynamics of stigmeric behaviour and how it facilitates and benefits the process of recording active contributions and passive interaction of users when participating in the grand purpose. The research is based on a mix-method approach comprised of a literature review content analysis, comparative case studies of existing Web sites, and finally experimentation and data analysis testing the stigmergy design patterns created as part this research.

The literature review has provided a thorough analysis of stigmergy exposing the complexities of the phenomenon and how to best incorporate the properties of stigmergy into a Web environment. The results of the initial analysis stage has led to the development of a model describing the attributes and dynamics of stigmergy along with documentation tracing its components back to the work performed by previous researchers. This provides the chain of evidence to validate the model and enable its correctness to be reviewed.

Due to the qualitative nature of the data collection, a comparative case study approach has been used [2] to provide legitimacy to the repeatability of the research findings. The pattern in the developed model has allowed the comparative case study to be performed against a selection of existing Web sites with varying levels of model alignment. Analysis of the case studies identified common solution patterns as well as proto-patterns representing solutions which provide more sophisticated implementation of the stigmergy varieties [3]. Targeting multiple sites for case studies has provided a vital cross section of sites displaying aspects that impact the simplistic entomological examples of stigmergy when applied to complex and cognitive human systems. Targeting multiple sites over a broad spectrum of social aspects of the Web has exposed the repetition of stigmergic patterns further enforcing the generic design of our model.

V. PROGRESS TO DATE

The investigative stages of the research plan have been completed including the literature review and initial case study. The literature review includes the analysis of stigmergy as a generic phenomenon and from the perspective of various algorithm designs. Previously [2], we have introduced the resulting model (see Figure 1) of stigmergy including the concept of a stigmergy grand purpose and the core components of stigmergy: the agent, the environment, and the sign.

![Figure 1. Stigmergy Cycle](image)

Stigmergy facilitates a grand purpose (or emergent behaviour) through the dynamics (or mechanisms) applied to its inherent attributes (or components) of the environment, agents, and artefacts. Our progress to date has provided clarification and the categorisation of virtual pheromones (and other traces) and their role as triggers. The development of our model has provided insight into various similar indirect methods of communication that are considered to be a superset of stigmergy: Behavioural Implicit Communication (BIC). BIC is considered outside of our research area of stigmeric communication. Our modelling of the concepts of implicit and indirect communication mechanisms has provided the missing holistic, conceptual synthesis of the phenomenon. Our intended contribution of analysing the efficacy of stigmergy within Web 2.0 sites will build on this contribution.
The model ties together the core components of stigmergy: an inner band representing the attributes of the components; and an outer band representing the dynamics acting on those attributes. The outer band dynamics are either internal to each component, or defining the interface between components. The model describes the dynamics of equilibrium between positive feedback (contributions) and negative feedback (decay) illustrating how the agent contributes the positive feedback, where the environment applies the negative feedback. This is a generic model of stigmergy that applies for the world of entomology, the human world and the virtual world. This paper focuses on how the varieties of stigmergy manifest as Web environment User Interface (UI) elements; therefore the three components of stigmergy correlate to the users of Web environments, and the contributions that the users make.

To incorporate stigmergy into WebML we need to understand the ways the system receives input and how it should display output. The contribution attribute of the model correlates with the user having an input mechanism to actuate the contribution to a sign; the signal diffusion attribute defines accessibility of an output mechanism presenting the transformed contributions as a signal to users. The environment requires the capacity to store contributions therefore requiring a stigmergy specific data model.

Our research has explored how the different varieties of stigmergy manifest as proto-patterns within the target case study sites [3]. The key concepts identify that there are consistencies between the input (actuators) and output (sensor) mechanisms for each variety of stigmergy. These findings highlight that the observed Web site cases can be implemented using reusable stigmergic mechanisms.

