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.

WWW 2011, March 28–April 1, 2011, Hyderabad, India.
ACM 978-1-4503-0637-9/11/03.

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 stigmergic 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 predicable 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.

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