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,

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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 sematectonic 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.

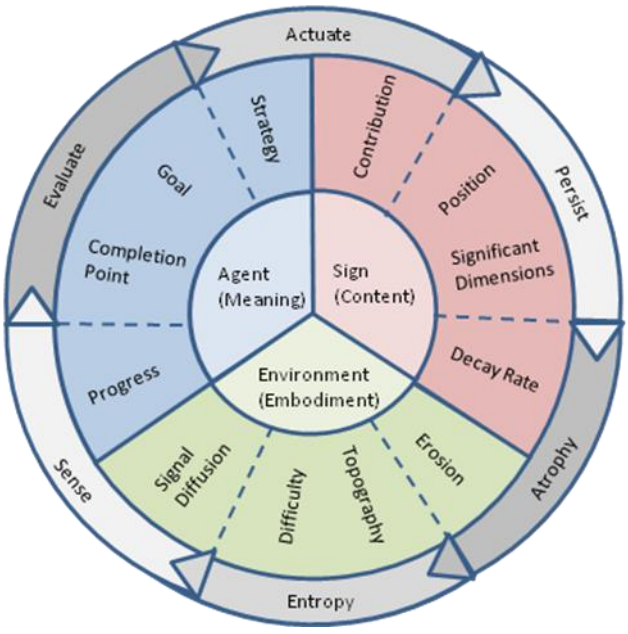

Figure 1. The Stigmergy Cycle

The model as illustrated in Figure 1 ties together a core representing the three major 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.

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 *agent*s 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 diametric 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 sematectontic 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 roll-backs 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 have the authoritive group for a specific topic and therefore wish to have the largest anthology of publications. Conversely, students wishing to minimise research effort might consider a smaller anthology of higher quality articles based on the total 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 stigmergic 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 ant 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.

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