The two simplest forms of input mechanism for marker-based stigmergy both enable a user to intentionally make a selection, whether as a single presented choice or as a single choice from a number of options. An example of the single presented option can be seen in Facebook with the “Like” feature where there is only one option presented to the user. An example of a single selection of multiple options can be seen in rating systems such as the one-five scale within eBay. More accurately the eBay example is a composite set of options where a group of categories are presented (e.g., communication quality, postage costs, etc.) with each choice selection aggregating into a single seller reputation metric. In the case of sematectonic stigmergy, the trigger for the contribution is hidden from the user and occurs unintentionally when the user interacts with site content or navigates to particular pages. An example of this is seen in the Facebook “Seen By” feature that records which users view a particular Group’s news-feed item.

The two simplest output mechanisms observed correspond to signal type: quantitative or qualitative. The Facebook quantitative signal type illustrates how the contributions are transformation into an aggregate summation presented to the user as a “ Liked” count. The eBay example provides a metric that is based on a more complex function but presented as a single percentage value. Our design facilitates both the storage of each of these types of contributions and each type of presentation.

The qualitative signal type is a detailed list of raw contributions and can be seen within the Facebook “ Share” feature. The user contribution broadcasts specific content displayed within the standard Facebook news-feed. The contribution is a reference to an article and is stored as a primary key value and specific data model entity name that that key relates to. The actuator input mechanism to record the contribution is the same as for the Facebook “Like” example. The sensor output mechanism of this example is the propagation of the sign to the recipients with accessibility to the signal as defined by signal diffusion.

Our most recent progress has been to implement proof-of-concept examples within the WebRatio development environment built on these -generic proto-patterns. The data model for our tests can be considered within three separate components: core entities for application functionality; supporting entities (e.g., user accessibility entities); and stigmergy entities.

Figure 2 shows the user accessibility entities (user, group and module) that are created by default within WebRatio. Also shown is the stigmergy specific data model that maps to the components and attributes as illustrated in Figure 1.

Our model requires that we add the self-referenced many-to-many relationship to the user entity and call the resulting relationship friends. It is possible that in future releases this enhancement would become a standard part of WebRatio given current social website networking trends.

The sign and contribution entities are associated (via Foreign Key) to the user and functions as the environmental persistence of the user contributions. The contribution is the result of the option selected (intentionally) or left (unintentionally) by the user as a byproduct of interaction with the input mechanism. The available options are those which have been defined as being presented for a particular

\[ \text{Figure 2. User Accessibility & Stigmergy Positive Feedback Data Model} \]

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sign. The difficulty entity defines the accessibility for to the actuator (or input) to particular users of the site, where signal diffusion defines accessibility to the signal sensor (or output) through the output mechanisms. The group entity is related to the difficulty and signal diffusion entities (resulting from the many-to-many relationships) defining accessibility and enabling users to set their own privacy levels of contributions. The deployment of this feature is dependent on site-specific implementations. For example, Facebook allows users to restrict the accessibility of their “Share” contributions but not their “Like” contributions. The capability to expose these features for one contribution and not the other are implemented in the sign definition as a dynamic feature based the stigmergy data model configuration. Finally, we could consider extending the implementation for position to include navigable connected graphs based on Web site hyperlinks but the added complexity is outside the scope of this research project.

The data model supports the definition of signs that fit different varieties of stigmergy. Our quantitative, marker-based example (as illustrated by the Facebook “Like” feature) is defined as a single sign record (e.g., of “Like”) and a corresponding single option record that has a value attribute of 1. The sign aggregationOptionFx attribute indicates the SUM function for the output mechanism to perform a sum function against to determine the “Like” count. Note: a COUNT function would produce the same result. Given our qualitative, marker-based example we assume that Facebook stores news-feed data in an associated table. The sign record defining the sign stores the table name in the positionEntity attribute and the name of the primary key field in the positionPrimaryKey attribute. This defines the content’s position for news feed articles being liked and how that content is referenced. The signal diffusion record for the sign is preset to visible to everyone and the sign.signalDiffusionUserConfigurable disabled because Facebook does not allow users to set privacy on who can see that they have liked something; anyone with access to the news-feed article can see the “Like” count. The contribution record would then store that a particular user deposited the “Like” option against a news-feed item that is identified by the primary value stored in the positionIndex attribute. The option should be presented as a single button (or hyperlink) being that there is only a single option in this instance, and is labeled using the string stored in the sign.uiLabelInput attribute. The output mechanism queries the stigmergy data and presents the result labeled using the string stored in the sign.uiLabelOutput attribute.

If we consider the quantitative, marker-based, eBay example for seller-reputation feedback, there is an input mechanism that allows the selection of a single option from multiple options defined against the sign. The input mechanism in our proof-of-concept implementation presents a number of options within a drop-down list; however it could also be presented as a radio-button group or a group of buttons / hyperlinks. This option presentation is designed into our generic WebRatio output mechanism component and should be dynamic in its ability to render itself according to whether one or many options are available for the sign. The storage of the contribution remains the same, as does the query used within the output mechanism. A slightly more complex query is required where a composite sign (sign made up of signs) has been defined. The result set is driven by a recursive tree-walk of the sign entity generating the collection of contribution data grouped by the positionPrimaryKey attribute. This applies the sign’s aggregationOptionFx attribute named function against the collection of children sign’s option.value attribute where multiple contributions exist. This functionality is hidden in the output mechanism and is transparent to both the user and developer. In the case of eBay where feedback appears to be an average or moving average, the output mechanism can be extended enabling the customization of the aggregation function; however the incorporation of more complex though standard functions can easily be included in the default output mechanism.

The Facebook “Share” feature is an example of qualitative, marker-based stigmergy and follows the same pattern where there is single option selection that is associated (via Foreign Key described by meta-data in the sign entity) against each news-feed article. Corollary the same data for the contribution would be stored; however the difference here is that the user is capable of specifying a different visibility level in signal diffusion for their individual contribution because that feature is offered to the user. The difference with the output mechanism is that the “Share” feature is provided as part of the core Facebook functionality. The sharing of a news-feed item means that it becomes accessible to the subset of users to whom the content has been shared with. The site functionality provides a qualitative listing (rather than quantitative aggregation function) to exploit this particular signal type. In this example the result set is driven by a query selecting data that is visible to the current user where the contributing user is related to them as defined by the friend entity relationship or group entity which they belong to.

The Facebook “Seen By” feature is an example of sematectonic stigmergy and follows the same pattern where a single option is stored as the contribution. This is the same sign and option configuration as outlined in the Facebook “Like” and “Share” examples. The only difference is that the user when navigating a hyperlink to specific content triggers the input mechanism unintentionally. The option record for the “Seen By” sign has a value attribute of 1 and has the same results as for the “Like” sign count. The input mechanism is associated to a hyperlink with the pre-defined option specified for the
contribution. The output mechanism in this example performs the same sum function of the contribution.value and where the positionIndex is equal to the current newsfeed entry’s primary key.

WebRatio provides a modeling interface for design a web application. Predefined components are provided which perform the presentation and transactional operations of a Web site. While stigmergy can be incorporated into a site as a design pattern the optimal approach is to provide reusable components performing the actuator and sensor dynamics of our model thereby providing reusable input and output mechanisms. Figure 3 provides an example of how an actuator can be built using standard WebRatio components based on our design pattern.

Figure 3. WebML “Like” Sign Actuator design

The example illustrates one way to implement the “Like” sign (predefined within the sign data model entity at primary key oid 1) against a particular group. The actuator is located on the page where group entities can be edited and in this example is provided by the link from the Entry Unit named “Modify Group” to the Create Unit named “Create Like”. The standard Create Unit is used to insert a record into the contribution entity and the row values area passed in through the links providing values for contributedOn, currentUserId, currentGroupId and the option entity foreign key. The positionIndex value is provided using the Link for the currently selected group data entry unit. The specific option to add as the contribution is provided by the Entry Unit named “Actuator Options”. The option value is restricted using a Relationship Condition between the “Like Sign selector” and the “Like Options selector”. NOTE: In the “Like” stigmergy example only a single option is presented to the user requiring the Entry Unit being configured to not be visible. For examples where multiple options are provided, a Selection Field must be included to present the alternate options within a drop-down list.

Figure 4 shows the same example when using our actuator Custom Unit within the WebML design. Also shown is our sensor Custom Unit. The dramatic simplification is obvious where current user and group values can be obtained within the web service context instead of model links; only the positionIndex value needs to be provided via a link. The primary key defining the options for the sign is specified as parameter of the unit, as shown in the Properties window. There is a web service associated with the unit providing database transactions, and more sophisticated algorithms pertaining to the difficulty and signal diffusion facets of the signal. The final runtime output is displayed in Figure 5.

Figure 4. Custom Unit “Like” Sign Actuator design

VI. PROBLEMS ENCOUNTERED

WebRatio is a relatively immature product with a small user group and support based. As such there have been a number of problems and impediments encountered.

Custom Units within WebRatio allow definition of page template content to be customized (using scripts) at page generation time, while mark-up tags enable dynamic content during page population at runtime. The limited available tutorials for WebRatio have impeded our progress in optimizing our actuator and sensor units’ implementation. A specific example can be seen in Figure 5 where the runtime actuator instance displays a drop-down list containing “Like” and also a button labeled “Like”. Our optimal design requires the capacity at page generation time to determine whether a specific sign has a single option, or multiple as defined in the option entity. Based on the result of this database query either a single button or a button with the drop-down list would be presented. At present only Custom Unit design-time properties such as the SignId as seen in Figure 4 have successfully been prototyped as available at page generation time. A simple work-around for our proof-of-concept has been to split our actuator into three separate Custom Units: marker-based (single option), marker-based (multiple options) and sematectonic based. The same applies for our sensor design where the Custom Unit split is based on signal type: quantitative and qualitative. Rather than rely on the work-around (which merely means the appropriate Custom Unit be selected for the associated sign data) we pursue the implementation of the consolidated actuator and consolidated sensor designs. Resolving this issue will also facilitate removing superfluous Custom Unit design-time properties of Stigmergy Type (for actuator) and Signal Type (for sensor), as they are also defined within the data model. Ideally we will succeed in accessing the stigmergy data model content to define these page qualities at page generation time. However, if we realize that this is not achievable within the WebRatio tool it does not impinge on the correctness of our
model or future experiments on the efficacy of including stigmergy in Web sites.

Since development of the actuator and sensor prototypes, we have reflected on potential design deficiencies when considering stigmergic mechanisms deployed against our case study Web sites. We have identified two areas for improvements: the ability to revoke a contribution (such as “Unlike” within Facebook); restricting accessibility to the actuator after a single contribution (such as providing transaction feedback within eBay). Both of these enhancements can easily be achieved by adding Boolean fields userRevokable,(as Boolean) uiLabelRevoke (as String) and singleContribution (as Boolean) to the sign entity. The singleContribution value will define additional accessibility to the actuator, and will provide alternative labeling for revocable contributions.

Progress so far only covers the user-centric dynamics (e.g., actuate and sense making) of stigmergy that provides the positive feedback system. To fully exploit stigmergy we must also implement the negative feedback illustrated as atrophy and entropy. WebML and WebRatio provide system events to trigger actions that can drive these environment-centric dynamics. Inclusion of these mechanisms into our proof-of-concept will complete our implementation by introducing the balancing negative feedback of stigmergy. We have yet to address some attributes presented in Figure 1: Progress, Goal, Completion Point, and Significant Dimensions. These attributes pertain to user-centric data (e.g., stored in users heads) and as such are arbitrary as to whether sites facilitate the recording and inclusion of such data. We anticipate addressing these issues in the future.

VII. CONCLUSION AND FUTURE WORK

Stigmergy can be seen throughout entomological, human and Web environments. Stigmergy provides a set of dynamics that facilitate a balance between positive and negative feedback within a system. Previously we have presented papers defining what stigmergy is. This paper presents how the positive feedback mechanisms of stigmergy can be architected into web sites incorporating reusable User Interface components. We have designed a data model supporting each stigmergy variety. Our generic implementation of input and output mechanism within WebRatio demonstrates the simplest examples of stigmergy.

We continue to refine our implementation of positive feedback mechanisms by addressing problems encountered during initial prototype development. Immediate future work is required to consolidate our sensor and actuator units. This requires resolving whether our chosen development environment is technically capable of allow database querying at page generation time, and not solely page population time. We intend to extend model functionality where a Web site design enables user revocation of a contribution or provides a restriction to single, irrevocable contributions. Further model validation will occur by developing prototypes encompassing stigmergy examples observed in alternative case study sites thereby, extending on our Facebook-centric examples. Finally we must extend this data model and include mechanisms that provide negative feedback.

Our proof-of-concept will be used to create an experimental Web site testing user interaction. The analysis will determine how best to employ stigmergy in site designs and assess if stigmergy improves user coordination.

REFERENCES

Chapter 9: Special Theory of Stigmergy: A Design Pattern for Web 2.0


Preamble

The initial prototype verified that a modular design was possible that could encapsulate stigmergy in components separate a core website development project. This encapsulation provides the hypothesised stigmergic components that can be added to existing and new website architecture for collaborative generation of domain knowledge. The initial prototype subsequently underwent a rigorous redesign to suit software architecture and development best practices. The resulting design was documented in a journal paper titled Special Theory of Stigmergy: A Design Pattern for Web 2.0 Collaboration (Aiden Dipple & Docherty, 2013) and included design evaluation of an experiment prototype using a case study. Performance testing of the self-organising properties and comparison of the design-pattern against other approaches is considered outside the scope of this paper.
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Chapter 10: Analysis and Conclusion

This chapter analyses the outcomes of each stage of the research project. The topics discussed will focus on each objective and discuss the results produced. In this chapter we will summarize what the project has covered in context with the data presented. The chapter will discuss the final interpretation of the findings and suggest the next level of question that is pertinent to future research.

The primary question of this research project was to determine how to build collaborative Web 2.0 sites in a consistent and efficient way when the attributes and dynamics of stigmergy are fully exploited. The project focused on 4 main research objects:

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<th>Research Objectives</th>
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<td>O1: To study selected Web sites which successfully implement Web N.0 as a collaborative environment identifying how specific technologies and mechanisms support stigmergy.</td>
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<tr>
<td>O2: To create a model of stigmergy in Web N.0 to clearly identify the attributes and dynamics as outlined in papers covered in the Literature Review.</td>
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<tr>
<td>O3: To analyse and interpret the data to evaluate the model and validate the model efficacy.</td>
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<tr>
<td>O4: To design a software design pattern to prescribe system architecture for collaborative generation of domain knowledge.</td>
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Prior to addressing Object 1 a thorough literature review was performed with the corpus the subject of a detailed content analysis. This content analysis was necessary to discover the breadth of concepts that document stigmergy and to identify contradictions in terminology and definitions. The output of this process
directly addressed Objective 2 producing an abstract model of stigmergy that provided the template for understanding the phenomenon when studying existing websites in context of stigmergy. The interdependency between Objective 1 and 2 provided the cross-correlation between the abstract model of stigmergy and observations of how that model identified website functionality supporting stigmergy. This cross-correlation addressed Objective 3 providing the data that would lead to the development of a software design pattern for incorporating stigmergy into websites as required in Objective 4. To test this design pattern a series of experimental prototypes were developed until the refined design pattern matured and demonstrated the capability of supporting the identified varieties of stigmergy. We consider that we have answered the research question of this project based on the close conformance of the design pattern to the abstract model of stigmergy and the successful implementation of the experimental prototype.

The two major contributions of this project has been the creation of a model of stigmergy and the subsequent creation of a software design pattern for including stigmergy into Web N.0 sites. We consider that both of these contributions have been successfully completed and tested. The published papers produced through the course of the project have provided a chain of evidence documenting the results of each of the eight project stages.

The research question originated from intuition inspired by stigmergy. It was only after the initial model development and the comparative case study observations that identified clear examples of the phenomenon pre-existing in websites. These examples closely correlated to the attributes and dynamics being described by researchers in fields outside of web science. For example, the Facebook website design has slowly been updated over the past 5 years during this project, and has
introduced User Interface (UI) components that map very convincingly to our model of stigmergy and the different varieties that it might take (e.g.: like, seen by, share, etc.). The fact that Facebook engineers have incorporated mechanisms that fit within our model of stigmergy underlies the usefulness of those mechanisms. Irrespective of whether the evolution of Facebook to include stigmergy-like components was haphazard or not, the observation of similar components in other websites (e.g.: eBay, Wikipedia, etc.) demonstrates that stigmergy (and specific Web 2.0 UI components) is present and a pattern is definitely observable. This encouraged us that a generic design pattern was possible that would allow seamless integration to websites.

The development of the model of stigmergy has provided a solid foundation for the posteriori design pattern and experimental prototype. The prior existence of such familiar and replicated examples of stigmergy has resulted in a compelling design pattern that paves the way for future research to find new nuances. The test cases verify the efficacy of the design pattern and demonstrate what can be found in the future.

Stigmergy provides a powerful, bio-inspired model that can be systematically engineered into Web software architecture for collaborative content self-organisation. The research project created a model that can accommodate environment embedded signs (virtual pheromones) denoting the relevance of content (signs) by how information is used and by whom. The distributed architecture of environment embedded processing and users’ (agents) activity would alleviate bottlenecks which limit traditional single-server-centric, brute force solutions. Summarising the research project answering the research question:
- Previous research has proven that stigmergy improves coordination and collaboration within Web 2.0;

- A model of stigmergy has been developed to provide a generalised definition of stigmergy supported by research that has preceded this research project;

- The model of stigmergy developed describes stigmergy within entomology, human society and engineered environments (e.g.: websites);

- A design pattern based on the model of stigmergy has been developed based on the model.

- The design pattern has been tested by building experimental prototype duplicating the examples of stigmergy observed in our comparative case studies.

- The experimental prototype has been tested and successfully performs in a manner similar to the original case study observations.

- Post hoc ergo propter hoc the full set of attributes and dynamics of stigmergy can be fully exploited in Web 2.0 sites and one such way is by using the design pattern created from this project.

Our research question asks whether it is possible to build collaborative Web 2.0 sites in a consistent and efficient way when the attributes and dynamics of stigmergy are fully exploited. We wish to do this because previous research illustrates that stigmergy is observed in numerous websites, and its efficacy has been tested and proven. This leads us to reason that understanding mechanisms that support virtual well-worn paths or pheromones (and understanding how to building those into websites) will lead to better decentralised coordination.
The first significant contribution of this project is a model of stigmergy (Aiden Dipple, et al., 2013a) standardizing the nomenclature while highlighting the origin of concepts of preeminent researchers. This model resolves contradictions in prior work while tracing the progression of research that has refined insight and inspired new terms. In these cases we have advanced the original work to reflect research progression by rewording problematic definitions. This has been done to aid in understanding the nuances our predecessors were describing. The resulting abstract model on the semantics of stigma in stigmergy synthesizes the macro-level dynamics along with a categorisation of the variables into similarly generalised attributes. The published general theory of stigmergy leaves the reader with an advanced understanding of the general topic. The consolidation of vocabulary and concepts is a significant contribution to future researchers.

This general theory was developed through a detailed content analysis of literature in conjunction with performing a comparative case study on websites displaying stigmergic traits. This has enabled the second significant contribution of this project: the development of a design pattern for incorporating stigmergic components into websites based on the model of stigmergy (Aiden Dipple & Docherty, 2013). This special theory has been used to develop an experimental prototype that has been tested and generated data that illustrates that the design is robust.

There are examples of stigmergy in Web 2.0 sites that our prototype did not implement. The scope of this project did not allow time to build more advanced cases of actuators and sensors, such as those seen where users can vote-up or vote-down particular social-media or collaborative entries. Given the object-oriented and extendible nature of the design pattern it would not be difficult to prototype these
examples and would be a suggested next-step for other researchers expanding on the design pattern. Similarly there are a number of additional examples of stigmergy within the web that we recommend for further research and development.

One such example is that of the tagging system used in Wikipedia to denote where an article requires further editing and what type of editing it requires. The tags used within Wikipedia represent a qualitative marker-based variety of stigmergy. The issue being that the experimental prototype demonstrated *implicit position* in terms of database records where the example of a Wikipedia position is within a single record’s text field. The development of a more complex construct such as a body of text in Wikipedia is a form of cognitive stigmergy where the knowledge article is a form of stimulus itself (separate to any tag being a marker indicating further revision is required). Our abstract design provides the capacity for a new concrete class that supports contributions located within free or rich text fields. We believe that this would not present a significant problem and a new concrete class extending the actuator could easily be built to facilitate text-editing fields in this way.

One aspect that this experimental prototype did not resolve is how users can create and use new signs themselves. Implementing an interface allowing users to create new sign meta-data is trivial. However, incorporating new signs into a website becomes problematic. Our experimental prototype requires sensors and actuators to be placed on specific pages at design time. Unlike using new signs and options within text areas, incorporating UI controls on website pages at run-time is clearly problematic. This research has identified that user interaction and inter-attraction is the source of new signs and meanings. To fully support stigmergy would require that the website must enable users to create their own signs and allocate their own meaning at run-time.
Our experimental prototype only implemented an immediate position type of location system. Given that websites are places where we can navigate URIs that define a graph structure we can easily develop an implementation of our ranged proximity locations that exploit the graph structure of hyperlinks. This design would then provide a facsimile of the osmotropotaxis gradient found within entomology.

Such an implementation would describe the distance of a target page compared to the users’ current *explicit position*. This would be expressed as a user’s *proximity* to a sign introducing the concept of *range* by using a web-crawl of hyperlinks. The distance is calculated as the number of hyperlinks that require traversing for the user to reach the target page location. This suggested extension would require that every page have the associated Sensor class instantiated to present the signal to the user as they navigate the website. Incorporating these sensors to be included on every page within a website could also be adopted to provide pervasive actuators. This would solve our problem of how to provide users with the facility to add new sign metadata at run-time. By ensuring actuators are present on every page we could exploit the Difficulty class to determine whether an actuator is visible rather than relying on page placement at design-time.

A design that enables users to define their own signs and meanings within sub-sets of users within the website would not only mean our generic design pattern facilitates the mechanics of stigmergy, but it would also support the evolving nature of the meaning of signs as a result of user interaction and inter-attraction. Furthermore it would provide the foundation for a centralised set of stigma that could be incorporated among multiple websites providing an even wider form of coordination for users.
Having a world embedded display which provides a holistic, interpreted view of the environment state provides an emergent level of knowledge. The consensus that can be shown when exploiting the intentional contributions through the power-of-the-crowd provides a compelling knowledge that is not easily counterfeited and is very expensive to subvert. The trustworthiness verified by implicit and unintentional contributions is a reliable mechanism that can also easily be included into websites. We have suggested technical areas that future work could follow to further this research. The abstract model of stigmergy and software design pattern produced from this project paves the way to explore those avenues.


